Chapter I:

INTRODUCTION

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Chapter 1: Introduction

1. Immersed Tube Tunnel Technology—an International Perspective

It is with great satisfaction that we present herewith our report on various aspects of immersed tube tunnel techniques, based on worldwide input of tunnel experts from the U.S.A.; from various European countries, including Sweden, Norway, Denmark, the United Kingdom, The Netherlands, Germany, Belgium, and Italy; and from Japan.

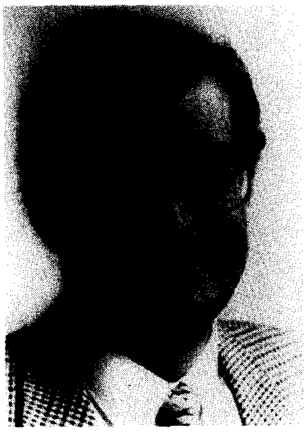
We trust that this report will contribute to a better understanding of the conditions under which immersed tunnels are designed and constructed, as well as the conditions under which floating tunnels will be built in the future.

2. History of the Working Group

The report has been prepared by the Working Group on Immersed and Floating Tunnels of the International Tunnelling Association. The Group was established in 1988, at the ITA's¡ conference in Madrid. Mr. V. L. Molenaar served as the Group's Animateur for one year, after which Mr. P. C. Van Milligen assumed this posistion. The Group's Tutor from 1988 to 1991 was Mr. B. Pigorini, who was succeeded by Prof. A. Glerum.

Work for the report has been carried out by various Sub-Working Groups, managed by Sub-Working Group leaders under the coordination of the Animateurs.

The first meeting of the Working Group was held in Manchester (United Kingdom) in 1989. At that meeting, the Group decided on the Sub-Working Groups for each topic. Each of the five groups established at the Manchester meeting have produced a section of this report.



PAUL C. VAN MILLIGEN
Animateur (Chairman)

Since then, the Working Group members have met about a dozen times within the past four years. In addition to special-purpose meetings, the Group met during ITA Congress meetings and during various speciality conferences.

During the 1989 meeting in Manchester, England, six topics were adopted for future publication. Five of these topics were selected for publication for the 1993 ITA meeting in Amsterdam. It is hoped that the remaining topic, the maintenance of immersed tunnels, will be examined and a report published in the near future.

From the beginning, the Working Group members displayed great interest in reviewing the state-of-the-art characteristics of immersed tube and floating tunnels. For immersed tube tunnels, the examination of the two major construction methods—one practiced in Europe, the other in the United States—was the focal point in setting the Group's agenda.

3. Contents of the Report

This report includes discussions on the state of the art of floating and immersed tube tunnels, with special emphasis on basic features of steel and concrete tube tunnel global construction practices.

Chapter 2 examines structural design features of steel and concrete immersed tube tunnels, including construction stages, accidental loads, load factors for combinations of loadings, and material specifications.

Chapter 3 provides general discussions of construction techniques for immersed tube tunnels, including special attention to data-collection methodology, dredging techniques, environmental impacts, and floating transport.

Chapter 4 deals with specific details for steel and concrete tunnels to obtain watertightness, concentrating mainly on the various joints for steel tunnels and on membranes, coating techniques and joints for concrete tunnels. The last part of this chapter briefly discusses the subject of maintenance in relation to eventual leakages; it is hoped that this topic will be addressed in detail in future publications.

Chapter 5 comprises a catalogue of immersed tube tunnels, both steel and concrete, starting with the first Detroit tunnel in 1910, and continuing through to very recent tunnels that are still under construction.

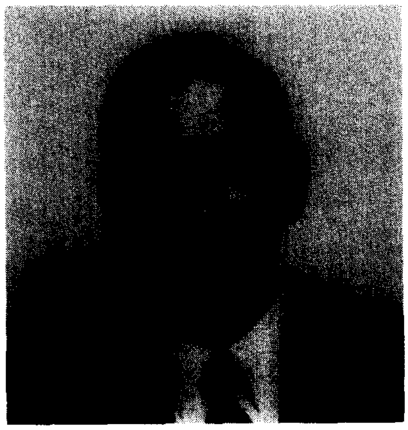
Chapter 6 covers a very special subject—floating tunnels. Although this type of tunnel has never been constructed, it has been sufficiently researched to provide details on possible floating tunnel configurations. The technically feasible techniques presented herein can offer solutions for crossings in very deep waters. Technically speaking, the floating tunnel options examined in this section offer well-known techniques from off-shore construction, as well as from immersed tube tunnel construction. We believe that the time to put such construction into practice has arrived.

4. Acknowledgments

The work presented in this publication represents the results of the Working Group's tireless efforts, conducted on a truly global scale. Credit is due to the principal authors and collaborating authors (listed separately for each section), who performed the work with dedication and care.

Technical editing was performed by Mr. Ahmet Gursoy, and overall editing of the material on submerged floating tunnels was performed by Mr. D. R. Culverwell. International coordination of the preparatory work was provided by Paul Van Milligen. Publication coordination, layout, copyrediting, and final production work were performed by Ms. Donna Ahrens, Managing Editor of *Tunnelling and Underground Space Technology*. Official ITA representatives to the Working Group, from 14 countries, are listed in Appendix A.

The Animateurs of the Working Group wish to extend their deep appreciation to the Working Group members and to the members of the ITA Executive Council for their continuing support during the last four years. The growing enthusiasm within the ITA and within the Working Group toward the "global sharing of knowledge" is a living testimony to the dedicated professionalism of its members, and a credit to the civil engineering profession.



AHMET GURSOY
Vice-Animateur (Vice-Chairman)

Chapter 2:

STRUCTURAL DESIGN OF IMMERSED TUNNELS

by

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Chapter 2: Structural Design of Immersed Tunnels

The purpose of this report is to develop an understanding of the state-of-the-art structural design for immersed road and railway tunnels. The report covers common and specific aspects of steel shell tunnels and concrete tunnels. It is the first time that engineers from Europe, the U.S.A., and Japan have collaborated on a report of this kind for immersed tunnels.

This report is very timely in that, in recent years, a longstanding tradition has begun to fade. No longer are steel shell tunnels the *only* types of tunnels constructed in the United States, and concrete box tunnels the *only* type of tunnels used in Europe. The steel shell was a serious contender in the competition for the Great Belt Tunnel in Denmark, while the concrete box will be used for the Fort Point Channel Tunnel in Boston (Massachusetts, U.S.A.), currently under design.

The history of immersed tunnel practice began in 1910, with the construction of a two-track railroad tunnel across the Detroit River between the United States and Canada. For the next thirty years or so, virtually all immersed tunnels were constructed in the United States. During this time a rather specific steel shell technology emerged—a technology that has continued largely unchanged up to the present. In 1941, construction of the Maas Tunnel in Rotterdam (The Netherlands) began, marking the beginning of the use of immersed tunnels in Europe.

Shallow river crossings with multiple-lane requirements led naturally to the concrete box scheme, a very different method of design and construction from the steel shell. A considerable number of tunnels were constructed in Europe with this method; and, as a result, engineers in The Netherlands, Germany, Sweden, France, Belgium and Denmark adopted the concrete box method exclusively. This tradition persists today.

Meanwhile, Japan was building tunnels of both types. The authors believe that Europe and the United States, as well as other countries, would do well to follow Japan's example.

It is hoped that this ITA Report will encourage engineers in making equal use of both of these basic technologies. Both have unique advantages and limitations, depending on the site. The selection of method should be made by engineers on the basis of job site conditions—not because of any lack of understanding of either method.

1. Introduction

Even though immersed tunnels are designed and constructed worldwide, special codes for immersed tunnels do not exist. Standard codes for highway structures are often used, although these codes relate to structures designed for different structural performance and generally more severe environmental exposure than immersed tunnels. The layout and design of an immersed tunnel is very much related to construction opportunities and site conditions. The state of the art described in this report covers different practices that serve the same goal: namely, to produce watertight and durable immersed tunnels.

An important issue for concrete tunnels is the difference in practices for providing watertightness and durability against aggressive groundwater. These practices cannot be evaluated properly without an understanding of the influence of the longitudinal performance of the tunnel structure. This topics is discussed in some depth herein, using numerical examples.

For the structural design of steel shell tunnels, the three basic construction stages require separate and different design analyses. These are described and the assumptions are detailed for each case.

2. Tunnel Practices

2.1 Immersed Tunnel—Definition

An immersed tunnel consists of several prefabricated tunnel elements, which are floated to the site; installed one by one; and connected to one another under water. An immersed tunnel is generally installed in a trench that has been dredged previously in the bottom of a waterway between structures constructed in the dry.

The space between the trench bottom and the soffit of the tunnel can be a previously prepared gravelbed, or sandbedding pumped or jetted underneath the tunnel.

Piled foundations are sometimes used, where soil conditions require them. As construction proceeds, the tunnel is backfilled. The completed tunnel is usually covered with a protective layer over the roof.

2.2 Fabrication

Concrete tunnel elements are prefabricated inside drydocks or specially constructed casting basins. Sometimes the cofferdam for the approach ramp structure is first used as a basin for the fabrication of the tunnel elements.

Steel shell tunnel elements are usually fabricated in a shipyard. After the element is launched, most of the interior concrete is installed while the element is floating. The element is then placed in the trench. Steel shell tunnels have also been fabricated and partly concreted in drydocks.

Definitions

Tunnel Element:
A section of the tunnel that is fabricated and immersed as one whole unit.

Intermediate Joint or Immersion Joint:
The joint between two tunnel elements.

Terminal Joint:
The joint between the terminal structure (e.g. ventilation building) and the immersed tunnel.

Final Joint or Closure Joint:
The last tunnel element to be immersed must fit in between two ends of the previously immersed elements, or between a previously immersed element and the terminal structure. At one end there can be a regular immersion joint. At the other end there must be a marginal gap to allow the element to move in its slot.

Expansion Joints:
Special watertight vertical joints between segments of a tunnel element, allowing limited movements between the segments. (used in concrete tunnels)

Tube:
In cross-section a tunnel can be structurally compartmented in various tubes (sometimes called "bores").

Gallery or Service Gallery:
A compartment of the cross-section used for services and/or pedestrian passage.

Ventilation Duct:
A compartment of the cross-section used for ventilation air supply or discharge.

2.3 *Joints*

All joints are gasketed and tightly closed. The immersion joints between the tunnel elements can be permanently flexible rubber compression gaskets, as is often the case for concrete tunnels. These gaskets are pre-installed at one end of each tunnel element.

Intermediate joints can also be made rigid. This is done at the inside of the temporary immersion seal by welding lapplates to the shells of steel tunnels or by placing concrete for concrete tunnels.

The final joint must always be made *in-situ*.

2.4 *Watertightness*

Immersed tunnels have a small number of *in-situ* joints. With regard to watertightness, this is quite an advantage over most bored tunnels. Immersed tunnels are designed to be watertight. Standards for acceptable leakage rates that are state-of-the-art for bored tunnels have no meaning for immersed tunnels.

Steel shell tunnels are watertight by virtue of the quality of the many welds of the shell made in the fabrication yard and by virtue of the quality of the *in-situ* joints.

The watertightness of concrete tunnels depends on the quality of the joints and on the absence of full-depth cracks in the concrete.

Many concrete tunnels are provided with watertight enveloping membranes. In addition to providing watertightness, this membrane is sometimes needed to shield the structural concrete against agressive chemical agents. There are distinctly different views among design engineers about the necessity of such membranes.

2.5 *Tunnel Cross-section*

The selection of the typical cross-section generally is determined by preferences based on successful previous experience in the specific region or country, as well as local site constraints (as witnessed by the practice in the U.S.A. of selecting steel shell tunnels; in northwest Europe, of selecting concrete tunnels; and in Japan, where both concepts are applied). Recent international immersed tenders in Europe have included alternative options for steel tunnels.

The structure of ***steel shell tunnels*** consists of relatively thin-walled composite steel and concrete rings. The steel shell provides the water barrier. The ballast concrete is placed outside of the shell in pockets formed between the structural diaphragms.

Concrete tunnels are monolithic structures in which most of the final weight is incorporated in the structural components.

There is a wide range of cross-section configurations, depending on the intended use of the tunnels. In determining the ultimate shape and size of the tunnel cross-section, the designers must consider, for example, whether the tunnel is to be used for railway or motor traffic; whether it will be a single tube, double tube, or multiple tube; what the ventilation requirements will be; and what construction practices will be applied.

2.5.1 Steel shell tunnels

For steel shell tunnels, a circular-shaped section for a single tube or a binocular shape for a double-tube cross-section are most economical for external pressure loading, as most sections of the structural ring or rings are in compression at all times. An additional benefit lies in the fact that the space between the roadway slab and the invert and the space above the suspended ceiling, if applied, can be used for air supply and exhaust for transverse ventilation. These spaces can also be used for services.

For larger vehicular tunnels, the usual configuration involves one or two tubes, each having two roadway lanes. The structure consists of a circular steel shell stiffened with steel diaphragms. A reinforced concrete ring installed inside the shell is tied to the shell and acts composite with the shell and the diaphragms. This is the main structure, designed to resist applied hydrostatic and soil loadings. Welded to the exterior flange plates of the diaphragms is a second "shell", the form plate, which contains the ballast concrete partly placed as tremie. This ballast weight provides the required negative buoyancy. This type of tunnel is called a "double-steel-shell tunnel".

The single-steel-shell concept is used for tunnels with one or two relatively narrow tubes, such as tunnels for metro rail transportation. The steel shell is on the outside and acts composite with the internal ring concrete. The ballast concrete, which is proportionately less than for the larger double-steel-shell tunnels, is placed on top of the element to keep the shell as small in section as possible. For single tubes, a circular shape is preferable; sharp corners are avoided. Single-steel-shell tunnels have little allowance for internal ducting.

Examples of steel shell tunnel cross-sections are shown in Figure 2-1.

2.5.2 Concrete Tunnels

For concrete tunnels, circular shapes have also been used for single tubes (in combination with transverse ventilation) and for relatively narrow service tunnels. For railway tunnels with two single-track tubes, the near binocular shape is often used because of the obvious advantage for transverse load transfer.

However, the shape most often used for double- and multiple-tube concrete traffic tunnels is the rectangular box, which may have to be widened with extra cells for ventilation air supply and services. The box shape best approaches the rectangular internal clearance required for motor traffic, with good conformity between resistance and weight. The box shape also permits practical concrete construction practice. When longitudinal ventilation would be sufficient, all of the services can be kept within the traffic tubes—that is, along the roof and inside the ballast concrete underneath the roadway or walkway. Often, however, a special services gallery is preferred or, sometimes, required by the fire department for emergency escape.

Examples of cross-sections of concrete immersed tunnels are shown in Figure 2-2.

2.5.3 Miscellaneous

Low-point drainage sumps have to be provided within the confines of the structure.

In binocular double-steel-shell tunnels, the sump can be placed between the tubes. In single-steel-shell and concrete tunnels, the sumps have to be placed underneath the roadway. The presence of service galleries is helpful in positioning the pumps.

Generally, for given cross-sectional requirements for vehicular space and ventilation, the concrete box section can be made shallower than the steel section. However, for the same conditions, the steel section is generally a narrower section.

3. Watertightness

3.1 *General*

Although watertightness is one of the primary objectives of any immersed tunnel design, the design would be deficient if the consequences of incidental small leakages were ignored. On the large perimeter surface of a tunnel element, the possibility of an undetected pinhole in a steel weld or an undetected construction imperfection of the concrete or waterproofing membrane cannot be ruled out completely.

Suitable repair methods exist and must be specified in the design. The build-up of water pressure within the tunnel wall system must be avoided by provision of proper drainage into the tunnel drainage system. Seepages of this kind are very small and do not require extra drainage and sump capacity.

3.2 *Steel Shell Tunnels*

For steel shell tunnel elements, watertightness is provided purely by the

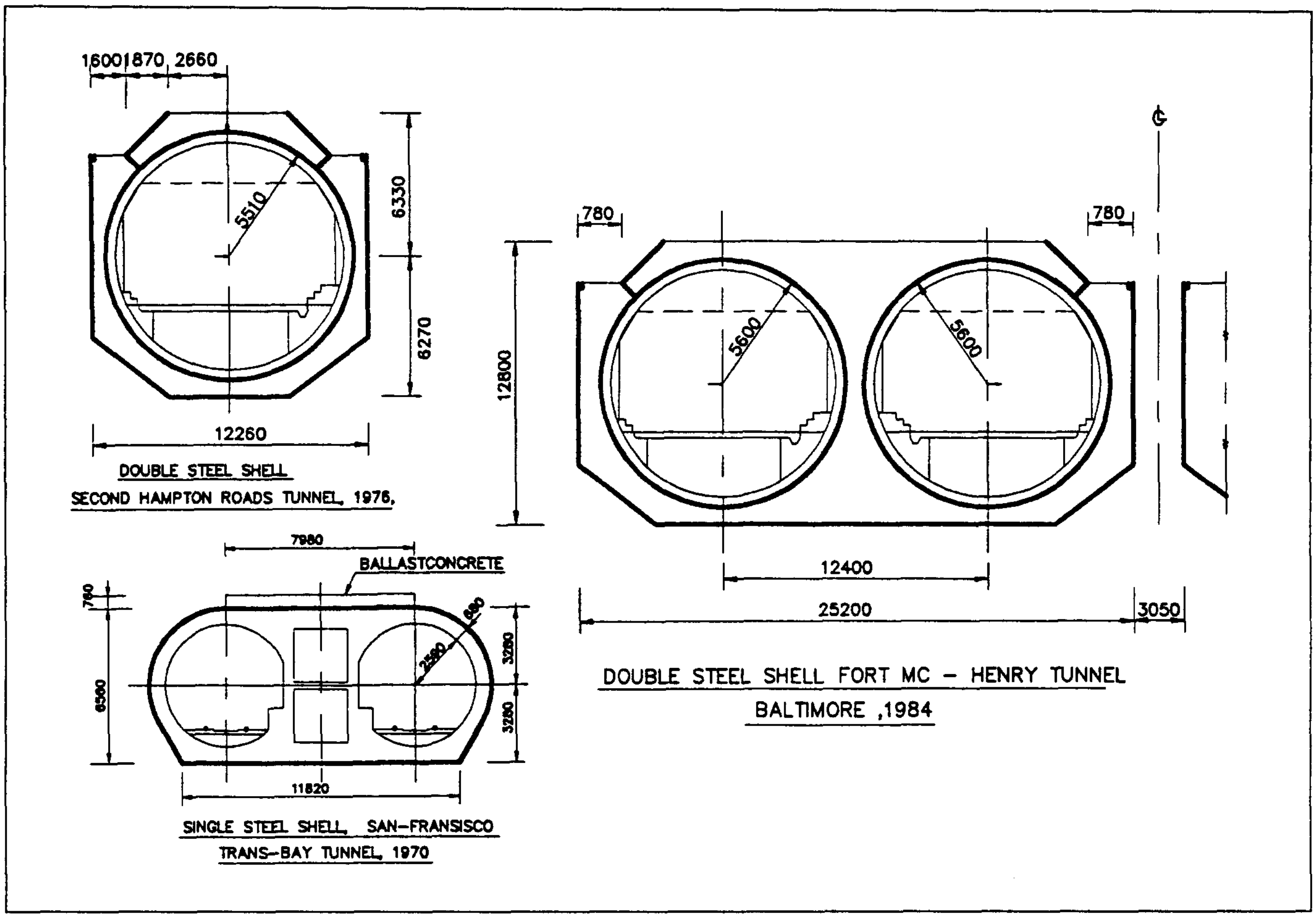


Figure 2-1. Examples of cross-sections of steel-shell tunnels.

steel shell itself. The watertightness relies on the quality of the large number of welds. The concrete inside the shell is transversely under compression.

3.3 Concrete Tunnels

For concrete tunnels, leakage is related to the development of cracks. Therefore, an understanding of the different structural behaviours in the transverse and longitudinal directions is important.

In the transverse direction, box-shaped reinforced concrete tunnels always have zones in the roof and base slabs that experience bending tension, notwithstanding the transverse compression. The tunnel section is designed so that the resulting cracks can only partially penetrate, leaving the concrete in the compression zone sufficiently thick to avoid leakage.

In the longitudinal direction, the stresses are of a much lower magnitude than in the transverse direction. The basic stress is marginal compression. Secondary effects that can cause partial tension should not lead to full depth cracks. Thermal shrinkage cracks are a typical secondary effect.

In thick concrete members, the heat of hydration causes substantial heating of the member. After some time the member will cool off to the ambient temperature. The resulting contraction of the now-hardened concrete is subjected to restraint. This occurs when casting the walls above the horizontal joint with a base slab that was cast at an earlier stage. The result of the cooling contraction of the wall connected to the rigid base slab is compression in the base slab and longitudinal tensile strain in the bottom part of the walls.

Unless proper measures are taken, vertical full-depth cracks can occur at about 5-m intervals. Satisfactory processes have been developed to avoid these construction cracks, namely by using concrete with relatively low cement content and forced cooling in the lower part of the walls (see Fig. 2-3). Sometimes this is done in combination with insulation and heating of the base slabs. If cracks nevertheless are found, remedial grouting appears to be effective.

Effective control of differential heat development largely depends on the heat of hydration of the concrete. This process, in turn, is a direct function of the amount of cement in the mix. Therefore, the use of typical concrete mixes with high cement factors (taken from highway structures codes) can be counterproductive in this respect.

There are basically two different concepts regarding control of leakages for concrete box tunnels:

1. The *expansion joint concept* involves avoiding longitudinal stresses that can cause cracks, thereby relying on the watertightness of the uncracked concrete.
2. The *waterproofing membrane concept* involves enveloping the concrete tunnel element in a waterproofing membrane.

Each of these concepts is discussed in more detail below.

3.4 The Expansion Joint Concept for Concrete Tunnel Waterproofing

The expansion joint concept involves achieving watertightness by avoiding transverse cracking of the concrete.

A tunnel element 100 m long or more is designed with expansion joints. The length between the expansion joints is determined by the practical length of a complete concrete pour, which is in the range of 20 m. The vertical joint between two segments is basically an unreinforced cold joint provided with a cast-in flexible waterstop. In this way, the tunnel element can be subjected to flexural deformations without developing

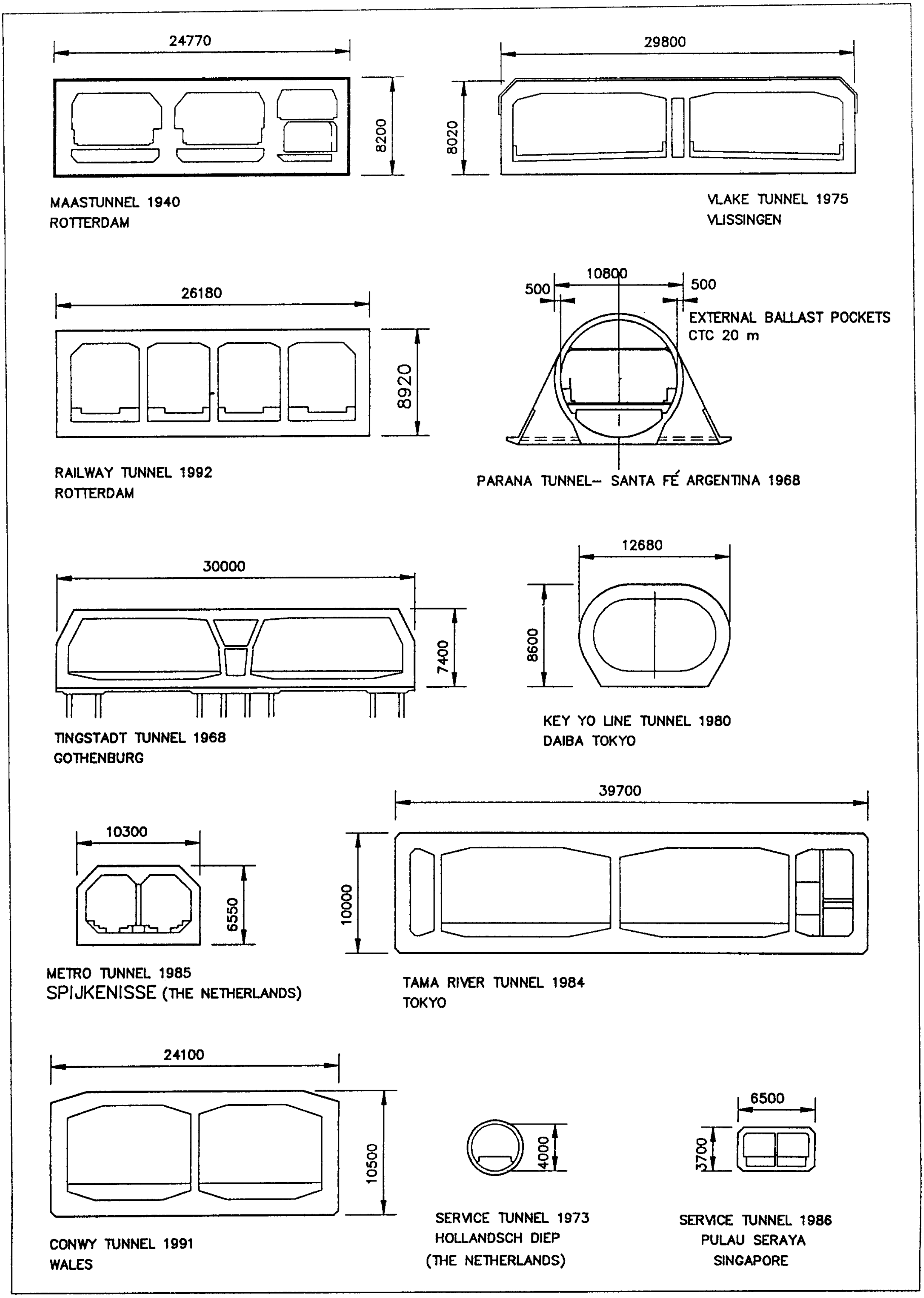


Figure 2-2. Examples of cross-sections of immersed concrete tunnels.

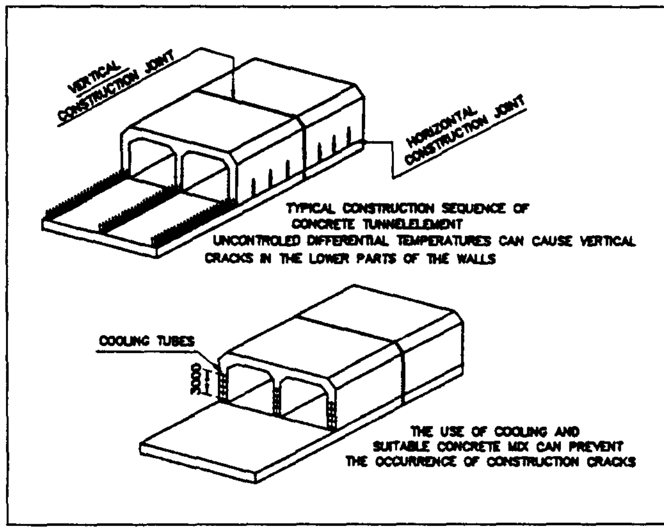
longitudinal tensile strain between the expansion joints, which can cause cracking of the concrete.

Great care must be taken to assure that shrinkage of thermal cracking does not occur in the segments and that any cracks which do occur are sealed prior to floating the element out of the casting basin.

During transportation and installation, the segments of such a tunnel element must be structurally coupled in the longitudinal direction. This can be done by temporary coupling rods, with or without prestress; or by temporary longitudinal prestressing tendons over the full length of the tunnel element.

The temporary prestressing tendons are usually cut after installation. However, they are sometimes maintained permanently—for example, when flexural bending of the tunnel is not expected, as may be the case with a piled foundation.

Figure 2-3. Thermal shrinkage problem and solution.



3.5 Waterproofing Membrane Concept

When a waterproofing membrane is used, the tunnel elements are made monolithic, using regular vertical construction joints with continuous longitudinal reinforcement. The waterproofing membrane is made continuous over the full length of the tunnel element. Full-depth transverse concrete cracks can develop, especially in the vertical construction joints. In this concept, full reliance is given to the membrane waterproofing that envelopes the element.

The following options are used for waterproofing membranes:

- Steel plate below the base, with bituminous or plastic membranes on the walls and roof.
- Steel plate below the base and on the sides, with bituminous or plastic membrane on the roof only.
- Steel plate all around.
- Plastic membranes all around.

Bituminous or plastic membranes must be protected against mechanical damage. This protection is usually provided by a concrete layer, which must be permanently held to the structure. Unfortunately, this arrangement requires anchors to penetrate the membrane. Other necessary penetrations are for bollard- and fender connections, access shafts, and certain immersion equipment.

Steel plate skins applied on the sides for waterproofing are also used as stay-in-place formwork for the walls of the element. For steel membranes across the roof area, holes can be left in the plates for placing and vibrating the concrete. The holes are closed up later. This method is more complicated for a flat roof than for an arched roof.

An alternative method is to apply the steel roof plates after concreting the roof. Steel rails are partly embedded in the top of the concrete. Steel plates will be welded to these rails and any voids will be grouted afterwards.

Steel plate membranes (typically 6 mm thick) are anchored into the concrete by welded studs, usually four studs per square meter. Because the thin plates are rather sensitive to temperature deformations, much care is required to keep the plates flat. The bond between the steel plate skin and the concrete should not be relied upon, notwithstanding the use of the studs, because the steel plate membrane does not provide a structural contribution to the concrete structure.

To protect the steel plate membranes against corrosion, impressed current cathodic protection can be installed. Sometimes coating of the steel plate is also specified, but it is practically impossible to provide it without some local deficiencies (e.g., at splices). Nevertheless, the coating, although imperfect, will reduce the direct current demand.

Obviously, a waterproofing membrane must be fully continuous around the whole of a tunnel element. The emphasis for steel plates is on the quality of the welds. For bituminous and plastic membranes, the emphasis must be on providing the proper application; observing the proper limitations for weather conditions; and providing good overlaps over the upstand of the steel membrane.

Sometimes the transition area is also clamped. A small leak in the membrane can cause water to flow underneath the membrane to weak spots in the concrete at other locations, thereby making the source of leakage difficult to trace.

A combination of the two methods—i.e., using both waterproofing membranes and the expansion joint method—is not considered cost-effective or advisable.

3.6 Protection of the Structural Concrete against Chemical Attack

The direct exposure of the structural concrete of immersed tunnels to their external ambient environment is much less severe than the exposure of highway structures to the atmosphere.

Observations in the course of durability investigations have attested to the long-term reliability of reinforced concrete structures permanently immersed in seawater.

In seawater, chloride ions will diffuse into the concrete, thereby depassivating the concrete. Corrosion of the steel reinforcement can begin when the depassivation front has reached the reinforcement. However, the corrosion of the reinforcement at the outside face of the concrete will not be effective, because of the very scarce supply of oxygen. The type of cement used and the density of the concrete are important factors for the penetration rate of chloride ions and oxygen. The chloride diffusion front may never penetrate to the inside face of the concrete.

Sulphate attack in seawater is not accompanied by expansion of the concrete because of the presence of chlorides. Gypsum and sulpho-aluminates, which are soluble in chloride-rich environments, are leached out. Therefore, special sulphate-resisting cement is not needed; and, moreover, would increase the sensitivity of the concrete to chloride penetration.

The inside face of the concrete, especially in road tunnels, is generally exposed to chloride attack in an oxygen-rich environment where the air may be aggressive. Furthermore, in many tunnels, passing vehibles bring in deicing salts, which add to the depassivation of the concrete by carbonation. The steel reinforcement also could be subject to corrosion. Again, the best practical protection is good concrete density and sufficient concrete cover.

Because the steel reinforcement is more sensitive to corrosion at the inside face of the concrete than at the outside face, the protective membrane waterproofing method is not used.

3.7 Longitudinal Prestressing

To avoid uncontrollable full-depth cracks, the longitudinal working tensile stress should not exceed the tensile strength of the concrete. Normally this requirement can be satisfied in the design of concrete tunnels. If needed, a fairly small rate of longitudinal prestress can substantially increase the allowable range of loading that causes tensile stresses. For example, for concrete with a tensile strength of 2 Mpa and 1 Mpa longitudinal prestress, the range of loading causing longitudinal tensile stress could be 50% higher.

4. Design of Typical Tunnel Section

4.1 Interior Geometry

The interior geometry of immersed tunnels depends largely on local, state or national highway design standards applicable to the type and volume of traffic for which the tunnel is designed. Interior clearance envelopes for ceiling height and width of lanes are set by these agencies. Other requirements may involve ventilation equipment; overhead sign clearances; safety and access walkways; placing of services; and use of suspended ceilings, curb details, etc.

Roadway drainage, superelevation, sight distance for horizontal, and vertical curvature may also play a part in the interior geometrical design. The vertical clearance should be extended to compensate for expected (unequal) settlements and dimensional inaccuracies. The horizontal clearance may have to be extended for horizontal inaccuracies.

4.2 Description of Typical Composite Steel Shell Cross-section

Figure 2-4 shows a typical cross-section of a double-steel-shell tunnel, which consists of an interior steel shell made composite with the interior reinforced concrete ring inside. The exterior steel, called the "form plate," envelopes the interior shell in an octogonal shape up to the elevation of the crown of the interior shells. The shell and the form plate are interconnected by steel plate diaphragms at 4- to 5-m centres. Exterior concrete fills the space between the shell and the formplate and covers the shell.

The bottom part and the roof part of the exterior concrete are poured in the dry and are part of the composite structure, along with the concrete ring inside the inner shell. The exterior concrete on the sides, which is poured under water, serves to restrain buckling of the diaphragm flanges and acts as ballast.

The interior steel shell is provided on the inside with J-shaped steel hooks that are stud-welded to the shell plate. These hooks tie the ring concrete and its reinforcing steel to the shell to provide the composite action.

The steel assembly is built on land and launched sideways or longitudinally, with the bottom part of the exterior concrete in place. This assembly is considered a "keel" for stability during towing. The ring concrete inside and remaining outside concrete ballast are placed when the assembly is afloat.

The structural loading during the subsequent construction stages is quite complex. The stresses in the shell are more severe during launching, towing and outfitting with interior concrete than when the element is finally immersed. The interior shell is about 8 mm thick and is stiffened with external longitudinal stiffeners. The form plate usually is 6 mm thick.

For double-shell design, a composite steel concrete tunnel is achieved by covering the steel shell all around with a thick concrete cover, which provides mechanical and corrosion protection for the steel shell. The double-steel-shell element end detail shown in Figure 2-5 illustrates the typical structural steel arrangement.

The single-steel-shell type of tunnel is simpler in concept, although also subject to more critical steel shell stresses in the launching stage, when the interior concrete is not yet installed. To stiffen and stabilise the element in the launching stage, the base of the interior concrete ring is installed prior to launching. The steel shell is stiffened with stiffening plates and temporary transverse spiderweb frames. For double-tube single-shell elements, a vertical longitudinal steel truss is constructed in the center. This truss will later be absorbed in the interior concrete and partly removed where cross-passages are required. Figure 2-1 shows an example of a single steel-shell element.

Cathodic protection is sometimes required for single-steel-shell tunnels if the tunnel passes through a zone of stray currents, such as a subway system or an industrial facility. In such cases, provisions are made to measure the currents at test locations. These tests will determine the required level of impressed current needed to prevent loss of steel section.

4.3 Description of Typical Concrete Box

The "concrete box" tunnel can be considered as a monolithic frame comprising base, walls and roof.

There is a horizontal construction joint between the base and the walls. Waterstops are sometimes provided in these construction joints (they are not used in The Netherlands). It should be noted that the application of a waterstop may obstruct the easy placing and compaction of the concrete, which is not the case on a clean flat surface. Generally the weight and downward forces in the whole of the wall provide enough pressure to make the joint watertight without special provisions.

The walls and slabs for a traffic tunnel are usually at least 1 m thick. To increase the resistance for shear and hogging moments, haunches are provided underneath the roof slab. When designed without haunches, the base slab is up to 1,5 times thicker than the roof, with the top following the cross-fall of the roadway. This arrangement not only is attractive for construction, but also provides mass stability to the tunnel element.

Sometimes the floating condition may require a thinner base with haunches in the corners. Base haunches require special attention for concreting. The ballast concrete is placed on top of the base.

Allowance for services in concrete tunnels. The main electrical feeders are usually placed in conduits in the ballast layer and/or are suspended from the roof. The services inside the tubes can be reduced to local distribution if a special services gallery is used. The exterior walls in the latter case would not require large panel recesses, which can act as crack initiators. The same could apply if the size of the low point drainage sump would require deep recessing into the base slab.

4.4 Weight Balance

The design of the cross-sectional geometry is very sensitive to variations in the density of the water and the construction materials; dimensional inaccuracies; and the weights of temporary equipment needed for transportation, temporary installation and the permanent condition.

A concrete tunnel element must be able to float with all temporary immersion equipment on board. The freeboard should be minimal to reduce the amount of permanent and temporary ballasting. The temporary on-bottom weight, with the water ballast tanks filled, must be sufficient. For the permanent condition, it must be guaranteed safe against uplift with the fixed ballast in place.

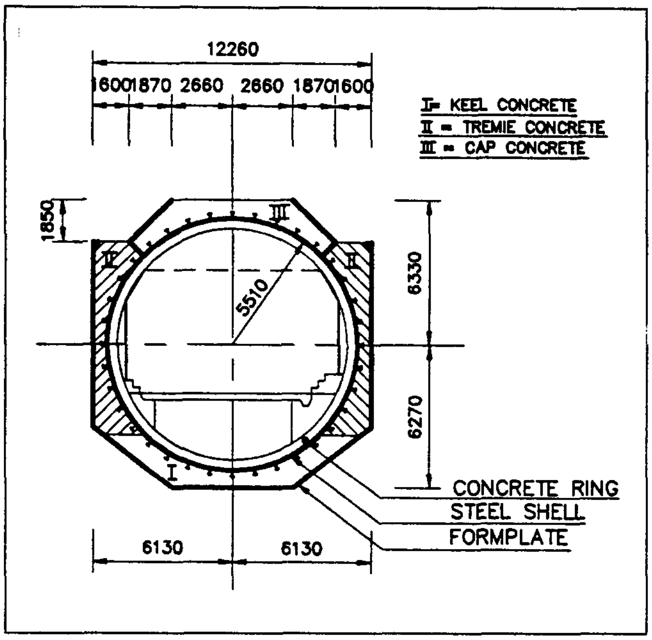


Figure 2-4. Typical cross-section of a double-steel-shell tunnel.

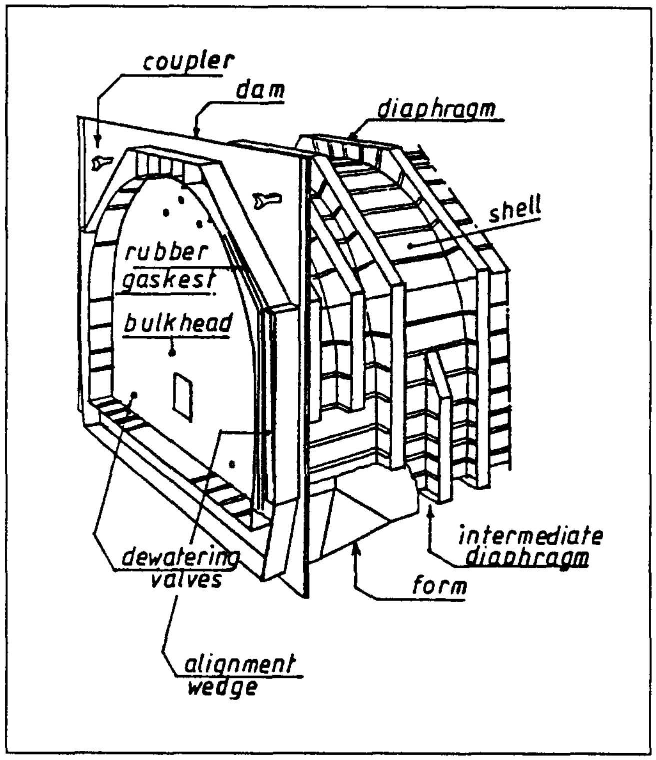


Figure 2-5. Double-steel-shell element and detail, and typical structural steel arrangement. Formplate is only partially indicated.

The roof is usually covered with a protective concrete layer that is also used for trimming purposes. When bituminous waterproofing membranes are applied to the walls, protective wood cover or concrete cover is also applied to the walls, as cast-in-place or precast panels. The roof edges are usually bevelled, to reduce the risk of hooking ship's anchors.

The minimum factor of safety for the permanent condition of immersed tunnels is often specified as 1.10, based on the following conditions:

1. *Uplift forces:*
   - Buoyancy by the water at the maximum expected density and according to the theoretical displacement.
   - Hydraulic lag, if applicable in tidal waterways.
2. *Stabilizing loads:*
   - The theoretical weight of the structural steel, concrete and reinforcement steel, assuming a realistic density for the concrete that will not exceed the actual density.
   - The fixed permanent ballast concrete, inside or outside.
   - The weight of protective membranes and cover concrete.
   - The roadway pavement, suspended roadway slabs, or fixed-track support concrete.

3. *Factors not considered as stabilizing are::*
   - Backfill surcharge and downward friction.
   - The weight of mechanical equipment and suspended ceilings.

These factors are used to determine the required geometry. The actual safety factor may be slightly higher or lower, depending on the actual as-built dimensions.

For example, a part of the stable type of roof protection, such as rip rap, may be allowed to be included in the safety factor of 1.10. Sometimes a minimum safety factor of 1.06 is applied for concrete tunnels with only the structural concrete and ballast concrete as stabilising factors. For steel shell tunnels, 1.07 is applied, excluding the contibution of the side walk concrete.

The minimum temporary safety factor during installation is usually 1.03 after release of the immersion equipment.

Sometimes allowance has to be made for uplift caused by hydraulic gradient. A hydraulic gradient can be caused by tidal lag of piezometric height underneath the tunnel, which can occur with silty or clayey backfill in tidal waterways. Another cause of hydraulic gradient is the suction caused by the squatting of ships passing over; however, this factor is only considered in the installation stage.

For steel shell tunnels, the total amount of concrete needed for the weight balance amply exceeds that required for strength. The external ballast concrete is the variable factor for the weight balance.

For concrete tunnels, the thickness of the structural concrete is generally sufficient for the strength. The determination of the final geometry is more complicated because the ballast concrete is on the inside. Variation of the internal ballast volume affects the internal geometry.

5. Longitudinal Articulation and Joints

Immersed tunnels are rigid structures in the longitudinal direction. The stresses with which the structure would respond to axial tensile strain (temperature) and longitudinal bending strain (unequal settlement or large surcharge discontinuities) depend on the material properties and the longitudinal articulation.

5.1 Steel Shell Tunnels

Steel shell tunnels have approximately the same longitudinal flexural rigidity as concrete tunnels. However, by virtue of the inherent ductility of the steel shell, they have a larger longitudinal strain capacity, and are therefore less sensitive to foundation discontinuities and temperature deformations than concrete tunnels. The concrete part of the composite structure inside the steel shell is not controlled in the design for transverse cracking under longitudinal tensile strain. It will not affect the hoop resistance of the composite ring.

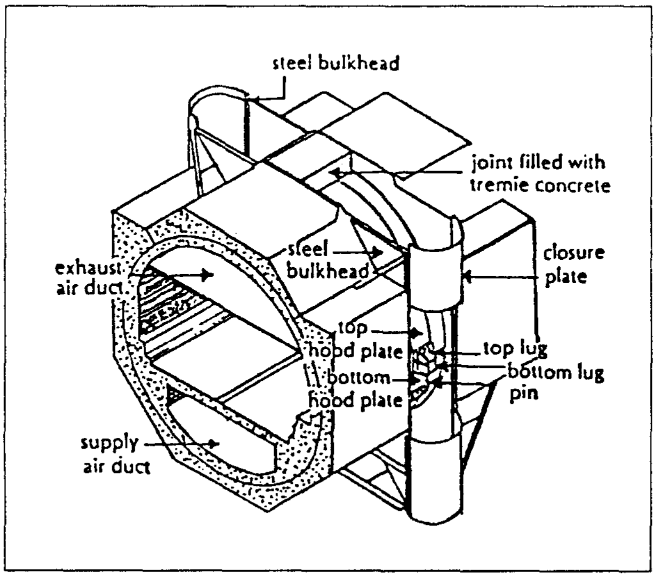


Figure 2-6. Typical tremie concrete joint for a double-shell steel tunnel.

