ANNEX 00 >> GLOSSARY OF TERMS

This glossary is intended to facilitate international communication on the subject of immersed tunnels in the English language. The terms defined relate to typical design and construction practice for steel and concrete immersed tunnels and submerged floating tunnels.

This glossary was originally published in the Immersed and Floating Tunnels State-of-the-Art Report 2nd Edition in 1997. In this edition it has had some additional items added to reflect current practice and developing terminology.

ACCESS SHAFT

Temporary access shafts are commonly provided to allow entry of personnel and occasionally equipment to the interior of an immersed tunnel while floating or submerged. The shafts are usually removed when alternate access is available, such as along the tunnel. The access shaft may be attached to the temporary end bulkhead or may be attached over a temporary hole in the structure which will later have to be made watertight.

ANCHOR RELEASE BANDS

See Rock Protection.

ARCHIMEDES BRIDGE

See Submerged Floating Tunnel.

BALLAST

(1) Permanent Ballast : Non-structural solid material placed inside or outside an immersed tunnel to increase its effective weight permanently. Material placed outside should either be attached to the tunnel or retained, thereby preventing accidental falling off or loss of the material. Backfill that may be scoured or accidentally dredged away is not ballast.

(2) Temporary Ballast : Material used to temporarily increase the effective weight of the tunnel or a tunnel element during the fabrication and installation phases until replaced by backfill or permanent ballast. The material may be solid or liquid.

BALLAST TANK

Temporary tanks constructed within a tunnel element for the purpose of filling with temporary water ballast to increase the weight of the tunnel in order to aid trimming of the element whilst floating, to provide overweight for immersion of the element and for temporarily holding the tunnel element in position on the bottom of the dredged trench until sufficient ballast weight is provided by permanent concrete ballast and backfill to prevent uplift.

BACKFILL

Material placed around the sides and over the top of the tunnel within the excavated trench after the tunnel is installed in the trench. The material is usually granular, rock, or excavated material.

BINOCULAR SECTION

A term used to describe an element consisting of two adjacent circular steel tunnels, usually each of two lanes, combined into a common structure.

BORE

A term borrowed from mined tunnelling to describe a cell.

BOX (SHAPE)

An indication that the overall cross-section of the tunnel is approximately rectangular.

BULKHEAD

An upright watertight partition used to generate compartments, usually totally closing off the inside of a cell. Temporary bulkheads are provided at the ends of tunnel elements to keep water out (make them watertight) during the floating and installation stages.

BUOYANCY

(1) The resultant upward force on a body partially or fully immersed in a liquid, caused by the pressure of the liquid acting on the body. The magnitude of the force is equal to the weight of liquid displaced. Silt, if disturbed, can effectively increase the density of water. Water may be saline and density may vary with depth.

(2) Positive buoyancy or Negative Buoyancy : Jargon expressions for the amount by which buoyancy exceeds the weight of a body when totally immersed in a liquid. Positive buoyancy indicates that the body tends to float (buoyancy > weight); negative, that it tends to sink (buoyancy < weight).

CASTING BASIN

A place where elements for immersed tunnels can be fabricated in the dry, and which can be flooded to allow the elements to be floated out and taken away. Generally used for concrete tunnels. It is often purpose-built.

CELL

Continuous space within the cross-section of an element, bounded by walls, floor and ceiling. A cross-section may contain many cells, hence multiple-cell box, where for example separate cells may be used for each traffic direction, emergency egress, utilities, supply air and exhaust air.

CHAMFER

Corners of box section tunnels are often chamfered (bevelled, with the corners missing) to remove unnecessary space where it serves no useful purpose, or thickened to reduce moments and shears (haunches) and to allow dragging anchors to pass more easily over the tunnel.

CILL

Usually the highest point of the floor of a fabrication facility on which or against which the gate rests, and over which elements must pass during removal from the fabrication facility.

CLOSURE JOINT

See Joint, closure.

CONCRETE COOLING

The process of pumping cooled water through a network of embedded pipes in the walls and/or slabs of a concrete immersed tunnel element, for the purpose of controlling temperature rise during curing to reduce or eliminate early age cracking due to restraint against expansion and shrinkage at early ages.

CONCRETE IMMERSED TUNNEL

Two main types of immersed tunnel have emerged, known as steel and concrete tunnels, terminology that relates to the method of fabrication. Both types perform the same function after installation. Concrete tunnels rely on steel reinforcing bars or prestressing cables for strength. It is usual for a concrete tunnel to leave the fabrication facility with the external concrete structure essentially complete. Steel plate, if used, is non-structural and is usually limited to acting as a waterproofing membrane. (See also Steel Immersed Tunnel). Two sub-types of tunnel element exist: Segmental elements are a relatively recent development from monolithic elements.

(1) Segmental. The concrete tunnel elements are formed with a series of match-cast segments which are discontinuous and able to rotate relative to each other. Segments are temporarily prestressed together during floating and immersion of the elements. The concrete is designed to be watertight, usually without external waterproofing.

(2) Monolithic. The concrete tunnel elements are constructed as a continuous concrete structure using construction joints with continuous reinforcement. The concrete is also designed to be watertight and an external waterproofing membrane is usually applied.

DRAFT

The depth below the still-water surface of the deepest part of a floating body.

DAM PLATE

Term used in the United States for the temporary end bulkhead.

DREDGING

The operation of excavating the trench. It is usually carried out in two stages, first bulk dredging, then trimming the excavation shortly before placing an element. Compensation dredging refers to additional dredging of a waterway to make up for loss of water cross-section elsewhere in the cross-section. Maintenance dredging refers to the removal of accumulated material, usually silt, that has reduced the channel depth within a waterway.

DRY DOCK

Usually a man-made area that can be dewatered for the repair of ships. A dry dock may also be a semi-submersible floating structure. Immersed tunnel elements are sometimes fabricated or repaired in dry docks. The term is also sometimes applied to a graving dock or casting basin.

DUCT

A term used to describe a cell, particularly for supply or exhaust ventilation, or for utilities.

ELEMENT

A length of tunnel that is floated and immersed as a single rigid unit. The rigidity may be temporary and later released.

END FRAME

The steel frame cast into the end of a tunnel element around the full perimeter of the tunnel upon which the Gina seal is mounted for the immersion joint between tunnel elements. Typically comprises an I-section cast into the concrete with shear connectors, and a secondary counter-plate welded between the exposed flanges to a close tolerance on which the Gina seal is mounted and secured using clamping bars.

END OF TUNNEL ELEMENT

(1) Primary or Inboard End : The end of the tunnel element that is to be connected first. This end will face either the previously immersed and adjoining element, or the terminal structure. This end is usually the end equipped with the immersion gasket.

(2) Secondary or Outboard End : The other end of the tunnel element.

FABRICATION

The stage of construction of a tunnel element before it can float. The fabrication facility may be a casting basin, graving dock, dry dock, ship yard or a green field site. The construction of a tunnel element may need to be completed at an outfitting dock.

FACTOR OF SAFETY (WITH REGARD TO UPLIFT)

The ratio of the weight of a tunnel, or a portion thereof, to the buoyancy. Different required factors of safety may be specified depending upon whether backfill is included or removable items are excluded, and depending upon the stage of construction. Water density must be specified, since buoyancy and hence the Factor of Safety will vary with changes in water density.

FITTING OUT

Also known as outfitting, this term refers to work that is carried out while the element is afloat. It may consist, for example, of completing any remaining necessary construction of the element prior to immersion, the addition of ballast, the installation or removal of temporary equipment such as bollards, navigation lights, survey beacons, and access shafts, and adjusting the trim of the floating element. Some of the work may be necessary before transportation (towing), but any remaining must be completed after towing. Additional construction applies mainly to steel tunnels where much of the internal structural concrete may not be completed until the element is close to its final destination. Some of the work may not be carried out until the element is supported by the immersion equipment.

FLOATING TUNNEL

See Submerged Floating Tunnel.

FREEBOARD

The height above the still-water surface of the highest part of a floating body.

FULL SECTION CASTING

A construction method for concrete segmental tunnels whereby the full cross section of the tunnel, over the length of a tunnel segment, is constructed in one continuous concreting operation. The method removes the need for construction joints around the tunnel perimeter and therefore eliminates the risk of early age cracking due to restraint at the construction joints.

GASKET

(1) A device that acts as a seal between two contacting surfaces.

(2) Gina Gasket : A proprietary form of gasket used to seal immersion joints, especially on concrete tunnels, that is capable of carrying the full hydraulic compression load. It consists of a full-bodied rubber section able to transfer large compression forces, and a soft nose able to provide an initial seal under low compression. For binocular sections, each circular tunnel usually has its own gasket around the perimeter, whereas most other forms of tunnel use a single gasket around the external perimeter. The gasket provides a temporary seal and compression contact face during immersion installation, remains in place, and may provide a permanent seal at flexible joints.

(3) Omega Gasket or Seal : This seal, shaped like the Greek letter Omega (Ω) is installed across flexible immersion joints from within a tunnel after immersion and joining is complete. It may form a secondary permanent seal or it may become the primary seal. It is bolted to the internal faces each side of the joint. It may be replaced in a similar manner on an as-needed basis. Because of its shape, it can sustain fairly large longitudinal and transverse movements at the joint.

(4) Soft-nosed Gasket : See Gina Gasket, above.

(5) Temporary Immersion Gasket or Seal : This is usually an extruded rubber section that acts as a seal when it is compressed. After completion of the permanent joint, the seal is no longer needed. It may be a type of Gina Gasket or may be another type of seal that cannot carry the full hydraulic compression load, such as is commonly used in the United States.

GATE

Usually either hinged to a wall or floating, this structure is used to close off the fabrication facility from the adjacent water to allow dewatering of the facility.

GRAVEL (BED) FOUNDATION

See Screeded Foundation.

GRAVING DOCK

An area that can be dewatered to form a casting basin.

GREEN FIELD SITE

An area above water level converted to enable construction of tunnel elements, usually steel immersed tunnels. The elements may be side or end launched into the water when capable of floating, or may be incrementally launched.

GROUTED FOUNDATION BED

A foundation formed by filling the space between the underside of an element and the underlying material, which may be the pre-excavated trench bottom, with grout. Until this operation is complete, elements require temporary support.

HAUNCH

A thickening of a wall or slab to increase locally the bending strength and shear capacity of the section.

IMMERSED TUNNEL

Immersed tunnels consist of very large pre-cast concrete or concrete-filled steel tunnel elements fabricated in the dry and installed under water. By definition, an immersed tunnel must be moved from its fabrication location to its final installed location by floating at least part of the way.

IMMERSION

The phase of construction covering the period between the element floating on the surface and installed on its foundation or temporary supports at bed level.

IMMERSION GASKET

See Gasket.

IMMERSION RIG

Floating equipment used to lower an immersed tunnel to its final position, usually consisting in part of floating pontoons or barges. For large tunnel elements, a pontoon may be placed on top of the floating element near each end and the element lowered from them. Instead of each pontoon on top, a pair of smaller pontoons is sometimes used, floating each side of the element and connected by a transverse beam from which the element is lowered, These are known as catamaran pontoons. Sometimes one long pontoon is used each side with two connecting beams. These are sometimes referred to as lay-barges.

INCREMENTAL CONSTRUCTION

A method of construction whereby a short section of an element is constructed, then jacked along to enable the adjacent section to be cast against the previous section.

INSTALLATION

This phase of construction covers preparation for immersion, the immersion, foundation preparation, backfilling, and completion of the interior works.

JET FAN

A ducted propeller, usually mounted adjacent to or above the traffic, that helps to maintain air velocity within that cell. Local variations in section are sometimes used to accommodate the fans.

JOINT

(1) Closure or Final Joint : Where the last element has to be inserted rather than appended to the end of the previous element, a marginal gap may exist at the secondary end. The short length of tunnel needed to seal this gap can be cast in situ and is known as the closure or final joint. Other methods used include using a wedge-shaped final piece or sliding out a section from within a large section to close the gap.

(2) Construction Joint : A horizontal or vertical connection between monolithic parts of a structure, used to facilitate construction. A waterstop is commonly placed in such a joint.

(3) Earthquake Joint : An immersion or other joint of special design to accommodate large differential movements in any direction due to a seismic event. It is also applied to a semi-rigid or flexible joint strengthened to carry seismic loads and across which stressed or unstressed prestressing components may be installed.

(4) Expansion Joint (also may be known as Segment Joint or Dilatation Joint) : A special moveable watertight joint between segments of a tunnel element.

(5) Immersion Joint: The watertight joint that is dewatered when an element is installed at the seabed. It may remain flexible or can be made rigid, as is common with steel tunnels. A temporary immersion gasket or soft nosed gasket is usually used, and an omega seal may also be installed later.

KEEL CLEARANCE

The least vertical distance between the deepest part of a floating body and the bed beneath.

KEEL CONCRETE

Concrete, often ballast, placed in the lowest portion of an element.

LAY BARGE

See Immersion Rig.

LIFTING LUGS

Temporary lifting points from which an element is suspended during immersion, usually removed after an element is set on its foundation.

LOCKING FILL

Backfill, usually granular, placed carefully around the lower part of a tunnel to hold it in position.

OUTFITTING

See Fitting Out.

PORTAL

The structure or the end face of the structure at the two ends of the tunnel at the interface of the covered and open sections.

PRESTRESS, TEMPORARY

Used mainly in concrete tunnels to temporarily lock a flexible joint, to modify stresses until immersion, or to provide additional strength during transportation and installation.

PULLING JACK

Device attached to primary end of a tunnel element being immersed, that connects to the secondary end of the previous tunnel element and enables the tunnel element to be pulled up to the previous element and create the initial seal of the Gina gasket.

PUMPED SAND FOUNDATION

See Sand Bedding.

RIGGING

A system of lines, winches and hoists used to control the position of an element, both horizontally and vertically, especially during immersion. Lines may be attached indirectly to the shore, anchors, pontoons, derrick barges or other lowering equipment.

ROCK PROTECTION OR ARMOUR

The provision of larger stone or rock to prevent erosion or dredging of required backfill or bed. The term is also applied to systems for protecting a tunnel against potential collisions and dragging anchors.

ROOF PROTECTION

Protection provided to the waterproofing on the roof against accidental damage. Also applied to combinations of backfill and rock protection placed above the roof to protect against sinking or grounding vessels, etc.

SAND BEDDING

A foundation formed by filling the space between the underside of an element and the pre-excavated trench bottom with sand. The sand is placed hydraulically with the sand-flow or sand-jetting method. Until this operation is complete, elements require temporary support. A small gap may exist at the underside of the element after this operation, so that the temporary supports must be released or deactivated to lower the element onto the foundation.

SAND FLOW

A method of sand bedding whereby the sand-water mix is transported through a pipe system with fixed outlets in the soffit of the element. The mix is usually discharged through one outlet at a time. As the velocity of the mix decreases after leaving the outlet, sand is deposited by gravity to form a firm pancake-shaped mound almost touching the underside of the tunnel, with a small depression beneath the outlet. While pancake dimensions vary, an area of 100 square metres would not be unusual. The sand-water mix may be supplied either externally though inlets in the roof or walls, or from inside through non-return valves.

SAND JETTING

A method of sand bedding whereby the sand-water mix is transported through a jet pipe which can be moved anywhere in the void between the underside of the tunnel and the trench bottom. As the velocity of the mix decreases after leaving the jet, sand is deposited by gravity. The resulting density of the sand is less than by the sand flow method. The work can only be done from the outside.

SCREEDED FOUNDATION

Following trench excavation and before immersing an element, a gravel foundation is prepared by screeding to close tolerances and onto which elements are placed directly without further adjustment. Temporary supports at bed level are not required. In seismic zones (where sand foundations are unsuitable), a rough screeded bed may be set low and a grouted foundation formed in the remaining space between the bed and tunnel soffit.

SEGMENT

A monolithic section of a tunnel element only separated from other segments by vertical joints. For concrete tunnels, a segment is typically the length of a single concrete placing operation. Some tunnel elements, particularly in the Netherlands, consist of a number of discrete segments held rigidly together during installation by temporary prestress and joined by expansion joints.

SHEAR DOWEL

A device to transfer shear across a joint. Shear dowels are sometimes used in concrete tunnel elements across immersion, closure or expansion joints to provide continuity of alignment. Such shear dowels must permit relative longitudinal movement. For immersion and closure joints, the dowels would be embedded in cast-in-place concrete at the joint face after immersion.

SHEAR KEY

A device to transfer shear across a joint, such as segment joints or non-rigid immersion joints. In concrete tunnels, the shear key components may form integral parts of the structure of each element. The keys are usually placed in the space between the end bulkheads adjacent to the immersion gaskets so» that they can be inspected and repaired if necessary.

SILL

Spelling in United States for Cill.

SNORKEL

See Access Shaft.

SQUAT

The additional draft of a floating body moving relative to the water in which it floats, as compared with the draft when stationary. It is caused by a reduction in water pressure below the body because of directional changes in flow around the body. When keel clearances are marginal, squat may cause elements under tow to touch the bottom. Similarly, an element below a passing vessel may experience uplift due to squat or propeller wash. This may need to be taken into account in selecting safety factors against uplift during installation.

STEEL IMMERSED TUNNEL

Steel tunnels use structural steel, usually in the form of stiffened plate, working compositely with the interior concrete as the structural system.

(1) Single Shell : Term applied to a tunnel consisting of elements where an outer structural steel membrane (the shell) is constructed first, very much in the manner of a ship. The steel plate also acts as a waterproofing membrane. Elements are usually designed to leave a green field site before the structural concrete is placed, though this may not be the case when other types of fabrication facility are used. Depending upon floating stability and strength requirements, keel concrete may or may not be placed prior to launching. In this condition, draft is usually less than 3 m, making long tows relatively easy while afloat. Nevertheless, transport on barges is not uncommon. The shell plate acts as the exterior form plate for the structural reinforced concrete with which it is designed to act compositely. While stability and strength requirements may require some of the structural concrete to be placed before transportation, it is usual for this concrete to be completed during outfitting, close to the final location. Ballast may be located inside, but more usually outside on top.

(2) Double Shell : An outer steel plate, usually octagonal in shape, is added to a single shell tunnel element to act as an external form plate for tremie concrete placed as permanent ballast on the sides and for structural concrete top and bottom. The tremie concrete protects the inner shell plate from corrosion, while the outer form plate is left as sacrificial. Behaviour of the inner shell plate, and the compositely acting reinforced concrete within it, is similar to a single shell tunnel element except that the stiffening elements are usually placed outside the inner shell plate.

(3) Sandwich : This construction type consists of concrete sandwiched between two steel shell plates. Steel webs between the shells are arranged to form closed cells that are filled individually with concrete. Both the inner and outer shells are load carrying and both act compositely with the contained concrete. The concrete is un-reinforced and is formulated to be non-shrink and self-consolidating. The inner surfaces of the steel shells are stiffened with plates and L-shaped ribs that also provide the connection required for composite action with the internal concrete. The internal concrete, once cured, carries compression loads and also serves to stiffen the steel shells. The steel shells carry the tension loads.

SUBMERSION

The part of the installation activity that takes an element from being afloat to sitting on the bed.

SUBMERGED FLOATING TUNNEL (SFT)

A tunnel through water that is not in direct contact with the bed. It may be either positively or negatively buoyant, and may be suspended from the surface, or supported from or tied down to the bed. In addition to most of the loads that can act on an immersed tunnel, other loads may exert static or dynamic loads of importance, such as traffic, fouling with marine growth, tides, waves, currents, vortex shedding, storms, variations in water density and tsunamis.

SUMP

Sumps (reservoirs) are provided at the portals and at low points (nadirs) to contain quantities of fire-fighting water, run-off and leakage water compatible with the duty cycles of the pumps provided. Oil-water separators are usually required, and sumps within a tunnel most often discharge to portal sumps.

SURVEY TOWER

Masts or towers are often installed near one or both ends of a tunnel so that the tunnel position, when out of sight beneath the water surface, can more easily be determined. The towers are tall enough to extend above the surface. Survey targets are usually attached.

SUSPENDED SLAB

Slab provided to span across a cell above a space, such as ceiling and roadway slabs when ventilation ducts above or below the roadway are used.

TERMINAL STRUCTURE

The non-immersed structure abutting the first and last immersed tunnel elements.

TETHERS

Cables between a submerged floating tunnel and the bed, used to secure the position of the tunnel, similar to that used for a tension leg oil platform.

TOWING OR TRANSPORTATION

Several phases of construction may involve towing. The first tow is only a short distance from the fabrication facility to the location where outfitting for the main tow is to be carried out, if needed. The main tow is to the location where outfitting for immersion is to be done, usually close to the immersion point. The final tow is to the immersion point.

TRENCH

The excavated space below bed level into which the immersed tunnel and its foundation will be placed.

TUBE

Roadway, track and service cells are each often referred to as tubes. Also used in the jargon expression immersed tube tunnel, meaning immersed tunnel (both circular and box shaped), perhaps originally intended to imply an immersed tunnel with a circular cross-section.

UNIT

Term sometimes used to refer to an element.

VENTILATION

(1) Longitudinal: A system in which fresh air is supplied at one end of the traffic tunnel and the polluted air is expelled at the other. Jet fans or Saccardo nozzles are often used to induce air movement.

(2) Semi-transverse : A system in which a separate ventilation duct is used for the supply of fresh air through many supply vents along the tunnel. The polluted air is discharged through the end of the traffic tunnel. Also used to describe a system where fresh air is supplied from the end of the tunnel and polluted air is drawn out over the length of the tunnel by exhaust fans.

(3) Transverse : A system in which separate supply and exhaust duct systems are used, so that fresh air is distributed and polluted air is collected over the length of the tunnel by supply and exhaust fans.

WATERPROOFING (MEMBRANE)

A skin provided external to the tunnel to improve the watertightness of concrete. The membrane may be of steel or other more flexible materials. It may either be sprayed on, or applied to the exterior surface, or the concrete may be placed onto or against it. Most types of flexible membrane require protection against damage by backfill.

WATERSTOP

Special components embedded in concrete construction joints to reduce the permeability of the joint. Waterstops may be flexible for expansion joints. Hydrophilic waterstops try to expand to several times their original size when in contact with water; special types are needed for saline conditions.

WATERTIGHTNESS

A measure of the capability of a tunnel to resist the penetration of water (leakage).

WARP

Cables used to move elements. Warping is the act of moving elements using warps, usually out of a narrow channel or dock.

For prefabricated tunnel-elements the main construction material is reinforced concrete. The concrete may be working compositely with structural steel or acting on its own with reinforcement. This theme only covers the requirements for the structural concrete.

WHAT

The concrete tunnel structure should create an accessible and dry enclosed space and allow for save passage during its intended lifetime. Therefore the concrete should keep out the external water, resist all the external water and soil pressures and exceptional loads and prevent ingress from water.
The concrete construction is subject to several external loads (water, soil pressure and temperature) and exceptional loads (see theme exceptional load cases). The concrete structure is strengthened by reinforcement and, if chosen, pre-stressing. The reinforcement must be checked to meet crack-width and durability requirements. This is applicable to both concrete and steel tunnels though the particular requirements may vary.
Concrete class is as required by structural strength, durability and exposure class. Water tightness and durability can be positively affected by a high concrete density (reduced permeability), the concrete constituents selected, control of the heat of hydration and adequate curing.

WHEN

Important issues for concrete construction are:
- Concrete characteristics should be defined at an early stage in the design process so that the principles can be carried through the full design, specification and construction process.
- Pre-testing and production testing for the required concrete class and in accordance with applicable standards and project specific requirements.
- Determine the adiabatic curve of the concrete mix for use in thermal stress analysis.
- Testing the workability of the concrete mix.
- Procedure for testing the specific concrete weight after construction.
- Procedure for injection of any cracks during construction.
- Procedure for checking water tightness after flooding of the casting basin.
- In operation monitoring of the concrete performance and condition is needed to check durability.

SPECIFICATIONS

Specifications are required for the functionality of the cast and hardened concrete:
- Concrete strength in accordance with applicable standards.
- All cracks that leak and wider than 0.15 mm should be injected.
- Where a temperature / stress analysis is used, the risk of cracking should be less than < 0.7.
- To prevent DEF (Delayed Ettringite Formation) the maximum concrete temperature during hardening should not exceed 65-70°C unless special concrete (not susceptible to DEF) is used.

The concrete mix design should be specified in terms of:
- Minimum cement content.
- Maximum water/cement ratio.
- Maximum initial chloride content.
- Density range in accordance with design.
- Permeability/chloride diffusion coefficient

The following are also recommended:
- Moist curing should continue until 90% of the concrete hydration has been reached.
- Stripping of forms should wait until 75% hydration has been reached.
- Use of Blast Furnace Cement or low heat cement.

DOCUMENTATION

Testing during concrete production should be fully documented by the contractor:
- Temperature development by monitoring the thermocouples, if used.
- Parameters of the cooling system, if used.
- Water / cement ratio
- Air content
- Slump
- Concrete strength at 7 and 28 days, and, if a high percentage of slag cement is used and / or retarders, a 56-day strength may be required.
- Concrete mix components including alkali aggregate reactivity.
- Chloride diffusivity and initial chloride content.
- Petrographic testing.
- Batching tolerances.
- Additives.
- For concrete immersed tunnel projects, full scale cross-section casting trials can reveal problems associated with formwork, rebar placing, concrete vibrating, curing, etc and help to resolve them.

Trials can also assist in checking procedures regarding embedded items and cooling.

Useful tests on hardened concrete include:
- Water penetration.
- Monitoring of cracks.
- Chloride penetration (during operational phase).
- Carbonation (during operational phase).

All test reports and materials test certificates should be retained for the as-built records.

EXPECTED VALUES

Concrete strength in accordance with standards.
Variation of unit weight for structural and ballast concrete should be assessed for use in basic design.
The following typical parameters often suitable for basic design:
- maximum unit-weight reinforced concrete (for buoyancy calculations): 25.4 kN/m^3
- minimum unit-weight reinforced concrete (for buoyancy calculations): 24.2 kN/m^3
- maximum unit-weight ballast concrete (for buoyancy calculations): 23.5 kN/m^3
- minimum unit-weight ballast concrete (for buoyancy calculations): 22.5 kN/m^3

ANALYSIS (REQUIREMENTS, TIMESCALE…)

Most tests and checks need to be carried out at specific points in time during and after placing concrete.
Pre-testing of concrete mixes should be carried out to enable detailed time-step analysis of early age temperature and stress development using finite element techniques.
Testing is needed for:
- Adiabatic heat development
- Compressive and tensile strength development
- Modulus of elasticity development
- Creep & shrinkage behaviour
- Density

Testing during concrete production and casting

should be in accordance with applicable standards.
Additional routine periodic testing may be needed for:

- Density of the cast and hardened concrete
- Specific weight
- Monitoring of cracks

Durability and permeability tests needed include:

- Water penetration test
- Chloride diffusion test
- Electrolytic chloride resistance test

Temperature and stress analyses are needed during the design stage to define the basis for how early age cracking will be controlled. During construction, analyses on a pour-by-pour basis are needed for actual site conditions.

Special tests may be needed for:

- check of unit weight (concrete, amount of reinforcement, thickness)

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

These should be derived from the design so that construction and operation can be monitored as described.

REMEDIAL MEASURES/ACTIONS (FOR UNEXPECTED BEHAVIOUR/VALUES)

For cracks see “Cracks – concrete construction”.

LINKS TO OTHER OWNERS GUIDE THEMES

Immersion joints
Segment joints
Cracks – concrete construction
Exceptional loads

PERFORMED BY / RESPONSIBLE
Subject to type of contract and / or risk allocation:
Functional requirements - Owner
Structural design & detailing – designer / contractor
Mix design – designer / contractor
Specifications of materials – designer / contractor
Thermal, stress and strain analysis – designer / contractor
Full scale cross sectional trial tests – contractor / designer
Monitoring concrete production and documentation – contractor
Monitoring temperature development in hardening concrete – contractor / designer
Leakage monitoring and repair during construction – contractor
Leakage monitoring and repair during operation – Owner

ANNEX 02 >> CRACKS – CONCRETE CONSTRUCTION

A concrete immersed tunnel is usually required to have a durability of at least 100 years and to be watertight. However reinforced concrete has the unfavorable property of forming cracks due to bending or tension. These cracks are "necessary" because otherwise the tension reinforcement in the concrete is not functional. The number and width of cracks has to be limited for durability and watertightness. Requirements for crack control will vary depending on the environment of the tunnel and whether the tunnel has an external waterproofing membrane..

WHAT

Cracks in concrete occur when tensile stresses in the concrete exceed its tensile strength. Subsequent to the cracking, all tensile forces must be carried by the reinforcement. Tensile stresses can be caused by external loading, either bending or tension, or by restrained deformation, which can be caused by temperature change or shrinkage, or any combination of these. The resulting crack widths depend partly on the amount, the area and the depth of the reinforcement. Good detailing of the reinforcement can reduce crack widths in such way that durability of this reinforcement is not a problem.

To ensure an adequate water retaining barrier, a minimum zone of the concrete must remain uncracked under all loading and restrained conditions. This implies full section tension cracks are unacceptable; one cause of such cracks is restrained deformation of green (hardening) concrete. Steel reinforcement can limit the number and width of cracks, but the predominant water retaining function will require the avoidance of full depth tension cracks. The thickness of the concrete structure in an immersed tunnel can usually be classified as "thick" concrete. Unless special precautions are taken, this can result in a larger temperature differential between the centre of a section and its surface than for thinner sections. Cracks may already have formed in the surface layers before the centre has cooled, and surface restraints may subsequently cause the centre to crack, forming through cracks. This is also a particular concern when casting against cooled concrete. For example, one method of reducing full depth cracking at this interface in green concrete, depending on the dimensions of the structure, is by reducing the heat rise of the new concrete. Methods used have included the use of cooling pipes within the concrete, the use of low heat cement, ground granulated blast furnace cement, increasing the PFA (pulverized fuel ash) content of the mix and assuring an unrestrained deformation of the hardening concrete.

Flexural cracking is restricted to the surface zones and can therefore be acceptable, provided the crack widths are controlled to preserve durability.

WHEN

Important issues to reduce or prevent cracking are:

Design stage

- Crack-width due to bending and tension shall be in accordance with applicable standards and depend on the environmental conditions.
- Crack-width in relation to water pressure must be considered.
- An adequate uncracked concrete depth must be assured.
- Methods to prevent full tension cracks of the green concrete, either by cooling or full section casting must be developed.
- Use 3D finite element models to design cooling systems or to prove functionality of unrestrained casting by defining temperature and related stress and strength development over time.

Pre-construction

- Determine the adiabatic curve of the concrete mix for use in thermal stress analysis.
- Pre-test concrete mixes for early age properties

SPECIFICATIONS

- Cracks carrying water and wider than 0.15mm must be injected.
- In temperature / stress analyses, the: risk of cracking (calculated tensile stress/available tensile strength at any point in time) must be below 0.7 for watertight concrete, and a target of 0.5 is recommended.
- Cooling pipes must be properly grouted after use.
- Limits on flexural crack widths for internal and external surfaces are needed

DOCUMENTATION

- Input for the temperature and stress analyses must be documented.
- Adiabatic curve of concrete mix and early age concrete mix properties, such as:
  - tensile and compressive strength, elastic modulus, creep and shrinkage parameters.
- Temperature and stress analyses should define:
  the intensity and duration of the cooling.
  location, flow rate, coolant used and size of cooling pipes.
  location of thermocouples.
  increase of in temperature of coolant.
- Temperature and stress analyses should predict the development of the cooling and the temperature development at the location of the thermocouples.
- Cooling pipes should be pressure tested at twice the expected maximum working pressure during cooling.
- Thermocouples and flow control devices should be tested before use.
- Temperature of fresh concrete mix at placing and ambient temperature.
- Limits on ambient conditions assumed in analyses i.e. maximum and minimum temperatures, wind speed, assumptions on formwork materials and curing mats.
- Actual temperature/time curves versus predicted should be compared to adjust mix.
- Records of crack surveys, mapping extent and width of cracks arising during construction.

EXPECTED VALUES

Measures to prevent cracking (e.g. use of cooling) are recommended for all concrete thicknesses exceeding 700 mm.

Maximum flexural crack width:
– internal surface = 0.25mm
– external surface = 0.15mm

Maximum flexural crack width for non-watertight concrete:
– internal surface = 0.25mm
– external surface = 0.2mm

To achieve an acceptable risk of cracking, maximum temperature differentials across construction joints or between the surface and core of the concrete may be specified, typically

D_{int} = 15°C

D_{ext} = 15°C

Temperature limits should also be derived, based on the stress analysis of the tunnel structure during early ages, as this may impose stricter limits than the D_{int} and D_{ext} values given above.

ANALYSIS (REQUIREMENTS, TIMESCALE ..)

Most tests and checks need to be carried out at specific points in time during construction.

Special tests may be needed for:

- check of unit weight (concrete, amount of reinforcement, thickness)
- crack-width due to bending and tension, limit-value depending on water pressure and durability

Routine periodic tests may be needed for:

- Concrete strength
- Durability (concrete cover)
- In case a cooling system is used:
- Temperature fresh concrete mix
- Temperature development of thermocouples
- Temperature of in and outgoing cooling water

Note: During operation, the monitoring of cracks should be carried out on a routine basis during planned structural inspections.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

These should be output from the design so that construction and operation can be monitored as described.

FUTURE REMEDIAL MEASURES/ ACTIONS (FOR UNEXPECTED BEHAVIOUR/VALUES)

Cracks leaking water and excessively wide cracks must be inspected and injected . However an inspection regime should be developed for the design life to monitor the effectiveness of remedial works.
The choice of repair material is important and aspects such as effectiveness, strength, flexibility and durability should be considered.

LINKS TO OTHER OWNERS GUIDE THEMES

Exceptional load cases
Immersion joints
Segmental joints

PERFORMED BY / RESPONSIBLE

The suggested responsibilities for elements relating to cracking in concrete are:

Design & detailing – designer / contractor
Specifications of materials – Owner / designer / contractor
Concrete batch testing – Contractor
Full scale cross sectional trial tests – Contractor/designer

Annex 03 >> FIRE PROTECTION

Fire protection materials can be applied to the interior of immersed tunnels where risks of exposure to fire are deemed to be high and the consequences in terms of structural failure, catastrophic inundation or loss of service are unacceptable. This annex is written with concrete tunnels in mind but the principles also apply to steel tunnels.

WHAT

It is common practice to apply fire protection material to inner faces of a tunnel above the roadway or railway and to exposed parts of walls in critical areas in order to minimise damage in the event of a fire occurring within the tunnel. The need for fire protection will depend on the likelihood and magnitude of fire that could occur in the tunnel.

The project objectives for protecting the tunnel against the effects of fire will depend on the Owner's view of the impact of closing the tunnel for repairs combined with the risk of such an event occurring, or even total collapse of the tunnel, weighed against the capital cost of installing the material. Minimum objectives should be:

- To prevent loss of life by maintaining structural integrity and preserving escape and intervention routes and safety critical systems.
- To ensure the structure can be inspected and repaired safely and be returned into service within a short time period after a fire.
- To prevent or limit spalling of concrete according to the Owner's criteria.
- To control temperatures to limit the loss of strength, permanent deformations and cracking in the structure.

To determine the magnitude and likelihood of a fire, a risk assessment should be undertaken- that considers passage of dangerous goods, traffic density, safety systems and emergency services response time etc. Decisions on the allowance of dangerous goods transports in the tunnel should be based on a separate principal risk assessment comparing the risks of transports in the tunnel with the risks of transports along alternative routes. However the normal outcome of such assessments for most major sub-aqueous road tunnels and rail tunnels is that fire protection should be provided. Owners have an important early input to a project in deciding the nature of goods that may be permitted through the tunnel.

Fire protection can be applied as a board or as a spray material. Board materials can be applied before concreting by placing the boards within the formwork and partially inserting screws into these boards to create a mechanical anchorage with the concrete once it is placed, or be applied subsequent to concreting by bolting. Surface-mounted boards can be temporarily removed for inspection of the sub-surface and replaced easily and quickly after a fire. Both board and spray applied materials can be coated to achieve required finishes for tunnel lighting and cleaning.

The use of polypropylene fibres in the concrete mix can be used to compliment the externally applied fire protection and to reduce spalling by absorbing high pressures in the concrete occurring due to evaporating water. This is a relatively recent innovation but has now been used on several immersed tunnels. Fibres will alter the properties of concrete and this must be considered in design. It is not recommended to use only polypropylene fibres without passive protection to the inside surfaces unless a thorough risk analysis and structural assessment has been performed for the expected fire load. Specific assessments must be made of strength loss and any consequential risk of failure or instability that may arise, particularly in tensile zones. Potential cracking of the structure due to distortions arising from high temperatures should also be assessed as these could give rise to leakage or a severe reduction in durability.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Important tests and procedures associated with fire protection are:

Furnace testing
Fire tests should be undertaken with representative samples of concrete (in terms of concrete composition, manufacturing/curing, geometry and mechanical loading, including restraint to thermal expansion) onto which fire protection has been applied. The method curing and sealing the samples during transit to the testing laboratory is important to ensure that the vapour pressure characteristics within the concrete matrix are retained when tested so that the risk of spalling can be correctly evaluated. This is especially important if a "no spalling" criteria is specified. Detailed specifications for furnace testing need to be developed on a project specific basis, to reflect the design fire curve specified and project specific conditions.

Furnace tests should ideally include fire testing of joint gaps (immersion joint and segment joint) to check that protection details at joints and joint sealing products used will limit the temperature at joint seals to acceptable levels. Testing should include anchors which are used to install the fire protection system at the correct spacing and the joint detail between board systems.

Guidance and specifications for fire testing are available from various testing institutions and authorities. For example: 2008-Efectis-R0695 - Fire Testing Procedure for Concrete Tunnel Linings. Although this is for bored tunnel linings the principles can be applied to immersed tunnels.

Trial panels
To demonstrate methods and finishes ahead of construction

Adhesion testing
Both on trial panels and in situ during application

Thickness measurement (spray material)
During application/manufacture

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY…)

Magnitude of fire and heat generation curves to be applied:

There are a number of fire curves that are used to replicate the heat generation of a fire.
- RWS curve (widely used and reflecting maximum temperatures likely to be attained in case of a heavy goods vehicle fire).
- ISO 834/EN 1363-1 (used for building applications, and for tunnels in which only cars are allowed).
- Hydrocarbon Eurocode 1 Curve (EN 1363-2) (not used very often for tunnels).
- HCM Modified Hydrocarbon Curve (French alternative to RWS).
- RABT curve (German approach).

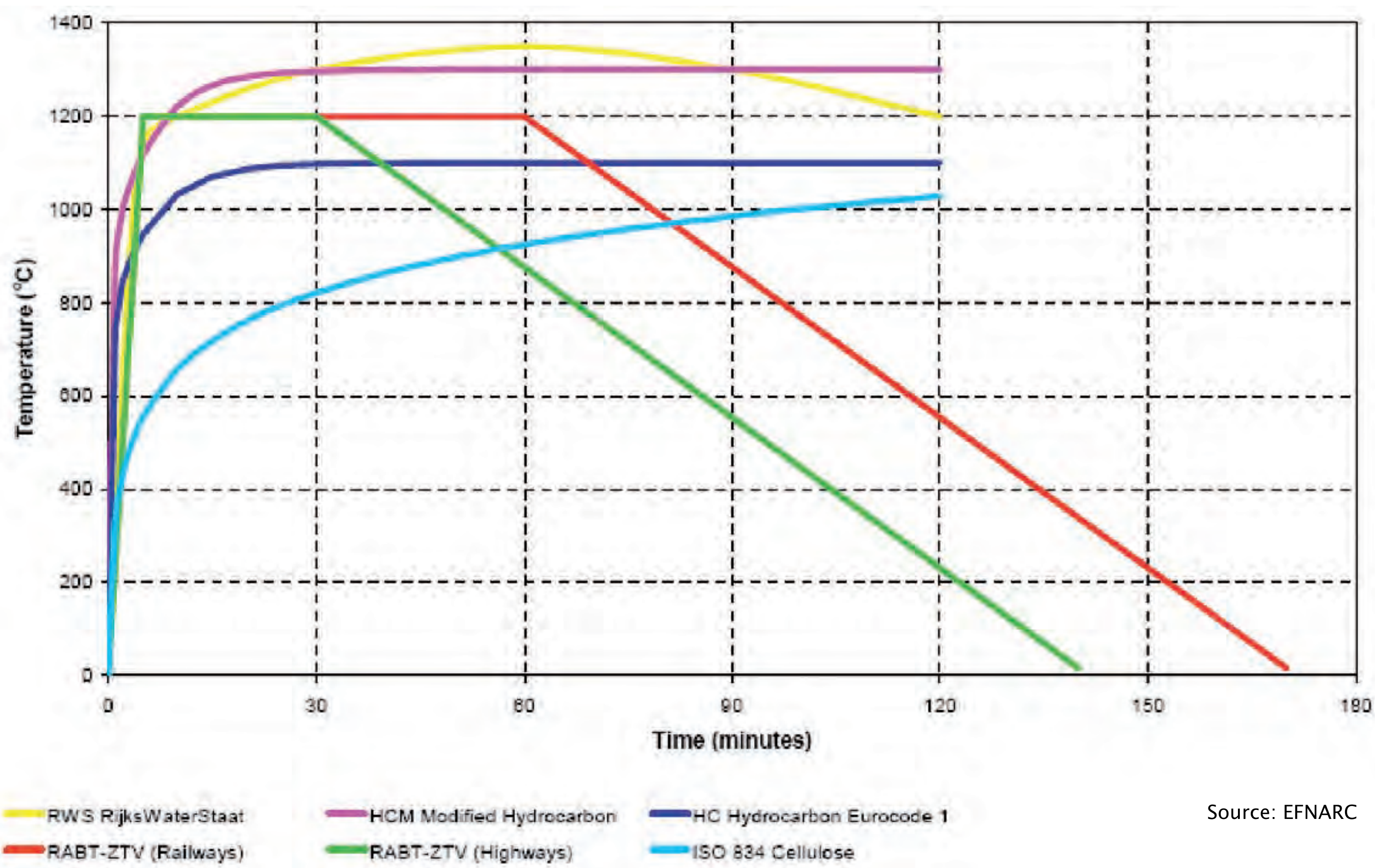
The most widely used of these fire curves is the RWS (Rijkswaterstaat) fire curve for maximum temperature and rate of rise in temperature; this represents a 300MW fire lasting 120 minutes reaching a maximum temperature of 1350°C. The modified hydrocarbon curve is also often used for the maximum total heat generated. The Hydrocarbon Eurocode 1 Curve is also sometimes applied for four hours. A combination of curves can be applied in design.

Fire curves up to 3 hours with or without a cooling phase have been adopted on some projects.

Extents of application

The top slab and external walls of the tunnel, where exposed above the roadway or trackform should be treated with fire protection material. These elements of the structure are the watertight elements and must remain watertight. Due to bending moments from external loads tension exists in the reinforcement at the inside faces. Loss of strength in the reinforcement could cause structural failure and permanent deformations, and so these areas should be protected. Inner walls of the structure are acting mainly in compression and have a high degree of redundancy. Loss of section can often be tolerated without causing major failure, provided deflections are controlled. Only repair would be required. It is therefore common to treat only the upper part of this wall where it connects to the more sensitive roof slab, and where temperatures are highest due to a fire. Owners should decide on the acceptability of undertaking repairs versus the cost of initial protection at inner walls.

External walls should be treated with fire protection unless it can be demonstrated by computer analysis that temperatures arising from a fire will remain at an acceptable level. It should be noted that wherever any loss of section or permanent loss of strength due to overheating occurs, the stress distribution



Source: EFNARC

in the structure will change and result in a permanent reduction in structural safety. Such reduction may or may not be acceptable.

Temperature limits to be achieved in concrete and reinforcement

A common specification used is:

- Maximum temperature at surface of concrete 250°C
- Maximum temperature of reinforcement 280°C

These criteria are intended to prevent permanent loss of strength and stiffness, and are intended to limit the risk of permanent plastic irreparable deformations. Note: this data applies to C30 siliceous concrete, for other concretes lower values may need to be determined. All parts of the structure should be assessed to determine whether less or more onerous requirements should be imposed. Prevention of surface spalling is not guaranteed by these temperature limits. If the Owner wishes there to be no spalling this should be clearly specified. If an amount of damage that will require repair can be accepted, then this should also be specified. Typically surface spalling may begin to occur at temperatures of about 200°C. In particular, special considerations have to be taken in case of the use of permanent pre-stressing in wide spanning top slabs.

Adhesion properties - to resist suction pressure

All fire protection systems should be designed to resist cyclical suction pressures arising from passing vehicles or trains. A pressure of 1.5 to 2.0kN/m^2 is typically specified in the absence of rigorous analysis and is a good guideline. Systems that are supported on frameworks or suspended ceilings may have additional requirements for the strength and stability of the framework under dynamic loading from vehicles and trains. Systems should be subject to testing to demonstrate adequate behaviour. The amount of cycles that a system should be tested for can vary depending on traffic intensity and suitable test criteria and acceptance limits should be developed.

Surface preparation specifications

For spray applied materials cleaning of concrete surfaces (in particular to remove curing agents, formwork release oils and similar) is essential and should be carried out by pressure washing. It is advisable to use a mesh attached to the substrate to ensure that physical bonding to the surface is achieved. For long term durability it is advisable to use 316 stainless steel or plastic coated galvanised steel mesh. Standard galvanised steel should not be used. Board materials require no specific surface preparation.

Density

Density of materials should be determined by testing

Material characteristics

Materials should be inert and not produce fumes under fire conditions. In order to be able to handle peak temperatures in tunnels fires the melting temperature of fire protection materials should exceed 1350C, regardless of the design time-temperature curve. Materials should be durable and resistant to the effects of moisture ingress and the corrosive environment within tunnels. Resistance to repeated wall and ceiling washing with detergents is necessary where this is done. Criteria for water pressure and distance applied should be developed according to the expected maintenance equipment and in consultation with the materials manufacturer.

Reflectance levels will be specified for the tunnel lighting design. Most fire protection materials can be finished with suitable coatings for this purpose, or separate cladding systems can be used.

Design life should be specified. It should be anticipated that replacement of the fire protection may be needed over the life of the structure. Common design life requirements are currently between 25 and 50 years. Materials bolted to the structure are simple and quick to replace. Boards cast into the structure and spray-applied materials may be more difficult and time consuming to replace or remove to inspect leaks. In all cases, utilities, lighting, fans, overhead power supply systems (rail), etc. and other items within the tunnel will be obstacles to work around during any replacement exercise.

Requirements for resistance to moisture (from seepage behind the material), frost or other specific environmental conditions relevant to the particular project should be specified. Other aspects could be specified by the Owner or be left to the supplier to recommend, such as:

- Minimum Compressive strength
- Thermal Conductivity
- Specific Heat
- Cohesive/Adhesive Strength

Health & Safety procedures for spray materials

These must be considered for operatives involved with spray applied materials. Products and their application that involve health risks should be avoided.

Joint filler materials

There are a limited number of products on the market that can be used for sealing joints and that can tolerate the high temperatures required by the fire curves. Care in the selection of these materials is necessary to ensure that the seals in the immersion joints, and the cast-in waterstops in segment joints are not damaged by heat. The surface sealant and joint gap filler material can be replaced whereas the main watertight seals cannot.

Sealants and filler material should be selected to be compatible with watertight seals and to limit temperatures at the watertight seals to levels acceptable to the seal manufacturers, so as not to impair their performance.

Density of Polypropylene fibres

If polypropylene fibres are introduced into the concrete mix the fibres may not need to be added to all parts of the structure, only the zones requiring protection. The quantity of fibres to be added to the concrete mix is in the order of 1-2kg/m^3. The properties of concrete must be thoroughly tested to understand the effect on strength, workability, leakage and characteristics relevant to controlling early age cracking. The inclusion of fibres may reduce spalling but may not eliminate it; ravelling during a fire has been shown in some tests to eventually result in a total loss of section. Polypropylene fibres will not prevent strength loss of materials or stiffness of the structure and would need to be used in conjunction with a passive fire protection layer.

DOCUMENTATION (FORMAT, DEADLINES)

Test reports to be expected include:
- Fire test reports (full description of all furnace testing of the complete system)
- Adhesion test reports
- Dynamic load test reports
- Material characteristics test reports

General test information can be obtained ahead of procurement and backed up by trials of the actual materials and conditions during the construction contract. Reports from testing carried out during construction should be retained in the project maintenance files.

EXPECTED VALUES

Thickness of applied spray material can be achieved to a high accuracy using automatic equipment that is controlled during application. Therefore no reduction below minimum thickness is expected. Board systems are manufactured to precise thicknesses, therefore the tolerance on thickness is expected to be in the order of -0mm / +3mm.

ANALYSIS (REQUIREMENTS, TIMESCALE ..)

Structural analysis of conditions during and after a potential fire is required to demonstrate that the subsequent strength capacity of the section exceeds the demand due to applied external loading, even if loss of material strength occurs due to overheated concrete and reinforcement. For the accidental load situation during the fire, the factors of safety may be reduced. If it is shown that there may be a loss of strength or reduction in stiffness, recommendations for how to recover the necessary factors of safety for continued use of the structure are required.

The potential effects on the long-term durability of the structure from large deformations causing cracking should also be investigated.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

Thicknesses of materials should be treated as minimum requirements. Furnace testing should meet the specified fire curve temperatures as a minimum requirement.

REMEDIAL MEASURES/ACTIONS (FOR UNEXPECTED BEHAVIOUR/VALUES)

Defects in materials can be rectified during construction without difficulty. Defects or damage arising during the operational design life due to accident or vehicle impact can be repaired locally for all types of fire protection. Subsequent to a fire, simple replacement of lost or fire damaged material while the structure is under load may of itself not be adequate and analyses should be made.

LINKS TO OTHER OWNERS GUIDE THEMES

Structural form
Internal finishing works
Concrete
Exceptional load cases
Joints- immersion
Joints - segment

PERFORMED BY / RESPONSIBLE

The suggested responsibilities for elements relating to fire protection materials are:

Design & detailing – designer
Performance requirements – Owner
Material specifications – designer/supplier
Witnessing of contract specific fire tests – Owner, designer & contractor
Repair during construction – Contractor
Repair during operation – Contractor or Owner (depending on contractual requirements for defects liability period after completion of construction)
Maintenance of replaceable items – Owner

Annex 04 >> Immersion Joints

Immersion joints are used for all forms of immersed tunnel. They are a logical result of using a construction method where precast elements are submerged and subsequently connected. The immersion joint is defined as the joint between immersed tunnel elements. It enables a long tunnel to be divided up into shorter elements for ease of construction, handling, launching, towing and installation as multiple pieces.

WHAT

Immersion joints are joints between tunnel elements and are the joints formed during the installation of the elements. These joints may be made rigid or they may remain flexible. Provisions for shear transfer, both horizontal and vertical, is almost always provided. Limits to the maximum relative displacement across a joint may also be provided.

Most concrete tunnels have flexible immersion joints without structural continuity through them. Conversely, it is more usual for steel immersed tunnels to have rigid immersion joints with structural continuity across the joint. Additional seismic restraining measures may also be incorporated into a flexible joint to restrain the joint from opening during a seismic event, preventing not only loss of watertightness but also entry of unwanted materials into the joint and thus preventing it from closing again; these additional measures may be active only during a seismic event.

Waterproofing of the joint is achieved with a combination of rubber seals. Three stages of sealing occur – initial, second and final. An initial seal is made by a soft flexible rubber seal which is compressed by pulling the element being immersed towards the previously placed element. This initial watertightness allows dewatering of the narrow chamber between the bulkheads of the adjacent elements. Hydraulic pressure created by dewatering will compress the seal and improve watertightness further.

The use of a Gina-type gasket (or seal) is becoming widespread. This combines the initial and second sealing process. It has a soft nose on the mating surface that acts as the initial seal while the main body of this seal is made from a harder rubber that is designed to carry the full compressive load resulting from dewatering the joint. The Gina seal is normally considered to be a permanent seal.

Most US steel tunnels use separate flap type seals as the initial and second seals. These seals cannot carry the compression load that occurs during dewatering, so a flat "stop bar" behind the seals carries this load.

Both the initial and second seals, which are flexible seals relying on contact pressure, will function properly only if the face onto which they are installed and the mating face are sufficiently smooth, planar and parallel. It is strongly recommended that the established solution using I-sections cast onto the ends of the tunnel elements with a close tolerance steel counter-plate welded onto both I-profiles is used unless very special installation facilities for the end frames are available at a reasonable cost. The established solution enables the necessary degree of accuracy in construction to be achieved.

Almost all flexible immersion joints today include an Omega-type seal as the third final seal, on the inside of the Gina seal and clamped to the internal perimeter of the end frame on which the Gina seal is mounted. This is treated as a permanent seal. Some specifications require these seals to be installed before removal of the temporary bulkheads at the immersion joints, on the basis of safety. Whilst this is recommended it is not essential but is a decision for Owners to take based on risk assessment considering site specific conditions, construction sequence, other safety provisions and preference. However it should be understood that it is a difficult process to install the seals in the restricted space between the bulkheads and installation may take time.

In theory, Omega seals can be replaced and it is important that joint details take this into account, with access for inspection and maintenance to be provided. In practice it would be undesirable to undertake such an extensive replacement operation and the hardware and all bolts will need to ensure durability for the life of the structure. Stainless steel hardware might therefore be appropriate, or the application of cathodic protection.

The space between the second and this third seal could fill with water if there is leakage at the second seal, Small drain pipes with plugs can be installed to drain off this leakage. This can be a significant issue in seismic areas where elasticity of the joint may be important; trapped water could burst the Omega-type seal during seismic motions. While it can be shown that Gina-type seals can slip across the mating face due to differential settlements without damage, instances where the seal rolled over and was damaged exist. In contrast, Omega-type seals will suffer shear deformations that must be taken into account in their design. The seals are clamped onto steel frames embedded at the end of each tunnel element. In Japanese concrete tunnels, M-shaped steel profiles are used instead, clamped and welded to the steel end collars.

The immersion joint can be made rigid for both concrete and steel tunnels. If there is a steel membrane or shell, the steel can be welded to make it continuous across the joint (thus forming the third seal) before completing the joint with concrete to make it rigid. The section properties across a rigid joint are often similar to the rest of the tunnel.

A flexible immersion joint permits longitudinal contraction and subsequent expansion, and permits rotation in the horizontal and vertical plane. Shear keys may limit or prevent vertical and horizontal relative shear movement across a joint. They are often located in the tunnel walls and slabs or in the ballast concrete layer. A number of different approaches to shear key design exist. Infill concrete or cover panels are placed on the inside of the joint to achieve a smooth finish within the tunnel. Rigid joints are sometimes used to carry seismic loads that exceed the capacity of shear keys in a flexible joint.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Important procedures and tests in connection with the immersion joints are:

- Production testing of rubber seal for defects e.g. pin holes.
- Production testing of rubber seal to verify mechanical properties, especially where bespoke seal designs are used.

- Procedure for vulcanising all rubber seals on site to suit as-built dimensions of the seal mounting frame.
- Procedure for lifting and fitting all rubber seals on site to ensure even clamping and correct alignment of pre-formed corner pieces.
- Checking planarity at element ends (end frames) of seal supporting and mating (counter-plate) surfaces to ensure specified tolerances are met, particularly at welds.
- Procedure for grouting and 100% filling of all voids behind the counter-plates, such as the space between an I-frame and counter-plate, and the rears of end frames.
- Verifying corrosion prevention measures are effective in advance of immersion e.g. checking electrical continuity of reinforcement, verifying isolation between items if specified and confirming electrical connections to CP anodes and monitoring equipment.
- Measurement of the joint gap after immersion to verify design assumptions and assist with final design of closure joint.
- Where an additional seal is installed at the joint from within the tunnel, such as an Omega-type seal, pressure test for this seal once installed to verify that the factor of safety against watertightness is achieved.
- Settlement measurement in relation to forming shear keys, to ensure all specified settlements have occurred before forming or fixing the key.
- Joint dewatering (from cleaning water) should be carried out during construction at regular intervals as soon as the infill concrete has been cast.
- Monitoring for long term seepage is desirable. Access points to enable checking for water in the bottom of the joint are needed if this is required.
- Routine inspection and dewatering of the immersion joint to ensure no build-up of water occurs in the base of the joint.
- Routine inspection of bearings in shear key assemblies, if used. Removable covers are required for this.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

Seals used for immersion joint dewatering (e.g. Gina-type seal)

For the type of seal used to get the initial seal:

- Height of soft nose or protrusion of flexible end
- Determination of the jacking force to obtain an initial seal
- General arrangement and procedure for making the initial seal.

Watertightness of the main dewatering seal should be specified. A common factor of safety to use is 2.5. However this is quite onerous for deep water conditions and a more refined approach could be used, based on a reliability approach considering water levels that may arise for appropriate return periods, with an additional margin of safety applied to this.

The capacity of the seal should be checked taking into account:

- Thermal variations.
- Shrinkage.
- Rotations of the joint caused by settlement.
- Out-of plane tolerances and local tolerances on the end frame.
- Tolerances in placing the tunnel element.
- Long term relaxation in the rubber.
- Backfill friction restraining longitudinal movement.
- Tidal variation in water levels.
- Provision of residual compression capacity (often 10mm) once all other effects are taken into account.
- Ensuring a minimum of 10mm compression is achieved above the level required to maintain a seal.
- Movement due to seismic action.

Seals should be solid rubber without any internal voids. Rubber material should be specified by the supplier taking into account requirements for design life within the service environment.

Design life should be specified for the full design life of the tunnel unless this seal is temporary.

Additional seals installed from within tunnel

When used, these seals are typically rubber or metal (e.g. Omega-type or M-type seals).

When the immersion joint is to be made rigid, the gap between the two tunnel elements is often sealed with steel closure plates welded between the end frames. The design life of these plates should be specified as the full design life of the tunnel. In this case, the seals used for dewatering are considered temporary. The closure plates may not be sufficient to transfer tension and compression across the joint; the rigid joint must be detailed to transfer load continuity across the joint.

When the immersion joint is to remain flexible, the design life specified should be the full design life of the tunnel. The need for replacement is not essential but detailing should permit this. The permissible shear deformation of the seal must be stated and design of the joint made such that the deformation cannot be exceeded. For rubber seals, the clamping torque required for the bolts to achieve adequate compression in the seal flanges must be stated to ensure watertightness. After installation, these seals should be tested for watertightness. Any rubber material and reinforcement layers should be specified by the supplier taking into account loading and requirements for design life within the service environment.

Steelwork

Clamping systems and the end frame on which the seal is mounted need to be designed to resist compressive forces exerted by the deforming seal. Design life should be specified to suit long term corrosion prevention strategy. Elements of the clamping system can be designed for short term life provided their corrosion has no consequential effect on parts of the frame required to achieve the full design life of the tunnel.

Corrosion protection measures should be specified to be compatible with the overall corrosion prevention strategy for the tunnel.

Tolerances specified for the end frame are typically ±3 mm for the counter-plate and ±5 mm for planarity over the height and width of the tunnel. Larger tolerances, e.g. ±4 mm and ±8 mm, can be specified if the seals are capable of absorbing the greater differences. In considering these tolerances it is necessary to consider the deflection of the element after it is floated and immersed, especially when parts of the element are completed afloat. As a result, the end faces could be pitched in opposite directions by an amount that could equal or exceed the planarity specified. This must be taken into account in setting the design slope of the end faces and in the design of the initial and dewatering seals.

Internal finishes to immersion joints

It is vital to the integrity of the tunnel that the seals are protected against damage including fire. Where joints are to remain flexible, the movement and sliding capability of cover panels and infill (e.g. concrete) should be specified along with compressibility of any joint gap filler and sealant materials.

Infill concrete and panels/covers in the walls should be designed for impact resistance and the materials specified for fire resistance.

Shear keys

For steelwork shear key assemblies, bolt torques may need to be specified where the keys are bolted back into the concrete structure supporting them. Movement capacities and load capacities for bearing components must be specified. It is very important also to specify the sequence of backfilling and at what point in time or after how much settlement the shear keys are to be fixed (locked). Even when immersion joints are to be made rigid, temporary shear keys may be required to ensure that excessive relative deflection across the joint does not occur prior to making the joint rigid. This is especially important in soft ground and for deep tunnels. Tests should be made to demonstrate that seals remain watertight, and that they slide and do not "roll" under proposed allowable relative movements.

Finishing seals

Finishing seals are need to be applied around the inside perimeter of the tunnel to seal joint gaps. Specifications are needed for the following characteristics of the seals:

- Compressibility characteristics
- Fire resistance properties
- Watertightness
- Durability properties – within the tunnel at road or track level, needs resistance to a wide variety of substances - cleaning detergents, hydrocarbons (liquid and vapour), particulate from vehicles, chemicals within vehicle emissions etc.

Frequency of replacement must be as long as possible to minimise maintenance closures in the tunnel. Seals under the roadway or track can be especially difficult to access; these seals should preferably be specified with the full design life.

DOCUMENTATION (FORMAT, DEADLINES)

Records of corrosion monitoring and leakage monitoring should be held on the maintenance files.
Movements of the joints versus time during construction should be held on the maintenance file.
Grouting records for the end frame should be held on the maintenance file.
Any tolerances outside of the specified limits should be recorded on the as-built drawings.

EXPECTED VALUES

The following movements are not prescriptive specifications but are typical values:

- Longitudinal movement; 25mm closing, 25mm opening (dependent on element length and thermal variation)
- Vertical shear movement ±0mm
- Horizontal shear movement ±0mm
- Vertical rotation 0.05 degrees
- Horizontal rotation 0 degrees

Note, if the tunnel is in a seismic region movements may be significantly greater and separate measures may be needed to limit opening of the joints.

ANALYSIS (REQUIREMENTS, TIMESCALE ..)

Most tests and checks need to be carried out at specific points in time during construction. Short term and long term settlement monitoring is required during and after backfilling in order to detect any problems that may require adjustment of procedures. Rotations can occur during backfilling. Surveying must always be carried back to a stable reference point since tunnel element movements may continue well beyond the construction period. It is particularly important that element positions be correctly known in the vicinity of closure and final joints.

Routine periodic tests may be needed for:

- Leakage monitoring
- Settlement monitoring for determining time to install shear keys and for understanding and monitoring long term behaviour.
- Corrosion monitoring
- Removal of water during construction before low point sumps become operational

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

Expected displacements and tolerances thereto upon which the design is based should be available throughout construction and operation. This will enable early remedial action to be taken when monitored movements approach or exceed design limits.

REMEDIAL MEASURES/ACTIONS (FOR UNEXPECTED BEHAVIOUR/VALUES)

Unexpected leakage behind the end frame may perhaps be corrected by grouting. However, an inspection regime should be developed for the long term to monitor the effectiveness of remedial works, particularly through seasonal changes.

LINKS TO OTHER OWNERS GUIDE THEMES

Cathodic protection – for steelwork mounting frame and clamping systems
Placing of tunnel elements
Fire protection

PERFORMED BY / RESPONSIBLE

The suggested responsibilities for elements relating to immersion joints are:

Design & detailing – designer
Specifications of materials – designer
Movement monitoring during construction – contractor
Leakage monitoring during construction – contractor
Leakage repair during construction - contractor
Movement monitoring over life – Owner

Leakage repair during operation – Contractor or Owner (depending on contractual requirements for defects liability period after completion of construction)
Maintenance of replaceable items e.g. bearings - Owner

ANNEX 05 >> SEGMENT JOINTS

Segment joints are relevant only to concrete tunnels that follow the philosophy of segmental construction with watertight concrete. The segment joint is defined as the joint between concrete segments which together form an immersed tunnel element. Sometimes also known as expansion joints, they are formed by match casting concrete against a previously cast segment.