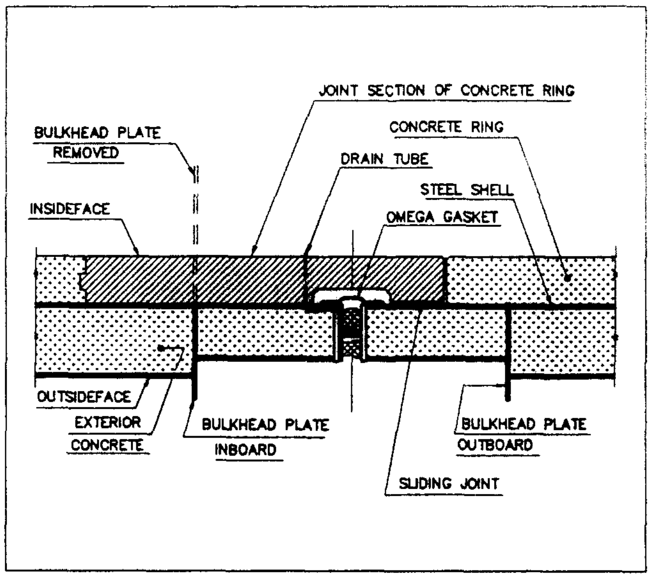


Figure 2-7. Intermediate joint with sliding arrangement for a double-steel-shell tunnel.

Generally the steel shell is made fully continuous between the tunnel and with special joints at the terminal structures (e.g., as for the BART railway tunnel in San Francisco); or with sleeved joints, as recently developed for Boston's Third Harbour Tunnel.

The continuity joint is often made by a bayonet-type fitting of the abutting ends of the interior shells, which are lapped by plates welded to them on the inside. Temporary watertightness is achieved by tremie concrete between the shell and a cofferdam formed by the "damplates" and side closure plates. This type of joint is called the "tremie concrete joint" (see Fig. 2-6).

5.2 Concrete Tunnels

Concrete tunnels are usually provided with permanent flexible joints to reduce restraint to temperature contraction and to reduce flexural bending. However, there is an example of a concrete tunnel made monolithic over 400 m, but with flexible terminal joints.

The type of solid rubber gaskets generally used between concrete immersion units normally can provide enough flexibility for this purpose without losing their sealing capacity. These rubber gaskets only transfer compression effectively. To prevent shear deformation in an intermediate joint, which is desirable for the alignment and for sealing performance, shear keys are required. An example of an intermediate joint for a double-steel-shell tunnel is shown in Figure 2-7.

5.3 Shear Transfer in Intermediate Joints

Transfer of large shear forces in intermediate joints can best be achieved by shear keys in the walls that are made *in situ* in front of the inner face of the permanent watertight gasket. They can also be installed prior to placement with provisions for *in-situ* adjustment.

Shear transfer for small shear forces can be accomplished using shear keys or longitudinally movable dowels in the base slab area of the joint.

Settlement discontinuities often occur at the terminal joint. Shear fixity is desirable, but the shear force and resulting bending moment can become very large. To reduce the shear, the following solutions, or a combination thereof, can be applied:

- Ground improvement, in the case of soft upper layers.
- Delaying the shear connection until a part of the settlement has taken place.
- Readjustment of the tunnel elevation with reinjection of bedding sand.
- Preloading by internal flooding.

5.4 Intermediate Flexible Rubber Joint Design

The type of solid rubber gasket sometimes referred to as the "Gina" gasket is used for practically all concrete tunnels. It is used as a temporary seal at the installation stage and remains as a flexible compression joint for the permanent stage. The facing tunnel element ends are lined with steel plates that are matched as parallel planes within ±5 mm tolerance. The gasket is clamped at its backside. The specifications for material characteristics and geometry are usually based on the permanent sealing requirement under expected long-term decompression and relaxation of the gasket. Nevertheless, a second flexible rubber water barrier is installed at the inside of a curved-slab-type rubber gasket. This gasket, often referred to as the "Omega" gasket, is considered to be the main seal. The space between the Gina gasket and the Omega seal is usually drained off to the inside of the tunnel.

An example of an intermediate flexible joint design for concrete tunnels is shown in Figure 2-8.

This type of joint can also be used for steel tunnels, when flexible joints are required.

The Gina-type gasket acts as a flexible joint under compression, and can practically be considered as a hinge in longitudinal moment transfer. Shear resistance can be ignored, because it has a tendency to slip along its base under shear deformation. For this reason, shear deformation across a joint is not limited by properties of the Gina gasket, but rather by the allowable shear strain of the Omega gasket, especially with regard to its corner sections.

The exterior rubber gasket should be placed as much as possible to the outside of the structure, in order to keep the recess between the side and the outside of the gasket shallow. This arrangement prevents backfill material from accumulating gradually and obstructing the proper movement of the joint.

5.5 Expansion Joints

These joints are applied in concrete tunnel elements at the location of the vertical construction joints. They are basically cold joints without steel reinforcement, provided with steel-rubber flexible waterstops. Special provisions are made to enable pressure grouting access around the waterstop after the main structural concrete is hardened. A typical Dutch expansion joint is shown in Figure 2-9.

When the tunnel in its permanent condition is subjected to longitudinal curvature, these joints will open at the "tension" side. However, tension cannot be transfered through these joints. This relieves the concrete between the expansion joints of longitudinal tension transfer.

5.6 Final Joint of Concrete Tunnels

The final joint cannot be made with the intermediate rubber compression joint that is used in the regular intermediate joints. Wedges are used inside the temporary watertight enclosure to maintain the longitudinal compression.

The joint can be made monolithic, with shear transfer provision to the concrete on one side of the joint and with a flexible waterstop on the other side. In this way, the joint will resemble the action of the expansion joint described in Section 5.5, above.

An example of a final joint for concrete tunnels is shown in Figure 2-10.

6. Structural Analysis for Concrete Tunnels

6.1 Transverse Analysis

For the transverse analysis, a concrete tunnel can be considered as a series of plane frames. When the loads and soil reactions are constant in the longitudinal direction, or vary only gradually in that direction, the frames can be analysed with balanced loads.

However, in areas of heavy surcharge, such as embankments, and, especially, near discontinuities of surcharge, as well as in areas of expected redistribution of soil reactions, the external vertical loads acting on the plane frame are not balanced. The shear forces between the adjacent frames need to be analysed for these conditions. An elastic beam analysis can be conducted to determine the longitudinal distribution of the vertical subsoil reaction, and the longitudinal shear distribution. The shear forces can then be entered as vertical loads acting along the vertical members of the frame.

The application of hydrostatic pressure and surcharge loads is straightforward. The magnitude of the lateral soil pressure and possible wall friction caused by the backfill cannot easily be determined. It is best to assume lower and upper bond values to find extreme bending in different members of the frame.

In numerical analysis, it is practical to model an elastic foundation for the base with a given spring constant. For the soft soil case, the effect on transverse moment distribution is practically the same as a uniform ground pressure distribution. In the case of hard subsoil, it is advisable to investigate the sensitivity to the spring constant, because the spring constant cannot precisely be determined and may vary in time.

6.1.1 Structural Resistance

Under some national codes, only the Ultimate Limit State (U.L.S.) is checked, using the appropriate load and material factors. In U.L.S., the reinforcement is yielding.

Other codes also require the control of crack width at the Service Limit State (S.L.S.). At this state, most of the loads are factored by unity, and the reinforcement is not yielding. The maximum allowed crack width varies in the different specifications; 0.2 mm is usually specified. Protective membranes are not used, in order to allow for greater crack width.

A distinction should be made between longitudinal cracks caused by transverse bending, and transverse cracks caused by longitudinal action. The transverse cracks will cause leakage.

An important contribution to the transverse bending moments in S.L.S. are the restraint moments caused by a temperature gradient across the thickness of the slabs and walls. The temperature gradient effect is not factored for the U.L.S. condition. Its contribution to the reinforcement steel stresses should be taken into account.

Special cases of concentrated loads have to be examined. Examples include temporary jacking pin supports, the effects of shear dowels, and discontinuities of cross-section that occur at the joints.

6.2 Longitudinal Analysis for Concrete Tunnels

The understanding of the longitudinal performance of concrete tunnels is important in view of the relatively low tensile strength capacity of the concrete and the desire to avoid

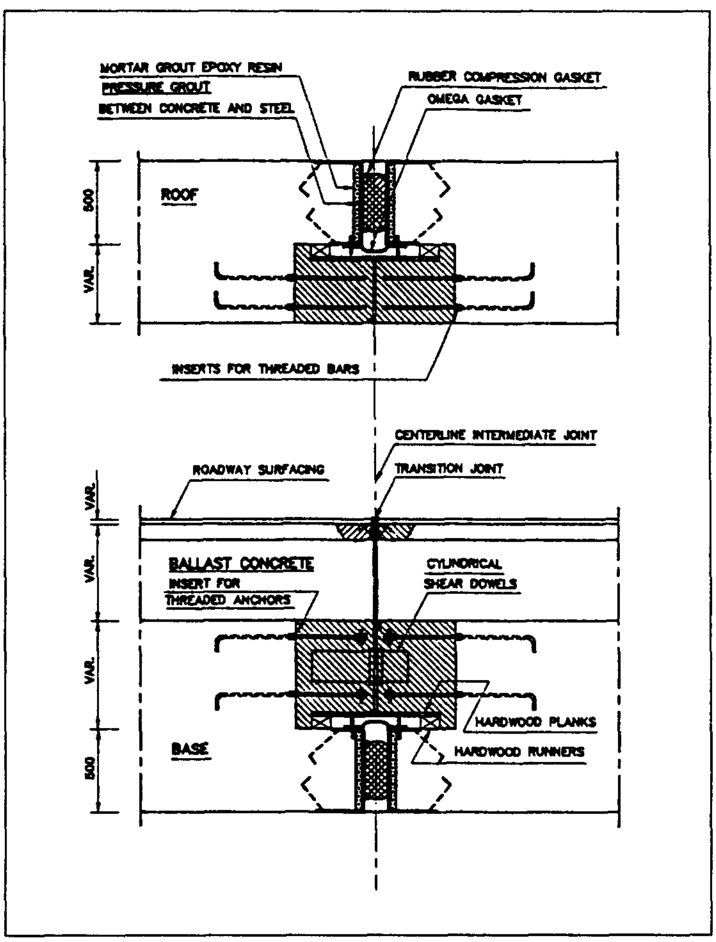


Figure 2-8. Intermediate flexible joint for concrete tunnels (Dutch solution).

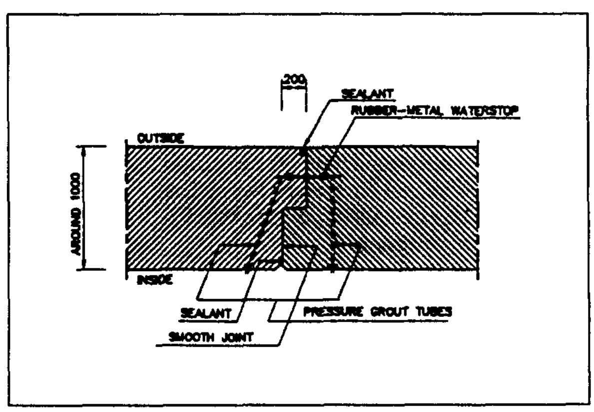


Figure 2-9. Typical Dutch expansion joint.

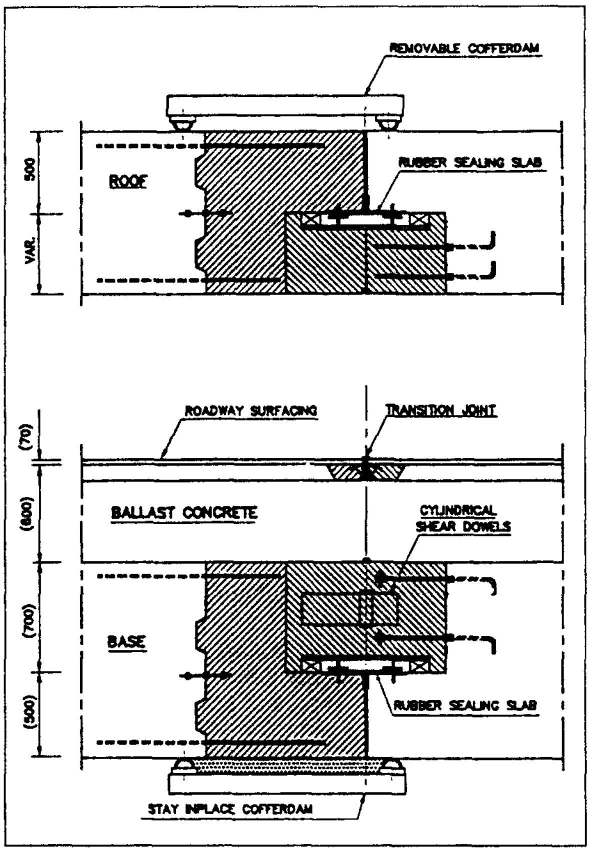


Figure 2-10. Example of the final joint for concrete tunnels.

transverse cracks. It has been shown that these cracks can indeed be avoided.

The effects of hydrostatic compression, temperature stresses and longitudinal bending on the longitudinal concrete stresses are explained below with numerical examples.

6.2.1 Longitudinal hydrostatic compression

The longitudinal hydrostatic compression force in any vertical section of the tunnel is equal to the water pressure that would act at the average depth, D (avg.), of that section times the gross area of that section. With the simplified assumption that the ratio between the gross area and the concrete area is equal to the ratio of the densities of concrete and water, a simple expression for the average concrete stress is:

fc (avg.) = D (avg.) * 0,024 Mpa, (D in m)

The longitudinal hydrostatic compression force will follow the changes in water depth (e.g., by the tide), as long as the immersed part of the tunnel has a free end and friction between the free end and the section under consideration can be ignored.

The hydrostatic compression will be fixed as soon as the tunnel is closed between the terminal structures.

The compression is assumed to act at the center of the structure when flexible intermediate compression joints are used.

Losses of the fixed hydrostatic compression. Losses of the fixed hydrostatic compression are caused by time-dependent relaxation of rubber compression joints and shortening of concrete, causing decompression of the joint.

The degree of relaxation of the rubber compression joints varies with the characteristics of the selected type and the range of compression. Generally the loss will be about 50% of the initial compression.

Typical performance rates for flexible rubber compression gaskets used as intermediate joints are shown in Figure 2-11.

Shortening of the concrete can be caused by shrinkage and temperature deformation. Creep of the concrete can be practically ignored.

The concrete codes do not provide proper parameters to determine the shrinkage strain for thick-walled concrete members of immersed concrete tunnels. If calculated according the FIP-CEB model code, a very small strain is found. The shrinkage strain is not restrained when flexible intermediate joints are utilised, but the resulting decompression of these joints will cause a minor loss of the locked-in compression force.

In The Netherlands, the shrinkage strain is ignored for tunnels in which the concrete is directly exposed at the outside.

Temperature deformation caused by a temperature decrease of the tunnel by 10°C. would cause a decompression of about 10 mm of joints positioned at 100-m intervals.

A numerical example of concrete compression, based on the use of a rubber compression joint, is shown below:

for D (avg.) = 20 m:
initially fc (avg.) = 20 x 0,024 = 0.48 Mpa
long-term fc (avg.) = 0,5 x 0,48 = 0,24 Mpa*

for D (avg.) = 6 m (near shallow end of a tunnel):
long-term fc (avg.) = 0,5 x 6 x 0,024
= 0,072 Mpa*

**the factor 0,5 is estimated*

It is noted that the compressive stress in the concrete by the hydrostatic compression, although very small, is sufficient to keep the joints sealed.

Because the rubber joints are flexible, the restraint to longitudinal strain of the tunnel elements is practically eliminated.

6.2.2 Concrete stresses by yemperature deformations

The relevant temperature changes of the concrete are of a seasonal nature. At the time of installation, the whole of the structure can be assumed to be the same temperature as the surrounding water.

The temperature changes of the concrete are usually specified in two parts:

1. An overall increase or decrease, relative to the ambient ground water, with a range from ± 15°C to ± 10°C.

2. A so-called "gradient" over the thickness of a wall or slab, which is a linear temperature variation from 0°C on the outside to ± 10°C on the inside. This gradient can be split in an overall increase or decrease of 5°C, to be added to (1), above, and a linear variation over the thickness from -5°C to +5°C, or vice-versa.

The overall increase or decrease of the temperature of the structure will lead to longitudinal deformation. For tunnels with monolithic intermediate joints between the terminals, this could lead to concrete stresses in the range of the tensile strength or yielding of the vertical joints.

Tunnels with intermediate flexible compression joints are not restrained to longitudinal deformation of the concrete, but the flexible joints will react with a minor increase or decrease of compression.

The linear temperature variation over the thickness of a wall or slab of +5°C to -5°C will cause bending stresses varying from -1.0 Mpa to +1.0 Mpa over the thickness of a concrete wall or slab. Although small, these stresses are a magnitude larger than the hydrostatic precompression. On the outside, there will be tension in the summer and compression in the winter.

The stress diagrams of Figure 2-12 clearly show that the temperature variations will not cause transverse cracks.

6.2.3 Longitudinal bending

Discontinuity of surcharge and discontinuity of settlement have the same effect. They cause longitudinal bending of the tunnel, which can be analysed as a beam on elastic foundation.

The large beam stiffness of the tunnel leads to high shear force and bending moment response to longitudinal bending. This is illustrated by the following theoretical example for a monolithic tunnel element (not segmented) that wants to settle 50 mm, but has shear restraint at one end (which could be the terminal joint). The joint is flexible for rotation. The main variable is the spring constant of the subgrade reaction.

For this example, Ko = 2 MN/m³ is used, corresponding to a deflection of 0,05 m under a pressure of 0.1 Mpa (or 10 t/m², as could be caused by heavy surcharge).

Figure 2-13 shows an example of longitudinal analysis for the response of concrete tunnels to unequal settlement.

Example calculation:

External cross-section:	h = 8 m, b = 30 m
Modulus of Inertia:	I = 1.200 m⁴
Section modulus:	S = 300 m³
Elastic modulus:	E = 2.10⁴ Mpa
Spring constant:	K = ko x b = 2 x 30 = 60 MN/m²
Characteristic length:	lo = 35.5 m
Undisturbed settlement:	Yo = 0,05 m
Maximum shear force (at fixed end):	V_{max} = 2 EI x Yo/lo³ = 53 MN

Maximum bending moment (at 3/4 lo from fixed end):

M_{max} = 0,322 lo x V_{max} = 612 MN/m

Maximum bending stress: fc (max) = 2.04 Mpa

This simple calculation shows that a range of 50 mm of such differential settlement can cause monolithic tunnel elements to crack transversely. These cracks would be full-depth over the thickness of the base slab and the walls.

While it is preferable to prevent forced deformations of such magnitude, sometimes it cannot be avoided. Controlling the width of such cracks by longitudinal reinforcement will not provide ductility of the tunnel element as a whole; furthermore, it is not economical. However, tranverse cracks in the concrete can be avoided by providing ductility at the construction joints.

Because the vertical construction joint cannot transfer concrete tensile stresses, it will crack at an early stage. The longitudinal reinforcement through the joint should not yield within the expected bending range, which should be safely below the bending capacity of the uncracked concrete. Beyond that range, the joint should yield, and thereby provide sufficient rotation capacity to avoid an increase in tensile stresses in the uncracked concrete. The resistance of the longitudinal reinforcement will not be mobilised, except in the joints. The concrete will not crack.

If the spring constant in the above example were four times higher, or if it were the same but the undisturbed settlement was limited to 25 mm, the maximum bending moment would only be 300 MN/m and the maximum concrete tensile stress would be 1.0 Mpa. The reinforcement through the construction joint could then be 0.25 % of the concrete area, without yielding of the joint.

Monolithic concrete tunnel elements can be designed with a relatively low amount of longitudinal reinforcement (similar to concrete tunnel elements with expansion joints), without the risk of concrete cracks resulting from the *in- situ* performance. However, special attention should be paid to the watertightness of the construction joints of monolithic tunnel elements, as is also the case for expansion joints. In addition, watertight enveloping membranes may require special attention at the construction joints, to keep them watertight in case of yielding of the construction joint.

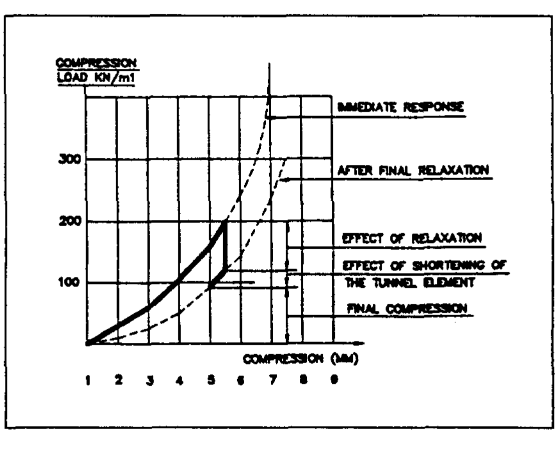


Figure 2-11. Typical performance of flexible rubber compression gaskets used for intermediate joints.

6.2.4 Temporary construction loads

The effects of temporary construction loads are of a temporary nature only. The tunnel elements are not uniformly loaded during the transportation and immersion stages.

The temporary bending moments for a tunnel element 120 m long for the given example are in the range of 50 to 100 MN/m, causing concrete stresses in the range of 0,15 Mpa to 0,30 Mpa. The longitudinal bending would increase with increased tunnel element length and by long waves, in the case of sea transportation.

For monolithic tunnel elements, the steel reinforcement stresses must be safely in the elastic range. For tunnel elements with expansion joints, temporary longitudinal prestressing is usually applied at the condition that the concrete will not receive tensile stresses.

6.2.5 Longitudinal reinforcement

The longitudinal concrete stresses are very small. The necessary ductility should be provided by the intermediate joints and expansion, or construction joints. If, instead, the longitudinal reinforcement of the homogenous sections would have to be activated for the longitudinal ductility, the concrete of these sections could be subjected to full-depth cracks.

The longitudinal reinforcement is designed to act as secondary reinforcement to the main transverse reinforcement or as minimum reinforcement for two-way slabs and walls, in compliance with the applicable concrete codes. This usually results in a longitudinal reinforcement of about 0,2 percent of the total concrete area, for a reinforcement yield stress of 500 N/mm². This same percentage, applied to the construction joint, would limit the maximum tensile stress in the concrete between these joints to about half the ultimate tensile strength.

6.2.6 Permanent longitudinal prestress

Longitudinal prestressing is not an effective way to economise in the design of the cross-section of concrete immersed tunnels, as it is for many other structures. It must be applied uniformly over the depth of a tunnel.

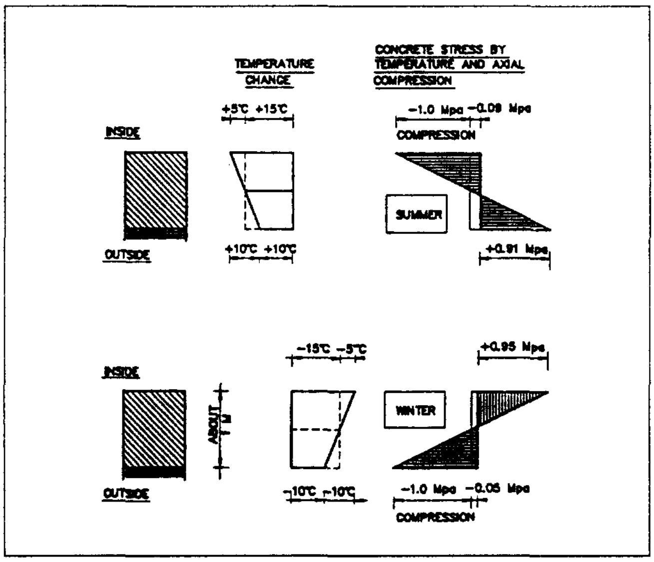


Figure 2-12. Diagrams of concrete temperature and stresses for summer and winter, valid for tunnels with flexible intermediate joints.

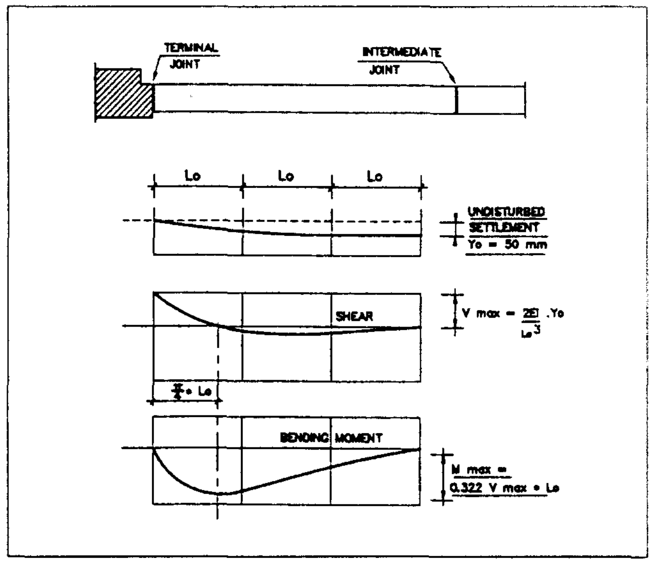


Figure 2-13. Examples of longitudinal analysis of the response of concrete tunnels to unequal settlement.

As can be seen from the previous example of longitudinal bending analysis, the prestress levels required would be very moderate. The longitudinal prestress can be used to allow higher longitudinal bending loads, causing tensile stresses. If concrete tensile stresses are not allowed to occur, as is often specified in the case of prestressing application, more prestress would be needed to compensate the tensile strength of the concrete in the operating condition.

Longitudinal prestress should be applied to increase the tension and bending capacity of the vertical construction joints, in particular, to a level where these joints will not open under certain extreme conditions such as earthquakes. The homogeneous concrete sections are always stronger than the construction joints because of their inherent tensile strength.

A typical example of longitudinal prestressing is Tokyo's Tama River Tunnel, which is located in an active earthquake zone. The tunnel elements were longitudinally prestressed in addition to the longitudinal reinforcement. Special prestressing tendons were installed and stressed *in-situ* to act as a flexible tie across the intermediate joints with rubber compression gaskets. The Tama River Tunnel is also provided with a watertight enveloping membrane.

7. Structural Analysis for Composite Steel Shell Tunnels

The design of steel shell immersed tunnels differ from concrete box tunnels because of the manner of their construction. Concrete box tunnels are cast in a basin, floated, and then placed and backfilled without much difference in the basic structural section. In contrast, the fabrication of steel shell elements involves a structure that undergoes a series of stages, each involving a basically different structure.

The description below applies to double-steel-shell type structures. The structural concept is simpler for the single-shell type tunnel because there is no exterior concrete, other than ballast concrete on the roof. However, the single-steel-shell tunnel undergoes the same stages of basically different structures. Because this type of shell has no external diaphagms, temporary internal spiderframes are utilised. In the case of double-tube shells, temporary longitudinal trusses also are utilised in the middle.

The structural stages are:

Stage 1: Fabrication and launching.

Stage 2: Internal outfitting with concrete.

Stage 3: Final condition after backfilling in place.

Each of these stages is described in detail below.

7.1 Stage 1: Fabrication and Launching

During Stage 1, the loads on the structure are largely a function of the method of support and launching, if the element is to be constructed on shipways. It may be launched sideways, or end-launched in either a controlled or uncontrolled launching.

As a recent example, the elements of the I-664 Tunnel in Hampton Road, Virginia (U.S.A.) were constructed in a drydock and floated out. In this case, all of the interior concrete was installed prior to installing the end bulkheads. However, in this tunnel the design was based on a launched element because the expectation had been that the elements would be constructed in the conventional way with outfitting being done in flotation. Boston's Third Harbor Tunnel is currently being constructed in the same drydock, although very little of the interior concrete will be placed prior to floating out.

During fabrication, each steel binocular or monocular module (about eight modules per element) must be supported adequately to avoid distortion or local buckling. In some cases, interior "spiders" may be required to maintain the roundness of the shell plate. Accurate roundness must be maintained to assure a uniform thickness of the interior ring concrete. This is critical to the eventual structural integrity of the elements when it is backfilled.

A portion of the exterior concrete about 1.5 m thick, called the "keel," is placed in the bottom of the formplate prior to launch. This provides protection for the bottom of the element during launch, as well as stability during towing. After this concrete is placed, the loads of the element are transferred to launching sleds or, in the case of end-launching, fore and aft poppets prior to launching. The shell and diaphragms may require reinforcements in either case.

The keel concrete is considered to be a longitudinal beam acting with the stiffened shell plate and diaphragms. The water pressures, both static and dynamic, which will occur during launch must also be determined and accounted for.

While the basic design of the elements takes into account some expected launching loads, the contractor must be made responsible for checking the element details for the proposed method of supporting and launching, and must provide whatever additional reinforcement that may be required.

Towing may impose longitudinal stresses on the steel element. Often the practice has been to tow the element under its own flotation, because the draft of an element not outfitted with interior concrete and the remainder of the exterior concrete is only about 2–3 m. If the elements are to be towed in ocean waters, the height of long periodic swells becomes important, because the swells impose significant longitudinal bending moments. Unless accounted for, these bending moments could cause buckling of the top shell.

Recently the practice has been to tow elements on large offshore construction barges in order to reduce this effect, when ocean towing is required.

7.2 Stage 2: Internal Outfitting with Concrete

During outfitting, the loading conditions on the shell change with each concrete placement. At first, the element is supported uniformly as it floats with a constant draft. The end bulkheads are quite heavy and impose a hogging moment on the element. As sections of the interior concrete are placed, additional moments are imposed on the shell. The sequence is designed to counteract the hogging effect and reduce its deflection so that at the end, the element is as straight as possible.

As the concrete weight is added, the element sinks lower in the water, thereby imposing transverse moments on the shell plate and diaphragm. The formplate does not take any of this load, as the water is allowed into the pockets between the shell and the form plates. The only exception occurs at the end pockets between the dam plate (extension of the bulkhead) and the first diaphragms. These pockets are filled with structural concrete, placed in the dry, to help resist the large forces that act on the joint during dewatering. Typically the shell plate is designed to take the water pressure as the outfitting progresses.

The placing sequence is determined by the engineer as a reasonable volume that can be placed while limiting the moments and shears in the exposed shell plate. The concrete placement should be symmetrical about the transverse and longitudinal centerlines of the element. As the head of water increases on the shell plate, the circumferential moments must be resisted by the diaphragms and shells embedded and, therefore, fixed in the keel concrete. This condition must be ckecked for each stage of the placement sequence; it generally becomes most critical during the placement of the heavy haunch sections.

Longitudinal loads are resisted by the shell plate and the radial stiffeners. Stress analysis for critical compressive stress for buckling of curved panels under uniform compression are used to determine moment capacity after applying a suitable safety factor.

The local buckling of the shell is investigated for loading in torsion and transverse shear. Buckling of the arch between stiffeners is investigated. The shell plate and longitudinal stiffeners are considered as a cylindrical shell spanning between diaphragms. The shell plate alone can resist water pressure as a ring structure and a cylindrical beam. Assumptions are made regarding how these loads are distributed between the shell and the stiffeners.

The diaphragm is designed as a ring structure, with its ends fixed in the keel concrete. The effective width of the shell plate, which acts with each diaphragm, is determined as a function of the centerline radius of the shell and its thickness.

7.3 Stage 3: Final Condition after Backfilling in Place

This final transverse analysis stage considers that the tunnel is completed and fully backfilled and is subjected to a series of loading combinations, listed below.

Bending moments and direct stresses are computed on the basis of six superimposed loading conditions:

1. Uniformly distributed loading—top.
2. Uniformly distributed loading—side.
3. Triangular side loading.
4. Loading from exterior upper quadrants.
5. Buoyancy forces.
6. Water surcharge.

Generally, the effect of these loading combinations results in a moment diagram with negative values (tension on the outside) near the center wall on the top and bottom and in the central portion of the exterior walls; and positive values (tension on the inside) in the regions in between. This is somewhat similar to the moment diagram for a two-cell rectangular box loaded top and bottom, as might be expected.

Axial thrusts act in addition to the moments and are caused by overburden and side pressures. These have the effect of reducing the tensile stresses caused by bending, while increasing the compressive stresses.

Before computers became readily available, the tunnel configuration assumed for analysis was simplified to circular or elliptical shapes in order to facilitate otherwise very difficult, or perhaps even impossible, calculations. Thanks to the availability of relatively inexpensive, accurate, and easy-to-use computer software such as STAAD III, STRUDL and others, the structure may be modelled to the exact shape of the proposed tunnel. Because the location of the frame line, the cross-section area, and the moment of inertia are all interrelated and affect the results (moments, shears, axial loads and deformations), an iterative design approach is necessary. Using such an approach, a series of computer runs are made, each using information from the previous run, to modify frame line location and member properties, thereby converging on an accurate and economical solution.

For the preliminary design, the total thickness of tunnel walls may be based on previous experience or very rough hand-calculations. The tunnel is drawn accurately and the frame line is laid out by "eye" or judgment, more or less along the mid-thickness of tunnel walls, discounting exterior tremie concrete.

Coordinates of selected "joints" along the frame line can be very conveniently obtained if the work is done by CADD drafting. Using the results of this first run, the design engineer can proportion steel and concrete depths and thicknesses based on stress analysis, and obtain new section properties. These data are used in turn as input for a second, more refined computer analysis, wherein the frame line is located at the center of gravity of the gross composite section and member properties are based on the same.

This process is repeated until the designer is satisfied that changes resulting from further refinement are negligible. Theoretically, the final computer run should be based on a frame line corresponding to the center of gravity of the cracked section, and member properties, area, and moment of inertia are based on the same.

It should be kept in mind that the composite three-dimensional tunnel structure with variations in loadings is extremely complex. The goal of the analysis should be to determine an envelope of maximum moments, shears and axial loads so that all possibilities of overstress are eliminated. For example, gross section properties may result from maximum effect at one location and minimum effect at another, whereas the cracked section may show the reverse. This approach, inconceivable in the past, is not at all difficult today with the help of clever computer programming.

Future analysis methods may make use of three-dimensional finite element modeling. This will be particularly interesting in the analysis of loadings such as ship collision, anchor dragging, and internal explosion. The longitudinal distribution of these loads is otherwise very difficult to determine.

7.4 Field Measurements

The final assessment of any design as complex as that for immersed elements can only be made on the basis of field measurements. To our knowledge, this has never been done for steel shell tunnels in any sophisticated way.

It has been proposed that strain gauges be attached to the diaphragms and interior reinforcing steel of the Third Harbor Tunnel in Boston, Massachusetts (U.S.A.) at various locations, representative of the wide range of imposed loading conditions that exist for this tunnel. If this program goes forward, the results obtained will increase our understanding of the structural action of steel shell tunnels and could lead to better, more economical designs in the future.

In the future, where unique conditions exist or, in general, where value can be gained from similar measurements of the action of immersed tunnel elements, there may be merit in including test programs of this type in the construction bid packages.

8. Loadings

8.1 Loading Combinations and Allowable Stress Increments

An indication of the types of loads and their combinations used for the design of immersed elements is given in Table 1. The table, based on data provided from the U.S.A., Japan, and The Netherlands, is not exhaustive. It should be noted that the factors given in the table are based entirely on the specific project conditions and requirements.

The reference projects in the table relate to tunnels of widely differing structural nature. They are intended to provide an understanding of the range of values for loading conditions that are encountered in immersed tunnel design(s).

The three reference projects used in the table are:

I: A steel shell traffic tunnel (Third Harbor Tunnel, Boston, Massachusetts, U.S.A.)

IIa: A longitudinally prestressed reinforced concrete traffic tunnel with waterproofing membrane (Tama River Tunnel, Japan).

IIb: A reinforced concrete railway tunnel with waterproofing membrane (Keyo-Line Daiba Tunnel, Japan).

III: A typical Dutch reinforced concrete traffic tunnel (Tunnel De Noord).

For reference II, only the ultimate-limit state factors are given. However, service-limit state verification is also done in view of watertightness requirements; for example, temperature restraint has to be considered.

8.2 Accidental Loads

Accidental loads to be considered may include:

1. Sunken ship loads.
2. Dropping or dragging ships anchors.
3. Flooding of the tunnel.
4. Internal explosion loads.

These loads are subject to different probability for each project. They are usually specified as deterministic loads, corresponding to an excedance probability of 10^{-4} per year. Increases in working stresses are usually allowed.

The discussion of earthquake loading is considered to be beyond the scope of this report. Immersed tunnels have withstood major earthquakes successfully. Ample experience with earthquake design for steel shell and concrete tunnels exists in the U.S.A. and Japan.

8.2.1 Sunken ship loads

For immersed tunnels in soft ground, the tunnel may respond more rigidly than the adjacent backfill. This can be accounted for in the load to be specified, usually as a uniform load over a minimum area. For the design of an immersed tunnel across the Great Belt in Denmark, which is an international waterway used by very large vessels, the specification was 100 kN/m^2 over 250 m^2.

8.2.2 Dropping and dragging anchors

Immersed tunnels are generally covered with a protective concrete layer on the roof. For navigation conditions, protective stone cover is also applied.

The energy of an object free falling in water has to be absorbed by the stone cover and partly by the crushing of the concrete cover layer. The structural roof load is related to the impact pattern. This factor can usually be accommodated without additional reinforcement.

The lateral load of a dragging anchor hooking behind the edge of the tunnel roof can be derived from the effective anchor-rope-breaking loads. For large vessels, the load can be in the range of 3000 kN, acting as low as 4 m below the rooftop, depending on the type of bottom material. The upper part of the walls should be provided with cover concrete to avoid mechanical damage to the structural concrete. Dragging anchor loads of this magnitude normally can be resisted by the available friction of the foundation.

8.2.3 Flooding of tunnels

The probability of internal flooding is very small during the operational life of the tunnel. However, it makes sense to investigate this type of incident in the light of possible undesirable settlements.

8.2.4 Internal explosion loads

The probability and extent of internal explosion loads depends very much on how the tunnel is to be used. A recent example is a tunnel in Belgium, located near an industrial area, which has been designed for an internal explosion pressure of 4 bar. This requirement substantially increased the amount of transverse reinforcement needed.

9. Typical Material Specifications

9.1 Structural Concrete for Concrete Tunnels

Although specifications vary considerably worldwide, a distinction can be made between two main groups of specifications. One group of contractors tends to use highway structure codes, which usually specify high-grade concretes, with characteristic strength in the range of 40 Mpa, and with durability requirements associated with sulphate attack. The latter requirements generally lead to the use of sulphate-resisting cement or Portland cement to which pulverised fly ash (p.f.a.) has been added.

The use of silicafumes with p.f.a. and Portland cement concrete is being considered in some countries.

The other group, of which The Netherlands are typically representative, use lower-grade concrete, with the emphasis on construction crack avoidance, low permeability, and chloride penetration resistance. Watertight membranes are not used.

A typical concrete specification for Dutch immersed tunnels is:

Characteristic strength:	22.5 Mpa
Cement types:	Dutch blast furnace cement (more than 65% slag)
Max. cement content:	2 75 kg/m^3
Max. water / cement ratio:	0.5
Permeability:	Less than 20 mm in penetration test, according to DIN 1048

Table 2-1. Indication of allowable stress increments or load factors for loading combinations.

Stress Increments (S) or Load Factor (F)	Type of Structure: I (S): Steel shell traffic tunnel (U.S.A.)	Type of Structure: II (S): Reinforced concrete tunnel with waterproofing membrane (Japan)	Type of Structure: III (F): Reinforced concrete traffic tunnel (Netherlands)
A. BASE LOADING Unfavorable combination of: • Dead load • Backfill • Surcharge and live load • Lateral earth pressure • Water pressure at mean high or low water	1.00	1.00	1.5*
B. TOTAL STRESS INCREMENT FOR COMBINATION OF BASE LOADING WITH ANY OF THE FOLLOWING:			
B1. Extreme high water	1.25		1.5***
B2. Anchor dragging or dropping	1.25		
B3. Sunken ship load	1.25		
B4 Temperature restraints	—		
B5. Unequal settlements	—	1.00 1.30**	—
B6. Temperature restraints and unequal settlements	—	1.15	—
B7. Internal explosion	—		1.0
B8. Earthquake, unequal settlement	—	1.50	—
B9. Earthquake, temperature restraints, unequal settlements	—	1.65	—
B10. Erection condition	—	1.30	

NOTE: A dash indicates that this aspect is known not to be reviewed, or is not critical.
* Refers to Dutch practice: the load factor used for the ultimate limit state is 1.7, reduced for the material factor incorporated.
** The factor 1.30 also includes extremely high water.
*** 1.4 * A + 1.15 * B1.

9.2 Materials for Steel Shell Tunnels

Typical material specifications for structural concrete and structural steel, as presently used in the U.S.A., are:

Structural concrete:

Strength: 4,000 psi (also for tremie concrete)

Cement: Portland Cement: AASHTO M85, Type I or II

Cement content: 565–610 lbs/yd.^{3}

Water/cement ratio: 0.48–0.50, depending on size of aggregate

Slump: 2 in.–5 in.

Permeability: 2,000 coulombs per 6 hours, where tested per AASHTO T-277

Fly ash: will be substituted for 5% of the cement for all concrete.

Structural steel: ASTM Grade A36 (mild steel with 36,000 psi yp)

Reinforcing steel: AASHTO M31 Grade 60 (60,000 psi yp)

Chapter 3:

CONSTRUCTION TECHNIQUES

by

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Chapter 3: Construction Techniques

0. Executive Summary

A number of techniques are available for the construction of tunnels. In comparison to bored tunnels, immersed tube tunnels have a number of advantages. The construction time can be shorter, and the risk in terms of time and cost overruns may be lower. Delays can be neutralised, for example, by accelerating certain activities or by using additional equipment—measures that are difficult, if not impossible, to use in construction of bored tunnels.

As the construction of immersed tube tunnels has increased considerably worldwide, the number of parties involved in such construction has increased proportionally. For those involved for the first time on such projects, the specific implications of this technology may pose difficulties. This situation can lead to an increased risk of accidents, delays and cost overruns.

This chapter summarises many key aspects of immersed tube tunnel technology. An integrated design and construction process is essential to the success of the project, as is the involvement of experienced and capable staff.

The construction techniques are very much influenced by the specific environmental conditions and requirements of the project. This means that great care must be given to the investigations and survey of environmental conditions, e.g., hydraulic conditions, weather conditions and geotechnical conditions. Often the effects of these conditions are interrelated and, thus, decisive for both the construction methods and the design.

The dredging and backfilling of a trench constitute an essential part of the construction of immersed tube tunnels. The effects of this work on the environment may temporarily change the ecological and biological conditions on the site, or even elsewhere. These effects can be positive or negative. In any case, the impact of this activity can be controlled by proper preparations and an intelligent selection of dredging techniques, adapted to the circumstances and criteria for the particular project. On a number of recent projects, the presumed contaminating effects of dredging have resulted in the choice of bored tunnels—a decision that accepts higher risks in time and cost overruns.

So-called unforeseen conditions have caused delays and cost overruns in a number of recent immersed tube tunnel projects. Could these have been foreseen and properly implemented during the design and construction of the projects (a process which, as noted above, relies on the skills, experience and know-how of professionals in the field)? The answer would depend on the collection of required data and, above all, proper judgement and implementation of these data. A summary of required data and relevant techniques is given in Section 5, which discusses construction techniques.

The availability of sufficient data, techniques and skilled personnel, supported by a strong organisation and good communication, is an additional factor in determining the success of a project. Whatever the legal and contractual relationships between the parties involved, the organisation on the site must be direct and open. All main parties involved should have access to relevant information and should have input in the decision-making process.

When the guidelines described in this chapter are properly followed, the result should be a successful operation for all parties involved, resulting in few, if any, cost and time overruns.

1. Introduction

The construction of immersed tube tunnels is arguably one of the most fascinating civil engineering achievements, because of the wide variety of construction techniques that are used and the many challenges posed by external conditions.

The construction of concrete or steel tunnel elements of high quality and accuracy, the necessity for precise dredging, the preparation of the foundation, and a number of sophisticated marine operations for placing the tunnel elements require professional engineering skills and experience, as well as sophisticated equipment. The construction techniques selected often have an important effect on the design of the tunnel.

Within the scope of the report by the International Tunnelling Association's Working Group on Immersed and Floating Tunnels, this chapter covers the various construction techniques related to the different types of immersed tube tunnels. The various conditions that may be encountered, and the various options available to deal with these conditions, are discussed. No specific recommendations are made with regard to the working methods to be selected under various circumstances, because every project is unique and no general rules can be devised.

For the engineering principal, this chapter offers an overview of the problems that may have to be faced and, therefore, must be considered on such a project. For those who have some experience and know-how, the chapter may serve as a checklist for immersed tunnel construction.

The material herein covers the main techniques that have been used to date on immersed tube tunnel construction. Construction of tunnels that depend upon the principle of "floating" (see Chapter 6) can be dealt with in more or less the same way. This chapter does not provide extensive details on the execution of floating tunnels, but rather deals with construction applications on existing projects.