WHAT

Segment joints are match cast joints within tunnel elements that have no longitudinal structural continuity through them. The joint usually contains a grout injectible waterstop cast with one half embedded each side of the joint; often a secondary seal is used, which could take a number of different forms: Some tunnels have no secondary seal, others have either a hydrophilic seal or a surface membrane/seal applied externally around the perimeter of the joint. Occasionally an omega seal has been used at the inside surface, but this is unusual due to its high cost and has only been required in special circumstances such as seismic conditions or great water depth.

The joint normally permits longitudinal compression and subsequent expansion, and permits rotation in the horizontal and vertical plane. Vertical and horizontal shear movement is prevented or limited by shear keys which may be located in the tunnel walls and slabs. A number of different approaches to shear key design exist.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Important issues for segment joint construction include

- Specific procedures to be followed when concreting around injectible waterstops, to ensure no voids in concrete.
- Trial grouting procedure to be undertaken prior to construction of the permanent works.
- Verification of grouting procedures on site should be carried out to ensure full grouting is achieved.
- Inspection of joints should be carried out during and on completion of dry dock or casting basin flooding.
- Inspection of joints should be carried out as soon as practicable after immersion.
- Leakage inspection should be carried out on regular basis throughout construction period
- Leakage inspection should be carried out prior to covering up base slab joints with road/rail construction
- Leakage inspection should be carried out on seasonal basis, especially during the first winter after construction and completion.
- Leakage inspection should be carried out after specific events such as accidental loading to the tunnel or a seismic event.

During float up, transportation and immersion of tunnel elements it is not normal practice to monitor joint behaviour. Temporary prestressing should ensure joints remain fully compressed throughout these activities. Simple measurement gauges can be installed on the inner walls of the tunnel to monitor openings and rotations of the joints if desired. This behaviour is most useful to monitor during construction as load comes onto the tunnel structure, sometimes unevenly, and joint movements can be compared to predicted values.

After immersion and construction is complete, joint rotations should change little during the design life but can be monitored on an ongoing basis with the settlement monitoring of the tunnel, if the Owner so desires. It is not an essential maintenance operation but will give ongoing knowledge of the tunnels performance.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY…)

The spacing of segment joints through the tunnel will depend on the thermal shrinkage behaviour of the tunnel concrete. The length of segment is chosen such that relatively free shrinkage can occur without the need for additional reinforcement in the structure to control cracking that may result from restraint to movement. The length of segment will also be governed by practical considerations of concrete pour size.

Specifications should require match cast surfaces to be smooth and debonded before casting the second phase concrete.

Shear keys formed within the structural walls and slabs should be detailed to allow for expansion and contraction of the concrete during curing and to avoid overstressing the concrete at localised features. Detailing should also allow long term rotations of the joint to occur without causing localised stress concentrations in the concrete.

Specification of the type of waterstop should suit expected joint rotations and opening to ensure centre bulbs in the waterstop are not torn.

Specification of joint seals

- External sealants are required to prevent backfill materials entering the joint gap during opening of the joint. Good adhesion and flexibility and durability in a submerged marine environment need to be considered in the specifications as they cannot be replaced.
- Internal seals in the joint gaps to prevent ingress of dirt into the joints need to be highly resistant to the aggressive internal tunnel environment and should be resistant to hydrocarbons, detergents, chemical deposits from vehicle exhausts, UV and oxidation. Replacement intervals for these sealants should be as long as possible to minimise tunnel maintenance activities.
- Seals in the upper part of the tunnel need to have adequate fire resistance properties to protect the joint from deterioration during a fire within the tunnel or have adequate protection from such a fire.

Specification for the grouting of the injectible waterstops should be developed with the supplier of the grout and subcontractor for injection, combined with a site trial to ensure complete filling of the injection sponge/tube will be achieved. Specification should state grouting distance and acceptable pressure ranges for injection. Grouting should be carried out before raising the water level on the outside of the tunnel.

Prestressing designed to achieve positive compression across all faces of the segment joint with a minimum compressive stress in the order of 0.1N/mm^2 is recommended from before launching until after installation. This minimum compression should be maintained throughout all temporary conditions, especially under dynamic loading of the element due to wave conditions.

Cutting of the prestressing is normally undertaken unless the tunnel has been specifically designed to allow the prestress to remain intact. A de-stressing sequence should be specified to ensure uneven loading of the tunnel does not result.

DOCUMENTATION (FORMAT, DEADLINES)

Records of grouting for each joint should be made and held on the maintenance file.

Movement against time during construction should be recorded and records kept on the maintenance file. This can be recorded as part of the ongoing settlement survey during construction.

Seasonal movement trends throughout life of structure, if recorded, should be kept with the maintenance records.

The Maintenance Manual should record the sources and suppliers of all joint materials and remedial works materials.

EXPECTED VALUES

The following movements are not prescriptive specifications but are typical limiting values for the opening, closing and rotational movements experienced at segment joints:

- Longitudinal movement 0mm closing, 15mm opening
- Vertical shear movement ±0mm
- Horizontal shear movement ±0mm
- Vertical rotation 0.05 degrees
- Horizontal rotation 0 degrees

ANALYSIS (REQUIREMENTS, TIMESCALE ..)

Settlement surveys during construction should normally be carried out on a monthly basis or following specific events during construction such as release of prestressing, placing ballast concrete or placing of fill over the tunnel.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

These should be obtained from the design so that construction and operation can be monitored as described.

REMEDIAL MEASURES/ACTIONS (FOR UNEXPECTED BEHAVIOUR/VALUES)

If unexpected opening of joints occurs, it will be accompanied by other effects such as large settlements. Remedial measures to mitigate against damage or loss of serviceability will depend on the particular structure.

Remedial measures for leakage include post construction grouting into the joint interface. The choice of grout and method of injection is particularly important to achieve a long term corrective repair, especially if the movement could continue.

Some tunnels incorporate leakage water pressure relief and all should have drainage systems to cater for the possibility of leakage at some point in the structure's life, so that water can be drained in a controlled manner not affecting appearance and so that road surfacing will not be affected.

LINKS TO OTHER OWNERS GUIDE THEMES

Prestressing
Internal finishing works
Structural form

PERFORMED BY / RESPONSIBLE

The suggested responsibilities for elements relating to segment joints are as follows:

Design & detailing – designer
Specifications of materials – designer
Movement monitoring during construction – contractor
Leakage monitoring during construction – contractor
Leakage repair during construction - contractor
Movement monitoring over life – Owner
Leakage repair during operation – Contractor or Owner (depending on contractual requirements for defects liability period after completion of construction).

Tunnel ventilation is needed to ensure that air quality criteria are fulfilled for tunnel users during operation. Ventilation is also required for smoke control in case of a fire in the tunnel.

WHAT

The tunnel ventilation system may have a significant impact on the main dimensions of the tunnel cross section, and the layout should therefore be determined at an early stage of the project. For short tunnels (less than 150-200m) and tunnels with small traffic volumes, natural ventilation may be sufficient. Apart from such cases, mechanical ventilation will be needed. There are three main principles for mechanical ventilation: longitudinal ventilation, semi-transverse ventilation and full transverse ventilation, as explained below.

A *longitudinal system* is suitable for a tunnel tube with unidirectional traffic. The air in the tunnel is blown in the direction of the traffic, either by jet fans mounted under the tunnel ceiling or by so-called Saccardo Nozzles which are nozzles injecting air, the flow being created by large ventilators mounted over the tunnel near the portals. The longitudinal system implies that concentration of the air pollutants is built up in the direction of the traffic, and for road tunnels, this implies a limitation of the length which can be satisfactorily ventilated, according to traffic density. In case of a fire, smoke is blown in the direction of the outgoing traffic, thus protecting motorists upstream of the fire.

A *semi-transverse system* involves injection of fresh air or removal of the polluted air through a separate duct connected with louvers to the traffic ducts. This will result in a more moderate built up of concentrations along the tunnel and thereby enable longer tunnel lengths. However, the air ducts along the traffic tubes will imply additional width or height of the cross section and result in higher costs than for a longitudinal system. In case of a fire, the smoke is extracted close to the location of a fire.

A full transverse system has ducts for supply of fresh air as well as for removal of the polluted air. It will give the most efficient ventilation but the ducts will lead to a relatively large increase in the cross section and the system will have the highest costs of the three systems.

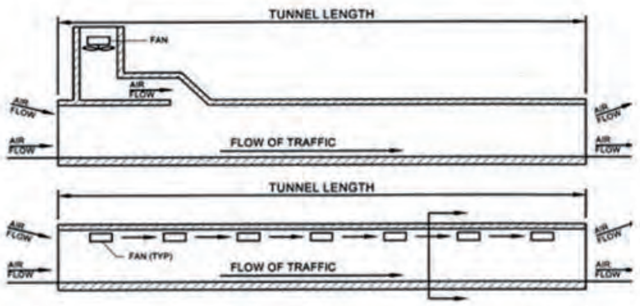
For rail tunnels, the piston effect created by the train will often be adequate for normal control of air quality, but mechanical ventilation may still be required to remove the heat from locomotives and air conditioning, and/or for fire ventilation.

These ventilation options are common to all forms of tunnel. They key issue for immersed tunnels is to choose a ventilation system and corresponding tunnel geometry to achieve an appropriate balance between safety/functionality and cost.
A further issue for immersed tunnels is to ensure that safe access is provided for escape and emergency intervention by the fire services. The need for additional tubes alongside the traffic tube must be considered at the conceptual design stage.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

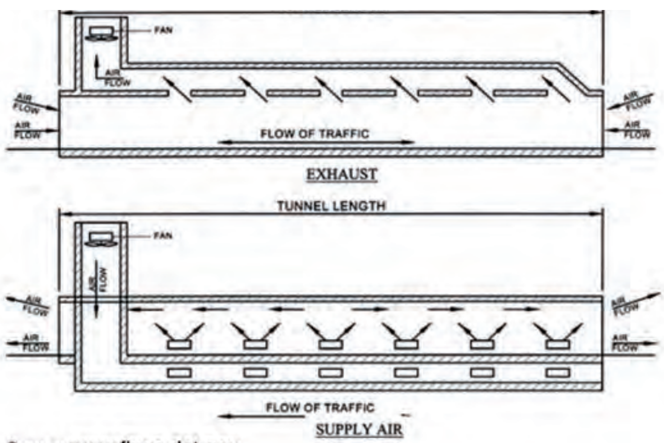
Testing during Construction
The functioning of the individual ventilation fans need to be factory tested. The overall function of the ventilator system, including fans and dampers, should be verified by full scale testing

longitudinal system



Source www.fhwa.dot.gov

semi-transverse system



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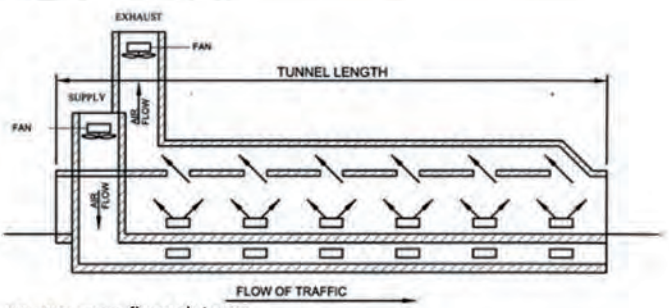
full transverse system



source: www.fhwa.dot.gov

for the relevant ventilation scenario prior to final commissioning of the tunnel. The noise level should also be verified by testing.

Control during Operation
During operation, the tunnel ventilation should be automatically controlled by a PLC (Programmable Logic Controller) system. The PLC system controls the normal ventilation system based on measurement of the pollution level and initiates fire ventilation in case of a fire alarm being activated. The PLC system also monitors the function and the air speed of the individual fans. The PLC system is connected to a SCADA (Supervisory Control And Data Acquisition) system for central supervisory control.

For highway tunnels, fires are usually detected by CCTV cameras observed by a Control Centre, whereas for rail tunnels they are typically detected by train drivers. A variety of smoke or heat detection systems are available and are commonly used in road and rail tunnels.

It should be possible to activate a number of automatic control sequences for fire ventilation from control panels located at each tunnel entrance or from the Control Centre.

Testing during Operation
Fans should be visual inspected weekly for any malfunction to be reported to the maintenance organization, which can arrange more detailed inspection or repair work. The function of dampers and the control system should also be checked at regular intervals.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY…)

A number of international standards exist including NFPA 130, NFPA 502, PIARC publications and many national design standards for road and rail tunnels

Ventilation for pollution control
The ventilation should ensure that limit values for air pollution in a tunnel tube are not exceeded. Air pollutants to be controlled are in particular CO (Carbon monoxide), NO (Nitric Oxide), NO2 (Nitrogen Dioxide) and particles. The noise level in the tunnel, with all fans running at maximum speed, should not exceed a specified noise rating.

The fans and their mountings should be designed for easy replacement requiring closure of no more than one traffic lane at a time. There should be a redundant number of fans, so that failure or maintenance of individual fans will not necessitate repairs or traffic restrictions at inconvenient times. Furthermore, failure of a group of fans should not present a risk to safety in the event of a fire.

Fire ventilation
The ventilation system should have sufficient capacity to transport smoke from the maximum design fire load, depending on the nature of heavy goods transport and risk assessment.

For a longitudinal system, the air speed should be controlled to maintain stratification (i.e. smoke at the top of the tunnel) and to be large enough to avoid back layering (i.e. the phenomenon that the upper layer of heated air flows in a direction contrary to the forced ventilation). Stratification may not be possible if fog, mist or deluge systems are used to reduce or extinguish fires.

Where possible, a semi-transverse system should be used in an exhaust mode.

DOCUMENTATION (FORMAT, DEADLINES)

Test reports following any testing should be prepared.

Operation and emergency plans should be developed during design by a safety committee and signed off by Owner, operator and emergency services.

EXPECTED VALUES

Ventilation air velocities may range up to 10 m/s, but should according to PIARC guidance not exceed this value, in order to ensure that a person can walk from a stopped car to an emergency telephone without difficulty.

ANALYSIS (REQUIREMENTS, TIMESCALE...)

Ventilation for pollution control
The traffic volumes and vehicle emissions should be estimated as a basis for calculation of the required capacity and design of the ventilation system. A set of emission values have been established by PIARC.

Fire Ventilation
For system design and planning of the optimum smoke control during a fire, the detailed air movements can be analysed by use of advanced numerical methods such as Computational Fluid Dynamics (CFD) model calculations.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS) Not applicable.

REMEDIAL MEASURES/ACTIONS (FOR UNEXPECTED BEAHAVIOUR/VALUES)
Not applicable.

LINKS TO OTHER OWNERS GUIDE THEMES

Design of the structural form of the tunnel

PERFORMED BY / RESPONSIBLE (100% CONTRACTOR…)

The suggested responsibilities for elements relating to ventilation are:

Design & detailing – designer
Specifications of performance or performance requirements – Owner
Detailed specifications for materials and equipment – designer/supplier/installation specialist
Witnessing of contract specific ventilation tests – Owner, designer & contractor
Repair during construction – Contractor
Repair during operation – Contractor or Owner (depending on contractual requirements for defects liability period after completion of construction and the contract form, whether e.g. «design and construct» or concession arrangements including design, construction, operation & maintenance and finance)
Maintenance of replaceable items - Contractor or Owner (depending on contract form as above)

Closure joints are relevant to all forms of immersed tunnels. If the approach tunnels have been completed before immersing the tunnel elements, then once all the tunnel elements have been immersed into the dredged trench a short gap will remain. The short length of tunnel to close this gap is known as the closure joint. The closure joint can be between two tunnel elements or between a tunnel element and the cut and cover tunnel at a landfall.

WHAT

During the immersion process a tunnel element must be lowered to its final level a short distance away from the tunnel element or cut and cover tunnel that it is being immersed against. The element is then pulled horizontally to close the gap between tunnel element and form the immersion joint. For the final element that is placed clearance is also needed at the secondary end of the element to avoid accidental damage during the immersion process. Therefore the gap into which a tunnel element is immersed must be greater than the length of the element itself.

The length of the gap is usually in the range of 0.5m to 2m longer than the tunnel element, but may be more.

The closure joint is the final piece of construction that fills this gap, thus making the tunnel complete and continuous. It can generally be constructed between any of the tunnel elements, or between tunnel terminal element and the landfall structure (usually an approach tunnel). Locations for closure joints will be decided by the preferred sequence of construction, the water depth, access for construction and site constraints. This short length of tunnel will need to be completed using special methods.

The need for a closure joint will depend primarily upon schedule. Often the approach structures will be built before the immersed tunnel is laid and so a closure joint is required within the waterway. However if the approach structures are completed after the immersed tunnel is placed then a closure joint is not needed.

There are three principle types of closure joint, with some additional minor variations :
1. In situ concrete
2. Terminal block
3. Key element or V-Wedge

In-situ concrete

For an in situ joint, the typical procedure is for divers to strut the gap between the tunnel elements and place external forms (closure panels) around the joint to seal it and allow it to be dewatered. It is essential to strut the gap to prevent relaxation of the locked-in compression within the immersion joints of the tunnel occurring during the dewatering process.

An in situ reinforced concrete joint can then be constructed within the dry space created within the formwork. Before the advent of adequate seals for joints, both steel and concrete tunnels sealed the joints using unreinforced tremie concrete placed within external forms. Such joints were rigid and required internal waterproofing to guard against leaks that occur when the tremie concrete cracks due to tunnel movement. A typical detail was to fillet-weld a non-structural plate across the gap around the periphery. Should the fillet weld fail, the joint will leak.

Modern tunnels utilise the joint seals that are used in segment and immersion joints and reinforcement is placed from within the tunnel. Often a combination of a rigid joint and a movement joint are used, as can be seen in Figure 1. The left hand diagram illustrates the temporary condition and the right hand side diagram illustrates the final condition.

Temporary works that are required for the in situ concrete solutions include :

- Temporary strutting of the gap to prevent movement of tunnel if the joint is dewatered before placing concrete. This can be with concrete or steel wedges, or jacks or a combination of these.
- External forms around the perimeter of the tunnel to provide the outer form for the concrete works.

It may be necessary to provide a greater amount of flexibility in the vicinity of the closure joint. For example, the element to one side of the closure joint can include a pre-compressed immersion joint and the first few meters of the adjacent element, while the element to the other side of the closure joint omits the first few meters and the width of the closure joint.

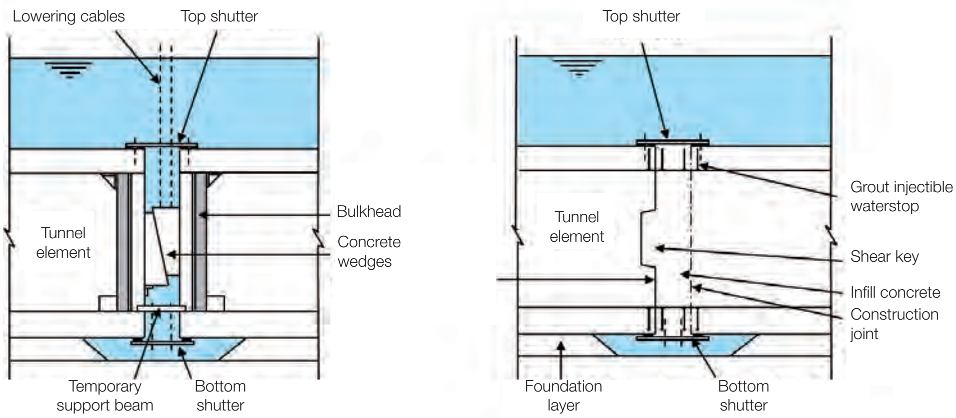


Figure 1 : Typical insitu closure joint

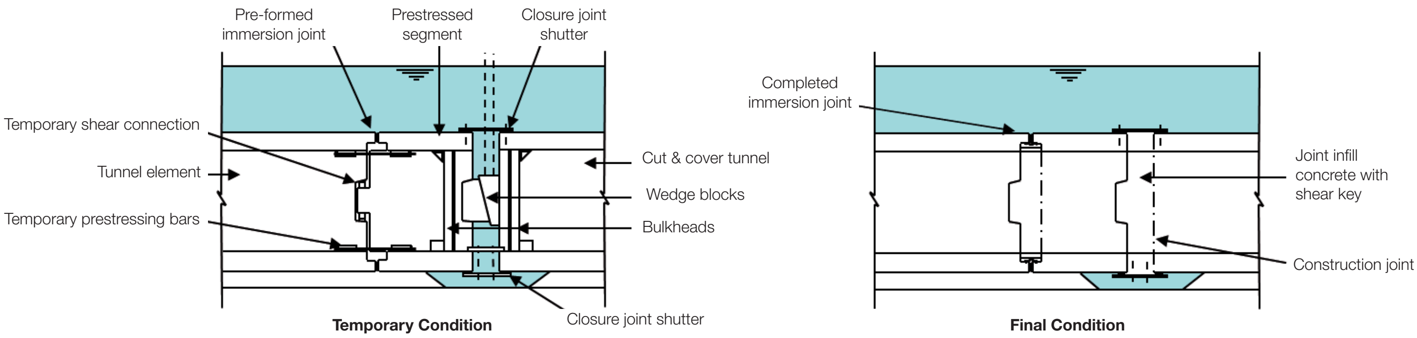


Figure 2 : Prestressed segment closure joint

A rigid final joint can therefore be made from within a temporary external seal, after which the pre-compressed immersion joint is released, creating an element approximately the same length as the others (between immersion joints). See Figure 2.

The tremie joint used on US steel tunnels is cast between an exterior sheet pile closure and overlapping collar and hood plate arrangement.. The arrangement is shown in Figure 3. This shows typical matching closure joint faces. The collar ring on each face receives a lower hood plate (on left) and upper hood plate (on right) forming a continuous seal that is variable longitudinally. Closure sheet piling attaches between opposing faces to vertical edges of the rectangular dam plates. This permits the space to be filled with tremie concrete.

Terminal block

For a terminal block closure joint, a short length of prefabricated tunnel is contained within the tunnel adjacent to the closure joint, outside a temporary bulkhead. This section can then be jacked or pulled out to meet the adjacent tunnel and fill the gap. Seals similar to the immersion joints can be used on the end face of this moving section. The concept is shown in Figure 4.

The gap between the moving section and the oversize tunnel surrounding it must also be capable of being sealed, perhaps using inflatable seals and grout. This method has been used for the Tamagawa and the Kawasaki Fairway Tunnels in Japan, and for the Söderström Tunnel in Sweden. Excellent alignment of the closure joint is achieved using this method, since its orientation is controlled within its housing. The use of divers is not required. If the load in the closure joint seal is less than other immersion joint seals, some relaxation of other immersion joint seals may occur.

Figure 3 : Steel closure joint Fort McHenry Tunnel, Baltimore

V-Wedge / Key element

The V-wedge closure joint is shown in Figure 5. This relies on the difference in hydrostatic pressure once the interior has been dewatered to keep the wedge in place. The approach has also applied to a full length element with wedge-shaped ends, known as a “Key Element”.

Both require reasonably accurate data about the width of joint to be filled. The drop-in wedge and key element both require an oversized interior (since the vertical position is not accurately known until placed). Dimensional tolerances must be small so that this section may need to be manufactured after the closure width is measured, or else the wedge/element will sit at the wrong level. The end faces of the adjacent elements must be sloping to match the wedge taper. Bulkheads are not required on the short V-wedge but are used on the key element in the same way as for a normal tunnel element. Rubber compression seals permit the joints each side of the wedge to be dewatered and the joint to be completed from within, though some warping of those seals under load may occur and the seals must be capable of being slid sideways into position. During dewatering some relaxation of the locked-in force at adjacent immersion joints may occur unless additional bracing of the closure joint gap is installed.

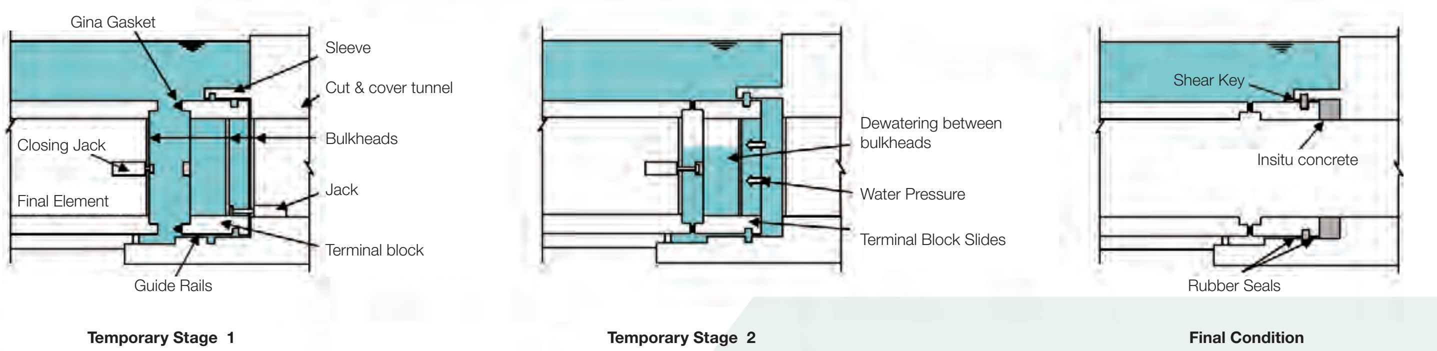


Figure 4 : Terminal block Closure Joint

After dewatering, further transverse displacement should be prevented. The V-wedge/key element method has been used for the Osaka Sakishima and Kobe Minatojima Tunnels in Japan. The use of divers is not required.

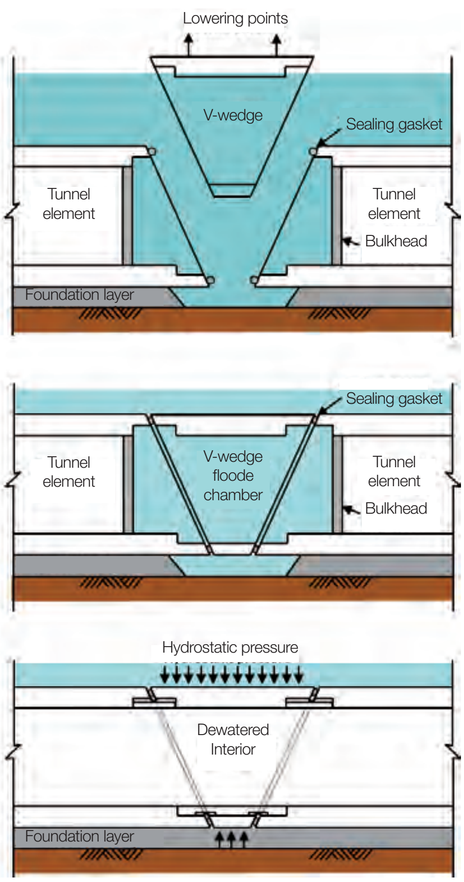


Figure 5 : V-Wedge closure joint

Foundation

The foundation beneath the tunnel is difficult to form over the length of the closure joint. Often the structure is left as a cantilever structure without underfilling. Gravel cannot be placed if an external form needs to be placed in the trench to enable it to be drawn up to the underside of the tunnel. The foundation could be formed by grouting or with grout bags. Sand flow could be used but this would be a discontinuous operation with the remainder of the sand flow and so might be expensive. Unless there is significant load, or variation in load that could cause undesirable settlement, the length of the joint can generally be left without a foundation.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Important procedures and tests related to closure joints include:

- Accurate measurement of as-built dimensions of the tunnel to enable accurate detailing of the closure joint permanent and temporary works. The space between the tunnel elements that has to be filled by the closure joint can be predicted but the final dimensions will depend on placing accuracy, the as-built dimensions of the tunnel elements and the amount of compression that has occurred in the seals in the immersion joints between other tunnel elements.
- Level control of the secondary ends of the tunnel elements at the closure joint to achieve the desired alignment and avoid any significant steps across the closure joint.
- Measures to achieve watertightness of the structure – e.g. cooling of concrete, special curing and thermal monitoring. The closure joint can have specific requirements in this respect and needs a different design and construction approach.
- Sealing of temporary closure panels for in situ concrete joints, typically achieved with a rubber seal, but may need additional measures applied by divers externally.
- Dewatering and cleaning of the joint space after the closure joint space has been dewatered, and ongoing monitoring of leakage.
- Monitoring of loads in jacks or condition of blocks placed in the joint space to preserve the joint gap until the in situ concrete closure joint is formed.
- Sequence of in situ concreting and removal of temporary wedge blocks/jacks to transfer the compression force into the permanent joint structure.
- Health and safety and emergency procedures for entering and working within a restricted environment between the bulkheads.
- Trials and testing for special concreting procedures e.g. pumping high flow concrete into roof slab element of the in situ concrete closure joint, or for spray applied concrete applied to the roof section of the closure joint.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY…)

For in situ concrete joints :

- Specification for temporary blocking should include the sequence of installation and the strength of materials or capacity of jacks.
- The location of jacks/blocks to ensure stability and even distribution of loading around perimeter should be shown on the construction drawings and considered in the design.
- The strength of concrete forming the joint to be achieved before releasing temporary blocking should be specified.
- Design of the joint movements should take account of the whole system of joints in the tunnel. Note that sometimes if the closure joint does not include an immersion joint arrangement the distance between the immersion joints may be increased resulting in greater movements ranges at the adjacent immersion joints.
- Formwork panels used around the perimeter of the joint for concrete tunnels are left in place but are not considered in the design for watertightness. Specifications for watertightness and durability should be prepared on this basis.
- Detailed work procedures should be developed as there are a number of high risk construction activities involving lifting, diver working, and working in confined spaces.
- A clear sequence of work is required, so that it can be assessed in the design. This is particularly important for considering the axial load transferring through the joint, initially through jacks and/or wedge blocks, and subsequently via the walls and slabs, when the jacks/blocks are removed.

For terminal block joints :

- Sufficient extra length tolerance is required for terminal block element to ensure the gap can be filled to take account of all immersed tunnel element length and immersion joint gap width tolerances elsewhere.
- Specification for location and capacity of jacks and method of adjusting alignment of terminal block
- Specification for method of sealing around perimeter of terminal block.
- The strength of concrete for locking the terminal block to be achieved before releasing temporary jacks should be specified.
- Clear sequence of work.

For V-wedge joints or key element :

- Specification for method of maintaining alignment of the wedge during insertion and any vertical jacking required.
- Clear sequence of work.

DOCUMENTATION (FORMAT, DEADLINES)

Accurate as-built record should be retained, as this part of works is susceptible to variation in detailing and geometry.

Cooling and curing records for in situ watertight concrete should be retained with the as-built records. Materials and construction records for special items e.g. high flow or spray applied concrete should be retained with the as-built records.

EXPECTED VALUES

The accuracy of placement and construction tolerances are generally as per immersion joints. The variation in the length of the joint will depend on the as-built length of previous tunnel elements and the actual compression achieved in the immersion joint seals compared to the expected values.

ANALYSIS (REQUIREMENTS, TIMESCALE…)

Survey of the installed length of tunnel is carried out as construction proceeds to determine any variation in the length of the closure joint.

Settlement survey during construction would normally be carried out on a monthly basis or after specific events during construction such as release of prestressing, placing ballast concrete or placing of fill over the tunnel.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

The accuracy of placement and tolerances to be allowed for in the design are as per immersion joints. Variation in the length of the joint can be allowed for in the design and need not be a significant issue.

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

If leakage occurs either in the concrete or at joints, injection grouting is the most likely remedial measure to be used.

LINKS TO OTHER OWNERS GUIDE THEMES

Immersion joints
Segment Joints
Element positioning
Watertightness
Tolerances

PERFORMED BY / RESPONSIBLE

The suggested responsibilities for elements relating to closure joints, subject to type of contract and/or risk allocation are :

Development of temporary blocking or jacking arrangement – Contractor
Method and sequencing of work - Contractor
Design & detailing of permanent structure – designer
Specifications of materials – designer
Movement monitoring during construction – contractor
Leakage monitoring and repair during construction – contractor
Movement monitoring over life – Owner
Monitoring & repair of leakage during operation – Contractor or Owner (depending on contractual requirements for defects correction)
Maintenance of replaceable items e.g. bearings – Owner

For prefabricated immersed tunnel elements the main construction material is concrete. The concrete may be working compositely with structural steel or acting on its own. This theme discusses aspects related to those immersed tunnel elements where the primary structure acts compositely with structural steel; such tunnels are termed “steel immersed tunnels”. For the construction of the end frames and bearing plates, refer to Theme “Immersion Joints”.

WHAT

The differences in general between steel and concrete immersed tunnels are discussed in Sections 2.4 and 2.7 of the main Owner’s Guide document to which this is an annex. A concrete tunnel with a steel non-structural waterproofing membrane is not considered as a steel tunnel.

There are three main types of steel immersed tunnel; double shell, single shell and sandwich. All three types of steel tunnel have a primary structure that resists the external loads, consisting of concrete bounded externally by relatively thin structural steel plates, sometimes described as shell plates. The sandwich tunnel has in addition structural steel plates on the inside face. All structural steel plates act compositely with the concrete contained within these plates. The term steel tunnel is thus an indicator that steel plates act compositely with concrete. For all steel tunnels, the steel shell external to the structural concrete doubles as a watertight membrane and thus requires some form of protection.

Since the required minimum weight of an immersed tunnel depends solely on the volume of air contained within it, both steel and concrete immersed tunnels contain almost the same weight of concrete. For all three types of steel tunnel, steel diaphragms and stiffeners embedded within the concrete are used to prevent plate buckling. Within double and single shell tunnels, the concrete is reinforced concrete and contains reinforcement whereas the sandwich tunnel concrete is unreinforced. Where concrete contains reinforcement, it must be checked to meet crack-width and durability requirements. This is applicable to both concrete and steel tunnels though the particular requirements may vary.

In the same way that concrete tunnel elements are constructed in bays (segments), steel tunnel elements are constructed in modules (subassemblies) that can be handled by cranes. These modules are then assembled and welded together to form an empty shell. By adding temporary bulkheads at the two ends, the empty shell essentially forms a steel “ship”. In many cases, construction takes place at a location above water level rather than in a dry dock or basin; in such cases, the essentially empty element is side or end launched down a slipway. To add stability and strength for the launch or float-out from a dock, some of the base slab concrete is often placed prior to launch (keel concrete for the double-shell). For the Söderström tunnel in Stockholm, the empty element was transported on a semi-submersible barge.

Empty steel tunnel elements may require some temporary internal bracing and stiffeners, usually around the entire steel periphery to stiffen the shell against the fluid pressures of the concrete as well as the rising external water pressure as the element’s draft increases during outfitting. It is usual for all the remaining structural concrete to be placed at an outfitting location close to the final tunnel location. The concrete placing sequence afloat is very important so that the steel shell maintains adequate freeboard and distortions (in bending) prevented. Hatches or access shafts are required for temporary access to place internal concrete.

To reduce ballasting requirements for immersion, it is advantageous to place permanent ballast to maintain a freeboard of 60 cm or less for the tow from the outfitting area to the immersion location. However, there are many instances where the tow from the fabrication location to the tunnel location may extend hundreds of kilometres; over such long distances, it is not unusual for empty elements to be transported on semi-submersible barges to the outfitting location.

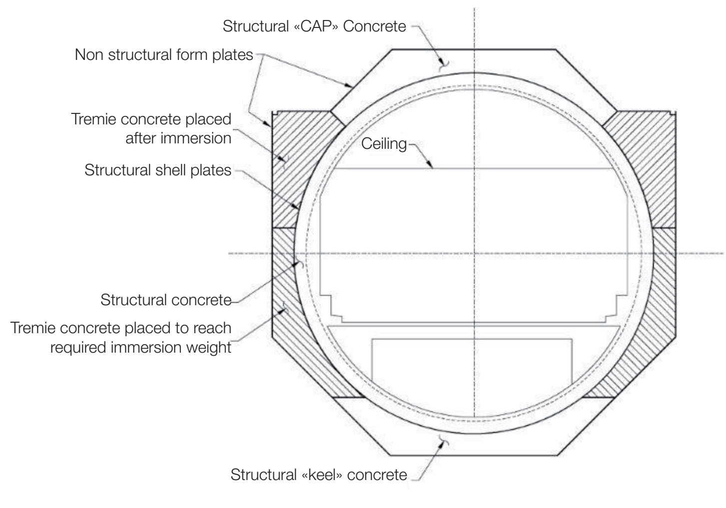


Figure 1 : Double-Shell Tunnel

Double shell tunnels

For the double-shell tunnel only (Figure 1), there is structural but unreinforced concrete external to the curved structural steel shell, namely the keel and cap concrete at the bottom and top. The keel concrete is placed first. The inner structural concrete provides the internal finish to the tunnel and is placed afloat, followed by the cap concrete. The non-structural form plates (forming an outer second "shell") function only as permanent forms for the cap concrete and as pockets for the tremie concrete. The tremie concrete not only provides the ballast that eventually ensures that the installed tunnel element cannot float but also acts as corrosion protection to the structural steel shell and adds stiffness to the whole.

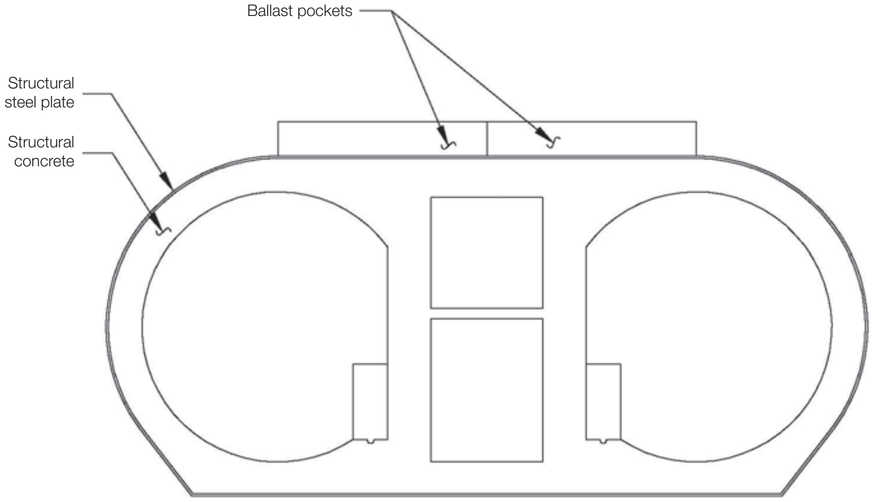


Figure 2 : Double-Shell Tunnel

Single shell tunnels

Most single-shell steel tunnels (Figure 2) are rectangular but can have any shape. The steel shell need not be on all sides, shell plates sometimes being omitted on the top. Stiffeners and temporary bracing are used to maintain stiffness and shape of the shell structure. Ballast concrete can be placed within the finished structure or on roof where it adds additional protection. For the BART tunnel, rock was placed in ballast pockets on the roof.

Since the structural steel is exposed, it will need to be protected against corrosion; methods used have included a coating of concrete and cathodic protection.

Steel sandwich tunnels

Steel shell sandwich tunnels have inner and outer stiffened shell plates forming the external structure that are connected by web plates to form closed cells with a volume typically of about 10m3 each. Self-compacting non-shrink concrete is placed through central pouring holes. Small air release holes around the edge of each cell also enable direct observation to confirm that cells have been completely filled.

The concrete is unreinforced and carries only compression loads while the steel carries all the tension loads. The concrete also helps to stiffen the inner and outer plates against buckling by anchoring the plate stiffeners. There is no restriction on the shape of the structure. Ballast to achieve the required final weight can be provided internally or externally in ballast pockets or on the roof. Since the structural steel is exposed, it will need to be protected against corrosion; cathodic protection is typically used. In case of leakage through the external shell, the inner shell in each cell should have a small hole to prevent pressure build-up on the interior shell.

For all tunnel types, the tunnel primary structure should create an accessible and dry enclosed space and allow for safe passage during its intended lifetime. Therefore the exterior structure should prevent ingress of water and resist pressures from all external loads (water, soil pressure and temperature) and exceptional loads (see theme exceptional load cases). The concrete class is as required by structural strength, durability and exposure (minimum 20 MPa for structural concrete and 15 MPa for tremie ballast concrete).

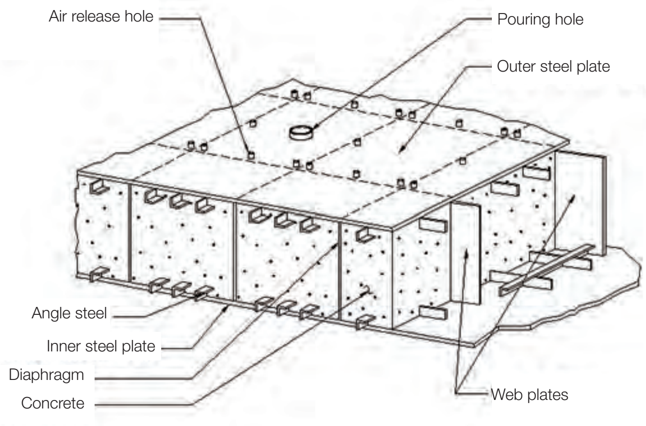


Figure 3 : Steel Sandwich Structure

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Important issues for steel tunnel construction are :

- The method of providing protection to the structural steel shell must be established early.
- Full penetration butt welds are required for the watertight exterior shell. Use methods such as soap bubble and compressed air to test all welds for leaks as construction proceeds.
- Test a certain percentage of welds for cracks and/or flaws as construction proceeds, using methods such as x-ray or dye penetrant.
- It is recommended that the steel shell acting as a waterproofing membrane be provided with barriers within the membrane (e.g. waterstops or ribs embedded in concrete) to reduce the spread of leakage water in case of puncture. Decision required early.
- It is advantageous to fix any internal reinforcing steel before the bulkheads are installed.
- Use tests for the specific weight of concrete as construction proceeds to ensure that the final weight of concrete will lie within design limits.
- Testing during initial installation of any cathodic protection is essential. In operation, monitoring is needed to check durability.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY…)

Besides applicable steel design and testing codes such as AISC, ASTM and applicable boiler codes, specifications are required for the structural steel shell (working compositely with concrete) as follows :

- Fabrication tolerances for the assembled shell
- Methods of testing for leaks
- Cathodic protection (if used)
- Weld quality testing

Guidance on specifications for reinforcement and structural concrete are stated in other theme appendices and should include :

- Functionality and durability requirements of the cast and hardened concrete.
- Concrete strength in accordance with applicable standards.
- To prevent DEF (Delayed Ettringite Formation) the maximum concrete temperature during hardening should not exceed 65-70°C unless special concrete (not susceptible to DEF) is used.

DOCUMENTATION (FORMAT, DEADLINES)

Design needs to document the assumptions on construction so that loads used in the design arising from fabrication, launching and concreting of the shell are not exceeded in practice.

Design output should include detailed steel fabrication specifications

Testing during structural steel fabrication should be fully documented by the contractor :

- Leak testing.
- Weld testing.
- Tolerances achieved during assembly.

Relevant testing during concrete production should be fully documented by the contractor. Typical details are given in other appendices and are not repeated here.

All test reports, materials test certificates and commissioning records for cathodic protection systems should be retained for the as-built records.

EXPECTED VALUES

Steel and concrete strength in accordance with standards.

Variation of unit weight for structural and ballast concrete should be assessed for use in basic design. The following typical parameters often suitable for basic design :

- maximum unit-weight reinforced concrete (for buoyancy calculations): 25.4 kN/m3
- minimum unit-weight reinforced concrete (for buoyancy calculations): 24.2 kN/m3
- maximum unit-weight ballast concrete (for buoyancy calculations): 23.5 kN/m3
- minimum unit-weight ballast concrete (for buoyancy calculations): 22.5 kN/m3

During construction the unit weight is a very important parameter to keep testing and controlling as the buoyancy and freeboard of the element depends on the total weight of concrete.

ANALYSIS (REQUIREMENTS, TIMESCALE...)

Tests and checks need to be carried out at specific points in time during fabrication and assembly of subassemblies, as well as during and after placing concrete. The timing of these should be specified prior to the start of construction.

Pre-testing of concrete mixes and testing during concrete production and casting should be in accordance with applicable standards. Strength, stiffness and density testing are of most importance.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

Tolerances should be derived from the design so that construction and operation can be monitored as described.

Regardless of strength requirements, an exterior steel shell thickness should not fall below 10 mm during the design life. Steel non-structural membranes should never be less than 8 mm thick.

REMEDIAL MEASURES/ACTIONS (FOR UNEXPECTED BEHAVIOUR/VALUES)

In the absence of guidelines by appropriate national standards, it is recommended that all cracks wider than 0.2 mm be repaired by injection.

For distortions occurring while concreting afloat, change the placing sequence and / or the quantities of concrete placed each time.

LINKS TO OTHER PROCESSES

Immersion joints
Concrete immersed tunnels
Exceptional loads
Cathodic protection

PERFORMED BY / RESPONSIBLE : (100% CONTRACTOR...)

The suggested responsibilities for elements relating to steel construction, subject to type of contract and/or risk allocation are :

QA/QC for structural steelwork – Owner / designer's site staff
Functional requirements - Owner
Structural design & detailing – designer / contractor
Mix design – designer / contractor
Specifications of materials – designer / contractor
Monitoring concrete production and documentation – contractor
Monitoring distortions while placing concrete afloat – contractor
Monitoring temperature development in hardening concrete – contractor / designer
Leakage monitoring and repair during construction – contractor
Leakage monitoring and repair during operation – Owner

ANNEX 09 >> ELEMENT CONSTRUCTION - CASTING BASIN

This Annex describes construction of tunnel elements in a purpose made casting basin is relation to concrete tunnels. The casting basin is normally built close to the tunnel site which minimizes the necessity for long transport of the elements but it should be stressed that it is not a requirement, as tunnel elements can be transported over long distances.

WHAT

The traditional construction method for concrete tunnel elements has been the use of a purpose built casting basin. The basin can be open earthworks or within retaining walls, in the following the word basin is used for all types. The basin can either be one big basin containing all elements or a smaller basin which is reused. The depth of the basin is just sufficient for the elements to be transported out of the basin after flooding the basin. The basin must have direct access to the transport route to the tunnel site.

Construction of concrete tunnel elements in a basin allows the option of constructing tunnel elements as monolithic or segmental tunnel elements.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Important issues for construction of the basin include :

- The location of the basin shall be accessible to an available transport route for the elements to tunnel site, and that deep water is available between the basin and the transport route.
- The soil condition at the location for the basin is of great importance as the basin shall be kept dry during the construction of the elements (ground water lowering) and the settlements of the basin floor shall be controlled (good uniform foundation for the tunnel elements).
- The basin is excavated and the soil may be stock piled close to the basin.
- The construction of the tunnel elements in the basin can take more than one year and therefore the conditions for the ground water lowering shall not only be suitable, with little environmental impact or effect on nearby structures, but also economically attractive.
- The basin must have sufficient areas around the basin to accommodate materials storage, a dedicated batching plant, areas for offices and laboratories etc.
- The environmental issues and possible requirements to the location of the basin shall be taken into account, and necessary permits shall be prepared for at an early stage to ensure availability of the site.
- The size of the basin can be reduced if it is possible to re-use the basin. In this case it is often necessary to have a mooring area outside the basin for parking tunnel elements before they are transported to site one by one.
- The size of the basin can be limited by the physical constraints in the area and therefore it will be necessary to reuse the basin.
- A reusable basin may be equipped with a gate that is designed to float and which is easy to manoeuvre in order to save time between the constructions of elements.
- After finishing construction of elements the basin may be backfilled with the excavated and stockpiled soils.

Figure 1 : Casting basins for Busan-Goeje, South Korea & Preveza-Aktio Greece

Important issues for construction of the tunnel elements include :

- In principal there are two casting methods:
  - A traditional casting sequence is where the bottom slab of the structure is cast first in segments and then the casting of walls and roof commences. This casting sequence creates a construction joint between bottom slab and walls. The behaviour of old concrete and fresh poured concrete due to differential shrinkage and temperature calls for a close control of the joint in order to avoid serious cracking that may later cause water ingress. The tunnel elements can either be constructed as monolithic reinforced elements or as segmental elements which must temporarily be longitudinally post tensioned before float-up and transportation of the elements to the site.
  - A more industrialised casting method is to cast the whole segment in one go. The forms (travelling form) must be purpose made and strong enough to carry the wet concrete during casting. The advantage with this method is the omission of the construction joint and thereby the tendency for crack development. The tunnel elements constructed as segmental elements must have temporary post tensioning for transport.
- The traditional approach to construction is to establish one or more casting basins as open excavations, where the elements are built. When the elements are completed they are provided with bulkheads, water ballast tanks, equipment for transport such as towing bollards, access tower(s) and survey tower(s) before the basin is filled with water. Once the initial fit-out is complete the basin can be flooded and elements floated. The basin gate is opened or the dike around the basin is locally removed and the elements are floated out one by one, transported to the tunnel site and sunk to their final position.
- In a traditional casting basin it is possible to construct tunnel elements that are curved by rotating the segments at the segment joint either vertically or horizontally. By curving tunnel elements it is possible to fit the tunnel element and cross section better to the alignment.
- During casting of the elements each batch of the concrete shall be tested. The tests shall confirm the concrete quality especially the permeability and the unit weight to ensure good water tightness and to control the weight of the final element.
- A detailed survey of the tunnel element shall be made for final calculation of the element weight and freeboard before float out.
- The concrete temperature shall be controlled and cooling of the concrete during casting is often necessary with thick structural members to prevent cracking.
- After casting the element shall be inspected for through going cracks. Injection of the cracks shall be carried out to seal them off. This sealing operation shall be in strict accordance with the manufacturer's requirements.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY…)

The concrete used for construction of concrete tunnel elements typically does not have a very high strength requirement. More important are the requirements for low concrete permeability and specified unit weight.

The concrete specifications shall contain specific requirements for the permeability and unit weight leading to a dense concrete mix with low water/cement ratio in the order of 0.40 – 0.42. The unit weight control is necessary to insure the element can float and be transported. The unit weight is also critical to the element's ultimate factor of safety against flotation after placement.

In case of monolithic tunnel elements where the reinforcement is continuous through construction and segment joints the element normally is provided with an outer water proofing membrane to seal any cracks that may have arisen from temperature movements in the final situation. The elements shall be checked for cracks and leakage before leaving the basin.

The membrane(s) shall have a lifetime equal to the design lifetime of the tunnel elements. Application of the membrane system shall be carried out in accordance with manufactures specifications and with high level of control.

Figure 2 : Example of a reusable basin at Barendrecht in the Netherlands

In case of segmental tunnel elements, where segment joints (without through going reinforcement) allow the tunnel segment to move due to shrinkage, creep, temperature etc. it is not necessary to apply an external water proofing membrane under normal conditions. A tunnel with extreme water depth however may benefit from the application of an external waterproofing membrane.

The segmentally constructed tunnel element shall be temporarily post tensioned longitudinal for transport to site. The post tensioning shall be grouted, but at segment joint the strands shall be non-bonding as the strands are cut when the element is in final position and fully backfilled. The bonded part of the post tensioning stays in the segments and strengthens them in longitudinal direction.

The construction of tunnel elements in a purpose made basin shall be carried out with control of the foundation behaviour during construction of the elements. The elements are very heavy and may introduce settlements of the basin bottom during construction. The tunnel elements shall be designed for the possible settlements in the basin.

DOCUMENTATION (FORMAT, DEADLINES)

Casting Basin :

- Monitoring of ground water lowering system.
- Stability monitoring of basin side slopes.
- Monitor stability of access road and settlements of basin bottom due to the weight of the element and from traffic and other activities.

Concrete tunnel elements :

- Record concrete parameters batch by batch.
- Record crack development and grouting.
- Record tunnel element final geometry.
- Record settlements during construction of tunnel elements.
- Survey of concrete elements and use of concrete test records to determine freeboard and ultimate factor of safety against floatation.
- Monitoring of heat and temperatures of concrete sections during casting to compare with anticipated values and to evaluate the potential for shrinkage cracking.

Recorded information shall be included in the as-built documentation and a summary in the maintenance manual for background information.

EXPECTED VALUES

The prescriptive specifications of typical values to monitor during construction are obtained from the design analyses.

- Differential settlements
- Longitudinal movement of joints
- Total settlement of the tunnel in time.

ANALYSIS (REQUIREMENTS, TIMESCALE...)

Design of basin earth works and ground water lowering system and continuous analyses and monitoring of basin behaviour and adjacent structures during construction.

Design of tunnel elements and analysis of casting sequences and hydration heat. Analyses of built-in forces in the tunnel element during construction.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

These shall be output from design analyses so that construction and operation can be monitored as described.

REMEDIAL MEASURES/ACTIONS (FOR UNEXPECTED BEHAVIOUR/VALUES)

During construction of basin and construction of the tunnel elements there shall be daily controls and monitoring of the basin and the construction of the elements.

The upmost shall be done to minimize failures, unexpected behaviour or accidents which will have high impact on economy and time. A construction risk analyses shall be performed and guidelines developed for remedial actions to be taken.

LINKS TO OTHER PROCESSES

Segment joints.
Immersion joints.
Water proofing membrane.
Transportation of tunnel elements.
Post-tensioning.
Concrete construction – concrete.
Concrete construction – cracks.
Element construction – Factory construction method.

PERFORMED BY / RESPONSIBLE: (100% CONTRACTOR...)

The suggested responsibilities for construction of concrete tunnel elements are as follows :

Design & detailing – Designer
Specifications of materials – Designer
Movement monitoring during construction – Contractor
Cracks monitoring during construction – Contractor
Cracks repair during construction - Contractor
Settlements monitoring during construction – Contractor
Environmental monitoring during construction – Contractor / Owner

ANNEX 10 >> SOIL CONDITIONS

A detailed understanding of the soil conditions along the immersed tunnel alignment is important for the design as well as construction. The programme for investigation and interpretation must therefore be carefully tailored, planned and executed.

WHAT

Scope

The soil conditions have to be known in sufficient details as basis for design and construction of the immersed tunnel. With regard to the design, the strength as well as the deformation properties of the soil shall be described for the relevant stress range for the tunnel and for the dredged trench slopes. The settlements resulting from unloading (during dredging) and reloading (during backfilling) must be taken into account. Conditions that involve long-term consolidation must be carefully evaluated.

For construction, knowledge of the soil conditions is important for mobilising the right dredging equipment, and for determining the construction time and costs.

Due to the low foundation pressures of immersed tunnels compared to other marine structures, the soil strength is usually not decisive for the foundation design of the tunnel, even for soft ground conditions, but it is important for the stability of the slopes of the dredged trench. However, the soil strength can be critical in case significant earthquakes can occur and cause stability failure or even soil liquefaction.

The deformation properties will by soil-structure interaction be important for the structural design of the tunnel. For monolithic tunnel elements, differential settlements due to variations in the soil stiffness in the longitudinal directions can lead to large bending moments in the tunnel structure, and for segmental tunnel elements they can induce high shear forces and large movements in the joints.

Finally, the chemical properties of the ground (soil and water) will influence the corrosive environment at the tunnel location. In addition, it is important to test for soil contamination in surface sediments for immersed tunnels in harbours and other polluted areas. The degree and depth of contaminants in the soils to be dredged must be determined for the environmentally sound design of the spoil disposal site. The design for the long-term usage for the disposal site is also an important aspect of the soils investigation.

Soil investigation programme

The soil investigation programme shall be specified and inspected by the Designer to determine important soil parameters needed for each phase of the design.

Geophysical survey like reflection seismic investigations which are particularly suited for marine environment may be carried out for mapping of spatial variations of the soil and rock layers and for selection of locations of boreholes in an alignment screening phase.

The investigations should in the preliminary and final phases comprise the following main components to be carried out in the alignment of the tunnel:

- Boreholes for the recovery of high quality, undisturbed soil samples.
- Boreholes to establish soil profiles and for in-situ testing, including Vane Shear Tests and SPT's (Standard Penetration Tests) to determine geotechnical properties and which may also include various customized geophysical borehole logging methods.
- CPTUs (Cone Penetration Tests with the measurement of pore pressure) for high resolution geotechnical investigations of soil properties in fine grained soils.

In addition to the off-shore investigations, detailed ground investigations are also important on shore along the cut and cover and ramp sections where the foundation depth and form of structure changes rapidly. The investigations on-shore shall also include testing for groundwater conditions, being important for design of temporary groundwater lowering systems during construction.

Laboratory testing of high quality is necessary to determine geotechnical properties from both disturbed samples for classification tests and undisturbed samples for more advanced laboratory testing.

Chemical testing of seawater, soil and groundwater is performed to establish a basis for durability design of the reinforced concrete and steel structures/components.

All tests shall be carried out according to internationally accepted standards and high quality, applying best practice with respect to investigation methods, type of equipment, test execution and interpretation of test results.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

At the early Feasibility Study stage it will often be possible to assume conditions and apply preliminary estimated soil parameters based on desk studies. Any existing data from previous investigations for construction projects in the area should also be collected as part of the desk study. Geophysical surveys over large areas may be carried out for optimisation of alignments and as an aid for the mapping and interpretation of stratigraphy and geological structures, if any.

For the preliminary investigation phase, the investigation may in turn be supplemented by an intermediate soil investigation program for the Owner's subsequent development of conceptual and preliminary design of the immersed tunnel project.

The final and detailed soil investigations must obviously be tailored on the basis of the preliminary investigation results available and the detailed knowledge of the needs for development of the detailed design. The project planning shall make realistic allowance for the duration of the contracting, execution and interpretation of the final investigations, to take place in advance of the detailed design.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY…)

General

The boreholes for recovery of undisturbed samples and for establishing soil profiles and in-situ testing can be carried out as adjacent pairs. For an immersed tunnel project, there may typically be one borehole pair per element.

The types and numbers of in-situ tests and laboratory tests will depend on the variability of the soil conditions and the Designers requirements for detailed knowledge of the design parameters. The type and number of all boreholes and tests shall be given in the specification.

Boreholes for the recovery of undisturbed soil samples.

The boreholes are carried out in fine-grained soils to obtain high quality continuous or discrete undisturbed soil samples for laboratory testing.

Boreholes for establishing soil profiles and in-situ testing.

The boreholes are carried out in soils and rock for obtaining samples of soil and cores of rock for classification purposes and for the performance of in-situ testing such as for example Vane Shear tests, SPTs, and geophysical borehole logging.

a) Vane Shear Tests

The Vane Field test is a simple and fast method used to estimate the undrained shear strength of fully saturated clays of soft to firm consistency. The vane shear test apparatus consists of a four-blade stainless steel vane attached to a steel rod that will be pushed into the ground and rotated. The undrained shear strength is estimated from the measured torque at failure.

b) SPTs (Standard Penetration Tests)

The SPT (Standard Penetration Testing) is a simple method largely used worldwide for estimate of soil density, strength and stiffness. The SPT can be used in even very dense granular soils and very stiff to hard layers of clays. It involves driving a standard sample tube into the ground at the bottom of the borehole by blows from a slide hammer with standard weight and falling distance. The soil properties are determined from the number of blows required for a certain penetration. However if an appreciation of soil properties for seismic design is required, measurement of the Energy Transfer Ratio of the SPT equipment is mandatory.

c) Geophysical borehole logging

Geophysical borehole logging may include Gamma logging, porosity / density logging, conductivity/resistivity logging and P (compressional) S (shear wave) logging. Gamma logging combined with porosity and density logging is widely used for qualitative appreciations of boundaries between fine grained (clay) and coarse grained (sand) layers. Geotechnical parameters may be derived under favourable conditions.

The suspension velocity logging is especially suited for marine applications; in this case both the electromagnetic wave source and the receivers are placed in the same borehole. Elastic rock properties like shear wave velocity, compressional wave velocity and dynamic Poisson ratio can be derived .The shear wave velocity can be used for determination of seismic strength parameters and resistance to liquefaction.

CPTUs

The CPTU (Cone Penetration test with the measurement of pore pressure) is a simple and effective method for determining soil layering and properties.

It is carried out by pushing a CPTU cone with a down facing tip and a surrounding sleeve into the ground at a standard velocity. The CPTU cone is designed to measure tip resistance, sleeve friction (along the side of the cone) and pore water pressure continuously during the push.

Some of the CPTUs shall be carried out adjacent to the geotechnical borings for calibration and cross correlation with laboratory test results. The cone penetration resistance values can then be correlated to give a profile of the shear strength of the soil using empirical curves, and they may also be correlated to the deformation parameters.

Figure 1 : Boring rig and SPT testing for the Hong Kong Zhuhai Macao immersed tunnel

A large number of CPTUs between the boreholes will provide a detailed mapping of the soil layers and variability along and across the tunnel alignment, which in particular is of importance in areas where the structural design is considered sensitive to stiffness variations in the ground.

Laboratory testing to determine geotechnical properties

The following laboratory tests are relevant:

a) *Classification tests*

The classification tests are carried out to determine basic properties including: moisture content, unit weight, specific gravity, Atterberg limits, grain size distribution, sensitivity and organic content. If relevant, the tests shall also cover contamination in accordance with the applicable standards and acceptance limits .

b) Tests of strength properties

The undrained and effective strength parameters are determined from triaxial tests. The test program should include consolidated undrained tests with simulation of the stress history corresponding to the unloading due to the trench dredging and subsequent reloading with the tunnel, backfill and re-sedimentation.

c) Tests of deformation properties

The deformation properties are determined by Oedometer tests to be performed at the relevant stress levels occurring during unloading due to the trench dredging and subsequent loading by the tunnel, backfill and re-sedimentation. An important objective is to determine the pre-consolidation stress and permeability as well as the deformation properties for loading, unloading and reloading.

Documentation (format, deadlines)

Documentation should be prepared in accordance with national or international standards, for example in Europe BS EN 1997-1 sets out what is expected to be contained in the various reports required

The borehole logs and test results are reported by the boring contractor and the laboratory in accordance with internationally recognized standards in a Geotechnical Factual Report. Results from in-situ tests and the tests carried out at the laboratory are also presented on the borehole log. The raw data and the results should further be delivered on electronic form in an internationally recognized format such as AGS.

Samples should retained by the testing laboratories for a period specified by the project owner.

The electronic data should be organised in a database providing easy handling of the data, a 3D geological model, and a comprehensive understanding of the variability of the soil properties in the project area.

The documentation should be retained for the life of the project as part of the maintenance manual, so that it available to the Owner in the event of an unexpected event such as settlement occurring during the operational phase.

EXPECTED VALUES

N.A. This will vary from project to project.

ANALYSIS (REQUIREMENTS, TIMESCALE...)

The Designer for either the client or the Design and Build contractor, depending on who is producing the final design for construction, will prepare a Geotechnical Interpretative Report (GIR) concerning the analysis carried out on the test results in order to derive the design parameters for the foundation design. Practice varies internationally on the name, format and content of this document, for example some countries refer to it as a Geotechnical Baseline Report (GBR). This terminology arises as the report sets out an agreed set of baseline conditions that can be used to assess contract claim. It is particularly used in tunnelling and is as applicable to immersed tunnels as any other form of tunnelling. Irrespective of its title it should be considered to be the final definitive document on the ground conditions, taking all investigations and historic data into account, and agreed by all parties.

BS EN 1997-1 also requires the Designer to produce a Geotechnical Design Report as part

Figure 2 : CPTU equipment in use and Oedometer test cells for the Hong Kong Zhuhai Macao immersed tunnel

of the design deliverables to explain and justify the design, with reference back to the GIR.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

The GIR or GBR should report on the potential variation in soil conditions and the range of values for each soil parameter that should be considered in the design.

REMEDIAL MEASURES/ACTIONS (FOR UNEXPECTED BEHAVIOUR/VALUES)

An experienced qualified geologist, ideally representing the Designer, should supervise the ground investigation programme to ensure that investigations, sampling and testing procedures are carried out in accordance with standards and good industry practise, to ensure the quality of the data and the eventual GIR can be relied upon.

LINKS TO OTHER PROCESSES

Foundation/ Settlement/ Backfill
Seismic

PERFORMED BY / RESPONSIBLE: (100% CONTRACTOR ...)

The suggested responsibilities for elements relating to soil conditions, subject to type of contract and/or risk allocation are:

Project phases prior to construction contract :

Specification of programme, supervision of boring and laboratory work, and interpretation of results - Designer
Contracting with boring contractor and laboratory - Owner or Designer

In the case of a design and build contract :

Additional investigations for Contractor's detailed design and construction - Contractor

In areas with earthquake activity, immersed tunnels shall be designed against the risk of seismic events during the design lifetime. Seismic events in the construction phase shall also be considered.

WHAT

Design scenario

It is normal to apply a two-level earthquake hazard design approach for immersed tunnel project, by considering an Operating Design Earthquake (ODE) and a Maximum Design Earthquake (MDE).

The ODE will have an estimated return period corresponding to the lifetime of the tunnel, typically 100 years. It is a Service Limit State event for which the structure should be designed to respond in an elastic manner. In some locations, earthquakes may be very rare but large, in which case it might be appropriate to choose the ODE equal the MDE (this was for example done for the Bosphorus tunnel in Istanbul, Turkey).

The return period of the MDE may typically be chosen in the range 500-2500 years, as governed by national codes or decided by the Owner from an assessment of the appropriate balance between risk and construction costs. The MDE is an Ultimate (Extreme) Limit State event for which the tunnel structures should be designed with adequate strength to survive the loads and deformations. Following the MDE, Owners may decide that the structures should remain functional; access for emergency traffic should be possible, damages should be repairable, and it should be possible to resume tunnel operation within a limited period.

Earthquake impacts on immersed tunnels can be divided into two groups :

A. Ground shaking causing deformations and sectional forces in the tunnel structure. The response is governed by the free-field deformation of the ground and its interaction with the tunnel structures. It is thus substantially different from the response of surface structures dominated by the base-induced inertial forces.
B. Ground failure such as liquefaction, slope instability and fault displacement.

Design methodology

The design of an immersed tunnel for earthquake will involve the following main tasks :

1. Investigation of the ground conditions, including geological conditions between the tunnel and the base rock, and characteristic soil parameters.
2. Conduction of a site-specific probabilistic seismic hazard study, extending to analysis of the ground motion in the bedrock horizontally along the alignment and vertically up through the sedimentary soil between the bedrock and the immersed tunnel.
3. Analysis of imposed deformations of the tunnel due to ground movements, the resulting joint movements and sectional forces, and design of possible provisions for mitigation
4. Analysis of the different modes of ground failure, and determination of any mitigating provisions to be taken in the design.

Task 1 is described in the below section «Specifications», and tasks 2, 3 and 4 are described in the below section «Analysis».

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

The design of an immersed tunnel for earthquake is carried out during the following main phases:

- Preliminary Design phase: Ground investigations, site-specific probabilistic seismic hazard study and preliminary seismic analysis and design
- Detailed Design phase: Final seismic analysis and design, based on final measured ground parameters

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY…)

In addition to the geotechnical parameters needed for static design analysis, the seismic analysis requires the characterization of the dynamic properties of all soils above the bedrock. These properties include the maximum shear modulus (very small strain value) for the elastic range, and the normalized modulus degradation curve and the damping ratio curve needed for modelling the inelastic non-linear behaviour of the soils.

The properties can be obtained from measurements of the shear wave velocity (Vs) using field suspension logging tests or from Resonant Column testing. High pressure dilatometer tests and cyclic tri-axial tests allow values at small and large strain to be obtained. The tests should be carried out on undisturbed samples of the soils at representative locations along the tunnel alignment and at appropriate stress and strain ranges.

Initially, for Preliminary Design analysis, the damping and degradation curves as function of strain level may be assessed by standard curves from literature.

DOCUMENTATION (FORMAT, DEADLINES)

Seismic design should be documented in the same manner as other design aspects.

EXPECTED VALUES

Design output should meet the requirements of the selected design codes and standards for the project.

ANALYSIS (REQUIREMENTS, TIMESCALE)

Seismic hazard study and analysis of ground motion

A site-specific probabilistic seismic hazard study for investigation of the seismic conditions of the tunnel region should be undertaken at the beginning of the project. The seismic hazard study involves historical records of earthquake activity, geology and previous studies in the region. It will address the location and activity of faults and lead to a description of the ODE and MDE events in terms of earthquake source location, magnitude and duration, and the resulting motion of the bedrock at the tunnel site.

The earthquake motion is described by the 3D acceleration, velocity and displacement time histories of a local control point at the surface of the bedrock and the design response spectrum. The design response spectrum is a plot showing the response to the ground motion of a single degree of freedom mass, in terms of its peak acceleration, velocity or displacement across the relevant range of natural oscillation periods for the mass. Examples of an acceleration time history and design response spectrum are shown in Figure 1 below.

The intensity at the tunnel site is expressed by the peak ground acceleration coefficient, i.e. the peak ground acceleration relative to acceleration due to gravity. For example, for the Busan Geoje immersed tunnel in South Korea, the peak ground acceleration coefficient was 0.15 for the 1000-year return period MDE, whereas for the Preveza Aktio immersed tunnel in Greece, it was 0.40g for a 950-year return period.

Following the definition of the set of starting time histories at the control point, the variations of bedrock motions along the tunnel axis can be determined, as governed by the horizontal seismic wave speed and angle, and by the ground motion coherency function used to characterize spatial variations.

The ground motions may be amplified significantly by the frequency dependent passage through soft soil layers up to the tunnel level. They can be estimated by wave propagation analysis using a site response analysis program such as SHAKE. The vertical variation is also very critical as mentioned below for the racking analysis of the structure.

Deformation of the tunnel due to ground shaking

The impacts on the tunnel structure includes :

- Axial compression and extension due to wave motion parallel to the tunnel axis
- Longitudinal bending and curvature in the vertical and horizontal planes due to wave motion perpendicular to the tunnel axis
- Distortion of the cross section (racking) due to shear wave propagation normal to the tunnel axis

The first and the second impacts can be analysed using a longitudinal global finite element model of the tunnel elements and joints, including cut & cover parts adjoining to the immersed tunnel at each end. The soil structure interaction is described by dynamic soil springs along the tunnel. The concept of the model is illustrated in Figure 2. Load effects in terms of joint movements and sectional forces (in particular shear key forces between tunnel elements) due to the earthquake are superimposed with effects due to the relevant dead and live loads including differential settlements and temperature movements.

The third impact illustrated in Figure 3 can be analysed with two dimensional plane strain seismic local models at locations representing the different soil conditions. The plane models are also used to obtain the soil springs for the global model.

The most significant seismic effects for the immersed tunnel will normally occur at locations with large variations in soil stiffness and at the joints with cut & cover tunnels at the ends. The earthquake loadings and deformations may require additional reinforcement and special provisions to limit joint openings. For the Preveza Aktio tunnel, joint openings were limited by pre-stressing cables, and for the Busan Geoje tunnel, tie bars were used across some joints. In Japan, special immersion joints have been developed to accommodate movements of up to 30 cm.

Wide (and therefore very stiff) tunnels are at a disadvantage when subject to seismic distortions.

Ground failure impacts

Ground failure with resultant loss of structural foundation support include liquefaction, slope instability and fault displacement.

Liquefaction of the ground occurs due to increase of pore pressure and consequent reduction in effective stresses in saturated cohesion-less soil.

The loss of shear strength can lead to tunnel floatation, large lateral displacements, and heave due to the large density of the liquid soil. The liquefaction potential depends upon the density of and particle distribution in the soil; the risk of liquefaction can be reduced or prevented by replacement or improvement of the mature soils at the tunnel and by appropriate specifications for foundation layers and backfill materials.

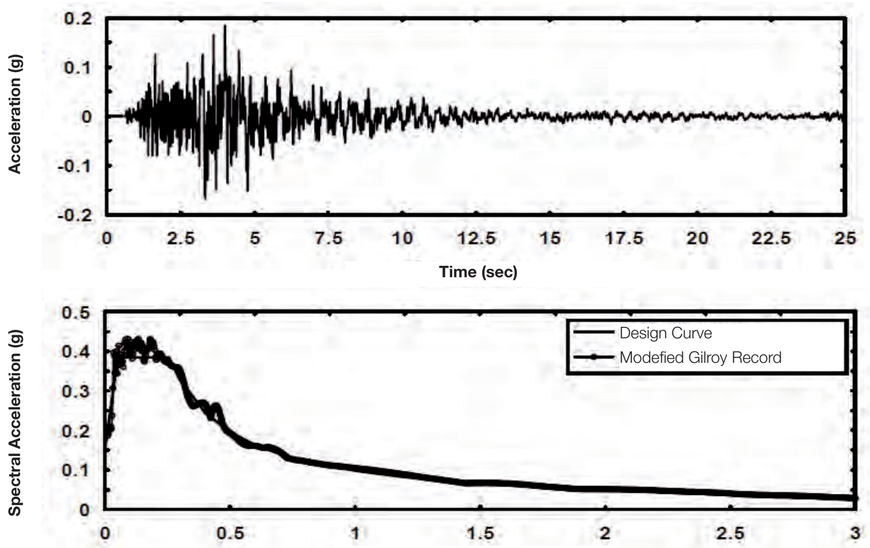


Figure 1 : Example of acceleration time history (above) and design response spectrum (below) applied for the MDE of the Busan Geoje Immersed tunnel

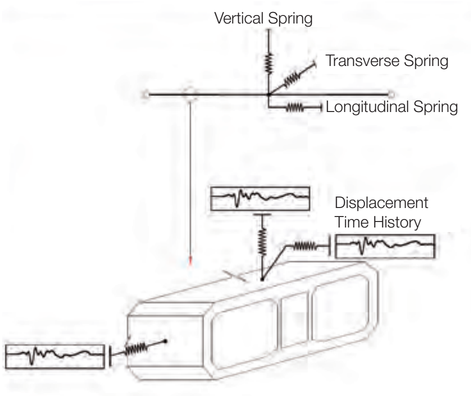


Figure 2 : Concept of global analysis model with dynamic soil springs

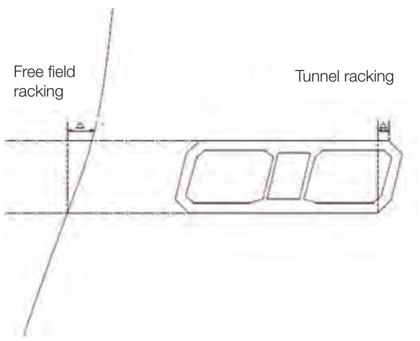


Figure 3 : Illustration of tunnel racking

As an example, soil improvement by stone columns was carried out for the Preveza Aktio tunnel and the Kaohsiung tunnel in Taiwan. They prevent liquefaction by providing adequate drainage to reduce excessive pore water pressure and by increasing the density of the silty sands and sandy silts under the tunnel. For the Bosphorus tunnel, in addition to concrete compaction piles, the tunnel was surrounded by stone with a path to bed level, again to reduce excessive pore water pressure.

Landslide or seismically induced slope movements of the dredged trench may impose excess lateral forces and displacement of the tunnel. This can be prevented by designing the trench with shallower slopes.

Where a tunnel crosses an active fault zone with the risk of very large displacements, it may not be possible to design a buried tunnel structure to withstand the displacements. At such locations, submerged floating tunnels (SFT) could be used.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

Deformations of the structure and associated ground movements will be an output of the design. Acceptable limits on movement will be dictated by the functional requirements under the ODE and MDE conditions.

REMEDIAL MEASURES/ACTIONS (FOR UNEXPECTED BEHAVIOUR/VALUES)

Following a seismic event a thorough inspection of the main tunnel structure and the tunnel joints will be required to determine its condition and whether remedial works are required. Survey of deformations should also be undertaken to ascertain if the structure behaved as predicted in the design.

LINKS TO OTHER PROCESSES

Soil conditions
Foundation, settlement & backfill
Immersion joints

PERFORMED BY / RESPONSIBLE: (100% CONTRACTOR ….)

The suggested responsibilities for elements relating to seismic issues, subject to type of contract and/or risk allocation are:

Ground investigations - Owner
Seismic Hazard Study - Owner or Designer
Preliminary and Detailed Design for seismic events - Designer

ANNEX 12 >> COMPACTION GROUTING

The design of immersed tunnels with regard to subsurface soil conditions is different from other structures in a number of ways. The immersed tunnel is placed in a dredged trench and weighs less than the soil it displaces. Therefore, the unit bearing stress is generally quite low implying that settlement is not likely to be a problem. Settlements can still occur however, during backfilling perhaps due to re-compaction of heave that occurred during dredging. Settlement might occur due the seismic liquefaction of unconsolidated sands or fill under the tunnel. Compaction grouting is a very useful tool that has been used for immersed tunnels to control settlements.

WHAT

Compaction grouting involves the injection of low-slump, low-mobility, cement mortar or grout into the unstable soil strata to compact it. This is done by drilling in a casing to a specified depth then pumping the grout into the treatment zone to form a bulb of a desired size at a designated pressure. This procedure usually starts at the bottom of the hole and is repeated sequentially by raising the casing in increments. The result is a column of grout bulbs that has compressed and densified the ground around it. This procedure is repeated in the form of a grid pattern thus tightening the desired area of the strata under the subgrade of the tunnel. It is important that the bulbs are contained by the overburden pressure and do not cause the ground above to heave. So in the case of an immersed tunnel, the ground treatment by compaction grouting should be done before the trench is dredged.

The soils that can be effectively compacted are open-grained sands and silts. Clay soils are more difficult but can be compacted if the proper grout mix design and injection pressures are determined. Pore pressure relief is important where finer grained soils are to be compacted.

The design of a compaction grouting undertaking begins with a detailed geotechnical investigation along the tunnel footprint. This includes Standard Penetration Tests (SPT) with spoon and undisturbed sampling and laboratory testing. Cone Penetrometer Tests (CPT) are used to gage the potential settlement as well as to later evaluate the effectiveness of the compaction grouting in reducing the amount of settlement likely to occur. The results may dictate a tighter or looser pattern than originally designed.

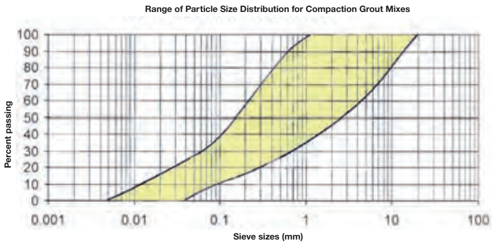


Figure 1 : Range of particle size of soils suitable for compaction grouting

The design of the grout mix is also based on the geotechnical finds regarding the material to be compacted. Generally the grout is a mixture of cement sand and small stone.

Bosphorus Rail Tunnel

An interesting case study is the Bosphorus Rail Tunnel in Istanbul where compaction grouting was used for unconsolidated sands beneath a zone of four elements of the tunnel. This involved compaction grouting in depths of 44-58m of water and soil with surface currents of up to 3m/s.

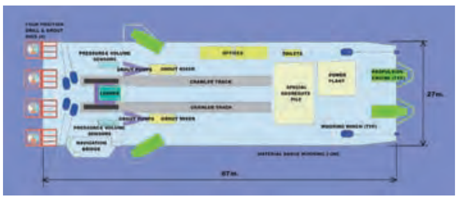


Figure 2 : Bosphorus tunnel compaction grouting barge

It is one thing to set up a compaction grouting operation for a land structure but something else entirely to do it for an immersed tunnel. In the latter case a barge must be equipped with drilling equipment, grout pumps, material hoppers, front end loaders or the like, manoeuvring winches, volume and pressure measuring devices, crew facilities, etc. The design and mobilization of such an operation is no small undertaking.

The barge layout is shown in Figure 1: It was self propelled with four steerable thrusters and was equipped with six mooring winches (because of the strong current this was later increased). Material for the grout mix was brought to the CPG Barge by barge and offloaded by a crawler crane. It was later handled by a smaller front-end loader.

The CPG pattern across the subgrade of the immersed tunnel required drill holes at a very accurate spacing of 1.7m on center. In order to maintain this spacing and protect the drill string from lateral deviation caused by the severe upper layer currents that were a daily occurrence (regardless of season) special framed towers of pipe were constructed down to a depth of 23m. These towers had four protective pipes spaced at the desired 1.7m spacing of the grout columns.

The four drill rigs were set up so that for a single barge position each could be rotated to drill and grout four CPG columns. The barge was accurately positioned and aligned using differential GPS checked with triangulation by ground survey.

The required area to be treated was designed to match the sand layers found to be potentially liquefiable beneath the subgrade of the tunnel.

The grout volume and pressure was carefully controlled for each column to produce bulbs of 143 litres vertically spaced by about 1/3m. Grout pressure varied up to about 3.5 MPa. Sensors in each grout line monitored these parameters continuously and each column was logged for a permanent record. Slump cones were taken both at the grout pump hopper and at the grout line input. Low slumps of 7cm at the hopper and 0cm at the casing were used.

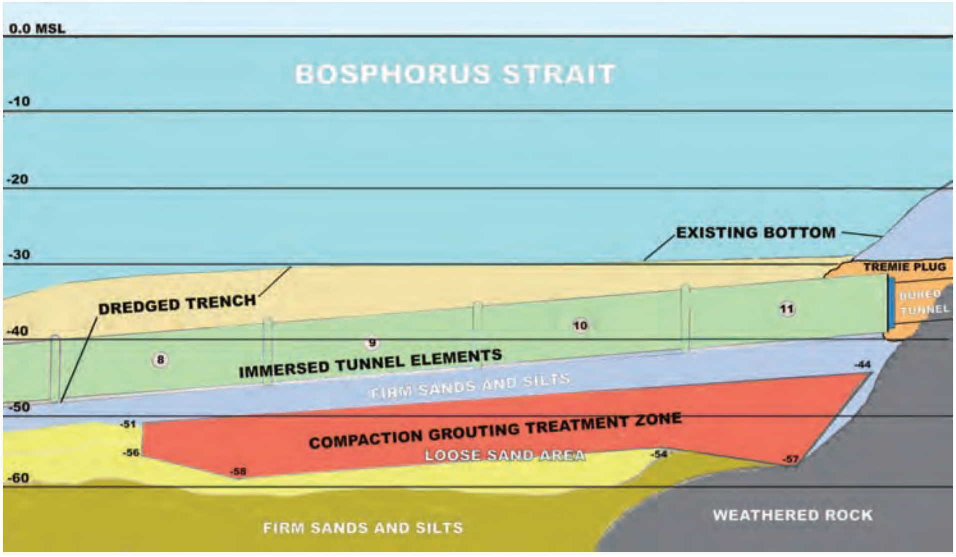


Figure 3 : Extent of compaction grouting on Bosphorus tunnel project

During the grouting process the standardized cone-penetrometer test (CPT) was used to determine the effectiveness of the process in reducing the potential for settlement in the weak zone being treated. There was always a residual settlement potential for the ground under the tunnel that was not included in the treatment. The results were very good and the deviations were slight and not a concern. Actually as the work progressed it was found the with the grouting of the full pattern, the central band of the pattern was tightening well beyond the desired values so, since it was not possible to change the column spacing from the 1.7m, it was decided to eliminate some of the columns. After this was done, the tightening of the ground was still in excess of the design values so the pattern was modified a second time. A total of some 1600 columns were drilled and grouted for the project.

Figure 4 : Barge with four drill towers

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Important issues for Compaction Grouting to improve ground stability for an immersed tunnel project are :

- Comprehensive geotechnical investigation of the subgrade zone of the tunnel.
- Evaluation of seismic effects if the tunnel site lies in such an area.
- Development of equipment requirements for the operation considering depth, water current, tidal action, storm contingencies, etc. Also needed are provisions for personnel, winter shelter, sanitary facilities, office space, etc.
- Provisions for positioning and location stability (moorings, navigation, survey, etc.
- Grout design based on material to be treated by CPG.
- Assure that overburden will confine the injection pressure so that the treatment zone will be properly compacted
- Compaction grouting in saturated soils will increase the pore pressure. This pore pressure must be dissipated for compaction to be effective.
- Soils that loose strength when remoulded such as fine grained or sensitive clays should be avoided.
- Thin stratified soils are difficult to densify by CPG.
- Evaluation of settlement that will occur below the area to be treated.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY…)

The specifications and documentation for the program of compaction grouting for an immersed tunnel must include :

- Staging with respect to the trench dredging so that adequate overburden will exist during treatment
- Target values for the cone penetrometer readings taken following CPG treatment in a defined zone.
- Spacing of columns
- Range of depth for each column.
- Logging of all grout volumes, depths and injection pressures, for each bulb of each column.
- Number of cone penetrometer readings to be taken to maintain an adequate control over actual results of treatment as work progresses.
- Environmental controls to prevent spillages of mortar, drill mud, waste materials, sanitary waste etc.
- Any limiting marine current and/or wave action whereby the work must be suspended.

DOCUMENTATION (FORMAT, DEADLINES)

Design documentation will show depth, spacing and target strengths. Construction logs and CPT results should be retained in the project maintenance manual.

EXPECTED VALUES

Expected values for post grouting cone penetrometer readings must be reasonably met to verify the stabilization of the desired soil strata

ANALYSIS (REQUIREMENTS, TIMESCALE…)

As CPT readings are taken analysis should be made how the treatment can be modified to improve it or make it more efficient. The cost of such an operation is high so that if the desired result can be obtained with less grout columns, so much the better.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

Deviation tolerances should be established early on in the design so that there is no question whether a treated area is acceptable or requires additional treatment columns.

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

Strategies for improving an area where it is found that the treatment has not met desired values should be available and not be prevented by the fixed nature of the equipment plant. In the case of the Bosphorus Tunnel, the spacing of columns was set and could not be changed. It would have been difficult if not impossible to insert columns between those already installed. Fortunately, the designed spacing turned out to be too dense, requiring opening of the pattern rather than the reverse.

LINKS TO OTHER OWNERS GUIDE THEMES

Soil conditions
Foundation, settlement & backfill
Seismic

PERFORMED BY / RESPONSIBLE

The suggested responsibilities for elements relating to compaction grouting, subject to type of contract and/or risk allocation are :

Functional requirements - Owner
Geotechnical investigations – Owner followed by Contractor
Compaction Grouting ground treatment program – Contractor checked by Owner.
Equipment design and procurement – Contractor
Equipment operation, positioning, survey, etc. - Contractor
Compaction grouting and logging– Contractor
Post grouting CPT testing – Contractor
Modification of programmed CPG pattern – Contract with Owner approval
Material Supply and delivery – Contractor
Environmental disposal of wastes – Contractor
Overall inspection - Owner

ANNEX 13 >> REFURBISHMENT

Refurbishments of immersed tunnels have some specific considerations. This annex deals with the items particular to immersed tunnels

WHAT

Items that may need refurbishing in an immersed tunnel include the main structure, joint components, internal finishes such as cladding and fire protection and M&E systems. A number of older tunnels have undergone seismic retrofits and many tunnels have been upgraded for new road or railway design, operational and safety standards. This may include improvements to ventilation systems, fire life safety systems, traffic vehicle clearances or new safety, operational or monitoring systems.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Most major refurbishments occur some 40-50 years after the initial construction. However, minor upgrades may occur at any time that standards are updated or safety and operational practices are changed. Repair of defects arising in the structure may be carried out as necessary. Most tunnel owners and operators will have a lifecycle plan in place that will predict when systems or components become life expired and will need replacing. This enables budgets for the future operation of the tunnel to be produced.

Determining the extent of or optimal time for refurbishment in the life span of the structure is not an easy task. Information necessary to assess the condition of the structure and its components (data and decay models) will not be obtained from one single inspection survey, but from a series of targeted surveys over several years, maybe even over a decade or two.

The installation of passive fire protection material in recent years has resulted in the covering of the surface of the structure.

Reference inspections points which are easily accessible should be established before a planned refurbishment, or in the original design if fire protection materials are to be applied from the outset.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY…)

Major refurbishments are generally undertaken to bring a tunnel up to current standards, wherever possible. If this is impracticable, departures from standard may need to be agreed with the Owner/operator, a national technical approval authority and the fire safety authorities.

There are no specific standards for refurbishment, although if the structure requires a load assessment as part of the refurbishment then most countries have national standards that would apply. Similarly there is no standard approach to refurbishment; each tunnel must be considered according to its particular condition and circumstances.

DOCUMENTATION (FORMAT, DEADLINES)

Detailed condition surveys are needed for the existing asset to determine the extent of refurbishment required. Some countries have a standard approach to this, such as the Federal Highway Administration (FHWA) in the USA. Regardless of the approach used, a systematic method of recording the condition and defects in the tunnel is needed that identifies each defect in detail and locates its position accurately within the tunnel. The asset inspection may include :

- A partial inspection looking for cracks, leaks and obvious damage such as broken ceiling hangers and exposed reinforcement,
- A full structural inspection,
- Intrusive investigation to determine strength and condition of materials
- Full operational test of floodgates, and
- Inspection and testing of all electrical and mechanical plant and equipment including operating, monitoring and control systems.

The extent of inspection necessary will depend upon the extent to which the tunnel has undergone periodic inspections throughout its life. The inspection and repair history should be fully documented as the start point for refurbishment. In addition future life predictions should be performed to compare with the Owner's aspirations and set the strategy and objectives for refurbishment. Any non-compliances with current design or operating standards should be identified to enable decisions to be made as to whether to bring the tunnel up to current standards or not. If refurbishment affects the structure's ballast, element/segment buoyancy calculations must be performed.

Geometric survey is also required to accompany the condition survey. The condition survey should record in detail all of the defects in the structure such as leakage, cracking in concrete and excessive joint movements or settlement.

Records of intrusive surveys and laboratory testing of samples should be provided by testing companies.

Design for the refurbishment works, including structural assessments should be documented and specifications produced for the materials and workmanship for construction works, and materials, performance and testing requirements for mechanical and electrical equipment required to be installed.

EXPECTED VALUES

Not applicable

ANALYSIS (REQUIREMENTS, TIMESCALE…)

Intrusive and non-destructive testing is often undertaken prior to a refurbishment to establish the condition of the tunnel structure. If access is restricted and this cannot be done in advance then the testing may be carried out as part of the refurbishment exercise.

Intrusive surveys may include :

- Ultrasound surveys of steel plate to assess residual thickness. Note that obtaining access to carry out such tests is difficult and large areas of concrete may need to be removed to get sufficient access to obtain a representative number of tests of the steel membrane behind.
- Measurement of chloride content in concrete vs depth from surface to predict chloride progression through the structure.
- Identification of carbonation of concrete.
- Testing of cores to determine strength of concrete.
- Removal of concrete where spalling or rust

staining is evident to assess extent of corrosion.

Non-intrusive surveys may include :

- Measurement of water inflow rates at points of leakage on a seasonal basis.
- Measurements of water inflow to sumps due to possible leakage in the tunnel or tunnel approaches.
- Reading of cathodic protection monitoring devices, if installed, to predict level of corrosion occurring and likely to occur over the life of the structure.
- Geometric survey for line and level to understand settlement compared to the initial as-built condition.
- Recording and measurement of damage, spalling or deterioration of the main tunnel structure.
- Measurement of cracks to determine necessity for sealing or injection to prevent future corrosion.
- Examination via inspection pipework at immersion joints, if present, to determine the presence of water between Gina and Omega seals or in the void to the inside of the Omega seals. It may be possible to access the void to the inside of the omega with remote cameras to inspect the condition of the Omega seal and its clamping bolts and plates
- Removal of any cover plates at immersion joints to visually inspect shear keys and Omega joint clamping bolts and plates, if accessible.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

Not applicable

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

Common remedial works included in refurbishments are :

Civil works :

- Replacement of roadway wearing surface in highway tunnels
- Replacement of rails in rail tunnels
- Replacement of floodgate seals and upgrade of mechanical and electrical plant for operation of gates
- Sealing of leakage by injection. Note it may be challenging to seal leaks at immersion joints made using tremie concrete
- Installation of drainage to manage leakage if it cannot be stopped
- Precautionary sealing of cracks in excess of 0.3 mm
- As a more extensive measure, through-going crack formation due to temperature movements may be stopped by pre-stressing with cables in the ballast concrete.
- Removal of spalled concrete and repair
- Renewing joint gap sealants and caulking at segment joints and immersion joints
- Replacement of damaged cladding, vehicle crash barriers and handrails to walkways
- Clearing and unblocking drainage systems
- Replacement of fire protection material or introduction of fire protection material if not present
- Renewal or new applications of corrosion prevention systems (including coatings to steelwork) at immersion joints, where accessible.
- Replacement of bearing components in shear keys at immersion joints, if used.
- Introduction of cathodic protection for the main structure reinforcement. If there is evidence of significant corrosion or the imminent onset of corrosion, CP may need to be considered. Fitting of sacrificial anodes in the external environment of the tunnel may be difficult and expensive, but necessary. Many tunnels are now fitted with facilities to allow the future application of impressed current cathodic protection.

It should be noted that it is possible in principle to replace the omega seals of immersion joints. In practice this would be a significant exercise that would cause disruption to the operation of the tunnel and require tunnel closures for a period of time. Components of the immersion joints are designed and specified to be durable for the full design life of the tunnel to avoid this.

Seismic retrofit is a specialist area and very expensive. Few if any tunnels before 1970 considered seismic effects. Retrofit usually requires the tunnel to remain operational and may therefore take considerable time. There is very limited space in an immersed tunnel within which to add new structural items to increase bending and shear strength which may result in no action being taken. Areas where retrofit may be practical include shear strength of joints (usually a weak link), measures to restrict the opening of joints, foundation material (e.g. grouting of sand) and improvement of soils adjacent to and beneath the tunnel to reduce the risk of liquefaction.

Retrofit measures to mitigate risk of liquefaction of surrounding soils may include gravel drains and ground densification this was carried out on the George Massey tunnel in Vancouver.

Increasing vehicle headroom can be carried out by lowering the road surface level. However the overall weight of the tunnel must be maintained at all times and the use of temporary kentlege or ballast, together with high density concrete, may need to be considered.

Stabilising settlements may be necessary if movements are excessive. This would be extremely difficult to do in the immersed section but techniques to improve or stabilise the surrounding soils and foundation, such as relief piles or underbase grouting, could be considered.

The approach works to the tunnel may have specific refurbishment requirements. Dealing with ground movement is a common requirement in refurbishment contracts, generally to limit or prevent further uplift or settlement from occurring. There are immersed tunnel projects where tension piles have failed in the tunnel approach ramps causing uplift and the ramps have been be stabilised by introducing additional piles or ground anchors, or by applying additional vertical load.

Mechanical and electrical systems:

It is difficult to change the internal geometry of a tunnel, so the ventilation system in operation will in most instances be retained but the equipment assessed and upgraded to meet current standards. New ventilation fans must be designed to fit in the available envelopes created by the original tunnel. The only real opportunity for increasing the number or size of fans will be at the tunnel portals where new fan housing structure can be constructed and the cut and cover tunnel be modified if necessary. This is expensive but has been carried out on occasion.

Occasionally the ventilation principle is altered from longitudinal to transverse, or vice versa and the utilisation of space within the tunnel is re-designed. An example is the Downtown tunnel in Virginia where a suspended ceiling was removed and the ventilation system changed from a transverse system to a longitudinal system using jet fans in the tunnel.

It has been established relatively recently that water deluge or water mist systems can be used to help manage a fire both in road and rail tunnels. Few tunnels have been constructed with such a fire safety system. Retrofitting of such a system can be practical.

The spray pipework can easily be fitted in the tunnel but it is more challenging to find space for the necessary supply pipework, valves and provide a compatible drainage system. This can be particularly helpful if the ventilation system cannot be fully brought up to current standards, as the water mist or deluge system can assist in keeping the fire growth under control. Note that this would not be a replacement for passive fire protection layer which would most likely still be required.

Most operating systems are common to all forms of tunnel and therefore do warrant particular discussion, but the key issue for them all is fitting replacement systems into the available space in the tunnel.

If the tunnel is provided with a dedicated service gallery then future refurbishment is made easier as cabling and control systems can be segregated from the operating tubes of the tunnel.

LINKS TO OTHER OWNERS GUIDE THEMES

Maintenance and Operation
Ventilation and Fire
Fire Protection
Cathodic protection
Immersion joints
Segment joints

PERFORMED BY / RESPONSIBLE

The suggested responsibilities for elements relating to refurbishment, subject to type of contract and/or risk allocation are:

Surveys – Owner or contractor depending on operating and procurement approach
Assessments & refurbishment design – designer
Specifications for civil works & performance requirements for M&E systems – designer
Detailed specifications for M&E systems – designer or suppliers
Refurbishment works – Contractor

ANNEX 14 >> TUNNEL ELEMENT ALIGNMENT

The precision of alignment of a tunnel horizontally and vertically is a critical matter. This Annex describes the methods used for alignment control for various types of immersed tunnel.

WHAT

Placing immersed tunnel elements may start at one end and progress to the other or start from both ends and meeting at some intermediate location in the waterway. The immersed tunnel alignment is very dependent on how the elements interact as each new element is added. The amount of drift from the theoretical line is particularly critical where the tunnel is started at both ends and a closure element is to fit into the final gap. The parameters to be controlled include the accurate match between the mating faces of the element being placed and the section of tunnel already in place and the horizontal, vertical, and longitudinal position of the outboard end of the new element. Axial rotation must also be controlled as each element is placed.

When fabricating the tunnel elements several tolerances can occur. These are mainly concrete tolerances and local geometry changes such as the orientation of the end mating faces. Most immersed tunnels use load-bearing rubber seals (Figure 1) between these faces that require uniform compression. Small angular errors in these faces can result in large displacements at the remote end.

Figure 1 : Typical Gina seal.

Besides ensuring that an immersed tunnel element is level transversely after placement, the elevation and lateral position at each end should fall within the design tolerances. If the foundation is prepared before placing the tunnel element, there is little that can be done about being level and changing the elevation at each end. If the foundation is constructed after placement, provision must be made for adjustment at least at the outboard (free) end whereas the inboard (mating) end could be supported off the previous element. There are two basic issues affecting horizontal alignments to consider during the placing of elements for any immersed tunnel :

- Relative position at the mating faces at the immersion joint. Provision of guide beams and receiving cams can make this easier providing they have been correctly positioned and account taken of tolerances.
- The location of the outboard end of the element after depressurization of the immersion joint. This depends largely on how accurately the immersion joint seal support plate and the corresponding bearing plate on the tunnel in place were installed and validated by survey. If the position of the outboard end deviates beyond the specified tolerances, some means must be available to correct the alignment.

The seal shown in Figure 1 is a GINA seal. To make an initial seal, it has a soft nose that has a useful operating range less than 4 cm for it to be effective in sealing the joint. Once the joint space is thus sealed it can be fully depressurised. This mobilizes the huge force produced by the ambient external pressure now acting only on the outboard end of the element. This then fully compresses the body of the GINA uniformly. This will move the outboard end of the element to a position hopefully within the specified tolerances; if not, the outboard end will need to be moved into tolerance.

Figure 2 shows a typical survey validation of the steel bearing rings of one of the elements for the Boston Ted Williams Tunnel.

The survey has confirmed the vertical and horizontal alignment of the end plane of the element in relation to its longitudinal axis. Local out of plane tolerances must be small to ensure the soft nose of the GINA immersion seal will engage to provide the initial seal so critical to the whole operation. The validation work was done at night to avoid any distortion that might have resulted from uneven solar heating during the day.

Figure 2 : Night survey validation of outboard face of a steel shell element.

The validation also checks the guide beams and receiving cams and bearing surfaces at both ends of each element while in dry dock to assure later proper joint match in relative elevation and rotation between elements when they are joined underwater.

Steel Shell Immersed Tunnels

Until recently, steel shell immersed tunnels were the only type of immersed tunnels being constructed in the United States. Furthermore, these tunnels were always constructed by first laying very accurately a screeded gravel bed onto which the element was placed. The earlier tunnels used seals that were not load-bearing, the load being carried on steel mating rings.

This foundation provided an immediate permanent support of the element and eliminated the need for a temporary support in the form of a jacking frame. It had the disadvantage of being prone to silting from sediments in a river, or bottom sediment blown onto the bedding by marine equipment propellers. The latter problem sometimes resulted in having to suspend a placing operation, remove the element, and re-screed the bedding before the work could proceed. This problem would make itself known when during placement the element would not reach the design elevation; it would end up with an undesirable rotation, or would not properly mate with the tunnel already in place.

The effect of the screeded bed was to establish the vertical position of the element being placed. The horizontal location at the outboard end was dependent on the trueness of the load-bearing steel mating rings. For the last two steel shell tunnels (Fort McHenry - Baltimore 1985 and Ted Williams – Boston 2005), very flat (1:20) adjustable wedges placed in the immersion joint were used very successfully to adjust horizontal alignment at the outboard end of an element that exceeded specified tolerance. These wedges located at the horizontal axis (see Figure 3), were fixed on the element in place and movable on the element being placed. For the Ted Williams tunnel, the wedges were adjusted to bear on each other when the GINA seal was fully compressed. Before placing the element, these were positioned based on the prior validation surveys of the opposing faces. After depressurizing the joint, if the outboard end was out of tolerance, the joint was flooded and pressurized enough so that the wedges could be readjusted to a calculated position based on the 1:20 machined taper and the amount necessary to throw the element on line.

Rectangular Concrete Tunnels

Since World War II, rectangular concrete tunnels developed as the preferred immersed tunnel technology in Europe and in other parts of the world. Most recently this type of tunnel has begun to take hold in the United States as well. Recently, the Bosphorus Rail Tunnel in Istanbul, Turkey set the record as the deepest immersed tunnel in the world at 58m depth.

Where the foundation below the tunnel element is formed after immersion, at least the outboard end must be placed on temporary supports

Rather than using hydraulic rams through the base slab, recent elements have been immersed onto some form of jacking frame usually only at the outboard end. Such frames can provide adjustment both vertically and horizontally. Alignment at the inboard end might use a heavy shear key and/or guide beams.

Figure 3 : Inboard joint showing movable wedge.

Figure 4 : Jacking frame - is hung beneath outboard end of element (Bosphorus Rail Tunnel).

Figure 5 : Inboard end of element with central shear key and two guide beams (Bosphorus Rail Tunnel).

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Important issues for the successful alignment of an immersed tunnel are :

- The determination of the methodology to be used for alignment control and measurement based on site conditions and limitations.
- The design of the tunnel elements to include adequate features and guides to assure practical placement facility and interconnection accuracy between element faces.

Monitoring / survey

The types of survey that can be used in determining the various stages of immersion:

During immersion :
1. Basic: no survey system required (when a single element is immersed within 2 fixed points ie. abutments)
2. Traditional survey System-1: survey tower and access shaft fitted with prisms and monitored by total stations (Figure 6)

Figure 6 : Tunnel element with access shaft (red) and survey tower (yellow)

3. Traditional survey System-2 : access shaft and survey tower fitted with DGPS and a gyrocompass (Figure 6+7). Or using a Gyro-Theodolite from the bottom of an access shaft or manhole, sighting the baseline for the rest of the tunnel.

Figure 7 : GPS towers with inset showing arrangement of equipment on towers. (Bosphorus tunnel)

4. Modern survey system: Tautwire System (Figure 8) with distance sensors for the final steps
5. Modern survey system: acoustic projectors mounted on the newly placed element and reflectors on the element already in place. Often combined with accelerometers inside the element.

Figure 8 : Tautwire system

All these instruments can be read on a display in the control cab (Figure 9).

After setting the element down:
1. Where an access shaft is present: azimuth alignment (drop down laser or optical plummet)
2. Where no access shaft is present: long optical baselines from tunnel access

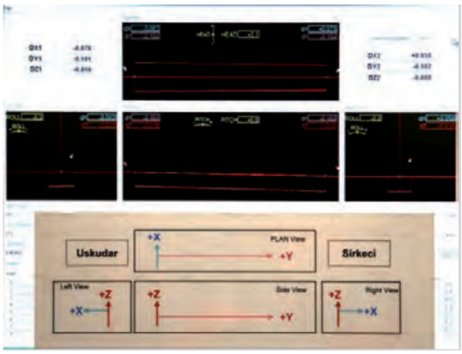


Figure 9 : Element attitude display in control cab.

Monitoring element position (long term):
1. Where shaft or tower is present : Total Station or DGPS survey
2. Where no shaft or tower is present: continuous survey by laser or total station through tunnel

Types of adjustment of alignment

Vertical (both inboard and outboard end) can be realigned
1. Adjustment of supports if present (inboard is difficult due to Gina reaction)
2. Scrading or screeding of gravel bed

Horizontal (only secondary end can be realigned) :
1. Realignment system with wedges in immersion joint
2. Longitudinal eccentric jacking in immersion joint
3. External jacking frame on secondary end (Figure 10)

Figure 10 : An adjustment jack being installed.

4. External Positioning System (innovation in BGFL project) (see Figure 11)

Figure11 : External Positioning System

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY…)

The specifications and documentation for the alignment of immersed tunnels are :
- Setting of desired tolerances of accuracy in horizontal and vertical position of each element with respect to the theoretical.
- Adjusting to out of tolerance conditions (sometimes these cannot be corrected and alignment readjustment to suit may be required).
- Measurement of post-placement settlements and/or lateral displacements short-term between subsequent element placement and long term resulting from backfill surcharging and/or subgrade consolidation. The former may require changing screeding elevations for the subsequent element for example. The latter may require realignment of interior features such as walkways, lighting, ceilings, etc. To provide a best-fit smooth appearing finished interior.
- Establishing a system of survey control to be used for the life of the tunnel for the possibility of long term changes due to settlement, loss of cover, or anything that might result in leakages or damage.

Allowable tolerances are typically determined by the owner or contractor's designer. These tolerances are based upon the method of immersion, the expected settlement over the lifespan of the tunnel and the execution tolerances of the geometry (concrete / steel).

Very tight tolerances apply to the fabrication of the end faces of the elements to ensure that an initial seal of the immersion joint can be obtained and that the seal is watertight in the final condition. Permissible tolerances for flatness and parallelism of the plates enclosing the immersion joint seal depend on the properties of the seal.

DOCUMENTATION (FORMAT, DEADLINES)

The interface between Owner and Contractor with respect to alignment can be managed as follows :

- Contractual agreement of who owns the processes and is responsible (RASCI) for the alignment in specific stages of the project.
- Functional or specific requirement on the allowable tolerances of immersion and immersed tunnels.

In case of Design/Build the Contractor is required to do this.

EXPECTED VALUES

Alignment must meet requirements to fit end portal structures or other constraints. Immersed tunnels started from both ends simultaneously must meet within the tolerance limitations of the structural details of the closure joints. A sudden angular correction at this location may not be acceptable where tight traffic envelop tolerances must be meet in the case of subway trains for example.
In immersed tunnels it is common for the Owner or the designer of the Owner to present general numerical requirements in making the output specifications for an immersed tunnel such as :

- Required xyz placing tolerances
- Philosophy of misalignment vs. working envelope
- Oversetting of the element in height to compensate for settlement
- Time when final construction works can take place (after xxx% settlement)
- Interfaces between choices made in permanent tunnel design (i.e. joints, requirements, etc.) and immersion design

In case of Design/Build the Contractor is required to do this.

ANALYSIS (REQUIREMENTS, TIMESCALE…)

The Owner or designer of the owner can provide an overall time schedule of what alignment is affected in what stages of the process. In case of Design/Build the Contractor is required to do this.

Survey crews preferably dedicated to the immersed tunnel part of the Project provided by both Contractor and Owner should work closely together.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

Some projects have used ±50 mm in all directions absolutely and ±25 mm across immersion joints.
±35 mm is a common specification for horizontal position of tunnel elements after placing.
±25mm is a common specification for vertical position of tunnel elements after placing.
In Design and Build contracts these tolerances can be left to the contractor to determine according to the choice of Gina gasket and the choice of survey and positioning systems, provided the overall deviation limits for the road or rail alignment set by the Owner are adhered to.

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

A risk based design approach asks for a Risk Inventory List (RIL), in which risk items with appropriate measures for survey and realignment system can be shown. In this RIL for instance actions required if realignment system fails / does not function properly.

LINKS TO OTHER OWNERS GUIDE THEMES

As built survey
Element construction
Element positioning
Foundation settlement
Joints – immersion
Joints – land
Leakages
Tolerances

PERFORMED BY / RESPONSIBLE

The suggested responsibilities for elements relating to tunnel element alignment, subject to type of contract and/or risk allocation are:

Plans and Specifications - Owner.
Construction tolerances to be achieved – designer/Owner.
Establishment and maintenance of project survey control system – Owner.
Survey planning and method statements – Contractor.
Design of survey systems – Contractor.
Design of guidance and positioning systems – Contractor.
Survey during construction – Contractor.
Check survey during construction – Owner/ independent survey team.
Acceptance of alignment on completion of immersion – Owner.

ANNEX 15 >> TUNNEL ELEMENT TRANSPORTATION

One of the main characteristics of an immersed tunnel is that it consists of one or more prefabricated tunnel elements. These elements can be fabricated on a shipway and launched, or fabricated/cast in an existing or purpose-built temporary dry dock. From there the element may be completed for placing at an outfitting jetty, stored at temporary moorings or transported directly to their placing location.

WHAT

Construction site

The construction site for the tunnel elements is usually situated at a location other than the immersion site. Depending on the local situation the tunnel elements can be built in the cofferdam for the approach ramps of the tunnel, in a specially constructed casting basin at the tunnel crossing site or at a remote location, in a ship dry dock or a shipyard. The capacity and size of the facility should be taken into account as well as the distance to the immersion location and the obstacles encountered on the transport route. The water depth along the proposed route must be safely adequate for the draft of the elements to be transported.

Types of transport

Dependent on the choice of location of the construction dock and the distance to the immersion location different methods of transport can be used.

Transport by means of winches

Tunnel elements fabricated in the cofferdam of the approach ramps in general are in line with the final tunnel alignment. After floatation the tunnel elements can be transported to their immersion location by winches. At least two longitudinal winches have to be used. When immersing in a river with current also transverse winches are required to keep the tunnel element in place. Similarly casting basins immediately alongside the tunnel approaches may permit transportation by winches with a similar arrangement of winches to control longitudinal and lateral position of the elements.

Transport by means of boats

Tunnel elements fabricated at a location further away from the immersion location have to be transported with tug and push boats. After floatation the tunnel elements are moored to prepare for transport. If necessary the tunnel elements will first be winched to a mooring location near the exit of the basin. After preparations tug boats and / or push boats will connect to the tunnel element for transportation to the immersion location.

Steel shell elements are often transported long distances simply floating with their inherent buoyancy or in some cases where transport of steel shell elements must cross open sea for large distances, a semi-submersible barge has been utilized. (Figure 1.)

Figure 1 : Example of tunnel element being transported by semi-submersible barge.

Outfitting

Steel shell tunnels are usually completed at an outfitting jetty where both the permanent internal and external concrete structure is cast. The steel shell element is also prepared at the outfitting jetty with temporary equipment mounted on it, which is needed for placement.

Concrete box tunnels may be completed and readied for placing at the casting yard or may be transported to a temporary location where they can be outfitted with the temporary equipment necessary for placing.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Construction site

The locations of the construction and outfitting sites have to be chosen at an early stage. Sometimes this may be pre-selected by the project owner, or it may be left up to the contractor. Transport from the element construction site to the immersion location must be possible and agreements must be made with waterway and port authorities.

Transport

After floatation a tunnel element often is moored at the launch or construction site to prepare it for transportation. Afterwards the tunnel element can be transported directly to the outfitting jetty, immersion location, or to a temporary mooring location. By using a temporary mooring location the construction of the tunnel element and its immersion can be made less dependent on each other.

The circumstances of the transport route should be investigated at an early stage. Several third parties have to be informed and permits can be required. The local weather and water conditions can be of influence on the time schedule and can restrict the opportunities to start transportation.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

Preparation for transport

The following aspect should be taken into account to prepare the tunnel element for transport:

- Trimming. After floatation the tunnel element will be trimmed to the required freeboard. Generally for a concrete tunnel element a minimum freeboard of 150mm is required floating in fresh water. If the tunnel element has to be transported over sea the minimum required freeboard increases to for example 300mm.
- For trimming a concrete tunnel sometimes ballast concrete will be applied. If ballast water is used for trimming the event

of sloshing water should be taken into account. Stability of the element is of great importance, therefore free water should be avoided as much as possible.

- Temporary equipment. The following equipment may be mounted on or in the tunnel element before or after transport to the outfitting or project site: pumping systems for ballast tanks and leakage water, lighting in the tunnel element, generator, bollards, fairleads, push boat frame, navigation lights, signal beacons, access shaft, survey tower, protection of Gina profile.
- Transport of steel shell elements can be done self-floating or on a semi submergible barge. Solid rigging and sea fastening is important when transporting on a semi sub. A sea worthy system should then be the result.
- Checks. Before transport for immersion checks are done on the state of tunnel element and all required equipment for transportation and immersion, including diving checks of the outside of the tunnel element.

Winching system

For a winching system the following equipment is used:

- Longitudinal winches
- Transverse winches (capacity dependent on current and other transverse forces)
- Winch foundations
- Winch wires
- Spuds for anchorage

Figure 2 shows an example of a winching system.

Transport by boats

Transportation of the tunnel element can be done by tug boats and push boats. In Figure 3 examples are given for two configurations. Sea transport can be done pulling forward on all tugs, because the transverse movement is of less impact (more space). The river transport should be done more controlled in transverse direction, and should be able to stop over short distances, therefore a 4-directional spread is used.

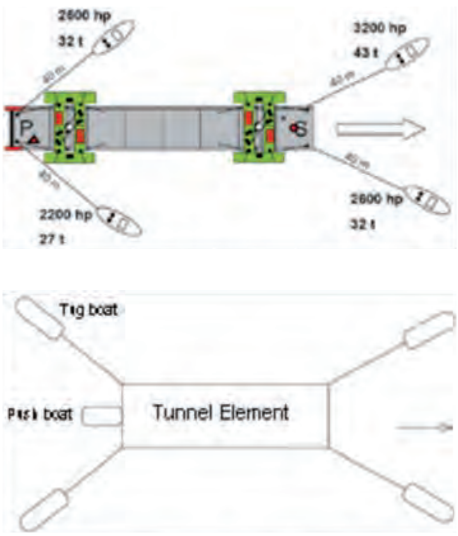


Figure 3 : Example for transport over sea

The capacity of the boats depends on the dimensions and weight of the tunnel element, the current flow forces, manoeuvrability and properties of the transport route.

For transport of the tunnel element the following stakeholders have to be consulted: contractor, transporter, client, waterway authorities, port authorities, warranty surveyor, pilots.

Before transportation several decision meetings are held with the stakeholders to decide if all requirements are met for the upcoming transportation of the tunnel element. For example the decision meetings can be held 48 hours, 24 hours and 3 hours before transport.

The following criteria can be checked in the decision meetings: preparation tunnel element, state of transport route, weather forecast, predictions tides and current flows, wave forecasts, expected shipping on transport route, survey transport route for obstacles.

Transport route

The following aspects should be taken into account for the transport route:

- Width of the navigation channel, side clearance / fendering
- Shipping lanes
- Necessary blockages of waterways if the transport interferes with the shipping channel too much
- Obstacles such as bridges (top clearance, passage width), locks (width, length, suction forces)
- Keel clearance on transport route
- Current flows in order to know the loads on the transport system
- Tides and tidal flows in order to know the loads on the transport system
- Possibility of transverse current flows at river crossings
- River bends
- Sea conditions (waves)
- Other shipping
- Required permits

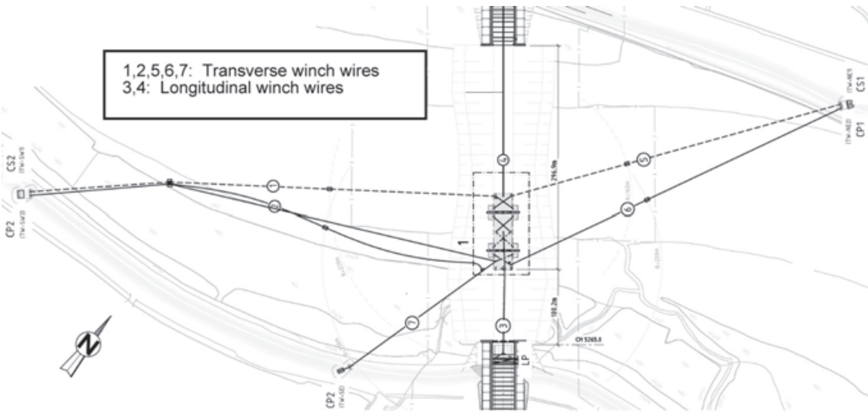


Figure 2 : Example winching system in tidal river

Wave, current and weather windows

Due to local circumstances the transport can be restricted to for example current flows, tides or wave heights. The impact of those influences on the transport configuration and the time schedule should be determined. If necessary the transport can be restricted towards for example tidal fluctuations. With all restricting influences combined time windows can be determined for transportation. From a safety point of view, one or more safe havens should be identified and prepared, to accommodate mooring of the configuration in unforeseen bad weather.

Floating stability

The floating stability encompasses the up-righting properties of the tunnel element when it is brought out of equilibrium or balance by a disturbance in the form of a force or a moment. As a result of these loads the tunnel element will rotate about its centre of gravity. It should be checked if the tunnel elements meet the requirements for the floating stability such as the position of the metacentre, the maximum angle of heel with a stabilising moment and the area underneath the static stability curve.

DOCUMENTATION (FORMAT, DEADLINES)

Time schedule

A detailed time schedule for each transport should be made as well as an overall schedule for all of the tunnel elements.

Method statement transport

Before transport a method statement should be made. The method statement contains the following items: decision meetings, parties involved, time schedule, transport route, transport configuration, emergency procedures.

EXPECTED VALUES

Freeboards for transport vary from 0.15 to 1.0m (dependent on expected wave conditions). Up to several meters of freeboard can be expected for light weight steel shell tunnel sections. Metacentric height G'M > 0.50m, maximum stabilizing angle up to 30 degrees. All depending on the applied Class Society regulations (Lloyds, DNV, TUV, etc). Which is often prescribed by the owner.

ANALYSIS (REQUIREMENTS, TIMESCALE…)

Insurance

Besides the normal project insurance an insurance with marine coverage is needed. The insurance company is usually involved in decision making and design checks during preparation works, and sometimes even during physical operations.

Risk assessment

Before transport a risk assessment has to be done. The following items can be part of this risk assessment:

- Leakage in tunnel element
- Failure of bulkhead caused by for example a collision
- Running aground
- Collision with obstacles (bridges, locks)
- Collision with floating objects (protection of)
- Failure of prestressing due to overload
- Unexpectedly worsening of wave and weather circumstances

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

Typical monitoring during transport consists of:

- Loads on system (bollard pull, winch loads, etc)
- Water levels
- Ballast levels
- Weather forecast updates and analysis
- Current and wave analysis
- Position in navigation channel based upon GPS or survey system

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

The following measures can be taken for unexpected behaviour/values:

- For a longer transport route a safe area can be designated where the tunnel element can be moored temporarily until the wave and weather circumstances are more favourable again.
- Tug configurations are prepared so that with loss of 1 tug, transport could still continue towards a safe haven.

LINKS TO OTHER OWNERS GUIDE THEMES

Element construction / dry dock
Joints – immersion
Joints - segment
Temporary Prestressing
Tunnel element temporary mounted equipment

PERFORMED BY / RESPONSIBLE

Determine position of construction site: Owner / Designer (preliminary/tender design phase if design-bid-build), Contractor (D&B tender/ detailed design phase)

Consultation with waterway and port authorities: Owner / Designer (preliminary/ tender design phase), Contractor (detailed design phase)

Functional requirements: Designer / Contractor

Design of temporary constructions & detailing: Contractor / Designer

ANNEX 16 >> TUNNEL ELEMENT TEMPORARY MOUNTED EQUIPMENT

The permanent structure of an immersed tunnel consists of either a concrete or steel outer shell. Most of the equipment for permanent works is placed inside the tunnel bores. Before transport, immersion and completing the foundation can take place, several items of temporary equipment must be mounted within and on the outside of the element. This chapter outlines this temporary mounted equipment.

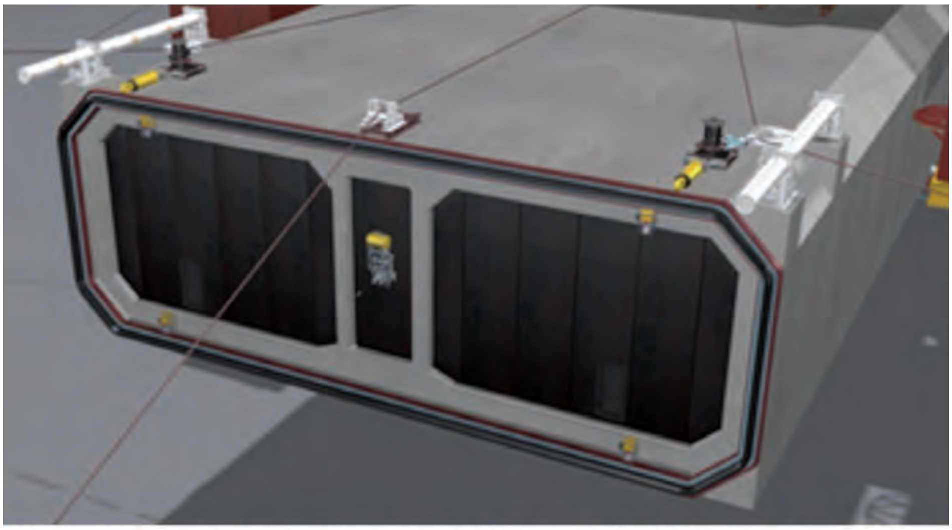


Figure 1 : Example of mounted equipment (bulkhead, pins, fairlead, etc

WHAT

The following systems / type of equipment are utilised:

- Bollards used for towing and mooring operations. A minimum of 4 bollards (1 on each corner) is required for towing an element, for other operations more bollards could be useful (mid-mid or primary/ secondary side). As each bollard impacts the permanent structure minimizing the amount is always the better option. Bollards are mainly used for connection of wires from tugs or winches.
- Suspension lugs for lowering and supporting the element when immersion takes place (Figure 2). The suspension lugs are positioned on the roof slab of the element in order to lift the element during immersion. Four lifting lugs are usually mounted on the element, positioned in the area where the bending moments of the element are least influenced.

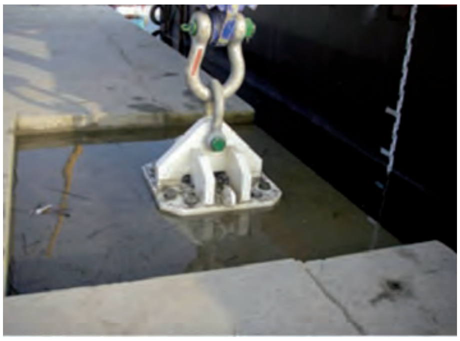


Figure 2 : Typical suspension lug

- Access shaft for temporary access through the roof of the element or through the bulkhead during outfitting for placement and emergency access after placing (Figure 3). One or more access shafts are mounted on the element for access and to mount GPS antennae / prisms for survey. Also a personnel extraction crane can be mounted if required, for use in the event of accidents inside the element.

Figure 3 : Typical (short) access shaft

- Supports (primary and secondary) (Figure 4) for temporary support of the tunnel element prior to sand flow or grouting operations.
- Bulkheads for closing off the ends of the element (Figure 5). Steel or concrete bulkheads are fitted.
- Survey tower for alignment control during placing (Figure 6). A survey tower is used in areas where the survey can take place from land and where shallow water (<30m) occurs. This tower is fitted with GPS antennae and prisms to monitor the movement of the element.
- Cast in sandflow or grouting pipes and temporary supply pipework and control valves, used to transport sand/water or grout mixture underneath the element to create a solid bedding.

Figure 4 : typical secondary support assembly

- Prestressing for holding the segments of the element together during transport (Figure 7), applicable for a segmental tunnel. Also indicated in the annex for Temporary Prestressing.
- Ballast tanks and ballast system for the ballasting and trimming of the element before transport and during immersion.
- External jacking frame and jacks (Figures 8 & 9). This frame can be implemented underneath an element and fitted with realignment jacks (lateral) to position the secondary end within the required tolerances.
- Gina and Omega Gaskets for watertight connection to the previously immersed element.
- Fairleads and other rigging for placing and manoeuvring.
- Power, control, signal and CCTV wiring including bulkhead penetrations.

Figure 5 : Steel bulkhead

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Equipment applicable to specific situations Prior to immersion (launching, towing, outfitting, immersion, alignment, etc.) a clear plan should be made regarding what equipment is required at each stage of the construction process. This plan should be input for the detailed design phase. For instance, some bollards can be removed before physical immersion starts. Equipment and materials necessary inside the element for ballasting and immersion are an important part of this process as once completed and prior to immersion, there is limited access to the inside of a tunnel element.

Removal

After immersion the temporary mounted equipment on the external faces of the element should be removed easily by divers or even without the use of divers at all (hydraulic or magnetic self-release systems). Safety is the most critical aspect in this design. All equipment should be easily removable by cranes or light equipment. Partitions in equipment (access shaft, survey mast) can help to reduce weights.

Figure 6 :Survey tower

For temporary equipment inside the tunnel often a phased removal is needed. For example the negative buoyancy of the tunnel element should be sufficient before the water in the ballast tanks and the ballast tanks themselves can be removed. This can be done with the use of ballast concrete in the bores. Another example is the sequence of removal of the bulkheads as frequently the permanent water seal (Omega) must first be installed and tested prior to the removal of closest bulkheads.

Figure 7 : Prestressing anchorages at end face of element

Design

Early stage interface design is of great importance, because choices made in position, size and number of temporary mounted equipment can have major impact on permanent works design. For example the location of lifting lugs or supports and consequently the forces transferred to the permanent construction.
Another example is the dimension and location of ballast tanks as these must contribute to satisfying buoyancy safety requirements of the element and of the segments in the various stages of immersion, and facilitate the casting of some ballast concrete before their removal. However it is usually considered that temporary mounted items such as bollard should be designed to fail before they could cause damage to the permanent structure they are mounted on.

A design basis specifically written on temporary works, which outlines all interfaces with other (permanent) works is highly efficient in communicating with third party designers. Detailed design must be governed by specified, conservative safety factors and safety design. Failure or damage of objects is not an option, since during the operation there is no chance of repair of the permanent works when, for instance, cast-in anchors break.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

Method of mounting equipment

Specifications should be prepared for items required for mounting equipment such as:
- Post tension anchors, concrete, glue, welding etc
- Regular steel T-headed or bolt anchors or cast in rebar with couplers
- High grade steel, post tension systems (ie, Diwydag, MacAlloy)

Tolerances of mounting

For the different objects different tolerances apply. Bollard and access shafts are less sensitive to tolerances than survey towers and suspension lugs. Tolerances should be noted on detailed drawings and design documents.