A special section on dredging and its environmental impacts (see Section 4) is included because of the increasing awareness of the interaction between the ecological process and dredging activities. Examples for predicting and controlling these environmental impacts are given.

This chapter does not deal with all relevant construction techniques. Watertightness and structural aspects, for example, are covered in other chapters of the report (see Chapters 2 and 4, respectively).

No judgment of the various techniques has been made, because such judgments are beyond the scope of this report. Construction techniques can be judged only when all conditions, criteria, and requirements for the specific project are known. A stated preference for a specific technique may lead to the wrong conclusion for a particular project.

2. Characteristics and Types of Immersed Tube Tunnels

2.1 Concrete Tunnels

The two basic types of immersed tube tunnels are *concrete tunnels* and *steel tunnels*.

Concrete immersed tube tunnels have their roots in Europe. More than half a century ago, the first European immersed tube tunnel was built in Rotterdam (The Netherlands). Since then, the construction methods have considerably been simplified and optimised. Today, about three dozen concrete tunnels have been built all over the world. The majority of concrete immersed tube tunnels have been built in Europe, and half of those in The Netherlands.

The main principle of a concrete immersed tunnel is that the tunnel elements are made of reinforced concrete, which serves for structural purposes as well as for ballast. Although most immersed tunnels built recently do not have a watertight membrane, older tunnels (as well as some more recent ones) typically used a watertight membrane of steel or asphalt bitumen.

Most completed concrete tunnel elements consist of a number of segments, limited in length to approximately 20–25 m, linked together by flexible joints. Because each segment is a structural entity, it is easier to control the concrete placement and to limit the structural forces in the elements. A few concrete tunnels have stiff tunnel elements.

2.2 Steel Tunnels

The first steel tunnels were built in North America at the beginning of the twentieth century. Steel tunnels are designed as a composite structure with steel and concrete. The steel serves as a watertight membrane and makes a significant structural contribution. The concrete is used primarily to take compression forces and as ballast, and also contributes to the structural requirements.

The completed tunnel elements form a monolithic structure that has some flexibility, thanks to the elastic characteristics of steel. Thirty-three steel tunnels have been built all over the world, but mainly in North America.

2.3 Comparison of Concrete and Steel Tunnel Techniques

Until recently, the concrete and the steel options were considered to be different worlds, divided by the Atlantic Ocean. Only recently have the two techniques competed on the same projects and compared properly. Such a comparison must take into account all of their aspects. Without being exhaustive, a few comparative notes are given below.

In addition to the different techniques used to construct the elements, the marine techniques for concrete and steel tunnels require different approaches. These differences are related to the principles of the different materials, as well as to the contractors' techniques, which have developed independently of one other in the different environments.

Each application has a different impact on the time schedule, the construction of the approach ramps, the casting yard and/or fabrication yard, etc. Time, for example, is of critical importance for privately financed projects. It may even result in the acceptance of higher direct costs.

With regard to cost, it cannot simply be said that concrete is more costly than steel. For example, because environmental requirements may increase the cost of a specially constructed casting yard for concrete tunnel elements, a steel tunnel solution may be chosen instead. The immersed part of a steel tunnel may be longer than that of a concrete tunnel, thus shortening the *in-situ* approach ramps—a factor that may influence the overall comparison.

The reasons for the differences in the American and European approaches have their roots in scientific and political developments. However, in general, history has proven that the end result—in terms of quality, watertightness, lifetime, reliability, maintenance, etc.—does not differ. Only the future will tell whether a combination of the existing techniques will lead to overall improvements in optimising them.

The remainder of this chapter compares some specific differences in the various aspects of steel and concrete solutions.

2.4 Floating Tunnels

Thus far, no floating tunnels have been constructed, although a number of studies for such tunnels have been reported. As noted above, this chapter does not deal with the construction details of projects not yet executed. However, based on the floating tunnel projects being studied, it can be reported that the main marine construction techniques are much the same as those for existing immersed tunnels.

For floating tunnels, the dredging process is replaced by the anchoring of the floating tunnel, which involves entirely different assumptions regarding buoyancy. Data collection and judgment of environmental impacts, execution techniques, etc., are comparable to those for normal immersed tunnels. Readers are referred to Chapter 6, which incorporates various data and techniques regarding floating tunnels.

3. External Aspects and Conditions Affecting the Construction Methods

3.1. Introduction and Set-up

External aspects and environmental conditions are factors of major importance for the design and construction of an immersed tunnel. As such, they must be known in detail in order to understand what conditions can occur. Moreover, these conditions must be monitored and predicted throughout the various phases of the execution of the project, in order to avoid unforeseen and nasty situations.

It is therefore essential to collect and properly judge the data available, and to be sure that these data will be registered and reported as the project proceeds. Depending upon the specific conditions, these data can have an impact on the methodology; and, in many cases, may be decisive for the method, equipment, and timing of the various activities.

An example of a scheme incorporating proper data collection and reporting is shown in Figure 3-1.

3.2 Hydraulic Aspects

3.2.1 Data collection and methodology

The collection of data depends upon the local conditions, the specific requirements of the project, and the information available. Many immersed tunnels are built in areas where considerable information about the specific hydraulic conditions already is available. Long-term information (i.e., data collected over a period of five to ten years) is desirable because the more that is known, the less likely that unforeseen events will occur.

In addition, considerable experience and skill is required to know what information is critical or vital, what information is important, what information could be of use—and how to deal with the information. The answer to the latter question will depend upon the specific requirements of the project. For example, transporting a tunnel element over sea requires a different approach from transporting an element over inland waterways. The immersing of elements in a river can be entirely different from immersing them in a canal. Tidal influences may create not only opportunities, but hazards as well.

The engineer also has to have a feeling for the behaviour of the river, canal, or sea strait during the execution of the work. What will be the effect of the trench? Will it cause sedimentation; will it collect bottom transport? What will be the effect of the shape of the trench? Will it cause a decrease in current velocity?

The level of detail of the information can also reflect the views of the contractor about the methodology and equipment to be used. In general, it is wise to design the working method and the equipment use to allow for some extra capacity, should unforeseen circumstances demand it.

Problems with tunnel projects in the past have often resulted from insufficient information, judged by unskilled personnel.

Too often we have been faced with the remark that unforeseen conditions occurred that cost the client and/or the contractor large sums of money. In many cases, these "unforeseen conditions" could have been avoided by involving skilled specialists in evaluating the conditions at an early stage of the project.

The following section summarises marine conditions that influence the construction techniques and, subsequently, the design of the project. Although this summary may be used as a basic checklist, specific site conditions must always be kept in mind.

3.2.2 Current—velocity and directions

Currents significantly influence the selection of the towing and construction technique for immersing the elements. The tunnel element to be towed and immersed is exposed to the current. To maintain control of the tunnel element, the tow capacity and immersing equipment and provisions in the element must take into account the

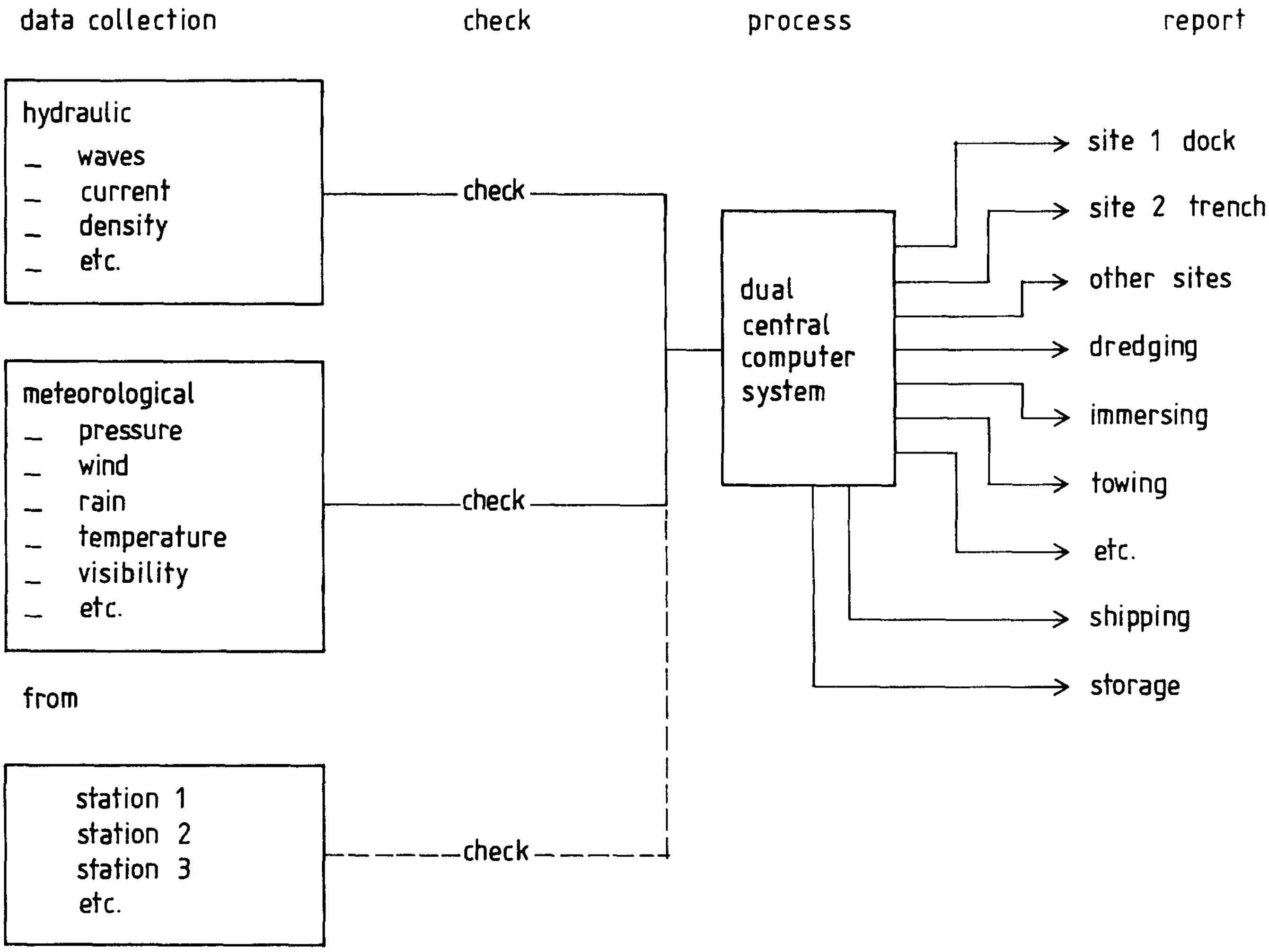

Figure 3-1. Scheme for data collection prior to and during a marine operation.

forces resulting from the current. These forces are:

- The outcome of the current velocity.
- The shape and size of the tunnel element.
- The width, depth and shape of the river or current-affected area.

In the past, these forces were—and, in many cases, still are—predicted by tests performed in hydraulic laboratories.

If the conditions at hand are not too different from those encountered in the past, the forces can be estimated based upon previous experience, and test results can be compared with real information available from past projects.

Current velocity and available space for maneuvering are often limiting factors for the length of tunnel elements. Tunnel elements 280 m long have been immersed in canals where there is almost no current. Experience has taught that tunnel elements are limited to 140 m when current velocities are as high as 1,5 m/sec. Higher current velocities, e.g., greater than 2 m/sec., have been dealt with successfully. A tunnel element more than 120 m long will require special procedures.

The directions of the current are also important considerations. A tunnel built in a tidal area offers opportunities to make use of tidal effects during transport. However, during the take-over from the transport phase to the immersing and other maneuvers, a very precise and good prediction of the current behaviour is required. In many cases, it is advisable to set up a system that measures the current velocity and registers the current directions during the marine operations.

3.2.3 Specific gravity

The handling of huge tunnel elements is very often controlled by the availability and use of local equipment and know-how. Tunnel elements weighing more than 45.000 tons have been built and transported for immersion at a distant location—a procedure that can be accomplished only by making use of the buoyancy caused by the water.

Because the design of an immersed tunnel is directly related to the principle of buoyancy, it is important to know the specific gravity precisely. However, the specific gravity can change over time with regard to place, depth, sedimentation, and temperature. Because it is not always possible to be entirely sure about these variations, a margin of error for must be agreed upon in advance.

Regarding time aspects, it should be noted that seasonal variation in the specific gravity may occur. This variation may result from changes in temperature, as well as from sedimentation, which may vary by season.

Differences in specific weight for fresh water versus salt water may be critical with respect to placement of the elements. This aspect, of course, depends on whether the tunnel is located at or close to the sea or inland. However, the water inland is not necessarily fresh. The heavier salt water may go inland, depending upon the local conditions, the quantity of water coming from inland, the water level at sea, etc. All of these matters are greatly influenced by meteorological conditions. It may be advisable—and, in some cases, essential—to know the relationship between the meteorological and hydraulic conditions.

The specific gravity will vary over the water depth as well. This variation can be caused by a number of factors. For example, the water temperature can vary over the depth of the water body—e.g., the heavier salt water will be near the bottom, while the fresh water will be at the surface. A complicated system of current-velocity and direction also may be caused by these differences in specific weight.

Thus far, specific gravities ranging from 0,9850 to 1.003 have been experienced on various projects in different locations; or on the same project, with variations occurring over time.

3.2.4 Tidal effects

The influence that tidal effects can have on the current velocity has been noted above. Tidal effects also cause differences in water height. These effects can influence the choice and/or the design of the casting yards. In addition, both the transport of elements over waterways and the immersing process are influenced by the height of the water. The length of the immersed section is influenced by the tide and by the water levels.

There may be an optimum period of tidal differences, ranging from spring to neap tide. At spring tide, the water can reach its maximum height (and minimum height as well), whereas at neap tide the current velocity will be lower. These phenomena may result in categorizing a number of days as presenting the best, or required, circumstances for the marine operations. These periods are called the "tidal windows".

3.2.5 Waves, swell and surf

In many cases, tunnels are built in relatively protected areas, where the waves have very little effect on the tunnel elements. In such cases, only the effect of waves going over the tunnel element during the towing and immersing operations may need be taken into account. However, under relatively exposed conditions offshore, the effect of waves and swell can be of considerable importance to the transport and immersing operations—and, consequently, to the design itself. For immersed outfalls, the surf will have to be taken into consideration as well.

Another aspect that must be considered is the frequency of the tunnel element itself in relation to the possible frequencies of waves or swell resulting from wind, offshore conditions, and/or navigation. Especially when the tunnel element is moored at an outfitting quay in a vulnerable place, waves and/or suction from passing ships can have an enormous effect on the forces on the tunnel elements.

3.2.6 Sedimentation

Most rivers pose specific problems with regard to sedimentation, silt, mudflows, and/or transport of material over the bottom. These conditions can affect the maintenance of the trench, the quality of the foundation, and the quality and quantity of the ballast system to be installed.

Experience has shown that sedimentation is different for every river, and depends entirely upon the local situation. These aspects have to be considered in advance. When this is done and possible outcomes are known, sedimentation need not be a problem, if proper precautions have been taken with regard to, e.g., cleaning the trench and the system for placing the final foundation.

Five main causes of sedimentation are given below. In many cases, a number of individual aspects alone or together influence the sedimentation.

1. A sudden decrease in the current-velocity in the trench may cause sedimentation of the materials being transported by the faster-flowing water.

2. Sediment suspended in fresh water, when mixed with salt water, will flocculate and settle on the bottom, forming a thin mud layer. As subsequent tides deposit more layers on top of it, consolidation may occur as a result of developing weight-pressure. The system for and frequency of trench cleaning may need to be adapted, depending on the rate of the sedimentation and consolidation, as well as the number of tides to which the dredged trench is exposed.

3. In a waterway characterised by high flows and high currents, existing materials may be carried by bottom transport. This material will settle readily in dredged trenches.

4. Under certain conditions, the activities for the project or in the environs of the project can increase the sedimentation. For example, placing the foundation underneath the tunnel may affect the concentration of suspended sediment in the remaining part of the trench.

5. In general, the occurrence of mudflows and sedimentation in rivers can be foreseen, although the quality and the quantity of this material is difficult to predict. In this regard, the advice of specialists is important because these matters can be of major importance to the success of the execution of the project, as well as the quality of the foundation.

3.2.7 Other river and/or sea characteristics and obstacles

In the design and planning of an immersed tube tunnel, the surrounding hydraulic conditions must be investigated carefully. Not all conditions have been mentioned herein, and each site may present another surprise. This report touches on only exceptional situations, such as those involving ice(bergs), seaweed, and shellfish (or other fish). These conditions may influence the location methods during the immersing operations.

Other unforeseen conditions also may occur. For example, obstacles—such as wrecks—at the location where the trench is to be dredged present an additional risk.

3.2.8 Hydraulic models

In order to investigate and determine the effects of the hydraulic conditions on the construction methodology, hydraulic tests performed in a laboratory will provide considerable information (see Fig. 3-2). In the meantime, many tests have been performed by a limited number of qualified laboratories. The results of these tests can be used to estimate the forces acting on the tunnel element and to forecast the behaviour of the tunnel element in the specific conditions of the given site, even without performing tests.

During the construction of tunnels in the past, the data resulting from the hydraulic model tests and the theoretical estimates have been compared with the real data. These comparisons have increased the quality of the information, not only regarding the immersing of the elements, but also concerning the conditions that will be encountered during the towing of the tunnel elements.

The forces of the water on a tunnel element are given by the formula:

$$F = 1/2 \cdot A \cdot r \cdot V^2 \cdot Cd$$

where

- A is the exposed surface of the element perpendicular to the current.
- r is the specific gravity of the water.
- V is the relative velocity, i.e., the difference between the speed of the element and the water.
- Cd is the friction coefficient (dragging coefficient).

This friction coefficient factor differs with the circumstances of the specific project. It is affected by the shape of the tunnel element, the shape of the river and the layout of the trench, the size of the element in the water-filled space, and the blockage factor of the element in the river.

This coefficient is the outcome of the laboratory tests and will vary according to the location of the tunnel element in the river. In past projects, these values have been compared with reality, and the comparison has shown that the tests have yielded relatively realistic outcomes. To demonstrate how important this factor can be, it should be noted that Cd values ranging from 0,75 to 5,2 have been recorded on one project. The latter value resulted in a decision to completely alter the operation in order to avoid these high forces. This aspect concerns the transport of tunnel elements, as well as the immersing procedure.

3.3. Meteorological Aspects

3.3.1 Data collection and methodology

Because they normally affect marine conditions, weather conditions must be taken into account. Weather conditions also can have an important direct effect on the marine operations. For example:

- Too much wind may be risky during the immersing.
- A lack of visibility may frustrate the location methodology of the operations.
- Ice may make it impossible to work with the equipment, ropes, etc.

In most cases, meteorologic data collection is no problem. Long-term data on weather conditions have been collected and are available in most parts of the world where the construction of immersed tunnels is being considered. In many (although not all) of these locations, the influence of the weather conditions on the hydraulic behaviour is known or can be known, when skilled specialists investigate and compare the data on weather conditions with the hydraulic conditions. When these data are not known, additional survey work will be required.

During the operations, it is necessary to be well-informed as far in advance as possible about the conditions that are occurring as the operations proceed. The sensitivity of the marine operation methods and the eventual risks related to a delay and/or sudden postponement of the immersing may even justify setting up a weather forecasting station at the site. Such a solution might be worth the investment, for example, when a tunnel has to be built in a busy harbour, because every (unforeseen) hour that the harbour is blocked has its price.

In connection with the hydraulic conditions, the possibility of hydraulic "windows" should be noted. Hydraulic windows represent the period of time during which conditions are acceptable for the towing and immersing operations. The same principle applies to weather "windows", i.e., the period during which weather conditions are acceptable for performing the towing and immersing. In practice, consideration of both types of windows is required.

3.3.2 Wind

As mentioned above, wind can have a strong influence on the hydraulic behaviour as well as on the operations, depending upon the equipment used. Wind also has a positive effect on visibility.

3.3.3 Temperature

The temperature can be a problem when it falls below a critical point in relation to humidity, thereby causing poor visibility. When frost occurs in conjunction with the low temperature

Figure 3-2. Testing a model of a tunnel element in a hydraulic laboratory.

of the water, ice may form on the equipment, anchor and mooring lines, creating difficulties.

3.3.4 Visibility

Poor visibility, one of the most difficult and unpredictable situations, can frustrate the positioning systems. Although it is possible to use the systems under poor visibility conditions, the cost of doing so may be very high compared to the benefits. These costs depend upon a number of factors, such as:

- The frequency of poor visibility.
- The number of tunnel elements to be installed.
- The risks and the results related to a delay or postponement of marine operations for the project itself.
- The economic effects of a sudden delay or postponement on the surrounding area.

3.3.5 Other meteorological matters

Although most of the vital meteorological consequences have been dealt with, other phenomena specific to the site will have to be considered. It is always wise to talk to local sailors or pilots about these matters.

Local conditions also may influence the accuracy of the positioning system used, or may frustrate communications. This can be the case with high and heavy steel structures or with high-voltage electricity cables in the surrounding area.

3.4 Shipping/Navigation

3.4.1 Ship movements during marine activities

Most immersed tube tunnels are built in waterways where there is heavy shipping. Hindrances that the marine operations present to shipping movements, especially in busy shipping waterways, must be avoided or kept to a minimum. Options for dealing with this situation depend upon the local conditions and requirements.

The marine operations that affect ship movements are the dredging activities; the transport of the tunnel elements; the immersing; and, possibly, the foundation work and the backfilling. In the first design phase of the tunnel, prior to the preparation of the tender documents, the shipping authorities and the pilots must be consulted. This consultation should be done with the help of an immersing specialist who is able to judge the influence of the requirements on the project possibilities and the cost. In reality, and in most (if not all) cases, it is possible to find an acceptable solution for all parties involved at no or minimal cost.

The working methods for dredging works on the trench can be adapted through the use of, e.g., floating pipelines, split or other barges, and excavating equipment. Experienced dredging companies are quite capable of dealing with the specific project requirements.

During the immersing operation, shipping often must be halted for a certain period. During transport, depending upon the space available, shipping traffic may or may not have to be stopped temporarily. It is wise to avoid all sudden movements in the water near the tunnel elements while vital activities are taking place, such as:

- The eventual takeover of the tunnel elements from the tugs to the anchor lines; or
- More importantly, the moment of placing the tunnel element against the previous element and closing the joint.

If complete blockage of shipping traffic should be required, it can be limited to a period of 12 hours or even less, depending upon the methodology used and the experience of the immersing contractor.

A number of techniques are available for the foundation work. Some techniques may influence shipping, while others will not influence it at all.

3.4.2 Suction caused by ships

Shipping movements can influence the tunnel elements as well. On a number of occasions, ships passing over a tunnel element have created a suction effect with the tunnel elements. This phenomenon depends upon the size of the ships; the size of the tunnel elements; the navigation speed of the ship; and, most importantly, the space between the ship and the tunnel element.

The maximum forces that have been measured are lifting forces up to 100 tons. If it is found that such high forces could occur, they must be taken into account during the various phases of the immersing. The possibility of such forces occurring will also affect the design criteria.

Another phenomenon is the effect that suctions and waves caused by ships can have on the tunnel element moored at a jetty. Under certain conditions related to the local situation, this action might increase the movements of the tunnel element in such a way that the anchor lines or mooring lines would break, if such a situation has not been foreseen. However, such effects can be estimated.

3.4.3. Navigational depth and clearance requirements

The available depth in the river used for the towing of the tunnel elements can be decisive with regard to the possibility of using a casting yard. Although this seldom will be a problem for steel tunnels, special precautions may have to be taken for concrete tunnels.

3.5 Soil Investigation

3.5.1 Data collection and methodology

A proper soil survey must provide information about the soil conditions that will be encountered. These soil conditions may influence the bearing capacity of the soil. Because the tunnel itself weighs less than the soil that is being replaced by the tunnel, the criteria for the required soil conditions are not too strict.

The methodology to be used can best be defined by the institution executing the survey. Questions to be answered will include the following:

- What is the geological history of the area?
- What works that have been performed in the area could affect the soil conditions?
- Are there rock formations?

In principle, the soil problems are not much different for immersed tunnels than for other civil engineering construction activities.

3.5.2 Trench dredging

To determine the shape of the trench and the dredging methodology, tests for slope stability should be performed. After deciding on the trench slopes, the additional effects of the current velocity in general and the specific conditions that will be encountered during the immersing must be considered, because a sudden slopefall during the immersing operations cannot be risked. In addition, the stability of the foundation and its material against currents or tidal effects should be verified.

A proper survey of the mineral, organic and biological composition of the soil is required in order to select the optimal dredging technology and to identify the effects that the dredging process will have on the environment. These effects can be negative as well as positive. See Section 4 for a discussion of dredging and its ecological effects on the environment.

3.5.3 Settlement

It must be kept in mind that when the tunnel is placed in the existing bottom, it replaces a volume of soil that is much heavier than the tunnel elements, with an overweight of approximately 10% of the weight of the soil volume. Depending upon the design methodology regarding the use of flexible joints or rigid constructions, some settlement is allowable. However, under very poor soil conditions, unacceptable risk may occur. To resolve this potential problem, a number of tunnels have been placed on long piles.

Except for the abovementioned extremely poor conditions, geotechnical conditions rarely, if ever, cause settlements. However, settlements do occur during the ballasting and backfilling of the tunnel elements. This settlement is caused by compaction of the foundation layer (discussed in more detail in Section 5.6). The settlement might also be caused by the effects of the dredging and cleaning of the trench (see Section 4 and Section 5.6.5 for further discussion).

3.6 Seismic Aspects

The structure of both steel and concrete tunnels allows for seismic movements.

With regard to the execution methodology, if fluidisation of the foundation underneath the tunnel element occurs, it will cause uplift. However, if a sand foundation is used and if the work is well executed, the characteristics of the sand will prevent liquefaction from occurring. In some cases, clinker is added to the sand underneath the tunnel in order to strengthen the structure of the foundation.

3.7. Fabrication Sites

The construction sites for the various techniques are summarised in Section 5, which deals with the construction of the tunnel elements. However, the choice of fabrication site not only depends upon the construction methodology, but is also very much influenced by environmental restrictions. The restrictions noted below should be kept in mind in selecting a site in relation to the system.

There may be restrictions in obtaining permission to install a casting yard with a dewatering system. Because such an arrangement may affect the environment, it can be rejected. Should this be the case, it may be possible to make a casting yard for all tunnel elements without the need for dewatering. Although such a solution necessarily increases the cost considerably, it can be competitive, especially if the site can be used more than once.

Another solution might be the construction of a smaller yard for just one or two elements. While this solution might decrease the cost of the casting yard, it will increase the time required for the construction of the tunnel elements and, therefore, the overall cost as well. Additionally, the fabrication process will have to be interrupted.

Another option is to construct the tunnel element(s) in the entrance ramps. However, this may only be possible for very short tunnels.

The above are only a few alternatives. Here again, experience will facilitate selection of the best option. In general, it can be said that steel tunnels offer more options for overcoming environmental limitations. This flexibility may compensate for accepting the higher costs of steel tunnels versus concrete tunnels. On the other hand, the longer transport routes are no problem for either of the options, provided that the water depth is sufficient. More aspects related to the fabrication site are discussed in Section 5, dealing with the construction of tunnel elements.

4. Dredging and Related Ecological and Environmental Impacts

4.1 General Matters

Dredging will affect the environment at the site. There has been some misunderstanding about the degree of disturbance of local conditions, due to a misunderstanding of the options for the dredging process. The degree to which this process will affect the site depends upon the local environment, soil characteristics, dredging techniques and equipment used, and budget available to minimise environmental impacts.

In the past, there has been a lack of awareness, know-how and vision concerning ways of dealing with dredging. In some cases, severe restrictions have been imposed without knowledge of their effects on the specific site conditions. The result has been high costs to the principal, often without achieving a proper solution to the problem. Occasionally, concerns about dredging have resulted in a bored tunnel rather than an immersed tunnel—a choice that involves higher risks for the principal.

The approach required for successful dredging comprises the following steps:

1. Investigate the geotechnical and environmental quality of the soil.
2. Investigate the hydraulic conditions of the river, canal or sea.
3. Investigate the various options for dredging technology and the effects of this technology under these specific circumstances.
4. Specify criteria for the dredging process, based upon the requirements for the environmental and ecological effects and the requirements for the construction of the tunnel.
5. Check the proposals of the dredging firms on the criteria specified.

Major dredging firms have invested considerable amounts of money in developing solutions to deal with the ecological and environmental effects of the dredging process. Many techniques have been developed to avoid polluting the bottoms of canals and rivers. New technical solutions are and will be available for the future. A proper judgment of the environmental results of these techniques for the specific site conditions is important. Part of the effort focused on the results of dredging concerns not only creation of the trench and backfilling, but also control of the environmental effects.

Experience has shown that the dredging process for a tunnel has only a temporary impact on the environment. The environmental conditions are greatly influenced by seasonal effects, which often are greater than the effects of dredging.

To overcome the resistance of interested parties (e.g., fishermen and environmentalists), it may be possible to combine the construction of a tunnel with measures to improve the ecological circumstances, e.g., by:

- Cleaning the bottom of the canal or river.
- Placing layers of stones on top of the tunnel. When this action is taken, measures for protecting the tunnel can be combined with measures to improve the environment, allowing for the development of new biological activities.
- Installing air injection equipment in the tunnel to improve the quality of the water flowing over the tunnel, after the tunnel has been finished.

4.2 Geotechnical, Hydraulic and Environmental Conditions

The following data are required for a proper judgment of environmental effects related to the advised or proposed dredging methodology.

Regarding the **soil in the trench**:

- *Mineralogical composition*. The nature and extent of turbidity differs for different minerals and the absorption of the contaminants of the mineral.
- *Granular composition*. Coarse particles are less susceptible to resuspension than fine particles. The occurrence of contaminants is greater in fine fractions because of the greater specific area and loading differences for clay mineral particles at the molecular level.
- *Density and the existence of stiff material*, which interacts with the dredging method.
- *Consistency* of the soil related to strength, cohesion, viscosity, and degree of consolidation.
- The nature and degree of *contamination*.
- The *suspension of organic matter*, which depends upon the content of the organic matter.

- The chemical nature and gas content of *coarse rubbish*.
- Other data, as needed.

With regard to the **hydrodynamic conditions**:

- The *nature and extent of the flow*, dispersion and suspension behaviour.
- *Wave effects*.
- *Flows resulting from wind*.
- *Water depth*.
- *Silt and bottom transport*.
- Other data, as needed.

Regarding **water quality**:

- *Density variations*, which influence the sedimentation of material.
- *Aerobic or anaerobic state of the layers*. This condition has an important impact.
- *Temperature*, as it relates to viscosity and density.

In order to be able to predict the effects of the project on the ecology at the site, the details of the ecological and biological processes taking place must be known. This information is not limited to the site, but also includes other areas affected by the activities at the site. Thus, an inventory of the ecological process has to be made in close cooperation with biologists aware of these local conditions.

Below is a summary of the ecological conditions that should be known.

Physical conditions:

- Temperature.
- Light intensity and penetration.
- Sediment characteristics.
- Sheltering areas and/or hiding places.
- Currents and wave energy.

Chemical conditions:

- Salinity.
- Oxygen concentration.
- Nutrients.
- Toxic substances.
- Flocculation.

Biological conditions:

- Food relationships.
- Accompanying species.

4.3 Criteria Related to the Trench

The trench serves a special purpose with regard to the placing of tunnel elements and the foundation underneath. Some requirements are related to the shape of the trench—for example, the trench being dredged must be sufficiently wide and deep, with stable slopes.

The bottom of the trench should be relatively flat. Too much difference in depth underneath the tunnel element will increase the cost of the foundation and may cause differential settlement. In addition, the trench bottom must be clean before the tunnel element can be placed. This requirement necessitates additional care in the dredging of the deepest part of the trench, and in cleaning the trench to avoid sedimentation and consolidation of sediment in the trench.

The normal tolerances for the bottom of the trench are ±15 cm. Because there is a minimum requirement related to the space underneath the tunnel element, a tolerance between +0 and -30 cm is required.

4.4 Evaluation of the Dredging Process—Technical Options

To properly evaluate the dredging process, the various activities that must take place prior to and after the placing of tunnel elements are identified below.

The making of the trench involves the following phases:

1. The cutting and excavating of the soil.

2. The vertical transport of the material.

3. The horizontal transport of the material.

4. The depositing of the material.

In principle, the maintenance and backfilling of the trench follow the same sequence, although the material and the related dredging techniques may be different.

The technical options for these activities are numerous. The technique selected has to take into consideration the requirements specified above or elsewhere in this chapter. These requirements are related to the structure of the tunnel, the environmental impact, the soil conditions, the shipping in the area, etc.

For the excavation, known techniques—e.g., those involving a bucket dredger, a cutter or suction dredger, or a grab crane—are good possibilities. In addition to the criteria listed in Section 4.3, and economic factors, the selection of excavation techniques depends upon the environmental requirements.

A **cutter dredger** stirs the material to be dredged (see Fig. 3-3). This process can have a negative effect on the environment. However, it involves closed vertical and, eventually, horizontal transport, when a floating pipe is used. Although stirring will not cause problems with clean, coarse material, it may be a disadvantage when slightly cohesive materials are present.

In contrast, a **bucket dredger** does not stir the soil very much. However, the vertical transport of the dredger, in addition to the overflow resulting from dumping the soil in barges for the horizontal transport, may cause contamination. This technique does not present a problem for cohesive and coarse materials; however, it could be a disadvantage when soft and cohesive material is present.

A **grab crane** presents much the same environmental disadvantages as a bucket dredger, although the problem can be partly solved by using a closed grab. The main disadvantage of a grab is the uneven bottom that results. Because this situation influences the foundation, the use of a grab crane may require additional precautions.

The effects of each of these techniques are very dependent upon the condition and characteristics of the soil and the local hydraulic conditions specified above. In less- or non-cohesive fine

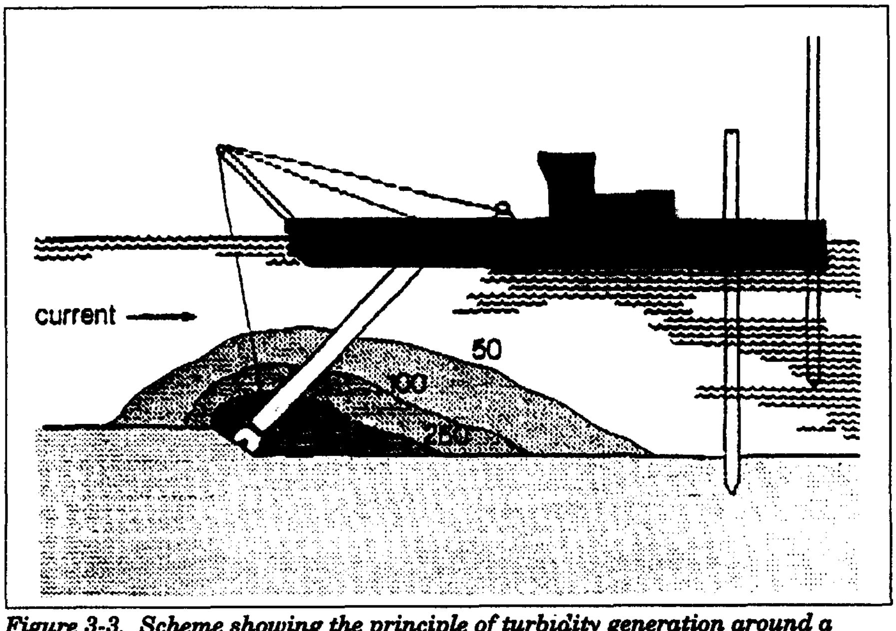

Figure 3-3. Scheme showing the principle of turbidity generation around a cutter suction dredger with 50, 100, and 250 mg/l concentration of suspended solids.

materials, contamination will be great. The use of a dustpan dredger, with an entirely closed transport system for the removal of this layer, may prove to be the best way to avoid negative environmental impacts.

In reality, a number of different techniques will have to be used in ecologically sensitive areas, because of the changing characteristics of the soil. New techniques, such as the use of an environmental disc bottom cutterhead, wormwheel or auger suction dredger, have been developed to avoid the disadvantages of the options described above.

For horizontal transport of the material, the main options are the use of a closed circuit with pipelines, or the use of barges. Shipping near the site, in relation to the available space at the site, has an important influence on the choice of transport technique. Although pipelines will avoid con-tamination around the line, the overflow from the depot could cause a problem that would require additional precautions. If barges are used, the contamination caused by the overflow and at the dumpsite has to be taken into consideration.

A number of systems have been developed for cleaning the trench. Normally a dustpan dredger is used. This is a suction dredger with a special type of opening at the end of the pipe that resembles the head of a Hoover vacuum. The dredger is moved over the bottom of the trench at intervals defined by the quantity of sedimentation and the risk of consolidation. It is not possible to clean the trench underneath an already immersed tunnel element because of the characteristics of the silt. If there is any concern that this space may fill up with silt, special precautions will be required, depending upon the foundation methods used.

For backfilling of the trench, several options are available as well. The type of material used is of crucial importance. Clean, coarse material will not cause any contamination, regardless of the technique used. A spreader or a diffuser will limit the exchange of material with the water in the river.

Other possibilities for limiting contamination include the use of silt screens, or sedimentation basins to hold the overflows of the deposits.

The following additional dredging-related aspects may influence the impact of the dredging process on the environment:

- The production level and/or the capacity of the dredger.
- The technical conditions of the dredger.
- The reliability of the methodology and equipment under varying conditions.
- The turbidity and spillage from the dredger.
- The accuracy and selectivity of dredging for the various layers.
- Use of modifications to limit the turbidity.
- The awareness and quality of the staff involved in the preparations and the operation of the dredging process.

4.5 Selecting the optimal solutions

A number of environmental, economic and technical aspects influencing the choice of techniques have been discussed above. However, optimising the choice in terms of effects and cost involves carefully weighing the various options. This process is influenced by proper judgment of the ecological effects of the dredging operation on the general characteristics of the specific body of water.

In a canal or river where there is little, if any, real biological or ecological activity, the conditions will not worsen as a result of dredging. In fact, local conditions can be improved through the removal of polluted soil.

Many rivers have a regime that is affected by the seasonal cycles. In these cycles, heavy rainfall or the influx of melting water may cause more siltation and contamination than does the dredging of a trench. The self-healing effects in most rivers are enormous, often eliminating the effects of the dredging work within one or a few seasons. The execution of dredging activities can be planned to work in harmony with both these seasonal effects and the cycles of biological activities.

In cases involving a sensitive area nearby (e.g., oyster beds, lobster nurseries, etc.), it is often possible to benefit from the current, which can be used to direct the siltation caused by dredging away from the sensitive area.

An accurate description of the dredging works to be executed and a proper definition of the dredging limitations in place and time, coupled with adequate control during execution, should suffice to limit the environmental effects of the dredging operations, both in the immediate project area and in the surrounding areas.

The possibility that the construction of the tunnel will permanently change the hydraulic circumstances, in terms of the cross-section of the river, must be taken into consideration. These effects could result in compensation elsewhere.

5. Available Techniques for Construction, Immersion and Foundation of Tunnel Elements

5.1 Construction of Tunnel Elements

5.1.1 General

The various aspects of the construction of steel and concrete tunnel elements are discussed in Chapter 2, which deals with structural design of these tunnels. Therefore, this section briefly summarises the main aspects of the construction methodology of these techniques.

5.1.2 Steel option

Steel shell tunnels are composed of a structural steel shell lining, which forms a composite structure with the concrete and also serves as ballast to the structure. A number of different construction methods and sequences can be used with the steel option.

To begin with, all or part of the steel shell is constructed. Some keel concrete may be added to the structure to increase its stability and rigidity. Subsequently the steel structure can be put afloat and the remaining part of the structure can be installed afloat.

This construction technique allows for the use of a shipyard, shipways, shiplifts, dry docks and/or a temporary construction basin. The tubes can be launched sideways or end-launched. This guided launching must be controlled by using properly levelled guided structures (winches and jacks, chains, etc.).

After the tunnel element has been put afloat, it is towed to an outfitting jetty for the finishing of the steel structure, if required; and the placing of all, or the remaining part, of the concrete. In addition, specific requirements for the marine operations—such as temporary bulkheads, joint structures, and access shafts—are installed.

Additional ballast—concrete and/or gravel—is placed on the tubes prior to immersing.

The design of the tubes will have to be adapted to the fabrication methodology and sequence. However, the design must allow for some flexibility in order to optimise the construction in relation to the fabrication capabilities.

5.1.3 Concrete option

Smaller concrete cross-sections can be launched or built on a shiplift, shipways, or other structure. This process is more difficult for bigger cross-sections, for which existing docks and excavated casting yards normally are used.

5.2 Finishing Jetty

The criteria for these docks are dictated by the draught of the tunnel elements. For concrete tunnel elements, the depth of the casting dock should be equal to the height of tunnel elements below low water. If this is a problem because of the possibilities related to the yard or the depth of the river where the tunnel element will have to be transported, the depth of the casting yard can be decreased if the tunnel elements are not entirely finished. Sections of the concrete in the roof and, eventually, in the bottom can be cast at a later stage at the finishing jetty, near the immersing place. In other cases, it has been possible to increase the water level in the canal temporarily.

Because of the growing number of restrictions regarding the dewatering of the casting yard, additional provisions may be necessary to avoid the disadvantages of dewatering. These provisions may, in turn, increase the costs of the casting yard. This problem has been solved by using existing casting yards, where problems with dewatering either have not occurred or have been solved, at locations far from the immersing site. In such cases, the transport of the huge tunnel elements is limited only by the required maneuvering space.

After the tunnel elements have been fabricated and ballasted, including many of the provisions for immersing, the dock is flooded and the tunnel elements can be put afloat. This is done by removing the ballast water. The tunnel elements are connected with anchor points and put afloat in a well-controlled way, in order to avoid drifting of the tunnel elements. The tunnel elements are then towed to the finishing jetty.

5.3 Transport of the Tunnel Elements

In transporting the tunnel elements, the following matters are important:

- The conditions to be met (see Section 3).
- The behaviour of the tunnel elements under the specific conditions at the site.
- The space available in the navigation channel.
- The type and capacity of the tugs.
- The location system and the way that these results are presented to the operation leader.
- The organisation of personnel and equipment involved in the transport operation.

Assuming that the conditions that may be encountered and the effects these conditions will have on the tunnel element during transport are well understood, the methodology to be used during transport can be defined. The capacity of and the number of tugs depend upon the resistance of the tunnel element in the river, canal, or at sea, as well as the space available for maneuvering. Another decisive factor may be the fleet available for the specific location.

When the available space is narrow, an accurate and fast-working navigation system is required to provide information about the position of the tunnel element in the available space. The faster the system, the more time is available to give instructions to the tug captains and to correct the position of the tunnel element. This is important because the huge mass of the tunnel elements causes a considerable delay in any corrective reaction that may be required for the tunnel elements.

In this regard, the type, the number, the capacity and the layout of the tugs must be considered. In principle, it is preferable to limit the number of tugs in order to limit the problems the operation will present to the maneuverability of the total system.

When the system passes a lock or a bridge with limited space, it may be advisable to use winches. If the transport from the finishing jetty to the immersing place is short, only winches can be used. Transferring the tunnel element from the tugs to the winches is an operation that must be properly planned in accordance with the site conditions.

Transport over sea is entirely different from transport in a river or canal. As noted above, sea transport requires that the structure of the tunnel be capable of handling the forces resulting from the swell.

The transport of a tunnel element afloat has been dealt with above. During part of the transport, depending upon the size of the elements, whether they are steel or concrete, and/or the the type of equipment used, the tunnel element may be connected to a piece of equipment that also serves for immersing. In this case, the tunnel element most often is already ballasted for the immersing operation.

Because transport of huge and complicated structures or structures composed of more segments (such as a tunnel element connected to the immersing equipment) has become more commonplace, a computer model has been developed to forecast forces on and in the structure (see Fig. 3-4). This so-called Ships Response System can be used for complicated situations.

As an example: for a tow operation under average conditions in a river, with tunnel elements weighing 30.000 to 40.000 tons, a total tow capacity of 10 to 20.000 HP with four tugs, eventually with push possibilities, will be required. This estimate assumes that 1000 HP results in a tow capacity of 10 tons. Depending upon the maneuverability, two or three times the theoretical capacity may be required to control the position of the tunnel element.

The tow operation must be scheduled to make maximum use of local tidal conditions, changes in water height, and current velocity and direction.