Figure 8 : Realignment Jacking frame

Figure 9 : Realignment jack

Durability/coating

Some temporary equipment is reusable and can be applied to more than one tunnel element. Sturdy coating and protection of the objects can be helpful to expand their life expectancy. Usually a light coloured coating is applied, to improve visibility under water for divers. The long term durability of cast in items must be carefully designed. Stainless steel or anti corrosion measures should be considered in designing these items and repair methods or surface treatments to be applied once the equipment is removed should be developed. Possible interaction with cathodic protection systems must be assessed.

Watertightness

All temporary mounted equipment which penetrates the outer watertight shell of the element, must be designed and detailed to preserve the watertightness of the structure. Points of attention are:
- Access shaft (penetration of roof). Watertightness to be guaranteed with the permanent closing details for the opening in the roof with reinforced structural concrete and, for example, a bolted cover plate gasketted to the surrounding waterproof membrane.
- Secondary supports (penetration of floor). After the temporary support function during the sand flow operation is finished, watertightness is to be guaranteed by sealing the recess with concrete after retracting the pins.
- Sand flow pipes. It is advised not to penetrate the floor structure with the pipes, but to divert the pipes through the floor/wall/roof or make a coupler on the external toe of the element, so that the travel from one external surface to another external surface.

DOCUMENTATION (FORMAT, DEADLINES)

Typical documentation includes:

- Construction method statements and work procedures explaining the necessity and functionality of equipment;
- Design basis for temporary works items;
- Temporary works design and check certification;
- Temporary works design reports and manufacturing and installation drawings;
- Manufacturers materials records and test certificates.

As-built survey records of the remaining temporary and permanent items must be documented and surveyed before immersion takes place. Detailed checklists should be used along with photography.

EXPECTED VALUES

Loads (for critical objects)

Bollards

Standardised bollard forces are established depending on the programmed pulling forces of tug arrays during various towing operations.

Suspension lugs

The suspension lug forces are based on the safe negative buoyancy to be used for largest element to be placed for a given tunnel. This negative buoyancy factor usually ranges between 2% and 6 % and is based on the range of water density, wave and current actions expected at the site.

Supports (primary and secondary)

In the final stages of immersion the loads on temporary supports used during sand flow or underbase grouting actions are determined by the presence of waves, shipping, sand flow, currents, etc. These loads are also determined in the design basis, before detailed design takes place.

Bulkheads

Loading on bulkheads (hydrostatic + waves) should be transferred to the permanent structure by means of cast in items / strips or consoles.

Access shafts / survey towers

Loads on access shafts / survey towers consist of wind, current, ship impact and waves. These loads impact the structure significantly when the element is immersed. Due to the length of the shaft and tower large bending moments are introduced locally on the structure.

ANALYSIS (REQUIREMENTS, TIMESCALE…)

Requirements of Temporary Structures:

Implications for concrete / rebar arising from the temporary equipment must be fully analysed in the design process. This may be in relation to forces arising from the different stages of transport and immersion, geometric requirements to accommodate the equipment or durability impacts such as the need to introduce cathodic protection.

Forces on the structure should be taken into account by the permanent works designer. Monitoring of the forces on temporary equipment (lifting lugs, bollards, etc) is a means of controlling the operation and limiting the risk of failure. Design loads can be derived from model testing and computational analysis of an element in current/waves/wind during transport and immersion.

Safety factors should be chosen according to the governing codes or Class Society regulations. The lifespan of temporary mounted structures should be assessed relative to the duration of the works and number of uses.

Logistics must be analysed by the Contractor in terms of efficient deployment of equipment.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

Not applicable.

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

Remedial mounting actions (extra anchors, repair, etc).

It is critical to always provide guidelines for installing anchors and cast in items on drawings or design interface documents. Mistakes can be costly if items like anchor bolts are not installed correctly, for example.

Risks

There are inherent risks present in the preparation and installation of temporary mounted equipment.

Time can be a critical issue. Since most temporary equipment can't be mounted very far ahead (access shaft, suspension lugs) the time required for redeployment should be planned for.

Properly designed temporary equipment includes conservative safety factors with their loadings taken into account in the structural design of the element in a manner not to cause local overstressing at the interface. There can be the risk that this design is not as carefully done as the permanent structure.

LINKS TO OTHER OWNERS GUIDE THEMES

Concrete – concrete construction
Durability
Tunnel element alignment
Tunnel element transportation
Joints - closure
Prestressing

PERFORMED BY/RESPONSIBLE

Pre-Tender design phase (Design of immersion system, geometry, support locations, support capacities etc.) : Owner & Owner's consultant.

Detailed design phase (Design of materials, capacities, safety, connections, details, interfaces, etc.) : Owner & Owner's consultant. or Contractor in Design and Build.

Detailed design temporary works (Design of subsystems, detailed execution design, etc.) : Contractor

Preparation : Contractor

Execution : Contractor

ANNEX 17 >> EXCEPTIONAL LOAD CASE

Exceptional load cases are those corresponding to events of very low occurrence probability. They may find their origin in a natural disaster (earthquakes, typhoons, floods etc.) or accidents of a human nature both inside of the tunnel (collisions, fires) and outside the tunnel (sunken or grounded ship, falling or dragging anchors). In order to carry out analysis, the effect of such events on structures like immersed tunnels needs to be translated into actual design loads, which in most cases is only possible within a certain bandwidth. Immersed tunnels are considered to be robust structures and, for peace of mind of the general public, need to be perceived as capable of dealing with exceptional loads.

WHAT

As for any civil structure design, immersed tunnel design has to address exceptional loads. To determine the magnitude and probability of exceptional loads, a risk assessment should be undertaken. For some exceptional loads typical for other structures, such as seismic loads and vehicle collision loads, they have become more and more regulated by Codes and Standards. But for others that are specific to immersed tunnels, such as a sunken or grounded ship or a tunnel fire, the loads are quite often based upon previous projects and interpolated or extrapolated for the actual project conditions.

Exceptional load cases considered for immersed tunnel design include.

- Seismic loads
- Fire loads
- Sunken or grounded ship loads
- Falling or dragging anchor loads
- Explosion or implosion loads
- Flooding of tunnel loads
- Extreme water levels and / or wave conditions (extreme weather conditions like typhoons or tsunami)
- Vehicle collision loads
- Loss of support

The impact of exceptional loads on the design of an immersed tunnel can be significant. However, since the relevant load combinations are to be considered as extreme or accidental load combinations and considering the fact that reduced material and / or load factors are applicable, the impact of exceptional loads is often not critical and the design is governed by the serviceability or ultimate limit state (SLS/ULS) design. However this is not always the case and so these must be investigated carefully.

An event may have consequences for the structural integrity or water tightness or a combination of both. Beside the fact that the structure always has to provide a safe environment for the escape of the tunnel users, it is also very relevant to assess the potential consequences in terms of a possible out of service period (fully, partial, none) after the event to allow for repair. In any case, it is also important to realize that the probability of an extreme event is by definition very small. Exceptional loads should be considered and addressed in the design as follows:

- The effect of the exceptional load is often very local (e.g. fire, sunken ship). Taking actions along the whole tunnel may be very expensive whereas minor but repairable damage may be acceptable as well.
- A staged approach in which events are classified according to the level of probability (e.g. minor or major seismic events) is helpful. Typically the design has to be capable of surviving the event either:
  a) without any damage or
  b) minor but repairable damage or
  c) with significant damage (life safety) under which users must still have safe escape from the tunnel.

Obviously the importance of the link in the road or rail system will play an important role in defining design requirements relative to exceptional loads, for example the availability of alternative routes in case the tunnel has to be taken out of service for repair. This implies that the allowable impact of an exceptional load in terms of damage and repair may be low for major links that have few or no alternative routes in case the link is put out of service. For less important links where an acceptable alternative route is available the allowable impact may be greater.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Important issues that may reduce the impact of exceptional loads are obviously related to the kind of exceptional load that is under consideration. Often at the early stages of design conservative assumptions have to be made, but it is important to carry out investigations and studies to refine any such assumptions as this may have a bearing on the final cost of the project:

Before Design Stage:

Seismic loads

- Thorough investigation of the seismic activity at the project location (site-specific Probabilistic Seismic Hazard Assessment - PHSA); this investigation shall also address the potential impact of tsunami including associated wave conditions at the project location.
- Thorough geotechnical investigation to identify soil layers that are sensitive to liquefaction (e.g. less dense sand layers) to enable proper design measures and soil treatment.

Fire and explosion loads

- Considerations of the type of traffic using the tunnel e.g. use by dangerous good vehicles will impact on the fire and explosion load to be assumed. This should be agreed through a fire life safety committee including the owner, operator and emergency services.

Sunken or grounded ship load

- Determine existing movements of shipping and proposed changes, including potential dredging to greater depths. Consider these in determining the shallowest vertical profile.

Falling or dragging anchor loads

- Research any history of vessels dragging anchors in the vicinity and whether dragging anchors is a possibility.

Extreme water levels and / or wave conditions

- Study and data collection of water levels and wave conditions at the project location and along likely transport routes (desk studies and / or metocean surveys).

Design Stage:

Seismic loads

- Damping measures in the structures that reduce the impact of seismic loads can be considered, especially in areas with more severe seismic activity. Mitigation measures may include special flexible joints (special purpose Gina), prestressing to limit movement across a joint and seismic joints.

Fire loads

- Ensure that there is an adequate ventilation system for smoke extraction both to allow a safe escape for the tunnel users and safe access for fire fighters.
- Include a fire protection material against the roof and walls to eliminate permanent loss of concrete and steel strength due to overheating and to reduce the risk of explosive spalling that would prevent fire fighters from approaching a fire to extinguish it.
- Make provision for a sprinkler or water deluge system to reduce the development of a fire.
- Protect critical details (seals, etc.) against high temperature.

Sunken or grounded ship loads

- Ensure that the vertical tunnel profile will provide sufficient thickness of protection over the tunnel for it to handle appropriate sunken or grounded ship loads and falling anchors (possible ship size varies with water depth) or else design the tunnel accordingly. For some alignments, it may be appropriate for the top of tunnel to protrude above general bed level.
- When selecting the vertical tunnel profile, consider the effects of errant ships colliding with the tunnel or provide bed level protection, especially where the tunnel protrudes above the general bed level. Protective measures may include gravel banks or underwater banks that prevent ships from approaching or landing on the tunnel

Falling or dragging anchor load

- Evaluate the necessary gradation and thickness of any protective layer over the tunnel.
- Shape the protective layer and the top corners of the tunnel in such a way that dragging anchors cannot easily snag the tunnel.
- Consider the need for, location of and appropriate gradation for anchor release bands located on each side of the tunnel to cause the anchor to ride up and out of the ground to slip over the tunnel.

Explosion/implosion loads

- Consider pressure release measures and failure modes for life safety in case of very high explosion/implosion loads.

Flooding of tunnel loads

- Reduce the probability of tunnel flooding.
- Provide protective dikes around the open approaches.
- Ensure that the approach alignment rises above flood level.
- Provide portal flood gates.

Extreme wave conditions

- Design the tunnel to be surrounded with gravel or rock to ensure immediate transmission of pore water pressures changes and thereby maintain the same relative hydraulic head around the tunnel (troughs of high waves travelling over the tunnel would otherwise tend to lift the tunnel).

Vehicle collision loads

- Include measures to prevent direct impact of vehicle collision to primary tunnel structure (crash barriers, etc.)

Loss of support

- The man-made foundation (gravel bed, sand flow foundation) is generally executed under relatively complicated marine conditions. It is important that the tunnel structure is capable of resisting a partial local loss of foundation support if there is any risk that inconsistencies may occur during the preparation of the man-made foundation. Loss of support should be considered in relation to the project specific foundation and construction method.

Construction Stage:

Seismic loads

- Use sandy gravel or gravel not only for the foundation but also for the locking fill adjacent to the tunnel, thus increasing horizontal and vertical stability and mitigating liquefaction risks by the efficient dissipation of excess pore water pressures. Note that a sand foundation could be prone to liquefaction.

Loss of support

- Inspect the dredged trench prior to the installation of the mad made foundation (e.g. gravel bed) or immersion.
- Inspect the gravel bed for inconsistencies prior to immersion.
- Monitor the installation of the sand pancakes (sand flow) thoroughly to ensure that an adequate foundation bed is prepared.

Operation Stage:

For the operation phase in particular, measures can be taken to reduce the risks of some of the exceptional loads, especially those involving people:

General

- Exceptional loads inevitably are related to emergency conditions. Critical issues for a successful management of an event are efficient escape measures for tunnel users and efficient access for intervention by emergency services. These should be fully documented as operational and emergency response procedures.

Fire, explosion and collision

- Reduce the possibility of an accident by a safety plan and traffic management system.
- Forbid the passage of dangerous and explosive goods through the tunnel (only when there are appropriate diversion routes available).
- Alternatively the operator may choose to implement an escort system to ensure safe passage through the tunnel.

Dragging or dropping anchors

- Proper signage on the navigation channels that clearly identifies the presence of a tunnel and a prohibition against dropping anchor.

Grounded ships

- Proper signage on the navigation channels that reduces the risk of ships sailing into shallow waters.

For loads caused by a natural disaster, pre-emptive operational measures may be more difficult to take unless they can be predicted by appropriate forecast systems; this could be the case for extreme weather conditions for which reason the tunnel could be closed to traffic. This may include lowering of flood gates (where included in the tunnel design) if flooding of the area would be a serious risk. Tunnel operators should be in contact with the appropriate agencies forecasting and predicting such events.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

See "Expected values" section for relevant information.

DOCUMENTATION (FORMAT, DEADLINES)

Design Stage:

Record all assumptions in a design basis summarising the results of investigations, studies and the derivation of appropriate load parameters. It is important for this to be agreed between the detailed designer and the Owner. Third parties may also need to give their agreement, for example the fire services (civil defence) or port operators.

Operational stage:

If an exceptional loading event occurs during the life of the tunnel, where possible the characteristics of the event (magnitude) and the response of the tunnel should be recorded. There are a growing number of immersed tunnels that are fitted out with a permanent monitoring system (Structural Health Monitoring System). Such a system can provide information on the state and performance of the structure, movements of the structure etc. In the design of the monitoring system account can be made for effects that can occur during an event and the way these effects can be recorded.

Following an event, the tunnel will need to be thoroughly inspected. Depending on the type of event, this can either be a local or a full inspection (also see "Remedial measures / actions"). It is recommended that plans for inspections for potential events be made in advance, so that swift and efficient inspections can take place. The inspections should be well documented, since they will be the basis for possible repair plans. In case of damage, the sooner the repair of the tunnel can be undertaken, the sooner the tunnel can be back in full operation again. This is described in more detail under Remedial Actions below.

EXPECTED VALUES

The values for exceptional loads are highly dependent on local circumstances. They can vary considerably from project to project. In addition, there seems to be a tendency for the values used for exceptional loads to increase with time, which may be an indication that more attention is being paid to these types of loads or that without giving it too much consideration values from one project are extrapolated to another.

Seismic loads

Many immersed tunnel have been constructed in heavy seismic areas such as Japan, Taiwan and California. These tunnels have survived major earthquakes with little damage. Immersed tunnels should be designed for seismic effects appropriate to their location. Where there is a reasonable probability for a smaller earthquake to occur during construction, this too must be considered. For the design of a tunnel several levels of magnitude of earthquake loading are to be considered. The way this is done may vary from Code to Code (e.g. Eurocode, AASHTO), although basic principles in many cases are similar. Reference should be made to the Seismic Annex.

Fire loads

- Refer to Annex on Fire Protection and Annex on Ventilation and Fire.

Sunken or grounded ship loads

- Values vary according to vessel type, cargo carried, vessel loaded draught, water depth at the tunnel site and any shallows on the vessel's route.
- In in-land ports sunken or grounded ship loads have been used varying from 20-70kN/m^2. More recently loads have been applied in sea ports from 100-150kN/m^2, to even 250-300kN/m2 in main sea ports where tidal ranges may result in a higher load in case the ship is grounded and the portion above water is increasing at low tide (less upward water pressure. The type of shipping and the type of cargo / loads that are carried obviously play an important role in the determination of the potential sunken or grounded ship loads as well.
- Port/harbour or coastguard authorities should be contacted to obtain records of vessel movements to understand the nature of vessels using the waterway and whether this may change in the future.

Falling or dragging anchor loads

- The magnitude of load depends on the location and the type of shipping at the tunnel location.
- The load transmitted to the tunnel structure depends on the type of protection on top of the tunnel.
- For the falling anchor allowance anchor masses of 8000kg to 20000kg and even 30000kg have been used for immersed tunnel design, obviously depending on the type of waterway and the local shipping. Falling anchors design velocities are taken in the range of 7-9m/s.
- For the dragging anchor allowance, chain breaking forces of 4.0 to 6.0MN have been used, with a dragging penetration depth of 2.5-3m.
- Refer to ITA State of the Art Report (Chapter 6) and CEB Bulletin d'Information no 187, August 1988.

Explosion / implosion loads

- The magnitude of load depends on the location of the tunnel and the availability of acceptable deviation routes for the transport of hazardous or explosive goods.
- Explosion / implosion shall be considered in all traffic tubes between the Portals.
- The loads to be applied are usually analysed as a static load, taking place in one tube only.

- In many tunnel projects the integrity of the emergency doors has to be guaranteed. They may break, but should not become projectiles.
- Typically in lieu of detailed analysis, a static equivalent equally distributed load of 100kN/m^2 is applied.
- In heavy industrial areas where deviation routes are not available 300-500kN/m2 have been used. This is unusual and will present the structure design with some challenges.

Load due to flooding of tunnel

- The tunnel should resist an accidental flooding of the tunnel in one of the tunnel tubes without any (significant) structural damage as a result of the settlements occurring during the period until the tunnel has been drained.
- In case damage is allowed (depending on the importance of link) easy and efficient repair should be possible.

Extreme wave conditions (e.g. due to extreme weather conditions like typhoons)

- The tunnel shall be able to resist a combined load of a high water level and related wave height. Return periods of 1000 to 10000 years have been used in immersed tunnel design.

Vehicle collision loads

- In many immersed tunnel projects the tunnel walls have to be able to resist a horizontal collision load acting some 1.25 m above road level in the order of:
- A longitudinally load of 1000 kN
- A transversally load of 500kN
- Crash barriers often are designed to resist a horizontal load of 150kN acting transversally 0.55 above the road level.
- Rail tunnels generally require derailment provisions to avoid collision impact.
- These loadings are usually defined in nationally applicable standards.

Prevention of floatation

- A minimum factor of safety during construction of 1.04 is typical, reduced for short periods to 1.025, whereas the long term factor used is 1.06 with all interior removable items removed and no erodible backfill on top of the tunnel.

ANALYSIS (REQUIREMENTS, TIMESCALE…)

The effects of loads are applied to a structure as load cases. Some may have minimum applied loads and others maximum. Exceptional loads are combined with other loads into accidental load combinations. In most countries reduced material and load factors apply. However the level of acceptable damage may vary:

- Level 1: No damage (Serviceability Limit State / Ultimate Limit State verification)
- Level 2: Slight damage, easy to repair (Ultimate Limit State / Accidental Limit State verification)
- Level 3: Heavy damage, preventing major failure (total collapse and catastrophic inundation) to maintain life safety (Accidental Limit State verification)

The level of acceptable damage is obviously related to the probability of occurrence (return period). In seismic design this has become an internationally accepted approach. The level of acceptable damage has been related to the return period and the probability of exceedance.

The analyses that have to be undertaken are related to the level of acceptable damage. When no damage is allowed, linear or simple non-linear analyses will be most appropriate. With an increasing level of acceptable damage it is likely that more advanced non-linear or plastic analyses are required in order to be able to assess the ultimate resistance of the structure.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

Not all loads will be known exactly and in some instances the designer may either need to opt for moderately conservative assumption or test sensitivities to evaluate the risks to the structure.

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

Inspections should be undertaken to identify the impact of an exceptional event. Depending on the type of event this can be either local (fire, vehicle collision, explosion, ship impact) or overall (earthquake, flooding). As a minimum, an inspection should at least be made inside the tunnel. In addition, external inspection may be essential where accessible, depending on the event.

Level of inspections:

- Quick scan inspection to assess whether the tunnel can stay in operation or whether immediate action is required (temporary support structures, temporary mitigation leakage etc).
- More detailed inspection to determine the repair plans and to set up the execution plans in relation to the operation of the tunnel.

Type of inspections:

- Inspection of the concrete structure for cracking, spalling or other forms of damage. It may be useful to start with the most sensitive parts of the tunnel such as the tunnel joints.
- Inspection of the rebar where exposed (e.g. due to fire and spalling of the concrete).
- Inspection for possible leakages.
- Inspection of fire protection material.
- Inspection of the tunnel joints (water tightness and structural damage).
- Measuring possible movements of the tunnel (permanent monitoring system would be appropriate). Regular inspection and maintenance of this monitoring system should be included in the maintenance manual of the tunnel to guarantee proper performance during an event.

Repair plans need to be developed in case of damage. Obviously the repair actions depend on the kind of damage. In terms of the timing of the repair it is advisable to consider the urgency of repair as well. In case there is no real urgency for immediate repair, the tunnel may remain (conditionally) open to traffic in peak hours and closed for repair in off-peak hours (nights, weekends). This will depend on the importance of the link and the availability of deviation routes.

LINKSTO OTHER OWNERS GUIDE THEMES

Structural form
Fire protection
Immersion Joints
Segment joints
Ventilation and fire
Seismic
Operation & Maintenance

PERFORMED BY / RESPONSIBLE

The suggested responsibilities with regard to the exceptional load cases are:

- Specification of the type of exceptional loads to be considered / Determination of the exceptional loads to be considered for the design : Owner (assisted by Consultant)
- Design and detailing : Designer
- Repair during construction : Contractor
- Inspection after an event : Owner/ Consultant/Inspection contractor
- Repair after an event : Contractor

Annex 18 >> approach structure

An immersed tunnel must connect to tunnel structures on the shore at each end of the tunnel. These may be cut and cover tunnels, portal structures, bored tunnels, pneumatic caissons or open ramp structures. These are all referred to as Approach Structures. They may have integrated operational and service buildings. Figure 1 shows a typical tunnel approach in a rural area.

Figure 1 : Limerick tunnel approach structure

WHAT

Generally, a road or railway will come up to ground level after it has passed through an immersed tunnel beneath a waterway. This requires a transition structure to be built on each approach to the immersed tunnel. The length of the approach structure is defined by the gradient of the road or railway it carries. Gradients are usually maximised in order to keep the structure as short as possible, but taking into account design speeds for traffic, the limitations for railway rolling stock and safety issues.

Several stages of construction are required so that the immersed tunnel can be connected to the approach structure. Either the immersed tunnel is placed first and then an earthworks bund constructed over the tunnel to allow the tunnel approach area to be excavated and dewatered, or the approach structure is built first within a dewatered excavation and then the earthworks is changed to expose the end of the cut and cover tunnel to the water and enable the immersed tunnel to be placed against it.

Approach structures to the immersed tunnel play a vital role in protecting the tunnel from inundation. They therefore will provide flood protection to the tunnel either with the structure or using earthworks, and in some instances with flood gates.

Occasionally the road or railway will pass into another tunnel constructed on land by different techniques such as by TBM.
This requires a specific solution in order to connect the two types of construction.

On many immersed tunnels the excavations required for the approach structure are used as a casting basin in which to build the immersed tunnel.

Many of the most complex aspects of design and construction arise in the approach structures as they have a changing foundation level that usually passes through ground of varying quality.

Cut and Cover Tunnels

Cut and cover tunnels are one of two types. They are reinforced concrete structures built in open dewatered excavations formed by earthworks or temporary retaining structures, or they are formed by embedded walls such as diaphragm walls or secant bored pile walls with the base and roof of the tunnel constructed as propping slabs. The options are shown in Figure 2. Space constraints often determine the type of approach tunnel to be constructed.

If the tunnel is built using embedded walls it may be built by a top-down method or a bottom-up method. Top-down methods are useful if the ground above the tunnel is needed for other purposes such as temporary or permanent roads. The top slab is built first, between the embedded walls, the structure is backfilled to the existing ground level and excavation then continues beneath the slab. This minimises the time for returning the land above back into use.

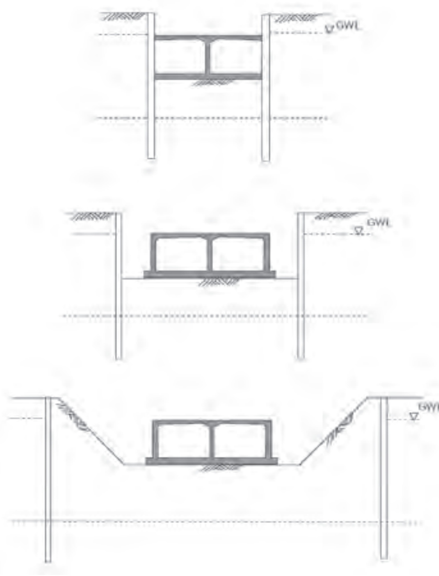


Figure 2 : Options for cut and cover tunnels

With the bottom-up method the full excavation is completed before casting the base slab first and then the top slab. Temporary props or ground anchors may be needed for the walls to enable the initial excavation.

Because of the weight of the structure in the temporary condition within the dewatered excavation, and because in the permanent condition there may be a significant amount of backfill over the tunnel, it is common to need a piled foundation beneath the cut and cover tunnel. This will depend on the ground conditions. The cut and cover tunnel will therefore usually have different settlement characteristics compared to the adjacent immersed tunnel.

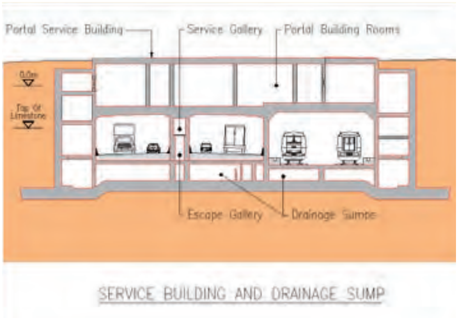


Figure 3 : Oresund Tunnel portal building cross section

Portal structures

Tunnel portal buildings are frequently combined with the approach structures. They may contain operation and control centres, maintenance and service facilities and plant and equipment rooms. Direct access into the tunnel may also be provided for the convenience of maintenance staff.
The buildings may also have ventilation towers, depending on the type and configuration of the ventilation system for the tunnel.

The resulting buildings can be quite complex. An example is shown in Figure 3 from the Oresund Tunnel project. The buildings would normally be built in-situ as an extension to the cut and cover tunnel.

However their plan area may be greater and the additional structure will create a different bearing pressure and may need a different foundation solution compared to the rest of the approach tunnel.

Open ramp structures

From the tunnel portal up to ground level, an open structure is required to carry to road or railway. This is typically a U-shaped reinforced concrete structure. Where retaining walls heights are greater than 8-10m permanent props are often used.
If there is a high water table in the tunnel approach then measures to prevent uplift may be needed. This can be either a ballast concrete layer similar to the immersed tunnel, or tension elements (piles or anchors) can be used. The latter is generally more efficient but particular care must be taken to ensure the durability of the tension elements for the design life of the structure.

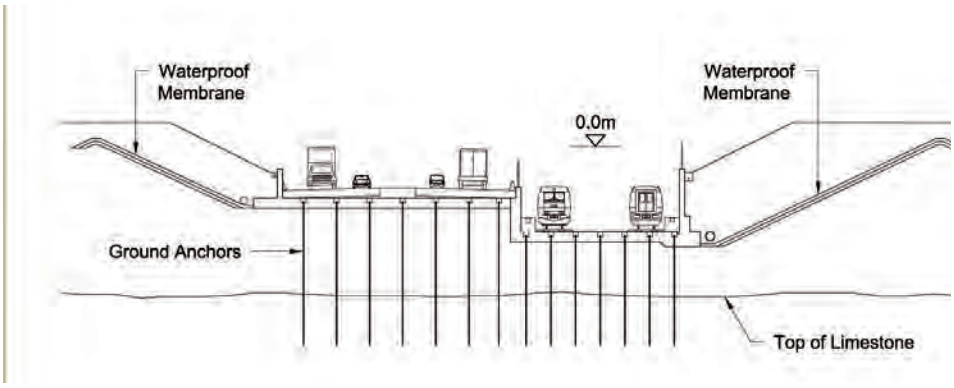


Figure 4 : Oresund Tunnel portal building cross section

A combination of structure and earthworks can be used. Often earthworks are used to form flood bunds and to open out the approach to give it a better aesthetic appearance. Buried watertight ground membranes can be used to prevent ground water from draining into the tunnel approach. Figure 4. shows an example. This is particularly the case at the high end of the approach structure.

Use of approaches for casting basin

Tunnel approaches are often used as casting basins in which to construct the immersed tunnel elements. Figure 5 shows an example of this at the Limerick Tunnel in Ireland. If this is done the approach excavations may need to be over-deepened. This will affect the final approach structure as there may be temporary retaining walls, foundations and slabs that need to be incorporated into the final structure.

A simple approach is to keep the temporary and permanent works separate and build the final structure within the approach once the tunnel elements have been floated out. However it can be beneficial to design the temporary works so they can contribute to the final approach structure.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

The sequence of construction of the approach structures compared to the immersed tunnel needs detailed consideration to optimise the construction programme. This can be left to the contractor to determine unless there is a constraint on the site or the tunnel approach is constructed as a separate contract to the immersed tunnel. In such circumstances the project client may decide how this interface is to be controlled.

The detailed requirements for construction will follow good practice for conventional sub-surface structures. Some particular areas for attention in terms of keeping good records are:

- Ground movement history during excavation and construction
- As-built dimensions to be recorded.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

Depending on the type of construction the detailed specifications for construction will vary. However the specifications for all forms of approach structures should include:

- Methods for achieving watertightness in the structure and its joints.

Figure 5 : Limerick tunnel elements in tunnel approach

- Requirements to maintain stability and resist uplift from hydrostatic pressures.
- Requirements for ground water control in the temporary construction stage.
- Alignment gradients for road or railway.
- Flood protection requirements (flood protection level for given return period).
- Design life and durability requirements.
- Requirements for control of differential settlement between immersed tunnel and approach structure.
- Drainage sumps.
- Aesthetic requirements, landscaping and architectural treatments.
- Requirements for light attenuation at tunnel portals.
- Safety related items such as escape routes.

The particular form of structure will also have detailed specifications for its construction, whether it is insitu concrete or insitu concrete combined with piling. In case that embedded walls are used, the durability requirements for their use for the permanent structure are important.

The details at the end of the cut and cover tunnel at the point of connection to the immersed tunnel will require preparation to act as an immersion joint or a closure joint, or there may be a specific terminal joint detail to be implemented. Reference should be made to the appropriate annex for requirements associated with these features.

DOCUMENTATION (FORMAT, DEADLINES)

The detailed requirements for construction will follow good practice for conventional sub-surface structures.

EXPECTED VALUES

N/A

ANALYSIS (REQUIREMENTS, TIMESCALE…)

The detailed requirements for construction will follow good practice for conventional sub-surface structures. Particular areas for attention that need to be analysed during construction include:

- Construction tolerances for retaining walls (verticality of piled walls and diaphragm walls is an important aspect).
- Deflections of retaining walls.
- Settlement and impact of dewatering on adjacent buildings.
- Earthworks balance including bulking effects of soil once excavated.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

The detailed requirements for construction will follow good practice for conventional sub-surface structures. Some particular issue to focus on in construction are:

Wall deflections and ground settlements :

Any building or structures falling within the 10mm settlement contour of the ground movement predictions should be assessed to determine if this is acceptable or whether protective measures should be implemented. For structures susceptible to ground movement a range of instrumentation can be utilised to monitor the works throughout the construction stage against pre-determined trigger levels.

Accuracy of pile installation :

Tolerances on verticality are usually specified in the design code. Any out-of-tolerance could lead to leakage in the joints between piles/ panels.

Surface tolerance and impact on stability :

against hydrostatic uplift and internal clearance envelopes.
As-built surveys should be taken and cross-checked against the original design before releasing dewatering measures.

Groundwater management :

Water quality and water discharge rates should be predefined to form the basis of the required construction permits. During construction the water flow will need to be controlled and monitored before the water is disposed of.

Protection levels against flooding :

The level will be defined by the economic value of the hinterland and the tunnel itself. Special attention should be paid during construction and operation phase to the fact that the tunnel will act as a syphon. When one part floods, the other part will flood as well.

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

The detailed requirements for construction will follow good practice for conventional sub-surface structures. Particular issues that may arise at approach structures include:

- Differential settlement. High settlement can be corrected by under-base grouting or installing settlement relief piles.
- Uplift due to tension pile failure. Remedial measures may include ballasting, installation of new piles. Works are likely to be expensive and disruptive to operation.
- Leakage or seepage of piled wall structures. If used for permanent works they should be provided with seepage/leakage management system of drainage pipework. Pipework needs to be maintainable and be cleaned regularly. Excessive seepage can be rectified by grouting if the drainage cannot cope with the water volumes.
- Early thermal cracking of thick concrete sections. Grout injection is usually used to prevent unsightly staining due to seepage and to prevent early corrosion of reinforcement.
- Construction time. The construction programme should define clearly when the approach structure should be ready and exposed to the waterway to receive the tunnel elements. The schedule should allow for sufficient float in case the construction of the approaches runs late.

LINKSTO OTHER OWNERS GUIDE THEMES

Concrete - Concrete construction
Cracks – Concrete construction
Durability
Foundation/Settlement/Backfill
Closure Joints
Terminal joints
Immersion joints

PERFORMED BY / RESPONSIBLE

Subject to type of contract and / or risk allocation:

Functional requirements - Owner
Structural design & detailing – designer/contractor
Construction specifications – designer/contractor
Construction – Contractor
Maintenance - Owner

Annex 19 >> Management of Immersed Tunnel Projects

Important aspects of the management of immersed tunnel projects are summarised as seen from the Owner's perspective. The Operation & Maintenance phase is not addressed, as this subject is dealt with by a separate theme.

WHAT

Project Plan

The Owner should initially compile a Project Plan defining the objectives and strategies, as well as the project context, main activities, time schedule and the organization necessary for completing the project. The organisation will normally consist of management staff employed by the Owner and external consultants for design, environmental investigations, etc.

Contract form

The scope of the Owner's management for an immersed tunnel project should primarily depend on the contract form under which the project will be implemented. Experience from immersed tunnel projects comprises:
- Construction according to the Owner's Detailed Design;
- Design & Construct;
- PPP (Public Private Partnership).

The contract form can be a recognised form of contract such as NEC or FIDIC, but as with other underground construction where ground conditions have a large influence on a project, it is important to achieve a fair allocation of risk within the contract, as discussed further in the section on risk management below.

National forms of contract developed by public authorities for road and rail projects are generally suitable; the nature of an immersed tunnel does not mean that an unusual contract form is needed. The unusual requirements of an immersed tunnel can generally be addressed within the particular information and specifications for the project.

Often bespoke contracts are prepared for major crossings if they are deemed high risk or high value, but this is no different for an immersed tunnel compared to say a bridge or a bored tunnel fixed link.

Apart from the tunnel elements, immersed tunnel projects usually include land-based approach structures in the form of cut & cover tunnels and approach ramps. As is common for underground construction projects, there are strong interfaces between the temporary and the permanent structures. Design & Construct, especially when considerable freedom is given to design, may be preferred to allow design optimisation and effective interface coordination by the Contractor and thus reduce costs.

A PPP Contract gives the possibility for the public Owner to share investment costs with a private consortium. This contract form should give the same advantages as mentioned above for Design & Construct. In addition, the operation and maintenance of the tunnel by the PPP consortium during a longer period has proven advantageous for optimising the performance and reliability of M&E installations. Design & Construct projects may emphasise minimum initial cost with higher maintenance costs, whereas PPP projects may result in minimum overall cost for construction plus maintenance through the design life, even if this results in a higher initial cost.

Further, for PPP projects, if the overall Concession Period includes the period of time taken to design and construct the works, the PPP Company can be given an incentive to construct the project faster and open it to traffic ahead of program, if he is entitled to earn toll revenue earlier and for a longer period.

Risk management

The scope of the Owner's management should also be influenced by the risks during the planning, design and construction, and the way they are distributed between the Owner and the Contractor.

The Owner should from the beginning apply methodological risk management techniques to identify and to mitigate, eliminate or contain all the relevant risks. It is recommended, and may be required as well for insurance reasons, that the risk management follows the approach advised by ITIG (the International Tunnel Insurance Group).

As to the allocation of the risks between the Owner and the Contractor, it is normally preferable that the responsibility shall be with the party who is in the best position to control and provide against the risks.

For a Design & Construct contract, by far the most normal and foreseeable risks should thus be allocated to the Contractor who is in position to select his design and construction methods to manage them. Examples of such risks for an immersed tunnel project are ground conditions being different from what was expected, inclement weather conditions and accidents during marine operations.

However, when a contractor tenders for a project he is often reliant on the information gathered by the Owner in advance of procurement, and a contractor would not have time to undertake further investigations during the tendering process, so a degree of risk sharing is appropriate for the information relied upon for the contractors planning and pricing. An effective way of doing this is for the Owner to take responsibility for the factual information issued and to establish a reference framework that gives boundaries for key parameters within which the contractor must expect to carry risk, but outside of which the Owner carries the risk. An example of the application of this principle is given in the below subsection on procurement.

There are likely to be some risks that are not appropriate to assign to the contractor. These concern the overall planning aspects and authority approvals which are to be defined, negotiated and implemented at an early project stage by the Owner. They may also comprise exceptional events which are outside the Contractor's control and/or may result in too expensive tenders due to high added contingencies if attributed to him.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Project phases

As part of the Project Plan, the project shall be divided into a number of main phases each, for example:

Project preparation :

- Feasibility Study and Conceptual Design
- Preliminary Design and EIA
- Submissions for planning approval and other early permits
- Public consultation documentation
- Procurement strategy
- Baseline time schedule
- Cost estimates for securing budgets
- Traffic and revenue forecasting for PPP business case (if applicable)

Procurement:

- Preparation of tender documents
- Tender preparation, tender evaluation and contracting

Project implementation:

- Detailed Design
- Construction
- Testing and commissioning
- O&M preparation

Some important management aspects of the three main phases are mentioned in the following.

Project Preparation

The Design Basis defining all the project site conditions and the design requirements is developed from the basic criteria known at the project start. An important part of the basis is the geotechnical design information which is to be defined from borehole and laboratory data. New ground investigations are usually a critical part of the programme to be managed by the Owner at this stage.

Alternative alignments and tunnel concepts are compared in terms of cost, risks and other key parameters during the early feasibility studies. The design of the preferred alternative is subsequently developed to a level with sufficient details to illustrate the Owner's needs, to demonstrate a possible way to comply with all constraints and requirements, and to provide the Contractor adequate information to bid.

As a special component of an immersed tunnel project, a suitable fabrication facility for tunnel element construction has to be identified. The Owner should ensure that at least one option either inside or outside the project right-of-way will be available.

The execution of the immersed tunnel project, including the element construction, will imply a number of authority approvals to be secured by the Owner during the project preparation. The most important will normally be the planning permit based on an EIA (Environmental Impact Assessment) and containing a number of essential conditions for the project, and the preparation of the EIA is accordingly an important task to be managed by the Owner.

For many projects, the dredging of the tunnel trench has become the main focus of the EIA, principally due to concerns that the sediment spillage plume will cause damage to the marine environment. However, it is worth noting that the experience gained from many immersed tunnel projects has demonstrated that it is usually possible to control the spillage to be within acceptable limits.

The tunnel safety provisions for prevention of traffic accidents, fires, etc., mitigation of consequences, escape, emergency response and rescue will need to be agreed with the relevant authorities and described in a Safety Concept.

Procurement

Four or five contractors typically prequalify to bid for an immersed tunnel project. Generally, a large degree of planning is required in the tendering process, so a greater number of bidders would not be reasonable considering the bidding costs. Qualified applicants are general contractors with a successful record with heavy civil engineering and marine works. They must also contain within their group a partner or sub-contractor experienced in the special immersed tunnel marine operations as well as (for Design & Construct and PPP procurement) a consultant with the immersed tunnel experience necessary for Detailed Design.

The tender competition is sometimes on price and based on the minimum design requirements, technical specifications and other conditions being defined in the tender documents. However, particularly for Design & Construct procurement, a mixture of quality and price is usual where the contractor's approach to management, design, safety and quality control is taken into consideration. Practice varies around the world as to the relative weightings and scoring mechanisms for the quality and price components. It can be as high as 60:40 quality/price in some European countries. The tender requirements with amendments agreed with the Contractor prior to contract award will transform into the final contract documents.

There may be additional tender documents for information which will not become part of the Contract. For Design & Construct and PPP projects, they may comprise the results of the Owner's site investigations as well as an illustrative Preliminary Design meeting the requirements.

For the Øresund Fixed Link immersed tunnel, the Owner defined a set of «reference conditions» within the Tender and Contract documents, each with assigned maximum and minimum values and frequencies for the ground, weather and hydraulic parameters. All variations in the range within these values were the risk of the contractor, and the Owner carried the risk outside the range.

The Contract for the Øresund Fixed Link was in addition very clear that all risks not explicitly defined as being the Owners risks were to be considered as being the Contractor's risks. In addition, the Contractor's scope included all works required to make the tunnel fit for its purpose, except those explicitly mentioned in the Contract as belonging to the Owner's scope. This was different from many traditional contracts, for which the Contractor is entitled to claim for all kinds of events and work items not explicitly stated to belong to his scope.

The principles of the Øresund Contract were found to lead to a more thorough risk management from the Contractor's side, a very low number of valid claims and substantially lower total costs to the Owner, as compared to traditional contract forms. Other immersed tunnel projects have taken a similar approach.

Project implementation

Both Consultants and contractors should be required to establish and adhere to a project Quality Management System based on ISO 9001 and covering the design and construction for all relevant temporary and permanent works, the external environment and the working environment. The system should be approved by the Owner.

For Design & Construct and PPP projects, the Contractor should make use of the freedom to optimise the design and construction methods as possible within the tender and contract requirements, and this could lead to design solutions different from those assumed by the Owner. The Contractors design preparation is often conducted in two stages: a Basic Design and a final Detailed Design.

The Basic Design shall have a level which is sufficient to verify that the design requirements are fulfilled, and to fix all main dimensions and interfaces. The Contractor should carry out his own geotechnical investigations in parallel; so that the resulting interpreted parameters can be implemented in time into the final Detailed Design. The level of the Detailed Design should be sufficient to serve as construction drawings, as it may be supplemented by bending schedules and workshop drawings for special items.

For Design & Construct and PPP projects, the Owner often chooses to assign an Independent Design Checker to verify by their own calculations that the design shown on the Contractor's drawings will fulfil the design requirements.

During Construction, the Owner should review the Contractors design and construction documentation for compliance with the requirements prior to approvals. For an Owner's Detailed Design contract, the Owner should employ a Designer representative or Engineer to supervise the construction, whereas for Design & Construct and PPP contracts, he should monitor that the supervision is done by the Contractor. The Owner should in general monitor the Contractor's compliance with the Quality Management System by inspections and Quality Audits.

Documentation for Operation & Maintenance manuals is delivered by the Contractor towards the end of construction. It should also be noted that there is an increasing awareness of the importance that the operational phase is already considered at an early stage of the scheme implementation, in order to ensure inspectability and maintainability and to establish operating budgets and principles.

By the end of construction, the implementation phase finally includes integration testing and commissioning of M&E and ITS systems and the tunnel operation and control facilities, as well as safety drills, in order to verify the functionality of all systems prior to opening for traffic.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

Not Applicable.

DOCUMENTATION (FORMAT, DEADLINES)

The following documentation is not different for an immersed tunnel compared to another form of waterway crossing, but is listed for completeness. The different requirements that relate to an immersed tunnel will be brought out in the content of the documents.

- Project Plan
- Quality Management System
- Studies and site investigation reports, e.g.
  - Traffic study
  - Metocean survey data and hydraulic study
  - Seismic hazard study
  - Ground investigation factual reports – prepared by GI contractor or Owner's consultant
  - Geotechnical Baseline report – usually prepared by Owner's consultant
  - Further geotechnical interpretative reports may be left to the contractor in D&B contracts
  - Durability assessment
  - Safety Concept
  - Operation risk assessment
- Design documentation from all project stages
  - Drawings
  - Design report
  - Construction specifications
- Environmental Impact Assessment
  - Conditions from the EIA should be transferred into contract requirements
- Tender documents
  - Instructions to tenderers including evaluation criteria
  - Form of tender
  - Pricing schedules
  - Contract documents
  - Form of contract
  - Contract conditions
  - Constructions specifications – materials and workmanship
    - Design requirements (if D&B)
    - Reference design/detailed design drawings
- Contractors construction plans and procedures
- Contractors test reports and inspection records
- Contractors as-built design
- Operation and maintenance plans
- Maintenance manual

EXPECTED VALUES

Not applicable.

ANALYSIS (REQUIREMENTS, TIMESCALE…)

Not applicable.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

Not applicable.

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

Not applicable.

LINKSTO OTHER OWNERS GUIDE THEMES

The management links in general to the technical processes described by the other themes of the Owner's Guide.

PERFORMED BY / RESPONSIBLE

- Overall Project Management - Owner or Owner's consultant/programme manager/ delivery partner.
- Design Management - Designer, whether appointed by the Owner or D&B contractor.
- Construction Management - Contractor

Few concrete structures are constructed in a single concrete placement. Most are therefore constructed with joints, either rigid (construction) or movement (expansion) joints, all of which must be made watertight. Some method of preventing the ingress of water is required at all joints. Waterstops are also used to prevent leaks along the interface between concrete and embedded metal, such as at steel end frames at immersion joints.

Special construction methods have been developed to ensure that immersed tunnels are watertight. For an immersed tunnel, movement joints include immersion joints, terminal joints, segment joints and seismic joints; closure joints can be either rigid or movement joints. Other annexes describe specific aspects of segment joints, immersion joints (including Gina-type and Omega-type seals), closure joints, terminal joints and waterproofing membranes.

This annex describes various types of waterstop found effective in the construction of immersed tunnels and where to use them. The waterstop to use will also depend upon the external water pressure, the type of water (fresh, salty or polluted) and the amount of movement and direction thereof that is expected at the joint. The concrete used must also be watertight for waterstops to be effective.

WHAT

External waterstop

External waterstops are mounted on the wet side of a concrete structure. There are versions suitable for both fixed and movement joints. For movement joints, there is a rectangular bulb to allow movement; for large movements, the outer side may be allowed to tear. This type of waterstop protects the joint against ingress not only of water but also of mud or any other substance. This waterstop is often installed in structures where double protection is required; the external seal is then the primary seal.

Internal waterstop

The most common type of seal between two concrete structures is the internal waterstop. The waterstop is preferably located in the compression zone of the concrete or else near the centre of the concrete section. When this type of waterstop is used to seal an expansion joint, the waterstop has a central bulb. The purpose of this central section is to form a free space in the concrete, which is necessary to allow movement. The central bulb usually consists of rubber with a central hole. An alternative arrangement in lieu of the bulb has rectangular strips of sponge rubber at the centre, one on each side, that are easier to fix in formwork without the risk of leaks. The concrete quality in the area around the waterstop is critical in ensuring water-tightness.

Rubber waterstop with vulcanised steel strips

When water pressures are higher, waterstops with steel strips vulcanized into the end bulbs of the rubber waterstop are used (Figure 1); segment joint waterstops typically use this type. Concrete does not adhere to rubber or PVC, but makes a good bond with the steel strip, providing the desired water-tightness. The steel strip also increases the path of leakage which decreases leakage problems.

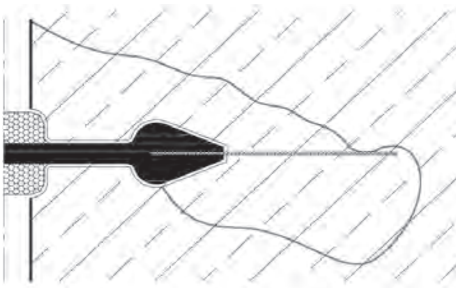


Figure 1 : waterstops with seal strips vulcanised into end bulbs

Injection waterstop

While the waterstop with vulcanised steel strips improves water tightness, in practice, fissures and gravel spots may occur due to concrete shrinkage and errors during casting. The concrete in the direct vicinity of the waterstop may therefore show seepage even though the waterstop is providing the required watertightness. In practice around 10% of all joints may have this leakage through the concrete.

To eliminate this leakage, there is a waterstop system that allows direct injection of epoxy resin or other products into the concrete around the edges of the waterstop (Figure 2). Injection systems are particularly sensitive to installation and should preferably be used as a backup system. Some injection hoses allow reinjection in case the first attempt to seal the leak is unsuccessful, but have not been successful on all projects.

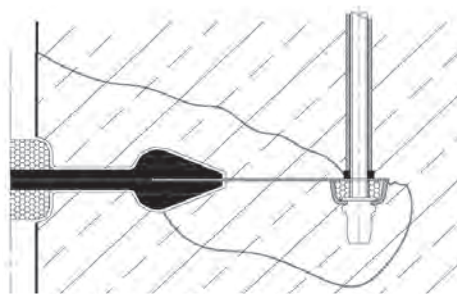


Figure 2 : waterstops with edge injection system

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Principles for making joints watertight should be set out in the design.

Selection of waterstop types and final configuration can be left to the contractor (or their designer if a D&B contract).

For sequence of construction and key issues for tunnel segment joints - see segment joints annex.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

Performance requirements for waterstops should be set out in design specifications. Specifications should be generic as far as possible to allow a choice of products.

Principles for watertightness should be clearly set out in the contract requirements or design requirements. These might include, for example:

- The number of watertight barriers within a joint. This is often specified as 2no. different methods of watertightness are to be provided.

- The design life of materials, the characteristics of materials such as chemical and abrasion resistance.
- The ability to replace components.
- Provisions for repair or future treatment of joints such as secondary grout tubes.

Material selection

The most common materials used for the manufacture of waterstops are rubber, PVC and vinyl. Waterstops typically have ribs to lengthen the water path to obtain the required seal. Rubber compounds available include Styrene Butadiene Rubber (SBR) Ethylene Propylene Diene Monomer (EPDM), Chloroprene Rubber (CR), Natural Rubber (NR) and Nitrile rubber (NBR), selection being made according to the surrounding environmental conditions.

In view of the long service life required and the fact that waterstops cannot be replaced, material has to be of a very high quality. Repair of leaking joints after construction using, for example, epoxy injection repair systems is a costly operation so the correct choice of the rubber quality is of paramount importance.

Mechanical Properties

All waterstops should be certified by laboratory tests and be accompanied by quality test certificates and conform to relevant standards.

Installation procedure

The water tightness of a joint is often determined by the method used to install the waterstop. The physical position and integrity of a waterstop is particularly vulnerable during its installation, during placement of reinforcement and while concreting. The internal waterstop supplied with vulcanised steel strips has holes in the strips for installation purposes, to allow it to be tied into the correct position.

It is important to ensure that the waterstop is placed at the design location relative to the joint and that the waterstop does not move during concrete placement. Waterstop movement is not uncommon when there are high concrete pressures during the concreting.

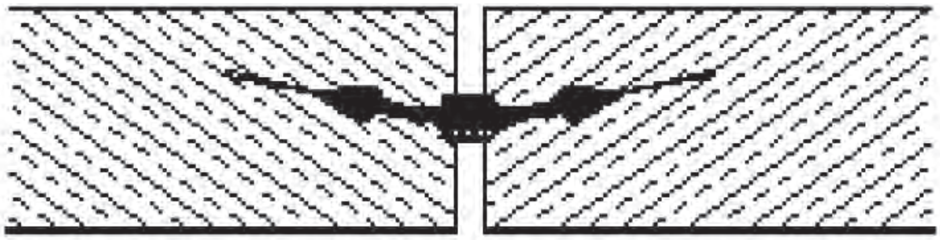


Figure 3 : horizontal waterstops with edges raised

The concrete beneath the waterstop must also be vibrated and consolidated during the concrete placement to prevent porosity, cavities and honey combing.

When the waterstop is mounted horizontally, it is advantageous for the sides to rise upwards to prevent air entrapment (see Figure 3); for the same reason, the number of longitudinal ridges should be minimised.

Corners/special constructions

There are prefabricated corner pieces available that cater for most changes of direction. Improved joint strength and security is achieved by producing these in the factory under ideal conditions.

Any joints required to be made on site should always be made in a straight length of waterstop. A joint requires a minimum straight length of 20 cm each side of the joint. Such joints should be vulcanised. If required, internal waterstops can be made with a radius (Figure 4).

Special solutions are available for:
- connections between different types of waterstop
- connections between a waterstop and sheet piling
- vulcanised steel endstrips.

Clamping joints

In new constructions waterstops are embedded in the concrete. When a watertight seal is desired between two existing structures or between an existing and a new structure, a different type of waterstop is needed. There are a a number of different waterstops (or clamping joints) available for this purpose,

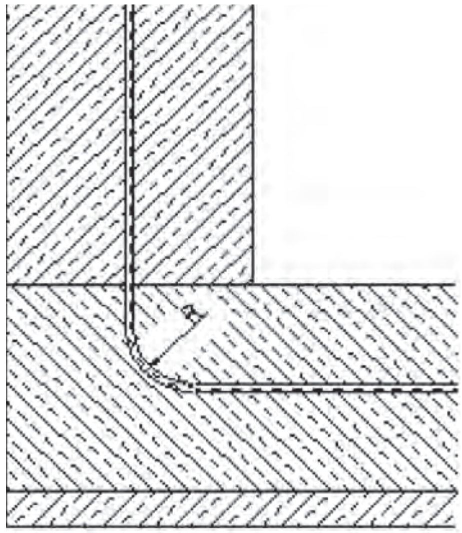


Figure 4 : waterstops corner radius

depending upon the circumstances such as permissible movement, water pressure and type of construction. Typical examples are shown in Figure 5.

Where a waterstop is placed on a rough surface, leakage can appear between the surface and the rubber waterstop. To prevent this, a flexible material is put between the surface and the waterstop. The waterstop manufacturer should be consulted about suitable products. For detailed design and selection of fastener the suppliers should be consulted.

Grouting

see segment joint annex

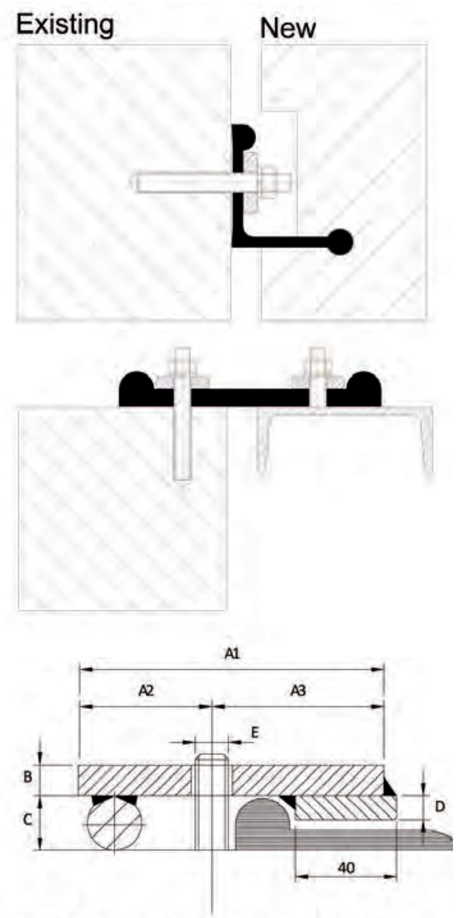


Figure 5 : examples of clamping arrangements

DOCUMENTATION (FORMAT, DEADLINES)

As-built drawings should record waterstop products manufacture, suppliers, installers, materials and final installation details, along with any defects or remedial works performed during the construction period.

Product data sheets and testing record should be retained in the as-built records and maintenance manuals.

Grouting records – materials and logs from grouting should be retained in the as-built records. Also see segment joint annex

The history of joint movements through construction should be retained in the maintenance manual.

EXPECTED VALUES

Some waterstops will be located in movement joints. The expected range of movement will depend on the structure geometry and characteristics. For typical movements at segment joints – see segment joint annex.

ANALYSIS (REQUIREMENTS, TIMESCALE…)

Assessment of joint movements should be made in the design and include for:

- Temperature variation – water, air temperature and structure temperature
- Settlement – global, differential and rotational effects
- Material creep/relaxation
- Construction tolerances
- Seismic load

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

Permitted limits of joint movement and tolerances for installation will vary according to characteristics of the tunnel and the configuration of joints. These should be set out in the design specifications.

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

Most joints are inaccessible after construction and leakage may need to be corrected by injection grouting. Some contract documents call for facilities for re-injection at a future date.

Also see segment joint annex.

Metal components exposed to the atmosphere or moisture may suffer corrosion and should be protected for the design life with an appropriate system.

LINKS TO OTHER OWNERS GUIDE THEMES

Segment joints
Immersion joints
Durability
Seismic design
Leakages

PERFORMED BY/RESPONSIBLE

Design & detailing – designer
Specifications of materials – designer
Movement monitoring during construction – contractor
Leakage monitoring during construction – contractor
Leakage repair during construction – contractor
Movement monitoring over life – Owner
Leakage repair during operation – Contractor or Owner (depending on contractual requirements for defects liability period after completion of construction)

The factory method for the construction of concrete immersed tunnel elements was first developed and used in the middle of the 1990's by the Øresund Tunnel Contractors for the construction of the Øresund immersed tunnel. It has also been applied for the Hong Kong Zhuhai Macao tunnel in China. The factory method of constructing immersed tunnel elements has introduced new production processes including large scale, full-section casting of concrete tunnel segments and launching of immersed tunnel elements.

WHAT

The factory method, as developed for the Øresund project is very briefly described below. For a more detailed description of the Øresund tunnel reference is made to "The Øresund Technical Publications; The Tunnel, May 2001, ISBN nr. 87-90020-56-1". Figure 1 shows an overview picture of the Øresund tunnel element production site.
The production process used for the Øresund Tunnel is characterized by:

- prefabricating complete reinforcement cages for each segment indoors
- full segment casting indoors
- initial concrete curing indoors
- construction of the tunnel elements above sea level
- horizontal transfer of the elements on skidding beams
- launching of the tunnel elements

Figures 2 shows schematically the lay-out of the production site with two production lines.

Some parts of this production process had been pioneered elsewhere before. For example full segment casting was first used in the beginning of the 1960's for the construction of the Rotterdam Metro Tunnel in the Netherlands.

In the reinforcement prefabrication building the reinforcement cage for one complete segment is prefabricated. The reinforcement cage is stored behind the casting area. At the casting area the reinforcement cage is placed in the formwork system after which the concrete is cast in one continuous pour. When sufficient concrete strength is reached, the formwork is removed and the segment is pushed forward

Figure 1 : Factory production site for Øresund Tunnel (Denmark)

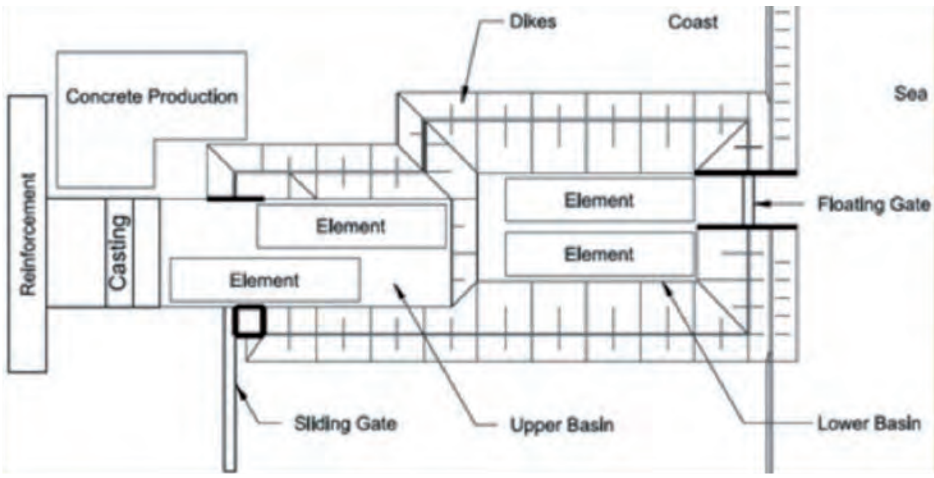


Figure 2 : Factory production site (schematic)

on the production line to create space for the next segment to be cast against it. This process of casting and pushing segments is repeated until a complete tunnel element is constructed.

The complete tunnel element is pushed all the way into the upper basin where the finishing works on the element take place. This gives space to allow the construction of segments for the next tunnel element. After the finishing of the element in the upper basin the sliding gate behind the element and the floating gate in front of the element are closed. Water is pumped into the launching basin until the element in the upper basin floats. The floating element is transferred to the lower basin after which the water level is lowered to sea level again and the gates are opened. The production of the next element has been going on uninterrupted during this process.

As further explained in the following, differences between constructing concrete tunnel elements with the Øresund method and traditional casting of element in a casting basin are:

- Structural clearance
- Construction site
- Support conditions during construction of segments
- Time schedule
- Protection against flooding
- Working logistics
- Controlled environment
- Quality Control

Structural clearance

The construction method used for the production of the Øresund tunnel elements results in straight elements, both in horizontal and vertical directions. The consequence is that the structural clearance profile for the cross section is not only determined by the required traffic clearance profile, the space needed for the technical installations and tolerances, but also by the additional space required to fit any curvature of the horizontal and vertical alignment over the length of the tunnel elements.

Construction site

As for the Øresund site, the production facility can be located above sea level the need for ground water lowering during the construction time of the tunnel elements can be avoided. During the construction period of the site itself local ground water lowering could be required.

The site area required for the factory construction method, specifically for longer immersed tunnels, can be expected to be less than for the casting basin construction method as the finished tunnel elements are directly transported away from the site. The number of production lines is dependent on the length of the immersed tunnel and the available construction time according to the time schedule.

Each production line requires a high investment costs to set up the line. The number of tunnel segments produced on each production line should be sufficiently high to be interesting in comparison with other construction methods. At Øresund the number of segments produced on each production line was 80.

Support conditions

Support conditions of tunnel segments during the construction process are important in general due to the significant dead weight of these structures when not submersed in water. At the Øresund construction site the hardened tunnel segments were supported at the wall by hydraulic jack supports which could slide over a foundation (skidding beams). It is important to control the load carried by these hydraulic supports for each segment to prevent overloading of the shear keys between the segments.

This specific situation requires attention in the design phase and monitoring during the construction phase. When the concrete for a segment is cast a significant part of the weight is carried by the formwork system as the concrete has no strength. After a short hardening period of the concrete the formwork is removed, at which moment weight is transferred from the formwork to the hydraulic supports. During this load transfer excessive loading on the shear keys should be avoided. Noting in particular that the shear keys have lower capacity due to the early age strength of the concrete at that time.

Careful attention must be paid to the accuracy of the sliding surface and the likely deformations of the skidding beams when the weight of the tunnel segment is applied during formwork release and the subsequent sliding activities. Either a high level of accuracy is needed or a well controlled hydraulic support system that evens out any variation in surface level. Otherwise distortions to the tunnel structure at early stages may cause overstressing and cracking in the concrete.