5.4 Immersing

5.4.1 General matters

The immersing of tunnel elements is a risky part of the job. Perhaps because those involved in these operations are aware of the risks, few accidents or failures have occurred, although some 500 or more tunnel elements have been immersed thus far. The technology involves working with huge elements under relatively difficult conditions, where much of the work is done without a direct view of the activities. Therefore, it is critical that the work:

- Be as simple as possible; and
- Benefit as much as possible from the natural capabilities of water.

Successfully accomplishing immersing work requires having information about the various environmental conditions (as specified earlier), as well as the skills, experience and know-how to be able to interpret and apply these data to the operations as planned. It is advisable to work with an overcapacity in the equipment, and with sufficient safety margins.

An integral part of the preparations for immersing is a proper risk analysis of the operations, with sufficient back-up facilities for the equipment. It is

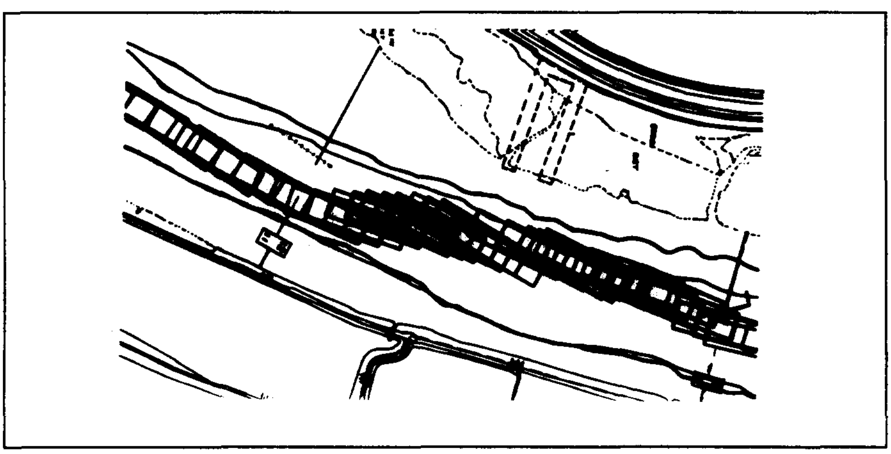

Figure 3-4. Computerized projection of the positions of a tunnel element in a river during transport.

advisable to make the operations reversible and to foresee the possibilities of performing the various operations step by step.

Figures 3-5, 3-6, and 3-7 illustrate immersing operations for steel tunnels, concrete tunnels, and pipeline tunnels and outfalls, respectively.

Immersing under normal, protected conditions is a rather straightforward process for the experienced tunnel builder, and need not be too difficult to prepare, if the criteria specified below are followed.

5.4.2 Vertical control

5.4.2.1 Steel tunnel elements

Prior to immersing, the tunnel elements are attached to the immersing pontoons. These pontoons normally consist of a set of two or four pontoons with bridges in between them. The tunnel element is suspended from these bridges.

In order to increase the weight of the steel tunnel elements, they can be ballasted by additional concrete and/or by gravel. This ballast is placed on top of the tunnel element when it is suspended from the immersing equipment.

The immersing takes place when the tunnel elements are lowered with winches on the pontoons. When the tunnel element is close to the bottom, it is lowered against the previous element before being placed on the gravel bed foundation. Temporary jointing is accomplished with rubber gaskets; permanent joints are made after the temporary bulkheads are removed.

5.4.2.2. Concrete tunnel elements

Vertical control of concrete tunnel elements may be different from control of steel elements. After these tunnel elements have been built in the casting yard, they are ballasted with water in order to remain at the bottom of the dock, while it is filled with water.

The ballast water is pumped out of the tunnel elements to make them float.

The equipment most often used consists of pontoons adapted for the job. These pontoons are placed on top of the tunnel elements, either before the element is put afloat, or at a later stage by floating cranes. The pontoons are equipped with winches to anchor both the tunnel elements and the pontoons, or the pontoons only.

After the tunnel element has been moored to the anchors, the ballast tanks are partly refilled with water until the tunnel element has sufficient negative buoyancy. If additional ballast is required during the immersing because of a change in density, water can be added.

Another option is to use additional floating bodies or stability towers with the tunnel elements. The stability towers, which are placed on top of the tunnel elements, need to have both sufficient floating capacity and a sufficiently large cross-section at the water level. The combination of stability towers and the ballast water provides excellent control of the tunnel elements.

When the tunnel elements are near the final position, they are placed on a temporary structure on the previous element, and on temporary struts at the free (or secondary) end of the tunnel elements. The final positioning is done with jacks in these struts, thereby allowing for correction of settlement, misplacement, etc.

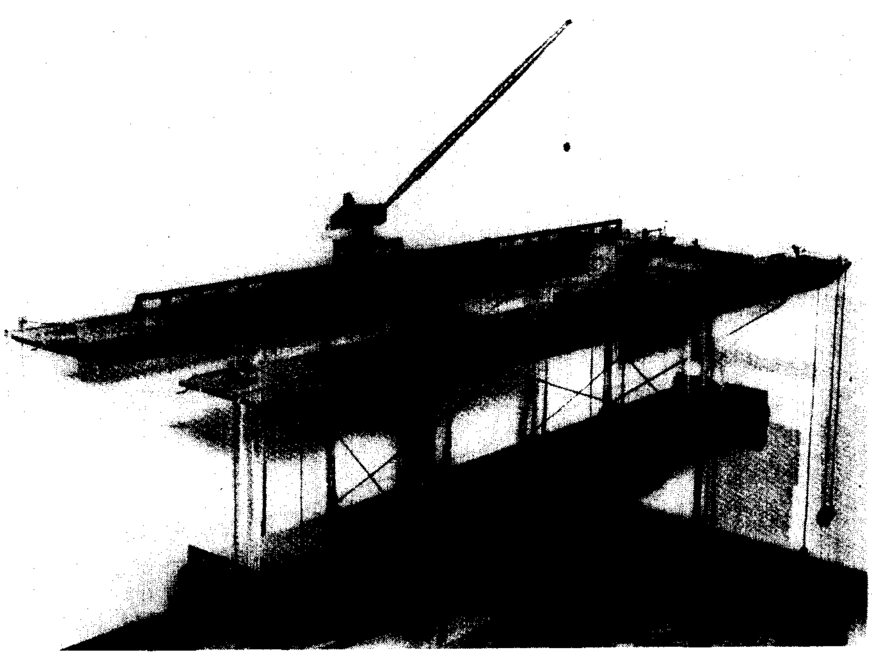

Figure 3-5. Model of a lay barge used to place the steel tunnel elements for the Bay Area Rapid Transit (BART) system's Transbay Tunnel in San Francisco, California (U.S.A.). (Photo source: Tunnel Engineering Handbook*).*

5.4.3 Horizontal control

The horizontal control of the tunnel element normally is created by winches, anchor lines and anchors in the water or ashore. These winches can be placed on the pontoons. However, when the current is fairly strong, it is important to have direct control over the movements of the element. This can be achieved by placing the winches in towers on top of the tunnel elements. Alternatively, the winches can be placed ashore.

Attaining horizontal control involves the following steps:

1. The tunnel elements are towed or winched to the immersing site.
2. While the elements are still afloat, the tugs are replaced by winches connected to anchors in the river or ashore.
3. During the lowering of the tunnel element, the horizontal position of the tunnel element is checked continuously.
4. Subsequently, the tunnel element is placed with the primary end on a guiding structure on the secondary end of the previous tunnel element.
5. The tremendous water pressure pushes the tunnel element firmly against the previous element, at the same time dictating the direction of the axis. The final axis of the tunnel is very much dictated by the precise measurement of the end rings of the tunnel elements containing the Gina profile.

5.4.4 Other equipment-related options

The working methods described above have become commonplace in imersed tube tunnelling, thanks largely to the availability of equipment and the experience with this method gained over time.

Another option, which involves the use of "spud", or self-elevating, pontoons, offers several advantages. With this type of equipment, the immersing operations on-site can be limited in time, and the intervals between the immersing of each tunnel element can be limited as well. To date, sequences of one tunnel element every 24 hours have been achieved.

The choice among these and other options depends upon a combination of considerations, such as the number of tunnel elements, site conditions, time schedule available, specific requirements from the client, and equipment available. Selecting the best option is a matter of economy, technique and, most of all, experience, skills and know-how.

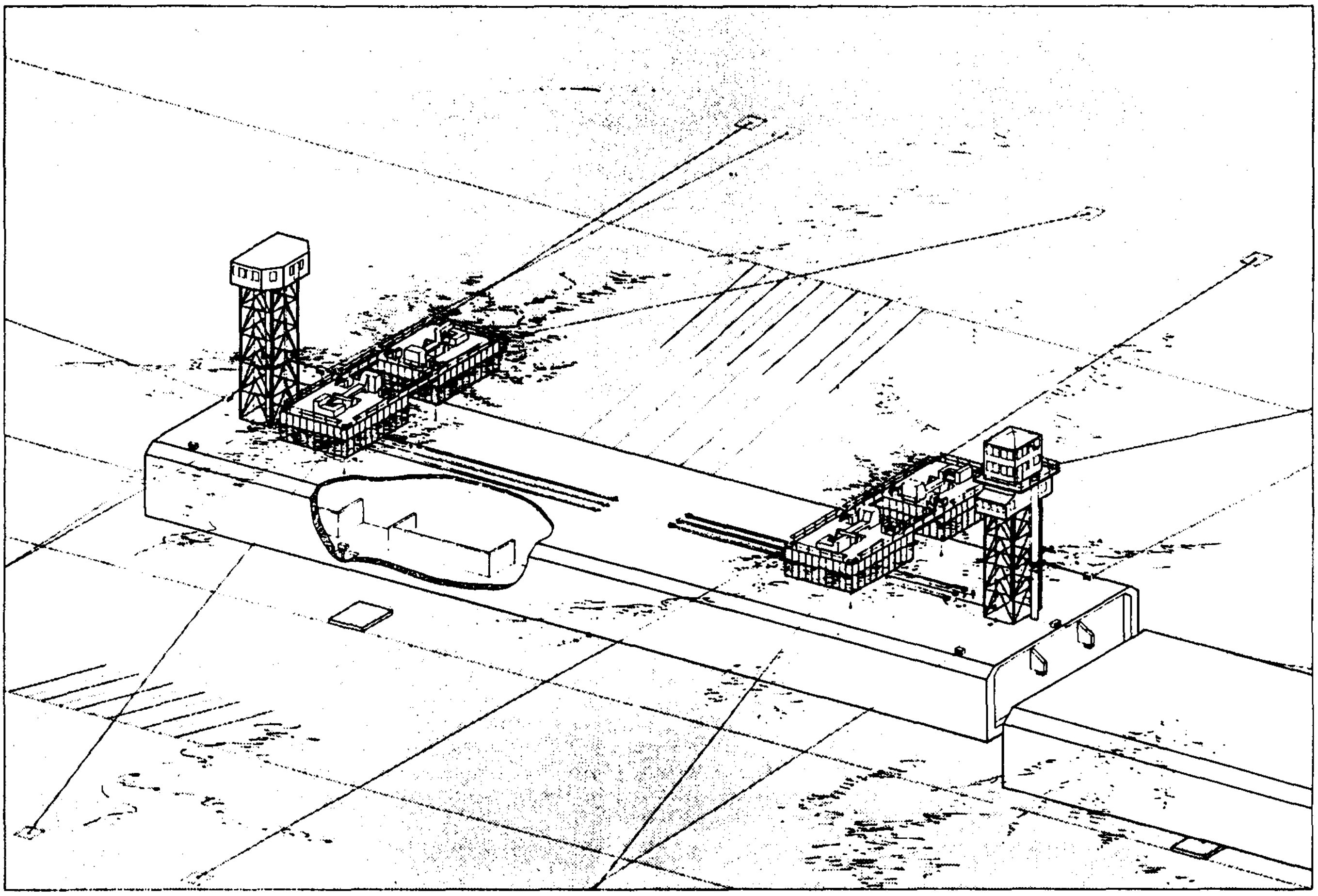

Figure 3-6. Standard immersing system for concrete tunnel elements.

5.5 Positioning

The system that precisely defines the location of the tunnel element in the river and/or the trench has undergone important changes in the past 20 years. These changes are the result of new technology in the possibilities for survey above, as well as under, water. Thanks to these developments, the period required for the immersing of a tunnel element is considerably shorter, and the risk of surpassing the time available has decreased.

The importance of a fast survey system during transport has been noted. During the immersing process, the accuracy of the system is paramount.

We must attend to the accuracy and vulnerability of the survey system for external, as well as internal, conditions. Activities prior to the immersing must be controlled in detail.

5.6 Tunnel Foundation

5.6.1 General Information

Three different foundation systems are available. In Europe, the sand-jetted and sand-flow systems are commonly used. In the U.S.A., the screeded gravel bed is common practice.

For a sand foundation, the tunnel element is temporarily founded directly after the immersing, until it can be lowered on the final foundation. The temporary foundation at the primary end—i.e., the end connected to the previous tunnel element—is the guided support of the tunnel element on a structure connected to the previous element.

The temporary foundation at the secondary (or free) end consists of concrete or steel slabs, placed in the trench prior to the immersing of the tunnel element. Attached to the tunnel element and located above these slabs is a steel structure consisting of bars and jacks connected to the tunnel element. This system allows for correcting the position of the element during the following phases.

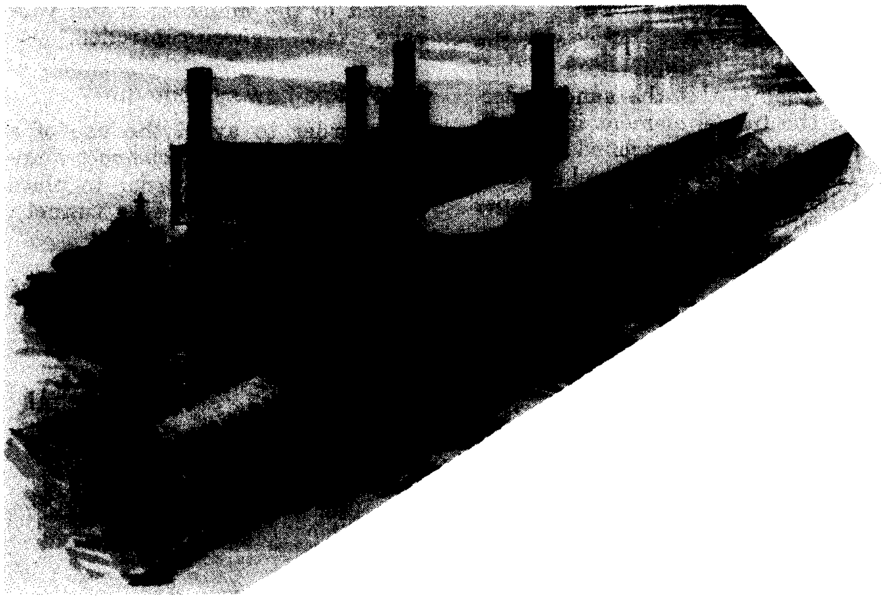

Figure 3-7. Immersing system used for pipeline tunnels and outfalls.

5.6.2 Screeded gravel bed

This foundation type is generally used in North America, with steel shell tunnels. Following the dredging of the trench, a layer of coarse sand or gravel is placed on the bottom of the trench. The gradation of the material must be related to the hydraulic conditions: the stronger the current, the higher the gradation. The layer will be approximately 0,70 m thick.

Careful attention must be paid to accurate levelling of the gravel bed. The required accuracy is ±3 cm, depending upon the local conditions, the gradation of the materials, and the equipment used. Levelling is done with a screed, suspended from winches on a carriage rolling on tracks supported on two pontoons.

The rig is anchored above the surface to be levelled. The screed suspension can be adjusted to compensate for changes in tide level. In order to exclude influences from the surface to the greatest extent possible, special equipment, based upon the principle of semi-submersibles, can be used. This method permits the screed to be directly connected to anchor blocks.

Figure 3-8 shows the screeding rig used for San Francisco's Transbay Tube.

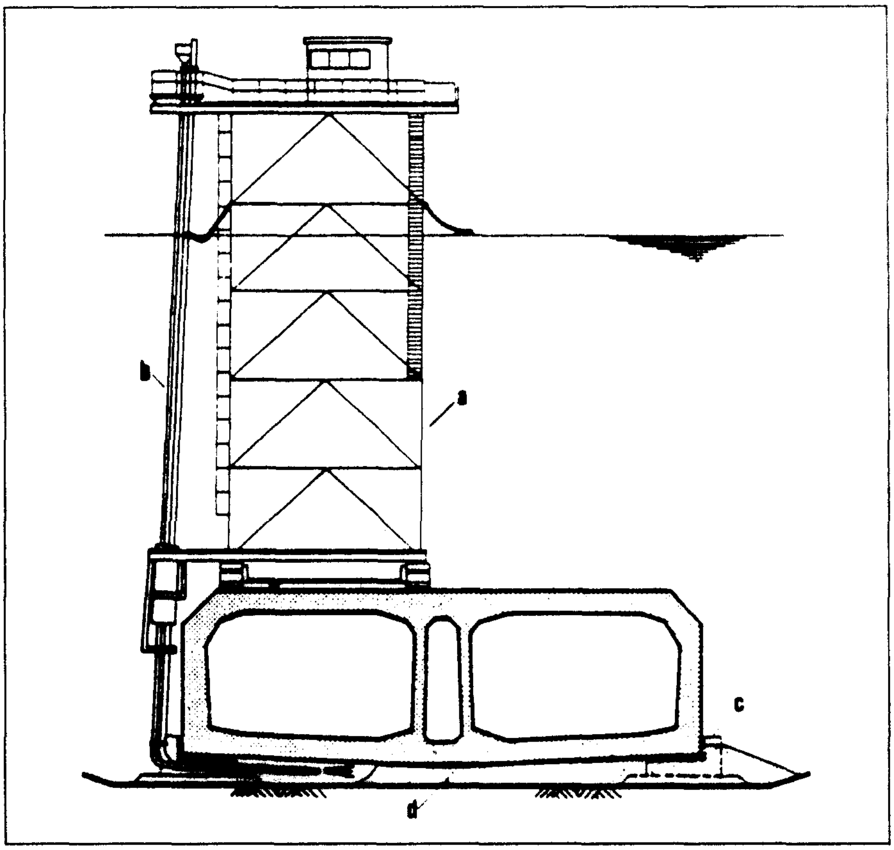

Figure 3-9. Principle of the C&N sand-jet system. a: gantry, movable along the tunnel axis. b: pipe system for sand supply. c: temporary foundation. d: jetted sand.

5.6.3 Sand-jetting foundation

The first system used to create a sand foundation was the C&N method, which uses a gantry of steel running over the tunnel element. Connected to this gantry are three adjacent pipes. This system of pipes leads to the space underneath the tunnel between the bottom of the tunnel and the bottom of the trench.

The biggest pipe is in the middle. Through this pipe, a sand/water mixture (the composition of which is well-controlled) is pumped underneath the tunnel element. The two pipes on either side of the large pipe suck the water back. This creates a flow action that settles the sand underneath the tunnel element in a well-defined and well-controlled pattern.

The gantry on the tunnel element and the possibility of turning the pipes around a vertical axis allow the entire space underneath the tunnel element to be covered. A space of about 1 m for moving the pipes underneath the tunnel elements is required.

The sand must be clean. The average grain size of the sand is approximately 0,5 mm. The concentration and the exit velocity of the sand/water mixture, which are directly related to the diameter of the pancake, must be well-controlled.

5.6.4 Sand-flow system

In order to avoid the use of a gantry, which might obstruct shipping traffic, and in order to place foundations under deeper tunnels, the so-called sand-flow method has been developed (see Fig. 3-10).

With this system, as for the sand-jetted system, a sand/water mixture is pumped through pipes to the space underneath the tunnel element (see Fig. 3-9). In this case, instead of using a movable system, a number of openings are created in the bottom of the tunnel element. These openings are connected to pipes placed either inside or outside the tunnel elements (the choice of placement depends upon shipping requirements, local conditions, and preferences of the contractor). When the pipes run from ashore through the tunnel to the opening to be filled, there is no hindrance at all to the shipping traffic.

The sand/water mixture is pumped through the openings in the tunnel element. The sand fills the space underneath the tunnel element until the "crater" touches the bottom of the element. Thereafter, an expanding pancake is formed underneath the tunnel, until the internal water pressure in the pancake surpasses a pre-established maximum. Subsequently, the next opening is opened and the previous one is closed.

The size and the pattern of the openings, the characteristics of the sand, the depth of the tunnel, the overweight of the elements, and other aspects are interrelated. This method is very fast

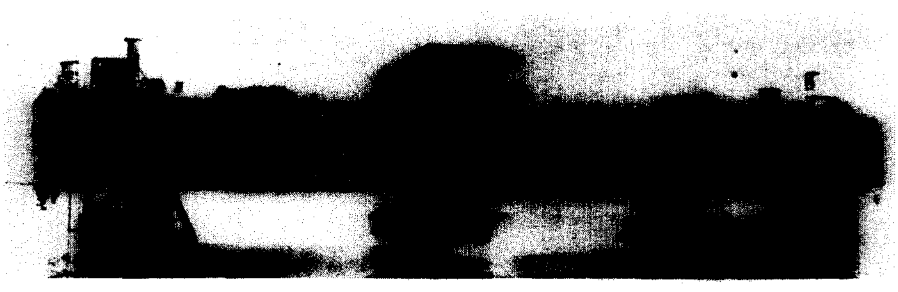

Figure 3-8. Model of a screeding rig used for the Transbay Tube. (Photo source: Tunnel Engineering Handbook*).*

and can fill the entire space underneath a tunnel element within 24 hours, thus avoiding the risk of siltation after the elements have been placed.

5.6.5 Cleaning of the trench

The cleaning of an open trench was mentioned in Section 4.4. Siltation of the trench has been a problem on a number of projects. Because the details of these problems are outside the scope of this report, the remarks herein are limited to the conclusions that can be drawn from these experiences.

If there is a risk of sedimentation by bottom transport and/or siltation in the river in the space underneath the tunnel elements, serious consideration must be given to the solution. In general, it can be stated that removing siltation from underneath a tunnel element is extremely costly. Therefore, it is essential to avoid this type of sedimentation.

When a gravel bed foundation is used, the risk of such sedimentation is nil because there is no open space underneath the tunnel element. With a sand-flow system, which involves transport through pipelines and openings in the tunnel bottom, these problems can easily be avoided as well. The system allows for very rapid filling of the space underneath the tunnel elements. The entire space under tunnel elements having a bottom surface of 3500 m² can be filled within a 24-hour period.

With the C&N sand-jetting system, the capacity of the system to remove the silt is limited, as is the capacity to fill the entire space underneath a tunnel element. Therefore, the matter of sedimentation must be given special care if a sand-jetting system is used.

6. General Matters

6.1 Quality Control

It has been emphasised that the quality control for an immersed tube tunnel must pay specific attention to a number of matters. In addition to the standard procedures for concrete and other related activities, special attention must be given to watertightness—of the concrete, for concrete tunnels, and of the steel shell, for steel tunnels. Steel will have to be X-rayed, while concrete will have to be checked for cracks.

It is possible to check the watertightness after the graving dock has been flooded. Although repair of eventual leaks at that time is expensive and best avoided, it is technically feasible.

The weight of the tunnel elements in relation to the size and buoyancy of the tunnel elements must be closely monitored.

The joints between the various segments of the tunnel elements require special care. A variety of methods have been developed to check and control the quality of the joints.

Quality control of the marine-related activities requires considerable attention. Proper testing of the system and equipment used for monitoring conditions and for positioning is essential. For example, it is very important to measure properly the depth of a trench, the siltation, etc. The ability to perform these measurements successfully is very dependent upon the conditions of the project and the capability of the equipment to deal with specific circumstances.

6.2 Risks

6.2.1 General considerations

The risks on a multi-disciplinary project such as an immersed tube tunnel can be distinguished as those related to technical matters, to time schedule, and to cost. The risks for these types of projects are not basically different from the risks for other civil engineering projects. This statement assumes, however, that the most important requirements—i.e., regarding input based on experience and know-how—are fulfilled on the project.

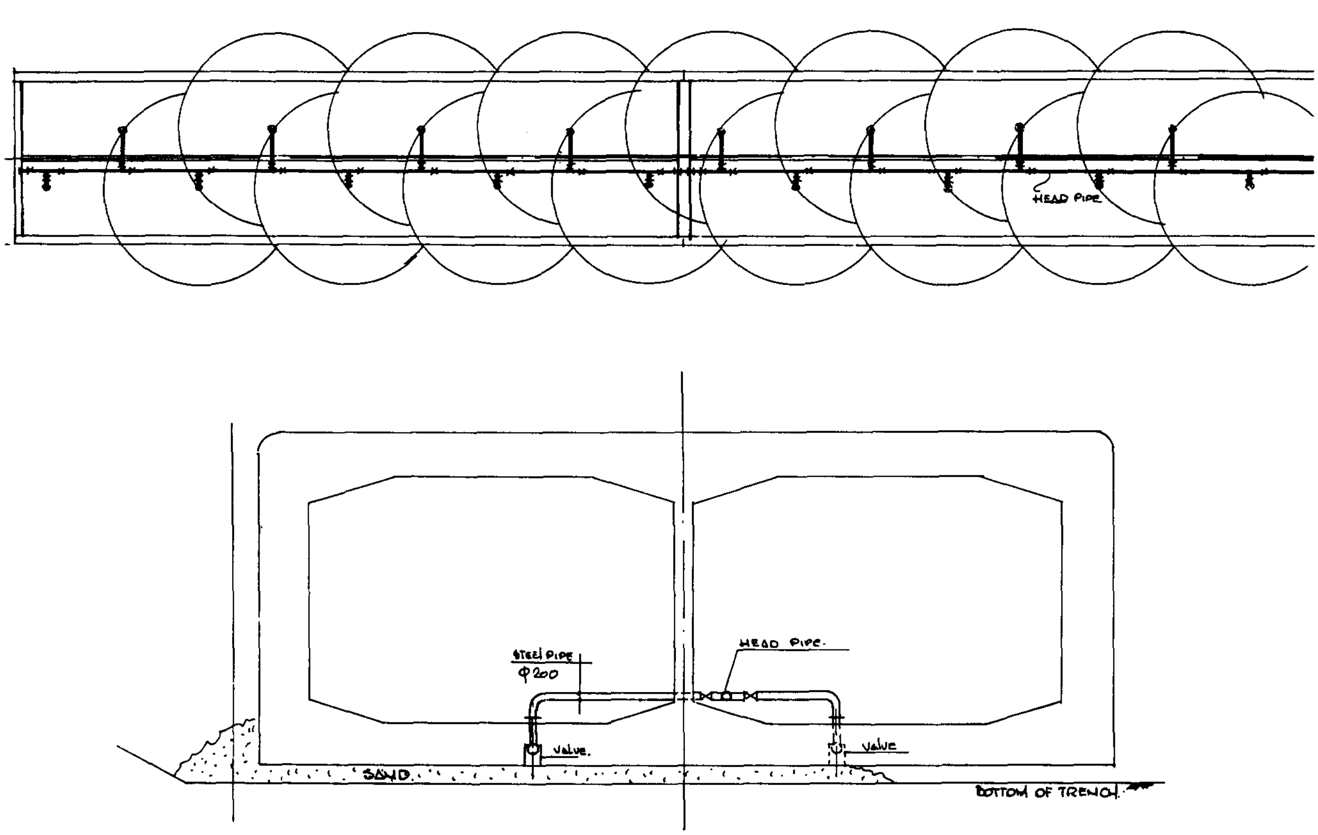

Figure 3-10. Principle of the sand-flow system, which uses a pattern of openings underneath the tunnel.

The history of immersed tube tunnels does not reveal any major accidents or events that have had an impact on the projects themselves or on third parties. The reason for this might be that much effort has been invested in proper preparation of the project activities—for example, in terms of risk analyses (long common to these type of projects), extensive survey work performed in advance, and back-up facilities included in the systems.

Compared to other big schemes, an immersed tunnel project may be viewed as a relatively safe and sound system. Highly dramatic events have not been associated with these types of projects.

However, a number of projects have experienced considerable cost and time overruns. Although these were often justified as the result of "unforeseen events", this does not necessarily mean that these events could not have been foreseen. A project under water in difficult conditions is indeed not easy to perform; but here again, it is a matter of properly investigating the external conditions, taking these into account in designing and building the tunnel, and properly controlling all relevant aspects of the project.

With regard to quality control, risks, and the structure of the organisation of the project, clients must be aware of the importance of both the decisions they make about technical aspects, and the parties they select to be involved in the design and construction process.

6.2.2 Time schedule

The construction of an immersed tunnel can be divided into a number of separate projects. The approach ramps, the construction of the tunnel elements, the marine activities, and the finishing of the works—civil as well as electromechanical—are essentially different projects, often performed at different locations. This division of the project will result in a number of activities being performed in parallel. They will have to mesh technically, as well as in the planning stage.

Some parts of these tasks involve repetitive activities—for example, construction of the tunnel elements and parts of the approach ramps, and the immersing process. Therefore, the negative effect of a sudden setback often can be neutralised by increasing the number of forms; by adding equipment; or by performing extra works at night, during the weekends and on holidays.

Furthermore, if there is a known risk associated with the functioning of a particular piece of equipment, back-up equipment—or at least fast and proper replacement of key equipment—can be planned for.

In comparison with bored tunnels, for example, the risk of time overruns for immersed tunnel projects is considerably lower. The time required for the construction of a bored tunnel depends very much upon the production outcome of the tunnel boring machine. It is difficult, if not impossible, to improve this rate during the course of the project. An immersed tunnel offers much more flexibility with regard to time scheduling.

6.2.3 Cost

As noted above, some immersed tunnel projects have had considerable cost overruns. These overruns may have resulted from an extension of the work needed because of additional requirements or resulting from unforeseen environmental circumstances.

In all levels of the organisation—design as well as construction—where skilled personnel are involved, the cost overruns should not exceed 5% of the value of the project. Moreover, experienced people can properly estimate the amount required to cover eventual cost overruns.

6.3 Project Management

The above discussion underscores the multi-disciplinary nature of immersed tube tunnels. In addition, the construction normally takes place at locations where other activities may interfere with it. For immersed tunnel construction, various sites are created, each shore has an approach ramp, and the marine operations take place in the area between these ramps. The elements are constructed at another location. All of these activities must be planned to mesh perfectly.

These aspects emphasise the need for excellent cooperation between the personnel and parties involved in the project. When cooperation fails, a problem at one location may result in a disaster at another.

Therefore, it is vitally important to establish perfect cooperation between all parties involved, guided by a skilled and experienced group of people. Some guidelines are given below:

1. All relevant parties must be defined at an early stage of the project. Their specific requirements, skills and contributions must be known to all parties involved and all aspects of their work must be covered.

2. A team of responsible key people must be established at an early stage of the project. This team should include skilled specialists for each discipline and must be guided by an experienced tunnel specialist.

3. Because design and construction are closely related, early input from the construction company regarding the design is advisable. The construction process must not be worked out in too much detail prior to the tender of the project.

4. This type of project is perfect for design-and-construct schemes. However, in order to limit the cost for the design as much as possible and to allow maximum competition, the client must put the maximum information available at the contractors' disposal. This information must be collected by specialists familiar with the local circumstances and by specialists in immersed tube tunnelling.

5. The team must operate independently of the contractual arrangements between parties.

6. Communication with third parties must be well organised. Especially during the marine operations, good communications are required in order to avoid problems that could have catastrophic results.

7. Each party must be informed of all available information and must have access to this information.

6.4 Project Finance

Recently, a number of immersed tunnel projects have been built with private financing. Although details of private financing are outside the scope of this report, this type of financing should be mentioned because it will have important implications for future immersed tunnel techniques and projects.

The time schedule is a major influence on privately financed projects: the tunnel must be built in the shortest period possible. The optimal period should be determined on the basis of the results of a cost-benefit analysis comparing the investment in rapid construction techniques, equipment, etc., with the savings in interest.

A tight time schedule should not be established at the cost of the quality of the work. Experience and know-how are needed to define the optimal schedule for a particular project. Furthermore, a tight time schedule will mean that the design must be optimised to take advantage of possibilities for saving time on various aspects of the project.

The difficulty with private financing often is that the politicians acting on behalf of society are neither willing to nor capable of defining the requirements regarding the total package of design-construct-finance-and-operate projects.

This means that the authorities advising the politicians in the interest of society must be capable of properly defining the technical and additional requirements of that society.

It is vital that all related parties be identified prior to the real start of the work, for the entire scope of the project. These parties must be capable of identifying and judging all risks—whether technical or financial—and of covering these risks.

Reference

Bickel, John O. and Kuesel, T. R., eds. 1982. Tunnel Engineering Handbook. New York: Van Nostrand Reinhold.

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The author, a consulting engineer, has made an inventory of the various construction techniques used thus far in immersed tube tunnelling. The result of his survey has been amended by a number of specialists. In particular, the author thanks Mr. Ahmet Gursoy, Ir. P. van Milligen and Ir. Gerard H. van Raalte for their advice.

Chapter 4:

WATERPROOFING AND MAINTENANCE

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Chapter 4: Waterproofing and Maintenance

1. Introduction and Background

This chapter deals with ensuring watertightness of immersed tunnels; and, specifically, with the methods used to ensure watertight integrity of immersed tunnels. Material in the chapter covers both steel shell tunnels and concrete box tunnels.

For concrete tunnels, the two basic watertightness design philosophies are described. The first uses applied exterior steel and/or bituminous membrane. The second uses no exterior waterproofing layer, but rather accomplishes waterproofing by dividing the element into separate segments where concrete shrinkage-cracking can be prevented.

Because steel tube tunnels are completely enclosed by the steel shell, the issue of waterproofing largely concerns the design of the joint between elements.

The development of the methods for providing watertightness in joints in steel shell tunnels over the past decades has been largely empirical and mainly the result of incorporating the experience gained on one tunnel in the design of the next. This process is ongoing in the United States. In the European countries, however, development has centered on concrete tunnels, constructed with or without membranes.

This chapter provides information on current design practice for types of joints, membranes and watertight concrete. It seems appropriate to begin this section on watertightness with a brief history of its evolution in immersed tunnelling.

The history of subaqueous immersed tunnels is about to attain its first centennial. In 1894, the first immersed tunnel large enough for a person to walk through was constructed. The Boston Metropolitan sewer, beneath Shirley Gut in Boston Harbour, used 15-m-long, 2.7-m-diameter elements consisting of brick and concrete, with 10-cm-thick exterior wood sheathing. Temporary wooden bulkheads were installed at both ends of each element, and external flanges with rubber gaskets were provided to permit the elements to be bolted together. Thus, the first immersed tunnel used rubber-gasketted joints.

In 1910, the Detroit River Railway Tunnel—considered to be the first full-scale immersed tunnel—used this same method. This tunnel was unusual by present-day standards in that it was of double-shell construction, placed on the bottom, with no concrete inside or out. The exterior concrete was then placed by tremie methods. After all the elements were in place, the tubes were accessed and the interior concrete lining was installed continuously, as a mined tunnel would be lined. The Detroit River Tunnel utilized rubber double-gasketted joints around each of the two tubes. The joint was made watertight by bolting it tight and then grouting the space between the two gaskets, in a manner not too unlike the Boston sewer built some 16 years previously. The shell was 9.5-mm riveted steel, lapped and ship-caulked.

The next immersed tunnel was only one element long. This was the La Salle St. railroad tunnel in Chicago, constructed in 1912. The ends of the element tied directly into cofferdams. Again, the shell consisted of riveted, ship-caulked and lapped construction.

With the third immersed tunnel, the Harlem River Tunnel in New York, constructed in 1914, the design of the joints between tubes took a significant turn. The design no longer used a rubber gasket (perhaps because of the difficulty anticipated in mating the four tubes incorporated in these elements). Instead, it used a riveted steel liner plate closure across a square-butted joint after the exterior had been concreted with a tremie enclosure between elements. The space behind the liner plate was grouted.

This method was quite successful and set the pattern for all of the immersed tunnels constructed subsequently in the U.S., until the Bay Area Rapid Transit (BART) Transbay Tunnel in San Francisco was constructed in 1970. The BART Transbay tunnel was the first to use the double rubber-gasketted joint now commonly used in the U.S. The grouted steel liner plate detail (welded) was used on the BART Tunnel and continues to be used on steel shell tunnels to this day.

The Posey Tunnel, constructed in 1928 in Oakland, California, and the Webster St. Tunnel—its near twin, constructed in 1962—are the only concrete tunnels without a steel shell ever constructed in the United States. Both tunnels were waterproofed with an external bituminous membrane protected with wood lagging, and both used tremie concrete joints.

The first immersed tunnel to use welding for its steel lining was the Detroit-Windsor vehicular tunnel, constructed in 1930. Only the longitudinal seams were welded; the circumferential seams were riveted, as in previous tunnels. The first all-welded steel shell was used for the elements of the Bankhead Tunnel, constructed in Mobile, Alabama, in 1940.

By the time the Transbay Tunnel for San Francisco's Bay Area Rapid Transit (BART) system was designed, concrete immersed tunnels had long been constructed in Europe and Canada using single main gaskets and mobilizing the water pressures to compress the gasket. The first such tunnel in North America was the Deas Island tunnel, constructed in 1959 in Vancouver, British Columbia (Canada), which used an inflatable rubber gasket for the initial seal and water pressure to effect the final seal.

Thereafter, the Gina and Omega profiles came into prevalent use in European countries, as well as in Japan; and were recently introduced in China for that country's first immersed tunnel, which is under construction in Guangzhou.

2. Steel Tunnels

2.1 Recent Joint Evolution

Apart from certain special considerations concerning corrosion, which are covered later in this chapter, the steel shell constitutes the basic waterproof enclosure of all single- and double- shell steel elements. It is therefore mostly in the joint area that refinements in design details can be made.

From 1930 through 1960, the design of the joints in steel shell elements in the United States did not change very much. The method of operation during placement remained basically the same as it had been for the previous fifty years.

The joint was mated and aligned and then pinned with two heavy steel pins. A form was installed on both sides of the joint and a massive tremie concrete pour was made, which completely enclosed the joint and hopefully sealed it sufficiently to allow the internal liner plates to be welded in place without great difficulty. This was not always the case, however, because tremie concrete is often imperfect. The joints would leak or, worse yet, the concrete would penetrate into the interior of the joint and harden, requiring a time-consuming "mining" operation to remove it. On the other hand, the tremie joint had one major benefit: it formed a rather strong structural connection between the elements.

Although the gasketted joint is very effective in providing a more reliable working environment than the tremie joint for the installation of the steel liner plate, a disadvantage is that the structure of the joint became inherently weaker. The former thick tremie concrete encasement, which helped to tie the elements together, was no longer used. In addition, in recent years the thickness of the structural interior concrete ring has been reduced, as higher-strength concrete and more sophisticated methods of analysis have come to be used.

These changes have resulted in an increasing problem with the effects of thermal expansion and contraction, causing longitudinal movements in the joints between elements and cracking and spalling of the interior finishes of the tunnel.

No leakages have yet been traced to these movements in any of the tunnels where they have been observed (two tunnels in Hampton Roads, Va., U.S.A., and the Fort McHenry Tunnel in Baltimore, Md., U.S.A.). However, there is concern that the liner plate—the major line of defense against eventual deterioration of the main gaskets—might begin to leak as a result of the seasonal joint contraction and compression; and, certainly, the effects on the wall tile are a serious maintenance consideration.

In the case of the Tunnel for the Central Artery/Third Harbour Tunnel Project in Boston, the design of the joint detail has been revised to accomplish two objectives:

1. To make the joint flexible, in order to prevent damage to the seal resulting from the motions that have been observed.
2. To provide a controlled location for the movement in the joint to appear in the surface of the wall.

This new joint detail may be said to constitute the state of the art, insofar as it has been recommended for the aforementioned project by the two American consulting firms that have designed the large majority of the steel shell tunnels in the U.S.A.

Therefore, this discussion of waterproofing as it relates to steel shell elements will use this most recent development as its main example for joint design. European designers will realize that this joint detail is very close to what is commonly used on the Continent for concrete box elements. In fact, the Gina type of profile was specified as an acceptable alternative type of main gasket for the Boston Harbour Tunnel.

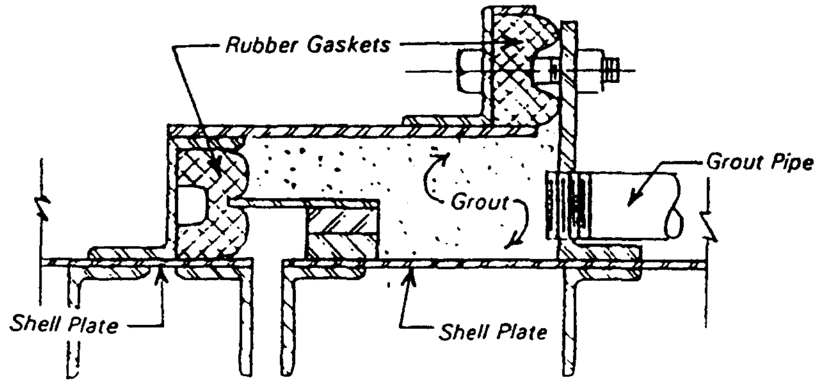

Figure 4-1a. Joint detail for the Detroit River Tunnel (1910).

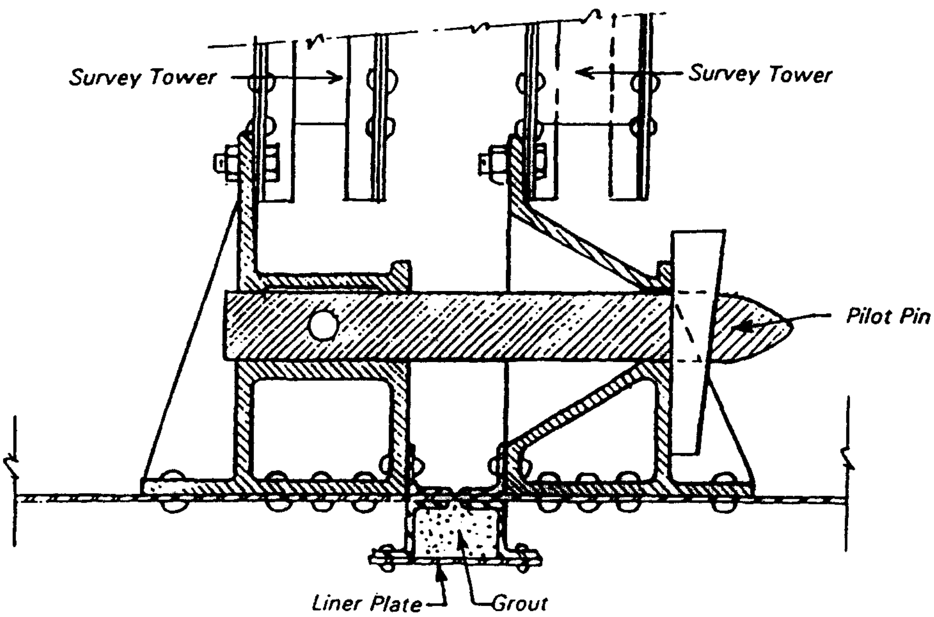

Figure 4-1b. Joint detail for the Harlem River Tunnel (1914).

2.2 Waterproof Joints for Immersed Tunnel Elements

2.2.1 Typical joints

For the purposes of this discussion, a "typical" joint is considered to be the joint used between almost all of the elements in an immersed tunnel. Typical joints are distinguished from certain other special joints designed for specific purposes, i.e.:

- *Closure joints*, which are used when the last element is placed somewhere in the middle of the immersed portion of the tunnel.
- *Terminal joints*, which are used between the shore ends of the immersed tunnel and the land portions.
- *Underwater joints* into rock, between steel shell elements and rock tunnels.
- *Seismic joints*, which are designed to absorb triaxial seismic displacements without structural failure or failure in watertightness.

Figures 4-1a and 4-1b show early examples of the "typical joint" for the Detroit River and the Harlem River Tunnels. Figures 4-2a and 4-2b show an isometric and a plan section of a typical tremie joint (a closure joint is very similar to this type of joint). Figure 4-3 shows the current design of the typical joint for steel shell tunnels that is proposed for use on the most recent Boston Harbour Tunnel design.

This new typical joint detail is designed to permit longitudinal movement generated by the temperature variation during seasonal cycles. It is also designed to transfer shear forces caused by seismic events, as well as differential settlements, which might cause small rotational movements in the joint.

The Omega gasket seals against water that might escape past the main exterior gaskets, and conducts it around and down to a drainage valve in the invert of the element. The valve relieves the pressure and drains the Omega gasket into the lower air supply duct. Although the Omega is rated for the ambient exterior water pressure, the main gaskets do most of the work; only a slight seepage or trickle might have to be intercepted by the Omega gasket.