Time Schedule

In the casting basin construction method the tunnel elements become available for the next activity (transport and immersion) all at once or in case of a longer tunnel in batches (when the size of the casting basin does not allow for all elements to be constructed at the same time). The activities of construction, transport and immersion take place in a staggered sequence. For the factory production method the opposite is valid. The elements become continuously available during the element construction process allowing the other activities to take place in parallel.

Protection against flooding

The level of the production line above sea level and the local variations in water levels determine the risk of flooding the site. When the site crosses a sea/river dike, its function shall be kept by relocating the dike around the site. Formal approval from authorities for making adjustments to the dike is usually needed.

Working logistics

The sequential construction of the tunnel segments in the factory construction method requires good construction logistics on the construction site, as a delay is more difficult to mitigate.

Controlled environment

Most of the construction activities, from construction of the reinforcement cages till the casting and curing of concrete, take place indoors. This results in that the environment/ conditions under which these construction activities take place can be controlled and become less weather dependent.

Quality Control

As a result of the indoor construction process of the tunnel segments and the application of standardisation the quality of the delivered product can be well controlled.

Developments following the Øresund tunnel project :

Busan-Geoje tunnel, South Korea
This project utilised a similar full-section casting but had moveable formwork and curing tents within a conventional casting basin which was used for a number of cycles of construction.

HZMB tunnel, China

This project used a process almost identical to the Øresund Tunnel but with a slightly different layout of the basins and some modifications to the detailed processes, for example, in the jack support system to the tunnel segments for sliding.

Fehmarnbelt tunnel, Denmark - Germany

This project is planned on the basis of the Øresund Tunnel factory production method but in order to meet the required production rate it requires 8 production lines. Longer tunnel elements are envisaged and a protective harbour around the production site will be constructed.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

The decision to utilise a factory type method is generally decided by the contractor when tendering. However for large immersed tunnel projects it may be a necessity to meet the required construction programme. This is the case for the Fehmarnbelt Tunnel. However, the precise details of the construction technique can be left to the contractor.

The choice of a factory type method is likely to meet programme, but it may also mitigate against risk of inclement weather and allows greater attention to construction quality through carefully developed processes.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

The Owner/contractor will need to develop a construction specification that covers the detailed processes for construction. Some critical areas are:

- Concrete curing procedures
- Formwork striking times
- Strength gain before sliding of elements
- Tolerances on sliding surface

DOCUMENTATION (FORMAT, DEADLINES)

Not applicable.

EXPECTED VALUES

The determined values (forces, pressures, deformations) from the structural analysis shall be verified/monitored during construction.

ANALYSIS (REQUIREMENTS, TIMESCALE…)

Structural analyses during the design phase are specifically recommended for:

- Determination of the stresses/forces in the segments and shear keys between the segments when supported by the hydraulic system as well as when the form work is removed.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

With this method small tolerances are achievable, e.g. enabling more simple end frames to be used for the immersion joints.

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

A contingency plan should be developed in case of a failed casting or problem in the sliding operation that would cause blocking of a production line.

LINKS TO OTHER OWNERS GUIDE THEMES

Alignment
Element Construction /dry dock
Concrete construction – concrete
Transportation
Soil conditions

PERFORMED BY / RESPONSIBLE

Design, outfitting and lay-out of the site – contractor

ANNEX 22 >> WATER CONDITIONS FOR IMMERSION

Water conditions determine immersion operations in different ways. Conditions are for instance current, waves, unit water weight (salinity) and tidal movement. In this article the influence of water conditions on an immersion operation are described.

WHAT

Current

Tidal movement (see figure 1), waves by vessels, wind, precipitation and manmade discharges determine whether currents will occur in certain situations. Tunnel elements, floated or submersed in water, will block the discharge. When flow is obstructed water will have to divert along and around the element thus creating loads and inducing forces on the element.

Hydraulic mechanical design according to known theories (Bernoulli, Navier-Stokes, etc) can be used to determine the amount of blockage and the expected current forces on the system.

A critical aspect is that the current loads change non-linearly to the current velocity. An increase of velocity by a factor of 2 results in an increase of loads by a factor of 4.

Other aspects which influence the resulting loads are the shape of the element (square or rounded edges, the so-called shape factor), the unit water weight and the element size related to the channel cross section.

Figure 1 : Tidal current

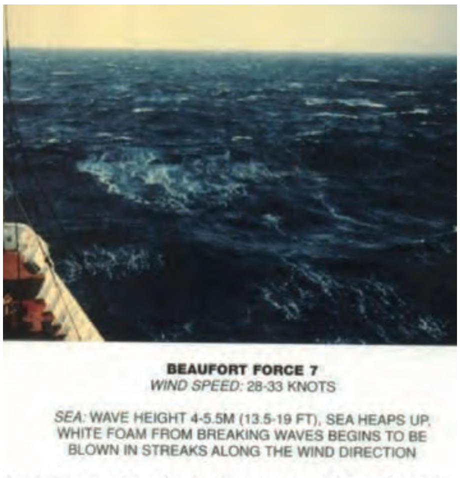


Figure 2 : Example of wind waves at Beaufort 7

Waves

Waves (see figure for example of waves at 7 Bft) come in 2 types: wind waves and swell waves. Waves are mostly generated by wind and build up strength depending on the situation (open ocean, near shore or sheltered area), wind direction and surrounding area (land masses, mountains, etc).

For immersion of tunnel elements mainly swell waves influence the operation. Dynamic movement of the elements during immersion is the governing factor. This movement translates into loads on cables, vessels and the element itself which need to be taken into account in design of the systems.

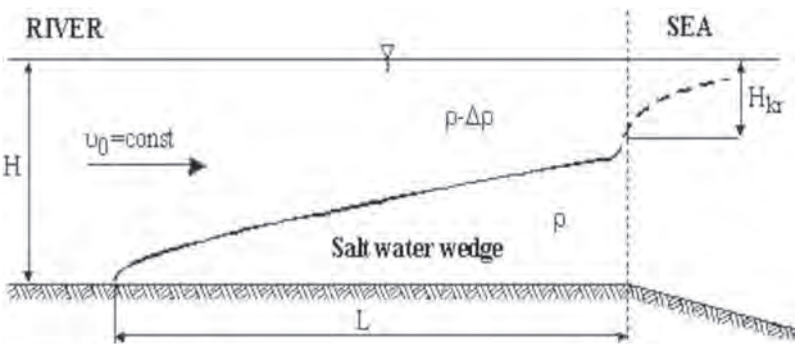


Figure 3 : Salt water wedge

Wind waves have an effect on the elements by flooding the deck of vessels and the element and therefore potentially making work unsafe. Smaller immersion pontoons are more susceptible to wind waves.

The limitations and definitions of wind and swell waves must be determined per project since it depends highly on the situation, element shape and behaviour of the element and immersion pontoon in water.

To determine the behaviour of elements and systems in waves, physical model tests and numerical analysis can be performed, from which operational constraints (limits) are derived and used for further design of immersion systems (transport, pontoons, winches, cables, anchors, etc).

Water density

The floating behaviour of an element (as per Archimedes principles) is determined by several factors among which is the unit water weight. A higher unit water weight will make the element float higher above the water level (freeboard).

The average unit water weight is determined by several aspects: Temperature, salinity (amount of dissolved saline particles) and silt content (floating particles other than salts). Changes of the unit weight over water depth can occur due to variance in these aspects. Typically water is denser within a dredged trench and ballasting systems need to be designed to take account of this.

Fresh water is mostly present in inland rivers and channels. Nearer to shore, salt water from the sea can penetrate the rivers and channels due to tidal movement and inland currents. In these areas differences over water depth can occur, as shown in Figure 3, therefore making immersion operations more sensitive to lifting load deviation.

Tidal movement

Off- and onshore, tidal movements can influence the immersion operation. Amplitude of tides depend on the location on the earth and the geographical situation.

Due to tidal movements the entire immersion system including tunnel element will undergo continuous vertical movements during lowering of the element which can influence the loads in cables and become more important in the final immersion steps (near the bottom of the immersion trench).

Predictions

Together with knowledge of allowable water conditions, accurate prediction makes an immersion operation controllable and safe. With the use of operational constraints, decisions can be made whether an operation may continue or even start. Predictions can be done in the following ways:

- Current: Currents from tidal movement can be predicted accurately based on the lunar cycle. However when precipitation, wind and discharges are present, values are less predictable. Models for currents can be found online or purchased from specialist companies.
- Waves: long term survey of waves using buoys makes prediction of waves possible. Data derived from the surveys is analysed and translated into a wind and wave model for specific locations. General ocean/sea wave models can be purchased or found online, however for unique projects or situations, specific software applications can be developed in order to predict waves.
- Unit water weight: Survey of unit water weight can be done in several ways. Simplest is the weighing a sample of water from a certain location. Salinity measurement is based on electric conductivity or light deflection. Silt can be measured by dry filtering the particles from a sample and weighing them. Predictions with reasonable accuracy can be made by long term analysis of survey data and expected precipitations.
- Tidal movements: Astronomical tide tables for locations all over the world are readily available. Mostly containing averages, max highs and lows and long term accurate predictions. These tables do not contain local influences like wind set-up and precipitations.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Pre-tender

To obtain more insight of the conditions on the construction site where the elements are built, moored and immersed, information on water conditions should be monitored. Existing weather stations may be available or the Owner may need to establish project specific monitoring stations to collect data. Data should be collected over several years to enable a good understanding of the baseline conditions.

With this information the pre-tender designers can assess the governing situations and loads on the elements in both temporary and permanent stages. The more water condition data is available the more accurate assessments can be made.

Tender

Given the information is available, the tender documents should contain a summary of the measurement results (wind rose plots, current plots, tidal graphs, etc. as shown in Figure 4). The effects on the tunnel, the element and the systems can now be assessed by the tenderers.

Construction phase

Additional continuous survey and measurements on water conditions will give better insight in specific situations and will make detailed designs more accurate. Design starts with model tests (if required) and design of the tunnel element behaviour in different water conditions. Detailed design is based upon the outcome of these model tests. Water condition prediction is used in this stage to serve as input for decision procedures.

Frequent analysis of the actual occurred water conditions after the immersion has finished is required to improve the next decisions and operations (hindcasting).

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

In order to obtain a clear view of the water conditions, several survey methods and frequencies should be taken into account. Current, waves and tidal movement can be continuously monitored with a survey buoy with wireless data upload link. This buoy can be active months to years prior to the actual construction works.

During each stage of the project the frequency and type of survey should be fit for purpose and analysis should be done accordingly. Thereby gaining higher accuracy in order to obtain information more fit for purpose.

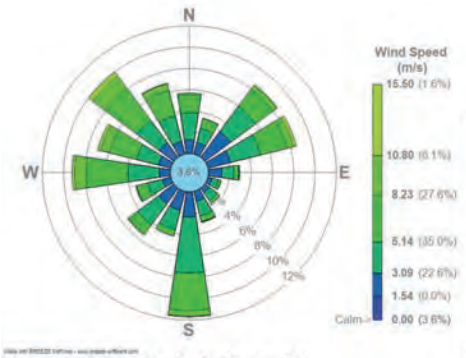
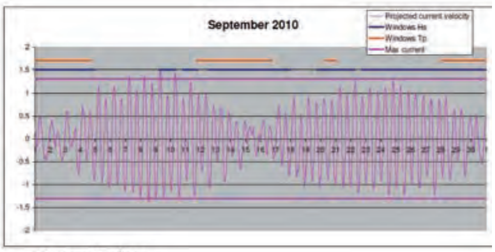


Figure 4 : Example of wind rose plots



Current plots

DOCUMENTATION (FORMAT, DEADLINES)

Water condition information should be time logged in a database and suitable for extraction to post-processing software. Format standards can be agreed with the supplier or parties involved.

EXPECTED VALUES

Current

Currents can vary differing from negligible to several meters per second. Since normal immersion operations are suited to take place in conditions up to 1-1.5 m/s, higher currents ask for special equipment (depending on the situation) and make diving works more challenging. For instance, when a rectangular free floating element of 200m long, 10m high subject to a current of v=1.2m/s (in fresh water) the current loads can go up to:
Fcurrent = 1730 kN (=170 tons).

But for an element of 120m and 8m high and with a current of v=0.5m/s the current is in the order of:
Fcurrent = 145 kN (=15 tons).

For deeper tunnels current may vary in speed and direction with increasing depth. For example the Marmaray tunnel was constructed under conditions of reversing current with depth in the Bosphorus Strait.

Waves

Swell and wind waves occur mainly on open sea or near shore. Rivers, channels and estuaries are less likely to suffer from swell waves but wind waves could occur here.

Due to the length of tunnel elements (anything from 100m up to a maximum of 175-225m) and the small freeboard, swell waves with periods of Tp > 6 to 7 sec have the most effect on loads and movement of an element. Wind waves can therefore be described with Tp < 6 to 7 sec.

The significant wave heights, which are governing for the design of immersion operations, depend on the type and layout of immersion system. Works can generally be impeded with wave heights above Hs = 1.5m.

These numbers depend heavily on the layout of the system, the size of the element and the water depth and should be specified / determined per project.

The wave conditions to be used for design of temporary plant and equipment, and to be used to derive loads on the tunnel elements in the temporary condition, should be assessed taking into account the duration of the tow and immersion work, the possibility to seek sheltered water during towing, the weather forecasting system to be used during construction and the flexibility in the construction programme to only work for a percentage of the available time. By this consideration the equipment and the tunnel do not have to be designed for the more severe possible conditions.

Water density values

Fresh water is noted as 1000 kg/m³. Seawater is normally noted as 1025 kg/m³. Depending on the location in the world higher or lower values may occur (see Figure 5.). Site investigation is the best method to find the specific unit water weight (varying on water depth).

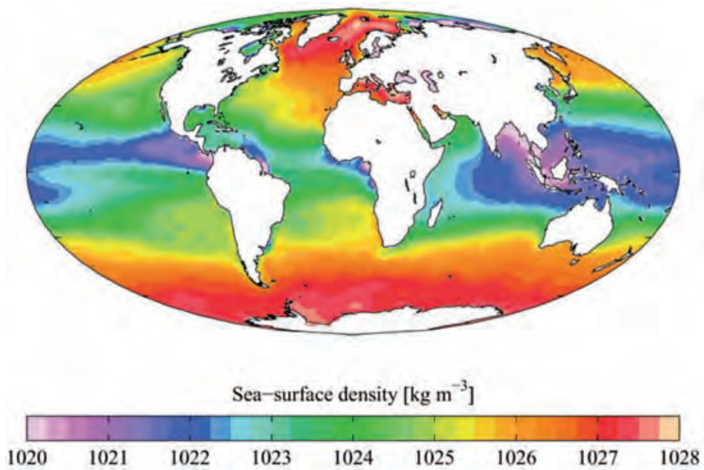


Figure 5 : Sea surface water density

Tidal movement

Tides occur all over the world (on- and offshore) and depend on the position on the earth, relative to the lunar cycle and sun. Water level variations from several cm's to over 14m can occur, for example see figure 6. Tide tables can be found or purchased for the appropriate locations.

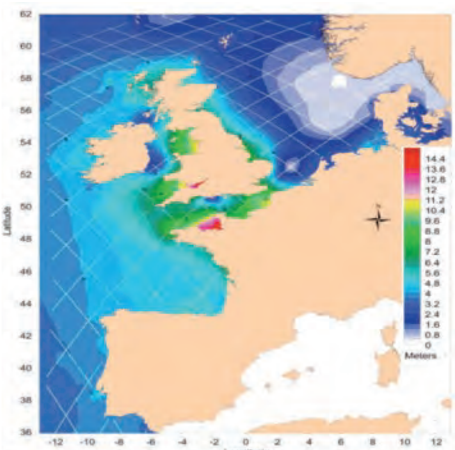


Figure 6 : Tidal movement Atlantic / North Sea

ANALYSIS (REQUIREMENTS, TIMESCALE…)

Analysis activities include:
- Appropriate inquiry for data request (what data, data format, when and where)
- Accurate survey / measurement system of water conditions (incl. maintenance).
- Data logging and readout.
- Processing, analysis and reports of logged data

It is recommended to record the following data for a minimum of a full year at one or more locations close to the project site and on towing routes if known and applicable:

- Salinity
- Temperature
- Current speed and direction
- Wave height, period and direction
- Swell wave height and direction
- Tide levels
- Suspended sediment
- Degree of ice coverage

Timescale

- Install and operate survey system months or preferably years during investigation phase (prior to tender).
- Availability of raw and analysed data during tender phase.
- Full continuous data logging and analysis during construction phase (extended detail level for decision procedures).

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

Possible variations in water conditions must be understood and allowed for in the design, planning and method statement/procedures. Single value parameters are not used, rather a range of values for each design parameter should be used with a degree of safety built in. Weather forecasting and regular sampling/ monitoring combined with go/no-go decision processes are used to ensure parameters outside of the assumed ranges are not encountered during construction.

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

Unexpected values should be taken into account as design values during the pre-tender and design phases.

LINKS TO OTHER OWNERS GUIDE THEMES

Dredging.

Tunnel element positioning.
Tunnel element transportation.
Tunnel element temporary mounted equipment.

PERFORMED BY/RESPONSIBLE

Pre-tender design phase:

100% Owner. Install and operate survey system, analysis and summarize data.

Tender design phase:

100% Owner (or 100% contractor in Design and Build). Analyse and incorporate data in tender designs (temporary works). Assess risks and opportunities from supplied data. Plan additional surveys for contract phase.

Detailed design phase:

Permanent works are designed by owner (or 100% contractor in Design and Build. Design of temporary immersion equipment and operation plans based on weather windows and conditions are generally done by the contractor who will also determine prediction system for water conditions.

Preparation:

100% Contractor. Monitor and use prediction systems together with operational constraints.

Execution:

100% Contractor. Monitor and use prediction systems together with operational constraints. Decision procedures based on prediction systems.

Waterproofing membranes are applied to the external surface of concrete tunnel elements that are constructed as monolithic structures. The membrane is applied to minimise the risk of leakage in the case where the concrete structure may have cracks through the full thickness of its walls or slabs due to thermal, shrinkage or tension behaviour. A number of membrane types are available and each has its specific considerations in construction.

Membranes are applied to individual tunnel elements during their construction within a dry dock or casting basin.

Figure 1 : The Aktio-Preveza tunnel has a spay applied membrane to the walls and roof, and a plastic membrane to underside of base

WHAT

Concrete immersed tunnel elements have either a segmental or monolithic structural form. Segmental tunnels are jointed at regular intervals (20-25m) and this enables watertight concrete construction to be reliably achieved. Monolithic tunnel elements are subject to greater bending moments, shears as well as thermal and shrinkage effects during and after their construction. They are therefore more susceptible to through-section cracking and there is a higher risk of leakage occurring through the structure. Permanent prestressing is sometimes used to place the tunnel in compression and minimise the possibility of leakage through cracks but it is a common approach to manage the risk of leakage by applying an external waterproofing membrane to the exterior surface of the tunnel structure.

Different forms of membrane are required for the underside of the tunnel element and for the walls/roof of the element. This is because the base slab of the tunnel element must be cast on top of the membrane as there is no access to the concrete surface to apply the membrane afterwards. Therefore a rigid or semi-rigid membrane is necessary that can be laid on the ground and retain its shape during the concreting operations and not suffer any damage. Steel plate has often been used for this part of the membrane and in some tunnels a stiff plastic sheet. The membrane will have preformed corners at the base/wall of the tunnel structure and the membrane returns some distance up the wall of the structure.

The height of the return up the wall may be a notional distance to get a good overlap with the wall membrane. In some instances it has been extended up so that it passes the construction joint in the concrete structure between the base slab and the walls. In other instances the steel has been extended for the whole height of the tunnel structure. The membrane is used as the formwork for the wall construction, with suitable temporary support from behind.

As the sides of the tunnel element are accessible after the concrete construction is complete, a spray applied membrane or sheet membrane can be used.

The roof of the tunnel element also has a spray applied membrane or sheet membrane as it is difficult to place concrete beneath a steel plate and ensure there are no voids. Although that technique is used for steel tunnels the curved shape of most steel tunnels helps limit the risk of voiding. Although not common a steel plate can be fixed after concrete work is complete e.g. Soderstrom tunnel. This had a facility for grouting the void space between the roof slab and the steel plate.

It is essential that good continuity is achieved between the base membrane and the wall/roof membrane. If a spray applied system is applied to the roof/walls then a suitable overlap of the spray onto the floor slab membrane should be achieved.

The types of membrane available are:

- Steel membrane
- Semi-rigid plastic membrane
- Spray membrane
- Sheet membrane
- Bitumen membrane

Steel Membranes

Steel membranes are made of mild steel and are typically 5-9mm thick excluding any corrosion allowance, and depending on the environment and the applied cathodic protection. The membrane is formed of panels welded with full penetration butt welds. All welds are tested for watertightness during fabrication. The membrane is keyed to the concrete using shear connectors. However there remains a risk of local separation of the membrane from the concrete so the membrane is partitioned by welded stiffener rails to avoid long water paths should water penetrate the steel. The membrane is made continuous with the immersion joint steelwork at the ends of the tunnel element. The membrane forms the shuttering for the concrete construction. It will require stiffening and a bracing frame for its assembly, and wall panels may require additional external support.

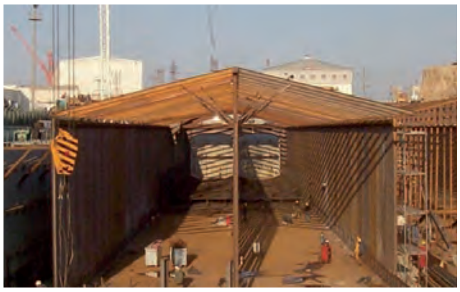


Figure 2 : Marmaray Tunnel steel membrane

Steel membranes have been used extensively around the world but are becoming less common as better oil-based products are developed which enable faster construction. One recent example was the deep Marmaray Tunnel beneath the Bosphorus Strait where the steel membrane encased base and walls.

Semi-rigid plastic membrane

Semi-rigid plastic membranes are formed with tough plastic compounds such as HDPE or PVC. The sheet is typically 1.5-3mm thick and is hot air welded to create a continuous sheet. Corner pieces between the base and wall sections are pre-formed. The membrane can be laid directly onto a granular formation surface or onto a no-fines concrete layer in the base of the casting basin/dock, provided this is smooth and has no sharp steps or protrusions. If a plastic membrane is used on the tunnel walls, it is supported against traditional formwork. Continuous T shaped locks or discrete Y shaped anchors ensure the connection between membrane and concrete

Figure 3 : T-lock plastic membrane

Sheet membranes

Sheet membranes are typically PVC and HDPE sheet materials applied bonded or un-bonded. They may be applied directly to finished and suitably prepared concrete surfaces In cut and cover tunnels they are sometimes applied to formwork, or on a suitable base layer for ground bearing slabs, and have concrete poured directly onto them. Some have integral 'waterbars' which serve to compartmentalise and limit the spread, and thus the potential impact, of local leakages.

Membranes of bituminous mats reinforced by polyester or glass fibre fabric can be used on the roof slab. The best elastic properties are obtained with polymer modified bitumen. The mats may be glued on with hot bitumen or by heating a bitumen layer applied to the mat during fabrication. The membrane has good ability to bridge cracks.

Pre-hydrated, high-density bentonite layers are an alternative to polymeric membranes. These are available in rolls with a geotextile covering and length of waterstop. This type of material has been used in many tunnelling projects.

However, dependent on the exposure conditions there are uncertainties over the effectiveness and life of bentonite-based systems, in particular in highly saline conditions and so they are not preferred.

Spray applied membranes

Wet-applied systems comprise a range of material types but are typically based on elastomeric polymer materials, methacrylates or polymer-modified cementitious materials. They are typically spray-applied on site to finished concrete surfaces, and require a high degree of site supervision and quality control to ensure their effectiveness. Nevertheless they have the potential to achieve an extremely watertight seamless membrane, and are particularly useful for dealing with irregular or complex element geometries, which are challenging for sheet materials.

The most robust spray membranes are a high build material, usually applied in two coats. The finished product can be tough and resistant to abrasion and minor impacts from construction operations. However, protection of the membrane will be required from large impacts and damage from winch cables used for towing, manoeuvring and immersion of the tunnel elements.

Membranes may require a primer to be applied to the surface of the tunnel or may be able to be applied direct to concrete and steel surfaces provided they are cleaned and free of oils or other substances that may prevent adhesion.

The materials used for different coats are often pigmented to provide an indicator to operatives and ensure full coverage of the surface is achieved.

Bitumen membranes

In earlier tunnels a bitumen membrane has been applied (e.g. the Ruppeltunnel, scheldetunnel & drechtstedentunnel). Typically these membranes consist of one or two layers of polyvinylalkohol fiber and two or three layers of oxidised bitumen. The roof and walls are often protected with protection concrete.

Figure 4 : Elastomeric polymer spray membrane

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Waterproofing membranes are applied during or after the construction of the tunnel elements within a dry dock or casting facility. This affords the opportunity for close control over the quality of the works.

All of the spray applied and some of the sheet membranes require that the concrete surface is properly cured.

Control of quality is achieved during the production process for sheet membranes and during the application process for both spray and sheet membranes.

Control of the quality of steel membrane construction is achieved through close attention to welding procedures and 100% checking of welds.

All membrane construction and application should be subject to rigorous testing to ensure the membrane is built in accordance with the design or applied in strict accordance with manufacturer's recommendations. In particular the specific details that may be unusual, such as treatment at overlaps between different membrane types, and at features such as corners and around cast-in items should receive particular attention in the quality control processes.

All works should be complete and verified, including curing of materials, ahead of the casting basin or dry dock being flooded to float up the tunnel elements. Protection to vulnerable parts of the membrane should be installed at this stage ahead of the marine activities commencing.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

General:

Specifications should include the following items:

- Material types acceptable to the client and suitable for the specific site conditions and required service lifetime.
- Nominal thickness and permitted variation.
- Methods of joining or welding to make the membrane continuous.
- Requirements for preparation of substrate.
- Specific requirements at interface with cast-in items.

All membrane types can be considered to have a finite design life. Therefore the concrete construction is usually specified to be watertight or to be constructed to limit the possibility of through-cracking, for example through temperature control during casting and curing. The expected design life of the membrane and the required quality of concrete construction must be clearly specified.

Steel and plastic membranes may be subject to thermal expansion prior to concreting when they are placed up against formwork or on the formation to base slabs. Limits on temperatures may need to be specified or suitable protective measure implemented to prevent distortion of the membrane.

Pre-pour surveys and inspections should check distortions due to temperature are within specified limits.

Steel membranes:

Welding procedures and testing for watertightness are the most important specification items. 100% testing of welds should be carried out using recognised methods such as soap bubble tests, dye penetrant tests or x-ray testing.

When applied, electrical testing of cathodic protection (CP) systems prior to concreting and after concreting to verify system is connected correctly.

Procedures for suitable lapping of sheet membranes to the steel at the overlap of the different membrane types should be specified and an inspection, testing and checking regime implemented. Overlap details between sheet and steel membranes usually include clamping systems

Plastic membranes:

Inspection and test plans for checking insitu hot air welding are required; procedures will be in accordance with manufacturer's instructions. Tests should include production tests for the sheet materials and 100% on-site testing of thermal welds for watertightness

Spray membranes:

Application procedures should be thoroughly developed based on standard procedures but enhance to deal with the specific circumstance on an immersed tunnel. Specific procedures should be developed for:

- Overlapping with steel or plastic membrane.
- Overlapping at immersion joint end frame steelwork.
- Treatment around cast in items for temporary works for tunnel immersion.
- Protective measures against damage during transport & immersion of the element, for example by winch cables running over the surface of the structure. Protection concrete on top of the spray membrane is a possibility.
- Repair procedures for defects and damages identified prior to flooding the casting basin/ dry dock.

The key tests for spray membranes are measurement of wet film thickness during application, and adhesion tests once the membrane has cured.

Product tests should include:

- Abrasion resistance.
- Accelerated aging tests.
- Crack bridging properties.

In situ tests should include :

- Adhesion tests.
- Thickness test.
- 100% surface area inspection for defects after initial application.
- 100% surface area inspection for defects prior to flooding of the casting basin/dry dock.
- 100% surface area inspection of tunnel roof prior to immersion.

Sheet membranes:

Specifications and testing requirements should be similar to the spray membranes and should focus on bonding, adhesion and effectiveness of sheet overlaps with respect to watertightness.

DOCUMENTATION (FORMAT, DEADLINES)

The following records should be retained for reference over the operational life of the tunnel:

Product test data

- General product data sheets for the maintenance manual.
- Material test records.
- QA/QC records for installation indicating non-conformances and repair works.

Insitu ITP records

- Weld test records.
- Thickness measurement records.
- Damage & repair records.

These may help pin-point locations of leakage if it were to occur during the lifetime of the structure

For steel membranes records for the commissioning of CP systems should be retained to assist in ongoing maintenance.

EXPECTED VALUES

Permitted tolerance on thickness should be specified by the designer. Typically a minimum thickness will be specified. The maximum thickness may depend on the method of the membrane material application or production and is a less critical item.

Welding testing 100% pass
Clamping tests e.g. bolt torque 100% pass
Adhesion testing 100% pass

ANALYSIS (REQUIREMENTS, TIMESCALE…)

Design specifications need to take into account the available systems and materials on the market, to ensure they are realistic and appropriate.

Confirmation of compliance with material and performance specifications and requirements should be demonstrated at an early stage of construction planning to give time for the design to incorporate any specific details related to a selected waterproofing system.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

As per Expected Values.

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

Remedial measures may be necessary to repair local damages caused during construction or to repair sections of membrane that were installed incorrectly.

Once the tunnel elements have been immersed there is no access available to undertake further repairs to the membrane. If leakage is found to occur then the only practical remedy is injection grouting from the inside of the tunnel. Determining the exact point of leakage, and therefore the point at which to inject grout, is very difficult. Therefore emphasis should be placed on achieving high quality, watertight initial construction to avoid this need.

Soil injection with sealing products could be considered but the reliability of such methods could not be expected to be 100%.

If steel membranes are fitted with CP then correct functioning of the CP system must be checked in the ongoing maintenance procedures. Failure of the CP system may require replacement of components where accessible. Requirements for monitoring and renewal of CP components should be set out in the operation and maintenance plan.

LINKS TO OTHER OWNERS GUIDE THEMES

Durability
Structural form
Welding – steel construction
Operation & Maintenance

PERFORMED BY / RESPONSIBLE

Design & detailing of permanent structure – designer
Method and sequencing of work - Contractor
Specifications of materials – supplier/designer
Inspection & repair during construction - contractor
Testing of CP system effectiveness (if used) - contractor.

ANNEX 24 >> TEMPORARY PRESTRESSING

An immersed tunnel usually consists of several elements; for a concrete tunnel each concrete element may consist of several separate segments (short lengths of tunnel). Before leaving the fabrication facility these segments are temporarily assembled into a single element using temporary prestressing cables in order that the element may be floated, transported and immersed as a single unit. This Annex covers the temporary prestressing of segmental tunnel elements. Prestress is also referred to as Post-Tensioning (PT).

WHAT

Segmental concrete tunnel elements are formed by a series of separate segments with typical lengths of 20-25m. The segments are cast independently from one another with a joint between them that can open and close and will allow the tunnel to articulate in the final placed condition.

To form a rigid tunnel element for the purpose of floating, transporting and immersing the element the segments of the element are stressed together using temporary prestressing cables running the length of the element. Water tightness is ensured by using cast-in waterstops in the segment joints.

To ensure that segment joints will not open up or fail during transport and immersion operations, the cables are designed in such a way that the joints will (under predefined load combinations) not open up and always remain under compression.

Loads which influence the required prestress amount include:

- Weight and buoyancy distribution of the assembled element, temporary bulkheads and other attachments;
- Ballast water in tanks;
- Wave and current actions;
- Hydrostatic and hydrodynamic loads on bulkheads;
- Changes in water density;
- Lifting lug loads;
- Temporary supports and sand flow foundation preparation (if used);
- Shipping passing above a placed tunnel element;
- Foundation below element and underlying materials.

Both at roof and bottom slab level, sufficient prestressing cables are provided to handle expected sagging and hogging bending moments. The cables are usually located within the slabs. Horizontal bending moments can also occur and be handled by the cables. Since segment joints are designed not to go into tension while the temporary prestress is in place, these joints can also carry shear forces.

Figure 1 : PT ducts fixed into reinforcement cage

The prestress cables are located within cable ducts (PT ducts) that provide corrosion resistance. Ducts within concrete are placed and secured in the reinforcement cages prior to placing concrete. Sufficient fixing and straightness of the PT ducts is required to make feeding of the prestressing cables possible and to minimise friction losses during stressing.

Figure 2 : Applying prestress with a hydraulic jack

After the concrete has hardened and the formwork has been removed, the prestressing cables can be fed through the ducts, stressed using hydraulic jacks and then anchored (locked in position). Final checks of correct installation are done by the engineer in charge by comparing the expected elongation of the cables against the actual elongation obtained. Finally, grouting of the PT ducts will ensure durability and adhesion of the cable to the surrounding concrete. This grout is also applied from the outer ends. Over the joint adhesion of the grout is prevented by taping in the PT duct (this allows for elastic behaviour of prestress strands in this area).

It is possible to use un-grouted tendons or even external tendons that can be removed after use. It should be noted that un-grouted arrangement are less efficient from a design perspective at meeting code requirements.

Figure 3 : Anchor heads after grouting

If tendons are within ducts cast into the concrete structure, but are left un-grouted with the intention of removing them, the remaining ducts will need to be grouted once the tendons are removed after immersion of the elements. This is possible but less practical than grouting the ducts in the casting basin where access is better and the operation can be planned into the construction schedule better.

The usual approach for segmental tunnels is to utilise a grouted system and the remainder of this Annex assumes this approach.

After immersion has been completed and the element supported on its foundation and backfilled, then the prestressing cables can be removed or disabled. This can be done by cutting or sawing the cables from within the element. For that purpose, special recesses in the roof and floor are prepared, in which a large bladed concrete saw or a long circular concrete drill can cut through the cables. The de-stressing should be carried out in a pre-determined pattern that has been designed to ensure even stress distributions are maintained in the tunnel structure.

It is noted that grouted prestress systems will leave some inherent benefit to the concrete structure in that it applies compression which would assist with closing any cracks from the construction process. This benefit is not lost if the tendons are cut. The remaining tendons are not considered in the structural design of the tunnel as the 20-25m long segments attract very little bending moments and so the prestress is of little benefit. There is also a risk of corrosion and loss of effectiveness in the long term.

A question that often arises is why should the prestress be cut and why not take the benefit of its presence in the long term. If an Owner is satisfied that corrosion is protected against in the long term then this is possible. However, the behaviour of the tunnel will be very different to that of a segmental tunnel as the elements will behave as monolithic. Settlement behaviour will be different and the benefit of the segmental articulation will be lost. The longitudinal shears and bending moments carried by the tunnel elements will also be different. The choice between segmental or monolithic elements should be made at the start of design and carried through to construction. It is not correct to design a tunnel as segmental and then leave the prestress in place as an afterthought without a full assessment of the consequences of such a decision. The risk in this is that rotations at immersion joints are more severe for a monolithic tunnel than a segmental tunnel and the prestress, which is designed for a temporary condition will have to carry permanent loads and if it is over-stressed and fails at a single joint, the load distribution, joint rotations and settlement behaviour could be unpredictable.

If monolithic element behaviour is assumed in design and segmental construction is preferred, the prestress can be designed for the permanent loads and settlements considered on the basis of monolithic elements. A satisfactory design may then be prepared.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Application of prestress system

During construction, the PT ducts and prestressing cables are installed while good access is still possible. This may require upper reinforcement layers not to be placed until all PT ducts are well secured and supported. Installation of the PT ducts may be done by the reinforcement supplier, since these specialists know best how to integrate the system into the reinforcement cages.

After hardening of the concrete (usually 28-day strength) the prestress cables can be tensioned.

Removal of prestress system.

The temporary prestressing cables are no longer required once the tunnel is locked in position by placing adjacent tunnel elements and each segment has sufficient temporary or permanent ballast. Cutting of the cables is one of the final actions of the permanent concrete works inside the element, and is very dependent upon the programme for completing the internal finishing works and the overall project time schedule.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

High tensile strength and ductile steel cables (1800N/mm^2 or more) are often used, the cables built up of 12, 15, 19 or even 22 strand. Alternative approaches are possible and any prestressing bar or cable system on the market could be applied.

The PT ducts are often made from stainless strip steel (thickness 0.6mm) in diameters varying from 60mm to 110mm. It is important that ducts are placed and secured tightly, so no additional curves or dents will occur, making insertion of the cables more difficult.

New developments are PE ducts which are more easily installed.

Figure 4 : 19 Strand cable and individual wires showing in anchor head (incl. wedges)

A typical cross section of a watertight construction joint is shown in Figure 5. The PT ducts usually run (as shown in this case) on the inside of the rubber water stop, to prevent leakages and to provide accessibility for cutting.

Number of joints

To optimize the number and location of prestressing cables, an uneven number of segments will ensure that the governing bending moment (usually a maximum due to wave action) will not occur at a joint (refer to Figure 5). This depends highly on the position of lifting lugs, ballast tanks etc. in the longitudinal direction of the element.

DOCUMENTATION (FORMAT, DEADLINES)

Design

A number of steps are required to design the temporary prestress, including:

1. Sizing the tunnel cross section (permanent works designer);
2. Selection of temporary loads and combinations of load (designer and immersed tunnel specialist);
3. Determining locations for ducts, additional reinforcement and anchor heads (permanent works designer);
4. Calculation of temporary works bending moments and shear forces (designer and immersed tunnel specialist);
5. Preliminary design of required PT ducts and cables (designer and immersed tunnel specialist);
6. Detailed design, including drawings of prestressing cables (designer and PT specialist).

Loads

Determining the magnitude of wave and current loading is a complex process and a critical item for the determining the amount of prestress; a high degree of cooperation is required between designer and contractor. Loads are typically determined by computer based dynamic analysis of the floating tunnel elements. This may require specialist input from naval architects. The loads (bending moments/shear) are sometimes validated by scale model testing in wave tanks by specialist hydraulic testing institutes. This takes considerable amount of time and so the initial design is normally based on preliminary loads and the final design based on the validated loads. The time to conduct the scale model tests needs to be considered in the design schedule.

Quality documents

To ensure quality control of the prestressing, documentation of the construction of PT ducts, provision of prestressing strands, prestressing cable loads and extensions and details of the grout mix and tests thereon should be documented. Specialized companies have developed documents for this.

EXPECTED VALUES

Number of cables

The number of cables applied in the cross section will depend upon:

- Cross section of tunnel element;
- Available space (spacing of cables/anchor heads usually 600-700mm)*;
- Required capacity for bending moments;
- Available room for applied splice reinforcement around element outer ends;
- Loads and combination of actions;
- Number of joints.

Prestressing cables for immersed tunnels are usually straight and parallel to the floor and roof, not draped.

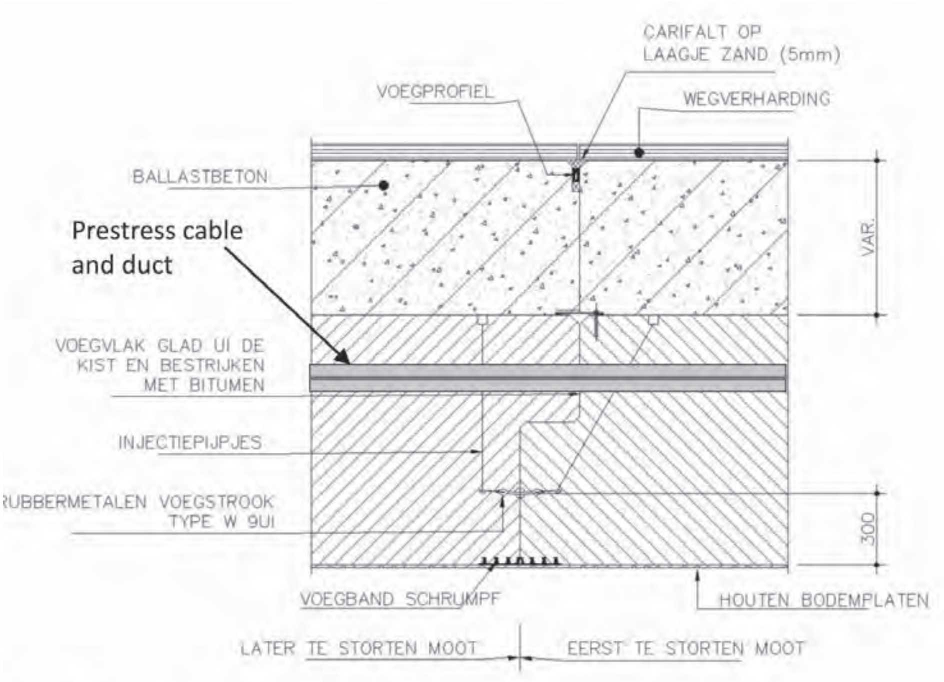


Figure 5 : Typical watertight floor joint (source: SATO)

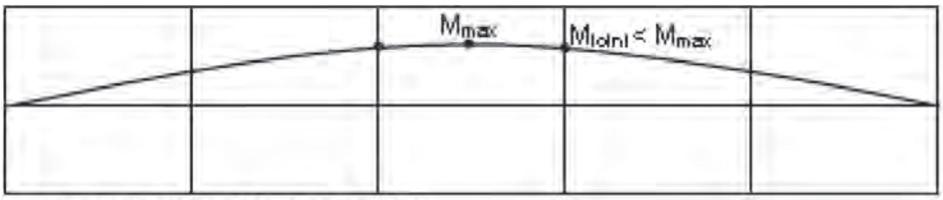


Figure 6 : Distribution of bending moments

Compressive stress in segment joints

The minimum required compressive stress in the segment joints during construction under the worst loading and taking the temporary prestressing into account will be defined by the Owner or his designer. Typical minimum values are 0.1N/mm² to 0.2N/mm². Under some circumstances (such as under extreme loads) 0N/mm² may be permitted, but this may depend upon the water tightness of the joints.

For example, if the concrete cross-sectional area is 60m² and if no bending moments are present, at least 4+3 12-strand cables would be required for 0.2 N/mm². Adding bending moments will increase the number of cables significantly.

Safety Factors

Because stresses calculated are working stresses, safety factors of 1.0 are applied to the loads and their combinations when calculating bending moments and shear forces.

ANALYSIS (REQUIREMENTS, TIMESCALE…)

Requirements

Information required prior to design of prestress:

- final cross section;
- final segment lengths and number of joints;
- external loads;

**Note that the size of prestressing cable anchor may be limited by the available space at the end of the element due to the presence of steelwork for the immersion joint, onto which the Gina-type and Omega-type seals are attached.*

- type of prestress (supplier and brand)
- interfaces with permanent works design (location, reinforcement, etc.);
- required compression in joint.

Timescale

Design of prestress is usually executed parallel to the permanent works design. Practice varies as to the responsibility for the design of prestress. Some contractors prefer to design the details of prestressing themselves while others prefer their designer to undertake the design. The permanent works designer needs to coordinate the prestressing anchors, ducts and bursting reinforcement with the other design requirements and should therefore produce the final construction drawings. If design is undertaken by the contractor, or specialist immersion contractor, then the permanent and temporary works design must be coordinated and prepared in time to meet the overall design schedule.

The PT ducts are installed during construction of the segments; early delivery of the PT system is therefore critical. The remaining operations involving the strands and grout are done in a later stage.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

Since the locations of the prestressing cables are set early in construction, allowable tolerances are small. Deviations in position exceeding 10mm must be reported to the designer prior to placing concrete; additional reinforcement may be necessary.

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

Broken strands

Should a prestressing strand break during tensioning, it may be possible to extract the broken one and replace it with a new strand. However, broken strands often coil up inside the PT duct and cannot be removed without damaging the duct. The provision of cables with more strands than needed, or spare ducts as a precaution against broken strands would be a wise precaution. Under no circumstances should the design load of the other strands be exceeded.

As similar approach can be used if ducts are partially blocked by cement grout that prevents the full number of strands being pulled through the duct.

Welding

Prestressing steel should never be welded on or come in contact with hot weld spatter. The capacity of the strands diminishes to almost nil once this has occurred. Removal and replacement of the strands that have been affected is required.

LINKS TO OTHER OWNERS GUIDE THEMES

Concrete – concrete construction
Durability
Element construction – casting basin
Joints – segment
Joints – immersion
Joints – closure
Leakages
Post immersion works

PERFORMED BY / RESPONSIBLE

Pre-tender design phase - 100% Owner/ Owner's consultant.

Tender design phase - 100% Owner (or 100% contractor in Design and Build)

Detailed design phase - 100% Contractor's designer with specialist subcontractor

Preparation - 100% Contractor

Execution - 100% Contractor

ANNEX 25 >> CATHODIC PROTECTION

The durability of an immersed tunnel structure is usually specified in terms of a design life, typically in the range of 100-120 years. Metal typically corrodes, such as structural steel, reinforcing bars and external waterproofing membranes. Corrosion of metal can shorten the life time. For corrosion to occur, a galvanic cell must form in which corrosion occurs at the anode. One way in which corrosion can be controlled is by providing cathodic protection in place of or in addition to providing a sacrificial thickness of metal.

WHAT

There are two basic methods of providing cathodic protection:

- Sacrificial Anode Cathodic Protection (SACP) - Passive protection using sacrificial anodes attached to the structure -
- Impressed Current Cathodic Protection (ICCP)

Both methods work by making the metal to be protected cathodic relative to its surroundings.

Anodes for both systems come in various shapes and sizes. Sacrificial anodes typically consist of zinc, magnesium or aluminium or alloys thereof. Zinc and aluminium are most appropriate for saline environments, and magnesium elsewhere.

Where sacrificial anodes are provided, the system should ensure that other unprotected structural steelwork and reinforcement does not become anodic with respect to the protected steelwork.

If the need for a possible future cathodic protection is demonstrated, sufficient electrical connections between the rebar and embedded items will be required to allow for the steel, embedded or otherwise, to be electrically continuous. This will require the use of weldable rebar to facilitate welded connections. Bolted connections can be used subject to checking sufficient electrical continuity exists across connections, typically checked by resistance testing.

Where practicable, each immersed tunnel element and segment should be electrically isolated from adjacent immersed tunnel elements and segments, and from any adjacent connection structures abutting the terminal elements. Utilities and pipes crossing the joints between elements and across the terminal joints should maintain this electrical isolation. All fixings used to support metallic service pipes/ducts should be non-metallic. Electrical isolation would not apply to rigid joints across which an external steel plate is continuous. Each individual tunnel element should be able to be treated as a separate entity prepared for its own cathodic protection system, which should be able to be energized at any time in the future. This applies to items to be installed in the future if and when a cathodic protection system is required, and includes:

- anode assemblies,
- power supply (including transformer rectifier units),
- anode feed cables,
- negative return cables,
- anode current control units
- reference electrodes

Space within each element will need to be provided for impressed current equipment if an impressed current system is to be utilized. As part of this provision, electrical continuity of the outer reinforcement cage within each reinforced concrete immersed tunnel element should be ensured during construction.

Reinforcement connections for negative cathodic protection returns should be provided at the internal face of the external walls. Connections should be provided to enable electrical bonding across isolation joints in the event that circumstances arise where it would become beneficial to have certain elements or even the whole tunnel electrically continuous. To achieve this, separate connections to reinforcement and to any internal and external shell plates at each end of each element should be provided, together with facilities for joining any or all of the connections.

Where metallic cover/fire plates are fixed across immersed element joints, they should be fixed to the substrate using non-metallic fixings that will remain secure in the event of a fire. An insulating pad should be placed at the interface between any metallic cover/fire plates if the plate is to be fixed to a metallic substrate.

All other metallic connections across element joints should be electrically isolated. This includes all service pipelines whose isolation should be achieved by the installation of insulating gaskets at each end of the tunnel.

It is desirable to keep the anode feed cables short; a connection through the roof of the element for future connection to the anode sled can assist in reducing losses.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

When a decision to use sacrificial anodes for passive protection has been made, anodes will usually be installed during construction of an element. Locations where anodes have been installed on some past projects or could be considered for future projects include;

- External steel waterproofing membranes.
- Steel shells of tunnels (single, double or sandwich).
- Immersion joint steel end frames.
- Isolated embedded items on the external face of the tunnel structure.

Provisions for impressed current systems are also installed during the construction of elements. Where this has been for possible future systems, this has been limited to bonding of the reinforcement and providing electrical connection points within the tunnel for future use. Monitoring systems are also installed so that the time for activating the impressed current system can be chosen, based on the risk of corrosion being initiated by the depth of chloride penetration through the concrete cover zone.

Sacrificial anodes for impressed current protection will usually be installed on sleds at bed level of the waterway at the time that protection is to be initiated, or can be placed within boreholes in the tunnel backfill. An electrical connection to the equipment within the tunnel element is required. Space is required with tunnel elements for the necessary power supply and connections.

An Owner may decide to make provision for future impressed current systems whether or not sacrificial anodes have been provided from the outset.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

Design life of a sacrificial anode system should consider whether replacement of the anodes is possible or not. In most instances, replacement will not be possible; those anodes will need to be designed for the full design life of the structure.

When sizing anodes, the design life of protective coatings to steelwork may be discounted from the overall design life, e.g. coatings with a design life of 20 years may allow the anodes to be sized for 100 years, giving an overall life of 120 years. The combination of coatings and sacrificial anodes is an effective approach because large areas of the coating system will remain intact well beyond its design life and the corrosion protection system only initially needs to deal with defects in the coating as they arise. Therefore the current demand is much reduced in the early part of the structure's design life, allowing a more cost effective solution for the corrosion protection system to be used.

Additional anodes or anode material should be provided to allow for variation in the anode sizing, errors in installation or defects in electrical connections.

Effects of current shielding must be considered to ensure anodes provide sufficient protection to all areas of the steelwork being protected.

The electrical bonding strategy should be clearly determined by the designer. This should state clearly the need for and locations for bonding or isolation between features of the tunnel. For example, immersion joint steel end frames may have a separate protection system to that of the structural reinforcement; in such a case, the two should be electrically isolated. However this is hard to achieve in practice and so the protection systems may need to be designed assuming electrical connections exist.

An alternative approach that has been adopted for some projects is to bond all steelwork items in the tunnel structure. When this is done, features that will have highest current demand will have the greatest influence over the sizing of anodes.

DOCUMENTATION (FORMAT, DEADLINES)

The Maintenance Manual should contain:

- Records of electrical continuity testing of reinforcement cages in tunnel segments and elements.
- Records of isolation tests conducted during construction.
- Initial readings of monitoring systems following commissioning.

EXPECTED VALUES

Predicted rates of chloride penetration through the concrete cover zone can be determined using one of a number of service life prediction durability models. These take account of concrete constituents and the density of the concrete matrix. If such predictions are made during the design of the tunnel, these should be transferred to the maintenance manual so that a comparison can be made to the actual progress of chlorides, based on actual potential readings obtained from corrosion monitoring probes.

Criteria for measurement of the effectiveness of the corrosion protection system should be developed together with the design and included in the maintenance manual, together with guidance on how to interpret monitoring systems and their expected readings.

ANALYSIS (REQUIREMENTS, TIMESCALE…)

For all types of tunnel, the expected rates of corrosion for permanently exposed and unprotected steelwork during the design life should be determined during design of the elements.

If cathodic protection systems are employed with consumable items such as sacrificial anodes, the rate of consumption should be assessed following tunnel inspections and the need for anode replacement determined.

Data Collection and Testing

It is recommended that each immersed tunnel element be provided with a corrosion monitoring system designed to enable monitoring of the corrosion condition of structural steel and/or reinforcement at or near the external surface.

The corrosion monitoring system should comprise permanent embeddable reference electrodes, reinforcement connections if relevant, reference electrode distribution boxes and monitoring facilities. It is recommended that reference electrodes be replaceable, or at least partially replaceable, from within the tunnel because they have a finite operating life (typically 20-25 years). It is recognised that this may not be practical since the ideal position for reference electrodes used for monitoring potentials within the concrete is adjacent to the outer face reinforcement.

In addition to reference electrodes in concrete immersed tunnels, it is recommended that embeddable corrosion monitoring probes be installed at regular intervals along the immersed tunnel to monitor the ingress of aggressive chloride ions though cover concrete; the monitoring facilities for these devices should be incorporated in the permanent reference electrode monitoring facility. It can also be useful to incorporate embedded resistivity probes at selected locations.

At the selected locations for monitoring, the reference electrodes and corrosion monitoring probes should be distributed around the perimeter of the tunnel to obtain data for the base, roof and walls of the tunnel separately. A reference electrode should also be included at the each location of the corrosion monitoring probes.

For external steelwork, reference electrodes should also be used to monitor potentials and hence the effectiveness of sacrificial anodes. If reference electrodes cannot be replaced then Zinc reference cells can also be used which have a longer design life and should be usable in the longer term.

The resistance between any cover/fire plate and a metallic substrate should be greater than 10 ohms, measured by the four-probe method. The resistance between any cover/fire plate and the reinforcement within a concrete substrate should be greater than 10 ohms, measured by the four-probe method.

Following welding, each connection provided for electrical bonding across isolation joints in the immersed tunnel should be checked for continuity. The criterion should be that the AC resistance, measured by the four-probe method, should be less than 0.1 ohm. Any connection failing to meet this criterion should be re-welded.

Operation stage monitoring

During operation, it is suggested that the frequency of monitoring of embedded corrosion monitoring probes and reference electrodes should initially be at 6 monthly intervals over the first 3 years and thereafter at longer intervals of approximately 3 years. It is important that this task is carried out by engineers experienced in the interpretation of this type of data. Typically the following types of measurement are taken:

- potential readings between the structural reinforcement and the reference electrode.
- current and potential readings between the anode arms and cathode base of the corrosion monitoring probes.
- resistivity readings.

Measurements should be included in the maintenance manual and readings plotted graphically to assist in identifying any trend over time and the likely progression of chloride through the cover zone of the concrete.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

Ranges of expected values should be specified to assess performance of a CP system, rather than single value targets or limits, as monitoring results require interpretation taking a number of factors into consideration.

Ideally the installed monitoring system will allow two methods for assessing corrosion risk, to cross-check the results and conclusions from the interpretation.

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

If the CP monitoring system identifies the components are expired, replacement is necessary, if such a provision has been made.

If the monitoring system fails components will need to be replaced as necessary or an alternative retro-fitted system introduced.

LINKS TO OTHER OWNERS GUIDE THEMES

Concrete construction
Immersion Joints
Durability
Steel construction

PERFORMED BY / RESPONSIBLE

Functional requirements - Owner
Structural design & detailing – designer / contractor
Specifications of materials – designer / contractor
Analyses – designer / contractor
Monitoring – contractor for commissioning and during construction / Owner (or his appointed specialist) during operation
Surveys – Owner / designer / contractor

Immersed tunnel elements are installed partially if not fully within a dredged trench (Fig 1) which is eventually backfilled sufficiently to provide protection around and over the tunnel.

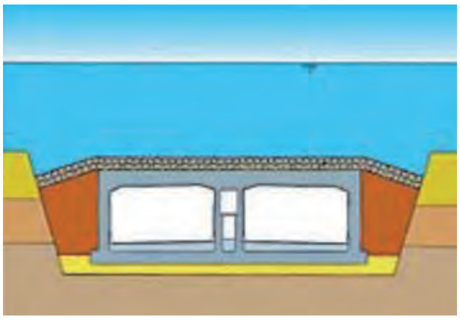


Figure 1 : Typical immersed tunnel trench

Dredging, i.e. the removal of soil below water, may also be required for associated works such as approach structures, the fabrication facility or an artificial island used as a transition between a bridge and an immersed tunnel (e.g. Figure 2, Chesapeake Bay Bridge-Tunnel) but are not specifically discussed here.

Dredging technology has improved considerably in recent years, and it is now possible to remove a wide variety of material underwater with little or no adverse effects on the environment of the waterway. However, this can be a particular challenge for rock removal that is too hard for a backhoe and needs chiselling or drilling and either blasting or splitting.

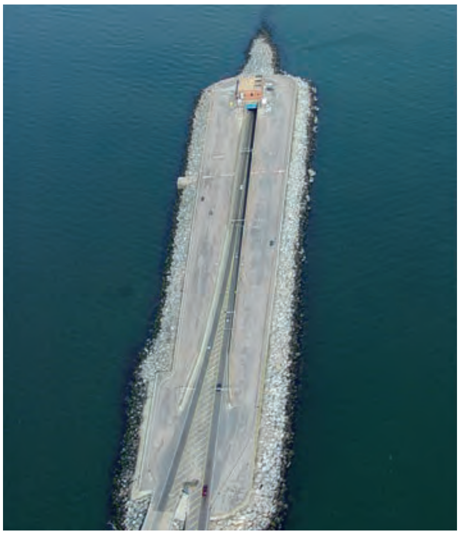


Figure 2 : Bridge-tunnel artificial island

This theme covers planning of the dredging works and how to select the best method and equipment for the project.

WHAT

A trench is required within which a tunnel foundation is to be constructed; the immersed tunnel will rest on the foundation layer and it will usually have backfill to the sides and a layer of protective backfill over the top. Some tunnels have substantially more fill over the top, particularly at the shoreline. In most cases the trench must be deep enough for the top of the protection to be no higher than the pre-existing waterway bed. However, under certain conditions, a shallower trench is used.

The side slopes of a trench may vary according to soil properties; in rock they may be near vertical (e.g. 2:1) and in soil often in the range of 1:3 to 1:5 or even flatter. In deep trenches an intermediate berm may be required in the slope. A slope of 1:1.5 is often achieved in reasonably firm soil. Some contracts specify minimum slopes to be used; others leave the slope to use at the contractor's discretion and risk. The contractor is usually best placed to decide this based on the time period he intends to leave the slope exposed for and how much cleaning he is prepared to undertake. Necessary side slopes may determine how close to an existing structure that a new excavation can be made, even if temporary excavation supports are used.
A major challenge for any project that involves dredging works will be to re-use as much excavated material as possible. Ideally, the material should be re-used without intermediate handling. In most cases disposal areas are required not only for materials suitable for re-use but also for unsuitable materials. Disposal areas may be either on land or under water. Since immersed tunnels are often in urban areas, temporary storage areas for re-use of materials are not easily found. Innovative ideas have found ways to re-use contaminated and unsuitable material within confined disposal areas. Options for the re-use of dredged materials in a beneficial way have included:

- Land reclamation, e.g. a new container terminal, dikes, raising low-lying land.
- Landscaping, recreation areas, agriculture, horticulture, forestry.
- Trench backfilling material.
- Engineered materials for use in construction (bricks, clay, concrete).
- Creation of new wetland habitats for wildlife.

Figure 3 : Disposal site for hydraulic dredged material from tunnel trench. Note division between foreground area used for dredged sandy material, and the far area used for muck. (Future container terminal)

Figure 4 : Re-use of dredged material as trench backfilling material for the NZL Metro project in Amsterdam

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Decisions regarding dredging activities as such are made by the owner early on in the design process because the extents and methods for environmental control usually need to be included in the project environmental impact assessment. The decisions will be based on results from soil investigations and advice from the designer. Contaminated materials must be removed before the main dredging operation starts. This is typically a regulated operation in shallow water. Sonar surveys can monitor where and measure how much of the material has been removed. Investigation of whether the spoil or soil is contaminated is a scope of works that should be done early in the design process. Following the removal of contaminated layers, the trench can be dredged as and when required.

Dredging is usually carried out as a two-stage process. Rough dredging to about 1m above final excavated elevation is usually carried out as a continuous operation. However the timing of this operation may depend upon availability of equipment, anticipated siltation, heave and settlement, or potential deterioration of the excavated surface. Leaving an open trench is considered a risk to all parties. Fine dredging to final dimensions is usually delayed until shortly before placing the foundation or the immersed tunnel element. Immediately before either of these is placed, the trench is checked for accumulation of silt or material sloughed down from the side slopes; it is essential that such material be removed.

Environmental regulations can play a large part in the operations and may require special sealed buckets and restrictions during certain seasons to avoid impact to marine species such as disturbing feeding or breeding grounds or interfering with annual migrations. Restricting the periods when dredging works may be carried out has been used to mitigate such impacts.

It is important to define the location where land based excavation, including approach works, is no longer practicable and where excavation by dredging should continue. In most cases, this will be where the immersed tunnel begins. There are several criteria that may determine where this interface can be located:

- Sufficient water depth to immerse a tunnel element.
- Available space to float or manoeuvre a tunnel element into place.
- Cost difference between the approaches and the immersed tunnel.
- Available construction time.

Technical requirements, such as dredging depth, soil strength, waves and currents will define which equipment is capable of carrying out the dredging. Dredging works can be executed in very soft up to very hard and stiff soils. Rocks can also be dredged up to about 15MPa compression strengths. Harder rocks will need chiselling or drilling and either blasting or splitting. Only the hardest rock types such as granite can be problematic and very time consuming. The suitability of this equipment should be investigated for the project area, in particular:

- Sufficient reach.
- size or capacity of the equipment too small or too large.
- unable to dredge certain materials.
- too low/high production rates.
- environmental restrictions, including suspended solids.

Having established that, the final selection of the most appropriate method is today more likely to be governed by environmental requirements. Such decisions are critical and may have a serious impact on construction cost and duration, or even whether it is acceptable. Leaving the dredging contractor unrestricted as to how contaminated materials are removed could expose the Owner to greater risk. Some dredged materials can be reused. This is desirable from a sustainability perspective but the practicalities of material storage and re-handling have to be considered.

Marine traffic information also plays a crucial part in the decision process; passing ships can cause extra constraints to the dredging process. Dredging is sometimes required to provide a temporary bypass channel for vessels to enable dredging to continue unhampered. Furthermore, adverse weather and water conditions such as high winds or large waves have been known to restrict dredging more to some months than others.

Dredging and transportation methods and equipment used should limit the dispersal of fine materials in the water. The effect on the environment would include the suspended solids due to dredging which will affect the flora and fauna.

Precautions should be taken to preserve suitable materials below and beyond lines of excavation. State-of-the-art positioning, navigational control systems and continuous sub-aqueous survey capability are used to maintain high accuracy during dredging operations. Measures may be necessary to ensure the safety and security of existing structures that might be affected by dredging, including underwater utilities. Temporary excavation support may be required before dredging close to existing shorelines or structures.

The possibility that over-dredging of unsuitable materials may be required should be considered when selecting the dredging equipment. If material unsuitable for supporting the tunnel structure is found below the foundation of the trench, the material should either be removed or processed to make it suitable. Remedial measures without removing the poor material have included vibroflotation, compaction piles, piles (wood, concrete or steel) and temporary surcharge (including dewatering). Over-dredged areas should usually be refilled with suitable material. Compaction of fill may be required such that the subsequent settlement together with the settlement of the foundation material itself meets design requirements.

Equipment

The dredging process consists of three essentially different phases – excavation, transport and placement. The excavation phase of the dredging process itself can be performed in three different ways – mechanically, hydraulically and hydro-mechanically. Equipment capable of these forms of excavation include:

- Air lift.
- Amphibious dredger.
- Backhoe dredger.
- Bucket ladder dredger.
- Bucket wheel dredger.
- Clamshell bucket dredge.
- Cutter suction dredger.
- Dipper dredger.
- Disc cutter dredger.
- Dustpan dredger.
- Grab dredger.
- Pneumatic dredger.
- Self-elevating dredger.
- Suction dredger.
- Trailing suction hopper dredger.
- Water injection dredger.