The interior structural ring in the joint area is mainly the typical structure, composed of the steel shell tied compositely to the concrete. However, 60 cm of the joint ring concrete overlaps from one tube to the other, to provide a full structural shear key from element to element. This overlap permits relative longitudinal motion between elements, by virtue of the fact that the concrete is entirely isolated from the steel shell in this zone by a section of joint filler that prevents bonding or jamming of the shear ring as it gradually moves in response to expansion and contraction.

2.2.2 Contingency method for sealing typical joints

All typical joints are equipped with vertical slots provided in the edges of the bulkheads to permit the installation of curved form plates so that the joint can be sealed using concrete in the event that a seal cannot be obtained in the usual manner with the gaskets. This curved form plate is identical to the one shown in Figure 4-2a for the typical tremie joint. Although this provision is always made, this second "line of defense" has rarely, if ever, been used.

2.3 Closure Joints

These joints are used at one end of the element that will close the gap in an immersed tunnel being constructed from both shores. The other end of this element is provided with a typical rubber-gasketted joint.

The closure joint provides roughly half a meter of joint adjustment for the accumulated variation in the length of the tunnels as they approach each other. It is initially sealed by tremie concrete contained within sheetpile enclosures and kept out of the interior of the joint using enclosures with overlapping top and bottom hoods, designed to provide the range of joint separation noted above. In contrast, the typical tremie joint does not provide for a range of joint separation.

2.4 Terminal Joints

Terminal joints are the interfaces between the portion of the tunnel constructed by means other than immersed elements and the immersed element portion of the tunnel. Terminal joints vary widely in design, depending on certain basic factors, such as:

- *The sequence of tube placement.* If the elements are placed first, the joint will usually be constructed in the dry. The detail is relatively simple in this case. If the terminal structures are constructed first, then these structures must be provided with a built-in element joint adaptor to which the first and/or last element can be attached, using normal placement procedures.
- *Seismic motions* may control the design of the joint and its waterproofing detailing. The terminal structure to which the end element must connect (e.g., a ventilation building) will usually have a very different natural period of vibration, which will cause large relative movements of the terminal structure with respect to the immersed tunnel. This condition may require a full seismic joint with triaxial motion capability. Such a joint was used for the Transbay Tunnel in San Francisco (see Section 2.6, below).
- *Anticipated expansion and contraction* between terminal elements and the terminal structures.
- *Differential settlement* between the immersed tunnel and the terminal structure may be an important aspect in the joint design if ground conditions are rather poor. Some designs (e.g., Fort McHenry Tunnel in Baltimore, Maryland, U.S.A.) have attempted to avoid high stresses in the immersed elements by permitting differential settlements at the joints. Other designs (e.g., Second Hampton Roads Tunnel, Hampton Roads, Virginia, U.S.A.) have been designed to allow for expansion and contraction but no vertical movement.

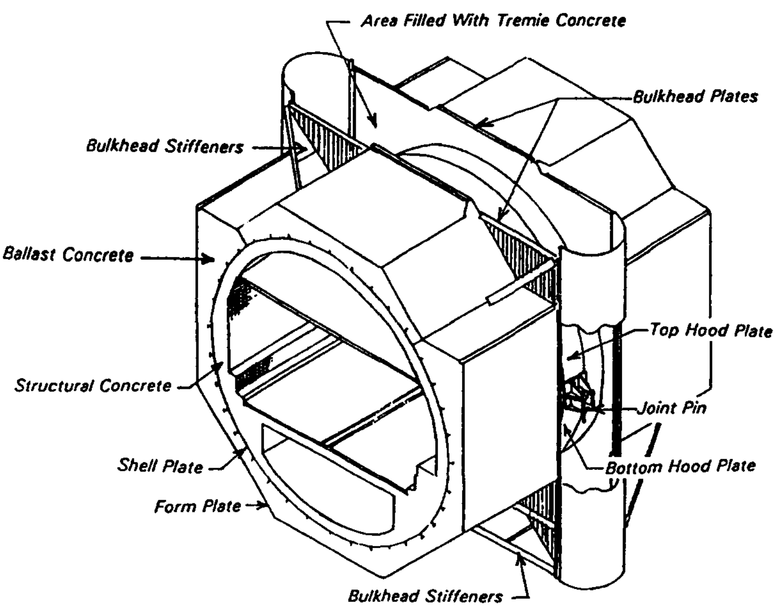

Figure 4-2a. Typical tremie concrete joint for a typical steel double-shell structure.

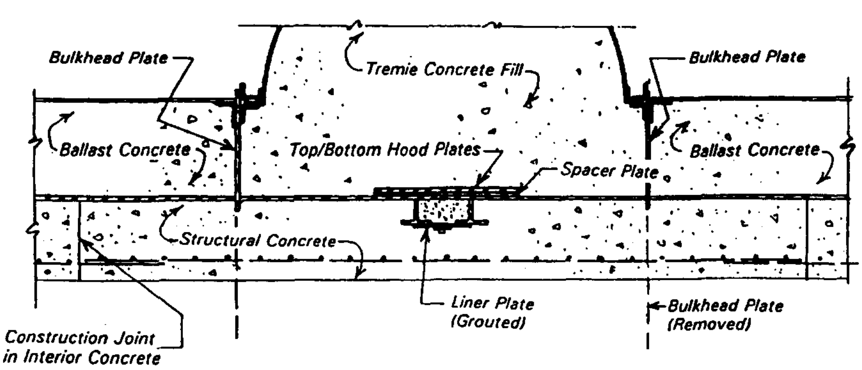

Figure 4-2b. Section through a typical tremie joint.

2.5 Underwater Connections to Terminal Elements Constructed in Rock

For the 63rd Street Tunnel (New York City, U.S.A.), two two-element tunnels were placed: one between the New York shore and Roosevelt Island, in the East River, and the other between the island and the Brooklyn shore. These two immersed tunnels were joined at the island by a rock tunnel.

At each end of the two immersed tunnels, an underwater portal face and pocket was blasted in the rock. After placing the element in this pocket in the rock face, the joint area was tremied to form a tight seal. Subsequently, the element was reached by mining through the rock and tremie seal and removing the end bulkhead. This joint was made watertight by a steel shell extension into the mined tunnel.

2.6 Seismic Joints

The only seismic joint design used to date in the United States was developed for the BART Transbay Tunnel in

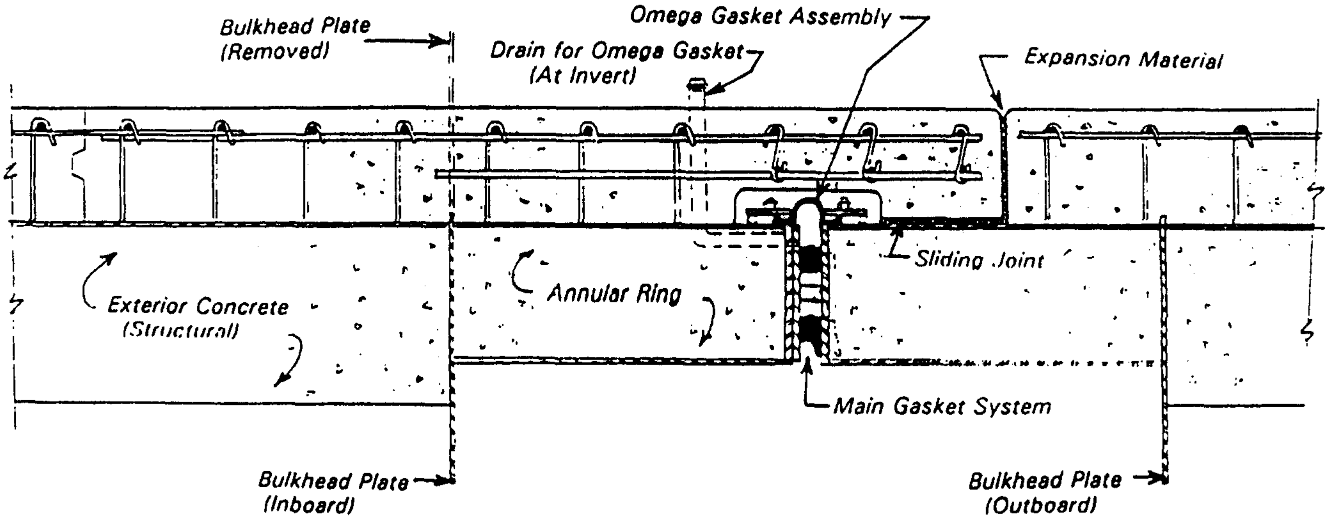

Figure 4-3. Typical joint detail for Boston's Third Harbor Tunnel.

San Francisco. The seismic joint was designed to permit triaxial displacements of ±8 cm in the longitudinal direction and ±15 cm in any direction in a vertical plane, while maintaining watertight integrity.

The vertical and transverse horizontal motions are permitted by precompressed rubber gaskets sliding on radial Teflon bearing surfaces. The longitudinal motion is taken by similar gaskets sliding on a circumferential Teflon bearing surface. Both sets of bearings are compressed by tensioned cables that allow the motions by rotating on Teflon-coated spherical bearings.

The assembly is protected from mud and the marine environment by exterior rubber boot enclosures. These assemblies were prefabricated, assembled and tested as units before being attached to the elements. Four of these seismic joints were required for the Transbay Tunnel. The joints performed well during the 1989 earthquake in San Francisco. Figure 4-4 shows the arrangement of this seismic joint.

2.7 Concrete Requirements

One of the basic advantages of steel shell tunnels lies in the fact that the watertightness does not rely heavily on the ability of the concrete to withstand cracking, as it does for concrete box tunnels. The concrete strength is important from the structural standpoint, and random temperature and shrinkage cracking is a concern in this regard, however, from a leakage standpoint, steel elements can tolerate a great deal more cracking in their concrete linings than can concrete box elements.

In addition, the concrete box is not as accommodating to variable ground settlements as is the steel shell tunnel. As a result, intermediate joints similar to those commonly used to introduce flexibility in concrete tunnels are not required. It should be noted that this situation can lead to designer complacency with regard to temperature and shrinkage control in the steel elements; and this can have the undesirable effect of introducing excessive reflected cracking in finished tile surfaces.

2.8 Cathodic Protection of Steel Elements

It has not been the practice in the United States to provide special protection to the steel shell of immersed tunnels, unless stray direct currents are determined to be present. Where stray currents do exist or are expected, such as in an electrified rapid transit tunnel, provisions may be made for coating the steel shell with materials such as coal tar epoxy and/or the provision of impressed current cathodic protection systems.

Alternatively, stray current test stations may be specified to permit periodic measurements at several locations along the steel shell of the immersed tunnel. This arrangement permits flexibility in adjusting the extent of the cathodic protection to the actual conditions encountered in the completed project. In this regard, the internal reinforcing steel and the steel shell must be carefully bonded electrically throughout the tunnel to prevent deterioration, or even accelerated localized corrosion, in the presence of stray currents.

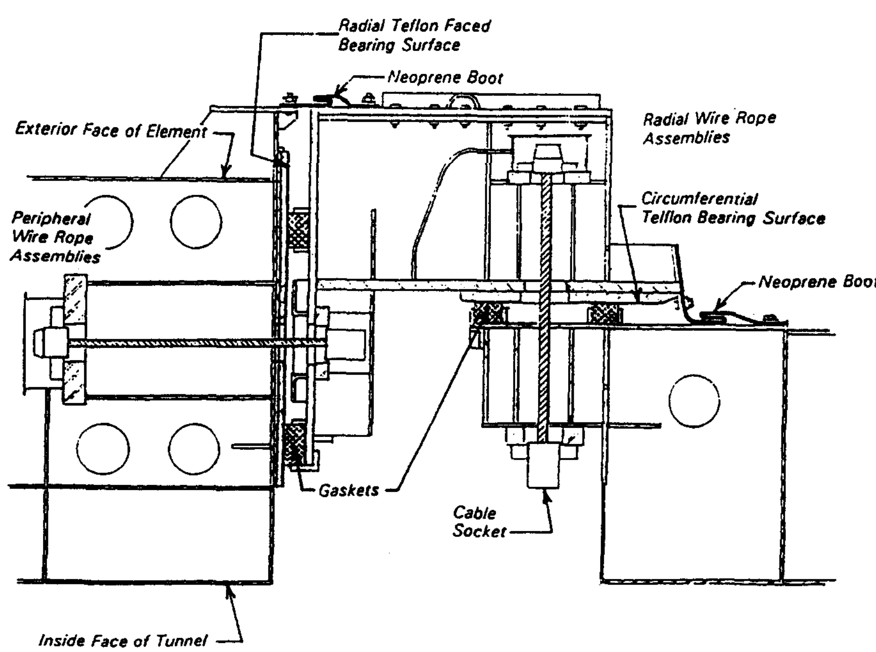

Figure 4-4. Patented seismic joint used for the Transbay Tunnel, San Francisco.

3. Concrete Tunnels

Because steel is expensive on the European mainland, alternatives to the steel shell have been developed. In the past, problems have occurred because the concrete was not watertight, due to the lack of density of the concrete and cracks.

Leakage water can enter the tunnel in two ways:

1. Through the concrete structure.
2. Through the joints.

These types of leakage are discussed below.

3.1 Water Leakge through the Concrete Structure

It is very important that the concrete be impermeable. Possible causes of cracks are climatic temperature fluctuations and hydration heat during the pour. If the concrete structure cracks, water can leak into the tunnel. Penetration of water into the concrete can cause corrosion of the reinforcement.

To prevent water from leaking into the tunnel through the concrete, two different measures are applied:

1. Membranes.
2. Cooling the concrete to avoid cracking.

It should be noted that no concrete is 100% watertight; some water seepage will occur even thorugh a dense concrete. The water will not be visible, because it evaporates at the inner face of the tunnel structures. If the water is saline, the salt will remain in the concrete and, after some years, may have contaminated it to such a level that it may cause corrosion of the reinforcement at the inner side of the structure. This has been the case in the Limfjord tunnel, where a combination of an imperfect membrane, saline water, and a concrete with many fine cracks has already caused chloride contamination above the critical level in some part of the tunnel.

3.1.1 Membranes

Membranes are provided on immersed tunnels to prevent outside water from entering the tunnel space. To achieve this goal, the membrane must have a life expectancy similar to that of concrete, and it must be chemically and biologically resistant to the environment. It also must be able to resist forces from outside during construction and in the permanent condition, and it must be sufficiently elastic to accommodate any cracks that may be expected in the structure.

It is advisable that the membrane adhere to the entire surface, thereby eliminating the possibility of water flow between the membrane and the concrete.

Several types of waterproofing membranes have been used for the construction of immersed concrete tunnels:

- Steel membranes.
- Bituminous membranes.
- Polymeric sheet membranes.
- Liquid-applied membranes.

Each of these types of membrane is discussed below.

3.1.1.1 Steel membranes

This is the oldest method used for preventing water from penetrating into the tunnel. The steel lining encases the tunnel completely and has no structural functions. Generally, the steel and concrete are not permitted to be considered as a composite structure.

Normally steel membranes consist of 6- to 8-mm-thick steel plates welded together. The connection between the membrane and the concrete structure is provided by shear studs welded to the membrane. In addition to normal control of the welds, all welds between plates are further tested for watertightness. This testing may be done rather simply by a portable vacuum box.

Because steel membranes are subject to corrosion, protective measures may be needed. If the tunnel is well below the water surface and is surrounded by backfill, corrosion will occur very slowly.

The following minimal measures must be taken in order to avoid local galvanic corrosion:

- Light sandblasting should be used to remove mill scale from the steel plates.
- Weld material should be cathodic, compared with the steel membrane.

For the Guldborgsund Tunnel in Denmark, the aforementioned measures have been considered sufficient to ensure a lifetime of 100 years of the steel membrane, which is placed at the bottom and the sides of the tunnel. If the planned inspections show that further measures are required, cathodic protection similar to that used on steel tunnels may be installed.

On the Conwy Tunnel in Wales and the Tingstad Tunnel in Sweden, the steel membrane has been protected with both painting and cathodic protection.

The shear studs connecting the membrane with the concrete structure should be designed so that they can transmit the shear forces from the soil. It should further be ensured that the number of studs is sufficient to limit differential movements between membrane and structure, so that individual studs are not overloaded—a situation that could create cracks through the membrane.

Although the concrete is placed against it, the steel membrane will not adhere to the concrete. The separation may take place in the casting basin because the temperatures of the membrane and concrete are different. The separation of steel and concrete will allow water from a leak in the membrane to find any leak in the concrete. In order to limit possible leakages, consideration may be given to dividing the membrane into minor areas of perhaps 10 x 10 m, using ribs welded onto the inner side of the membrane.

Steel membranes have mainly been used at the bottom or the bottom and sides of immersed tunnels. The remaining part of the tunnel surface has then been covered with another type of membrane, usually a bituminous membrane. The transition between steel and bituminous membrane requires complex clamping in order to ensure permanent watertightness.

A few concrete tunnels, including the Tingstad Tunnel in Sweden and the Deas Island Tunnel in Canada, have been provided with steel membrane all around.

Steel membranes have the following advantages:

- Good experience has been gained with such membranes in the past.
- It is a well-known technology.
- It yields savings in formwork.
- The membranes are robust.

The disadvantages of steel membranes are:

- There is a risk of corrosion and they require protection.
- A leakage in the membrane may cause water penetration into the tunnel far from the leak in the membrane.
- The membranes are quite costly.
- A leakage in the membrane cannot be repaired.

3.1.1.2 Bituminous membranes

Bituminous membranes generally are prefabricated mats reinforced by polyester or glass-fibre fabric. They may be glued on with hot bitumen or by warming a bitumen layer applied to the mat during fabrication. The bitumen may be either hotblown or polymer-modified bitumen. The latter has better elastic properties than the former, a factor that is important, e.g., in clamping strips at the edges.

For tunnel waterproofing, the polymer-modified bituminous membrane is preferable to the normal bituminous membrane because it reduces plastic deformations and loss of pressure under the clamping plates. The mem-

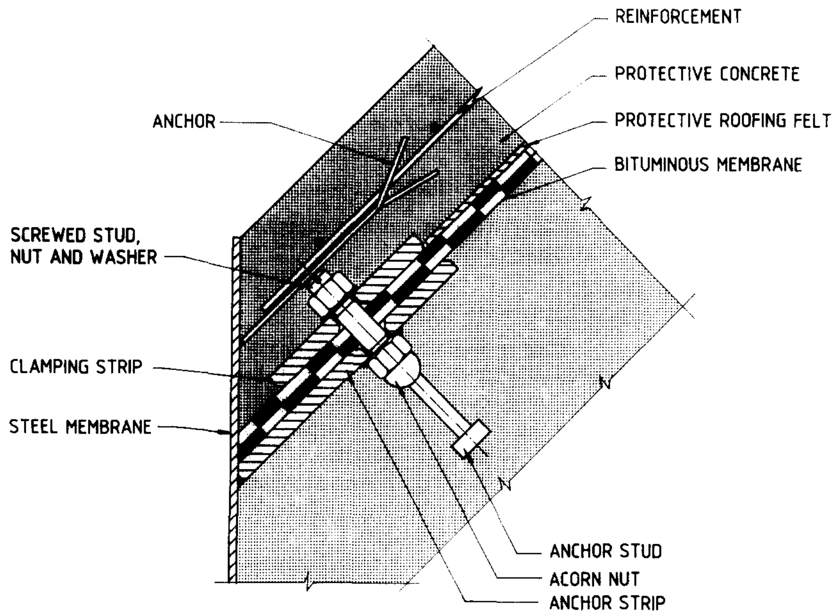

Figure 4-5. Connection between steel and bituminous membrane.

branes must fully adhere to the primed concrete surfaces in order to prevent water ingression through leaks in the membrane to flow in the space between the membrane and the concrete structure.

A bituminous membrane is normally composed of two layers of bitumen-impregnated mats. The mats are placed with at least 100 mm overlap and the joints in the two layers are staggered.

In order to avoid water seeping from behind the membrane, all free edges of the membrane must be clamped, e.g., by clamping strips of steel (see Fig. 4-5).

A concrete slab 100 mm to 150 mm thick initially protects the bituminous membrane when it is placed on the tunnel roof. Because the bituminous membrane cannot transmit shear forces of long duration, it is necessary to anchor the protection slab (see Fig. 4-6).

If the membrane is used on the tunnel sides, a sliding layer of soft bitumen is applied to reduce shear transfer from the backfill (as was done at the Rupel Tunnel in Belgium), or protected by 100-mm-thick concrete plates bolted to the walls (as at the Drecht Tunnel in The Netherlands). At the tunnel bottom, where it is difficult and complicated to secure the membrane to the concrete, steel plate is still used.

Bituminous membranes at the tunnel roof have often been combined with steel membranes at the sides (and bottom) of the tunnels. This method has been applied to the Elbe Tunnel in Germany, the Conwy Tunnel in Wales, and the Guldborgsund Tunnel in Denmark.

Bituminous membranes have the following advantages:

- They are cheaper than steel.
- Their performance has been demonstrated to be successful.
- The membranes are relatively robust, if placed in two layers.
- The membranes can bridge normal fissures.
- The membranes can be applied on roofs, where steel membranes are difficult to place.

The following disadvantages are associated with bituminous membranes:

- The success of the membrane depends on an experienced labour force to ensure watertightness at the edges and at anchor bolts for protection of the concrete.
- Because the application of the membrane can only be started after the structural concrete is properly cured and is dry, this operation is on the critical path. Therefore, the timing between concreting and flooding of the casting basin requires close coordination with a specialist subcontractor.
- Bituminous membranes do not transfer shear in the membrane plane.
- Special arrangements at expansion joints (steel Omega or similar) may be required.
- A durable and complete adhesion to the concrete surface is difficult to obtain.
- A leakage in membrane may cause water to penetrate into the tunnel far from the place where the leak in the membrane occurred.

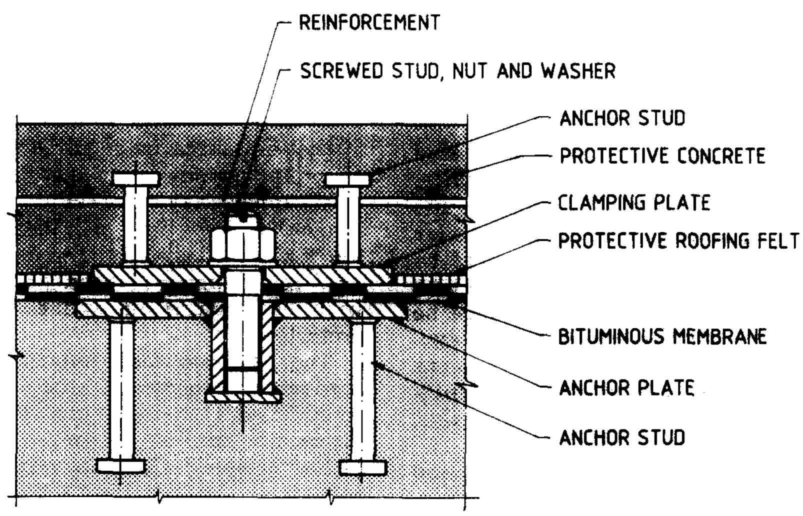

Figure 4-6. Connection between structural and protective concrete.

3.1.1.3 Polymeric sheet membranes

Polymeric sheet membranes may be thermoplastic materials such as polyvinyl chloride (PVC), polyethylene (PE), chlorinated polyethylene (PEC), and polyisobuthylene (PIB), or elastomeric materials as chlorosulphanated polyethylene (CSM), polychloroprene (Neoprene) (CR) and isoprene-isobuthylene (butyl rubber) (IIR).

Thermoplastic materials may be joined by hot air or plate welding, which are rather simple operations. Elastomeric materials are joined by adhesion, while the rubber types (neoprene, butyl, etc.) may be vulcanized. Although fairly expensive, vulcanization provides a strong connection.

These types of membranes are very thin and, therefore, are very vulnerable to mechanical damage during construction.

The butyl rubber membrane used on Denmark's Limfjord Tunnel was glued on by a polymer-modified cement slurry.

The advantages of polymeric sheet membranes are:

- They are low-cost, in comparison to membranes.
- Fewer discontinuities in details, thereby reducing the chance of errors.
- They are less subject to damage during and after construction.
- Better concrete quality can be maintained.
- They permit reduction in construction time.
- They facilitate a clean and straightforward design.

The disadvantages of butyl rubber membranes are:

- Workmanship problems with the joining of the sheets.
- If applied in only one layer, they are very vulnerable, especially immediately after application.
- Degradation of seams occurs over time.
- Embrittlement and degradation of the sheets occurs over time.
- Tensile and puncture strength may be inadequate.
- A durable and complete adhesion to the concrete surface is difficult to obtain.
- A leakage in membrane may cause water to penetrate into the tunnel far from the place where the leak in the membrane occurred.
- A leakage in the membrane cannot be repaired.

3.1.1.4 Liquid-applied membranes

Liquid-applied membranes, which may be epoxy-based or polyurethane-based, can be applied by spraying or by rolling. The concrete surface must be clean and dry in order to achieve good adhesion. If the membrane does not separate from the concrete around fissures, the elongation of the membrane over a fissure formed after spraying will be infinite.

Sprayed membranes have not often been used in the past, although recently a sprayed membrane was used in the construction of a tunnel in Hong Kong. The membrane consisted of a 0.08-in.-(2.0-mm-) thick layer of epoxy tar. Unfortunately, the first tunnel elements leaked because the coating was not able to absorb the strain when cracking of the concrete occurred after the waterproofing had been applied (*Engineering News Record*, July 13, 1989). Later on the project, elements sprayed with an improved membrane showed a better performance.

Advantages of liquid-applied membranes are:

- They are low in cost.
- They are continuous, i.e., without joints.
- They may transfer shear.

The following disadvantages are associated with these membranes:

- Difficulties in bridging fissures may occur after the membranes have been applied.
- There has been little proof of their performance.
- A leakage in the membrane cannot be repaired.

3.1.2 Cooling the concrete to prevent cracking

During the pouring of the walls on the floor, the temperature in the walls increases because of hydration heat. When the walls are cooling down, the shrinkage is obstructed by the cool floor, creating tensile stresses in the concrete. When the tensile stresses exceed the ultimate strength of the concrete, cracks will occur.

To prevent the extreme rise in temperature that can lead to the above scenario, low cement contents are applied (275 kg/cm^3), and the cement that is used develops relatively little hydration heat (blast furnace cement with more than 65% slag). Moreover, the lower parts of the outer walls are cooled during the first days after pouring. This is done by pumping water through cast-in steel tubes. The controlled process results in a considerably reduced maximum concrete temperature just above the floor slab, while a gradual temperature increase is obtained from this spot to the uncooled concrete in the upper part of the walls and the roof. In addition, the length of each pour may be limited to approximately 25 m.

This method of preventing cracks in the walls has been successfully applied in The Netherlands since the late 1970's. Belgium and Germany have also adopted this method (e.g., on the Liefkenshoek and Ems Tunnels, respectively).

Compared with membranes, the cost of cooling is low and it reduces construction time. Even though cracks cannot be avoided totally, those cracks that still appear can be injected prior to flooding the casting basin. Injection must be done in the absence of water flow; otherwise, the crack will stay open and water will continue to flow into the tunnel.

3.2 Joints

The following subsections discuss requirements for joint design and provide examples of joint layout. The following types of joints are normally used in immersed concrete tunnels:

- *Intermediate joint*: used between tunnel elements.
- *Terminal joint*: the joint between the shore end of the immersed tunnel and the land structures.
- *Closure joint*: the joint made *in-situ* after the last element has been placed.
- *Expansion joint*: used within each individual tunnel element, without continuous reinforcement.
- *Construction joint*: used within the individual tunnel element, with continuous reinforcement.
- *Joints between precast units* for prestressed tunnel elements.

Many tunnels have been designed without expansion joints. In such cases, the intermediate joints, terminal joints and/or closure joints are normally maintained as permanent expansion joints. Permanent expansion joints are arranged approximately every 25 m. Because these joints are generally difficult to execute, there may be a risk of leakage occurring at the joints.

A few tunnels have been designed as monolithic tunnels. The following descriptions deal mainly with immersed concrete tunnels provided with waterproofing membranes.

3.2.1 Assumptions for joint design

The purpose of a joint is:

- To connect individual castings or prefabricated units.
- To allow for movements caused by differential settlements, temperature, creep and shrinkage.
- To facilitate construction.

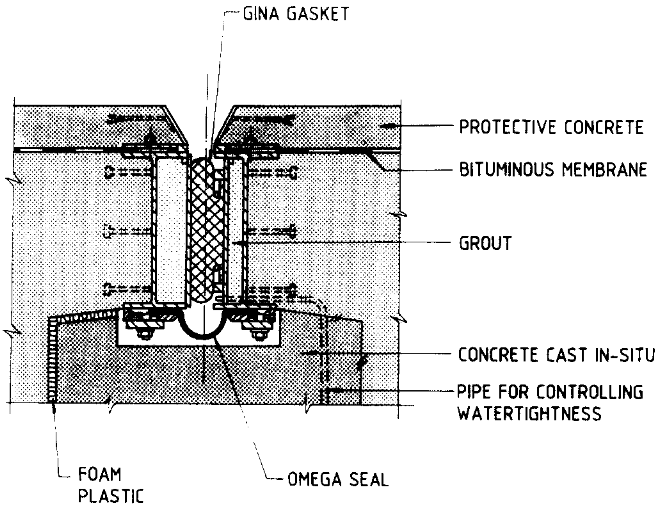

Figure 4-7. Intermediate joint.

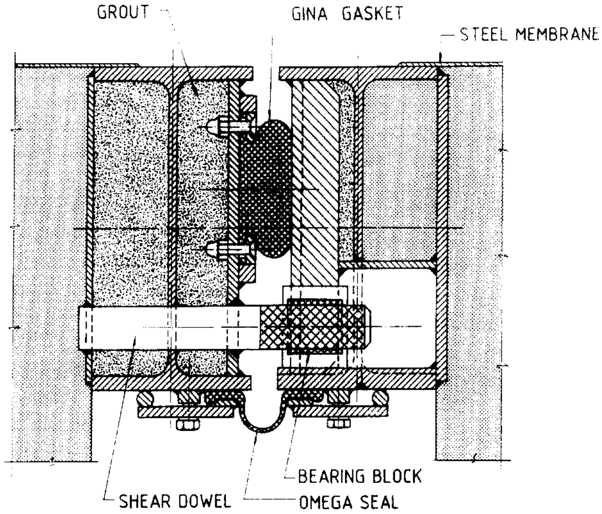

Figure 4-8. Shear key of steel at intermediate joint.

A joint is a discontinuity in the normal homogeneous concrete structure. Therefore, one of the main tasks in joint design is to ensure watertightness within the expansion limits for which the joint should act.

In a tunnel with a membrane, two waterproof barriers exist: (1) the reinforced concrete, and (2) the membrane.

For the design of watertightness in the joints, it is important that joint movements, alignment and tolerance limits have been investigated and specified. The max-imum water pressure for which the joint should be watertight should also be specified.

It is essential to know the properties of the joint materials, not only when new but also when aged, as well as their lifetimes. Joints can only be replaced if this possibility is foreseen in the design stage.

3.2.2 Intermediate joints

Normally the intermediate joints are provided with a Gina gasket and an Omega seal (see Fig. 4-7).

The Gina gasket is mounted on a steel frame at the primary end of the tunnel element. After the tunnel element is placed, this end is drawn against the secondary end of the previous tunnel element, which has been provided with a matching steel frame.

In some early immersed tunnels (e.g., the Limfjord Tunnel), the frames were made of U-profiles. Although cast-in separately, the frames could not be adjusted, after the concrete had been cast, to ensure sufficiently accurate alignment.

The Dutch tunnels and other recent tunnels (e.g., the Elbe, Conwy and Guldborgsund Tunnels), have used an H-profile, and the end plates of the frames were welded after the concrete had been cast. The space behind the plates was injected with grout. This method permits very small tolerances to be met.

After installing the Omega seal, the two tunnel elements are connected by casting reinforced concrete in the remaining space between them. This procedure was used on the Limfjord and the Guldborgsund Tunnels.

Alternatively, a permanent expansion joint with shear keys may be carried out. The shear keys may be constructed of reinforced concrete or of steel. This method was used on the Conwy Tunnel, the Singapore Cable Tunnel, and the new Bilbao (Spain) Metro Tunnel (see Fig. 4-8).

If the shear keys are of reinforced concrete, which has been common practice until recently, access to the Omega seal is hindered, whereas access is retained if shear keys of steel are used. The shear keys of Dutch tunnels are installed only in the floor and are made of steel tubes filled with concrete (see Fig. 4-9).

Even when the joint is used as a permanent expansion joint, the movements are usually not large and the Gina gasket stays watertight. This means that the Gina and the Omega constitute a watertight barrier in the joint. No serious leakages of this type of joint have been reported.

3.2.3 Terminal Joints

This type of joint is often identical to the element joints, if the portal has been built before the element is placed. In this case, the sea or river end of the portal building is provided with a bulkhead and a cast-in steel frame, like the secondary ends of the tunnel elements.

If the elements are built in the entrance, as for the Guldborgsund Tunnel and the Prinses Margriet Tunnel (in The Netherlands), the joints will be sealed temporarily between the tunnel element and the entrance structure. The permanent water-tightening Omega seal could be constructed as shown in Figure 4-10.

The possibility of differential settlements between the *in-situ* constructed part and the immersed tunnel part must always be considered. With a sand-jetted or sand-flow foundation, a certain settlement must be foreseen when the load on the temporary foundations is transferred to the sand foundation.

In Dutch tunnels, the shear keys in the floor are placed as late as possible in the construction process, in order to let the sand settle. The shear keys prevent unequal settlement between the immersed element and portal, while allowing for rotation when the opposite end of the immersed segment settles.

3.2.4 Closure joints

After the last tunnel element has been placed, a remaining gap, approximately 1 m wide, normally has to be closed. The closure joint is located between the last tunnel element and either a previously placed tunnel element (as an *in-situ*-cast tunnel) or a portal structure. After closure panels have been installed all around the tunnel, the gap can be closed from the inside of the tunnel by casting reinforced concrete.

In order to facilitate placing and watertightening of the panels, the end of the last tunnel element and the structure to which it shall be connected are normally given a rectangular outer shape. The two parts can be monolithically connected, or a permanent expansion joint can be installed. Figure 4-11 shows an example of a closure joint for a tunnel provided with a waterproofing membrane.

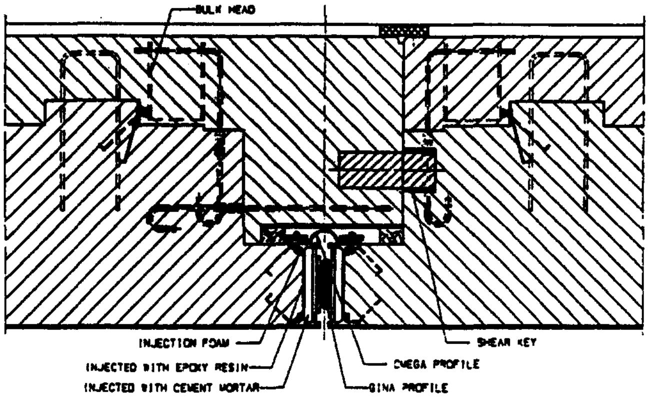

Figure 4-9. Shear key in floor.

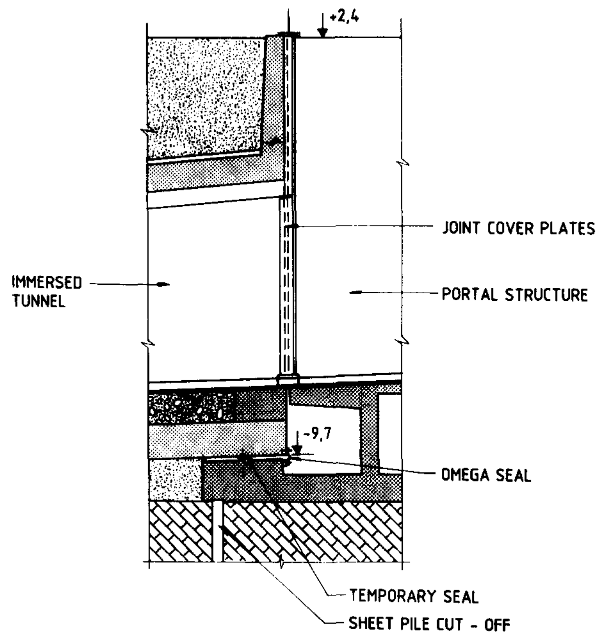

Figure 4-10. Terminal joint at the Guldborgsund Tunnel.

In the older Dutch tunnels, the closure joints were provided with a so-called double-Omega profile (see Fig. 4-12). This type of joint can be very vulnerable. In construction practice today, a segment of a normal cross-section of the tunnel is built into the closure joint (see Fig. 4-13), while normal rubber-metal waterstops provide the watertightness.

3.2.5 Expansion joints

Depending on the local conditions, the individual tunnel elements may be provided with a number of expansion joints.

In order to facilitate handling of the tunnel elements, these joints are fixed in the construction stage, normally by prestressing cables or rods (see Fig. 4-14). After the element is placed, these connections are released or cut in order to allow free expansion.

The watertightness of the expansion joints is ensured by cast-in waterstops. The tunnel membrane can be continued across the joint in the form of a steel Omega profile, as was done at the Elbe and the Conwy Tunnels (see Fig. 4-15).

The design of the steel Omega profile, where the corners are especially critical, has been verified by full-scale testing.

Since the mid-1970's, all of the immersed tunnels in The Netherlands have been constructed in segments, with the lower portions of the walls cooled and the membranes omitted. The only waterstop in the expansion joint is a rubber-metal waterstop. Because the rubber is subject to deformation by the water pressure, the metal strip in the concrete is used to guarantee watertightness. This single waterstop must be of high quality. To ensure that the waterstop works properly, injection tubes at the end of the metal strap are provided, as shown in Figure 4-16.

Temperature fluctuations cause the joint to open and close. When the joint opens because of shrinkage, sand or soil can enter the joint. Then, when the tunnel section expands, the joint cannot close up again because of the sand or soil in the joint. To keep the joint clean, it is provided with a rubber gasket, as shown in Figure 4-17. Because it is difficult to place the gasket in the bottom slab, the gasket is replaced by a steel strip, as shown in Figure 4-18.

3.2.6 Construction Joints

Construction joints may be designed as expansion joints; generally, however, at least some of the construction joints are made with continuous reinforcement.

Even though good adhesion between the concrete at each side of the joint is achieved by sandblasting or waterjetting of the primary concrete face, there is always a risk that a crack will arise at the joint. Therefore, the joints normally are provided with waterstops that act as a secondary barrier for tunnels provided with a membrane, which is carried continuously across the joint (see Fig. 4-19).

Another type of construction joint is the joint between precast segments of prestressed tunnels. An example from a cable tunnel in Singapore is shown in Figure 4-20.

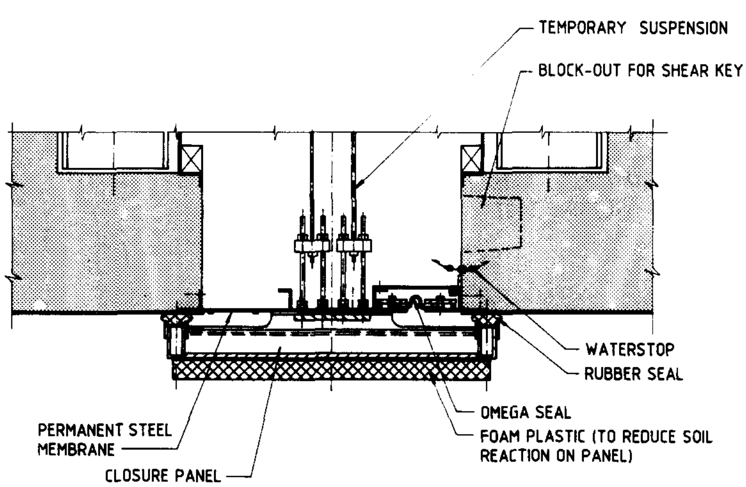

Figure 4-11. Closure joint at bottom slab.

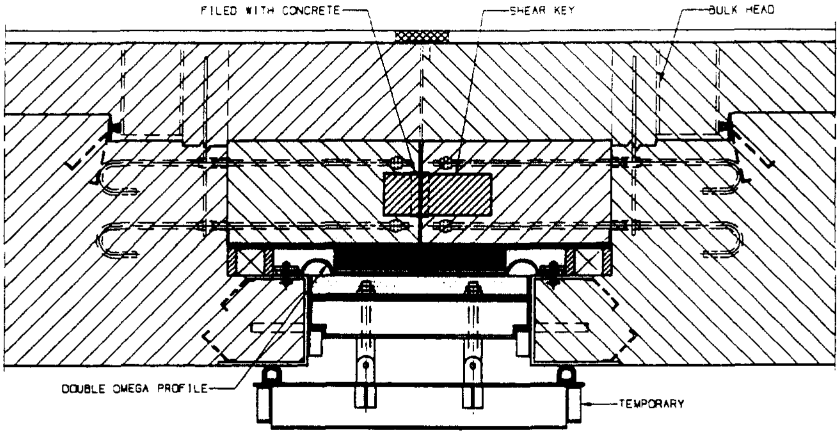

Figure 4-12. Closure joint formerly used in Dutch tunnels.

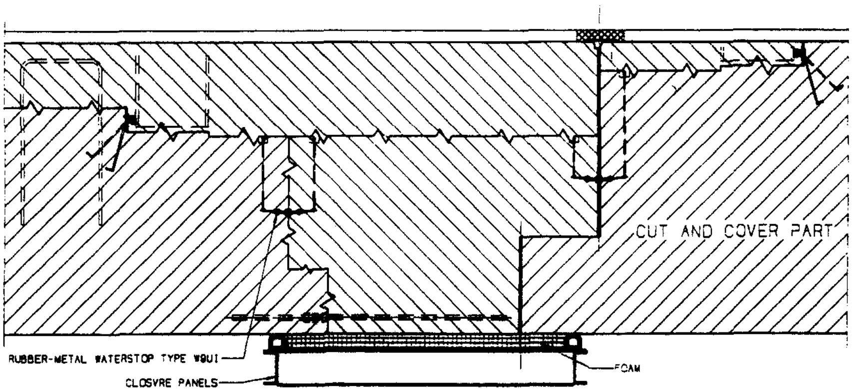

Figure 4-13. Closure joint used on modern Dutch tunnels.

4. Maintenance

4.1 Experience with Leakage in Steel Shell Tunnels

Leakage in the immersed portion of steel shell tunnels generally is minimal. Watertightness depends to the greatest extent on the care with which the integrity of the shell is maintained through design and execution.

Therefore, tunnel specifications must require suitable welder qualification, as well as radiographic, ultrasonic and dye-penetration methods of weld inspection and tests for watertightness during fabrication.

Permanent penetrations of the shell are to be avoided whenever possible in the design. Where openings are provided for access or concrete placement, great care must be taken to inspect and test welds of the closure plates for watertightness.

The soap bubble and vacuum box test is a good watertightness test for smaller openings in the shell, after the concrete has been placed. Temporary piping used in placing operations must be cut off and sealed, with a cover plate seal-welded over the opening. Special details such as cross-passages between tubes must permit good welding accessibility to assure quality welding.

Although the experience with watertightness of steel shell tunnels has been very good, given proper design and fabrication procedures, if a leakage problem arises, it usually occurs at the terminal joints with the land sections. The problem usually stems from the transition from a totally enclosing steel shell to a conventional exterior structure waterproofing system. In addition, there may be problems in keeping the excavation area dry where the waterproofing is being installed. Therefore, proper detailing at this interface is critical.

4.2 Leakage in Concrete Tunnels

4.2.1 Leakage through the tunnel structure

Reports of leakages in concrete tunnels in some Dutch tunnels, both with and without membranes, have mainly concerned minor leakages through the floor, walls and roof.

In tunnels with membranes, leakage through cracks in walls or floor is difficult to repair because it is almost impossible to find the leak in the membrane. In such cases, the leakage is stopped by injecting all cracks. When leakage through one crack is stopped, water seeks, and will appear through, another crack.

It is easier to stop leakage in tunnels without membranes, because the leakage point can be detected.

In both cases, the injection has to be done without a water stream.

There have been some leakage problems at the Limfjord Tunnel in Denmark. The leaks mainly have occurred through transverse construction joints, which have not been provided with waterstops.