Except for a cutter suction dredge that transports material by pipeline, dredged material is most commonly transported by barge. For suitable materials to be disposed of in deep water, bottom-dump barges might be used. The dredged soil would typically be transported from the point of excavation to the point of placement by one or more of the following type of primary or ancillary equipment:

Figure 6 : Backhoe dredger

- Barges (flat top or hopper, and either dumb or self-propelled).
- Booster Station (floating, submerged or on land).
- Pipeline (floating, submerged or on land).
- Trailing Suction Hopper Dredger.

The dredged soil might be placed in a reclamation area or disposed of in marine or land based disposal areas by one or more of the following :

- Barges (side or bottom dumping).
- Barge Unloading Dredger.
- Crane Barge.
- Dump trucks.
- Fall or drop pipe installation.
- Jetting or rainbowing.
- Pipelines (floating, submerged or on land).
- Side-casting.

Data Collection and Testing

Official approvals may be required for any borings needed in order to carry out a geotechnical investigation. Laboratory tests are needed to provide data for design and construction analyses. Some projects require a full Geotechnical Design Report (GDR) encompassing the entire project to be prepared from which such information can be extracted.

The Owner should obtain information spanning longer periods regarding type and frequency of vessels passing the crossing. This data can really affect the risk profile for the tunnel construction period. Records of tonnage, size and speed are vital because not only the tunnel but also the temporary works including dredging must be designed for

Figure 5 : Clamshell dredger with 28 m^3 bucket

Figure 7 : Trailing Suction Hopper Dredger

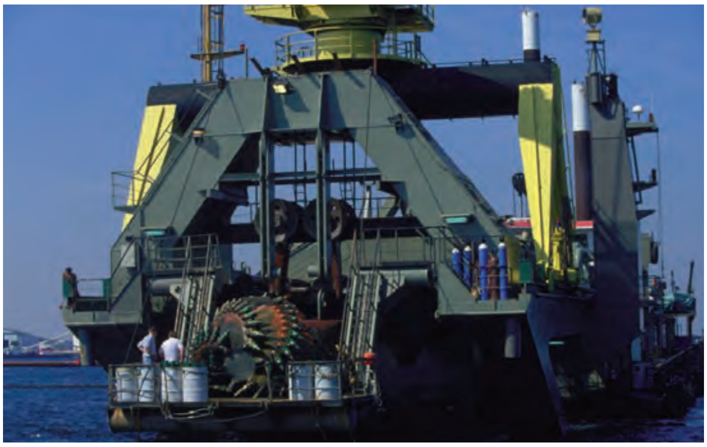


Figure 8 : Cutter Suction Dredger

these conditions. Maritime, harbour and river authorities also have requirements in terms of ensuring that shipping can pass freely or under certain constraints.

Bed surveys related to dredging would typically extend 100m or more from the tunnel centreline on a 10m grid. Slow survey vessel speeds relative to the bed (less than 3 knots) are typical. Accuracy would typically be ±1m horizontally and ±200mm vertically. Results should include:

- Contoured sounding plan (e.g. swath multi-beam bathymetry).
- Contoured plans of subsurface layers can also be very useful.
- Seismic profiles along and close to the tunnel alignment can be very useful.

Other information that might be needed includes:

- Extreme water level statistics (min and max) over longer periods, i.e. 100 to 1000 year intervals.
- Typical river or harbour conditions over the years, including the location of vanished structures (timber piles, stone jetties, etc) and shoreline changes.
- Wreckage or other constraints in the ground (e.g. locations of ferrous metal objects at or close to bed level).
- Seabed features from side scan sonar.
- Locations of anticipated unexploded ordnance.
- Current velocity parameters and extreme values, including variation with depth.
- Tidal data.
- Suspended solids.
- Siltation information or updated forecasts.
- Salinity levels, including variation with depth.
- Water temperatures (to convert salinity to density).
- Wave climate.
- Expected tsunami height and period
- Air temperature.
- Wind history and frequency of storms during the year, especially hurricanes and typhoons.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

Specifications will need to transfer any requirements from the EIA, planning approvals or consultations with the licensing authorities into the contract. These may include:

- Restrictions on dredging methods, moorings, or requirements for working within shipping lanes.
- Requirements for testing and analysis of soils pre-construction and during construction.
- Dredging tolerances to be achieved.
- Requirements for disposal of dredging spoil.
- Requirements for spill monitoring and water quality monitoring.
- Treatment of overdredged areas.
- Methods and required accuracy of surveys for bathymetry before and after dredging.

Currents caused by ship propellers and during element placement can cause soil displacement, perhaps into the dredged trench, and can also displace fill from the top and sides of installed tunnel elements. Research into these issues locally is needed. Speed restrictions for vessels may therefore be appropriate and the state of currents carefully selected when elements are to be placed; if not, dredging may need to be repeated.

Immersed tunnel elements are installed partially if not fully within a dredged trench (Fig 1) which is eventually backfilled sufficiently to provide protection around and over the tunnel. Dredging, i.e. the removal of soil below water, may also be required for associated works such as approach structures, the fabrication facility or an artificial island used as a transition between a bridge and an immersed tunnel (e.g. Figure 2, Chesapeake Bay Bridge-Tunnel) but are not specifically discussed here.

Dredging technology has improved considerably in recent years, and it is now possible to remove a wide variety of material underwater with little or no adverse effects on the environment of the waterway. However, this can be a particular challenge for rock removal that is too hard for a backhoe and needs chiselling or drilling and either blasting or splitting.
This theme covers planning of the dredging works and how to select the best method and equipment for the project.

WHAT

A trench is required within which a tunnel foundation is to be constructed; the immersed tunnel will rest on the foundation layer and it will usually have backfill to the sides and a layer of protective backfill over the top. Some tunnels have substantially more fill over the top, particularly at the shoreline. In most cases the trench must be deep enough for the top of the protection to be no higher than the pre-existing waterway bed. However, under certain conditions, a shallower trench is used.

The side slopes of a trench may vary according to soil properties; in rock they may be near vertical (e.g. 2:1) and in soil often in the range of 1:3 to 1:5 or even flatter. In deep trenches an intermediate berm may be required in the slope. A slope of 1:1.5 is often achieved in reasonably firm soil. Some contracts specify minimum slopes to be used; others leave the slope to use at the contractor's discretion and risk. The contractor is usually best placed to decide this based on the time period he intends to leave the slope exposed for and how much cleaning he is prepared to undertake. Necessary side slopes may determine how close to an existing structure that a new excavation can be made, even if temporary excavation supports are used. A major challenge for any project that involves dredging works will be to re-use as much excavated material as possible. Ideally, the material should be re-used without intermediate handling. In most cases disposal areas are required not only for materials suitable for re-use but also for unsuitable materials. Disposal areas may be either on land or under water. Since immersed tunnels are often in urban areas, temporary storage areas for re-use of materials are not easily found. Innovative ideas have found ways to re-use contaminated and unsuitable material within confined disposal areas. Options for the re-use of dredged materials in a beneficial way have included:

- Land reclamation, e.g. a new container terminal, dikes, raising low-lying land.
- Landscaping, recreation areas, agriculture, horticulture, forestry.
- Trench backfilling material.
- Engineered materials for use in construction (bricks, clay, concrete).
- Creation of new wetland habitats for wildlife.

DOCUMENTATION (FORMAT, DEADLINES)

Prior to any consideration of dredging, the following investigations should have been completed and the results available:

- Environmental baseline survey, the work for which can take several years.
- Meteorological survey.
- Hydrographical survey of existing bed including track plot.
- Geotechnical survey, which can be time consuming. In deep water this is very expensive.
- Other information may also be relevant in some areas and can provide valuable data, such as hydraulic modelling and data analysis.

The following design calculations are required in order to determine the shape of the dredged trench and the depths of excavation.

- Slope stability.
- Settlement/heave.

For the actual execution of the dredging works, the following documentation is required:

- Methods statements for dredging, transport and disposal are required before start of work.
- Bed Surveys to establish progress and volumes (before, during and after dredging).
- Environmental monitoring (suspended particles/contaminations) method statements before start of work plus documentation of results during dredging to measure compliance.

Contract documents should clearly identify ownership of risk with regard to the final quantities dredged versus the estimated volumes during bid preparation, taking onto account bulking factors. The payment mechanisms for the dredging activities should be clearly laid out in the contract documents, both for the bulk dredging and subsequent cleaning/maintenance of the trench.

Prior to using disposal areas for dredged material, site plans should show:

- The location and approximate boundaries of the disposal area;
- Access routes to the area, including haul roads, shipping channels and constructed or natural waterways used for discharge;
- Procedures to minimize erosion and siltation;
- Provision of environmentally compatible restoration, including drainage, screening and cover vegetation, if required;
- Other uses of the disposal site;
- A sequence and schedule to achieve the plan;
- Permission for use and constraints imposed by the licensing authority.

EXPECTED VALUES

N/A

ANALYSIS (REQUIREMENTS, TIMESCALE…)

Appropriate data should be collected for geotechnical evaluation of the stability of trench side slopes and base. The slope stability of a trench will typically need to be analysed for the following failure mechanisms (timescale: weeks):

- macro stability
- static liquefaction
- erosion
- uplift
- piping
- squeeze

The required total depth of excavation and the timing of it may be affected by the following analyses (timescale: weeks):

- Potential heave and settlement of the proposed tunnel foundation and underlying soils;
- Dredging tolerances during trench excavation;
- Dredging tolerances of the waterway after project completion.

In seismic areas, analyses to determine the liquefaction potential of existing soils are required.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

Tolerances for dredging works may be specified by the designer to limit the variation in thickness of the tunnel foundation layer, or by the Owner to set parameters for control of the work or to meet environmental limits on dredged volumes. Typical excavation tolerances in sand or soft soils are between +0 mm and -500 mm or less for the trench. Nowadays these tolerances can be more stringent but that does demand more sophisticated excavation equipment. Tolerances for slopes are in the same range but are not critical in terms of alignment or foundation layer depth.

A +/- level tolerance to be achieved against the design level for the trench base is often specified. This will vary according to water depth and the type of equipment that is envisaged.

A layer of spoil (unsuitable material) from the dredging equipment is usually left behind in the base of the trench. As this is poor quality material that may be compressible a maximum thickness of this layer is often specified to prevent excessive settlement of the tunnel. This would need to be checked by sampling once dredging is complete.

The maximum amount of sediment that is allowed to accumulate in the base of the trench is often specified, again to prevent excessive settlement of the tunnel. Sediment in excess of this thickness would need to be removed by the maintenance dredging equipment.

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

Out of tolerance dredging will require re-dredging or reinstatement of overdredge. Reinstatement of overdredge usually requires a specified material type and method of placement which may include compaction of the material.

Spill is the amount of sediment released into the water column from the dredging activities and which does not settle within the area of the excavation. Spill can cause an impact on the environment and often spill requirements are set to protect the environment from the effects of these suspended sediments by means of spill requirements.

A receptor-based approach to spill requirements is often used. In this approach the environmentally sensitive areas are identified and restrictions are set at the boundaries of these areas. For instance a maximum sedimentation rate can be required to avoid "burying" certain species or a maximum turbidity is set in the contract during the growing season, depending upon the species to be protected in those areas. This receptor-based approach is intended to leave some space for a dredging contractor to optimize his working method around the dredging areas. This will limit the spill by the related design criteria for the sensitive areas.

Figure 9 : Environmental monitoring of spill at Øresund Link project

LINKSTO OTHER OWNERS GUIDE THEMES

Backfill and protection
Contaminated soils
Soil conditions
Water conditions
Dualling of tunnels
Foundation
Backfill
Settlement

PERFORMED BY / RESPONSIBLE

Subject to type of contract and / or risk allocation:

Functional requirements - Owner
Structural design & detailing – designer / contractor
Environmental assessment – Owner
Preparation Investigation – Owner
Specifications of materials – designer / contractor
Analyses – designer / contractor
Monitoring excavation – contractor
Monitoring environment – Owner / contractor

Annex 27 >> OPERATION AND MAINTENANCE

The operation and maintenance (O&M) of an immersed tunnel is little different to any other tunnel in most respects. However there are a few specific maintenance aspects that should be considered.

WHAT

Operation

A tunnel will have an operating authority. This may be a transport authority (road or rail) or a concessionaire who has contracted to operate the tunnel for a set period. This is often connected to a PPP or DBFO form of procurement under which the tunnel is constructed. The operator may have its own maintenance crews and equipment or may subcontract the maintenance activities.

Accident & vehicle recovery may be part of the Operator's duties or responsibility of police. Similarly escorting of wide vehicles or vehicles carrying hazardous goods may be allocated to the Operator or the traffic police.

Most transportation tunnels will have an operation and control centre (OCC) which may be adjacent to the tunnel or located at some distance away. Typically road tunnels have an OCC located in the tunnel approach. Often the OCC has a view over one of the tunnel approaches but this is not strictly necessary as full camera coverage of the highway is usually provided. If it is located close to the portal it can be combined with plant and equipment rooms which are generally located there to minimise cabling distances from transformers into the tunnel. The optimum location is often determined by the highway layout and the need to give quick access to the tunnel.

An OCC building is usually manned and may have maintenance facilities such as storage sheds, workshops and maintenance compounds combined with it. A typical list of facilities for an OCC is:

- Control room
- Plant and equipment rooms
- Welfare accommodation
- Maintenance workshops
- Storage for spares
- Vehicle recovery
- Tolling facilities – barriers, offices
- Border control facilities
- Maintenance access roads/tunnels
- Incident room where emergency services can coordinate information and response

Facilities for break-down recovery of road vehicles may also be provided though it is not uncommon for this to be outsourced to an off-site specialist company.

A remote OCC is more typical for urban situations with multiple road tunnels in a concentrated area, or for rail tunnels. Rail tunnels are more likely to have a remote OCC that controls the wider rail network. There will still be a need for a small unmanned facility at the tunnel location to house essential plant and equipment.

Maintenance

Maintenance activities in a tunnel are predominantly associated with the mechanical and electrical systems that have been installed. A programme of regular maintenance will be established by the tunnel operator along with a programme for ongoing replacement of life-expired items of equipment. The latter is a necessary planning exercise to ensure suitable budget is allocated.

Procedures for the various maintenance and replacement operations will be set out in advance to ensure the work can be done safely and in a manner to minimise disruption to the operation of the tunnel. Maintenance of the civil works will be a relatively small task as the structures are predominantly reinforced concrete. Regular inspections will be carried out. These are typically on a 1 year and 5 or 6 year cycle.

Some particular maintenance activities may be required for the tunnel joints but otherwise the maintenance activities are quite conventional for tunnel structures.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Development of the operating principles should be carried out at the outline design stage by a safety committee. This committee will work alongside the designer but has a specific remit to ensure the tunnel will adhere to current safety standards and legislation and reflects the particular operational strategy that is desired.

The safety committee has different names in different countries. In the UK for example it is the Tunnel Safety Design Consultation Group (TDSCG). This group should contain representatives from the fire and ambulance services, police, tunnel operator and the designer.

Requirements from the safety committee should be captured in a design brief / AIP (often referred to as the Safety Concept) that forms the basis of the ongoing design work.

Development of detailed O&M plans and procedures will be carried out during the preparation of the detailed design.

Operation activities will commence on hand-over of the tunnel to the Owner/operator. In advance of this, full operational documentation should be prepared.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

The contract documents prepared by the client should clearly state the requirements for the documentation to be prepared for the operational phase of the tunnel. Maintenance manuals are usually prepared by the designer of the M&E systems and the contractor who built the works.

Operational manuals are usually prepared by the designer for the M&E systems who will have been part of the safety committee determining the principles of operation for the tunnel at the early stages of design. There will, however be additional documents that the tunnel operator will prepare. Responsibility for compiling the full set of documentation should be clearly assigned in the specifications.

Detailed contents lists for the documentation should be provided to the designer/contractor to ensure the required quality of documentation is provided.

For PPP projects or other O&M concession forms of contract, there will also be hand-back documentation to be prepared that the concession company will prepare to hand to the Client at the end of the operating period covered by the concession. This will include condition surveys sufficient to demonstrate the residual life of the assets. It will also include records of all major maintenance undertaken throughout the life of the structure since the works were constructed. The initial specifications for the project should clearly describe the type of documentation required. As the documentation is likely to be voluminous, the method of data storage should also be specified.

DOCUMENTATION (FORMAT, DEADLINES)

To operate the tunnel safely and effectively a suite of documentation is required to be produced during the design and construction phase of the project. Once the tunnel is in operation the O&M plans are live documents and should be updated with new/changing information over the life of the tunnel. Essential operation and maintenance documents include:

Maintenance manuals.

These should contain details of all elements of the constructed civil engineering works and the installed equipment within the tunnel. Detailed records are required including sources of materials, suppliers, manufacturer's recommendations for maintenance, as-built survey records and records of all non-conformances that arose during construction and how they were addressed.

Commissioning records for all mechanical and electrical systems should be retained in the maintenance manual.

Survey records should include:
- Level survey through the tunnel.
- Condition surveys for defects that arose during construction.

A maintenance plan should set out the regular routine maintenance procedures, periodic maintenance procedures and longer term maintenance procedures and refurbishment plans. It should contain descriptions of the specific procedures to be followed for the replacement of parts and components of M&E systems and the tunnel structure.

Operating Procedures

Operation manuals/plans should include detailed procedures for both normal operating conditions and emergency conditions.

The "normal operation" includes the traffic operation mode during maintenance work. Early during the design phase it should be decided whether the closure of one tunnel tube for maintenance shall imply bi-directional or alternating traffic in the other tube. This aspect may be of larger importance for an immersed tunnel than for a tunnel in a city environment with other options for diversion of the traffic to an adjacent street network.

The emergency operating plans should describe the response that should be implemented to all potential incidents that could arise in the tunnel, for example fire and vehicle accident or breakdown. The operating procedures will describe the operation and control procedures for each individual system installed in the tunnel and the response required for any alarm raised by a particular system.

Automated sequences may be set up for different incident scenarios, for example, the sequence of ventilation fan operation for a fire breaking out at a specific location.

There should be clarity of the response expected from the emergency services – fire, ambulance, police – and of the operator so there is no confusion or delay is reacting to the incident, and this should be tested by drills. This is particularly important if responsibilities differ on either side of the tunnel due to the tunnel crossing borders or county/borough jurisdictions.

Contact details for the emergency services should be contained in the O&M manual.

Traffic management plans

Traffic management plans should be in place for a variety of circumstances such as:
- Lane or tube closure for vehicle recovery or inspections and minor maintenance;
- Tube or tunnel closures for periodic maintenance activities;
- Implementing traffic diversions to alternative routes in the event of tunnel closures.

Such traffic management plans are usually agreed with the highway authority and traffic police in advance.

EXPECTED VALUES

Typical values for replacement of equipment within a tunnel, to act as a guide, are shown in the table below.

TYPICAL EQUIPMENT AND COMPONENT REPLACEMENT PERIODS	
Lighting replacement	35 years
Suspended ceiling replacement	75 years
Wall tile replacement	75 years
Rebuild roadway	50 years
Replace pumps	15 years
Replace fan motors	50 years
Electrical repair & maintenance	1 year
Switchgear, etc.	2 years
Motor starter maintenance	3 years
UPS battery replacement	10 years
Roadway overlay replacement	15 years
Fireproofing replacement	25-50 years
Traffic marking	4 years

The frequency of activites related to defects such as leakage repair will depend on the nature of any defects.

ANALYSIS (REQUIREMENTS, TIMESCALE…)

For maintenance activities it is typical to have a schedule of tasks that are required on a periodic basis. Washing of a tunnel interior is normally carried out on a regular basis at between 1 and 3 month intervals. However this will depend on traffic density and the speed of dirt build-up.

For the M&E systems the schedule of tasks will be the same as any other tunnel and will set out system by system what requires inspection, testing and replacement, and the timescales for each.

The tunnel structure is not the same as other forms of tunnel and so has some specific requirements. A typical checklist for an immersed tunnel structure is given below. This is based on the UK system of General (yearly) and Principle (6-yearly) inspections set out by the UK Highways Agency. There are also items that would be carried out on a routine basis, which may be monthly or to coincide with night-time closures for regular washing activities. This Schedule should be adapted according to particular authority requirements. Some authorities may have a simpler process and implement a full process at, say, 2 year intervals.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

N/A

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

Defects in the tunnel structure that are identified by the inspection regime will need to be fully documented in the inspection reports and recommendations given as to whether further investigations are required, what remedial work may be needed and the timescale that it should be completed in.

Monitoring systems installed in the tunnel that are monitoring the structural health may also identify when a remedial work is required. Readings and interpretation of readings from the monitoring systems should form part of each inspection report (also refer to Annex on durability).

Defects in M&E systems, particularly the lighting need to be reported on a regular basis so that replacement and renewals can be planned into the routine maintenance activities.

M&E systems should be designed such that minor failures are always compensated for by there being a level of redundancy and back-up in the design such that there is no safety risk to the tunnel users from minor failures. Planned renewals over the life of the tunnel ensure this condition is always maintained.

There should be a clear communication and reporting process whereby the inspection or maintenance team can raise an item for urgent attention of the Operator if it constitutes a safety risk to users of the tunnel.

LINKS TO OTHER OWNERS GUIDE THEMES

Durability
Joints – immersion
Joints –segment
Cathodic protection
Approach works
Structural form

PERFORMED BY / RESPONSIBLE

Development of operation and safety strategy – Owner / Operator / Designer / Emergency services

Preparation of O&M plans – Designer creates initial documents to be developed further and taken over by the Operator

Operation – Owner/Concessionaire

Inspections – Owner/Specialist

Maintenance – Owner / Operator / Maintainer

ELEMENT	COMPONENT	MAINTENANCE	
		Activity	Frequency
Structure	Internal surface	Inspection for seepage, staining, spalling	Routine
		Mapping of cracks – check for changes	General
		Mapping of cracks – re-mapping	Principal
		Testing for carbonation and chloride ingress	Principal
		Re-application of silane	As required
	Shear keys	Inspection for signs of distress at bearing surfaces and corrosion of steel components	Principal
		Inspection for deterioration of bearings (if used)	Principal
	General	Corrosion cell monitoring	General
		Performance of sacrificial anodes	General
		Activate impressed current or alternative CP system	As required
	Settlement	Level survey through tunnel and approaches, check for rotation	General
Immersion Joints	Omega seals	Inspection of seal and clamping system condition if access is available. Replacement is not an anticipated maintenance activity.	Principal
	End Frame steel	Test performance of sacrificial anodes, if installed	General
	Void spaces	Check for water between Gina seal and Omega Seal and if present check if saline/fresh	General
		Void spaces	General
		Renew internal sacrificial anodes to joint steelwork (if used, and accessible)	As required
	General	Check tunnel interior perimeter for evidence of leakage	Routine
		General	General
	Structure seal	Inspect if visible on walls and roof, for signs of deterioration or leakage	General
	Ballast seal	Inspect during road surface renewal.	As required
	Road surface seal	Inspection for deterioration and leakage	Routine
Segment Joints	Structure seal	Inspection for signs of deterioration or leakage - walls & soffit	Routine
	Ballast seal	Inspect during road surface renewal.	As required
	Road surface seal	Inspection for signs of deterioration or leakage	Routine
Internal Finishes	Fire Protection Boards	Inspect for deterioration of surface colour, integrity of fixings, damage to boards and joint overlap details	General
	Spray applied fire protection	Inspect for delamination, spalling, dampness, deterioration of surface coating and integrity of joint overlap details	General
	Cladding Panels	Inspect security and integrity of fixings, corrosion of support frame and deterioration or discolouration of surface coating	General
	Tiles	Inspect for delamination, cracked tiles, staining/leakage	Routine
	Paint	Inspect for deterioration of coating layer or surface colour	Routine
	Finished surfaces	Test luminance levels are satisfactory	Principal
	Cleaning	Overall clean of interior structure, cladding etc.	Routine

Courtesy Lunniss & Baber 2013

Routine = monthly or 3 monthly; General = yearly; Principle = 6 year interval (Based on UK practise)

The foundation principles for an immersed tunnels are different from other tunnel structures. The immersed tunnel is placed in a dredged trench but since dredging tolerances generally can not meet the foundation design requirements for the tunnel structure, additional foundation works are required. Therefore the foundation of an immersed tunnel generally consists of two components:

1. Original soil layers underlying the man made foundation, in some cases treated to improve or achieve uniform soil conditions;

2. Man-made foundation to overcome the dredging tolerances described above and acting as a transition between the original soil and the tunnel base. The tunnel elements can be immersed directly onto a pre-installed gravel bed or immersed onto temporary supports leaving a gap between the tunnel base and the trench, which is then filled with sand using the sand flow method. If unacceptable settlements are predicted it is possible to use soil treatment, pile foundations or to apply load reductions (e.g. light back fill material)

After the placement of the individual tunnel elements, the trench is backfilled and in most cases the tunnel is provided with a protective layer of rock material.

WHAT

Generally the tunnel weighs less than the soil it displaces. Therefore, the unit bearing stress is generally quite low implying that settlements are not likely to be a problem. Vertical displacements (settlement or heave) still occur however, during and after backfilling. This can be due to re-compaction or heave compensation that occurred as a result of the dredging works or if dredged material is replaced by heavier backfill material.

Due to the low foundation pressures of immersed tunnels compared to other marine structures, the soil strength is usually not decisive for the foundation design of the tunnel, even for soft ground conditions, but it is important for the stability of the slopes of the dredged trench which influences the dredging quantities. However, the soil strength can still be critical in areas where heavy earthquakes can occur, causing instability or soil liquefaction. In those cases additional treatment of the original soil or additional foundation components may be required.

The deformation properties will by soil-structure interaction be important for the structural design of the tunnel. Thus for monolithic tunnel elements, differential settlements due to variations in the soil stiffness in the longitudinal direction can lead to large bending moments, and for segmental tunnel elements they can imply critically high shear forces and large movements in the joints.

Man Made Foundations

Sand jetting

The technique of sand jetting was developed in the 1930s by the Danish contractor Christiani Nielsen. With this technique the tunnel element is temporarily supported above the bed of the trench (space 0.6-1.0 m). A sand/water mixture is injected into the space under the element using equipment mounted on the tunnel roof and travelling longitudinally along the tunnel. Prior to the installation of the tunnel element the trench is cleaned to remove any obstacles and / or sedimentation.

Sand flow

With the increasing depth of the tunnels and more stringent requirements with regard to the navigation channels, the use of sand jetting equipment riding over the tunnel roof became a challenge. In the 1970s the Dutch developed the sand flow method, a method close to the sand jetting, but meeting above requirements / challenges.

The sand-water mixture is transported through a pipe system with fixed outlets in the soffit of the element. The mix is usually discharged through one outlet at a time. As the velocity of the mix decreases after leaving the outlet, sand is deposited by gravity to form a firm pancake-shaped mound touching the underside of the tunnel, with a small depression beneath the outlet. While sand pancake dimensions vary, an area of l00 m^2 (diameter 10 – 15 m) is achievable. The sand/water mixture may be supplied either externally though inlets in the roof or walls, or from inside through non-return valves. Care should be taken with sealing off of the supply lines, as they may lead to leaks.

Prior to the installation of the tunnel element the trench is cleaned up to remove any obstacles and / or sedimentation.

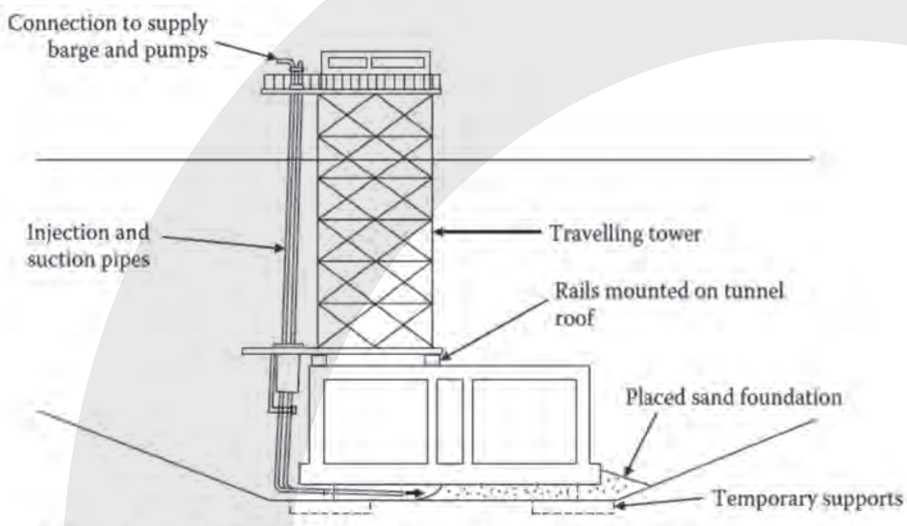


Figure 1 : Sand jetting equipment (ref : Immersed Tunnels, Lunniss/Baber).

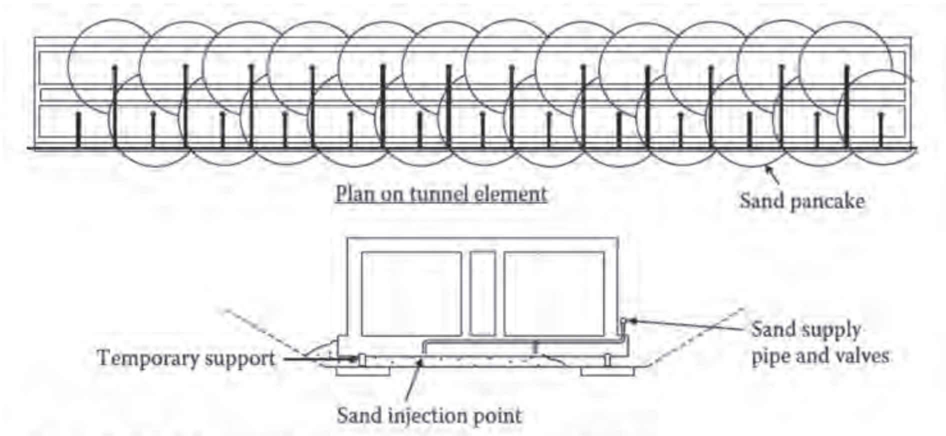


Figure 2 : Sand flow arangement (ref : Immersed Tunnels, Lunniss/Baber).

Gravel bed foundation

Following trench excavation and before immersing an element, a gravel foundation is prepared to close tolerances and onto which elements are placed directly without further adjustment. Temporary supports at bed level are not required.

Traditionally uniform gravel beds were applied. After the initial placing of the gravel, an underwater screeding frame that comprises a simple steel frame spanning across the width of the tunnel, pushes the gravel into a uniform thickness layer to a tolerance of 2-4 cm (depending on the water depth, condition of the trench and the wave and wind conditions while screeding).

This form of foundation has been used for many tunnels in the USA that were relatively narrow in width and for which the tunnel structure was not sensitive to variations in the surface level.

In the 1990s the Scrading Method was developed by Boskalis in Europe using gravel bunds that were placed by a special purpose pontoon within a tolerance of 2.5cm, while installing the gravel bed. Special equipment having real-time adjustment was developed to allow for placement within tight tolerances.

The gravel bed formed by the Scrading Method creates a series of discrete bunds that are able to absorb some sedimentation without compromising the quality of the foundation bed. However, this is limited and it may still be necessary to clean the gravel bed prior to the immersion of the tunnel element.

Additionally gravel bed foundations are suitable to meet requirements associated with seismic events.

Grouted gravel foundation bed

Grouted foundations are used in circumstances where placement of conventional sand or gravel bed foundations is complicated for example due to deep water or strong current conditions.

There is a trade-off between the cost of using sophisticated equipment to form a gravel bed to a tight tolerance versus the cost of a coarsely screeded bed plus grouting operation, and this is assessed on a project by project basis. However, the grouted type of foundation tends to be more expensive.

After installing and screeding the gravel bed, the tunnel element is placed onto temporary supports, leaving a space of 10-15cm under the element. This space is injected with a fat grout through a series of pipes set into the base slab. This is carried out from within the tunnel element.

Additional foundation components

Additional measures may still be needed depending on project specific circumstances. Whether these are required is generally determined by:

- Settlement criteria applicable to the project (total settlements and differential settlements).
- Unacceptable forces that develop in the tunnel structure due to local soil conditions.
- Accidental load cases such as earthquakes or sunken ships.

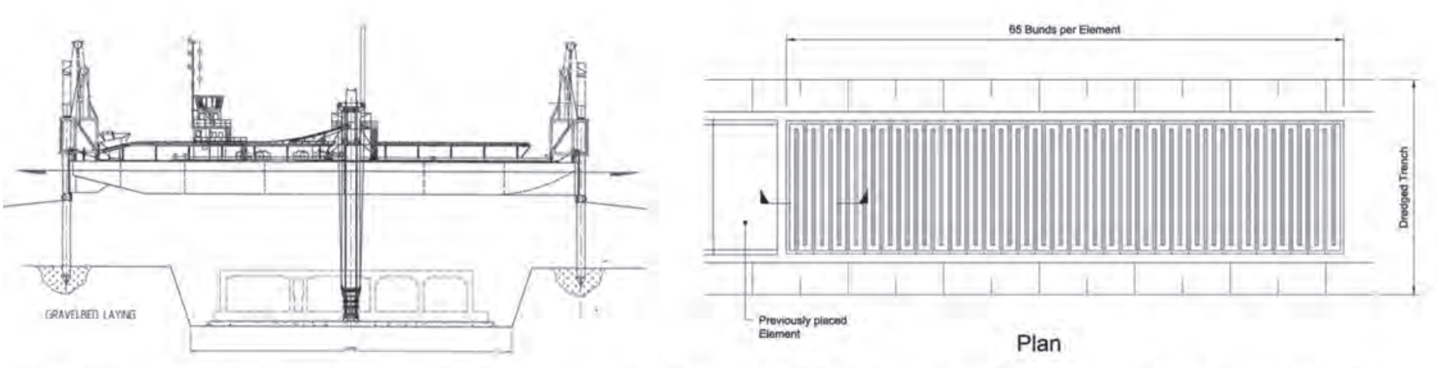


Figure 3 : Arrangement multi-purpose pontoon (Boskalis) and geometry of a gravel bed for the Φresund Tunnel (ref : Immersed Tunnels, Lunniss/Baber).

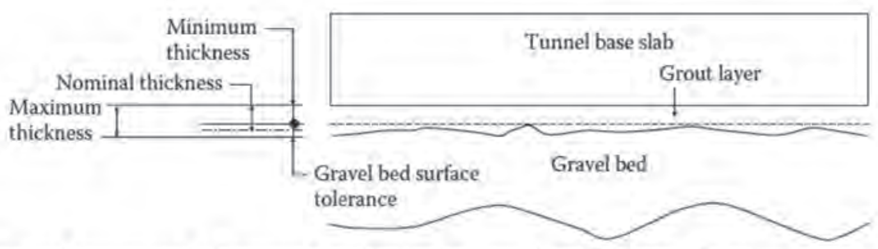


Figure 4 : Arrangement of a grouted bed (ref : Immersed Tunnels, Lunniss/Baber).

Various options are available. Very soft layers or large variations in the subsoil can be treated in various ways, such as sand (compaction) piles, cement deep mixing piles, stone columns etc. Also replacement of soft layers directly under the tunnel by sandy gravel or gravel can be carried out.

In rare cases piles have been used to solve critical or uncertain foundation issues. These can be complex arrangements and it is noted that it may be undesirable to restrain the tunnel from horizontal movement due to temperature variations. Sand layers with a low compaction underlying the tunnel may be susceptible to liquefaction. Treatment may be required (also see annex 12 Compaction Grouting).

Settlements

Immersed tunnels are generally placed in underwater trenches and add little net load to the foundation soils (in many cases there will be even a reduction of the load). Even so, reloading of the underlying soil, compression of the man-made foundation layer and construction activities generally result in settlement of the tunnel and in some cases considerable settlements. The settlements will develop during the various stages of realisation of the tunnel:

- Placing the tunnel element onto the foundation bed
- Placement of back fill material (including down drag effects) and protective layers on top of the tunnel (especially when back fill material is heavier than original soil).
- Ballast exchange and finishing works (asphalt, side-walks, M&E etc).
- Sedimentation on the tunnel roof (with time).
- Live loads (cars, trains, etc).
- Accidental loads (sunken ships, flooding of the tunnel, seismic event etc.)

Global settlement is important to understand as the final road or railway alignment will depend on this. Tunnel elements are installed at an elevation that considers an allowance for settlement such that after completion of the foundation works and all backfilling, they will be expected to be located within a limited tolerance (e.g. 50 mm) laterally and vertically from their theoretical location.

Like many structures, immersed tunnels can tolerate large uniform settlements under relatively uniform support and load conditions. However, in case of variation in support or when load conditions vary substantially over a short distance, careful consideration of the settlement behaviour is needed.

Variation in support conditions can be initiated by a variation in the original subsoil, by a variation in the man-made foundation properties (often construction related) or by a variation in foundation type (e.g. between the immersed tunnel and the connecting cut & cover tunnels). Significant variation in load conditions can involve a variation in surcharge (e.g. increasing ground loads on top of the tunnel close to banks) or accidental loads like sunken ships.

It is not always easy to decide what the actual variation in the support conditions is, since the tunnel structure will level out this effect which results in the development of internal forces within the tunnel structure. To limit this effect many tunnels are accommodated with segment joints that allow some movement (rotation) in the joint, but no differential settlement since most segment joints have shear keys to avoid any differential vertical and horizontal movement over the joint. Joint openings may be an indication of a variation in support condition.

Differential settlements between tunnel elements may arise due to non-uniform soil conditions and execution tolerances of the dredging and foundation layers. These differential settlements develop in the early stage, before the shear keys in the immersion joints are constructed. After the shear keys in the immersion joints are constructed the elements are coupled and cannot develop any more differential settlement. Differential support conditions causing differential settlements from this point on result in forces within the shear keys.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

In the preliminary design stages it should be assessed whether a particular foundation solution is needed e.g. for seismic criteria or tolerance criteria. If not the choice can be left to the contractor and their designer to develop a solution according to performance criteria.

Important issues for foundation design:

- Selection of foundation (sand flow, gravel bed, piles) including general design criteria e.g. settlement criteria.
  - Depending on the purpose of the tunnel (road, rail) different settlement criteria may apply.
  - Accidental load cases such as earthquake may be critical to the selection of the foundation method or treatment of deep soil layers (also see Annex 12: Compaction Grouting).
- Selection of construction equipment:
  - Specific equipment used for the gravel bed installation may have an effect on the tolerances and therefore may have an effect on the design support conditions (including the variation)
  - Different dredging equipment will have different dredging tolerances, that may have an effect on the design support conditions (including the variation).
- Limitations on potential construction close to the installed tunnel:
  - Equipment / construction activities causing vibration and potential compaction

(settlements) of the sand flow layer (e.g. the extraction of piles or sheet piles).

- Soil treatment:
  - In case soil treatment is considered as a design measure to improve the uniformity of the soil (support conditions) or to limit the general settlement development, it is important to decide if the treatment should take place before or after trench dredging. When treatment takes place after trench dredging account should be made in the design for the impact that the actual execution of the treatment works can have on the quality of the bed.
- Staging of the foundation related works:
  - In case trench dredging has to be carried out in stages (e.g. due to navigational restrictions or seasonal restrictions), this may have an effect on the ground behaviour (especially when cohesive layers are involved) and therefore the support conditions for the tunnel.

Important issues for the execution of the foundation work

- General
  - Navigational restrictions in relation to the execution of the tunnel foundation related works (e.g. sand flow or gravel bed installation) should be well communicated with the Authorities in charge (e.g. Port Authorities).
- Sand flow foundation
  - Clean trench from sedimentation and siltation immediate before immersion
  - Monitoring of development of siltation in the trench. This may be important for the selection of the side slopes. Steeper slopes may collect more sedimentation whereas less steep slopes may induce a self-cleaning effect.
- Gravel bed foundation
  - Placement of berms just before immersion
  - Depending on the expected sedimentation / siltation the clearances between the individual berms need to be decided on.
- Soil treatment
  - If the soil treatment is installed after dredging, the trench should be checked for any materials remaining from the treatment works and cleaned when this may affect the quality of the tunnel foundation.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

General:

- In some projects the finishing works (2nd stage ballast concrete, road surfacing, barriers etc) is not permitted to start until 90% of the expected settlements have occurred. In this way the 2nd stage ballast concrete and the road surfacing can be constructed following the theoretical road and/or rail alignment.
- For many tunnels the structural connection (shear keys) between the individual tunnel elements in the immersion joint is not formed until after a significant part of the settlements have taken place. Constructing the connection at a late moment will reduce the forces acting on the shear keys, although generally design is based on an early connection. Therefore in most cases a specific requirement is not specified, unless the design is based on a late connection.

Minimum and maximum tolerances for the execution of the main works involved:

- Dredging tolerances, depending on the dredging equipment that is used, in the range of 15 to 50 cm. In case the allowable dredging tolerances are small, specific tender requirements may have to be defined (that may result in special or specific dredging equipment).
- Man-made foundation bed installation tolerances:
  - Sand flow thickness variation depends on the dredging tolerances (typically between 60-90 cm)
  - Gravel bed thickness variation depends on the dredging tolerances and the gravel bed installation equipment (tolerance level to the top of the gravel bed is typically in the range of 2-10cm).
  - Indicative acceptance criteria

  Sand flow
  · CPT values for sand flow layer to check compaction/density (CPT>6MPa)
  · Volumes of sand used in relation to the theoretical space to be filled
  · Bunds alongside the tunnel (approx. min. 1 m above the underside floor slab)

  Gravel bed
  · +/- 25 mm in case stiff sub soil conditions (in order to limit structural implications for the tunnel).

DOCUMENTATION (FORMAT, DEADLINES)

Settlement surveys generally start when the elements are placed and usually continue throughout the subsequent phases of construction until the tunnel is opened to traffic. With readings throughout construction the effects of the individual activities can be identified.

Settlement monitoring of tunnel elements should be carried out using the survey markers installed inside the elements. The frequency of measurements may depend on the typical development of settlements in combination with the predictions of the settlements associated with the various project stages.

In general terms levels are recorded more frequently (e.g. weekly) until completion of backfilling of the subsequent element to ensure no remedial action is required and with a lower frequency (e.g. monthly) thereafter until settlement becomes negligible. Since the majority of the settlements occur during the construction phase, settlement monitoring is not always continued in the operation phase. It should be noted that movements of the tunnel generally do not end at the completion of the construction works.

As part of a structural health monitoring program it is now more common for movements of the tunnel (settlements and joint movements) to be surveyed during the operation phase. It is important to have a clear handover of monitoring results from the construction phase (monitoring often carried out by contractor) to the operational phase. A good understanding of the total movements of the tunnel (vertically and horizontally) is very important to the Owner / Operator of the tunnel and can help to organize maintenance / repair based upon the readings and supported with back analyses and / or settlement predictions to keep the tunnel in shape and in operation throughout the full design life.

EXPECTED VALUES

Records from various tunnels (W. Grantz, TUST 16 2001 195-201 & 203-210) show that immersed tunnels have experienced and handled successfully settlements in a range of 2 to 20 cm. This range is obviously decided by specific load conditions and the foundation characteristics (man-made foundation and subsoil) and should be supported by settlement predictions in the design stage. Generally the settlement curves show a logarithmic development and should be supported by settlement predictions. A deviation from this may be a reason to check whether the tunnel has been subjected to unexpected overburden, irregularities in the foundation or irregularities/ deviations that took place during the execution of the works.

It should be noted that the immersion of tunnel elements generally results in an initial settlement of 1 to 3 cm, caused by a compaction of the man-made foundation. Gravel bed foundations are generally on the lower end of the bandwidth (1 cm) and sand foundations on the higher end (2-3cm). A significant deviation to these values may indicate the presence of sedimentation / siltation or other soft materials (dredging spillage) under the tunnel element that was not properly removed prior to immersion.

ANALYSIS (REQUIREMENTS, TIMESCALE…)

Settlement calculations

The basic geotechnical analyses for an immersed tunnel generally do not really differ from other tunnel structures:

- Bearing capacity of the foundation using conventional 2D calculation methods.
- Settlement calculation using conventional 2D calculation methods (e.g. Terzaghi) or 2D/3D FE analyses using software such as Plaxis, Flac etc. in which various construction stages can be incorporated.

Analyses should also be performed to estimate the longitudinal and transverse differential settlement within each tunnel element, between adjoining tunnel elements, and at the transitions at the ends of the immersed tunnel. Especially when relatively soft and cohesive ground layers with time dependent behaviour are involved more advanced FE analyses considering the construction staging should be undertaken.

Structural calculations

The settlement calculations can be used as input for the structural calculations. However, it should be noted that settlement calculations generally provide input in terms of an average bedding stiffness, but local variations in support and load conditions, that are often critical to the structure, are generally assessed separately. Various methods are available but generally an upper bound approach is applied which is based on experience rather than on a scientific basis. However, the uncertainties associated with immersed tunnel construction (dredging tolerances, sedimentation, foundation bed installation etc.) should be addressed properly. The justification for these upper bound approaches lies within the fact that detailed inspection of the foundation is complicated and repair of the foundation or the structure is complicated, expensive, time consuming and may put the tunnel out of operation for a significant amount of time.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

Settlement survey data should be documented and used to check against settlement criteria that were used for the design. These verifications should cover all construction stages and may have to extend during the operation phase.

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

In general terms immersed tunnels are robust structures designed to cover a significant bandwidth of potential load and support conditions. However, it cannot be excluded that unexpected settlement behaviour can result in local structural damage e.g. to shear keys. Depending on the form of shear keys this may not affect the structural integrity of the tunnel or result in leakage. This would be the case for shear keys located in internal walls of the tunnel. However if a spigot/socket arrangement in the walls and slabs that form the perimeter of the tunnel is used, damage and leakage of the main structure could occur. This may, at least on the long term, affect the operation (availability) of the tunnel. Remedial measures/actions are generally tailor made and depend on project specific conditions.

LINKS TO OTHER OWNERS GUIDE THEMES

Annex 06: Immersion Joints
Annex 05: Segment Joints
Annex 12: Compaction grouting
Annex 17: Exceptional load cases
Annex 36: Tolerances

PERFORMED BY / RESPONSIBLE

The suggested responsibilities with regard to the foundation and settlements are:

- Design and detailing: Designer.
- Specification of construction tolerances (where relevant to the design): Designer.
- Specification of construction requirements (where relevant to the environment): Owner (e.g. spillage or turbulence requirements for dredging operations).
- Settlement monitoring during construction: Contractor, verification survey by Owner.
- Settlement monitoring and joint movements during operation phase (combined with inspection): Owner.
- Repair or preventive measures during construction: Contractor.
- Repair or preventive measures during Operation: Owner / Contractor.

Annex 29 >> Backfill

After placing a tunnel element on its foundation within a dredged trench, the trench around the tunnel must be backfilled and (usually) provided with a protective layer. This annex deals with these aspects.

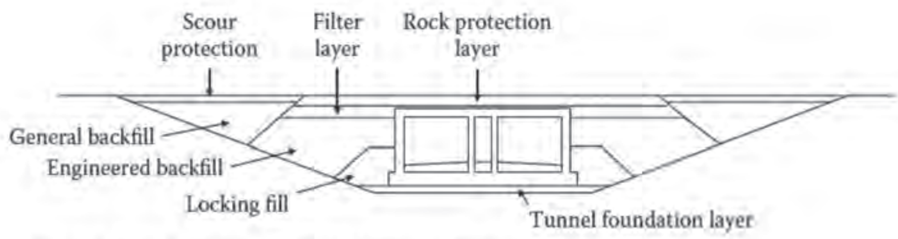


Figure 1 : Typical arrangement for backfill (ref : Immersed Tunnels, Lunniss/Baber 2013).

WHAT

The backfill usually consist of the following:

- Locking fill to secure the elements laterally in temporary conditions during construction.
- General and engineered backfill to the sides of the tunnel structure, providing permanent fixation of the tunnel elements. In some circumstances fill may be provided above the tunnel e.g. for providing an impact-absorbing / load-spreading layer above the tunnel.
- A protection layer above and adjacent to the tunnel to provide scour and impact protection. This layer normally consists of rock and is therefore often called "rock protection layer".
- Rock-fill anchor-release bands at both sides of the tunnel are sometimes provided as part of the rock protection layer.

Locking Fill

Locking fill is placed in the trench after a tunnel element is placed and the joint to the adjacent tunnel has been dewatered. The purpose of the locking fill is to secure the tunnel element in its lateral position in the short-term period before the final fixation and backfill is installed.

Locking backfill is placed in layers of uniform thickness, such that the effects of lateral and vertical forces on the tunnel element are minimized and no displacement of the element occurs due to the installation procedure. Placement of locking backfill proceeds from the primary (jointed) end of tunnel elements and progresses towards the secondary end of tunnel elements in a manner that produces a dense backfill bearing tightly against the tunnel periphery.

General and engineered backfill

General backfill should be used to fill the remainder of the trench above the selected locking fill up to the underside of any protection layer, or to the pre-existing seabed level if no protection layer is used. The general backfill ensures the permanent fixation of the tunnel horizontally and, in case the tunnel is constructed with a toe, also provides weight for the vertical stability. Close to the tunnel the backfill will have selected engineering properties and hence is sometimes known as Engineered backfill. This will typically be granular material to ensure good compaction and support of the rock layer. Further from the tunnel it may be possible to use non-engineered materials.

Light backfill material can be used to avoid or minimize settlements in case of relatively soft ground layers below the tunnel base.

Filter Layer

With various layers of different material around and above the tunnel, it is important to ensure that each layer stays in place and is not susceptible to the migration of material through adjacent layers. Normal Terzaghi filter criteria are used to establish compatibility between the various layers. Phase differences in tidal zones may also need to be considered.

Protection layer

The purpose of the protection layer is to protect the tunnel structure from the impact of falling or dragging anchors, sunken or grounded ship loads. Design of the protective layer addresses impact loads and hydraulic stability of the individual stones. Protection must remain in place when subjected to currents and waves and/or ship propeller effects.

The protection layer is placed on top of the backfill. It normally extends some 15 m each side of the tunnel so that it can deform into the depression made by any scour and maintain its protection to the tunnel backfill. The size of the rock depends on the stone weight required to prevent it from being washed away by the currents in the waterway. For a typical waterway with only small navigation, a 750 mm thick layer with D50 of typically 150 mm single sized stones should be sufficient, and for a larger waterway, a 1.5–2.0 m thick layer of stone with D50 of 500 mm is typical, but calculation will always be needed to verify this.

The elevation of the top of the protection layer should approximate pre-existing seabed levels unless instructed otherwise. However in certain

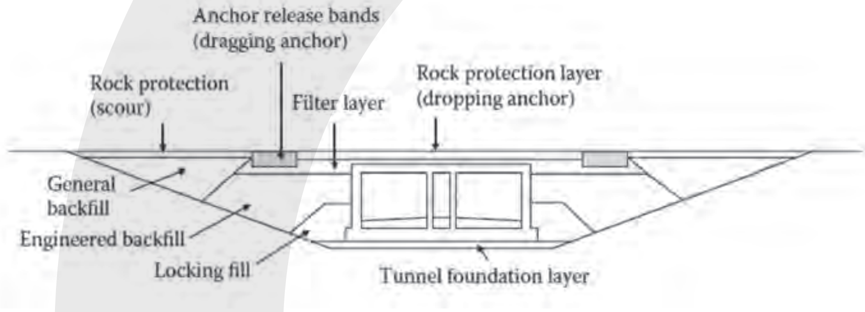


Figure 2 : Typical arrangement of anchor realease bands (ref : Immersed Tunnels, Lunniss/Baber 2013).

situations, the top of the tunnel can extend above the original seabed in an underwater embankment if permitted. In this situation, the protective blanket shall be provided above the embankment backfill.

It is also an option to construct the protection layer out of concrete. This is mostly applicable in locations where there is limited water depth. In case a concrete protection layer is chosen it must be carefully considered how this impacts the design, construction and transportation of the tunnel elements.

Anchor Release Protection

In navigable waters, anchor release protection should be provided, if required, and if the tunnel cover extends above the bed. Rock armour for anchor release bands should be of sound, dense, rock in clean angular pieces and well graded. The intent of the anchor release protection is to bring the anchor to the surface and choke the gape (the space between the hook and the shank) such that the anchor will release. The size of the anchor considered should be appropriate to the vessels plying those waters. The material needs to be durable for at least the design life of the tunnel.

Another option is to extend the rock protection on both sides of the tunnel for at least 15 m and under an inclination of approx. 1:2. See Figure 3.

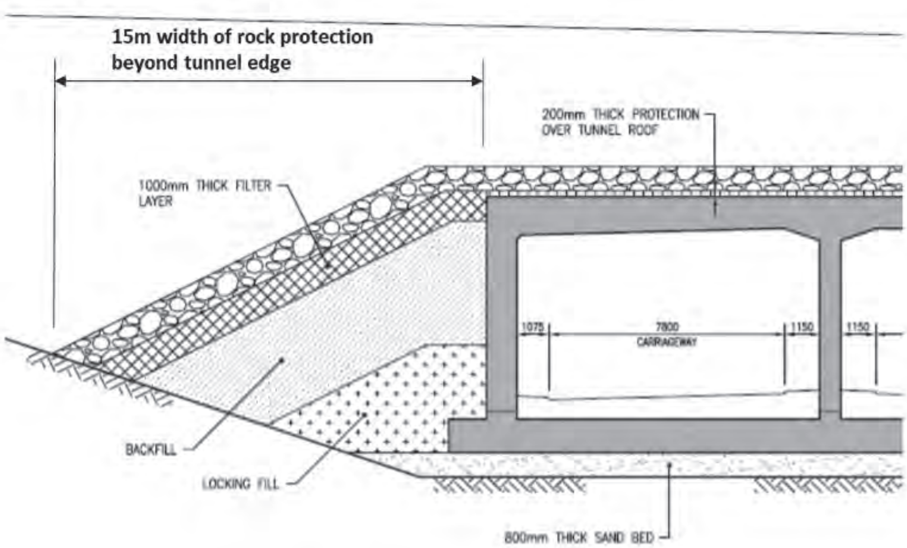


Figure 3 : Inclined side rock protection arrangement.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Important issues associated with backfill works are:

- The works are carried using marine equipment that may interfere with the port operations (if any). In those cases close consultation in an early stage with the responsible port authorities and other stakeholders is essential;
- Prior to and during the placing of fill, the trench should be checked for sediment. Sediment that is detrimental to the performance of the material being placed should be removed.
- All underwater filling and rock protection material should be placed in a way that avoids damage to the waterproofing membranes (if present) or to the structure from impact or abrasion.
- The material should be placed in even layers on either side of the tunnel to avoid unequal horizontal pressures on the structures, and should be placed by means of buckets or tremie pipe (limitation of difference in level between both sides of the tunnel, is typically in the order of 1m).

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

Locking fill

- Commonly the locking fill is placed to a level of approximately half the height of each element to ensure proper resistance towards wave action and currents.
- Locking fill should usually extend at least 2 m horizontally from the tunnel element before being allowed to slope down. It is recommended the slope is no steeper than 1:2.
- Locking fill should be placed in layers of uniform thickness typically not exceeding 0.6m.
- The locking fill should be a granular, clean, sound, hard, durable material that will compact naturally and that will remain stable under both non-seismic and seismic conditions (where required). It may include crushed sound rock or gravel. Well graded sub-angular sand may be included. Sand fill, if used, should be free-draining.

General and engineered backfill

- Backfill should be placed by a method that avoids segregation or misplacement of the fill. The properties of backfill must suit the proposed design and method of placing.
- The selection of the backfill material must ensure the tunnel is stable during seismic events (earthquake or tsunami) if applicable at the location of the tunnel.
- Engineered backfill is usually granular material that enables good compaction on placing and limits subsequent settlement within the fill layer and settlement of the rock protection layer.
- General backfill may comprise soft non-cohesive material that will remain stable. However, there are usually additional restrictions imposed by the river or environmental authorities. There may be a requirement that the backfill is non-cohesive as the loss of fine material during the placing of cohesive material would be unacceptable in the watercourse. Often the dredged materials for the trench are suitable as general backfill.

Rock protection layer

- Rock protection material should consist of hard inert material, usually sound, dense, newly quarried rock in clean angular pieces, and be well graded typically between 25 mm and 250 mm. The material should be durable for at least the design life of the tunnel.
- The method of placing this material must ensure that the large-size stones do not penetrate the general backfill and must cause no damage to water proofing of the tunnel (if used).
- It is recommended that the protection layer is not placed by bottom dumping, unless measures are taken to avoid damage on the tunnel structure.

DOCUMENTATION (FORMAT, DEADLINES)

Materials:

- Specification and testing (if relevant) of the various materials in terms of strength and grain/size distribution / rock sizes.

Installation works

- Inspection of the trench before placement.
- Multibeam survey after various stages of installation.
- Bathometric survey after construction.

EXPECTED VALUES

The accuracy of placement and construction tolerances are generally as per typical marine works and dredging works activities (also depend on the water depth, wave climate and the marine equipment that is used).

ANALYSIS (REQUIREMENTS, TIMESCALE…)

All fill materials subject to waves and currents should be designed to prevent scour and erosion. In this respect the temporary condition during construction may also be considered if the tunnel is to be left partially backfilled for any significant length of time. The design should take into account the suitability of excavated material for use as backfill.

The analyses with respect to backfill design involves:

- In seismic areas where there is a risk of liquefaction, the foundation and backfill should be designed as free-draining to prevent the development of excess pore-water pressure during and following a seismic event.

The analyses with respect to the protective layer design involve:

- Rock protection on top of the tunnel, if needed, should be provided to prevent long-term loss of backfill at the sides and on top of the tunnel.
- Design rock protection (grading) and or mattress in relation to:
  - · Propeller action
  - · Wave and current action
  - · Anchor penetration
  - · Dragging anchor dislodgement

The design should ensure that backfill placed next to the immersed tunnel is placed uniformly on both sides of the structure to avoid imbalanced lateral loads on the structure. The maximum difference in backfill level outside such structures above the locking fill should typically be 1m until the lower side has been filled to its final level. Elements with more than 1m difference in backfill level should be designed to accommodate the resulting transverse loads.

The rock protection layer over the tunnel should be designed to dislodge the dragging anchors and prevent them impacting on the tunnel, so it is normal practice not to apply any horizontal loading resulting from this to the tunnel.

Impacts from sinking vessels or vessels that are off course from the navigation channel may need to be considered in design, depending on the tunnel location and the nature of shipping. This may influence the earthworks solution around the tunnel if protective berms are required or increased depth of backfill and protection works are needed to absorb and spread the impact load from the ship such that the tunnel is not damaged.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

The accuracy of placement and construction tolerances are generally as per general marine works and dredging works (also depend on the water depth, wave climate and the marine equipment that is used).

For the placement of the tunnel protection layers or tunnel protection works the tolerances should be considered in respect to navigational requirements.

It is common for minimum fill layer thicknesses to be specified to ensure the correct performance of the rock and filter layers.

Typically a +0mm tolerance may be specified to the top surface of rock protection to prevent infringement of navigation channel clearances profiles, and the -tolerance is typically specified according to construction accuracy achievable.

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

Check / inspection and (potential) repair of rock protection in case of:

- Anchors have touched the rock protection.
- Exceptional propeller loads.
- Ship impact.
- Extreme wave and current events.

LINKS TO OTHER OWNERS GUIDE THEMES

Annex 35: Navigation safety.
Annex 28: Foundations and Settlement.
Annex 36: Tolerances.

PERFORMED BY / RESPONSIBLE

The suggested responsibilities with regard to back fill and protective layers are:

- Design and detailing and relation with tunnel structure: Designer.
- Specification of construction tolerances (where relevant to the design): Designer.
- Specification of construction requirements (where relevant to the environment): Owner (e.g. placement of the backfill and protective layers).
- Repair during construction: Contractor.
- Repair during Operation: Owner / Contractor.

Annex 30 >> Immersion Joint Seals

Immersion joints require a seal or gasket (the terms are used interchangeably) around the perimeter of the tunnel element joint in order to make the joint fluid-tight. When a new tunnel element is moved up against the end face of a previously placed element, the gasket traps water in a chamber formed within the perimeter of the gasket and between the now adjacent end bulkheads of the two tunnel elements. As this trapped water is gradually removed from within this sealed chamber, the water pressure is hence removed; and the out-of-balance water pressure acting on the new element forces the gasket to be compressed and take up the lost load, rather like a giant hydraulic jack.

To start this process, the chamber needs to have an initial seal. The construction tolerances inherent in the gasket itself and the face against which it rests usually requires some initial compression of the gasket that is provided externally, usually in the form of some kind of pulling jack. In order to keep this initial force low, a soft nose on the gasket or a soft flap seal is usually used.

A secondary replaceable seal is always installed within the primary seal as a backup in case of leakage. For tunnels that are to be made continuous, the secondary seal might be welded steel plate and reinforced concrete. For tunnels where the joints are to remain flexible, the secondary seal is typically an "omega" shaped seal that is installed after the immersion joint is dewatered.

WHAT

The primary seal, i.e. the first barrier to water ingress, is typically a Gina-type profile or, on older tunnels in the USA, has sometimes been a pair of seals. Tremie concrete joints are essentially no longer used on new tunnels.

The primary purpose of the Gina-type gasket is to enable the immersion joint to be dewatered and the joint to be completed in the dry from within. For most tunnels, the gasket is considered to be primary and must therefore last the life of the structure. Alternatively, it can be considered secondary (temporary) and the primary seal then constructed from within after dewatering the joint, but this approach is not common.

Figure 1 illustrates a Gina-type and omega combination, where the omega is the secondary seal. The upper figure shows the situation just before the Gina-type soft nose touches the bearing plate; no omega is present. The lower figure shows the completed joint with the Gina-type carrying the load and the omega installed.

Figure 2 illustrates the double initial seal arrangement which was typical in the USA. If this joint is to be made rigid, a steel plate welded across the joint would be typical rather than the omega backup seal shown.

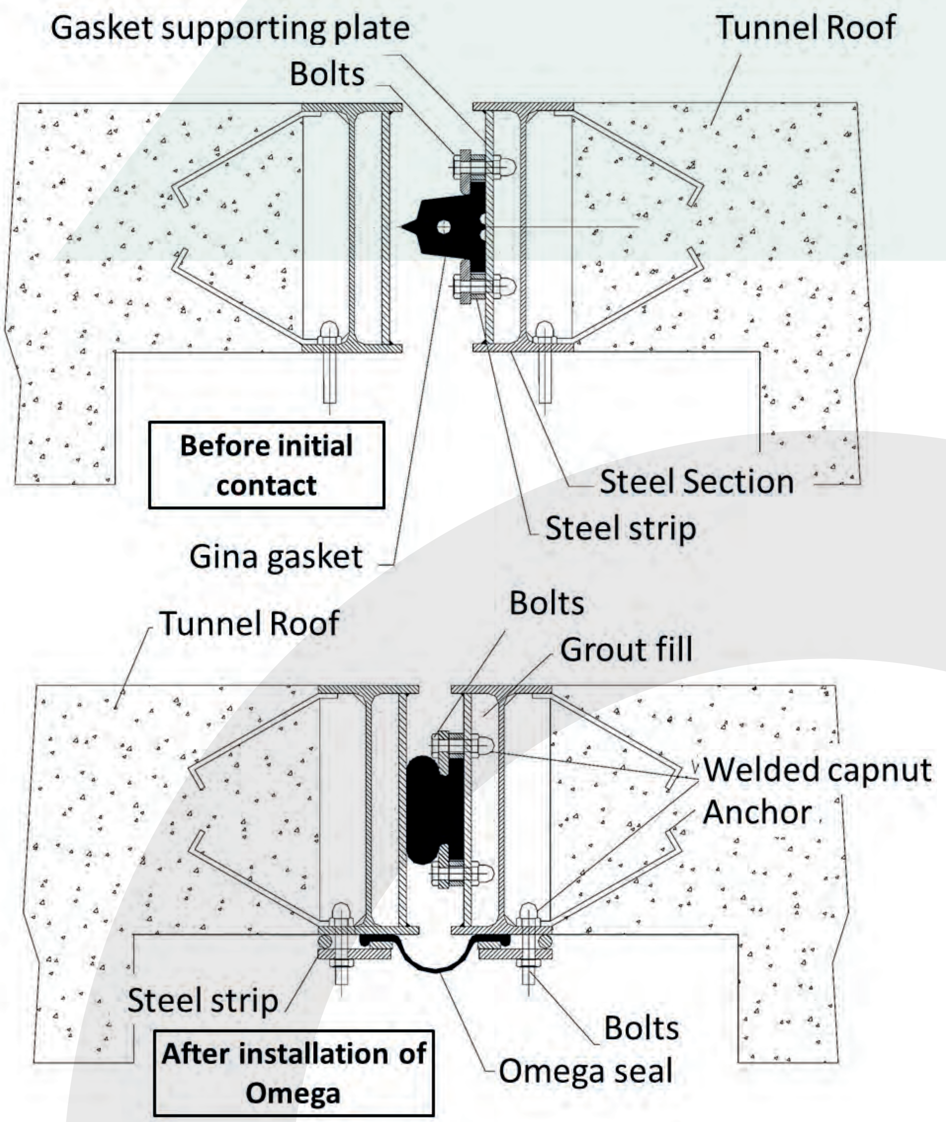


Figure 1 Flexible joint: Gina-type and omega combination.

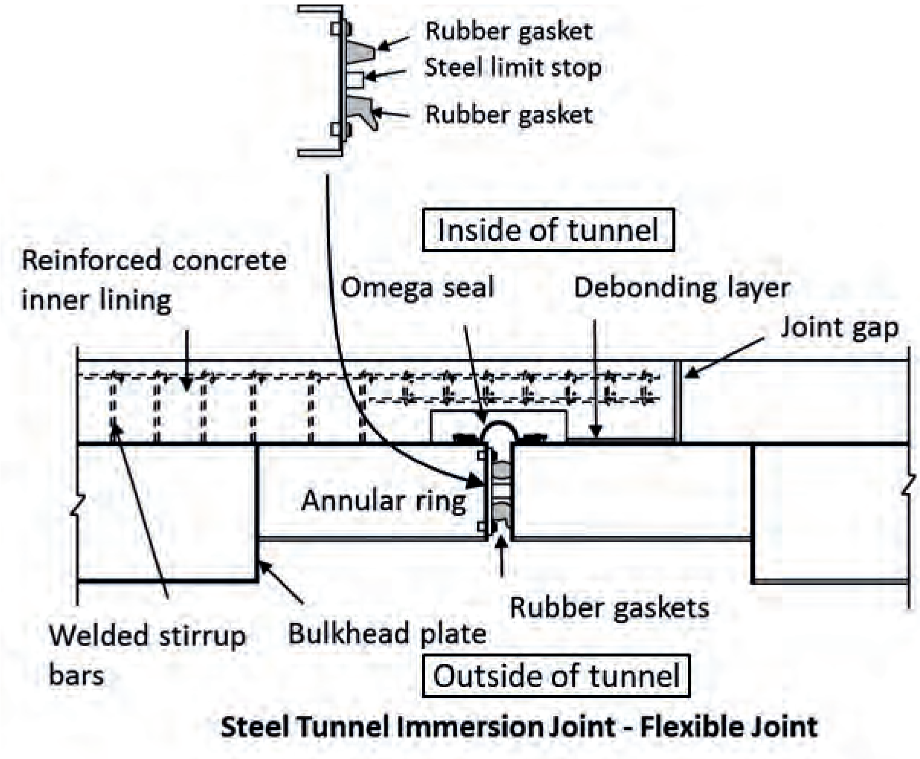


Figure 2 Rigid joint: Double gasket and omega combination.

Any shape or combination of seals should be acceptable, provided the performance requirements are met. The critical design conditions of the Gina-type gasket are usually the maximum compression capacity and the ability to remain watertight under minimum compression, taking into account all potential movements and changes in seal material characteristics over the life of the tunnel.

Gina-type gaskets

“Gina” is the proprietary name for the flexible gasket shape used for immersed tunnel immersion joints as manufactured by one supplier; however, it has become the name used for similar shapes made by other manufacturers, of whom few exist.

The supplier of the Gina-type gasket has to show by calculations using (a) measured force-compression curves and (b) force-water pressure to cause leakage curves, both obtained using a sample of the seal, that the selected Gina-type gasket satisfies the following conditions within agreed safety limits:

1. Transfer of the hydrostatic loads at high water level within the maximum compression capacity of the Gina-type gasket;
2. Sealing at all water levels for all joints, including the effect of gap variations due to smoothness of tunnel faces, non-parallel faces (construction tolerance), rotation of immersed tunnel element (settlement, etc.), creep and shrinkage of the concrete material and temperature effects;
3. Calculation of the restoring moments to re-align by misalignment of a tunnel during element placement;
4. Calculation of the proper functioning of the Gina-type gasket after re-alignment with respect to prevention of leakage at the gap opening side and prevention of overload at the gap closing side;
5. Above mentioned sealing properties should incorporate the effect of relaxation on the rubber material of the seal over the tunnel life time period;
6. The Gina flange construction, i.e. the retaining method of the Gina-type gasket, should be able to withstand additional loads without dislocation, and loads that arise from shear of the compressed Gina-type gasket in case of differential tunnel settlement.

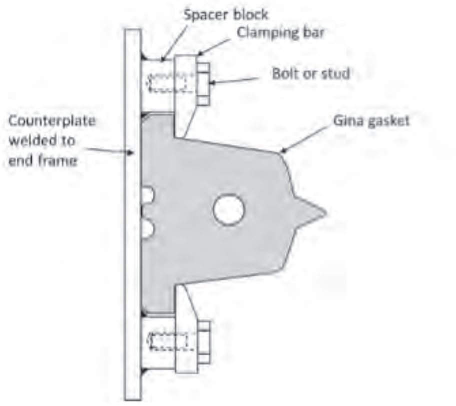


Figure 3. Typical Gina gasket.

Omega seals

Because the Gina-type seal is compressed between the ends of adjacent elements, it is not replaceable in the event that it starts to leak. The omega shaped seal was originally designed as a secondary and replaceable seal for immersed tunnel immersion joints where the primary seal between elements was a Gina-type seal. The omega seal is installed across the joint from the inside after the joint is dewatered. It is necessary for the Omega seal to be mounted against smooth surfaces.

The omega seal is able to withstand high water pressure in combination with large movements in all directions. The omega seal provides an ideal water proofing solution for joints where large gap movements can be expected as a result of creep, shrinkage, temperature, settlement and seismic effects.

Annex 30 >> Immersion Joint Seals

The preferred system for retaining an omega seal is one in which the flange is clamped while the bolt fastens the steel parts (Figure 4). This system of fastening the omega seal provides optimum safety and prevention of leakage. The seal installation is also easier. Special corner fastening pieces are required in order to prevent leakage at the corners of seals.

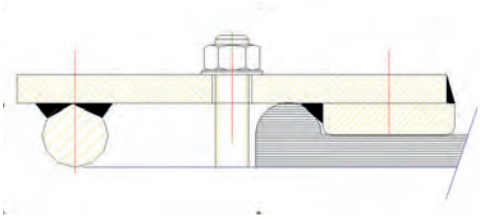


Figure 4: Conventional omega clamping system with bolts outside the flange of the seal.

Experience has shown that the bolts, fasteners and faces beneath the seal are particularly prone to corrosion; provision for ensuring the design life of these parts is essential. Similar corrosion can occur for the Gina-type gasket attachment system, but since the seal is in compression, lateral displacement of that seal is unlikely after the joint has been dewatered.

The pressure differential across the omega seal wall results in tension forces within the wall of the seal itself. The magnitude of these forces depends upon the seal shape and dimensions. The forces in the wall of the seal are transferred into the clamping system. These forces are restrained by a combination of clamping force due to the bolts and friction under the clamping strip. The initial clamping force will relax over time. The relaxation of the SBR flange is typically 5% to 6% per decade, which results in a considerable loss of force over time; this should be considered in the design of the required initial clamping force and the bolt tension required.

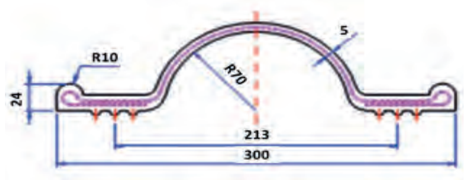


Figure 5: Conventional omega clamping system with bolts outside the flange of the seal.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

The concept of joint flexibility or continuity should be determined at outline design stage according to ground conditions and expected loads and joint movements. The details of the joint will follow from this concept.

The decision can be left to the design-build contractor unless the Owner has particular concerns over one solution, for example behaviour under seismic load, the expected settlement profile or loading that may result from a particular solution.

Specifications should be developed in the tender documents to document all Owner requirements in terms of performance, redundancy in design, factors of safety, selection of materials and testing.

Choice of seal types can be made at detailed design to comply with the project specifications

Production tests should accompany each gasket type and size.

Following the installation of tunnel elements, the actual compression of Gina-type gaskets compared to design values should be compared, since this will affect final tunnel geometry and the length of the closure joint.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY ...)

Gina gasket

Where the Gina-type gasket forms the primary seal, the supplier should show by material tests that the expected material life of the gasket exceeds the tunnel design life and that the system is functioning correctly even at the end of this period, taking the effect of relaxation on the sealing properties into account.

The Gina seal is manufactured from a blend of styrene butadiene rubber and natural rubber. The blend combines excellent mechanical properties with low water absorption and good resistance against chemical and bacteriological attack. The selected material for a Gina-type seal should match the design life of the tunnel. Low values for relaxation, i.e. decrease in reaction force at fixed deformation, are beneficial to the long-term behaviour of the sealing system.

The supplier should have a Quality System that is certified for engineering and manufacturing of technical elastomeric products relevant to the gaskets according to standard ISO 9001and 14001.

The supplier should provide storage instructions in accordance with international standard ISO 2230. During storage it is important to prevent damage such as ozone cracking. During transport and unpacking, damage should also be avoided. Transport procedures should also be based on an ISO specification.

Installation procedures with guidelines for proper installation should be provided by the supplier. The gasket attachment system onto the tunnel elements should be approved by the supplier. A special hoisting beam is usually required to hoist the Gina gasket, which should be connected to the hoisting beam by a large number of nylon slings. Sometimes extra protection caps are required to prevent damage to soft nose sections. The hoisting operation should be executed very carefully to prevent local damage and overloading due to weight.

Technical information needed from the Buyer should at least contain following information:

- number of joints.
- cross section size of gasket support frames and the proposed attachment method.
- proposed corrosion protection to gasket bearing surfaces and attachment system. If surfaces are coated, include the coefficient of friction.
- lengths of tunnel elements.
- water depth at each joint.
- tide variations.
- specific weight of water.
- all movements and gap variations of the joint in axial and transverse directions.
- specific conditions for installation.
- expected seismic movements.

Omega seals

Based on current literature, the expected design life of an omega seal is at least 100 years. The operating temperature should be within –30° C and +70° C. The seal should not come into contact with chemicals such as hydrocarbons.

Using the suppliers force-compression curves and elongation limits at various water pressures, the omega seal should be selected to satisfy at least the following conditions within agreed safety limits:

1. the Omega seal should withstand the water pressure and accommodate the expected gap movements in three dimensions.

2. the clamping system should be capable of holding the omega flange in position and sealing against the water pressure whilst at the same time allowing for all gap movements and the relaxation effect of the rubber flange over the expected tunnel design life.

Manufacturers can provide graphs that show the allowable movements of the omega seal for various water depths and pressures. The maximum water pressure usually includes a safety factor of 2.5 on the breaking strength of the Omega wall construction.

General

Manufacturers of Gina-type and omega seals have standard ranges of straight and corner moulds in a number of sizes. For economic solutions and shorter delivery times, selection should be made from the standard range of seals, which should accommodate most required performance specifications. Manufacturers may make non-standard sizes and shapes to order, but testing etc. may extend delivery times significantly.

Some seals, especially omega seals, may require on-site assembly by vulcanising.

The designer and supplier should jointly develop the specifications for the materials and surface tolerances of the mounting surfaces for seals. Maximum permissible steps and deviations from a true flat surface should be specified.

Testing procedures to verify correct installation of seals should be set out by the designer. For example a watertightness test is required for omega seals, either by pressurised air or water testing, usually conducted over a 24 hour period.

Redundancy in design should be specified, for example a reserve compression capacity of 10mm is recommended for Gina-type gaskets.

DOCUMENTATION (FORMAT, DEADLINES)

Method statements are required for:

- Seal production
- Transportation of seals to site
- Installation
- Final vulcanisation
- Post installation testing for compliance

Records to be held in maintenance manual:

- Production test records
- Materials test records
- Material data sheets
- Installation records
- ITP records from on-site installation and vulcanisation activities
- Record of installed joint gap and variation experienced through construction
- Non-conformances and repairs

EXPECTED VALUES

The expected compression of gaskets should be obtained from the design process.

Materials ageing tests should demonstrate a design life equal to or exceeding that of the structure if seals are intended to provide watertightness throughout the design life.

ANALYSIS (REQUIREMENTS, TIMESCALE…)

Factor of safety (FoS) for watertightness should be checked in the design. Clear definition of the FoS is needed to ensure that it applies at the end of the design life after creep relaxation in the rubber materials has occurred.

FoS calculations should be based on data from supplier watertightness tests.

During production, each seal should be carefully checked for the following:

- Rubber properties.
- Reinforcement properties.
- Visual inspection.
- Dimensions.

Accelerated ageing tests of the materials should be carried out by the supplier to demonstrate design life, considering exposure to likely environments.

Chemical resistance tests should be carried out by the supplier to demonstrate resistance to harmful substances such as hydrocarbons or acids that could accidentally be spilled onto the seals during the construction process.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

Force compression curves for Gina gaskets from suppliers typically have an accuracy of +/-10% which must be taken into account in design.

Typical surface deviations for mounting surfaces are:

- No steps
- Maximum angular deviation
- Planar deviation +/-5mm

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

Production defects should be identified by the supplier and products should be rejected.

Steps or deviations in the mounting surfaces for the seals can be corrected by grinding and repainting of the supporting structure (usually steel). Building up of paint thickness on steelwork to correct deviations should be avoided unless it is within the paint manufacturers recommendations for thickness.

Watertightness tests for omega seals may require re-fixing the seal or tightening the clamping bolts if the test fails.

Misalignment of joint faces may require remedial measures, such as accelerating settlement of one element relative to the next. This can cause a shear deformation of the gaskets. Any impact on the sealing behaviour of the gaskets should be checked with the supplier.

Damage to gaskets should be referred to suppliers for recommendations on remedial action.

LINKS TO OTHER OWNERS GUIDE THEMES

Annex 06: Immersion Joints.
Annex 32: Durability.

PERFORMED BY / RESPONSIBLE

Performance requirements – Owner or designer.
Specifications and design – Designer with support from supplier.
Selection of products – Contractor/designer.
Production testing – Supplier.
Installation testing – Contractor/supplier.
As-built record - Contractor.

Annex 31 >> Immersion & Buoyancy

Construction of an immersed tunnel differs from other tunnel projects in that there are several very distinct phases. The elements are prefabricated in a dry location, floated and transported to their final location, immersed against a terminal structure or adjacent element, and ballasted to ensure negative buoyancy and stability. Understanding and controlling the buoyancy of the tunnel elements is fundamental to the construction method of an immersed tunnel. This Annex describes the issues regarding buoyancy control and the immersion operation during the marine operations.

WHAT

Buoyancy is the uplift on a submerged object due to the weight of water displaced by the object (Archimedes principle). Insufficient buoyancy causes an object to sink instead of floating. Buoyancy control is carried out through all phases of a tunnel project. Planning of the immersion operation itself must start early in the design phase so that necessary equipment, space and facilities can be designed and included during construction.

The majority of immersed tunnel projects feature tunnel elements that have a positive buoyancy (floats) when considering just the main structure. In this instance the act of placing ballast in the element changes the balance to negative buoyancy (sinks). Some smaller utility tunnels have been constructed with natural negative buoyancy and have been transported and placed using floating cranes rather than relying on any natural buoyancy characteristics.

Since in most cases the element must be capable of floating, weight control of the tunnel elements during construction is crucial. Similarly, after immersion, enough weight must be present to prevent floating. Critical parameters to be considered in the buoyancy control include:

- density of concrete used,
- weights of equipment to handle and control elements while they are afloat and during immersion,
- how temporary ballast will be provided for immersion,
- how permanent ballast will be provided and the method of ballast exchange,
- the minimum likely surface water density at any time an element might be floating,
- the maximum water density in the tunnel trench at any time of the year prior to backfilling, including suspended solids present in the water,
- the magnitude of any likely forces that could be imposed on a tunnel element placed in the trench such as propeller wash, wave effects and current,
- Likely wind, wave and current conditions at any temporary mooring locations, during towing and during immersion.

Monitoring of ambient conditions at all activity locations once construction has begun is essential. Predictive models are utilised, particularly for more extreme and offshore conditions, to determine when acceptable conditions for marine operations might occur.

The following discussion is based on elements constructed with a facility that must be flooded to float the elements out. Other methods of construction exist, to which similar methodology can be applied. The typical activities with respect to buoyancy and immersion of the elements are as follows:

Preparation, float up and parking of a tunnel element in the construction dock.

When a fabrication facility is flooded, it is usual that ballast tanks within the tunnel elements are filled with sufficient water to overcome buoyancy and hold the elements on the bottom of the construction dock, thus avoiding accidental damage.

It is recommended that tunnel elements be floated up one by one in a controlled manner to avoid damage. Before float-up a safety factor against flotation is used to determine the minimum required amount of ballast in the tunnel element. Temporary water ballast in temporary internal tanks is usually used, but other forms of ballast, inside or out, can be used. During float-up, the element should be controlled horizontally by winch wires and a de-ballasting method used to ensure minimum movement during float up, usually by floating one end up first.

Figure 1: Controlled sequence of Float up.

Figure 2: Inundation of the construction dock.

After float up, the element can be hauled by winch wires or tug boats to a temporary parking location where the tunnel element is moored and can be outfitted for transport and/or immersion. For transport, bollards, pushing and pulling points are installed on the element. For immersion additional equipment is installed on the element including lifting points, survey equipment, access shafts and various guidance devices (Refer to Annex 16).

Transport of a floating tunnel element

After float up, the weight analysis of the tunnel element is checked with as-built data and a ballast calculation is made for the transport phase to achieve the chosen freeboard and to meet stability requirements. Where waves can occur that could result in water flowing onto or over the top of the element, sufficient buoyancy and stability is required for the water to run off and for the tunnel to remain right-side-up. At this time checks should also be made to verify the element's weight against the theoretical for the purpose of determining the final ballast necessary to achieve the prescribed safety factor against flotation.

Ballasting and immersion of a tunnel element

A tunnel element can be outfitted for immersion while floating and at the same time, the ballasting plan for immersion can be finalised based on the most recent as-built data and the expected environmental conditions, such as tides and water density. Density is one of the most important parameters at this stage as it can vary with depth, temperature, salinity and suspended solids. Disturbance of very soft silt at bed level during immersion will increase water density and the ability to add more ballast during immersion can be an advantage.
For immersion to commence sufficient temporary ballast to overcome the positive buoyancy must be provided, either in tanks inside or, for example, blocks placed outside on the roof. Usually a pre-determined overweight is achieved to ensure the element remains negatively buoyant during all processes and for minor variations in conditions.

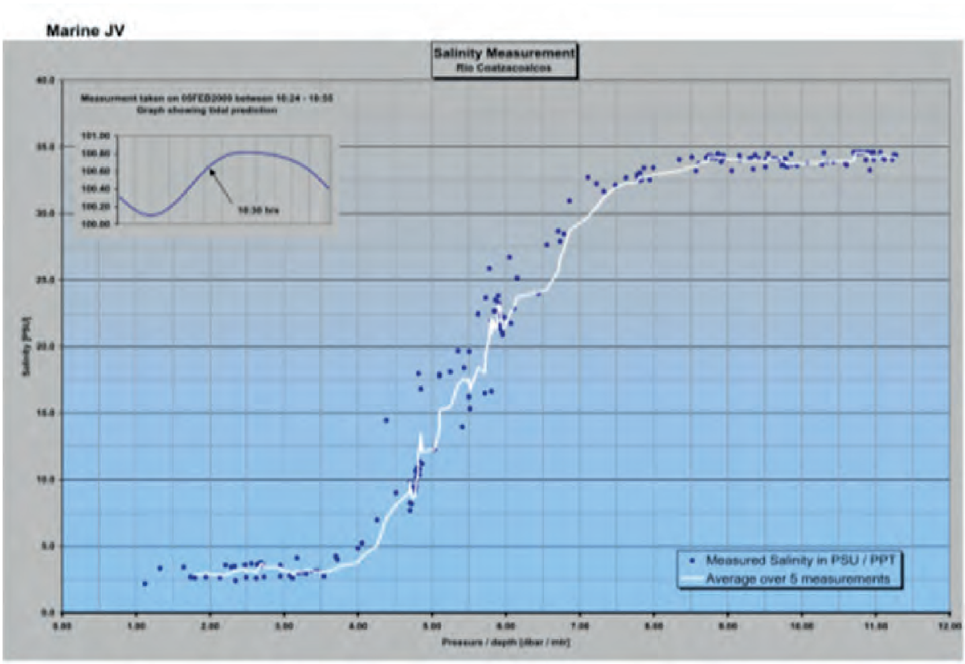


Figure 3: Typical salinity profile over the water depth of the trench.

Figure 4: Tunnel element moored after transport at temporary parking location, near immersion location.

Figure 5: Immersion configuration of equipment.

Horizontal positioning

An immersion operation will start by manoeuvring the tunnel element into position on its alignment above the dredged trench and clear of the structure to which it will be joined. From there, the actual immersion process can start.

Ballasting

During the immersion operation, both the ballast plan and the installation method should be followed. Once the element has been lowered sufficiently until it is submerged, the next step would typically be to adjust the slope of the element to match its in-place design gradient. Lowering would then continue to the bottom of the immersion location safely and in a controlled manner until just clear of its final position, within installation tolerances. Alignment devices to guide lateral positioning may be employed at this stage.

Touch-down and connection

The element is manoeuvred further along its alignment until it is very close to the adjacent structure. If the element is to be set on a prepared gravel foundation, a small proportion of the load carried by the floating immersion equipment may be released at this stage so that the element bears lightly on its foundation. While not essential, this manoeuvring can be made easier with a device such as a pin and catcher. After an inspection (by diver or ROV) is made of the immersion joint and any gravel bed to make sure it is clear of the joint, the tunnel element can be pulled towards the previously immersed bulkhead to create the initial seal around the joint gasket. The pulling can use diver-installed pulling jacks or the catching device.

After the immersion joint is drained and the immersion joint seal is formed the position of the element is confirmed by survey and position adjustments made as required. (Refer to Annex 14). Once an acceptable position is confirmed, the element is allowed to fully bear on its foundation and the lowering equipment can be released.

Removing immersion equipment

Additional ballast is usually required after release of the lowering equipment to increase the negative buoyancy further to an acceptable level of stability for the duration of finishing works. Typically a minimum factor safety against uplift will be specified at this stage for the safety of the works. This may be less than the permanent FoS due to the short timescales involved, and is sometimes specified as 1.025, but this is a risk-based criteria that should be set according to the project conditions.

Installation of permanent ballast material in an immersed tunnel element.

After immersion operations are complete, temporary ballast must be exchanged for permanent ballast in a controlled sequence. A minimum factor of safety against uplift for the tunnel element must be maintained during each step of the exchange process to ensure negative buoyancy requirements are maintained. This can be done by pouring ballast concrete into the tunnel in stages as determined in the buoyancy control method developed during the design phase. Ballast tanks may then be removed. Further ballast may be required to bring the weight of the tunnel elements up to achieve the final factor of safety against uplift for the permanent structure. This is often specified as 1.06 or 1.1 depending on which components of the completed tunnel are included.

WHEN (start-finish & measurement frequency)

Buoyancy control forms a large part of every stage of the immersed tunnel project:

- Design phase – buoyancy is considered in sizing of the structure.
- Preparations phase (project engineering)
- Construction of elements and approach structures
- Preparations of marine operations (immersion engineering)
- Marine operations
- Final ballasting
- Finishing works inside tunnel

An Owner or marine authority can prescribe the periods foreseen for planning the marine operations. If preparations are done at an early stage during the project, more time for as-built and other checks will be available to verify estimates. After a period of monitoring environmental conditions or taking statistical data, a workability analysis and prediction can be added to the work method statements to mitigate risks during the execution of marine operations.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

An Owner has to prescribe the standards, codes and regulations (national or international) that apply to the contract, and the project specific requirements. These should detail the technical requirements for the permanent structure of the tunnel and also technical requirements for the different stages of marine operations where an Owner wishes to impose a particular safety level. They may also prescribe the methodology to be used during buoyancy control and transport and immersion. A technical requirement could describe for example on-bottom safety before float up and after immersion, minimum freeboard during transport etc.

DOCUMENTATION (FORMAT, DEADLINES)

During the design phase of a tunnel project, the immersion philosophy will be outlined. This will document environmental data acquired from historical records, statistical analysis or by monitoring, combined with weather reports monitoring. A risk register should be started and be kept up to date with the progress of the design. Measures that are taken in the design phase should be documented and checked for their inclusion in design reports and drawings.

After awarding the contract, the design reports for temporary works and the risk register should be handed over to the contractor who will update them to include risks involved in executing the works. Safety measures should be documented in work method statements.

Documents to be assembled during various stages of the project relating to immersion and buoyancy control are:

- Design reports and drawings immersion provisions
- Method statements and drawings for marine operations including assessment on health and safety
- Equipment specifications and configurations
- Risk assessment
- Contingency scenarios
- Weight Analysis design phase
- Weight Analysis As-built, 3D model of the element and ballast plan.

Figure 6: Lowering of a tunnel element through the waterline by catamaran.

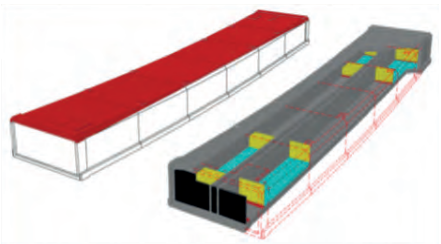


Figure 7: 3D model for As-Built Weight Analysis of tunnel element

Detailed method statements for all marine operations, works within a closed tunnel element and joints need to be prepared and checked by the contractor. These include float up plans, mooring arrangements, transport configurations and plans, ballast plans, immersion configuration of equipment, immersion plans and contingency measures.

As each tunnel element may be different, every operation should be prepared and planned for each individual tunnel element. These plans and calculations must be updated with as-built construction data for the tunnel elements together with gathered environmental data and site particulars such as shipping traffic etc. as the project proceeds.

EXPECTED VALUES

Not applicable. Factors of safety achieved during various stages of construction are described elsewhere in the text of this Annex.

ANALYSIS (REQUIREMENTS, TIMESCALE…)

The following main items are analysed in order to come to a controlled and safe working method:

- Weight analysis of the tunnel elements
- Analysis of loads on the tunnel element and equipment due to the execution of marine operations.
- Workability analysis of environmental conditions, tides and weather and site particulars.
- Choice and configuration of suitable

Figure 8: Wave loads on tunnel element during sea transport.

Figure 9: Horizontal positioning of an element before immersion.

equipment with regard to site particulars such as shipping traffic, environmental conditions and immersion provisions.

- As-Built Analysis of the tunnel elements, in particular the immersion joint initial sealing gasket, its supporting system and the faces against which it seals around the two bulkheads.

These items will be monitored and checked during design phase, construction phase of the tunnel elements and after flooding of the fabrication facility in order to prepare for immersion operations and to check the chosen working method.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

An Owner can specify as-built tolerances (x,y,z) for the permanent structure of the tunnel. The Owner may also specify several operational limits to ensure safety of the chosen work method and quality of the end product. The contractor will have to prescribe the following in its work method statements to meet those criteria:

- Operational criteria per operation, depending on equipment and immersion provisions
- On-bottom safety factor of the tunnel element for every stage of the marine operations while the tunnel element is submerged on the bottom.
- Operational target values for control of installation procedures, such as freeboard value, horizontal and vertical winch loads etc.
- Installation tolerances
- Contingency measures and methods to restore installation tolerances
- Testing criteria and testing procedures of gaskets, special joints etc.

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

The following items can be considered in the design phase of an immersed tunnel to minimise risk of remedial works:

- Consideration of upper and lower bound parameters for environmental conditions and material densities,
- Requirements for structural safety and types of temporary bulkheads and ballast tanks, etc.
- Requirements for the type of ballast pipe system and equipment

Examples of measures that can be part of the preparation and execution of the immersion operations are:

- Measures to pump sufficient ballast water at all times
- Working sequence during float up and immersion to maximise control of buoyancy of the element and maximise safety of operations

- Equipment and procedures (including testing) for ballast and communication systems
- Testing and certification of all equipment and back up/spare or even standby equipment
- Description of contingency scenarios and contingency plan
- Active risk management
- Work method describing control of the horizontal and vertical position of a floating tunnel element before and during a vertical translation operation (such as float up or immersion).
- Working with an experienced crew and supervision.

LINKS TO OTHER OWNERS GUIDE ANNEXES

Annex 06 Immersion Joints
Annex 07 Closure joints
Annex 14 Tunnel Element Alignment
Annex 15 Tunnel Element Transportation
Annex 16 Tunnel Element Mounted Equipment
Annex 21 Element Construction / factory Method
Annex 40 Health & Safety

PERFORMED BY / RESPONSIBLE

Roles and responsibilities:

Owner

- Ensure competency of contractors in marine and immersion works through prequalification and contract award processes.
- Specify project requirements regarding weight control and safety during transport and during immersion operations
- Collect statistical site data on environmental and weather conditions

Designer

- Permanent works design of structural cross section including risk assessment
- Structural design during floating stage
- Buoyancy control (on-bottom safety before float-up and after immersion)

Contractor

- Immersion engineering in all phases of the project; temporary structures, equipment, working methods and environmental conditions/site particulars
- Buoyancy control during all phases of marine operations
- Suitability of equipment for all marine operations
- Monitoring of local environmental conditions and weather predictions
- Workability analysis regarding weather and environmental conditions (GO-NO GO procedure)
- Able and experienced crew
- Risk assessment, risk management and contingency plans
- Safe execution of all operations and installation of the immersed tunnel according to all requirements.
- As built measurements.

ANNEX 32 >> DURABILITY

The design life of an immersed tunnel is generally specified as either 100 years or 120 years, depending on the requirements of the country in which it is constructed. To meet this requirement the durability of the materials used in the construction needs careful consideration. The design and detailing of the works also needs careful attention. Construction monitoring and testing plans must be implemented, and monitoring and maintenance regimes for operation stage need to be thoroughly developed.

WHAT

The most common deterioration mechanisms include:

- Chloride-ingress causing reinforcement corrosion.
- Leakage or steel corrosion due to through-section cracking.
- Carbonation of concrete.
- ASR (Alkali Silica Reaction) in concrete
- DEF (Delayed Ettringite Formation) in concrete.
- Sulfate attack of concrete.
- Bimetallic corrosion.

The objective of design and construction should be to manage the deterioration of materials such that deterioration is either prevented or does not occur over the design life to the extent that serviceability is affected by:

- selection of appropriate materials
- careful detailing
- implementing protective measures
- preventing leakage
- installing monitoring systems
- considering maintenance regime
- designing for inherent longevity

These are discussed in turn below.

Selection of materials

For concrete tunnel structures the selection of concrete mix constituents plays a vital. part in ensuring the durability is achieved.
Good practice should be observed with respect to limiting alkali content in the concrete mix and protecting against known deleterious effects such as ASR.

The benefits of introducing cement replacement materials such as PFA (Pulverised Fuel Ash) and GGBFS (Ground Granulated Blast Furnace Slag) are to reduce the heat generation during the curing process. This in turn can reduce the expansion and contraction of newly placed concrete and hence the risk of cracking due to restraint at early ages.

Aggregate selection will also influence the stiffness and behaviour of the concrete with respect to crack control as it affects stiffness.

The benefit of cement replacement mineral additions such as microsilica is to increase fines in the mix and therefore reduce permeability. However this can increase concrete strength which is not always wanted.

These and other measures to reduce potential cracking during casting should be implemented in conjunction with industry recommendations for hot and cold weather concreting and curing.

In steel tunnel structures the concrete requirements may be similar but requirements for crack-free concrete may not be so strict. Primary watertightness is provided by the steel shell. Recognised steel grades and methods of fabrication and inspection should be used to ensure the quality will lead to the required durability, as well as post-yield capacity in case of overload. In particular, stringent high quality welding is required to assure a watertight steel lining.

Joints between tunnel elements and between tunnel segments (for concrete segmental tunnels) will feature some form of rubber sealing gaskets, plastic or rubber/metal waterstops, and steel clamping and mounting systems. These items need to be specified to include durable materials that have a suitable predicted life that is demonstrated by advanced testing.

Design & detailing

Designs should be prepared in accordance with appropriate national and international codes and recommended durability parameters for the exposure environment. These will include crack width limitations and minimum cover depth to reinforcement. The correct choice of these parameters is essential for achieving durability.

Crack width control is important for both early age cracking that can be through-section and cause leakage and subsequent durability problems, and flexural cracking that can cause durability problems if widths are not controlled sufficiently to limit chloride ingress and promote self-healing.

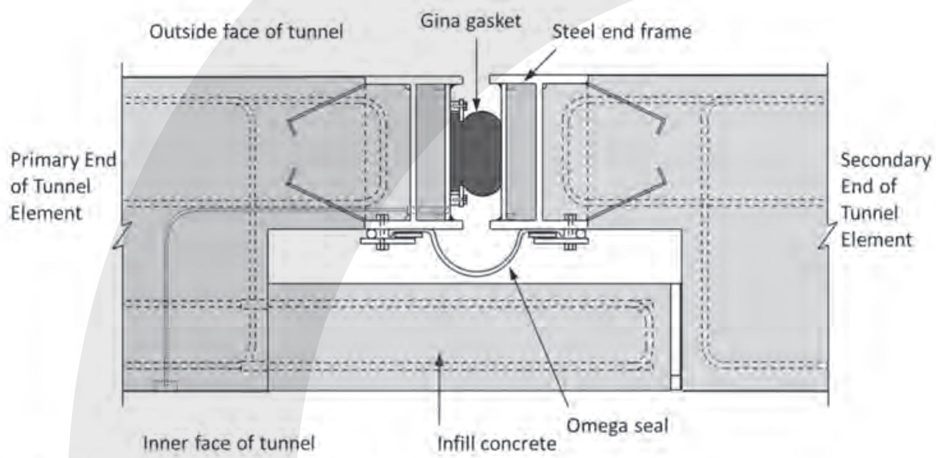


Figure 1: Typical immersion joint detail for a concrete tunnel.

Joints must be designed to be as simple as possible to enable a high quality of construction, such that they do not introduce the risks of void formation, creation of waterpaths, or establishment of corrosion cells that could lead to premature corrosion. A typical immersion joint arrangement is shown in Figure 1. This illustrates the complexity of detailing at the joints and why care must be taken in the design process.

Protective measures

Protective measures may be required to enhance the durability levels achievable by the concrete mix alone or from the selection of materials and components. This will be determined by the durability strategy developed for the specific environmental conditions.

One common additional protective measure is the addition of an external waterproofing membrane to the tunnel structure (see separate Annex). These come in a number of forms and are applied more specifically to monolithic concrete tunnel elements.

In order to assist in the protection of metal components in the structure, it may be appropriate to use cathodic protection (see separate Annex). Components that may be protected include steel shells, steel membranes and embedded steel components such as reinforcement and the steel end frames of immersion joints.

Cathodic protection systems may be either installed at the outset of the project life using sacrificial anodes attached to the structure, or may be installed later when monitoring identifies them as necessary. In the latter case impressed current systems are used. If it is envisaged that a system might be needed in the future, provision for its installation must be incorporated into the structure at the time of its construction. For example the reinforcement bars should be electronically connected for effectiveness, and connection plates for achieving electrical continuity across joints and for attaching anodes and monitoring equipment.

Protective coatings may be applied to steelwork as a single measure or in combination with cathodic protection. Coatings are more likely to be applied to localised embedded metals in a concrete tunnel such as immersion joint end frames, rather than to large surface areas.

For areas which are especially vulnerable to corrosion, or difficult to protect and to access for repair, materials can be used that are less prone to corrosion effects, such as stainless steel. When applying different steel types special attention should be paid to isolating these steel parts in order to avoid bimetallic corrosion.

Preventing leakage

Leakage must be prevented through the main external tunnel structure and through the joints connecting tunnel elements and segments. Leakage can lead to corrosion either of reinforcement within the tunnel concrete, or of steel components that may be providing a watertightness or a strength function.

Leakage through the structure can be prevented by high quality concrete or steel construction (see relevant Annex).

Leakage through the joints may be prevented by selecting reliable joint sealing products that are durable and resistant to damage from movements of the tunnel, and that are durable in both the internal and external tunnel environment. The internal tunnel environment must consider the spillage of hazardous or harmful materials such as chemicals and petroleum products, as well as exhaust fumes and particulates arising from vehicles.

Good detailing of the joints is essential to maximise the possible water leakage paths and ensure all potential water paths are sealed.

The effects of a fire on sealing products within the tunnel may be reduced by the selection of appropriate products or the provision of insulation to critical areas.

Monitoring systems

Installation of monitoring systems allow the "health" of the structure to be assessed continuously throughout its life. The systems may reveal early action to be taken to ensure durability of the structure. Monitoring systems can be used in immersed tunnels to measure at least the following:

- Effectiveness of cathodic protection systems
- Chloride penetration through concrete cover zones
- Joint movements
- Water ingress/accumulation at joints
- Settlement
- Seismic acceleration/displacement
- Temperature/humidity

Many of these items can be monitored remotely rather than requiring entry into the tunnel.

Other monitoring may be carried out on a periodic basis in relation to assessing remaining design life, such as taking samples from the structure to assess carbonation in concrete, corrosion of steel, chloride content in concrete etc..

All tunnels need a programmed inspection regime to be defined in their maintenance and operation manual. This should include details of each type of inspection required, the frequency required, the information to be gathered, the method to be employed and how the data is to be used and conclusions to be drawn.

It is becoming more common to provide specific inspection facilities for critical components of the structure. These can include:

- pipework to permit water sampling / removal at the low point at each immersion joint.
- Access pipes for cameras to inspect the immersion joint space.
- Pipework to access space between the primary and secondary immersion joint seals.

An example from the Bjørvika tunnel in Oslo of how some of these features can eb applied is shown in Figure 2.

Designing for inherent longevity

The use of tried and tested components can be an advantage in ensuring durability. Selection of materials beyond the basic concrete and steel tunnel structure with low susceptibility to deterioration is beneficial i.e. using inert material that does not react to the surrounding environment.

Innovation is important to the construction industry as it brings benefits to cost, programme and to technical solutions. However when new materials and methods are introduced in relation to providing durability, this must be done without introducing risk. Therefore new or alternative materials should always be subjected to thorough testing and research to get good predictions of their service life, and critical durability reviews should be undertaken to demonstrate that a new approach will genuinely bring overall benefit to a project when all aspects are considered.

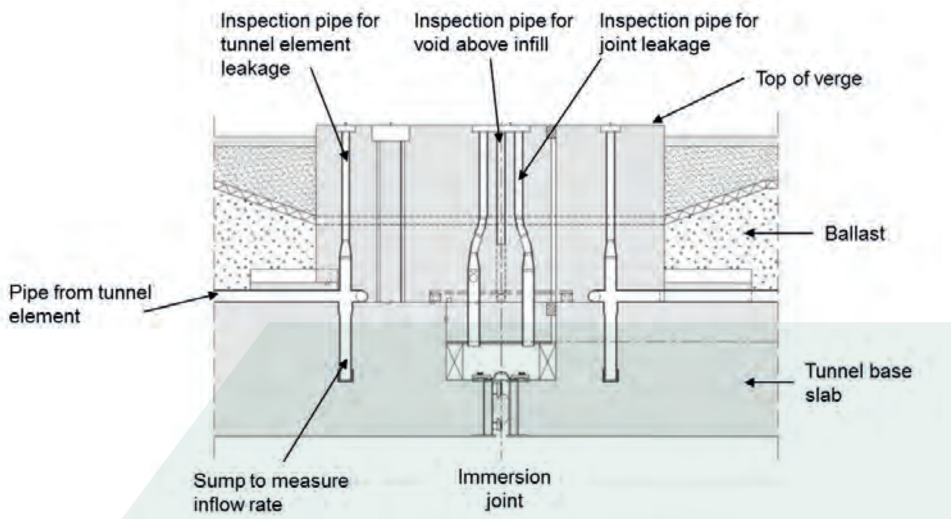


Figure 2: Inspection pipework installed in Bjorvika tunnel immersion joint. (Long section through verge to side of carriageway shown).

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Investigations of the environmental conditions e.g. ground water aggressivity, should be carried out by the Owner at the initial stages of scheme development.

The approach strategy to controlling durability should be prepared with the reference design and set out in the Client's contract documents. Final durability assessments and designs should be carried out at the start of the detailed design stage.

Monitoring of structure should commence during construction by the contractor and be handed over to the Owner/operator following completion. Initial frequencies of monitoring and inspection should be set out in the maintenance manual on completion of the design but may need to be adjusted depending on actual behaviour

The initial maintenance plan for refurbishment and replacement of components should be set out in the maintenance manual on completion of the design but may need to be adjusted depending on actual performance of the tunnel structure throughout the operation stage.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

Concrete mix specifications should follow best international practice for structures in the proposed environment taking into account concrete placing and curing methods to be used. Risk of cracking for early age effects should be limited to 0.7. (ratio of tensile stress : tensile strength - see separate Annex: Concrete-cracks).

Sufficient corrosion monitoring should be carried out along the tunnel. Typically this may be at the centre/low-point of the tunnel, at quarter points and at each end. For longer tunnels monitoring systems are installed typically every 500-1000m.

Design life should be clearly specified for all critical components installed in and comprising the tunnel, and for all chosen protective measures e.g. membranes, coatings and cathodic protection systems.

DOCUMENTATION (FORMAT, DEADLINES)

The following important documents will be produced over the life of a tunnel that should be retained:

Design stage:

- Durability assessment reports including corrosion prevention strategy and concrete mix designs.
- Design documentation including design basis, assumptions, design calculations, reports and drawings.

Construction stage:

- Final mix designs
- As-built documentation
- Testing and commissioning records
- Non-conformance reports
- Maintenance manuals

Operation:

- Monitoring and survey records.
- Condition surveys and inspection reports.
- Records of replacement and repair.

EXPECTED VALUES

It can often be demonstrated using chloride transport models that, for a well-designed concrete mix, corrosion due to chloride ingress should not extend beyond the cover depth before the end of the design life. Cathodic protection systems are therefore usually intended as a back-up in case unexpected behaviour occurs.

Corrosion rates for steelwork will depend on the specific environment of the tunnel and whether general corrosion, pitting corrosion of bacterial corrosion may be expected.

ANALYSIS (REQUIREMENTS, TIMESCALE…)

Inspection and Maintenance

Inspections are separated into different categories. Regular inspections should be carried out at approximately 3 monthly intervals to coincide with routine closures of the tunnel for cleaning and minor repairs.

These will typically be quick visual inspections of key areas and the general condition of the tunnel, with the aim of identifying items in need of repair/replacement or exhibiting signs of deterioration in their condition.

More detailed inspections would be carried out on a yearly basis when programmed works are implemented for repairs and replacement of items. Such inspections could be more intrusive e.g. removal of a selected number of cladding panels and joint covers to check on the condition of joints and the tunnel structure.

Every 5-6 years a full inspection will normally be carried out to establish the condition of all parts of the structure and what repairs are needed to ensure durability. Specific inspections might be similar to the annual inspections but in greater depth. Detailed condition reports prepared following each inspection should contain a record of the tunnel's condition, along with recommendations for both short term and long term repair, replacement and refurbishment of the tunnel. Design life predictions may also be updated on the basis of the inspection results.

In order to set budgets most tunnel operators have a forward plan of intended maintenance activities. It is known that regular maintenance can extend the life of a structure beyond its original design life, so it is important to plan and implement this process from the outset.

In a PPP project where an operator/maintainer is appointed for a concession period, the concessionaire must plan and budget for renewals and major refurbishments such that the tunnel and its installed systems meet a pre-specified set of conditions when it is handed back at the end of the concession.

All components installed within the tunnel will have a predicted life and so a maintenance plan can be developed for progressive replacement of items over the tunnels life and a budget calculated accordingly.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

Clear criteria should be stated in the maintenance manual for the monitoring systems to enable the operator to decide when behaviour is not in accordance with the predicted behaviour, and when remedial measures need to be considered.

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

Unexpected behaviour with respect to durability tends to be very project specific. Thus it is difficult to specify general remedial measures. Some examples of durability issues that have arisen on projects are given below.

General corrosion issues can usually be addressed through repairs and by retrofitting corrosion protection systems usually some form of cathodic protection. It should be noted that this is always more expensive to retrofit if no provisions have been built into the original construction.

In this respect it is prudent to design on the basis of the worst case. For example immersion joint end frames are often designed to be isolated from the main structural reinforcement. However if accidental electrical continuity occurs corrosion of the end frame could be accelerated. It is cheaper to allow for this in the original design that to post-fit a corrosion protection system.

Leakage through the structure can usually be treated with some form of injection grouting but this can be expensive and time consuming. There are many examples of injection works where the apparent source of leakage simply moves along the tunnel as each injection is carried out. It can be difficult to identify the real source of the problem.

Grouting of joints can be successful but the continual movement of joints through the seasons and as temperatures increase and decrease can often cause leaks to reappear.

Insufficient control of tensile stresses that result in leakage and corrosion can require very expensive remedial works. The Limfjord tunnel is an interesting example of this where due to an ineffective external membrane and insufficient reinforcement to control cracks at construction joints, significant leakage and deterioration of the tunnel concrete occurred. The tunnel elements were retrospectively post-tensioned to limit tension in the structure, a grout injection programme was instigated and a significant proportion of the internal concrete was replaced due to chloride ingress. The remedial works were successful but at a high cost.

Some corrosion issues may only become apparent when another behaviour is shown. For example there have been projects with tension piles used in the tunnel approach ramps which have suffered corrosion at the connection between the piles and the base slab of the ramp. The problem is only identified when the structure begins to move upward following the loss of tension restraint. This type of problem could be overcome by introducing additional ballasting or additional restraint piles, but it is an expensive remedy.

LINKS TO OTHER OWNERS GUIDE THEMES

Annex 25: Cathodic protection
Annex 02: Concrete construction - cracks
Annex 01: Concrete construction – concrete
Annex 08: Steel construction
Annex 23: Waterproofing membranes

PERFORMED BY / RESPONSIBLE

Durability concept – Owner/Designer
Detailed durability assessment and design – Designer
Concrete mix design – Owner/Contractor
Monitoring & Inspection – Owner/Specialist
Maintenance & Repair - Owner

ANNEX 33 >> TERMINAL JOINTS

The joints between the immersed section of a tunnel and the adjoining land structures or “terminal” structures are known as Terminal joints. They may have some particular characteristics that make them different to a regular immersion joint and they may need to be designed to accommodate deviations in alignment and large movements, such as settlement, thermal effects, shrinkage or seismic effects.

WHAT

The Terminal joint is the joint between the end of the immersed tunnel and the adjacent terminal structure. The terminal structure may be a building or another form of tunnel such as cut and cover (most typical) or bored tunnel. Note that final joints formed between two tunnel elements are not covered in the Annex but are described in Annex 07 Closure Joints.

The terminal joint can serve a variety of functions. They are normally designed to accommodate longitudinal, vertical and transverse movements and differential movements due to ground movement or thermal variations.

They may take the form of a:
- Conventional immersion joint
- Bespoke immersion joint, e.g. if connecting to more complex structural arrangement such as may be present at a ventilation stack/ service building
- Closure joint
- High capacity movement joint
- Reception chamber for a TBM

Different configurations may be required depending upon the construction sequence of the tunnel. If the tunnel elements are placed before the terminal structure is constructed then the joint detailing may be different and some additional temporary works are usually required.

Conventional immersion joint

A conventional immersion joint is often used, similar to those between immersed tunnel elements. Refer to Annex 04 for typical arrangements. This can be applicable if the terminal structure has been constructed first and there are no significant differences in the

Figure 1. Fort McHenry Tunnel, USA

longitudinal, vertical or horizontal movements to be accommodated by the terminal joint compared to the other immersion joints.

Bespoke Immersion joint

Shear loadings often increase in the area of the terminal joint as backfill height can increase as the tunnel reaches the shoreline and passes beneath river walls or flood protection dikes. The jointing systems are not necessarily affected but shear keys may need to have additional capacity at this location.

Many tunnels have been constructed that feature a support slab beneath the end of the last tunnel element. The support slab typically extends from the terminal structure and is structurally continuous with the terminal structure. The slab helps accommodate large shear forces and prevents differential settlements at this joint.

Closure joint

Closure joints options are described in Annex 07. Depending upon the construction sequence, the connection between the immersed tunnel and the terminal structure can be used for a closure joint location. This may have some advantages, being closer to the shore. Access may be easier, conditions more sheltered from shipping and the environment, or perhaps constructed in the dry (Figure 1).

In summary, this is typically a 1.5m-2.0m wide section constructed in place to close the final gap once all tunnel elements have been placed.

Immersed tunnel placed in advance of terminal structure

If the immersed tunnel is placed before the terminal structure is constructed then a water cut-off system is required around the tunnel to enable the approach area to be excavated and dewatered. The fill may incorporate cut-off features within it such as clay cores. Alternatively, a positive cut-off system must be constructed around the tunnel, e.g. a cofferdam system consisting of sheet pile or structural walls connected to the sides and roof of the tunnel element, together with some form of water cut-off beneath the tunnel element, possibly incorporating a soft gasket upon which the tunnel element can rest.

Dewatering removes the axial hydrostatic forces on the end face of the tunnel; strutting or other means may be required to prevent axial movement of the already placed elements, movement that might otherwise reduce load in immersion joints already compressed unless the joints have been locked.

Sufficient friction to prevent movement may perhaps be mobilised by fill around the tunnel, allowing the tunnel ends to be exposed (Figure 1). Horizontal forces could be transmitted down to temporary foundations e.g. the Medway Tunnel, UK (Figure 2).

In this case the joint between the last immersed tunnel element and the terminal structure can be relatively simple. Immersion joint type arrangements are not often used and the sealing arrangement can be simpler.

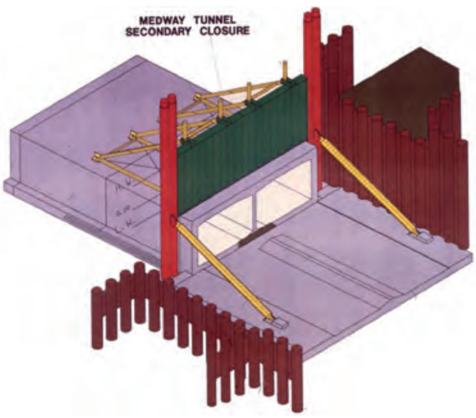


Figure 2: Medway tunnel, UK.

High capacity movement joint

Terminal structures, particularly when they extend above the water table, can exert significantly higher bearing pressures than a buoyant immersed tunnel. They are often founded in soft ground and may therefore be subject to greater settlement. The use of ground improvement and deep foundations may reduce settlements, but there could still remain a significant difference between it and the immersed tunnel.

Large longitudinal movements may have to be accommodated at the terminal joints. Some steel tunnels are made continuous at their immersion joints and so thermal expansion and contraction has to be taken at the terminal joints (less any reduction for ground friction effects).

The BART tunnel in San Francisco has high movement capacity joints to accommodate seismic movement. Similarly, the more recent Marmaray tunnel beneath the Bosphorus Strait in Istanbul has high movement capacity seismic joints. The tunnel is continuous and so these also allow movement for thermal expansion and contraction to occur. The flexible joint on that project is located in the adjacent bored tunnel just beyond the connection between the immersed and bored tunnel structure.

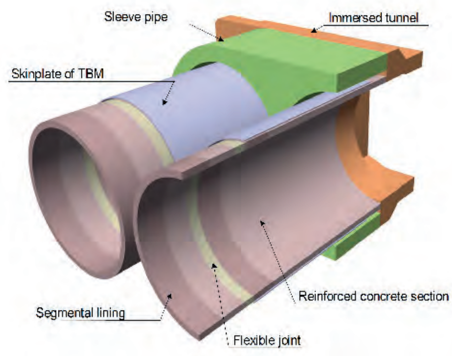


Figure 3: Marmaray tunnel seismic joint.

Connection to Bored Tunnels

An unusual arrangement arises when an immersed tunnel has to connect directly to a bored tunnel. This has been achieved in Hong Kong (MTRC Contract 103 Cross Harbour tunnel) and in Istanbul (Marmaray tunnel). To enable this, the end of the immersed tunnel was modified to act as a reception chamber for the TBM. The TBM could then drive directly into the opening at the end of the immersed tunnel; the bored tunnel lining is then sealed against the tunnel element to make a watertight connection.

Following construction of the immersed tunnel, a key consideration is to backfill the space around the end of the tunnel with material suitable for the TBM to drive through. Typically the end of the tunnel element is surrounded either by tremie concrete or treated backfill.

The size of the opening at the end of the immersed tunnel will need to be sufficient for the TBM driving tolerances, but not too great, since it will need to be sealed either by a temporary seal while a permanent seal is constructed or directly by the permanent seal.

A conceptual arrangement is shown in Figure 4. The end of the chamber may be filled with lightweight/foamed concrete for the TBM to bore into. Double bulkheads are used behind this for safety against water ingress.

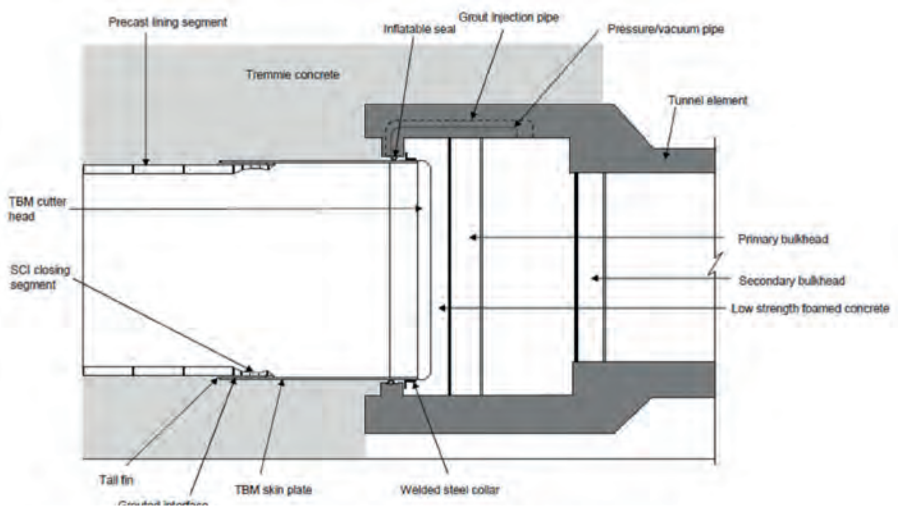


Figure 4: Concept for TBM reception chamber at end of immersed tunnel element.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

The designer should determine likely settlement movements and seismic movements early in the preliminary design and the project Owner should perform ground investigation so that the joint and this part of the tunnel can be designed correctly. The different masses of the immersed tunnel and the terminal structure are likely to cause differential movements across the joint, all of which must be taken into account. At least under normal working conditions, it is highly desirable to eliminate relative displacements, although it might be comparatively simple to accommodate axial relative movements.

In the early planning of the tunnel, the constraints to the project should be assessed to decide if there are requirements as to the construction sequence that may require either the tunnel elements to be placed ahead of building the terminal structure, or whether the terminal joint location needs to be used for the closure joint. If there are no constraints it is best to allow the contractor to make the final design and choose the sequence and joint arrangements to suit the preferred method of working.

If the design is to be performed by the contractor, all functional requirements related to the terminal joint should be well specified by the Owner

During the detailed design, determine risks and what measures are required to mitigate against large movements and maintaining watertightness of the tunnel.

The designer should set clear criteria for construction, such as maximum differential movement allowed at the joint interface with respect to the movement capacity of joint seals and the ability of the shear keys to carry load.

The designer should also set criteria for acceptable alignment deviation at preliminary design stage and record in the project design basis. This is particularly important for high speed rail tunnels. Alignment deviation criteria will need to be specified to match the required comfort levels for all users of the tunnel and for designing equipment in the tunnel, e.g. piping. For tunnels in seismic regions dynamic modelling should be undertaken in the preliminary design stage and at detailed design stage to understand the loading and movement that must be designed for at the terminal joints.

As built baseline surveys should be made early on to document settlements during backfilling and onward.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

For information on specifications see Annex 06 Immersion Joints.

DOCUMENTATION (FORMAT, DEADLINES)

For information on documentation see Annex 06 Immersion Joints.

The design basis should record:

- Design life and durability requirements.
- Thermal movement ranges.
- Differential settlement criteria to be met with respect to road/rail alignment.
- Ground conditions.
- Seismic load.
- Seismic movement range to be designed for.
- Loading cases and combinations at the shoreline, particularly unusual load cases such as ice build-up loads and surcharge allowance to be made for future development over the tunnel.
- Fabrication tolerances and element alignment tolerances.

Construction specifications should include:

- Sequences of installation for joint components.
- Time related requirements for construction of shear keys relative to predicted settlement behaviour.

Specific procedures and method statements may need to be developed for unusual activities such as the sequence of operations for TBM entering the end of an immersed tunnel element, or sliding procedures associated with closure joint features.

Movement records should be maintained throughout construction and from periodic surveys during operation. After specific events there may be a need to survey terminal joints, for example if high movement capacity is provided for seismic events the observed movements in a seismic event will form a valuable record for future tunnels.

As-built records should include:

- Movements observed during construction.
- Materials test records for seals and joint components.

EXPECTED VALUES

Movements and rotations may be similar to conventional immersion joints as described in Annex 06 unless the terminal joint has to accommodate high seismic or thermal movements for a continuous tunnel.

ANALYSIS (REQUIREMENTS, TIMESCALE…)

For information on analysis see Annex 04 Immersion Joints.

Analysis of all potential movements is required during design and should be fully documented in the design output.

Joint components should have performance tests prior to supply and installation.

Carry out as-built survey as soon as joint is formed.

Perform ongoing survey as construction proceeds and foundation pressures change with changing loads.

Monitor settlement at regular intervals over first years of operation, gradually decreasing frequency as steady conditions are reached.

If any leakage is observed after construction that required remedial works, a regular inspection programme should be established to detect if leakage re-occurs.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

Joint seals should have spare capacity built into the design to accommodate unexpected behaviour.

Shear keys for control of differential movement should have a suitable factor of safety and conservative assumptions if this joint is considered higher risk than the general immersion joints.

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

For information on remedial measures see Annex 04 Immersion Joints.

LINKS TO OTHER OWNERS GUIDE THEMES

Annex 06: Immersion joints
Annex 07: Closure joints
Annex 11: Seismic design
Annex 18: Approach structures

PERFORMED BY / RESPONSIBLE

Design & detailing – designer
Specifications of materials – designer
Movement monitoring during construction – contractor
Leakage monitoring during construction – contractor
Leakage repair during construction - contractor
Movement monitoring over life – Owner
Leakage repair during operation – Contractor or Owner (depending on contractual requirements for defects liability period after completion of construction)
Maintenance of replaceable items e.g. bearings - Owner.

ANNEX 34 >> HEALTH & SAFETY

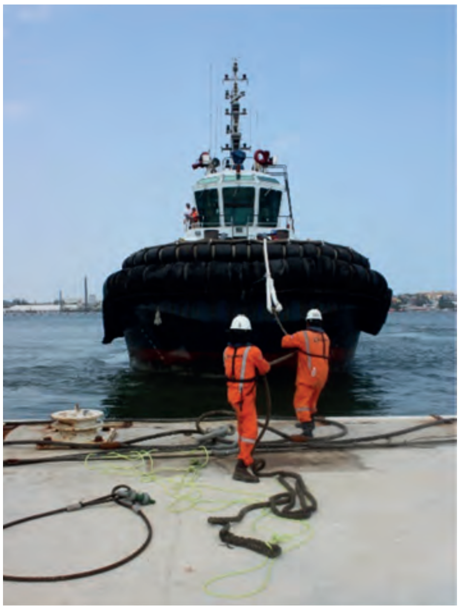


Figure 1: Elements are temporary closed off by bulkheads

Figure 2: Elements are transported with tugboats.

Immersed tunnel projects give rise to risks for occupational health and safety that are different from other construction projects. These risks are described in this annex.

WHAT

The premise of this annex is that immersed tunnels are constructed in accordance to the 'Guideline for good occupational health and safety practice in tunnel construction' ITA report No001 by Working Group 5 (WG5). The risks that are specific to immersed tunnels are not described in that report, therefore it is recommended that both the WG5 report and this annex be considered. Both should be read as guidelines additional to local Health and Safety law.

According to the location of the project, the relevant applicable legislation for construction works should be followed. In addition recognised health and safety practice related to construction in the marine environment should be followed, for example the guidelines and standards published by DNV GL, the UK HSE's Approved codes of practice for diving at work, and safety guidelines published by the International Marine Contractors Association.

The basis for managing health and safety on tunnel projects as described in the WG5 report is the risk assessment (paragraph 1.1.15).
This assessment should:

- Identify the hazards (HAZID)
- Identify who is affected by the hazard and how
- Evaluate the risk
- Identify and prioritize appropriate control measures

A recognised approach to risk management such as that described in the ITIG Code of Practice for Risk Management of Tunnel Works is recommended to be followed. By reviewing all activities in relation to the tunnel environment all hazards will be identified. For an immersed tunnel all immersion related activities and especially some unusual workplaces require attention.

Within this annex the activities related to preparation of the construction location, construction of the tunnel elements, dredging and finishing (road works and internal installations) of the tunnel are not considered; as they are regarded as general tunnel construction activities for which industry guidance is available.

The guidance in this annex is not intended to be prescriptive or comprehensive, or to replace any legislative requirements, but merely to raise awareness of areas for attention that are associated with the immersed tunnel method of construction.