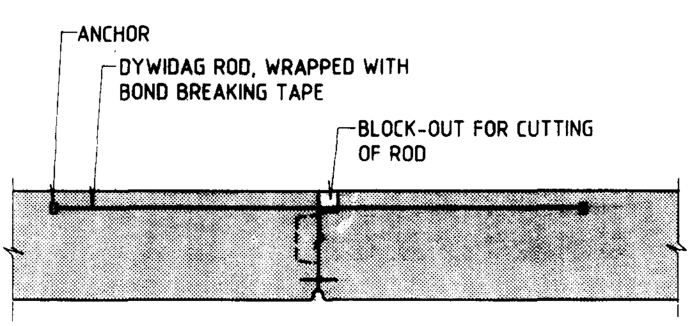

Figure 4-14. Temporary reinforcement at expansion joint.

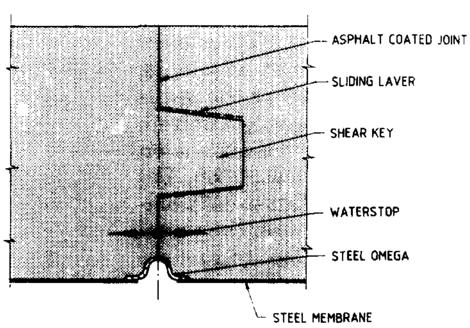

Figure 4-15. Expansion joint with steel Omega profile.

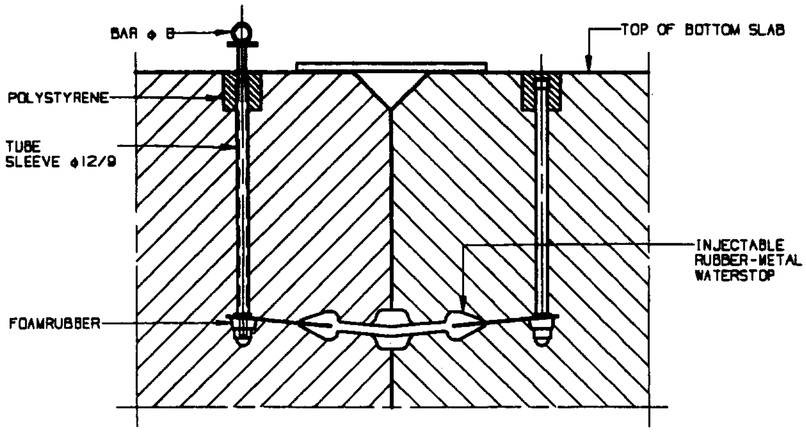

Figure 4-16. Injectable rubber-metal waterstop.

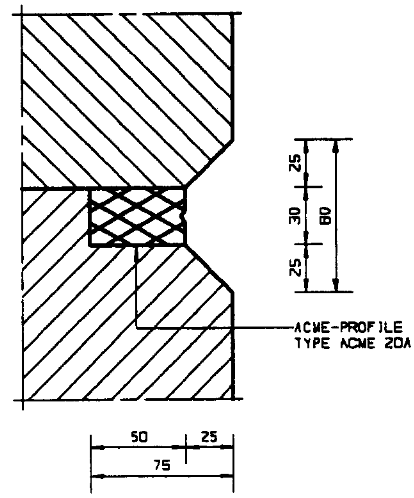

Figure 4-17. Expansion joint in walls.

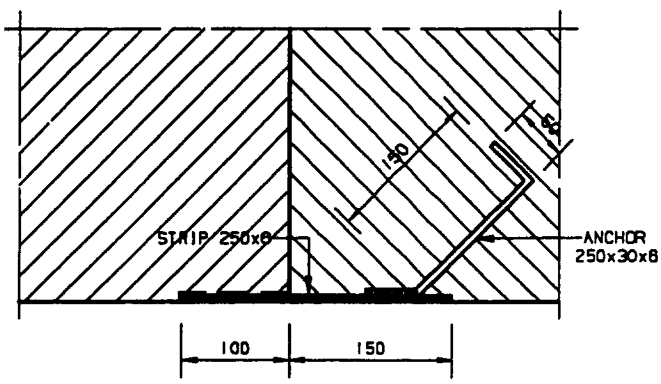

Figure 4-18. Expansion joint in floor.

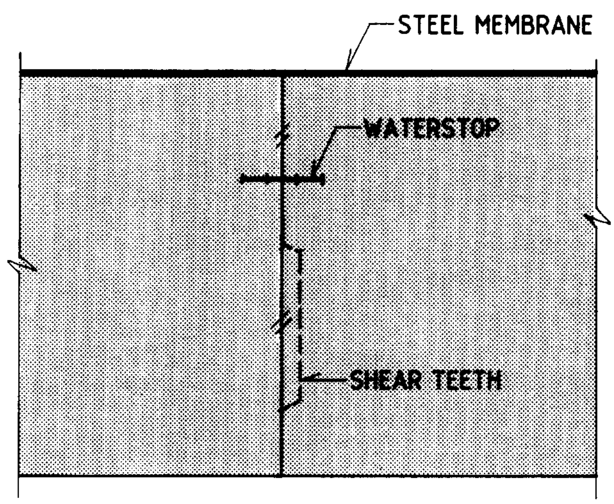

Figure 4-19. Construction joint.

The total amount of water leakage in the tunnel israther small—on the order of 50–100 l/hour (based upon measurements of a minor area). However, even small amounts of leakage through the concrete structure are unacceptable, as the water in the fjord is saline and therefore has caused corrosion of the reinforcement in the tunnel structure.

The tunnel is provided with a membrane of butyl rubber. Obviously, this membrane is not watertight; and, because the adhesion to the concrete is probably insufficient, the water may spread between the membrane and the structure.

The leakages began during the construction stage. Since then, more attempts have been made to stop the water seepage. Trial injections have been made with epoxy, polyurethane and acrylic gel. The latter have produced the best results, but in all cases

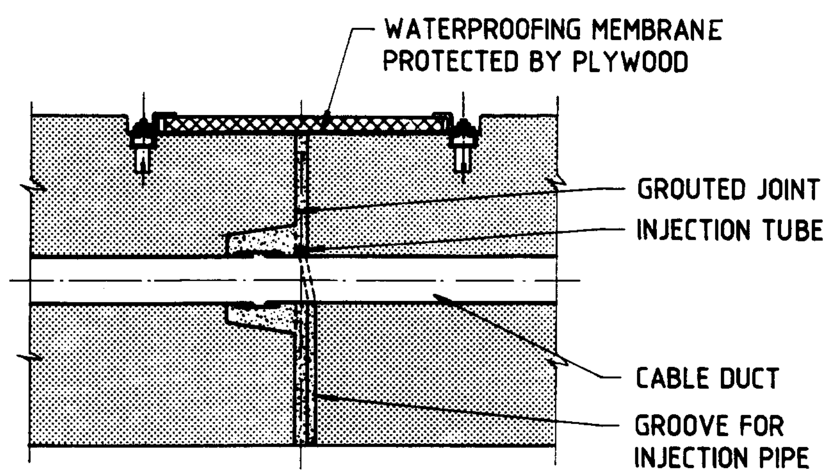

Figure 4-20. Joint between precast segments.

the leaks have started again some time after the injection has been performed. It is assumed that the reason for this is that because of the seasonal temperature variations, the long monolithic tunnel is alternately exposed to tension and compression, causing movements of the cracks.

Other measures, such as internal membranes (polyurethane and fiber-texture-reinforced cement-paste membrane) have been tested. The adhesion of the polyurethane membrane to the concrete was not sufficient, and the cement paste membrane was very expensive. Therefore, attempts to find a suitable repair method are continuing.

4.2.2 Leakage through joints

Leakages through expansion joints are usually caused by gravel pockets that formed under the rubber-metal waterstop during the pour. Leakage problems are usually handled by injection; however, if injection is not successful, the water must be directed to the drains.

In Dutch tunnels, a control system is available to detect leakage through the Gina gasket. During construction, a ½-inch pipe is embedded in the concrete, connecting the space between the Gina and Omega to the central gallery.

A leak through the Gina was detected at the Zeeburger Tunnel. However, the water did not enter the tunnel, which means that the Omega seal is watertight.

This type of leakage occurs because of the high positioning of the terminal joint, which lies just below the surface of the water. During winter, when the river freezes, the Gina loses its elasticity and the tunnel shrinks, causing the joints to open. The stiff Gina cannot swell to keep the gap closed.

A survey of leakage of existing tunnels was performed within the Working Group. The responses indicated no serious leakages, and only some small drippings, for both steel and concrete immersed tunnels.

References

Reina, Peter and Naoaki, Usui. 1989. "Sunken tube tunnels proliferate. How*Engineering News Record*, July 13, 1989, 30–37."

Chapter 5:

CATALOG OF IMMERSED TUNNELS

by

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Chapter 5: CATALOG OF IMMERSED TUNNELS

1. **INTRODUCTION**
2. **REFERENCE TABLE OF IMMERSED TUNNELS**
3. **IMMERSED TUNNEL FILES**

1. Introduction

During the early meetings of the Immersed and Floating Tunnels Working Group of the International Tunnelling Association (ITA), it was clear that a catalog of immersed tunnels would provide an important contribution to a better worldwide understanding of the history and technology in this field of tunnel engineering. At its 1989 meeting in Toronto, Canada, the Group decided to develop such a catalog for future publication.

This catalog, which focuses specifically on the immersed tunnels designed for rail and highway tunnels, is not intended to be complete, as a much more comprehensive catalog of all tunnels worldwide is already published by the ITA. Rather, the intent is to provide a summary of as much engineering information as can be found in various papers and articles in a concise, useful manner for the designers of this type of tunnel.

Over the past century, fewer than 100 railroad or highway tunnels have been designed worldwide. Two basic techniques have evolved:

1. The steel shell method, commonly used in the United States; and

2. The concrete box method, used in Europe.

More recently, these techniques have merged in the Far East, Hong Kong and Japan.

This catalog attempts to highlight the principal aspects of each project (a total of 91 projects are presented), as well as documenting both the earliest methods used (some of which are very innovative, even by today's standards) and the most current techniques. In doing so, it is hoped that the engineers who are in the process of conceptualizing a new tunnel crossing can use this catalog as a source of ideas for developing their designs.

The catalog also represents the range of dimensional features of immersed elements.

Other aspects covered, where data were available at this writing, include methods of fabrication, material specifications, methods of foundation placement, environmental conditions, safety factors, and types of tunnel joints used.

Finally, where data were available, the owner, designer and construction contractors have been listed as a reference, as well as an acknowledgment of the work undertaken by them.

Also included in a number of the catalogue listings are one or more cross-sectional drawings of the tunnel. We are most grateful to Mr. D. R. Culverwell, who has granted permission to reprint drawings used to illustrate his "World List of Immersed Tubes", published in *Tunnels & Tunnelling* in March and April 1988. Thanks are also due to Mr. Nestor Rasmussen, of Christiani & Nielsen A/S, for providing illustrations for other tunnels listed in the catalogue.

This report has been developed over the past four years by soliciting information from various members of the Subworking Group. This was done following the basic format presented herein as a questionnaire. The research work involved in collecting this information was a time-consuming, difficult undertaking. We therefore are very grateful to our colleagues who have contributed to the catalogue.

As the catalog has been reviewed by the Subworking Group members in draft form, interest has increased and more information has been forthcoming. While the inventory is not as complete as might be desired, we feel it is important that the inventory now be printed so that it can reach a wider audience.

It is hoped that readers will excuse any omissions. In this regard, the Subworking Group will welcome any corrections or contributions of additional information. It is expected that the catalog will be amplified and reprinted from time to time to incorporate new information. Additional information may be sent to the author of this chapter at the following address: Bechtel/Parsons Brinckerhoff, One South Station, Boston, MA, 02110, U.S.A.

New tunnels are started every year, and new techniques will be developed. We hope that the reader will find this catalogue both interesting and useful.

Table 1. Reference list of tunnels included in the catalogue of immersed tunnels on pages 174–258.

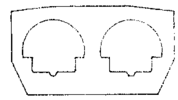
Reference No.	Tunnel	Country	Year Completed (* indicates unknown construction start date)
1	Detroit River	U.S.A.	1910
2	La Salle St.	U.S.A.	1912
3	Harlem River	U.S.A.	1914
4	Freidrichshafen	Germany	1927
5	Oakland-Alameda (Posey)	U.S.A.	1928
6	Detroit Windsor	U.S.A.	1930
7	Bankhead	U.S.A.	1940
8	Maas	Netherlands	1941
9	State Street	U.S.A.	1942
10	Aji River	Japan	1944
11	Washburn	U.S.A.	1950
12	Elizabeth River	U.S.A.	1952
13	Baytown	U.S.A.	1953
14	Baltimore Harbor	U.S.A.	1957
15	Hampton Roads Bridge Tunnel	U.S.A.	1957
16	Havana	Cuba	1958
17	Deas Island	Canada	1959
18	Rendsburg	Germany	1961
19	Webster Street	U.S.A.	1962
20	Elizabeth River Tunnel No. 2	U.S.A.	1962
21	Chesapeake Bay Bridge Tunnels	U.S.A.	1964
22	Liljeholmsviken	Sweden	1964
23	Haneda (vehicular tunnel)	Japan	1964
24	Haneda (monorail tunnel)	Japan	1964
25	Coen	Netherlands	1966
26	Wolfburg Pedestrian Tunnels	Germany	1966
27	Benelux	Netherlands	1967
28	Lafontaine	Canada	1967
29	Vieux-Port	France	1967
30	Tingstad	Sweden	1968
31	Rotterdam Metro Tunnels	Netherlands	1968
32	Ij	Netherlands	1969
33	Scheldt E3 (JFK Tunnel)	Belgium	1969
34	Heinenoord	Netherlands	1969
35	Limfjord	Denmark	1969
36	Parana (Hernandias)	Argentina	1969
37	Dojima River	Japan	1969
38	Dohtonbori River	Japan	1969
39	Haneda (Tama River)	Japan	1970
40	Haneda (Keihin Channel)	Japan	1970
41	Bay Area Rapid Transit Tunnel	U.S.A.	1970
42	Charles River	U.S.A.	1971
43	Cross Harbour	Hong Kong	1972
44	63rd Street	U.S.A.	1973
45	Mobile (I-10)	U.S.A.	1973

continued on following page

Reference No.	Tunnel	Country	Year Completed (* indicates planned or under construction)
46	Kinuura Harbour	Japan	1973
47	Ohgishima	Japan	1974
48	Elbe	Germany	1975
49	Vlake	Netherlands	1975
50	Sumida	Japan	1975
51	Hampton Roads Bridge Tunnel No. 2	U.S.A.	1976
52	Paris Metro	France	1976
53	Tokyo Port	Japan	1976
54	Drecht	Netherlands	1977
55	Prinses Margriet	Netherlands	1978
56	Kil	Netherlands	1978
57	WMATA Washington (D.C.) Channel	U.S.A.	1979
58	Kawasaki	Japan	1981
59	Hong Kong Mass Transit	Hong Kong	1979
60	Hemspoor	Netherlands	1980
61	Botlek	Netherlands	1980
62	Daiba	Japan	1980
63	Tokyo Port Dainikoro	Japan	1980
64	Rupel	Belgium	1982
65	Metropolitan Rail Tunnel (Main)	Germany	1983
66	Bastia Old Harbour	France	1983
67	Spijkenisse Metro	Netherlands	1984
68	Coolhaven	Netherlands	1984
69	Kaohsiung Harbour	Republic of China	1984
70	Fort McHenry	U.S.A.	1987
71	Second Downtown	U.S.A.	1988
72	Guldborgsund	Denmark	1988
73	Ems	Germany	1989
74	Marne River	France	1989
75	Zeeburger	Netherlands	1989
76	Hong Kong Eastern Harbour Crossing	Hong Kong	1990
77	Conwy	U.K.	1991
78	Liefkenshoek	Belgium	1991
79	Interstate 664	U.S.A.	1992
80	Third Harbor	U.S.A.	1994*
81	Willemspoor	Netherlands	*
82	Niigata Port Road Tunnel	Japan	*
83	Tama River	Japan	*
84	Kawasaki Fairway	Japan	*
85	Sydney Harbour	Australia	*
86	Osaka South Port	Japan	*
87	Bilbao Metro	Spain	*
88	Noord	Netherlands	*
89	Grouw	Netherlands	1993*
90	Medway	U.K.	1995*
91	Schipol Railway Tunnel	Netherlands	1994*

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Detroit River Tunnel; International tunnel between Detroit, Michigan, U.S.A. and Windsor, Canada; 1910

File No. 1



TUNNEL TYPE AND USE:	LANES/TRACKS:
Railroad tunnel; steel shell lined with concrete. Exterior concrete ballast.	Two tubes, one track each way.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
11	80 m	9.4 m	17 m

TOTAL IMMERSED LENGTH:	DEPTH AT BOTTOM OF STRUCTURE:
800 m	24.4 m

UNUSUAL FEATURES:	Method of construction involved sinking elements by flooding them with water and controlling escaping air. Elements were lowered to steel grillages on the bottom, where all exterior concrete was then placed. Later, the interior of the element was dewatered and the concrete lining was then installed under water.
ENVIRONMENTAL CONDITIONS	River currents.

FABRICATION METHOD:	OUTFITTING:	JOINT TYPE:
Shipyard	Underwater after placement.	Unique rubber

WATERPROOFING METHOD:	Continuous steel shell plate.
PLACEMENT METHOD:	Pontoons were used to control sinking.
FOUNDATION METHOD:	Steel grillages were placed to exact grade and tubes were lowered to them. Tremie concrete, used to make the interface contact with the dredged trench, became the foundation for the tunnel elements.
DREDGING METHOD:	Dipper dredge for first 14 m; remainder was done by clamshell dredge.
COVER AND TYPE:	Riprap covering over side backfills to protect them from scouring. Tunnel roof at grade of river bottom.
ADDITIONAL INFORMATION:	If this tunnel were to be constructed today, it would be regarded as incorporating many innovative ideas because it is so different from the way we currently do immersed tube tunnels. Some of the ideas could be very useful someday in a particular situation because they apparently were successful. OWNER: Michigan Central Railroad. DESIGNER: Detroit River Tunnel Company.

TUNNEL NAME/ LOCATION/ DATE OF COMPLETION:
La Salle St.; Chicago, Illinois, U.S.A.; 1912

File No. 2

TUNNEL TYPE AND USE:
Railway; single steel shell (riveted).

LANES/TRACKS:
Two tubes, each with one track.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
1	84.8 m	7.3 m	12.5 m

TOTAL IMMERSED LENGTH:
84.8 m

DEPTH AT BOTTOM OF STRUCTURE:
15.5 m

UNUSUAL FEATURES:
Was replacement for masonry tunnel on the same alignment. The masonry tunnel was demolished and removed by dredging. Crossing was made with a single element. Interior lining increased in thickness from top to bottom. Underside of tube had "V" shape to make backfilling easier. Structure had longitudinal central truss encased in concrete.

FABRICATION METHOD:
Constructed in a dry dock in Chicago using a riveted steel shell (to boiler specifications) lined with concrete. Timber end bulkheads were provided. Internal ballast tanks were installed in each tube at each end, operated by remotely controlled valves and pumps.

OUTFITTING:
Interior concrete for the center wall and lower keel area were placed first in dry dock. The element was then floated to the outfitting dock (3,000 tons), where the rest of the interior concrete was placed, bringing the total to 8,000 tons. Steel shell roundness was maintained with struts and tierods.

JOINT TYPE:
Special diaphragms were provided at the two ends of the single element, to which cofferdams could be engaged to permit land-side construction to proceed. Two manhole shafts were provided at each end of the element for access during and after placement. Cofferdam detail provided for later bridge pier to straddle the tunnel, if required.

WATERPROOFING METHOD:
Double butt strap caulked longitudinal joints and alternate inside and outside lap circumferential caulked joints. Steel shell provided watertightness. Coated with red-lead paint.

PLACEMENT METHOD:
Internal water ballast was used for placement. Pile driver barges and/or hoisting engines on adjacent piers were used for control of alignment and grade during placement.

FOUNDATION METHOD:
Two-pile supported piers were provided for temporary support. Piles were installed by statically loading them to a known load, rather than driving, in the expectation that adjustments to grade could be made by overloading by a known amount. As tube was placed on supports and adjusted to grade, sand fill was placed around it.

DREDGING METHOD:
A dipper dredge and a clamshell dredge were used. A great deal of difficulty was involved in removing the old tunnel, the roof of which had been demolished by blasting.

VENTILATION TYPE:
Piston action of trains.

ADDITIONAL INFORMATION:
OWNER: Chicago Railways Company.
DESIGNERS: E.C. & R.M. Shankland and J. W. Pearl.
CONTRACTOR: M.H. McGovern/J.A. Green/Charles Green and R.H. Green.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Harlem River Tunnel; New York City, NY, U.S.A.; 1914

File No. 3

TUNNEL TYPE AND USE:
Railroad tunnel; steel shell.

LANES/TRACKS:
Four tubes; one track each.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
5	67 m	7.5 m	23.2 m

TOTAL IMMERSED LENGTH:
329 m

DEPTH AT BOTTOM OF STRUCTURE:
15.2

UNUSUAL FEATURES:
Four tubes in a single element section. Element placement closely followed Detroit River Tunnel method where element was lowered to grade filled with water and exterior concrete jacket was placed by tremie. Later interior was pumped out and lined with concrete.

FABRICATION METHOD:
At yard 1 mile from tunnel site. Launched by floating off shipways on nine canal boats, then sinking the canal boats out from under the element.

OUTFITTING:
Interior concrete linings were installed after the five elements were placed and tremied and the tunnel had been pumped out between bulkheads placed at the ends. Connections to the land sections were made later through cofferdams. Leakage was minimal.

JOINT TYPE:
Rivetted liner plate over steel butt joint; grouted.

WATERPROOFING METHOD:
Continuous steel shell.

PLACEMENT METHOD:
12 in. valves were opened in the bottom of the bulkheads in the two outside tubes, allowing them to fill gradually. The two inner tubes were open. The rate of sinking after the tubes were half full was controlled by air valves. Trim was accomplished by half bulkheads at two central locations to allow adjustment of filled portions. As the tubes became completely filled, the flotation was carried by four pontoons, which were partially filled and went down with the element. The rest of the weight was carried by derrick boats moored on either side. Masts were used to measure line and grade. Once in place, the space below the bottom of the element caused by overdredging was filled with lean tremie concrete. Then each pocket formed by the diaphragms and wood side lagging was filled with structural concrete by the same method.

FOUNDATION METHOD:
Tremie concrete placed after element was in position.

VENTILATION TYPE:
Piston action of trains.

ADDITIONAL INFORMATION:
OWNER: New York City Rapid Transit System.
CONTRACTOR: Arthur McMullen and Hoff Company.

TUNNEL NAME / LOCATION/ DATE COMPLETED: Freidrichshafen; Berlin, Germany; 1927			File No. 4
TUNNEL TYPE AND USE: Pedestrian; reinforced concrete.		LANES/TRACKS: Footway.	
NO. OF ELEMENTS: 2	LENGTH: 52.9 m	HEIGHT: 6.67 m	WIDTH: 7.65 m
TOTAL IMMERSED LENGTH: 105.8 m		DEPTH AT BOTTOM OF STRUCTURE: 10.8 m	
UNUSUAL FEATURES:	Constructed as two pneumatic caissons. Element structure was constructed on fill placed halfway to center of river. Excavation under this structure, which was provided with cutting edges, allowed it to be lowered to grade below the river bottom. One side was done at a time. The two elements were sealed at the middle joint after the second element was at grade.		
FABRICATION METHOD: In place.		JOINT TYPE: Concrete joint formed in cofferdam.	
WATERPROOFING METHOD:	Concrete-protected membrane all around.		
PLACEMENT METHOD:	Caisson method.		
FOUNDATION METHOD:	Concrete filled caisson under tunnel tube.		
VENTILATION TYPE:	Natural ventilation.		
COVER AND TYPE:	1.5 m backfill.		

TUNNEL NAME/ LOCATION/ DATE COMPLETED: Oakland-Alemeda (Posey) Tunnel; between Oakland and Alameda, CA, U.S.A.; 1928	File No. 5

TUNNEL TYPE AND USE: Vehicular; reinforced concrete cylindrical section.	LANES/TRACKS: One tube; two lanes; one each way.

NO. OF ELEMENTS: 12	LENGTH: 61.9 m	HEIGHT: 11.7 m	WIDTH: 11.6 m

TOTAL IMMERSED LENGTH: 742 m	DEPTH AT BOTTOM OF STRUCTURE: 25.5 m

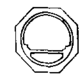
UNUSUAL FEATURES:	Circular concrete section (without steel shell) was cast in a drydock. Waterproofed with external membrane protected with timber lagging. Invert waterproofing was laid on timber lagging and ended by metal flashing at end brackets. Roadway slab and ceiling tierods were used for structural members. Placement and foundation methods were very unusual.

FABRICATION METHOD: In drydock with five elements per cycle, chuted concrete, steel forms.	OUTFITTING: At time of fabrication.	JOINT TYPE: Tremie concrete joints.

WATERPROOFING METHOD:	As described above.
PLACEMENT METHOD:	Ballasting involved placing dry sand on the floor slab before and after the element was positioned over the trench. The lower duct was filled with sea water and an additional load of sand was placed. The final load adjustement was made by wetting the sand on the roadway slab. For the first five joints, sand jacks mounted on pile supported piers were used to land the elements. This method was simplified by using timber grillages lowered to bear on piles driven 15 cm high, to allow for settlement. This grillage was intended to crush under settlement. If the element was not to suitable grade, some of the sand bed had to be removed—a very difficult and time-consuming operation. The elements were supported by a derrick barge at one end and leads from a pile driver at the other. Lateral movements were controlled by lines from winches mounted on dolphins. Immediately after being set in position, more water ballast was added. The exterior sand bed was placed by pumping a sand slurry under the element as directed by divers. On completion of the sand bed, the element was filled with water. The tremie joint was made and completed from inside later. Before dewatering or removing ballast, at least 3.4 m of backfill had to be placed to overcome buoyancy (the stability of the tunnel depends on this cover being maintained throughout its life!).
VENTILATION TYPE:	Fully transverse, using lower duct for supply and upper for exhaust.
COVER AND TYPE:	See above.
ADDITIONAL INFORMATION:	OWNER: Alameda County bond holders. DESIGNER: George A. Posey Chief Engineer; W.H. Burr, Ole Singstad, and Charles Derleth, Jr. CONTRACTOR: California Bridge and Tunnel Co.

TUNNEL NAME AND LOCATION/ DATE COMPLETED:
Detroit Windsor Tunnel; International tunnel between Detroit, Michigan, U.S.A. and Windsor, Canada; 1930

File No. 6



TUNNEL TYPE AND USE: Vehicular; double steel shell elements.	LANES/TRACKS: Two lanes, one each way.

NO. OF ELEMENTS: 9	LENGTH: 76 m	HEIGHT: 10.6 m	WIDTH: 10.6 m

TOTAL IMMERSED LENGTH: 670 m	DEPTH AT BOTTOM OF STRUCTURE: 18.5 m

UNUSUAL FEATURES:	The tunnel project was a combination of open approach structures, cut-and-cover structures, shield-driven tunnelling, and immersed tunnel construction.

FABRICATION METHOD: Welded steel construction. Steel fabricator; controlled side launching into river 6 miles from site.	OUTFITTING: At dock near tunnel site. Exterior formwork was erected at outfitting pier.	JOINT TYPE: Tremie concrete.

WATERPROOFING METHOD:	Continuous steel shell.
PLACEMENT METHOD:	Ballasting was done to bring the element to near neutral buoyancy. Concrete blocks were placed at one end to sink it some five feet. A barge was placed transversely to the end and lowering cables were attached. After this was also done at the opposite end, the element could be raised or lowered using these barges.
FOUNDATION METHOD:	Screeded bedding.
VENTILATION TYPE:	Fully transverse ventilation system.
COVER AND TYPE:	No cover.
ADDITIONAL INFORMATION:	OWNER: Detroit & Canada Trunnel Corporation. DESIGNER: Parsons Klapp Brinckerhoff & Douglas. CONTRACTOR: Porter Brothers and Robert Porter of Spokane.

TUNNEL NAME AND LOCATION/ DATE COMPLETED:
Bankhead Tunnel; Mobile, Alabama, U.S.A.; 1940

File No. 7

TUNNEL TYPE AND USE: Vehicular; double steel shell tunnel.	LANES/TRACKS: Two lanes; one each way.

NO. OF ELEMENTS: 7	LENGTH: 90.8 m	HEIGHT: 10.4 m	WIDTH: 10.4 m

TOTAL IMMERSED LENGTH: 610 m	DEPTH AT BOTTOM OF STRUCTURE: 25 m

UNUSUAL FEATURES:	Placed from pile-supported frames. Foundation material was placed with element held in position from frames. Elements were placed a few inches high to accommodate settlement.
ENVIRONMENTAL CONDITIONS	Close to mouth of river at Mobile Bay, with fresh water wedge sometimes extending beyond the site. The variation from upper salt water into fresh water had to be taken into account in sinking the elements. Hurricane tide gates were provided at the portals.

FABRICATION METHOD: In shipyard 1 km away from site. The elements were side-launched into river, then placed in shipyard's dry dock for placement of keel concrete (for stability). The element was then towed to the outfitting yard near the site.	OUTFITTING: Concrete was placed from floating batch plant.	JOINT TYPE: Tremie concrete.

WATERPROOFING METHOD:	Continuous steel shell.
PLACEMENT METHOD:	Gallows frames supported from H-pile clusters.
FOUNDATION METHOD:	Element was held at grade while sand was placed along the sides with tremie pipes.
VENTILATION TYPE:	Longitudinal; fresh air enters at portals, exhausted by air duct (roadway flues near tunnel midpoint).
COVER AND TYPE:	A minimum of 3 m of backfill.
ADDITIONAL INFORMATION:	OWNER: City of Mobile revenue bond issue. DESIGNER: Messrs. Wilberding and Palmer, Inc. CONTRACTOR: Arundel Corporation and the Alabama Drydock and Shipbuilding Company.

TUNNEL NAME / LOCATION/ DATE COMPLETED: **Maas Tunnel; Rotterdam, The Netherlands, under Nieuwm Maas-River; 1941**	**File No. 8** 

TUNNEL TYPE AND USE: Vehicles, cyclists, pedestrians; concrete-box elements.	LANES/TRACKS: Four lanes in two tubes for vehicles. One tube for cyclists and one tube for pedestrians.

NO. OF ELEMENTS: 9	LENGTH: 61.35 m	HEIGHT: 8.39 m	WIDTH: 24.77 m

TOTAL IMMERSED LENGTH: 584 m	DEPTH AT BOTTOM OF STRUCTURE:

UNUSUAL FEATURES:	Immersed tunnel terminated in ventilation buildings constructed as pneumatic caissons. Construction spanned the occupation of Holland during the Second World War.
FABRICATION METHOD:	Casting basin in Heyse Harbor. Roof slab was left off until the element was in position in Waal Harbor. Three cycles of three elements were used.
WATERPROOFING METHOD:	6-mm steel membrane covered with coating of concrete to inhibit rusting.
PLACEMENT METHOD:	Lowering by means of floating cranes. Pontoons along the sides of the elements were used to provide positive buoyancy.
FOUNDATION METHOD:	Sand-jetted foundation. Very first application of Christiani & Nielsen method.
VENTILATION TYPE:	Semi-transverse ventilation system.
ADDITIONAL INFORMATION:	OWNER: Municipality of Rotterdam. DESIGNER AND CONTRACTOR: Christiani & Nielsen, N.V.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
State Street Tunnel; Chicago, Illinois, U.S.A.; 1942

File No. 9

TUNNEL TYPE AND USE:
Railway; double shell steel elements.

LANES/TRACKS:
Two tubes; one track each.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
1	61 m	7 m	12.0 m

TOTAL IMMERSED LENGTH:
61 m

DEPTH AT BOTTOM OF STRUCTURE:
15.8 m

ENVIRONMENTAL CONDITIONS
Mild currents.

FABRICATION METHOD:
In a drydock. Welded construction. Pressurized to 0.5 psi for soap bubble test. 1,000 cu. m placed in drydock.

OUTFITTING:
At a dock with 6 m of draft available.

JOINT TYPE:
Tremie concrete.

WATERPROOFING METHOD:
Continuous steel shell.

PLACEMENT METHOD:
Element hung from under scows by cables fed through wells. Element had to be sunk below scows to attach them.

FOUNDATION METHOD:
Element was landed on tremie concrete pads formed to exact grade; screw jacks on the corners were used to level the element. A screeded bed was placed as well.

DREDGING METHOD:
2.5-cu.-m clamshell ring.

VENTILATION TYPE:
Piston action of trains.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Aji River; Osaka, Japan; 1944

File No. 10

TUNNEL TYPE AND USE:
Vehicular and pedestrian; steel-plate-covered reinforced concrete elements

LANES/TRACKS:
Two lanes with sidewalk.

NO. OF ELEMENTS:
1

LENGTH:
49.2 m

HEIGHT:
7.2 m

WIDTH:
14.0 m

TOTAL IMMERSED LENGTH:
49.2

DEPTH AT BOTTOM OF STRUCTURE:
14.9 m

UNUSUAL FEATURES:
Structure acts like a bridge in soft muddy soil. Supported at both ends by abutments constructed by pneumatic caisson method. Single concrete element reinforced with reinforcing steel and rolled steel sections.

ENVIRONMENTAL CONDITIONS
The depth of water was only 5.5–6.3 m. All navigation had to be stopped for nearly 15 hours.

FABRICATION METHOD:
The outside 9-mm shell was fabricated at a shipyard. The element was then outfitted with reinforcing steel and concrete at a dock.

OUTFITTING:
In flotation at dockside 14 km from tunnel site in Osaka Bay.

JOINT TYPE:
Rigid concrete filled joint to abutment structures.

WATERPROOFING METHOD:
Continuous steel shell.

PLACEMENT METHOD:
The element was towed supported by two barges and placed using floating cranes. Exact position between elements was controlled by divers.

FOUNDATION METHOD:
Two L-shaped abutment caissons were sunk in place at the river shorelines. The river bed between the abutments was excavated and the element was supported on the abutments, rather than on a prepared foundation, as might normally be the case.

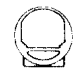
VENTILATION TYPE:
A semi-transverse ventilation system was first adopted; however, the tunnel ventilation was later converted to a longitudinal system.

TUNNEL NAME/ LOCATION/ DATE COMPLETED: **Washburn; between Houston and Galveston, Texas, U.S.A.; 1950**	**File No. 11**
TUNNEL TYPE AND USE: Vehicular tunnel; double shell steel elements.	LANES/TRACKS: One tube; two lanes, one each way.
NO. OF ELEMENTS: 4	LENGTH: 114.3 m
TOTAL IMMERSED LENGTH: 457 m	DEPTH AT BOTTOM OF STRUCTURE:
FABRICATION METHOD: At shipyard in Pascagoula, Miss. and launched and towed 640 km to Pasadena, Texas. Special launching reinforcing was removed and ballast concrete was placed at an outfitting dock before the tow to Texas.	JOINT TYPE: Tremie concrete.
WATERPROOFING METHOD:	Continuous steel shell.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:			File No. 12
Elizabeth River Tunnel; between Norfolk and Portsmouth, Virginia, U.S.A.; 1952			
TUNNEL TYPE AND USE: Vehicular; double shell steel elements.		LANES/TRACKS: Singular tube; two lanes, one each way.	
NO. OF ELEMENTS: 7	LENGTH: 91.5 m	HEIGHT: 11.0 m	WIDTH: 10.8 m
TOTAL IMMERSED LENGTH: 638 m		DEPTH AT BOTTOM OF STRUCTURE: 29 m	
UNUSUAL FEATURES:	Sequence of construction started with Element A being placed prior to construction of west cut-and-cover section. Elements B, C, etc,. followed, until the final element was placed and connected under water to east cut-and-cover section already in place. Water depth required that the last element be temporarily "parked" some 0.5 m beyond the next to-the-last section until that section was connected to the preceding one. The final section was then moved back and connected to both the preceiding element and the cut-and-cover section. This was done within a sheeted trench, using land cranes. Ventilation building was independently supported on piles off to to one side of the tunnel. Ventilation ducts had flexible connections to the tunnel structure, to allow for differential settlements.		
FABRICATION METHOD: Fabricated on shipways, provided with 1,000 tons of concrete for keel, fitted with a launching bow and end-launched.		OUTFITTING: At dock near tunnel site.	JOINT TYPE: Tremie concrete joint.
WATERPROOFING METHOD:	Continuous steel shell.		
PLACEMENT METHOD:	Two floating derricks; 100-ton negative buoyancy.		
FOUNDATION METHOD:	Screeded bedding.		
VENTILATION TYPE:	Semi-transverse system, whereby vitiated air is withdrawn at top and bottom air ducts and fresh air enters through portals.		
COVER AND TYPE:	1.5 m minimum backfill.		
ADDITIONAL INFORMATION:	OWNER: Elizabeth River Tunnel Commission. DESIGNER: Parsons Brinckerhoff Quade & Douglas.		

TUNNEL NAME AND LOCATION/ DATE COMPLETED:
Baytown Tunnel; Baytown, Texas, U.S.A.; 1953

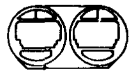
File No. 13



TUNNEL TYPE AND USE: Vehicular; single tube single steel shell elements.	LANES/TRACKS: Two lanes; one each way.
NO. OF ELEMENTS: 9	LENGTH: 90.3 m
TOTAL IMMERSED LENGTH: 780 m	DEPTH AT BOTTOM OF STRUCTURE: 33.5 m
UNUSUAL FEATURES:	Circular element with 12-mm exterior steel shell. Interior concrete ring 91 cm thick. Temporarily supported on fabricated steel chair until backfilled. Two alternates were bid; the other was a double shell steel design.
OUTFITTING: At work pier constructed near site.	JOINT TYPE: Tremie concrete joint.
WATERPROOFING METHOD:	Continuous steel shell plate.
PLACEMENT METHOD:	Supported by two straddling barges attached with the element sitting on bottom.
FOUNDATION METHOD:	Screeded bedding.
VENTILATION TYPE:	Semi-transverse with fresh air supplied through lower, under-roadway air duct and exhausted at portals.
COVER AND TYPE:	1.5 m minimum backfill.
ADDITIONAL INFORMATION:	OWNER: State of Texas Highway Department. DESIGNER: Parsons Brinckerhoff Hall and McDonald. CONTRACTOR: Brown & Root, Inc.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Baltimore Harbor Tunnel; Baltimore, Maryland, U.S.A.; 1957

File No. 14



TUNNEL TYPE AND USE:
Vehicular tunnel; two-tube double-steel shell elements

LANES/TRACKS:
Four lanes; two each way

NO. OF ELEMENTS:
21

LENGTH:
91.4 m

HEIGHT:
10.7 m

WIDTH:
21.3 m

TOTAL IMMERSED LENGTH:
1920 m

DEPTH AT BOTTOM OF STRUCTURE:
30 m

UNUSUAL FEATURES:
Shell plate protected with 6.4-cm gunnite coating over exterior 120-degree section of both tubes.

ENVIRONMENTAL CONDITIONS
Mild currents and tides.

FABRICATION METHOD:
Shipyard in Baltimore and end-launched from shipways.

OUTFITTING:
At dock near site.

JOINT TYPE:
Tremie concrete joints.

WATERPROOFING METHOD:
Continuous steel shell.

PLACEMENT METHOD:
Two to four floating derricks were used.

FOUNDATION METHOD:
Screeded bedding.

DREDGING METHOD:
Cutterhead suction dredge spoil used for development of port site.

VENTILATION TYPE:
Fully transverse ventilation system.

ADDITIONAL INFORMATION:
Owner: Maryland State Roads Commission.
Designer: Singstad & Baillie.
Contractor: Merritt-Chapman & Scott, Inc.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:	File No. 15
Hampton Roads Bridge Tunnel; Hampton Roads, Virginia, U.S.A.; 1957	

TUNNEL TYPE AND USE:
Vehicular tunnel; single tube, double steel shell elements

LANES/TRACKS:
Two lanes; one each way (later became northbound lanes when Second HRT was completed in 1976).

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
23	91.5 m	11.3 m	11.3 m

TOTAL IMMERSED LENGTH:	DEPTH AT BOTTOM OF STRUCTURE:
2091 m	37 m

UNUSUAL FEATURES: First immersed tunnel to be constructed from two manmade islands. From the islands, this crossing reached the shores by way of two causeways. Later, four other tunnels using this same arrangement were constructed in the Hampton Roads and Chesapeake Bay area.

ENVIRONMENTAL CONDITIONS Strong currents and wave action made island building difficult until rock dikes were constructed. Seaward face of islands had to be protected by cyclopean-sized riprap to prevent erosion.

FABRICATION METHOD:	OUTFITTING:	JOINT TYPE:
Shipyard in Baltimore.	At dock near site of tunnel.	Tremie concrete joints.

WATERPROOFING METHOD: Continuous steel shell plate.

PLACEMENT METHOD: Catamaran barges.

FOUNDATION METHOD: Screeded bedding.

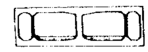
DREDGING METHOD: Cutterhead suction dredge for shallower portions of trench. Sand was used to build the islands. Deeper portions were done with a clamshell bucket dredge.

VENTILATION TYPE: Full transverse system.

COVER AND TYPE: 1.5 m of sand, in some cases protected with riprap against scour. Backfill came from channel dredging being done concurrently by U.S. Corps of Engineers.

ADDITIONAL INFORMATION:
OWNER: Virginia Highway Department.
DESIGNER: Parsons Brinckerhoff Hall and McDonald.
CONTRATOR: Merritt-Chapment & Scott, Inc.

TUNNEL NAME/ LOCATION/ DATE COMPLETED: **Havana Tunnel; Havana, Cuba; 1958**			**File No. 16** 
TUNNEL TYPE AND USE: Vehicular tunnel; prestressed concrete box elements.		LANES/TRACKS: Two tubes; two lanes each.	
NO. OF ELEMENTS: 5	LENGTH: 4 @ 107.5 m and 1 @ 90 m	HEIGHT: 7.10 m	WIDTH: 21.85 m
TOTAL IMMERSED LENGTH: 520 m		DEPTH AT BOTTOM OF STRUCTURE: 23 m	
UNUSUAL FEATURES:	First fully prestressed immersed tunnel. Both longitudinal and transverse prestressing was utilized.		
FABRICATION METHOD: All by non-reusable timber formwork in a casting basin in groups of two.		JOINT TYPE: Tremie concrete joints.	
PLACEMENT METHOD:	Placed from catamaran placing barges. Pontoons were used to assist flotation of element prior to sinking.		
ADDITIONAL INFORMATION:	DESIGNER/CONTRACTOR: Société des Grands Travaux de Marseille.		

TUNNEL NAME/ LOCATION/ DATE COMPLETED:	File No. 17
Deas Island Tunnel; Vancouver, British Columbia, Canada; 1959	

TUNNEL TYPE AND USE:	LANES/TRACKS:
Vehicular tunnel; reinforced concrete box elements.	Two tubes; four lanes (two in each tube).

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
6	104.9 m	7.16 m	23.8 m

TOTAL IMMERSED LENGTH:	DEPTH AT BOTTOM OF STRUCTURE:
629 m	22 m

UNUSUAL FEATURES:	Designed for earthquake loadings (Zone 3).	
ENVIRONMENTAL CONDITIONS:	Extensive river, tunnel placement, and cover stability laboratory modelling was conducted.	
FABRICATION METHOD: Casting basin next to tunnel site for all six elements.	OUTFITTING: At outfitting jetty next to tunnel site.	JOINT TYPE: Inflatable rubber-gasketted joint used for initial seal. Final seal made in conventional way, by dewatering joint and mobilizing hydrostatic pressure. Monolithic permanent joint.
WATERPROOFING METHOD:	5-mm steel plate on bottom lapping with membrane up the sides and over the roof slab. The waterproofing was protected with a 10-cm layer of reinforced concrete under the bottom and on the top and by 10 cm of wood planking on the walls.	
PLACEMENT METHOD:	Four barges, two on each side of the element, were arrayed in a catamaran arrangement. Manuevering lines included vertical lifting lines, transverse and longitudinal tag lines and rigging from fairleads on the element, acting horizontally to main anchors. Control and survey towers were used to access the inside of the elements and control the positioning of the element.	
FOUNDATION METHOD:	Sand-jetted foundation.	
DREDGING METHOD:	Cutterhead suction dredging; also used for casting basin.	
VENTILATION TYPE:	Semi-transverse from two ventilation buildings. Fresh air is drawn into the tunnel through the portal. In the second half, air is introduced into the tube and leaves the tunnel at the exit portal.	
COVER AND TYPE:	Double layers of 1,500-lb. stone on top of the structure with additional protection of the sides consisting of 500-lb. stone extending out 50 ft. on either side of the tunnel box.	
ADDITIONAL INFORMATION:	OWNER: Department of Highways of British Columbia. DESIGNERS: Foundation of Canada Engineering Corporation, Ltd. and Christiani & Nielsen. CONTRACTOR: Peter Kiewit & Sons Co. of Canada Ltd. and B.C. Bridge and Dredging Co., Ltd. Joint Venture; Narod Construction Ltd. and Dawson and Hall.	

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Rendsburg Tunnel; Keil Cana, Rendsburg, West Germany; 1961

File No. 18

TUNNEL TYPE AND USE:
Vehicular tunnel; reinforced concrete box elements.

LANES/TRACKS:
Two tube; two lanes each.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
1	140 m	7.3 m	20.2 m

TOTAL IMMERSED LENGTH:
140 m

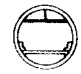
DEPTH AT BOTTOM OF STRUCTURE:
22 m

FABRICATION METHOD:
Cast in approach section. Composed of seven 20-m sections tied together with reinforcing steel. Steel shell exterior.

OUTFITTING:

JOINT TYPE:
Gasketted joint.

WATERPROOFING METHOD:	Steel shell on sides and bottom; membrane over top.
PLACEMENT METHOD:	Hung from pile-supported jacking devices.
FOUNDATION METHOD:	Bottom screeded from special screed system attached to rails on side of element, which planed the bottom before lowering the element to final position.

TUNNEL NAME/ LOCATION/ DATE COMPLETED: **Webster Street Tunnel; Between Oakland and Alameda, California, U.S.A.; 1962**	**File No. 19** 
TUNNEL TYPE AND USE: Vehicular tunnel; cylindrical reinforced concrete elements.	**LANES/TRACKS:** Single tube, two lanes.
NO. OF ELEMENTS: 12	**LENGTH:** 61 m
TOTAL IMMERSED LENGTH: 732 m	**DEPTH AT BOTTOM OF STRUCTURE:**

UNUSUAL FEATURES:	See below.

FABRICATION METHOD: Constructed in a graving dock excavted 2 miles from the project site. Two elements were constructed per cycle. A 70-ton stop-log gate, which could be removed by a floating crane, was used to permit the elements to exit the graving dock.	**OUTFITTING:** During fabrication in graving dock.	**JOINT TYPE:** Tremie concrete joints.

WATERPROOFING METHOD:	Membrane with timber protection.
PLACEMENT METHOD:	Element first brought to 100-ton positive buoyancy with combination of dry ballast spread on roadway and water ballast in tanks under roadway. The 100 tons were offset and a 50-ton negative buoyancy was developed using water sprinkled on the dry ballast. Derricks on each end supported this modest load and lowered the unit in place. Wood chips were used to extend the dry ballast volume.
FOUNDATION METHOD:	Placed on temporary supports with capacity to take section ballasted to 300 tons. Sand placed with tremie pipe bent to direct ballast under element. Additional turbulence at the end of the pipe was produced using a water jet. Each element was bedded into the original deposit of sand by ballasting to more than 600 tons. This weight was sufficient to guarantee failure of the temporary support after a minimum settlement of 10 cm. Actual settlements were only 2.5 cm, assuring that the load was picked up by the bedding. In the channel,13,000 tons of iron ore were used to provide additional ballast because sand ballast alone could not provide the required weight in the available vertical distance.
ADDITIONAL INFORMATION:	OWNER: California Division of Highways. CONTRACTOR: Pomeroy-Bates and Rogers-Gerwick.

TUNNEL NAME/ LOCATION/ DATE COMPLETED: **Elizabeth River Tunnel No. 2; Between Norfolk and Portsmouth, Virginia, U.S.A.; 1962**	**File No. 20**

TUNNEL TYPE AND USE: Vehicular tunnel; double shell steel tunnel.	LANES/TRACKS: Single tube; two lanes, one each way.

NO. OF ELEMENTS: 12

TOTAL IMMERSED LENGTH: 1056 m	DEPTH AT BOTTOM OF STRUCTURE: 30 m

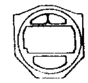
UNUSUAL FEATURES:	Due to very poor soil conditions, Element No. 1 was supported on timber compaction piles.
ENVIRONMENTAL CONDITIONS	Mild currents and tides.

FABRICATION METHOD: Side-launched (uncontrolled) from shipyard in Port Deposit, Maryland, about 300 km away. Keel concrete placed for towing stability.	OUTFITTING: At dock near tunnel site.	JOINT TYPE: Tremie concrete.

WATERPROOFING METHOD:	Continuous steel shell plate.
PLACEMENT METHOD:	Placement with floating cranes.
FOUNDATION METHOD:	Screeded bedding.
DREDGING METHOD:	Clamshell dredging.
VENTILATION TYPE:	Semi-transverse ventilation system.
ADDITIONAL INFORMATION:	OWNER: Elizabeth River Tunnel Commission. DESIGNER: Parsons Brinckerhoff Hall and McDonald. CONTRACTOR: Merritt-Chapman & Scott Corporation.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Chesapeake Bay Bridge Tunnel; between Norfolk and Cape Charles, Virginia, U.S.A.; 1964

File No. 21



TUNNEL TYPE AND USE:
Vehicular; double-shell steel elements.

LANES/TRACKS:
Single tube; two lanes, one each way.

NO. OF ELEMENTS:
Thimble Shoal: 19
Baltimore Chan.: 18

LENGTH:
91.4 m

HEIGHT:
11.3 m

WIDTH:
11.3 m

TOTAL IMMERSED LENGTH:
1750 m

UNUSUAL FEATURES:
Part of the 29-km crossing of Chesapeake Bay. The immersed tunnel consisted of two separate tunnels under the two shipping channels: (1) the Thimble Shoal Channel and (2) the Baltimore Channel. Construction was accomplished in virtually open ocean conditions. Tunnels terminated in manmade islands, similar to those constructed for the first Hampton Roads Tunnel.

ENVIRONMENTAL CONDITIONS
Severe storm exposure. Hurricane destroyed the "Big D" jackleg platform.

FABRICATION METHOD:
Shipyard in Orange, Texas; end-launched. Trimmed with "stern" 4 ft. low for better ocean towing.

OUTFITTING:
At dock near tunnel site.

JOINT TYPE:
Tremie concrete joints.

VENTILATION TYPE:
Fully transverse ventilation system.

COVER AND TYPE:
3 m of selected backfill.

ADDITIONAL INFORMATION:
OWNER: The Chesapeake Bay Bridge and Tunnel Commission.
DESIGNER: Sverdrup & Parcel and Associates.
CONTRACTOR: Joint venture of Tidewater Construction Corp., Merritt-Chapman & Scott, Raymond International Inc., and Peter Kiewit Sons Co.

TUNNEL NAME/LOCATION/ DATE COMPLETED: **Liljeholmsviken; Stockholm, Sweden; 1964**	**File No. 22**

TUNNEL TYPE AND USE: Railroad tunnel; prestressed concrete box element	LANES/TRACKS: Two tracks.

NO. OF ELEMENTS: 1	LENGTH: 124 m	HEIGHT: 6.03 m	WIDTH: 8.82 m

TOTAL IMMERSED LENGTH: 123 m	DEPTH AT BOTTOM OF STRUCTURE: 13 m

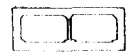
UNUSUAL FEATURES:	This tunnel was constructed in two separate sections, which were post-tensioned together in flotation and placed as a single unit. This unit was designed to act as a continuous structure to span 53 m between two supports in rock. In effect, this was an underwater bridge between two rock slopes. A year after completion, a compressive force of 5000 tons was introduced into a temporary joint between a non-prestressed section constructed in a cofferdam and the abutting immersed tunnel. Jacks were used. This arrangement put the whole tunnel into a longitudinal prestressed condition. No leakage has been reported.
ENVIRONMENTAL CONDITIONS	Crossing between two rock faces underwater.

FABRICATION METHOD: In a drydock.	JOINT TYPE: Constructed in dry cofferdams.

WATERPROOFING METHOD:	Temperature matching between the top and bottom sections of the walls was used to prevent cracking. The lower part of the structure was warmed before casting the upper part to avoid tensile cracking in the walls. Waterproof concrete and the full prestressing in all three axes made the section virtually watertight. No membrane was employed.
PLACEMENT METHOD:	Lowered by heavy lift cranes. Ballasting by partial water fill.
FOUNDATION METHOD:	Lowered onto fixed supports.
DREDGING METHOD:	None required for approaches.
VENTILATION TYPE:	Piston action of trains.
COVER AND TYPE:	Tunnel was not covered.
ADDITIONAL INFORMATION:	The tunnel has been designed to withstand the load of a 1,500 ton ship resting on or completely filling with water.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Haneda Tunnel (Ebitori River Tunnel); Tokyo, Japan; 1964

File No. 23



TUNNEL TYPE AND USE:	LANES/TRACKS:
Vehicular; steel shell rectangular section.	Two tubes; two lanes in each tube.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
1	56.0 m	7.4 m	20.0 m

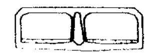
TOTAL IMMERSED LENGTH:	DEPTH AT BOTTOM OF STRUCTURE:
56.0 m	12 m

UNUSUAL FEATURES:	Element is supported on caisson foundations at both ends (i.e., creating a sort of bridge under water). The design provided for composite action between steel shell and concrete structure. See also "Fabrication Method," described below.
ENVIRONMENTAL CONDITIONS	Haneda International Airport is located near the site.

FABRICATION METHOD:	JOINT TYPE:
Steel shell was constructed in shipyard. Concrete for bottom slab was placed in flotation. The sidewalls and roof slab were pumped with concrete after the element was placed.	U-shaped steel plate over rubber joint.

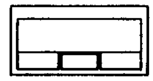
WATERPROOFING METHOD:	Steel skin on sides and bottom. Concrete protected membrane on top of element.
PLACEMENT METHOD:	Three heavy lift cranes were used to control placement.
FOUNDATION METHOD:	Caisson foundations.
VENTILATION TYPE:	Longitudinal ventilation.
ADDITIONAL INFORMATION:	OWNER: Metropolitan Expressway Public Corporation.

TUNNEL NAME/LOCATION/ DATE COMPLETED: Haneda Tunnel (Ebitori River Tunnel); Tokyo, Japan; 1964			File No. 24
TUNNEL TYPE AND USE: Monorail system; single-shell steel box section.		LANES/TRACKS: Single tube; two tracks.	
NO. OF ELEMENTS: 1	LENGTH: 56 m	HEIGHT: 7.4 m	WIDTH: 10.95 m
TOTAL IMMERSED LENGTH: 56 m		DEPTH AT BOTTOM OF STRUCTURE: 11.7 m	
UNUSUAL FEATURES:	Monorail tunnel. The tunnel is supported at both ends on caisson abutments in common with the Haneda vehicular tunnel adjacent to it to it (see File No. 23).		
ENVIRONMENTAL CONDITIONS	Height of crane booms was limited because the tunnel's proximity to Haneda International Airport.		
FABRICATION METHOD: Rectangular steel box section fabricated at the IHI dockyard.		OUTFITTING: After launching, the element was towed to a pier near the tunnel site. The floor slab concrete and protective roof concrete were placed in flotation. The side-wall concrete and ceiling concrete were placed by pumping after the element was immersed.	JOINT TYPE: Rubber gasketted joint.
WATERPROOFING METHOD:	Continuous steel shell.		
PLACEMENT METHOD:	Heavy lift cranes.		
FOUNDATION METHOD:	Element spans between abutments. No special foundation preparation.		
DREDGING METHOD:	Excavation by grab bucket to depth of 11.9 m.		
VENTILATION TYPE:	Piston action of trains.		
COVER AND TYPE:	Backfill with sand and counterweight of slag on top of tunnel.		
ADDITIONAL INFORMATION:	Cathodic protection was applied to steel shell plate. OWNER: Hitachi Transport, Tokyo Monorail Corporation.		

TUNNEL NAME/LOCATION/ DATE COMPLETED: **Coen Tunnel; Amsterdam, Netherlands; 1966**			**File No. 25** 
TUNNEL TYPE AND USE: Vehicular; reinforced concrete box section .		LANES/TRACKS: Two tubes; two lanes in each tube.	
NO. OF ELEMENTS: 6	LENGTH: 90 m	HEIGHT: 7.74 m	WIDTH: 23.33 m
TOTAL IMMERSED LENGTH: 540 m		DEPTH AT BOTTOM OF STRUCTURE:	
FABRICATION METHOD: In a casting basin dredged for the purpose. All six sections were cast in one cycle.		OUTFITTING: Outfitting was done partly at the time of fabrication in the basin and partly at the outfitting jetty in the flooded basin.	JOINT TYPE: Gina-type gasket system.
WATERPROOFING METHOD:	Asphalt bitumen covered with fiberglass was used to provide a waterproof covering about 1 cm thick. This material was in turn covered with concrete, which was attached to the main concrete box using ramset studs, each with special waterproof steel collars.		
PLACEMENT METHOD:	Four pontoons were used to lower the sections. Towers for survey control and for operations control and access were provided (one tower at each end of the elements).		
FOUNDATION METHOD:	Placed on four screeded piles of gravel and adjusted to grade, using jacks. Sand was later jetted under the elements.		
DREDGING METHOD:	Hydraulic dredge.		
VENTILATION TYPE:	Semi-transverse system.		
ADDITIONAL INFORMATION:	OWNER: Rijkswaterstaat, Directie Sluizen & Stuwen. DESIGNER: By the owner, with Christiani & Nielsen as consultants.		

TUNNEL NAME/LOCATION/ DATE COMPLETED:
Wolfburg Pedestrian Tunnels; Wolfburg, Germany—two tunnels under Mittelland Canal, opposite the VW plant; 1966

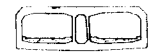
File No. 26



TUNNEL TYPE AND USE: Pedestrian; reinforced concrete box elements.		LANES/TRACKS: Footways.	
NO. OF ELEMENTS: 1 for each tunnel	TOTAL LENGTH: 58.0 m	HEIGHT: 5.10 m	WIDTH: 11.0 m (12.52 m at the ventilation shafts)
DEPTH AT BOTTOM OF STRUCTURE: 10 m below mean water level.			
UNUSUAL FEATURES:	Because of the narrow shipping canal and the high groundwater level in the adjacent excavations, the ends of the floating elements had to be provided with an upwards bend to allow for connections to the landside tunnels.		
ENVIRONMENTAL CONDITIONS	Virtually no current.		
FABRICATION METHOD: Cast in approach excavation.		OUTFITTING: In casting basin during fabrication.	JOINT TYPE: Construction in the dry. Joint made watertight with bitumen seal coat.
WATERPROOFING METHOD:	All around, multiple-layer bitumen seal protected by pearl gravel. Roof slab membrane protected with reinforced concrete slab.		
PLACEMENT METHOD:	Floating and lowering using block and tackle from transverse steel girders supported on the outboard ends of the support of excavation for the approach tunnels.		
FOUNDATION METHOD:	Bottom screeded by a plow (girder) attached to steel girders, which ran on slide rails set to grade.		
DREDGING METHOD:	Clamshell and hydraulic dredges.		
VENTILATION TYPE:	Natural ventilation. Fresh air supply at entrances and exhaust at ventilation shafts also was provided for.		
COVER AND TYPE:	Sandfill.		
ADDITIONAL INFORMATION:	OWNER: Volkswagen AG, Wolfsburg. OPERATOR: Volkswagen AG, Wolfsburg. DESIGNER: Philipp Holzmann AG, Frankfurt. CONTRACTOR: Philipp Holzmann AG, Frankfurt.		

TUNNEL NAME/LOCATION/ DATE COMPLETED:
Benelux; Rotterdam, The Netherlands; 1967

File No. 27



TUNNEL TYPE AND USE:
Vehicular tunnel; reinforced concrete box sections.

LANES/TRACKS:
Two tubes; two lanes of traffic in each tube..

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
8	93 m	7.84 m	23.9 m

TOTAL IMMERSED LENGTH:
745 m

DEPTH AT BOTTOM OF STRUCTURE:
24 m

UNUSUAL FEATURES:
Tunnel is completely curved, with all tubes cast as identical curved sections.

ENVIRONMENTAL CONDITIONS
Swift river currents created problems in dredging the soft sediments.

FABRICATION METHOD:
At casting basin constructed for the tunnel. All eight sections were cast at the same time.

OUTFITTING:
Part of fabrication operation in casting basin.

JOINT TYPE:
Pulled together using a hook, the Gina-type gasket was engaged; conventional dewatering followed to make up the joint.

WATERPROOFING METHOD:
Bituminous membrane, protected by reinforced concrete.

PLACEMENT METHOD:
Used four pontoons for lowering. A tower for survey was provided at the outboard end of the tube; a tower for access and control was provided on the inboard end.

FOUNDATION METHOD:
Used foundation plates supported on layer of gravel for temporary grade adjustment. Sand was then jetted using tunnel elements, after acceptable conditions were obtained. Silt skirts were used to protect the area under the elements from being filled with soft silt scour off the bottom of the river.

VENTILATION TYPE:
Longitudinal, using jet fans.

ADDITIONAL INFORMATION:
OWNER: Amsterdam Public Works Department.
DESIGNER: Locks and Weirs Department of the APWD.
CONTRACTOR: N.V. Amsterdamsche Ballast Mij; Christiani & Nielsen N.V.; Internationale Gewapendbeton-Bouw N.S.; Nederlandsche Aanneming Mij, v/h firma H.F. Boersma and N.V. Nederlandsche Beton Maatschappij.

TUNNEL NAME /LOCATION/ DATE COMPLETED: **Lafontaine Tunnel; Montreal, Canada; 1967**			**File No. 28** 
TUNNEL TYPE AND USE: Vehicular tunnel; prestressed concrete box section.		LANES/TRACKS: Two tubes; three lanes in each tube.	
NO. OF ELEMENTS: 7	LENGTH: 109.7 m	HEIGHT: 7.84 m	WIDTH: 36.75 m
TOTAL IMMERSED LENGTH: 768 m		DEPTH AT BOTTOM OF STRUCTURE: 27.5 m	
UNUSUAL FEATURES:	Because of difficulty in applying high prestressing forces after the element was placed, combined with the fact that the same forces could not be applied before placing, temporary vertical midspan prestressing was applied to prevent upward buckling of the roof slab. This permitted the transverse prestressing to be fully applied prior to placement.		
FABRICATION METHOD: In casting basin constructed in conjunction with approach area. Capacity for four elements at a time.		OUTFITTING: As part of fabrication in casting basin.	JOINT TYPE: Gina-type rubber gasketted joint.
WATERPROOFING METHOD:	Bituminous membrane on walls and roof. Steel membrane on bottom.		
PLACEMENT METHOD:	Catamaran barges. Lowering using linear winches. Temporarily supported on four piles.		
FOUNDATION METHOD:	Sand-jetted foundation.		
COVER AND TYPE:	Backfill with minimum thickness of approximately 2 m.		
ADDITIONAL INFORMATION:	OWNER: Department of Highways, Province of Quebec, Canada. DESIGNERS: Brett & Ouellette, Lalonde & Valois and Per Hall & Associates. Christiani & Nielsen designed the sand-jetting operation.		

TUNNEL NAME/ LOCATION/ DATE COMPLETED: **Vieux-Port Tunnel; Marseilles, France; 1967**	**File No. 29** 
TUNNEL TYPE AND USE: Vehicular tunnel; two side-by-side concrete box sections.	LANES/TRACKS: Two single tube sections, each with two lanes.
TOTAL LENGTH: 273 m	

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Tingstad Tunnel; Gothenburg, Sweden; 1968

File No. 30

TUNNEL TYPE AND USE:
Vehicular tunnel; concrete box tunnel.

LANES/TRACKS:
Two tubes; three lanes each way.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
5	4 elements—93.5 m; 1 element—80 m	7.3 m	30 m

TOTAL IMMERSED LENGTH:
455 m

DEPTH AT BOTTOM OF STRUCTURE:
16 m

ENVIRONMENTAL CONDITIONS: Siltation of bottom during placement of elements.

FABRICATION METHOD:
In a drydock, one at a time. Partial roof was constructed to be finished later in flotation.

OUTFITTING:
Completion of roof of elements was done in floating condition at dockside.

JOINT TYPE: Gasketed joints. Vertical joints are spaced at intervals of approximately 15 m.

WATERPROOFING METHOD: 6-mm steel membrane all around. Roof and slanting parts coated with 10 cm of concrete; remainder protected by anti-corrosive paint. Cathodic protection is also provided.

FOUNDATION METHOD: Elements were placed on large nylon sacks that could be pumped full of grout. These sacks formed the adjustment between the element and piled foundations along the element. After the bottom of the trench was levelled with gravel, timber piles approximately 22-m long were driven into the clay, which is 80–100 m deep. The space under the elements at the pile groups had to be protected against the incursion of mud. After the sacks had been grouted first, to assure good contact, the other areas were also grouted.

VENTILATION TYPE: Semi-transverse ventilation, with ventilation building at each end of the tunnel.

BUOYANCY SF: 1.1

CONCRETE CUBE STRESS: 35 MN/sq. m

COVER AND TYPE: Protection stone layer 0.5 m thick was placed over the tunnel.

ADDITIONAL INFORMATION:
No damage to the concrete has been observed. The lower parts of the walls are covered by tiles because the tunnel was opened. No unexpected settlements have occurred. Maximum settlements,most of it occurring early, ranged between 40 mm and 50 mm. Minor cracks occurred in the wall and roof. Cathodic protection has been renewed once. Settlements directly after immersion were approximately 10 mm. After backfilling, the settlements increased to 20 mm. Backfill surcharge was approximately 50 kN/sq. m. The differences in settlements were caused by variation in ground conditions and depth of surcharge. Areas of the facilities that were not pile-supported have settled more than 0.5 m.

OWNER: Swedish National Road Administration.
DESIGNER: Skanska.
CONTRACTOR: Skanska.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Rotterdam Metro Tunnels; Rotterdam, The Netherlands; 1968

File No. 31

TUNNEL TYPE AND USE:
Metro rail system; reinforced concrete sections.

LANES/TRACKS:
Two tubes; one track in each tube.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
36	90 m	6.0 m	10.0 m

TOTAL IMMERSED LENGTH:
1040 m under the Nieuwe Maas and 1,815 m between Central Station and Leuvehaven.

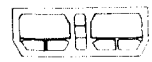
UNUSUAL FEATURES:	Because of high ground water and favorable alignment conditions, 24 elements were floated in along the land portion of the Metro system. This included partial station sections as well. Inflatable adjustable pile caps were used to support the tunnel elements.
ENVIRONMENTAL CONDITIONS:	Construction in high ground water table. Construction through densely populated urban area.

FABRICATION METHOD:	OUTFITTING:	JOINT TYPE:
Made of 15-m sections temporarily post-tensioned together into 90-m elements, in a casting basin excavated near the site.	Part of fabrication operation.	Gina rubber joints.

WATERPROOFING METHOD:	Bituminized felt-covered glass covered with fiberglass fabric. Top and bottom portions were protected with concrete attached with dowels.
PLACEMENT METHOD:	Catamaran barges were used for the water crossing. Monorails and hoists were suspended from the upper bracing for the elements placed inside the trenches on land. Water ballast tanks were used for both areas to lower the elements.
FOUNDATION METHOD:	Pile foundations were used. Adjustable pile caps inflated with grout were used to support the elements.
VENTILATION TYPE:	Piston action of trains.
ADDITIONAL INFORMATION:	OWNER: Municipality of Rotterdam. DESIGNER: The client, Christiani & Nilsen and Hollandsche Beton. CONTRACTORS: Christiani & Nielsen N.V. and Hollandsche Beton Maatschappi; sinking was done by the client's organization.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Ij Tunnel; Amsterdam, The Netherlands; 1969

File No. 32



TUNNEL TYPE AND USE:
Vehicular tunnel; reinforced concrete box section.

LANES/TRACKS:
Two tubes; two lanes in each tube.

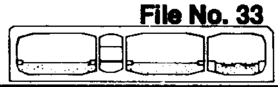
NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
9	90 m	8.55 m	23.9 m

TOTAL IMMERSED LENGTH: 790 m

UNUSUAL FEATURES:	Two sections on precast piles were made in open excavation between sheet pile walls; one section was made by means of four pneumatic caissons. Each of the immersed sections was subdivided by two temporary joints and was supported on four pile caps constructed in the dry at the bottom of the river under a pressurized air chamber.

FABRICATION METHOD:	OUTFITTING:	JOINT TYPE:
In groups of two in a casting basin.	Part of fabrication operation in the casting basin.	Gina-type gasket.

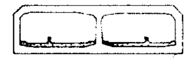
PLACEMENT METHOD:	Tunnel elements were pulled downward onto the two central pile caps, using multipart lines. Water ballast was added to provide a negative buoyancy of 200 tons. The cables were disconnected and jacking devices were installed by divers to pull the element in and make initial gasket contact. The water pressure in the joint space was then released to compress the gasket. The end sections were closed using exterior plates with rubber gaskets, which permitted the joint concrete to be formed in a dry environment.
FOUNDATION METHOD:	Elements were placed on cast-in-place pile caps described above.
VENTILATION TYPE:	Fully transverse, with air supply and exhaust ducts under roadway. Fresh air enters on the right side and crosses to the left side, exiting through large louvres.

TUNNEL NAME /LOCATION/ DATE COMPLETED: **Scheldt E3 (J.F.K. Tunnel); Antwerp, Belgium; 1969**	**File No. 33** 

TUNNEL TYPE AND USE: Vehicular and railroad; prestressed concrete box elements.		LANES/TRACKS: Two roadway tubes with three lanes in each tube; one railroad tube with two tracks.	
NO. OF ELEMENTS: 5	LENGTH: Four elements @ 99 m One element @ 115 m	HEIGHT: 10.1 m	WIDTH: 47.85 M
TOTAL IMMERSED LENGTH: 510 m		DEPTH AT BOTTOM OF STRUCTURE: 25 m	
UNUSUAL FEATURES:	Extremely wide tunnel with combined rail and road usage. The project used the largest tunnel elements ever constructed (47,000 tons) at the time. A quay wall, which was replaced over and supported on the tunnel, was constructed as hollow concrete caissons.		
ENVIRONMENTAL CONDITIONS:	River currents of up to 3.0 m/s. Tides with a mean range of 4.8 m and a maximum range of 8.86 m.		
FABRICATION METHOD: All five elements were cast in one cycle in a casting basin near the tunnel site.		JOINT TYPE: Gina joint.	
WATERPROOFING METHOD:	5-mm-thick steel sheet on bottom painted with tar epoxy. Joints between the single sheet were sealed with bituminous strips. Walls and roofs were provided with a three-ply membrane. On the walls, membrane was protected by timber sheeting supported on steel beams fixed to the concrete. The 3-cm space between the timber and the membrane was filled with mortar. Roof protection consisted of a 10-cm-thick reinforced concrete slab. Bulkheads were constructed of 14-mm-thick steel plate supported on horizontal and vertical beams (to save weight). The joints between the sheets were covered with bitumen mastic and the whole bulkhead was covered with a 2-mm butyl membrane.		
PLACEMENT METHOD:	Ten tugs (12,000 HP) were required to place the first element. Barges transverse to the element were used with control and survey towers in customary fashion.		
FOUNDATION METHOD:	Because of high water velocities, siltation was a serious problem. Skirts around the bottom of the elements were tried, but silt penetrated beneath them. A special patented sand jetting system, devised by Christiani & Nielsen, removed the silt and replaced it with sand.		
DREDGING METHOD:	River sediments, mainly loamy sand, were removed by cutterhead suction dredges. Stiff clay was removed by a chain bucket dredge which could dredge to 30 m. Because of current velocities at midstream, the dredge had to excavate the upstream slope and the downstream slope alternately. In addition, the trench was dredged wide enough to accommodate the elements moored in the direction of the current (floating in the event of an emergency).		
VENTILATION:	Semi-transverse system with fresh air supply.		
COVER AND TYPE:	No cover over elements, other than 10 cm concrete.		
CONCRETE CUBE STRESS: 450 kg/sq. cm		POST-TENSIONING: Partial: 235-ton tendons at 0.5 m.	
ADDITIONAL INFORMATION:	OWNER: Intercommunale E3. DESIGNER/CONTRACTORS: Enterprises Ackermans & van Haaren, Compagnie d'Entreprises C.F.E., Compagnie International des Pieux Armes Frankignol and Société Belge des Betons and Christiani & Nielsen.		

TUNNEL NAME /LOCATION/ DATE COMPLETED:
Heinenoord Tunnel; Barendrecht, The Netherlands; 1969

File No. 34



TUNNEL TYPE AND USE:
Vehicular tunnel; reinforced concrete box elements.

LANES/TRACKS:
Two tubes, three lanes each.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
5	115 m	8.8 m	30.7 m

TOTAL IMMERSED LENGTH:
574 m

DEPTH AT BOTTOM OF STRUCTURE:
28 m

UNUSUAL FEATURES:
The third lane in each direction is provided for slow-moving traffic such as cyclists, tractors, and mopeds. Elevators at both ends of the tunnel permit cyclists and pedestrians to avoid the long, steep grades. Placement of elements used a three-point bearing method, two outboard foundation blocks, and a single point at the tunnel in place.

FABRICATION METHOD:
All five elements were fabricated in one cycle in a casting basin.

JOINT TYPE:
Gina joint.

WATERPROOFING METHOD:
Bottom covered with 6-mm steel plate. Walls and roof waterproofed with three layers of asphalt-impregnated membrane. Roof protected with 15 cm of reinforced concrete.

PLACEMENT METHOD:
Two pontoons were arranged transversely over the element at each end with control and survey towers in conventional fashion. Elements were placed on plates; vertical jacks were used for vertical alignment adjustments.

FOUNDATION METHOD:
Three-point temporary foundation with pivot arrangement to allow good register between the tunnel and the element being placed. Jetted sand used for foundation.

VENTILATION TYPE:
Longitudinal, using jet fans.

ADDITIONAL INFORMATION:
OWNER: Rijkswaterstaad, Direktie Sluizen & Stuwen.
DESIGNER: by the client.
CONTRACTORS: Christiani & Nielsen N.V. in joint venture with six other Dutch contractors known as the Nestum II Group.

TUNNEL NAME/LOCATION/ DATE COMPLETED:
Limfjord Tunnel; Arlborg, Denmark; 1969

File No. 35

TUNNEL TYPE AND USE: Vehicular; reinforced concrete box section.	LANES/TRACKS: Two tubes, each with three lanes.

NO. OF ELEMENTS: 5	LENGTH: 102 m	HEIGHT: 8.54 m	WIDTH: 27.4 m

TOTAL IMMERSED LENGTH: 510 m	DEPTH AT BOTTOM OF STRUCTURE: 20.81 m

UNUSUAL FEATURES:	Surcharged sandfill was used to support immersed tunnel. Tension piles were used to support and hold down open approach and cut-and-cover sections of tunnel.

FABRICATION METHOD: Cast in a casting basin excavated for the purpose, about 10 km from the tunnel site. Elements were cast in 12.8-m- long sections—first the bottom; then the walls; and, last, the roof. The sections were separated by a 1.8-m-gap into which rebar protruded. These gaps were filled after concrete shrinkage had taken place.	OUTFITTING: Elements were outfitted at a pier after floating with temporary steel foundation blocks at the free end, two alignment towers and two sets of sinking rigs, each consisting of two 150-ton pontoons connected by steel girders.	JOINT TYPE: Gina type. Special gasketted end closure plates allowed connection to submerged face of cast-in-place tunnel sections. Sequence of element placement was from one shore to the other. Immersed tunnel is monolithic, with a contraction joint between it and the cast-in-place tunnel and a combined expansion-contraction joint between it and the north portal building. The joints are made watertight with rubber gaskets.

WATERPROOFING METHOD:	The elements are waterproofed with a 2-mm butyl membrane, protected on the bottom by a 9-cm-thick layer of reinforced concrete and on the top by a 20-cm-thick layer of reinforced concrete, and glued to the bottom protection and to the walls and roof of the tunnel by a PVC cement slurry.
PLACEMENT METHOD:	Four straddling placement barges were used. Horizontal alignment was accomplished by lines connected at the top of the element.
FOUNDATION METHOD:	Sand-jetting.
DREDGING METHOD:	Dredging was taken down to -31 m and backfilled to grade with clean sand because of soft mud layers in the riverbed. The sand was surcharged with additional sand to a load equal to the tunnel weight to cause early settlement to take place. The sand was removed shortly before placing the elements.
VENTILATION TYPE:	Longitudinally; jet fans.
COVER AND TYPE:	No cover provided. 20 cm of reinforced concrete is the only protection to the waterproofing layer.
ADDITIONAL INFORMATION:	The tunnel is designed to be unmanned, with automatic ventilation and lighting controls, and automatic and remote control used for traffic control. Aluminum sunscreens are used at the approaches. An acoustic suspended ceiling is provided. OWNER: Ministry of Public Works. DESIGNER: Christiani & Nielsen A/S. CONTRACTOR: Various Danish contractors. The tunnel sections by NYBYG and Christiani & Nielsen carried out the installation of the elements, including sand-jetting.

TUNNEL NAME/ LOCATION/ DATE COMPLETED: **Parana (Hernandias) Tunnel; between Santa Fe and Parana, Argentina; 1969**			**File No. 36**
TUNNEL TYPE AND USE: Vehicular; circular reinforced concrete tube.		LANES/TRACKS: Single tube; two lanes .	
NO. OF ELEMENTS: 36	LENGTH: 65.5 m	WIDTH: 10.8 m (one 10.75 m element was used on the Parana side, to make 37).	
TOTAL IMMERSED LENGTH: 2,367 m		DEPTH AT BOTTOM OF STRUCTURE: 32 m	
UNUSUAL FEATURES:	Light elements, filled with water to induce final settlement, were held down with six outrigger pockets each. Backfill was vibrocompacted around the element. A jack-up barge was used for element and locking fill placement. Partial ballasting was accomplished by filling between light end bulkheads and interior bulkheads (the latter capable of taking submerged water pressure), spaced at 13-m intervals. The exterior bulkheads could be detached and floated to the dock for reuse.		
ENVIRONMENTAL CONDITIONS:	Design current: 1.35 m/s (2.63 knots).		
FABRICATION METHOD: A casting basin, designed for nine cycles, was excavated. Four elements were produced on a three-month cycle. The basin was 156 m long, 46 m wide, and 13 m high. The dock was closed by a 15-m-high, 23-m-dia. floating cylindrical caisson acting against two fixed cylindrical tanks with 50 cm wall thickness.		JOINT TYPE: A tremie concrete joint using inflatable gaskets was used for all elements. A bottom slab was used to form the tremie. Concrete hoods and collars were used.	
WATERPROOFING METHOD:	4-mm preformed three-layer glass-fiber-reinforced polyester resin waterproofing all around the cylinder. No protection was used.		
PLACEMENT METHOD:	Model tests were done. The element was first brought to the site parallel to the current to the centerline of the tunnel, using six 465-HP pusher rigs mounted on flexifloats. Two other similar units were used to guide the element parallel to the current. At the jack-up rig, the element was turned transverse to the current using winches mounted on pontoons. A trolley running under the platform of the jack-up rig moved the element to its final position. It was then handled by four vertical and horizontal winches of the jack-up rig. Two ballast chambers under the roadway on both sides of the interior bulkheads were filled with water to produce 150 tons of negative buoyancy.		
FOUNDATION METHOD:	Sand fill was compacted around each element, using deep compactors.		
DREDGING METHOD:	A cutterhead suction dredge was used to dredge the trench and place backfill.		
VENTILATION TYPE:	Fully transverse.		
COVER AND TYPE:	4.0 m of compacted sand fill.		
ADDITIONAL INFORMATION:	OWNER: Argentine government. DESIGNER/CONTRACTORS: Consortium of Hochtief AG, Vianini SpA and Sailav SA..		

TUNNEL NAME /LOCATION/ DATE COMPLETED:
Dojima River Tunnel (Osaka Subway Tunnel); Osaka, Japan; 1969

File No. 37

TUNNEL TYPE AND USE:
Railway; reinforced concrete box section.

LANES/TRACKS:
Two tubes, one track each.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
2	36/34.5 m	7.78 m	10.43 m–11.04 m

TOTAL IMMERSED LENGTH:
70.5 m

DEPTH AT BOTTOM OF STRUCTURE:
14.3 m

UNUSUAL FEATURES:
Constructed in very tight quarters. Tunnel crossing is askew the Dojima River. Two elements were immersed between caissons at both banks. Immersed elements were fabricated inside the excavation for cut-and-cover approach tunnels.

ENVIRONMENTAL CONDITIONS:
Tidal river.

FABRICATION METHOD:
Reinforced concrete elements were fabricated one by one in a coffered dock provided near two Nakanoshima caissons, which later became part of the tunnel. The elements were enclosed in 6-m-thick steel plate. These were prefabricated in six sections and welded together inside the cofferdam.

JOINT TYPE:
Single çatilever gasket in combination with heavy Omega gasket. Space between gaskets was filled with tremie concrete.

WATERPROOFING METHOD:
6-mm steel shell all-around element.

PLACEMENT METHOD:
Catamaran barges. Water ballast was used for each element.

FOUNDATION METHOD:
Screed rails were installed at grade, attached to steel piles. Spreader box was fed by four hopper pipes. Spreader system was supported on floats and guided by lines from placement barges. Crushed stone 20 mm to 40 mm in size was placed to form a foundation course, approximately 0.60 m thick, which was grouted after the elements were in place.

DREDGING METHOD:
Grab bucket.

VENTILATION TYPE:
Piston effect of trains.

COVER AND TYPE:
3.47 m of backfill, including a layer of concrete protection 0.50 m thick on the top.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Dohtonbori River Tunnel; Osaka, Japan; 1969

File No. 38

TUNNEL TYPE AND USE:
Railway; single-shell steel box.

LANES/TRACKS:
Two tubes; one track each.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
1	24.9 m	6.96 m	9.65 m

TOTAL IMMERSED LENGTH:
25 m

DEPTH AT BOTTOM OF STRUCTURE:
10 m

FABRICATION METHOD:
A temporary working platform was constructed at the site and the steel shell element was fabricated on this platform.

JOINT TYPE:
One end is a rigid joint; the other is an expansion joint.

WATERPROOFING METHOD:	Continuous steel shell treated with a cathodic protection system.
PLACEMENT METHOD:	A portal crane was used for placement.
FOUNDATION METHOD:	The steel shell element was supported at both ends by caissons in the manner of a submerged bridge.
VENTILATION TYPE:	Piston action of trains.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Haneda Tunnel (Under Tama River); Tokyo, Japan; 1970

File No. 39

TUNNEL TYPE AND USE:	LANES/TRACKS:
Railway; single-shell steel binocular section.	Two tubes, one trach each.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
6	80 m	7.95 m	13.0 m

TOTAL IMMERSED LENGTH:	DEPTH AT BOTTOM OF STRUCTURE:
480 m	17 m below datum.

UNUSUAL FEATURES:	Heavy binocular steel-shell section for railway tunnels was largely determined by earthquake forces. Immersed elements tie into pneumatic caissons at both ends. Three pickup points were used for placing. Ventilation tower was constructed by pneumatic caisson method. Last element was specially designed to transition to bored tunnels.
ENVIRONMENTAL CONDITIONS:	Height of crane booms limited by adjacent Haneda International Airport.

FABRICATION METHOD:	OUTFITTING:	JOINT TYPE:
Steel shell fabricated at shipyard.	At dock in back of trench excavation.	Rubber gaskets similar to system used in the U.S., except that joint connection sealing area provided outside of main tunnel structural section to permit rigid joint.

WATERPROOFING METHOD:	Continuous steel shell provided with cathodic protection.
PLACEMENT METHOD:	Placed from catamaran barges.
FOUNDATION METHOD:	70 cm of 20- to 40-mm crushed stone was placed and screeded. Bell hole was filled with tremie concrete. Screed used mechanical spreading device and screed box. Five vertical riser pipes equipped with hoppers fed material to screed box. Spreader ran on rails installed underwater, supported on piles.
DREDGING METHOD:	Cutterhead suction dredge.
VENTILATION TYPE:	Piston effect of trains.
COVER AND TYPE:	3 m of protection using riprapped slopes of crushed stone and sand backfill.
ADDITIONAL INFORMATION:	Special pressure tests were made on the cantilever gasket.

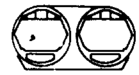
TUNNEL NAME/ LOCATION/ DATE COMPLETED: **Haneda Tunnel (Under Keihin Channel); Tokyo, Japan; 1970**			**File No. 40**
TUNNEL TYPE AND USE: Railway; single-shell steel binocular section.		LANES/TRACKS: Two tubes, one track each.	
NO. OF ELEMENTS: 4	LENGTH: 82.0 m	HEIGHT: 7.97 m	WIDTH: 12.74 m
TOTAL IMMERSED LENGTH: 328 m		DEPTH AT BOTTOM OF STRUCTURE: 17.70 m	
UNUSUAL FEATURES:	Heavy binocular steel section for railway tunnels. Design of cross-section largely determined by earthquake forces. Immersed tunnel elements tie into pneumatic caissons at both ends of tunnel.		
ENVIRONMENTAL CONDITIONS:	The height of crane booms was limited by the proximity to Haneda International Airport.		
FABRICATION METHOD: Steel shell fabricated at shipyard.		OUTFITTING: At dock near site.	JOINT TYPE: Double rubber gaskets. Joint connection sealing area is provided outside of main tunnel structural section, permitting rigid connection.
WATERPROOFING METHOD:	Continuous steel shell provided with cathodic protection system.		
PLACEMENT METHOD:	Placed from catamaran barges.		
FOUNDATION METHOD:	70 cm of 20 mm–40 mm crushed stone was placed and screeded using screed box and mechanical screeding device. Five vertical riser pipes equipped with hoppers fed material to the screed box. This spreader ran on rails installed under water and supported on piles.		
DREDGING METHOD:	Cutterhead suction dredge.		
VENTILATION TYPE:	Piston action of trains.		
COVER AND TYPE:	3 m of protection using riprapped slopes of crushed stone and sand backfill.		

TUNNEL NAME/ LOCATION/ DATE COMPLETED: Bay Area Rapid Transit Tunnel; San Francisco, California, U.S.A.; 1970			File No. 41
TUNNEL TYPE AND USE: Railway; single shell steel binocular section		LANES/TRACKS: Two tubes, one track each	
NO. OF ELEMENTS: 58	LENGTH: 111 m	HEIGHT: 6.5 m	WIDTH: 14.6 m
TOTAL IMMERSED LENGTH: 5,825 m		DEPTH AT BOTTOM OF STRUCTURE: 40.5 m	
UNUSUAL FEATURES:	Longest immersed tube tunnel. Triaxial earthquake joints. Ventilation building constructed as caisson. Connections to shield-driven soft ground tunnels.		
ENVIRONMENTAL CONDITIONS:	Constructed across.		
FABRICATION METHOD: On shipways and end-launched.		OUTFITTING: At dockside near project site.	JOINT TYPE: Double rubber-gasketted joints with steel closure plates. Special triaxial earthquake joints.
WATERPROOFING METHOD:	Continuous steel shell; cathodic protection.		
PLACEMENT METHOD:	Catamaran barges straddling elements.		
FOUNDATION METHOD:	Screeded foundation. Sand fed into screed box.		
DREDGING METHOD:	Cutterhead suction (shallow); 13 CY clamshell (deep).		
VENTILATION TYPE:	Piston action of trains; exhaust system for smoke during fire emergency using central duct.		
COVER AND TYPE:	0.6 m fill plus 1.6-m stone blanket.		
ADDITIONAL INFORMATION:	OWNER: Bay Area Rapid Transit System. DESIGNER: Joint venture: Parsons-Brinckerhoff-Tudor-Bechtel. CONTRACTOR: Trans-Bay Constructors and joint venture of Peter Kiewit & Sons Co., Raymond International Tidewater Construction Co., and Healy Tibbets Construction Co.		

TUNNEL NAME AND LOCATION/ DATE COMPLETED: **Charles River Tunnel; Boston, Massachusetts, U.S.A.; 1971**			**File No. 42** 
TUNNEL TYPE AND USE: Railway; double-shell steel binocular section		LANES/TRACKS: Two tubes; one track each.	
NO. OF ELEMENTS: 2	LENGTH: 73 m	HEIGHT: 6.86 m	WIDTH: 11.4 m
TOTAL IMMERSED LENGTH: 146 m		DEPTH AT BOTTOM OF STRUCTURE: 12.3 m below MLW	
UNUSUAL FEATURES:	Selected as option to cofferdam method of crossing river. Transition sections in 29-m-dia. compression ring cofferdam shafts.		
FABRICATION METHOD: Shipyard. Side launched.		OUTFITTING: At dockside near tunnel site.	JOINT TYPE: Tremie joint.
WATERPROOFING METHOD:	Continuous steel shell.		
PLACEMENT METHOD:	Lowered from pile-supported structures.		
FOUNDATION METHOD:	Screeded foundation course.		
VENTILATION TYPE:	Piston action of trains.		
ADDITIONAL INFORMATION:	OWNER: Massachusetts Bay Rapid Transit Authority. DESIGNER: Praeger Kavanagh and Waterbury. CONTRACTOR: Steel shells by Wiley Manufacturing.		