The immersed tunnel activities, considered here, along with the common hazards associated with them are summarised in Table 1. It is important to mention that this list is not limited and not project specific. For each project and more importantly for each project location the hazards need to be listed by specialists and reviewed by the Owner, and eventually managed by an appropriately experienced contractor.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

The specific immersion-related health and safety risks are present in the period between closing the element with bulkheads in the dry dock and removing the last bulkhead when the tunnel is in its final position.

Matrix of key activities and common hazards associated with immersed tunnel construction methods	Common hazards								
Activity	Drowning in open water	Getting caught inside a flooding joint or tunnel element	Health consequences (illness) from the climate in the tunnel (humidity, temperature, air quality, light/dark, noise)	Worsening of injuries caused by limited evacuation routes and poor access for emergency services	Accidents related to diving	Falling accidents	Accidents related to towing	Accidents related to heavy lifting	Accidents related to working with heavy machinery (e.g. sand, gravel supply or demolition works)
Preparation, float up and temporary mooring of a tunnel element in the construction dock.	⚠	⚠	⚠	⚠		⚠			
Transport of a floating tunnel element	⚠						⚠		
Ballasting and immersion of a tunnel element	⚠	⚠	⚠	⚠		⚠		⚠	
Foundation installation (gravel bed or sand flow)	⚠				⚠				⚠
Removing immersion equipment	⚠				⚠			⚠	
Placing ballast concrete in an immersed tunnel element			⚠	⚠		⚠			⚠
Installation of the primary joint seal and construction of the immersion joint			⚠	⚠		⚠			
Construction of the closure joint	⚠	⚠	⚠	⚠	⚠	⚠		⚠	⚠
Demolition of the bulkheads and ballast tanks			⚠	⚠					⚠

Table 1. Key activities and common hazards

Figure 3: During transport waterways are closed off for ship traffic.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

Just like other tunnel projects an Owner has to prescribe the health and safety regulations (national or international) that apply to the contract and can also prescribe the methodology for the health and safety management (for example OHSAS 18000).

DOCUMENTATION (FORMAT, DEADLINES)

In the design phase of a tunnel project a risk register should be started and kept up to date as the design progresses. Measures that are taken in the design phase should be documented and checked to ensure inclusion in design reports and drawings. Residual risks are identified in the risk register.

For the construction phase of the contract the risk register should be updated by the contractor to include further risks involved in the works. Safety measures documented in work method statements should be communicated by: site induction, work instruction and toolbox meetings (which should be documented).

Detailed method statements for all marine operations, works in the closed tunnel element and construction of joints need to be prepared and checked by the contractor.

In case of an incident or accident during construction of the tunnel or during a marine operation a report has to be filled in by the contractor. Applicable legislation will also apply.

After completion of the project the set of health and safety related documents should incorporate:

- Health and safety risk register
- Design reports
- Method statements
- Inductions
- Toolbox meetings
- Incident reports
- Accident reports
- Health and safety documents as required by applicable legislation»

Figure 4: Personal safety equipment.

EXPECTED VALUES

Part of the risk evaluation is adding probability (chance of occurrence) and the impact (consequence class) to each hazard, before and after measures. By doing this the greatest risks within the project can be shown at the top of the register.

The risk level is the highest during transport, ballasting and immersion, because of the floating environment, the action of water pressure on the element and the limited entry and escape routes.

Probability \ Impact	Very Low 1	Low 2	Medium 3	High 4	Very High 5
Very High 5	5	10	15	20	25
High 4	4	8	12	16	20
Medium 3	3	6	9	12	15
Low 2	2	4	6	8	10
Very Low 1	1	2	3	4	5

Figure 5: Quantitative Risk Assessment.

After taking control measures the risk should be set at a value that is called ALARP (As Low As Reasonably Practicable). When this is done correctly the risks associated with an immersed tunnel project can be reduced to an acceptable manageable level and can be comparable to other major infrastructure projects.

Figure 6: Element just below waterline.

ANALYSIS (REQUIREMENTS, TIMESCALE…)

By performing a HAZID (Hazard Identification) analysis all risks can be assessed and documented. A part of the assessment is the preparation of emergency plans, e.g. failure of equipment or leakage in the tunnel during transport or immersion.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

Not applicable.

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

A suggested list of measures to reduce hazards during immersion operations is provided below. The measures are examples and are divided into the different phases of the project.

The following measures can be used as a starting point for health and safety in the construction phase of an immersed tunnel:

- Back up measures to improve water tightness of the tunnel element joints e.g. injectable water stops in the segment joints.

- Requirements for structural safety of temporary bulkheads and ballast tanks including appropriate factors of safety and robust detailing.
- Requirements and number of escape routes before, during and after immersion. Typically people are prohibited from being inside the tunnel element during the process of float up, ballasting and immersion of the tunnel element. Controlled access procedures shall be implemented wherever staff are required to enter zones of the tunnel with only one escape route, or only a single barrier to water ingress e.g. between bulkheads or into the floating or last placed tunnel element.
- Requirements for ventilation, temporary lighting and communication (see chapters 7, 8 and 17 of ITA report No001)
- Sequence of removal of bulkheads, installation of the primary seals and the completion of the immersion joint. Typically a minimum of two independent functioning bulkheads shall be maintained at the free end of the immersed tunnel during construction.
- Minimum factor of safety against uplift in temporary and permanent conditions.
- Requirements for the type of bulkhead and ballast tank (plastic, steel or concrete) to reduce the hazards during removal.
- Additional safety provisions requested by the marine insurers.

Examples of measures that can be part of the preparation and execution of the immersion operations are:

- Testing procedures for ballasting and for communication systems.
- Testing and certification of all equipment and back up equipment.
- Preparing regulations (minimum set-off distance) for sailing during diving activities.
- Keeping a dedicated crew boat with an operator on stand-by in case of a man over board situation.
- Prepare regulations for entering and exiting tunnel elements (covering aspects such as: oxygen measurement, communication test, fall protection, personal protection gear, never working alone).
- Preparing specific procedures for working in confined and enclosed space. It is noted that tunnel elements when first placed are not generally considered to be confined spaces in terms of safety procedures and training requirements. However this should be considered case-by-case according to applicable legislation and project circumstances.
- Working with an experienced crew and supervision.
- Making a workability analysis and checking environmental conditions in relation to the marine operations (GO-NO GO procedure).
- Using ROV (Remote Operated Vehicle) instead of divers for inspection and under water construction.
- Prescribing certified PPE (helmet, safety boots, lifejackets, climbing gear, radio, lights, gas-detectors).

LINKS TO OTHER OWNERS GUIDE ANNEXES

All annexes should be considered in health and safety. Some particular ones noted for attention are:
Annex 09: Element construction / casting basin
Annex 21: Element construction/ Factory method
Annex 14: Element alignment
Annex 15: Element transportation
Annex 07: Closure Joints
Annex 06: Immersion joints

Other documents :

ITA Working Group 5 Health and safety:
- Safe working in tunnelling (2011)
- Guidelines for good occupational health and safety practice in tunnel construction (2008).

PERFORMED BY / RESPONSIBLE

Responsibilities of contracted parties are usually defined in law, along with the rules and limitations for delegating responsibilities to other parties. These may vary country by country but typically the Owner is responsible for all safety aspects in the planning and maintenance phase. Responsibilities are likely to include:

- Selection of competent, experienced and certified designers and contractors.
- Getting work permits.
- Contact with port authorities regarding impact of the works on ship traffic.
- Contact with emergency services (police, fire brigade, ambulance) in order to react fast in case of an accident.
- Information to the Public (residents, local and national media).

Figure 7: Diver is prepared to enter the water.

The designer is responsible for all safety aspects in the design phase, including items such as:

- Structural design.
- Buoyancy control (assure sufficient safety against sinking and against uplift).
- Interfaces between temporary structures and tunnel construction.
- Preparation of preliminary H&S documentation.

The contractor is responsible for all safety aspects in the construction phase, including:

- Risk management and assessments, work procedures and method statements to implement safe working methods.
- Structural safety of temporary constructions.
- Safety of equipment.
- Training and supervision of personnel.
- Handover of all documentation to the owner including final H&S documentation.

Particular care is necessary to understand safety obligations where safety of the workforce is reliant on a combination of permanent and temporary works.

Annex 35 >> Navigational Safety

During the construction phase of an immersed tunnel project there is often a major interface to manage with the navigation of shipping using the waterway. The relationship with ship traffic can be less than with a cut and cover tunnel, which may partly block the fairway during construction, but will be more than for a bored tunnel. This annex focusses on the construction phase of an immersed tunnel and the methods to manage navigation matters

WHAT

The tunnel construction world is a very different world than the nautical world, understanding the processes in both worlds and managing the interface between the two is necessary to smooth the construction process and decrease the risk of accidents.

Early involvement of the responsible body for the navigational safety in the project can enhance the chances for practical and workable solutions without increasing the risks. Examples of practical and workable solutions can be:

- Agreement for reduced sailing speed at the construction site;
- Identifying time windows where no major vessels such as cruise ships will have to pass the worksite,
- Usage of harbour facilities like quay lines for the safe temporary mooring of the tunnel elements rather than in the waterway;
- The use of fendering and protection constructions around the site and on the tunnel elements;
- Usage of buoys and markers around the construction site and the (temporary moored) tunnel elements.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

The planning, construction and maintenance phases require some specific considerations as follows:

Planning phase

The following should be considered during early scheme development, in the design and then subsequently by the contractor performing the detailed planning of the project:

- Impact of complete or part closure of the waterway.
- Impact of speed reduction at the construction site.
- Impact of narrowing the fairway at the construction site.
- Impact of transport of tunnel elements.
- Risk assessment of vessel collisions with tunnel elements or with temporary works such as cofferdams at the shoreline.
- Impact of soil investigations / survey on site.

Construction phase

The following activities may impact on the navigation channel during construction and will require specific navigation planning:

- Floating demolition / installation of (sheet) piles and bank protection-works.
- Dredging works.
- Diving works.
- Transportation of tunnel elements.
- Immersion of tunnel elements.
- Sand flow / gravel bed works.
- Backfill works.
- Finishing works.

Maintenance phase

During operation there may need to be some maintenance activities that could affect navigation as follows:

- Survey inspections on the protection layers.

During all phases close communication with the harbour/navigation authorities and all other relevant stakeholders is very important and should be started as soon as possible in the project.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

Closure

The complete closure of the waterway for shipping traffic is clearly the activity that would have the most impact to navigation. In most projects the waterway is completely closed during the immersion of each of the tunnel elements. This closure typically takes 48-120 hours, although in the process of immersion certain windows can be created to let ships pass under restrictions of speed and location within the closure. The number of closures depends on the number of tunnel elements. It would be unusual to implement a full closure for the dredging and backfill operations but this might be considered for narrow waterways or for use of specific equipment.

Depending on the execution method the tunnel elements can be immersed with large intervals of 6-8 months (the time it takes to produce a tunnel element) or relatively short intervals of minimum 2 weeks if the tunnel elements are all ready and moored on a site nearby.

Fixing the dates for the closures at an early stage can be beneficial for all parties. This enables the harbour authorities or waterway and shipping administration to communicate these dates in a timely manner to the relevant stakeholders and shipping companies. It is advisable to reserve more closures than strictly necessary as backup for cancelations of the immersion operation due to weather conditions or other reasons. The determination of the closures (duration and time) is ideally done in close cooperation between the client, the contractor and the harbour authority or other responsible body for the navigation.

The execution of the immersion works is drawn up in several specific method statements and communication plans. Shortly before a closure there are a number of Go-NoGo decisions where the client, the contractor and the harbour authority sit together to discuss the continuation of the plan. Navigational considerations will be considered in this decision making process.

During the immersion the waterway is closed mainly because of the presence of the floating tunnel element and the steel cables running to the shores. The immersion spread has a typically low visibility to shipping because of the low freeboard of the tunnel element and the long steel cables running from shore to shore. Visibility of the floating element and cables is especially poor at night.

This closure is often guarded by the authorities with patrol vessels on either side of the site. Experience shows that smaller vessels do not always obey the signs and notifications. Small vessels, fishing boats and recreational vessels do not always have a radio on board and can move fast. Therefore, the guarding patrol boats need to be able to approach them and stop them before they arrive on the immersion site.

If the immersion operation runs smoothly sometimes the closure can be ended sooner and waiting ships can pass over the just immersed tunnel element.

Speed reduction

Passing ships can produce waves and currents which can hinder the immersion works. The magnitude of the effects of waves and currents is related to the ship's speed squared. The project is especially vulnerable to the influences of passing ships when a tunnel element is present, moored or just immersed. The determination of loads and load cases from passing ships on a tunnel element is derived from complex modelling and calculations.

The minimum speed for a ship to be able to manoeuvre without the aid of tugboats varies per ship and ship type, wind conditions, channel width and current speeds. Ship speeds below 2 Knots (3.7 km/hr) are normally not possible. The required minimum ship speed is relative to the water, so the minimal speed over ground (SOG) can be different when there is current. Going upstream the SOG can be less than going downstream.

Narrowing the shipping channel

Any works that can lead to a change in the width or position of the original fairway should be communicated well in advance with the waterways and shipping administration or any other responsible body. They can investigate if the proposed temporary situation is safe for navigation and communicate these changes in a timely manner to the relevant stakeholders by releasing an announcement to shipping. Sometimes a licence for these works needs to be applied for.

The work site has to be marked with the appropriate signs, buoys and lights.

Transport of a tunnel element

Tunnel elements can be produced at remote location to the construction site. Sometimes the production location can be many kilometres away from the immersion location. Transporting the floating tunnel element from the production location to the immersion location or temporary mooring location is a marine operation which usually involves a spread of tugboats. This operation will require a thorough investigation of navigational issues that may arise along the tow route.

Because of the large weight of a tunnel element, the spread does not react very responsively to changes in course or speed (manoeuvrability). The main characteristics are that it usually moves slow, it is long and wide, has a draft of approx. 10m and is hardy visible because of the low freeboard, approx. 0.2 – 0.5m. Therefore, it can be a hazard to other shipping.

Because of this the transport route needs to be evaluated in detail, if needed with the help of ship simulation software. Sometimes the shipping traffic on this route will have to be stopped temporarily.

This evaluation can be part of the transport plan.

Important things to consider are:

- Type of waterway: River, canals, lakes, inland waterways, offshore.
- Physical obstruction: water depth, bridges, locks, quay walls, channel alignment.
- Navigation aspects: ship traffic, temporary relocation or closing of shipping channels.
- Hydraulic aspects: current, tides, waves, water densities.
- Meteorological aspects: wind, fog, storms, hurricanes, typhoons.
- Refuge areas: shelter areas and moorings during severe weather.
- Towing aspects: towing speed, manoeuvrability, width of towing array of tugs, escort by maritime authorities.

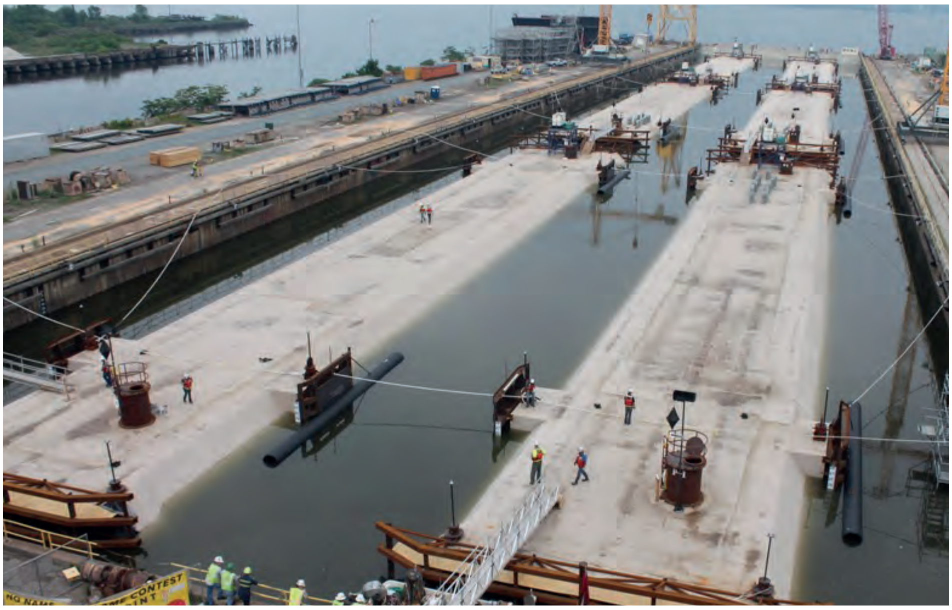


Figure 1 : Elements in flooded dry-dock.

- Harbour facilities: departure and arrival facilities in case a transportation barge is used. Sufficient sheltered water depth is needed to float the element on and off the barge.
- Structural capability: the element must withstand the anticipated load to which it will be subjected during transport.
- Environmental aspects: avoid the need to dredge waterways to provide passage for elements.
- Other issues: the skill of the people planning and participating in the transport operations, provision for contingencies such as tug breakdown, broken cables, leakage in the element, and so on.

Collision between a ship and a tunnel element

In the unlikely event of a collision between a ship and a (concrete) tunnel element, the ship is likely to suffer more damage than the tunnel element because of the strong heavy reinforced concrete construction.

There are three weak points on a tunnel element nevertheless, that mean navigational measures are needed to prevent collisions occurring:

1) The bulkheads on either side are much thinner than the rest of the tunnel. A direct hit with the bulb bow of a ship could lead to failure of a bulkhead and the tunnel element would sink. The bulkheads are placed just in from the end of the tunnel element where they are better protected.
2) The prestress system. When a tunnel element is built from segments of about 20-25m long, the segments are temporary joined together by prestressed cables. The load from a ship impact could be higher than the load the prestress system is designed for, which could lead to failure of the structural integrity of the tunnel element. This accidental load is not normally designed for and other measures such as navigational controls are put in place to reduce the risk to an acceptable level.
3) The Gina gasket on the primary end is easily damaged, even by small crew boats. During transport the Gina is protected by a temporary structure and fenders. For this reason, tunnel elements are often transported with the secondary end (the end without Gina) as bow.

Figure 2 : Elements in flooded dry-dock.

DOCUMENTATION (FORMAT, DEADLINES)

The proposals for managing the navigation in the waterway during construction should be documented in the project method statements, risk assessments, work procedures, safety and emergency plans.

The requirements that have been agreed with the responsible navigation authority should be captured in design and planning documents early on so that they form the basis of the project development and are built into the construction contract procurement documentation.

EXPECTED VALUES

(Temporary) mooring location– Navigational Safety

In order to ensure the safety of the tunnel elements at a temporary mooring location a combination of the following signaling devices can be used. Namely;

- Signage
- Buoys
- Lighting
- Virtual AIS (Automatic identification System)

Signage

Each country has its own guidelines regarding the waterways and shipping marks. Depending on the country the markings have to meet the requirements. In this document the Dutch requirements are used as an example.

Full obstruction

One of the options often chosen for construction is to fully close the waterway. In this case all the shipping has to be diverted to another waterway. According to the Dutch guidelines, Richtlijnen Scheepsvaarttekens -RST 2008, the following sign may be applied for this case.

- A.1. Sailing into, out, or passage prohibited (general sign).
  When using this mark for permanent one-way traffic at fixed bridges a D.1b sign is placed on the side where passage is allowed.

A1.

D1.b.

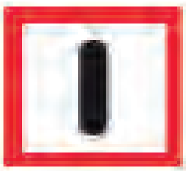
• A1.a: Sailing into, out or passage prohibited from both sides.
Waterway is out of order. The prohibition doesn't apply to small ships, not being a motorized vessel.

Partial obstruction

Another way is to close the waterway partially. In this case the following signs may be applied. Namely;

• A.9. Forbidden to cause inconvenient water movement.
The sign is used in places where it is not clearly visible to the skipper if any nuisance could occur without changing the boat speed.

• B.8. Obligation to pay particular attention to.
It is recommended that this sign is provided with an explanatory text below.
If waterway narrowing, limiting the depth of water or limiting the vertical clearance is indicated, it is necessary to make use of the relevant limitation signs, (C-marks), with a sub-sign with explanatory text.



• B11. Obligation to use a radio.
Obligation to use the radio using the appropriate rules laid down by general legislation, or to report at the designated VHF channel. With the introduction of the radio requirement (one or two radios depends on the fairway) and the blocked channel, the use of this traffic sign is increasing in popularity. Usually the number of the relevant VHF channel is indicated onto the sign.

• C3. Limited width of passage or fairway.
The available width is indicated in meters. The sign is used to draw attention to the limitations of normal width available.
It is recommended to indicate the reason for the restriction on a sign below.

• C.5: The fairway is located at some distance from the shore.
The fairway is located at some distance from the shore. The common number on the sign indicates the distance in meters that ships should remain from the shore, measured from the board. The sign may be used in waterways, in particular canals, where the use of buoys and / or means of signaling is not practical. The sign serves as a warning for shallows along riverbanks, where rocks may cause hazard to shipping.

The signs C3 and C5 are often combined with the sign A.2:
Running along not allowed. Normally it is used in situations where passing or overtaking is impossible or can be hazardous.

SIGNAGE SUMMARY		
In, out or passage prohibited (general sign)	A.1.	
Forbidden to cause inconvenient water movement.	A.9.	
Sailing into, out or passage prohibited from both sides	A.1.a	
Obligation to pay particular attention to	B.8	
Obligation to use a radio	B.11	
Limited width of passage or fairway	C.3	
The fairway is located at some distance from the shore	C.5	
Overtaking could be impossible or can be hazardous	A.2	

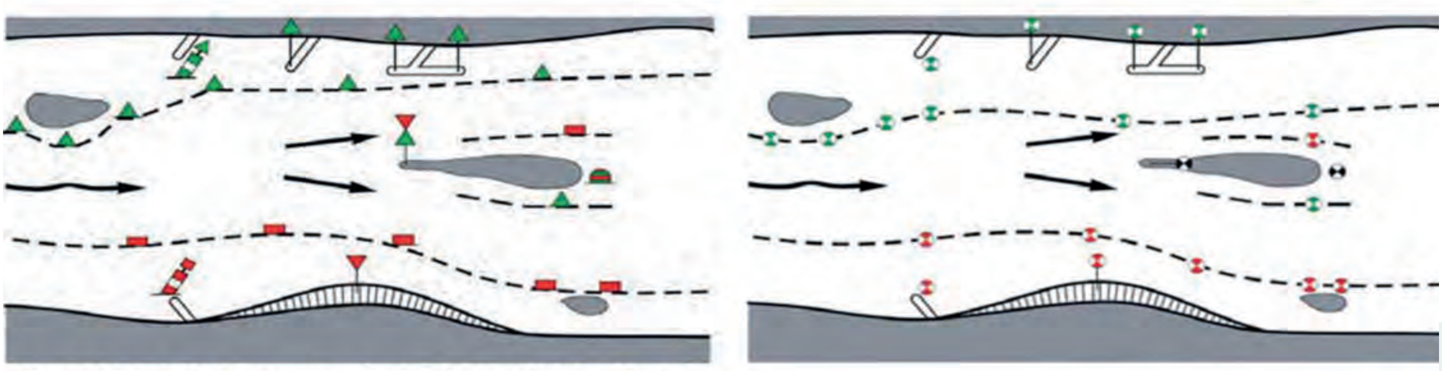


Figure 3: Marks in the SIGNI-system - daytime (left) and nightime (right).

Marks in the water

There are multiple systems to mark the fairway/ waterway depending on the country. For example, in the Netherlands there are two systems, SIGNI and CEVNI. The IALA-system is an international system that marks the fairway on open sea.

The buoys are equipped with lights, power supply by solar panels and a radar-reflector on top of the buoy.

Examples of markings are shown in Figure 3

Cardinal buoys

Another option to mark an obstacle in the fairway is to use cardinal buoys. As seen in the Figure 4. Every side (north, south, east and west) of the obstacle is distinguished by a specific buoy. Through the specific buoy you can determine were the obstacle is located, even if it's under water.

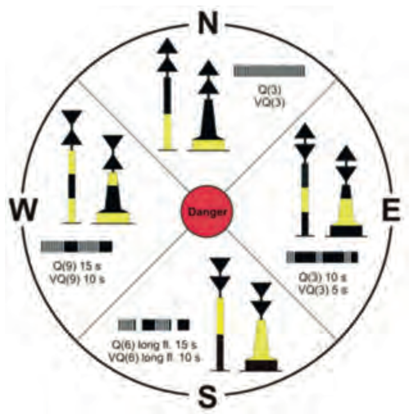
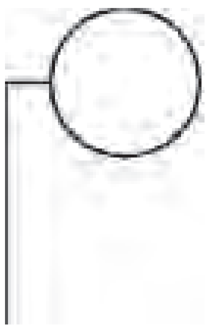


Figure 4 : Cardinal buoys.

Lighting

The Dutch requirements state that an obstacle in the fairway must be marked by lights with a 360-degree visibility angle.

Used symbol:



An immersion element can be marked as in the Figure 5. There have to be multiple lights on the element that are visible during day and night with a 360-degree angle.

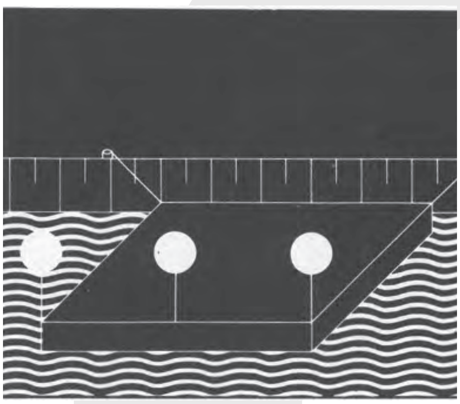


Figure 5 : Lighting of moored objects.

For a moored floating object signal lights on waterways have to meet a certain illumination defined in standards and to be safe the lights on the element could be chosen based on these requirements. This makes sure the lights are always visible during day and night and doesn't blind people because they are too bright.

DRIP (Dynamic Route Information Panel)

By calling the obstacle to the attention of shipping long before the obstacle, the ships are able to anticipate earlier. These warnings can be shown on a mobile DRIP with a warning text on it.

Figure 6 : Mobile DRIP.

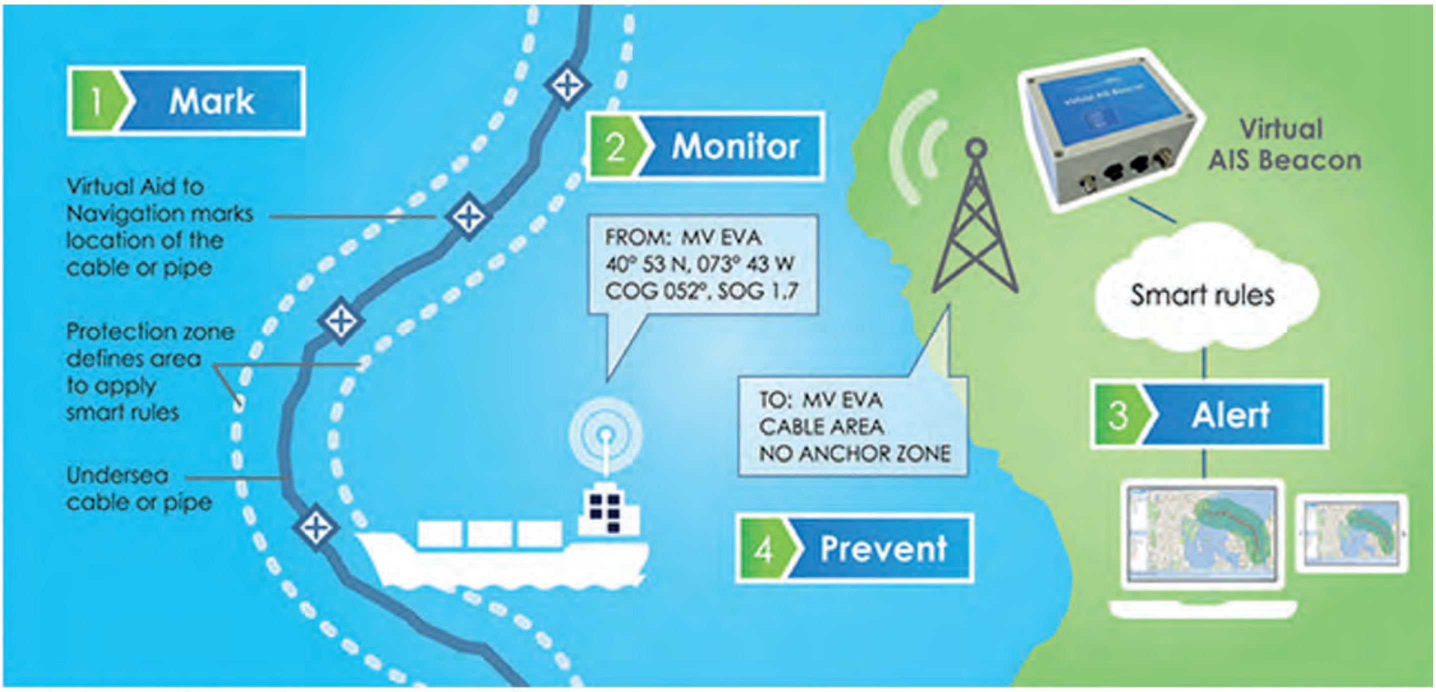


Figure 7: Virtual AIS example.

Virtual AIS

AIS (Automatic Identification System) is used to identify objects in the waterway. These objects can be ships or in this case a tunnel element. Nowadays it's possible to use virtual AIS beacons. The virtual AIS beacons can be installed on any location on shore. The beacon can be programmed to make an AIS spot on a random location like somewhere on open sea or on an immersion element. The element will be visible on all AIS systems and ECDIS on board. The great benefit is that no beacons have to be mounted on top of the element. This option will probably only be used for long-term mooring.

ANALYSIS (REQUIREMENTS, TIMESCALE…)

For some projects with high marine traffic volumes or with large vessels using the waterway, navigation computer modelling is performed. Modelling can be used to assess the safety for vessels for different scenarios for diversions or restrictions to the widths of navigational channels, to determine the acceptability of measures and to satisfy authorities. The outcome of the modelling can then be used to define the project requirements for the contractor. The necessity for such modelling should be discussed with the relevant authorities at an early stage in the project planning.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

N/A

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

Specific nautical things to consider from a project point of view:

- The time scheme of arrival and departure of some ships can be very hard and costly to alter.
- Ships cannot stop instantly.
- Ships need a minimal speed to be able to manoeuvre / steer.
- Line of sight from the bridge is not great, there are large dead corners around a ship. Small vessels, wires and an almost completely submerged tunnel element can easily be missed. Make use of signs, buoys, lights, radar reflectors and AIS markers.
- If the passage looks free, some boats might give it a try anyway.
- Communication directly with the ships and harbour authorities is best done by one person who is aware of the local protocols.

Specific items to consider from a nautical point of view for immersed tunnel transport and immersion:

- A tunnel element is a large concrete hollow box with a displacement of approx. 20.000-60.000 tonnes with a freeboard of only a few decimetres.
- Steel wires run from shore to shore and are not visible.
- The immersion operation is very slow, hardly any movement or action visible, it is a very difficult and delicate operation though.
- Diving works are part of the immersion operation.

- The construction crew might use the radio in a different way and may not understand specific wording.
- When passing the construction site observe the maximum (reduced) speed, since the tunnel element is very sensitive to return currents from ships in this phase.

LINKS TO OTHER OWNERS GUIDE THEMES

Annex 15 Tunnel element transportation.
Annex 26 Dredging
Annex 28 Foundations and Settlement
Annex 29 Backfill

PERFORMED BY / RESPONSIBLE

Owner/Owner's consultant:

Early engagement with authorities during design development.

Designer:

Development of the scheme to account for authority requirements.

Contractor:

Detailed planning of works and navigational provisions in consultation with authorities.

Implementation :

Coordination with authorities for notices to mariner and supervision of navigation through the work site.

Annex 36 >> Tolerances

During the construction of an immersed tunnel the accuracy of the construction is critical. The +/- tolerance that has been assumed in the design for each dimension, level or material density should be clearly specified in the construction documentation. Tolerances should be determined in relation to the plant and equipment envisaged for construction and the performance requirements of the tunnel, such as the factor of safety against uplift or the required accuracy of the road or railway alignment.

This annex summarises the critical areas that should be considered. Many items are also dealt with in other annexes but are included here for completeness.

WHAT

Every aspect of construction requires a dimensional tolerance to be considered. Once a tolerance has been assumed in a design it becomes a constraint for construction. Failure to build the tunnel within the allowed tolerances may result in a non-compliance with the project design or operational criteria.

Tolerances should be considered early in the design process and the potential impact of accumulating tolerances should also be considered. The immersed tunnel method of construction requires specific consideration in the following areas:

Vertical stability against uplift

The possible variation in construction dimensions and variation in materials properties must be considered in the vertical stability assessment. The possibility of thinner structural sections in the tunnel elements leading to less weight must be considered and lower bound materials densities should be considered.

It would be unrealistic to assume that the worst case structural thickness tolerances apply for a whole tunnel element. A probabilistic approach to account for structural tolerances is therefore appropriate in the early design phase and as-built survey should finally be used to confirm geometry.

The combination of thin structural sections and lower bound material properties should be used to determine the temporary ballasting requirements for immersion of the tunnel elements.

Floating freeboard

Upper bound material densities should be considered together with variations in structural section thicknesses that increase the weight of the tunnel element. The design should ensure a minimum freeboard is attained in all conditions that meets the requirements of the transportation and immersion methodology.

Watertightness of immersion joints

The design of the primary sealing gasket in the immersion joint should take into account the following:

- Tolerance to the mounting surface
- Joint opening/closing due to rotation caused by settlement
- Placing accuracy of the tunnel elements
- Variation in environmental conditions

The specified factor of safety on sealing pressure should be achieved in all circumstances.

Alignment of road or railway

The accumulation of vertical positional tolerances should be considered for the effect that these may have on the final alignment of the tunnel. The effects of initial placing accuracy should be considered together with the short term and long term settlements. This applies to all transportation tunnels but becomes more important for railway tunnels which have strict alignment criteria.

The tunnel structural dimension tolerances must also be considered to determine the additional space that must be provided on the outside of vehicle clearance profiles to ensure that the profiles are always maintained.

Forming closure/terminal joints

The last piece of construction for an immersed tunnel is usually the closure joint or terminal joint which completes the space between the last two tunnel elements that are placed, or between the immersed tunnel and the approach tunnels.

These joints need to allow for potential variation in the length of the space to be filled due to an accumulation of +/- tolerance on each tunnel element or in the final compression of the Gina gaskets. This variation must be considered both for the permanent works and the temporary works equipment e.g. for dimensioning the closure formwork panels placed around the tunnel to enclose the space and enable internal dewatering.

Precast closure joint systems such as the V-wedge are particularly sensitive to tolerances and final sizing and construction of these may wait until the joint gap can be measured. Insitu closure joint construction can compensate for variations in geometry more easily.

Specific tolerance considerations

To ensure the above aspects are controlled in the design and construction process the following areas must be considered:

- Structural tolerances
- Immersion joint tolerances
- Foundation and settlement tolerances
- Element placing tolerances
- Internal spatial allowances

1) Structural tolerances

Dimensional tolerances for the formed surfaces of a concrete structure are dependent on the type of formwork and falsework used. National specifications and design codes for general civil engineering concrete works often set out requirements for dimensional accuracy of member thicknesses and span dimensions and can be used in the absence of other specified requirements

Factory construction of tunnel elements using hydraulically controlled steel formwork can usually be completed to a greater accuracy than elements constructed insitu. However, this type of construction should not be considered as being “precast” but a higher accuracy than a conventional insitu operation is achievable.

The accuracy of steel construction member thicknesses and span dimensions is controlled by the specifications applied in the cutting and fabrication processes and a high level of accuracy can usually be obtained.

2) Immersion joint tolerances

Immersion joint tolerances comprise planar and local tolerances. These must be considered together and for each side of the immersion joint to assess the likely joint gap and the impact on the sealing behaviour of the gina and omega gaskets, see Figure 1.

3) Foundation and settlement tolerances

Foundation tolerances should include the tolerance of gravel bed or the accuracy of the support jacks (if a sand foundation is used) and the dredging tolerance. These combine to determine the nominal thickness of the foundation layer, see Figure 2 for the gravel bed solution.

Settlement can cause variation in the dimension of the immersion joint gaps, see Figure 3.

4) Element placing tolerances

Both vertical and horizontal accuracy of placing elements needs to be considered. Space is usually allowed in the internal clearances to accommodate possible steps in alignment between adjacent tunnel elements.

The primary end of a tunnel element can have smaller tolerances due to the guidance systems used during immersion, the secondary end is free and is controlled with less accurate systems so a larger tolerance is usually allowed.

Deviation of the secondary end from its intended alignment will result in variation in the gap between immersion joint end frames at the primary end.

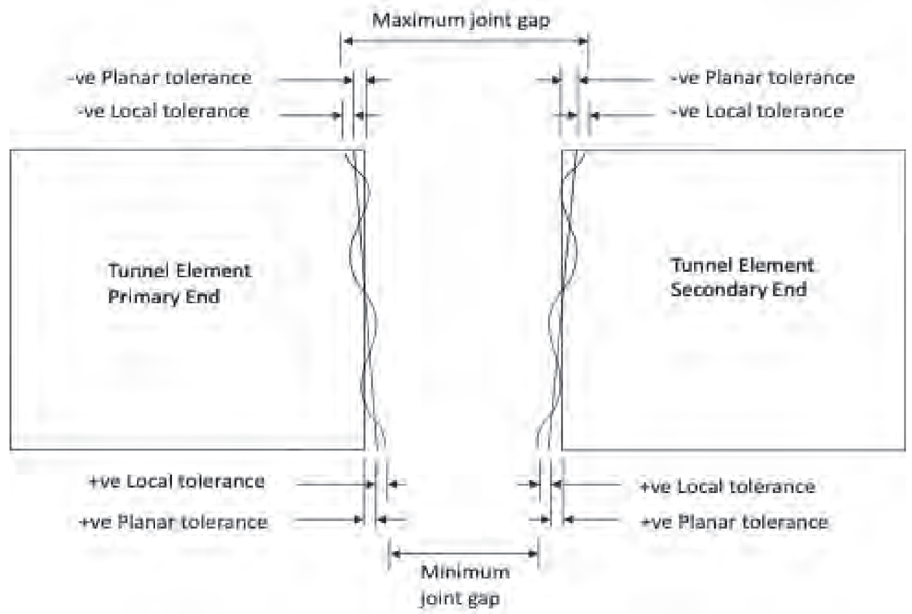


Figure 1 : Tolerances on immersion joint end frames (Lunniss & Baber 2013).

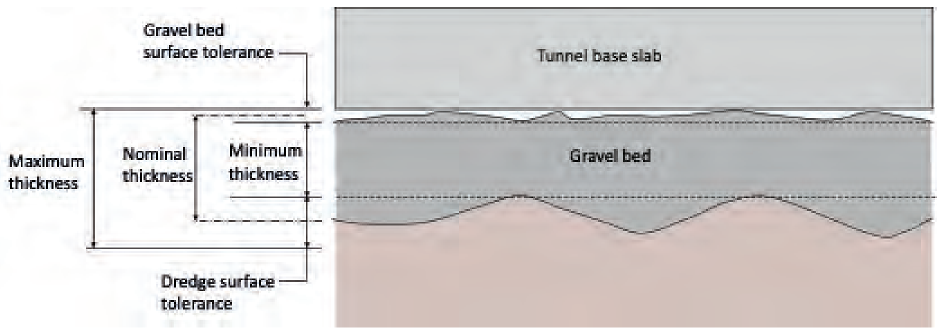


Figure 2 : Gravel bed tolerances (Lunniss & Baber 2013).

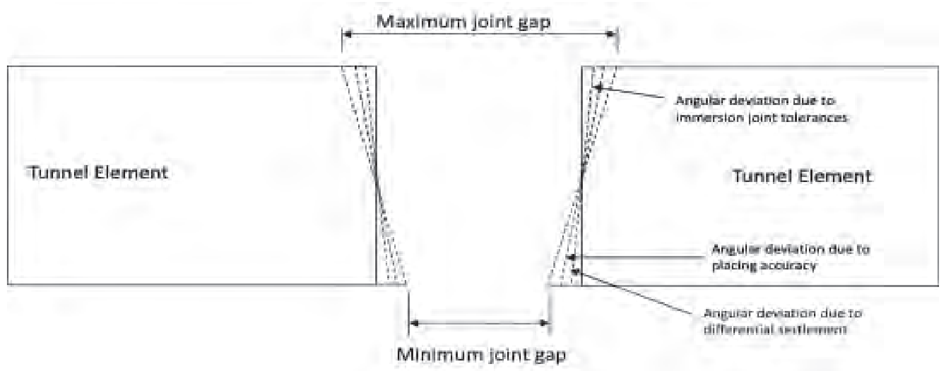


Figure 3 : Tolerances affecting immersion joint gap (Lunniss & Baber 2013).

5) Internal spatial allowances

There are a number of spatial allowances that must be considered for the internal height and width of the tunnel tubes:

- Deflections of structural spans when formwork is released and as a result of long term creep.
- Differential settlement is a critical aspect to consider and usually some space is added into the tunnel to allow for this to occur. A proportion of the short term settlement may be compensated for if it occurs before the shear key connections between tunnel elements are formed. Indeed it may be an advantage to allow a degree of differential settlement to occur so that shear key loads are reduced, provided there is no detrimental effect to the immersion joint sealing and sufficient spatial allowance has been made.
- Long term shrinkage and thermal expansion and contraction will have a very small effect on clearances but should always be considered.
- Traffic, operational and equipment clearances.
- Alignment curvature within straight tunnel elements. This may require additional headroom or width.
- Installation tolerance of rails and trackbed or road surface construction.

TYPICAL VALUES	
Structural thickness	Often defined in design codes but should be reviewed according to the method of construction. Typically +/-10mm tolerance is specified on the concrete section thickness and setting out dimensions and a lesser +/- tolerance on steel thickness.
Rail alignment	Often defined as angular deviation from designed alignment over a specified distance. This can require special features at joints such as rocker slabs, to smooth deviations.
Steps between adjacent tunnel elements	Depends on accuracy of screeded gravel or control of support jacks. Typically +/- 20mm.
Global settlement	Often this is not an issue and so is not specified as a limit. Differential settlement and alignment criteria more often will govern.
Differential settlement	There is no need to specify a limit if design can accommodate it and the performance/ functional requirements are met. If defined, it must be very clear how the limit is to be assessed e.g. across joints or over a specified distance.
End frame	+/-3mm on mounting surface for Gina gasket is typical. Local tolerance needs to be considered e.g. steps at welds, as well as planar deviations over the width/height of the end frame. Combined tolerance on both the Gina mounting plate and the opposite sealing plate needs to be considered to ensure the combined effect on the sealing is acceptable.
Dredging	Depends on depth of water a dredging equipment. Typically +0, -250mm to -500mm.
Gravel bed surface	+/- 25mm can be achieved in good conditions. In offshore conditions may need to relax to +/-40mm. Accuracy achievable will also depend on water depth and river/sea conditions. Accuracy of survey equipment must also be taken into account.
Vertical position of tunnel elements	• **Gravel foundation -** Depends on gravel bed screeding accuracy. Also need to consider bedding in and immediate settlement to get initial position on placing of the element. • **Sand foundation –** Depends on accuracy of control of support jacks, typically within +-20mm.
Horizontal position of tunnel elements	At primary end +/-20mm should be easily achieved with guides. At secondary end typically +/-35mm but may be greater. This depends on length of the tunnel elements and control systems for immersion.
Material densities	For design allow +/-5% around characteristic values if no specific testing data is available. Narrower band can be used during construction as density is verified by testing.

Table 1 : Typical values.

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

Design stage

A strategy for dealing with the tolerances described should be developed during the preliminary design stages and during the tender design on Design and Build projects.

Construction stage

Surveys to check compliance with the stated tolerance limits are required:

- Dimensional survey of immersion joint end frames to verify accuracy of gina mounting surface.
- Survey of dredged surface and gravel bed level accuracy is needed ahead of placing tunnel elements.
- Weight survey of the tunnel elements is needed ahead of floatation. This needs detailed geometric survey and core samples to determine concrete density.
- As placed position of tunnel elements in three dimensions is needed before marine equipment is released to enable adjustments to position is necessary.
- Settlement surveys are needed throughout construction after elements have been placed to record settlement per element/ segment as different stages of the project are complete e.g. ballasting and backfill.
- Final geometric survey should be completed before handover to the client as part of the as-built records.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY ...)

Common tolerances specified include:

- Structural thickness
- Steps between adjacent tunnel elements

- Tolerances in relation to alignment e.g. permitted angular deviation over specified length.
- Limitations on global settlement
- Limitations on differential settlement
- End frame planar surface variation
- Dredging accuracy
- Accuracy of gravel bed surface
- Vertical position of tunnel element on temporary supports
- Variation in material densities
- Horizontal placing accuracy of tunnel elements
- Survey accuracy

DOCUMENTATION (FORMAT, DEADLINES)

Design

Assumptions have to be made during the initial design, based on experience of what can be achieved in construction. The assumed tolerances should be documented in a design basis. For detailed design, if performed for a client, the tolerance assumptions should be transferred to the contractor in the contract documents.

If detailed design is performed by a contractor the client's specifications should be as open as possible, to allow the contractor freedom to meet performance requirements in the manner which is most optimum for them. In this instance the contractor needs to document how performance requirements will be met by the design and construction method.

It is advisable to prepare a combined tolerances drawing for the tunnel cross section showing all assumed tolerances to verify nothing has been overlooked.

Construction:

Tolerances to be achieved should be stated within the construction method statements together with the survey procedures to verify compliance.

As-built drawings and records:

As-build records should include all survey records obtained during construction and non-conformance close-out records.

EXPECTED VALUES

Typical values are shown in table 1.

ANALYSIS (REQUIREMENTS, TIMESCALE…)

Design should identify all tolerances and combinations of tolerances to develop the internal space proofing, to ensure the design alignments can be achieved and to carry out the design of the tunnel joints. Validation of design is also required for these aspects.

Survey control is required during construction (see earlier).

Equipment and devices for construction should be selected/designed to achieve required accuracy.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

N/A

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

If the tolerances assumed in the design are exceeded it can result in non-compliance with the design criteria or functional requirements of a project.

The more significant impacts arising from "out-of-tolerance" could be:

1) Unable to meet alignment design criteria for road or railway.

If the design approach is thorough and sufficient internal space has been provided the risk of this occurring should be low. Clear criteria for acceptance are needed for placing tunnel elements that are signed off by client and contractor following survey immediately after placement. Pre-determined remedial actions for potential non-conformances should be developed as part of the method statement e.g. what are the criteria that would trigger the need for re-immersion?

Settlement compensation e.g. preloading to force early settlement of one element to bring into alignment is not generally recommended. It may accelerate settlement in short term but generally evens out in long term and there could be a risk of overloading structure shear keys.

2) Structure is too heavy leading to low freeboard or inability to float, or too light leading to inadequate FoS against uplift in permanent condition.

The risk should be low if construction surveys are undertaken on dimensions and material densities. These should give time for remedial measures to be developed.

3) Immersion joint seals have insufficient FoS for sealing against external water pressure.

Detailed surveys are required during construction to identify any out-of-tolerance. Steel mounting surfaces can be built up or ground down as needed.

4) Difficulty in completing the internal finishing works e.g. joint finishing concrete, continuous cladding, drainage etc.

Steps across joints needs to be within defined limited to ensure facilities can cross the joint interface. Detailing of internal facilities must account for an amount of joint misalignment and variation in joint gap.

LINKS TO OTHER OWNERS GUIDE THEMES

Annex 14: Tunnel Element Alignment
Annex 06: Immersion Joints

PERFORMED BY / RESPONSIBLE

The suggested responsibilities with regard to tolerances are:

- Specification of construction tolerances (where relevant to the design): Designer/ Owner
- Specification of construction tolerances (where relevant to methods): Contractor
- Verification by survey of compliance with tolerances during construction: Contractor
- Remedial measures during construction: Contractor

Annex 37 >> Dualling Tunnels

Due to the limited space and clustering of infrastructure, new tunnels more and more have to be constructed in the close vicinity of an existing tunnel, which usually has not been designed for that scenario (Figure 1). The list of projects (realised or under construction) shows that this so-called 'dualling of tunnels' is becoming common. Recent examples include the 2nd Coen tunnel and 2nd Benelux tunnel in The Netherlands, New Tyne Crossing in the United Kingdom, 2nd Midtown tunnel and the Thimble Shoal tunnel in the United States.

WHAT

The construction activities for a new tunnel might influence the behaviour of an existing structure, either by affecting the foundation strength and stability (e.g. causing compaction or liquefaction due to vibrations) or by disturbing the equilibrium state (due to excavation/ dredging).

In order to control the risks involved, the dualling of tunnels imposes specific requirements on both design and construction stages.

The key parameters are the distance between the tunnels and their (relative) depth. As the distance between the tunnels increases, attention should still be paid, but extensive measures can be avoided. An illustrative example is the 2nd Benelux Tunnel near Rotterdam in The Netherlands (Figure 2). The clear distance between the two tunnels is approximately 35 m, and the trench was made as a sloped excavation, leaving the support stability and the lateral equilibrium of the existing tunnel more or less unaffected.

When the two tunnels are sufficiently close that construction of the new tunnel could affect the old, construction methodology might have a strong influence on the design, e.g. the 2nd Coen tunnel Project near the Dutch capital Amsterdam (Figure 3). The clear distance between the tunnels is 12 m, whereas the trench depth was almost 10m. A separation wall prevented loss of stability of the existing tunnel.

In the case of the parallel Second Midtown Tunnel (Norfolk, Virginia, US) the alignment of the new tunnel was made to curve away from the existing tunnel so that the separation was greater as the tunnel grew deeper. This provided greater safety in dredging in the softer bottom materials.

In general, the primary risk generated by the construction of a new tunnel adjacent to an existing one is failure of the existing structure to maintain water-tightness, safeguard the public and fulfil its functions. A typical ultimate limit state failure might be complete structural failure or inundation, whereas a serviceability limit state failure might be unacceptably large deformations or leakage. The primary risks are related to and can be expressed in terms of the behaviour of the tunnel itself, such as sand flow bed compaction or joint failure. In order to manage such primary risks, protective measures may have to be taken, such as protective walls, compensation excavation (to avoid disturbing equilibrium), ground treatment or strengthening.

Secondary risks are related to failure of these protective measures, such as a landslide in the trench slope, erosion due to current or propeller wash, or separation wall failure, perhaps due to wave loads or a dragging anchor. The construction of the protective measures themselves (such as the separation wall) could impose secondary risks for the existing structure as well, due to e.g. settlements caused by vibrations.

Figure 1 : Immersion operations next to existing immersed tunnel (left).

WHEN (START-FINISH & MEASUREMENT FREQUENCY)

In the design development and contractor's bidding phase attention should be paid to the risks involved with the existing tunnel and the possible need for costly mitigating measures. The need for and the feasibility of protective measures should be examined, as well as the effectiveness of mitigating measures in case of failure of the protective measures. A preliminary design is needed to have a clear insight to feasibility and risks.

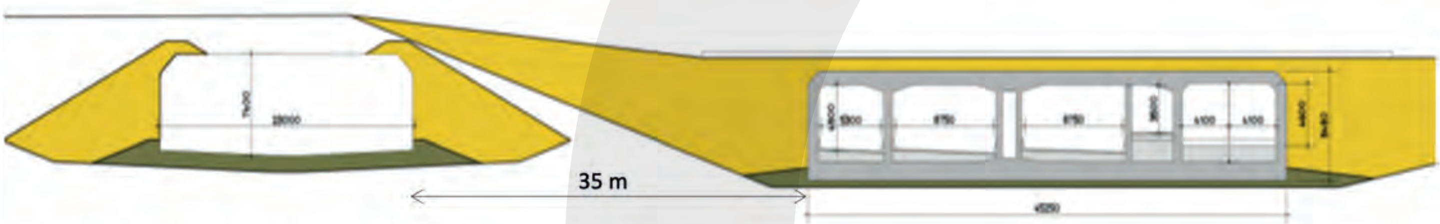


Figure 1: Existing (left) ans 2nd Benelux tunnel.

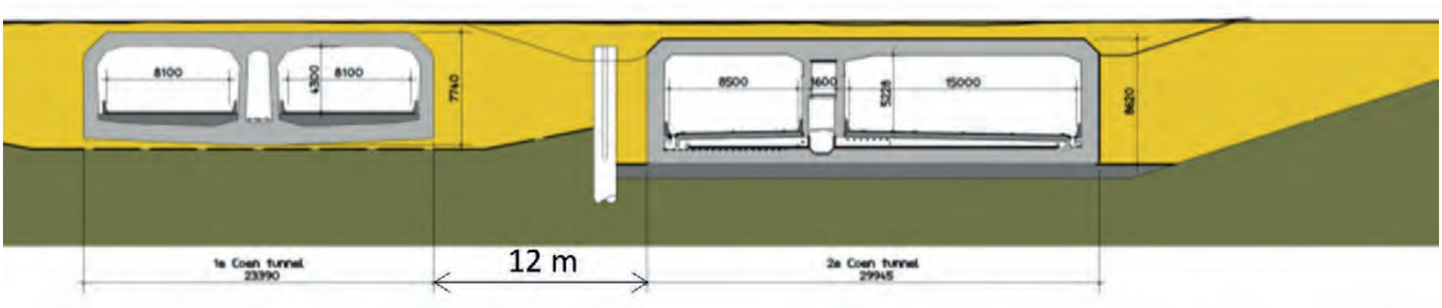


Figure 3 : Existing (left) and 2nd Coen tunnel.

In order to avoid unnecessary risk reservations from contractors, soil investigation results have to be provided by the client. The client has also to provide some risk related performance indicators (such as acceptable deformations or leakage flows) and criteria (maximum allowable values).

In the detailed design phase, the risks have to be quantified and transformed into design scenarios. The design of protective measures will result in requirements and specifications for the construction phase. For example, a separation wall design depends on the trench depth, which is influenced by the tolerances related to the dredging equipment. The design of protective measures therefore has a close connection to other aspects of design and the construction methods to be applied. In this phase, extensive soil investigation has to be carried out to obtain well defined boundary conditions.

In this phase too, a monitoring system should be designed and implemented to acquire baseline information about the movements of the existing tunnel prior to construction as well as new movements during construction. In addition to this monitoring system, mitigating measures should be designed in case the stability or integrity of the existing structure is in danger - measures ranging from modifications of the construction process, to extensive measures to secure the stability of the existing structure. At all times the safety of people should be guaranteed, especially when the existing tunnel is still in use during construction as is usually the case.

Special requirements to the construction phase are related to construction methods, monitoring and mitigation when needed.

The presence of the vulnerable existing structure influences the choice for pile systems and suitable separation wall application methods (low-vibration). Pile systems may need to be installed prior to the start of any excavation. In order to avoid failure of the separation wall, or instability of a sloped excavation, dredging equipment should be handled with care and within tight tolerances. Loads or scouring from propeller thrust can be reduced by restrictions related to velocity or manoeuvring.

Throughout the construction process, the existing structure and the protective measures should be monitored continuously. When monitoring data indicates movements are reaching or have exceeded certain well-defined limit values, often called trigger values, mitigating measures should be taken.

SPECIFICATIONS (NUMBER, PRECISION, PLACEMENT, REDUNDANCY …)

As every situation is unique so it is difficult to provide common specifications related to design and construction of tunnels in close vicinity of an existing tunnel.

As a minimum, permitted behaviour of the existing structure should be defined beforehand. The most practical way to do this, is to limit the deformations, rotations and displacements of the existing structure. These limits should be closely and meaningfully related to failure mechanisms. Loss of stability can be expressed in absolute displacements, whereas joint failure has to be expressed in joint deformations (extension, rotation). In order to define the risk of cracking, strains should be limited, but it is hard to choose satisfactory and realistic indicators due to the very local character of this risk (close to joints and at unreachable locations). Besides that, the stresses already present in the structure are unknown. Therefore in practice, only limit values are defined in terms of displacements and joint deformations. When the existing tunnel has no expansion joints, the global curvature can be a useful indicator to limit deformations related to cracking. A more indirect way is to limit the change in condition, e.g. no increase in leakage or no change in existing crack widths is allowed.

It should be realised that it is difficult to establish the condition of an existing tunnel, to determine the baseline condition to measure against and to define the allowable deviations from this baseline.

Any chosen limit value system should be defined in detail and should allow for proper monitoring and mitigation. Definitions like 'no damage' or 'no movement' are too generic or unrealistic. The limit value system should be defined prior to awarding the construction contract, to avoid negotiations on this subject.

It should be noted that expansion joints may have a large deformation capacity with respect to extension and bending, but almost no deformation capacity with respect to shear and torsion.

The monitoring should be designed to capture at least the deformations related to the specified limits. The measurement accuracy has to be chosen according to the sensitivity of the system to variation of the deformations.

For the existing tunnel structure, a typical monitoring system could measure absolute displacements and rotations, relative deformations (curvatures) and relative joint displacements. Outside the tunnel, ground movements could be measured, together with the deformation of temporary works like retaining/separation walls.

DOCUMENTATION (FORMAT, DEADLINES)

With respect to documentation of the design, no specific requirements for the dualling of tunnels exist. Protective measures for existing and potential future adjacent structures form an integral part of any design, perhaps more challenging due to the depth and location of an immersed tunnel and available construction methods for the protective measures. Design decisions should be recorded, in order to be able to evaluate the influence of design modifications on the risks related to the existing structure properly.

Another documentation issue is the disclosure of the monitoring data, and the associated alert system with threshold values. In order to be able to intervene immediately, the monitoring data should be disclosed real-time, e.g. in a web-based environment. As soon as threshold values are exceeded, the system should issue a warning, preferably automatically.

The rationale behind any deformation limit should be documented in the design reports and reference condition surveys, analysis and predictions.

EXPECTED VALUES

Threshold values for the alert system should be low enough to enable timely mitigation, but not too low in order to avoid unnecessary process interruptions. The threshold values should relate to causing permanent deformation or damage and to preserving safety; the trigger levels might be different for each of these.

In order to obtain a clear understanding of the autonomous behaviour of the existing tunnel, the monitoring system should be put into service at least a year before the start of the construction activities in the vicinity of the existing tunnel so that seasonal variations and tidal effects (if any) can be recorded.

The threshold values should be well beyond the autonomous behaviour.

ANALYSIS (REQUIREMENTS, TIMESCALE…)

This section provides some guidelines for the (structural) analyses related to risk assessment or design.

Both risk assessment and the design of measures are based on a clear understanding of the structural behaviour of the existing tunnel in its temporary environment.

Regarding the structure itself, information about the geometry and details is required, including all vulnerable parts. This information enables the development of a proper simulation model, and the identification of failure modes.

In order to limit the structural model and to reduce computational cost, the surrounding environment can be represented in design scenarios, to be expressed by boundary conditions and applied loadings. Both can be regular (support stiffness and strength, soil pressures) or accidental (loss of support, dragging anchor). Risk assessment and design will benefit from a comprehensive identification of possible events related to boundary conditions and loadings. The unique character of any project makes it impossible to give a complete list of possible events here and these will need to be developed on a project-specific basis.

At least worst case scenarios have to be defined (e.g. complete failure of the separation wall over its length or a specified length). More realistic scenarios can be used with respect to the design of mitigating measures and to judge their effectiveness.

Related to the structural calculations a few guidelines for modelling are given here.

For the global behaviour of the existing tunnel, a supported beam model may be sufficient in most cases. The design scenarios might be simulated for instance by local reduction of strength and/or stiffness of the supports, or by addition of a lateral unbalance pressure. As an alternative, an integral structural-geotechnical model can be used.

Depending on the local joint geometry, nonlinear hinges/releases in all directions might be necessary in order to capture the correct behaviour of joints or the complex characteristics of compressed Gina-type gaskets in the immersion joints.

Soil springs might be applied in all directions. Depending on the level of accuracy to be achieved, nonlinear springs could be applied to account for active/passive soil behaviour and, for example, to incorporate shear strength.

For the assessment of local strength (e.g. shear key strength), a detailed model has to be used.

All models to be used should be capable of relating the design scenarios to the indicators and corresponding threshold values/limits provided by the client.

BEHAVIOURAL TOLERANCES (LIMITS, DEVIATIONS)

As stated before, the criteria provided by the client should be meaningful related to failure mechanisms and should be unambiguous.

The criteria should be defined with respect to avoidance of ultimate limit state failure like structural failure or complete inundation. Besides that, the criteria definition should prevent serviceability limit state failure like unacceptable deformations or leakage.

For the 2nd Coen tunnel Project, the client demanded zero joint displacements in the transverse direction (horizontal and vertical), and relative deformations within the so-called risk-diamond between sections at 30 m intervals (Figure 5). The risk diamond allowed relative displacements of 4 mm in horizontal direction and 10 mm in vertical direction.

This criterion however addressed neither the joint rotations nor the curvatures of the tunnel elements. By good approximation tunnel boxes between joints can be considered rigid though, compared to the rotation capacity of the joints.

REMEDIAL MEASURES (FOR UNEXPECTED BEHAVIOUR/VALUES)

A large part of the risk management during construction will be monitoring by observation. Unexpected or undesirable observed behaviour should therefore be acted upon using predefined mitigating measures. A few examples are given here.

Where a separation wall is used, a low-vibration or vibration free installation method is preferred in order to avoid settlements in a loosely compacted material including any sand flow foundation. When wall elements cannot easily be brought in deep enough, methods such as jetting or soil fluidization might help to avoid ramming.

The wall elements can be provided with injection tubes to seal any gaps between them.

A barge with a supply of sand at close hand could enable immediate stabilisation of a side slope failure in the trench or a failing separation wall section.

The existing tunnel can be excavated on both sides to avoid unbalanced horizontal soil pressures.

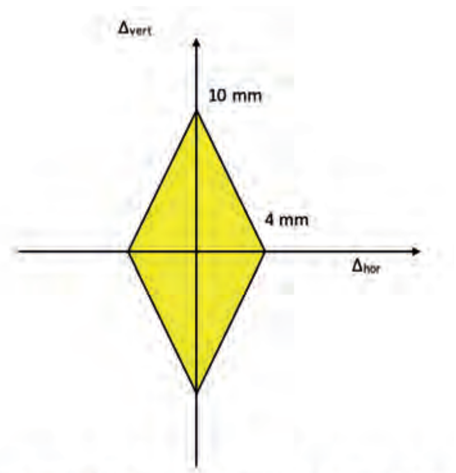


Figure 4 : 2nd Coen tunnel 'risk diamond' with allowable differential displacements in sections at 30m intervals. No torsion or longitudinal limit values were given.

LINKS TO OTHER OWNERS GUIDE THEMES

Annex 28: Foundations and Settlement
Annex 29: Backfill
Annex 26: Dredging

PERFORMED BY / RESPONSIBLE

Design & detailing – designer

Specification of limits for monitoring – Owner

Condition survey of existing structure – Owner (preferably in cooperation with contractor)

Development of construction methods – Contractor

Movement monitoring during construction – contractor (in cooperation with Owner)

Leakage monitoring during construction – contractor

Leakage repair during construction – contractor

Movement monitoring over life – Owner

Leakage repair during operation – Contractor or Owner (depending on contractual requirements for defects liability period after completion of construction)