TUNNEL NAME AND LOCATION/ DATE COMPLETED:
Cross Harbour Tunnel; Hong Kong Harbour; 1972

File No. 43



TUNNEL TYPE AND USE: Vehicular; single-shell steel binocular sections

LANES/TRACKS: Two tubes; two lanes each way

NO. OF ELEMENTS: 15

LENGTH: 114 m

HEIGHT: 11 m

WIDTH: 22.16 m

TOTAL IMMERSED LENGTH: 1,600 m

DEPTH AT BOTTOM OF STRUCTURE: 28 m

UNUSUAL FEATURES:	Ballast concrete in midsection between tubes. No side ballast pockets. Steel shell protected with concrete covering. Fast-track design in New York; rolling plate in England and fabrication of elements in Hong Kong. Ventilation building was held down using 100-ton rock anchors to develop a 1.25 safety factor against buoyancy.
ENVIRONMENTAL CONDITIONS:	Potential for typhoon conditions dictated heavy cover protection. Possibility of out-of-control ships dragging anchor over tunnel or even sinking. Provision made for 1000 PSF allowed for this loading of sunken ship.

FABRICATION METHOD: Shipyard in Hong Kong. Plates curved by rolls were fabricated into cans measuring 10.36-m dia. by 3.5 m long. Five cans were placed on a manipulator to allow them to be welded together automatically. The cans were, in turn, welded together to form each element. Controlled side-launch was used.

OUTFITTING: At dock near the tunnel site.

JOINT TYPE: Tremie concrete joints.

WATERPROOFING METHOD:	Continuous steel shell protected with concrete coating.
PLACEMENT METHOD:	Catamaran straddling barges.
FOUNDATION METHOD:	Screeded bedding.
VENTILATION TYPE:	Semi-transverse exhaust at portals.
COVER AND TYPE:	1.0 m stone cover over 1.3 m crushed stone filter layer.
ADDITIONAL INFORMATION:	OWNER: Hong Kong Cross-Harbour Tunnel Co. DESIGNER: Parsons Brinckerhoff Quade & Douglas, Inc. CONTRACTOR: Consortium headed by Constain International Ltd.; other members were Raymond International, Inc. and Paul Y. Construction Co. Ltd.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
63rd Street Tunnel; New York City, New York, U.S.A.; 1973

File No. 44

TUNNEL TYPE AND USE:
Railway and subway; single-shell steel elements.

LANES/TRACKS:
Two NYC transit tracks over two Long Island Railraod tracks. Four tubes; one track in each.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
4	114.3 m	11.2 m	11.7 m

TOTAL IMMERSED LENGTH:
Two tunnels, each 229 m long.

DEPTH AT BOTTOM OF STRUCTURE:
30 m

UNUSUAL FEATURES:
Only two-over-two tunnel ever constructed. Actually two separate tunnels: one section between New York City and Welfare Island, and the other between Welfare Island and Brooklyn. The ends of each tunnel section were tremied into slots blasted into the rock shores. Once in place, the four ends of the two tunnels were accessed by mining to them. Tunnel was constructed in very strong current conditions.

ENVIRONMENTAL CONDITIONS:
Very swift current of 2.7 m/s (5.2 knots).

FABRICATION METHOD: Riverside shipyard at Port Deposit, Maryland; uncontrolled side-launch.

OUTFITTING: At dockside in Norfolk, Virginia, and towed to New York with full draft.

JOINT TYPE: Tremie concrete joints.

WATERPROOFING METHOD:
Continuous steel shell; cathodic protection.

PLACEMENT METHOD:
Placed from straddling catamaran barges.

FOUNDATION METHOD:
Screeded foundation consisting of large (15 cm) stone was used due to high current velocities in the East River.

DREDGING METHOD:
Barge-mounted excavators.

VENTILATION TYPE:
Train piston action.

COVER AND TYPE:
1.3 m riprap over .9 m of crushed stone.

ADDITIONAL INFORMATION:
OWNER: Metropolitan Transportation Authority and the New York City Transit Authority.
DESIGNER: Parsons Brinckerhoff Quade & Douglas, Inc.
CONTRACTOR: Joint Venture: Kiewit-Slattery-Morrison Knudsen.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Interstate Route 10 (Mobile) Tunnel; Mobile, Alabama, U.S.A.; 1973

File No. 45

TUNNEL TYPE AND USE:
Vehicular; double steel shell binocular elements.

LANES/TRACKS:
Two tubes; two lanes each.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
7	106 m	12.2 m	24.5 m

TOTAL IMMERSED LENGTH:
747 m

DEPTH AT BOTTOM OF STRUCTURE:
30 m

UNUSUAL FEATURES: Portal ventilation buildings equipped with steel joint transition structures to which elements are attached. First project in U.S.A. to use modern sand-jetting method for foundation.

FABRICATION METHOD: Fabrication yard set up on site. Uncontrolled side launch.

OUTFITTING: At pier near site.

JOINT TYPE: Tremie concrete joints.

WATERPROOFING METHOD: Continuous steel shell plate.

PLACEMENT METHOD: Four barges straddling the element. Element placed on temporary footings and adjusted to line and grade.

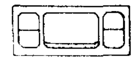
FOUNDATION METHOD: Jetted sand foundation.

VENTILATION TYPE: Semi-transverse ventilation. Air supplied through lower air duct travels longitudinally to portal ventilation buildings.

ADDITIONAL INFORMATION:
OWNER: Massachusetts Bay Rapid Transit Authority.
DESIGNER: Praeger Kavanagh and Waterbury.
CONTRACTOR: Steel shells by Wiley Manufacturing Co.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Kinuura Harbour Tunnel; Kinuura City near Nagoya, Japan; 1973

File No. 46



TUNNEL TYPE AND USE:
Vehicular; single-shell steel box elements.

LANES/TRACKS:
One tube with two lanes.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
6	80 m	7.10 m	15.6 m

TOTAL IMMERSED LENGTH:
480 m

DEPTH AT BOTTOM OF STRUCTURE:
21.7 m

UNUSUAL FEATURES:	Ventilation structures constructed by pneumatic caisson method. Unusually wide box section for steel shell construction. Structural requirements were mainly determined by earthquake design loads.
ENVIRONMENTAL CONDITIONS:	Severe earthquake loading requirements.

FABRICATION METHOD:	OUTFITTING:	JOINT TYPE:
Screeded gravel bed, which was later grouted with a sand-mortar mix.	Reinforcing steel and concrete was placed in the steel shells. The two alignment towers, and various equipment needed for placing the elements, were installed at the outfitting pier.	Rigid joint with single cantilever-type gasket.

WATERPROOFING METHOD:	Continuous steel shell around reinforced concrete box structure.
PLACEMENT METHOD:	Element was supported from pontoons and ballasted with water using tanks inside the element.
FOUNDATION METHOD:	Screeded gravel bed which was later grouted with a sand-mortar mix.
DREDGING METHOD:	Suction dredge was used to remove soft mud; bucket dredge was used for sand.
VENTILATION TYPE:	Semi-transverse ventilation system.
COVER AND TYPE:	2.0 m of crushed stone was used as protection against ships' anchors.

BUOYANCY SF: 1.10 for earthquake; 1.20 for normal conditions.

CONCRETE WORKING STRESS: 80 kgf/sq. cm

ADDITIONAL INFORMATION:	Primary external forces due to earthquake.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Ohgishima Tunnel; Kawasaki, Japan; 1974

File No. 47

TUNNEL TYPE AND USE:
Vehicular and utility; single shell.

LANES/TRACKS:
Two tubes; two lanes each.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
6	110 m	6.9 m	21.6 m

TOTAL IMMERSED LENGTH:
664 m

DEPTH AT BOTTOM OF STRUCTURE:
21 m

UNUSUAL FEATURES:	Jetted sand foundation treated with cement clinker of various sizes and a special binder to help achieve compaction and preclude liquefaction. Steel shell used to provide flexibility for better earthquake resistance. Closures to cut-and-cover land structures made using gasketted steel panels for joint seal.
ENVIRONMENTAL CONDITIONS:	0.4 m/s current, 3.2 m high, with waves 6.8-m long.

FABRICATION METHOD:	OUTFITTING:	JOINT TYPE:
Steel shell assembled in shallow drydock 3.3 km from tunnel site. Fully closed box section was constructed including bulkheads and interior reinforcing steel.	Outfitted at a wharf 1.6 km from the tunnel site; concrete placed from barges.	Gina-type joints with steel Omega; steel rods coupled across joints; steel panel joints at cut-and-cover structures.

WATERPROOFING METHOD:	Continuous steel shell.
PLACEMENT METHOD:	Transverse pontoons and two alignment/control towers with interior access. Joint closure and alignment jacks actuated from within the element.
FOUNDATION METHOD:	Jetted sand foundation treated to prevent liquefaction (see above).
DREDGING METHOD:	Grab bucket dredger.
VENTILATION TYPE:	Longitudinal ventilation.
COVER AND TYPE:	Sand backfill and rubble stone protection.
ADDITIONAL INFORMATION:	OWNER: Nippon Kokan Kabushiki Kaisha. DESIGNER: Christiani & Nielsen. CONTRACTOR: Taisei Corporation.

TUNNEL NAME /LOCATION/ DATE COMPLETED:
Elbe Tunnel; Hamburg, Germany; 1975

File No. 48

TUNNEL TYPE AND USE:
Vehicular; reinforced concrete box section .

LANES/TRACKS:
Three tubes; two lanes each .

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
8	132 m	8.4 m	41.7 m

TOTAL IMMERSED LENGTH:
1,056 m

DEPTH AT BOTTOM OF STRUCTURE:
29 m

UNUSUAL FEATURES:
Very wide tunnel, with six lanes providing reverse traffic flow in middle two lanes. Prestressed concrete design was investigated for both transverse and longitudinal loads; conclusion was that it was not economical. Joints were provided at 27-m intervals for both temperature and settlement effects. Initially it was decided that these intermediate joints were unnecessary; however, because of uncertainty in predicting settlements, they were eventually included. Special exterior Omega steel plates were used at these joints. Joint was held together by prestress bars until tunnel element was in place on jetted foundation; bars were then cut to allow flexibility. The river channel was switched from one side of the river to the other during construction.

ENVIRONMENTAL CONDITIONS:
River currents of 1.3 m/s (flood).

FABRICATION METHOD: All eight elements were constructed at the same time in a casting basin. 190,000 cu. m were first removed by dredging. Then, after closing the end with a 250 x 11 m cofferdam, 380,000 cu. m were excavated in the dry.

JOINT TYPE: Gina gasket joint with rubber Omega interior gasket. Joint allows for longitudinal expansion and contraction.

WATERPROOFING METHOD:
Steel membrane on bottom and side. Bituminous membrane on top protected with 15 cm of concrete. Waterstops and steel Omega (re-entrant) joints at intermediate joints (corners formed, not mitered).

PLACEMENT METHOD:
Transverse pontoons with control and alignment towers. Each tunnel element had 12 ballast tanks with a total capacity of about 5,000 cu. m. Buoyancy depended almost entirely on the weight of the concrete. The density, as well as the concrete dimensions, were continuously controlled and the findings treated statistically, in order to maintain the total weight within 0.5% of theoretical. Because of the river currents, piled anchorages to pull against were established in the river bottom. Between seven and nine 1,200-Hp tugs were used to tow and position elements.

FOUNDATION METHOD:
Sand-jetting. Element No. 8 ran into a problem with excess mud deposits. The return system of the sand-jetting equipment was used to remove this material before placing the sand.

DREDGING METHOD:
The trench was 45 m wide, with side slopes of 1:3. A cutterhead suction dredge was used to -15 m; thereafter, a bucket dredge was used, down to -30 m.

VENTILATION TYPE:
Fully transverse.

ADDITIONAL INFORMATION:
OWNER: Freie und Hansestadt Hamburg.
DESIGNER & CONTRACTOR: Joint Venture "E3 Elbtunnel."

TUNNEL NAME/ LOCATION/ DATE COMPLETED: **Vlake Tunnel; Zeeland, The Netherlands; 1975**			**File No. 49** 
TUNNEL TYPE AND USE: Vehicular; reinforced concrete box sections.		LANES/TRACKS: Two tubes; three lanes each (two active, one breakdown).	
NO. OF ELEMENTS: 2	LENGTH: 125 m	HEIGHT: 8 m	WIDTH: 29.8 m
TOTAL IMMERSED LENGTH: 250 m		DEPTH AT BOTTOM OF STRUCTURE: 17 m	
UNUSUAL FEATURES:	Used cooling water in wall pours to reduce shrinkage cracking so that exterior waterproofing membrane could be eliminated. First use of the sand-flow method, whereby sand/water slurry is pumped under the element from internal ports.		
FABRICATION METHOD: Casting basin next to tunnel site, later to become part of projected canal widening.		WATERPROOFING METHOD: Shrinkage control and division of elements into shorter lengths of 21 m, post-tensioned together.	
PLACEMENT METHOD:	Transverse pontoons with two control and alignment towers. Three-point bearing method used for alignment adjustement.		
FOUNDATION METHOD:	Sand-flow method (used for the first time on this project).		
DREDGING METHOD:	Cutterhead suction dredge.		
VENTILATION TYPE:	Longitudinal.		
ADDITIONAL INFORMATION:	OWNER: Rijkswaterstaad. DESIGNER: Rijkswaterstaad. CONTRACTOR: Kombinatie Vlake joint venture of Hollandsche Beton Maatschappij B.V., de Amsterdamse Ballast-Beton en Waterbouw N.V.		

TUNNEL NAME/ LOCATION/ DATE COMPLETED: **Sumida River Tunnel; Tokyo, Japan, 1975**			**File No. 50** 
TUNNEL TYPE AND USE: Railway; single shell steel.		LANES/TRACKS: Two tubes; one track each.	
NO. OF ELEMENTS: 3	LENGTH: 67 m	HEIGHT: 7.8 m	WIDTH: 10.30 m
TOTAL IMMERSED LENGTH: 201.5 m		WATERPROOFING METHOD:Continuous steel shell.	
VENTILATION TYPE: Piston action of trains.			

TUNNEL NAME/ LOCATION/ DATE COMPLETED: **2nd Hampton Roads Bridge Tunnel; Hampton Roads, Virginia, U.S.A.; 1976**			File No. 51
TUNNEL TYPE AND USE: Vehicular; double steel shell elements.		LANES/TRACKS: One tube ; two lanes.	
NO. OF ELEMENTS: 21	LENGTH: 105 m	HEIGHT: 12.3 m	WIDTH: 12.0 m
TOTAL IMMERSED LENGTH: 2229 m		DEPTH AT BOTTOM OF STRUCTURE: 37 m	
UNUSUAL FEATURES:	This tunnel was constructed adjacent to the existing tunnel about 75 m away without damaging it. Ground near the south half length of the tunnels was very poor. Sand drains and surcharge were used to stabilize the expanded South Island before the elements could be placed and before the ventilation building and open approach structures could be constructed.		
ENVIRONMENTAL CONDITIONS:	Fairly severe winds, waves and currents during storm conditions. Currents about 1 m/s (2 knots).		
FABRICATION METHOD: At a shipyard at Port Deposit, Maryland about 300 km by water from the site. Elements were side-launched (uncontrolled). Draft slightly more than 2 m.		OUTFITTING: At a pier about 5 km from tunnel site. Up to six elements were outfitted with concrete at one time along one side of a pier (elements were moored in twos).	JOINT TYPE: Double rubber gasket system with interior liner plate to join steel shells.
WATERPROOFING METHOD:	Continuous steel shell joined at joints, with welded and liner plates tested for watertightness.		
PLACEMENT METHOD:	Straddling laybarge, consisting of two railroad car barges with support beams between them in catamaran form.		
FOUNDATION METHOD:	Screeded foundation. Screed rig was designed to be unaffected by tidal variations by being taut moored with flotation tanks held underwater. Three elements had to be removed from trench and reset after rescreeding due to siltation of screeded foundation.		
DREDGING METHOD:	Cutterhead suction dredge used for depths up to 15 m; then a 12-m^3 clamshell bucket dredge was used for deeper work. Surcharge sand on South Island was pumped to construct North Island using a booster pump to mix sand and water under a truck grizzly.		
VENTILATION TYPE:	Fully transverse ventilation, divided between two ventilation buildings.		
COVER AND TYPE:	1.5 m sand cover, with some areas of riprap protection against scour.		
ADDITIONAL INFORMATION:	OWNER: Virginia Department of Highways and Transportation. DESIGNER: Parsons Brinckerhoff Quade & Douglas, Inc. CONTRACTOR: Tidewater Construction Corp., Raymond International and Peter Kiewit and Sons, Inc.		

TUNNEL NAME/ LOCATION/ DATE COMPLETED: **Paris Metro Tunnel; Paris, France; 1976**		**File No. 52** 
TUNNEL TYPE AND USE: Railway; reinforced concrete box.	LANES/TRACKS: One tube, two tracks.	TOTAL IMMERSED LENGTH: 128 m

TUNNEL NAME/ LOCATION/ DATE COMPLETED: **Tokyo Port Tunnel; Tokyo, Japan; 1976**			**File No. 53** 
TUNNEL TYPE AND USE: Vehicular; reinforced concrete box section.		LANES/TRACKS: Two tubes, three lanes each.	
NO. OF ELEMENTS: 9	LENGTH: 115 m	HEIGHT: 8.80 m	WIDTH: 37.4 m
TOTAL IMMERSED LENGTH: 1,035 m		DEPTH AT BOTTOM OF STRUCTURE: 23 m	
UNUSUAL FEATURES:	1. Flexible seismic joints were provided. 2. Steel pipe pile foundation was adopted for elements near ventilation shafts to limit force due to consolidation. 3. New foundation method was developed whereby bentonite mortar was pumped from inside the elements. Very wide, heavy elements.		
ENVIRONMENTAL CONDITIONS:	Site is located in fairway.		
FABRICATION METHOD: Casting basin close to site for all nine elements.		OUTFITTING: In casting basin, using travelling forms.	JOINT TYPE: Flexible joint using Gina type joint. A steel Omega-type gasket was also used.
WATERPROOFING METHOD:	6-mm steel skin on sides and bottom. Concrete protected rubber membrane on top of element.		
PLACEMENT METHOD:	Placed from catamaran barges.		
FOUNDATION METHOD:	A bentonite mortar layer 0.5 m thick was pumped under the elements over a 0.7-m-thick crushed sandstone layer. Edges of elements were sealed with sand/gravel filter to prevent mortar from escaping. Steel pile foundation was used for terminal elements.		
DREDGING METHOD:	Cutterhead suction dredging.		
VENTILATION TYPE:	Semi-transverse, using side and center ducts.		
COVER AND TYPE:	1.5 m sandstone riprap for protective cover. Sandstone rock spoil used for locking fill.		
BUOYANCY SF: 1.10		CONCRETE WORKING STRESS: Approx. 90 kgf/sq. cm	

TUNNEL NAME/LOCATION/ DATE COMPLETED:
Drecht Tunnel; Dordrecht, The Netherlands; 1977

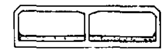
File No. 54

TUNNEL TYPE AND USE: Vehicular; reinforced concrete box elements.		LANES/TRACKS: Four tubes; two lanes in each tube.	
NO. OF ELEMENTS: 3	LENGTH: 115 m	HEIGHT: 8.7 m	WIDTH: 48.6 m
TOTAL IMMERSED LENGTH: 347 m		DEPTH AT BOTTOM OF STRUCTURE: 15 m	

UNUSUAL FEATURES:	Widest elements ever constructed. Displacement 45,000 MT. Approach structures are of a very unusual construction, utilizing drained slabs and top-down construction, with slurry walls carried to clay. Tunnel elements were attached to end structures already in place—on one end of tunnel, using a Gina joint; and on the other, using a gasketted plate joint system. Two-lane spans were used to reduce depth of elements. Sand-flow method was used for second time.
ENVIRONMENTAL CONDITIONS:	River currents.

FABRICATION METHOD: At casting yard at Barendrecht (used previously for the Heinenoord and some pipeline tunnels), 12 km from site.	JOINT TYPE: Gina-type joints.

WATERPROOFING METHOD:	Membrane waterproofing was used because of the great width of the tunnel. The elements were divided into six subsections with temporary prestress, which was cut after backfilling.
PLACEMENT METHOD:	Model tests were used to determine the number of tugs required to handle the segment. The tests indicated 5,000 to 6,000 HP; however, 11,000 HP eventually were provided for safety. Clearances for towing were very restricted, and an elaborate electronic horizontal control method was implemented to keep elements from running aground. Element blocked 40% of river at times during towing. Transverse pontoons with two control/alignment towers were used for placement. Four-point support was used at placement because of the width of the section. Vertical and horizontal jacks were used for adjustment of alignment.
FOUNDATION METHOD:	The sand-flow method used on the Vlake tunnel was repeated for this tunnel.
DREDGING METHOD:	Because of the tunnel width, rough dredging was done and the variations were compensated for with the placement of the sand foundation.
VENTILATION TYPE:	Longitudinal; jet fans.

TUNNEL NAME/ LOCATION/ DATE COMPLETED: **Prinses Margriet Tunnel; Sneek, The Netherlands; 1978**			**File No. 55** 
TUNNEL TYPE AND USE: Vehicular; reinforced concrete box element.		LANES/TRACKS: Two tubes; three lanes each.	
NO. OF ELEMENTS: 1	LENGTH: 77 m	HEIGHT: 8.0 m	WIDTH: 28.5 m
TOTAL IMMERSED LENGTH: 77 m			
UNUSUAL FEATURES:	Single element designed to engage the walls of both open-approach structures. Element was constructed in one of the approaches with transverse wingwalls attached. The element was floated into position and sealed using inflatable gaskets.		
FABRICATION METHOD: Fabricated in open approach section. Element was cast in four articulated sections to limit shrinkage cracking.		JOINT TYPE: Inflatable gaskets at both ends of element in wingwalls and along bottom. This arrangement was used as a temporary seal so that permanent closure could be cast.	
WATERPROOFING METHOD:	6-mm steel membrane on bottom. Two-ply bituminous membrane of sides and top. Top protected with layer of concrete.		
PLACEMENT METHOD:	Floated into position and lowered by winching. Clearance of wingwalls only 4.5 cm. Ballast tanks were used.		
VENTILATION TYPE:	None required; natural ventilation.		

TUNNEL NAME/LOCATION/ DATE COMPLETED: **Kil Tunnel; Dordrecht, The Netherlands; 1978**			**File No. 56** 
TUNNEL TYPE AND USE: Vehicular; reinforced concrete box elements.		LANES/TRACKS: Two tubes; three lanes each. Two lanes for fast-moving traffic and one truck lane.	
NO. OF ELEMENTS: 3	LENGTH: 111.5 m	HEIGHT: 8.75 m	WIDTH: 31.0 m
TOTAL IMMERSED LENGTH: 330 m			
FABRICATION METHOD: At the Barendrecht basin alongside the elements for plates at the end joint.		JOINT TYPE: Gina gasketted joints on the elements. Gasketted plates at the end joint.	
PLACEMENT METHOD:	Transverse pontoons with two control/survey towers.		
FOUNDATION METHOD:	Sand-flow method, similar to Vlake and Drecht Tunnels.		
VENTILATION TYPE:	Longitudinal.		

TUNNEL NAME/LOCATION/ DATE COMPLETED: **WMATA Washington Channel Tunnel; Washington, D.C., U.S.A.; 1979**			**File No. 57** 
TUNNEL TYPE AND USE: Railway; double-shell steel elements.		LANES/TRACKS: Two tubes; one track each.	
NO. OF ELEMENTS: 3	LENGTH: 103.6	HEIGHT: 6.7 m	WIDTH: 11.3 m
TOTAL IMMERSED LENGTH: 311 m		UNUSUAL FEATURES: Use of double steel shell is somewhat unusual for a transit tunnel.	
FABRICATION METHOD: At shipyard at Port Deposit, Maryland, about 120 km from the site. Uncontrolled side launching was used.		OUTFITTING: At dockside at fabrication yard in Port Deposit.	
WATERPROOFING METHOD:	Continuous sheel shell.		
PLACEMENT METHOD:	Winches from pile-supported guide beams.		
FOUNDATION METHOD:	Screeded bedding.		
VENTILATION TYPE:	Piston action of trains.		
ADDITIONAL INFORMATION:	OWNER: Washington Metropolitan Transit Authority (WMATA). DESIGNER: Parsons Brinckerhoff Quade & Douglas, Inc. CONTRACTOR: Joint venture of Perrini, Horn and Morrison-Knudsen.		

TUNNEL NAME /LOCATION/ DATE COMPLETED:
Kawasaki Tunnel; Kawasaki City, near Tokyo, Japan; 1981

File No. 58

TUNNEL TYPE AND USE:
Vehicular; single-shell steel box elements.

LANES/TRACKS:
Two tubes; two lanes each.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
8	100–110 m	8.8 m	31.0 m

TOTAL IMMERSED LENGTH: 840 m

DEPTH AT BOTTOM OF STRUCTURE: 22 m

UNUSUAL FEATURES:	Wide box section for steel shell construction. Land tunnel support on steel pipe piles. Sectional dimensions mainly based on earthquake loadings. Earthquake observations have been carried out since 1980 on this tunnel.
ENVIRONMENTAL CONDITIONS:	Severe earthquake loading requirements.

FABRICATION METHOD:
Steel shells were fabricated at shipyard next to outfitting pier.

OUTFITTING:
Reinforcing steel and concrete were placed at outfitting pier with element in flotation. Alignment towers and placement equipment also were installed at the outfitting pier.

JOINT TYPE:
Rigid joint with rubber gaskets. Flexible joint was used between terminal element and ventilation tower.

WATERPROOFING METHOD:	Continuous steel shell.
PLACEMENT METHOD:	Element supported by pontoons. Ballasting with water into tanks in element.
FOUNDATION METHOD:	Mortar bed pumped in place from inside elements.
DREDGING METHOD:	A bucket dredge was used to dredge the main trench. A suction dredge was used to eliminate soft mud and sand that drifted into the trench.
VENTILATION TYPE:	Semi-transverse ventilation system.
COVER AND TYPE:	1.5 m of gravel was used over the tubes as a protective layer.

BUOYANCY SF:
1.1 for earthquake and 1.2 for normal conditions.

CONCRETE WORKING STRESS:
100 kgf/sq. cm

ADDITIONAL INFORMATION:	Deformed bars of 51-mm dia. were used for longitudinal reinforcement to resist axial earthquake forces.

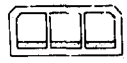
TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Hong Kong Mass Transit Tunnel; Hong Kong Harbour, between Kowloon and Victoria Island; 1979

File No. 59

TUNNEL TYPE AND USE: Railway; reinforced concrete double binocular elements, longitudinally prestressed.		LANES/TRACKS: Two tubes; one track each.	
NO. OF ELEMENTS: 14	LENGTH: 100 m	HEIGHT: 6.6 m	WIDTH: 13.1 m
TOTAL IMMERSED LENGTH: 1,400 m			
UNUSUAL FEATURES:	Screeding and placing of elements using same jack-up rig. Caisson ventilation buildings set on end elements.		
ENVIRONMENTAL CONDITIONS:	Currents of 1.5 m/s (2.9 knots). Several typhoons had to be contended with during construction. Tunnel was designed for 5-m tides.		
FABRICATION METHOD: Casting basin.		JOINT TYPE: Gina gasketted joints.	
WATERPROOFING METHOD:	From the bottom to the first construction joint, 6-mm steel plate treated with corrosion protection. The remainder was waterproofed with two-ply bit and two-ply protective membrane.		
PLACEMENT METHOD:	Used jack-leg special marine platform.		
FOUNDATION METHOD:	Screeded bedding, using jack-up rig.		
DREDGING METHOD:	To -19 m, with bucket dredge; finished with clamshell dredge using 2.5-cu.-m to 14-cu.-m buckets.		
VENTILATION TYPE: Piston action of trains.		BUOYANCY SF: 1.20	
ADDITIONAL INFORMATION:	OWNER: Mass Transit Railway Corporation. DESIGNER: Freeman Fox and Partners (Far East) Per Hall Consultants Ltd. CONTRACTOR: Kumagai Gumi Co. Ltd.		

TUNNEL NAME/LOCATION/ DATE COMPLETED:
Hemspoor Tunnel; Amsterdam, The Netherlands; 1980

File No. 60



TUNNEL TYPE AND USE: Railway; reinforced concrete box elements.	LANES/TRACKS: Three tubes; one track each.

NO. OF ELEMENTS: 7	LENGTH: See "Unusual Features"	HEIGHT: 8.7 m	WIDTH: 21.5 m

TOTAL IMMERSED LENGTH: 1,475 m	DEPTH AT BOTTOM OF STRUCTURE: 26 m

UNUSUAL FEATURES:	Three-track tunnel; middle track is used for wide goods trains. Four straight elements were constructed twice as long (268 m) as the remaining three curved elements (134 m). These long elements displaced a record 50,000 tonnes. This was possible because there is no current in the North Sea Canal and there was sufficient room to manuever. The sections of each element were temporarily tied together with plain reinforcing steel instead of prestressing rods. As in other tunnels, these ties were cut after the element was in its final condition.
ENVIRONMENTAL CONDITIONS:	Virtually no current in canal.

FABRICATION METHOD: In the combined casting basin of the Coen and Ij Tunnels.	JOINT TYPE: Gina joints. Last joint was made using gasketted plates to permit joint dewatering.

WATERPROOFING METHOD:	Intermediate joints at 22.35-m intervals were provided to reduce shrinkage cracking and accommodate settlements. The roof was protected with a concrete slab placed just prior to sinking the tube. This reduced the freeboard to only 5 cm.
PLACEMENT METHOD:	Transverse placement barges on top of element. Survey towers were not used, but an access shaft was provided on each element. The center between immersion load lines was used for positioning. Proper register between elements was obtained with a sensor operated between the bulkheads. Levelling was done internally.
FOUNDATION METHOD:	The sand-flow method was different, in that sand slurry was pumped into the individual elements through hoses attached by divers.
DREDGING METHOD:	Cutterhead suction dredges, placing spoil in adjacent land areas.
VENTILATION TYPE:	Piston action of trains.
ADDITIONAL INFORMATION:	OWNER: Dutch Ministry of Public Works. DESIGNER: Locks and Weirs Division of the National Public Works. CONTRACTOR: Hemspoor joint venture (Royal Bos Kalis Westminster Group N.V. Stevin Groep N.V.)

TUNNEL NAME/LOCATION/ DATE COMPLETED:
Botlek Tunnel; Rotterdam, The Netherlands; 1980

File No. 61

TUNNEL TYPE AND USE:
Vehicular; prestressed concrete box elements.

LANES/TRACKS:
Two tubes; three lanes each (two traffic lanes plus a breakdown lane).

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
5	105 m	8.8 m	30.9 m

TOTAL IMMERSED LENGTH:
508 m (4 elements @ 105 m; 1 element @ 87.5 m)

DEPTH AT BOTTOM OF STRUCTURE:
23.3 m

UNUSUAL FEATURES:
Heavy floating shear leg cranes were used for placement.

FABRICATION METHOD:
In a casting basin, for all five elements. The sections were left submerged for about three months. They were refloated without problems by pumping out ballast water.

JOINT TYPE:
Gina joints were used, except at the end tube, where gasketted plates were employed.

WATERPROOFING METHOD:
The elements were constructed of six 17.5-m sections post-tensioned together. The post-tensioning was bonded. The wall pours were cooled using water pipes to eliminate cracking due to heat of hydration.

PLACEMENT METHOD:
Elements were placed using shear leg cranes. Survey and control towers were used for alignment control and access.

FOUNDATION METHOD:
Sand-flow method. As for the Hemspoor Tunnel, sand slurry was pumped into each individual element directly.

DREDGING METHOD:
Cuttersuction dredger.

VENTILATION TYPE:
Longitudinal, using jet fans.

ADDITIONAL INFORMATION:
OWNER: Municipality of Rotterdam.
DESIGNER: Gemeentewerken Rotterdam (GWR).
CONTRACTOR: Joint venture of Voormolen and Wayys & Fretag.

TUNNEL NAME/LOCATION/ DATE COMPLETED:
Daiba Tunnel; around Tokyo Port (Japan); 1980

File No. 62

TUNNEL TYPE AND USE:
Railway; single-shell steel binocular.

LANES/TRACKS:
Two tubes; one track each.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
7	96.6 m	8.05	12.68 m to 17.53 m

TOTAL IMMERSED LENGTH:
672 m

DEPTH AT BOTTOM OF STRUCTURE:
23.9 m

UNUSUAL FEATURES:
Tunnel was designed to be sufficiently flexible to accommodate up to 1.2 m of settlement and survive a severe earthquake. Joints are tied together with cables, but allow some flexibility. These flexible joints are provided between all of the elements and at the terminal joints. Immersed elements tie into pneumatic caissons at both ends of tunnel. Element Nos. 5–7 transition 5 m in width to meet bored tubes.

ENVIRONMENTAL CONDITIONS:
Site is situated in fairway of an active port area.

FABRICATION METHOD:
Steel shells were fabricated at shipyard. Bulkheads and rubber gaskets were installed and the elements were towed to pier at outfitting yard.

OUTFITTING:
Concrete reinforcement, and concrete was placed in flotation at outfitting dock near tunnel site. Alignment towers and placement barges were installed.

JOINT TYPE:
Joints between elements have a rubber gasket on the outside and a small gap on the inside for flexibility. Cables through the joints tie the elements together. H-shaped steel members form a shear key embedded in the ends of the elements at each joint to prevent excessive vertical and horizontal displacement under settlement and earthquake loadings. Caissons were used for the end structures to protect existing port structures.

WATERPROOFING METHOD:
Continuous steel shell. Each element was protected with 200 aluminum anodes, giving an estimated life of 60 years.

PLACEMENT METHOD:
Placement from semi-submersible jack-leg platform because of space restrictions in Port area precluded use of anchor lines. Crushed stone was used for placement ballast.

FOUNDATION METHOD:
A 70-cm-thick, 12.4-m-wide layer of 30-mm to 40-mm crushed stone foundation course, screeded from jack-leg platform.

DREDGING METHOD:
Bucket dredge was used for sand; a cutterhead suction dredge was used for the soft mud.

VENTILATION TYPE:
Piston action of trains.

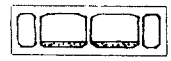
BUOYANCY SF:
1.1

COVER AND TYPE:
1.1 m of crushed stone.

ADDITIONAL INFORMATION:
OWNER AND DESIGNER: Japan Railway Construction Public Corp.
CONTRACTOR: Joint venture of Kajima Corp., Sato Kokyo Co. and Tekken Construction Co.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Tokyo Port Dainikoro Tunnel; Tokyo, Japan; 1980

File No. 63



TUNNEL TYPE AND USE:
Vehicular; reinforced concrete box elements.

LANES/TRACKS:
Two tubes; two lanes each.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
6	124 m	8.8 m	28.4 m

TOTAL IMMERSED LENGTH: 744 m

DEPTH AT BOTTOM OF STRUCTURE: 23 m

UNUSUAL FEATURES:	1. Use of bentonite mortar mixture, pumped in the manner of a sand-flow system for the foundation of the tunnel elements. 2. Flexible joints for earthquake displacements. 3. Moderate longitudinal prestress used to control cracking and resist earthquake stress.

FABRICATION METHOD:
At a casting basin near the tunnel site. One cycle for all six elements. Approximately two years was required to establish the basin and produce the elements.

JOINT TYPE:
Gina/Omega gasket between elements; gasketted plates to cut-and-cover sections.

WATERPROOFING METHOD:	8-mm steel plate on bottom and sides; 2.5-mm membrane on top of element, protected with 15 cm of reinforced concrete.
PLACEMENT METHOD:	Catamaran barges.
FOUNDATION METHOD:	Modification of sand flow method. Instead of plain sand slurry, bentonite mortar was injected into a cobble-stone bedding.
DREDGING METHOD:	Grab bucket dredger for rough dredging; a cutterhead suction dredge for fine dredging and clean-up.
VENTILATION TYPE:	Semi-transverse ventilation, using side ducts with a ventilation building at each end of the tunnel.
COVER AND TYPE:	Fine crushed stone on both sides, with crusher run on top.
ADDITIONAL INFORMATION:	OWNER AND DESIGNER: Japan Railway Construction Public Corp. CONTRACTOR: Joint Venture of Kajima Corp., Sato Kokyo Co. and Tekken Construction Co.

TUNNEL NAME/ LOCATION/ DATE COMPLETED: **Rupel Tunnel; Boom, Belgium; 1982**			**File No. 64** 
TUNNEL TYPE AND USE: Vehicular; reinforced concrete box elements.		LANES/TRACKS: Two tubes; three lanes each.	
NO. OF ELEMENTS: 3	LENGTH: 138 m	HEIGHT: 9.35 m	WIDTH: 53.10 m
TOTAL IMMERSED LENGTH: 336 m		FABRICATION METHOD: Elements were cast in the open approaches to the tunnel.	
WATERPROOFING METHOD:	Steel plate on bottom of elements and bituminous membrane on the sides and top.		
PLACEMENT METHOD:	Conventional for concrete elements.		
FOUNDATION METHOD:	Jetted-sand method.		
VENTILATION TYPE:	Longitudinal, using booster fans.		

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Metropolitan Railway Tunnel under the Main; Frankfort/Main, Germany; 1983

File No. 65

TUNNEL TYPE AND USE:
Railway; reinforced concrete box elements.

LANES/TRACKS:
Two tubes; one track each tube.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
2	1 element @ 61.5 m 1 element @ 62 m	8.55 m 8.55 m to 10.28 m	12.10 m–13.10 m 12.10 m–12.70 m

TOTAL IMMERSED LENGTH:
123.5 m

DEPTH AT BOTTOM OF STRUCTURE:
17 m below water level.

UNUSUAL FEATURES: Varying cross-sections.

ENVIRONMENTAL CONDITIONS: Mild currents; flow of bottom sediments during periods of high water.

FABRICATION METHOD:
Casting basin in the approaches on each side. Intermediate joints provided at 13.70-m spacing to reduce temperature and shrinkage cracking.

OUTFITTING:
In casting basin as part of fabrication operation.

JOINT TYPE:
Gina/Omega joints.

WATERPROOFING METHOD: Impermeable reinforced concrete.

PLACEMENT METHOD: Lowering from bridging frame over the excavation and from a pontoon bridge in the river.

FOUNDATION METHOD: Sand-flow method, using openings in bottom slab.

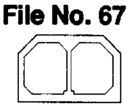
DREDGING METHOD: Upper portion of sloped trench above 7 m was dredged using regular dredge; lower portion was cut between sheetpile walls using a large floating backhoe dredge capable of 19 m depth.

VENTILATION TYPE: Piston action of trains.

COVER AND TYPE: Fill plus stone blanket.

ADDITIONAL INFORMATION:
OWNER: Deutsche Bundesbahn (German Railway).
OPERATOR: Deutsche Bundesbahn, Frankfurter Verkenrsverbund (FVV).
DESIGNER: Deutsche Bundesbahn.
CONTRACTOR: Joint Venture: Dyckerhoff + Widmann AG, Frankfurt; Bilfinger + Berger, Frankfurt; Josef Riepl AG, Strabag AG.

TUNNEL NAME/LOCATION/ DATE COMPLETED: **Bastia Old Harbour Tunnel; under Old Harbour in Bastia, Corsica, France; 1983**			**File No. 66**
TUNNEL TYPE AND USE: Vehicular; concrete box elements.		LANES/TRACKS: One tube; two lanes, plus shoulders.	TOTAL IMMERSED LENGTH: 249.72 m
NO. OF ELEMENTS: 4	LENGTH: 62.33 m	HEIGHT: 7.58 + .5 m	WIDTH: 14.10 m
ADDITIONAL INFORMATION:	CONTRACTORS: G.T.M. France.		

TUNNEL NAME/ LOCATION/ DATE COMPLETED: **Spijkenisse Metro Tunnel; Rotterdam, The Netherlands; 1984**			**File No. 67** 
TUNNEL TYPE AND USE: Railway; reinforced concrete box elements.		LANES/TRACKS: Two tubes; one track each.	
NO. OF ELEMENTS: 6	LENGTH: 82 m	HEIGHT: 6.55 m	WIDTH: 10.3 mm
TOTAL IMMERSED LENGTH: 530 m		ENVIRONMENTAL CONDITIONS: River currents.	
FABRICATION METHOD: Elements were cast in casting basin used previously for the elements for the Rotterdam Metro. Three elements were cast at a time, in two cycles.		JOINT TYPE: Gina/Omega rubber joints between element. Final joint between last two elements was made using gasketted steel plates installed by divers. Provision was made in joint to the land section for settlement.	
PLACEMENT METHOD:	Lowered by cranes. Survey tower on outboard end.		
FOUNDATION METHOD:	Jetted-sand method was used. Silt was first removed by air-jetting for agitation and the action of the river current. At one end, unsuitable material was removed by over-excavation and replaced with sand, which was then vibro-compacted.		
DREDGING METHOD:	Cutterhead suction dredge.		
VENTILATION TYPE:	Piston action of trains.		
ADDITIONAL INFORMATION:	OWNER: Municipality of Rotterdam. DESIGNER: Gemeentewen Rotterdam (G.W.R.). CONTRACTOR: Van Hattum & Blankevoort, Netherlands.		

TUNNEL NAME/ LOCATION/ DATE COMPLETED: Coolhaven Tunnel; Rotterdam, The Netherlands; 1984	**File No. 68**

TUNNEL TYPE AND USE: Metro railway; reinforced concrete box elements.	LANES/TRACKS: Single tube; two tracks.

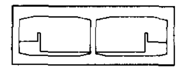
NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
7	3 elements @ 45.59 m 3 elements @ 74.98 m 1element @ 49.00 m	6.35 m	9.64 m

TOTAL IMMERSED LENGTH: 411 m	DEPTH AT BOTTOM OF STRUCTURE: Shallow metro tunnels.

UNUSUAL FEATURES:	Elements were floated into place between cross-braced sheetpile walls. They were then hooked up at both ends to carriers, which ran on rails supported on the sheet piling. The elements were then ballasted internally and drawn together with jacks on the top slab. The water pressure was then released in the joint area in the conventional way. The foundation was also unique, as it utilized special piles provided with tops that could be adjusted to the underside of the tunnel element by inflation with grout. This was accomplished with a precast upper section connected to the lower section with a guiding dowel. The expandable section was enclosed within a folded nylon bag.
ENVIRONMENTAL CONDITIONS: Construction through residential urban area and existing canal.	JOINT TYPE: Gina-type joint.
PLACEMENT METHOD:	Lowered from carriers on rails (see above).
FOUNDATION METHOD:	Installed on adjustable piling (see above).
DREDGING METHOD:	Clamshell bucket excavation.
VENTILATION TYPE:	Piston action of trains.
ADDITIONAL INFORMATION:	OWNER: Gemeentebestuur Rotterdam. CONTRACTOR: Hoofdaannemer BBM, Bredase Beton-en Aanneming Maatschappij B.V.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Kaohsiung Cross Harbour Tunnel; Kaohsiung, Taiwan, Republic of China; 1984

File No. 69



TUNNEL TYPE AND USE:
Vehicular; reinforced concrete box section.

LANES/TRACKS:
Two tubes; two lanes each. Each tube is also provided with 2.6-m-wide motorcycle way.

NO. OF ELEMENTS:
6

LENGTH:
120 m

HEIGHT:
9.35 m

WIDTH:
24.4 m

TOTAL IMMERSED LENGTH:
720 m

DEPTH AT BOTTOM OF STRUCTURE:
23 m

UNUSUAL FEATURES:
Used to interconnect the harbour facilities. Longitudinal post-tensioning was used for the immersed elements.

ENVIRONMENTAL CONDITIONS:
Designed to take loads of a sunken ship or earthquake, including consideration of liquefaction of the silty sands beneath the tunnel, differential settlements, and frictional restraint of movement caused by temperature, shrinkage, and creep.

FABRICATION METHOD:
Casting basin constructed near the site. All elements cast in a single cycle.

JOINT TYPE:
Gina/Omega system was utilized. Tension ties were provided across the joints for earthquake loads.

WATERPROOFING METHOD:
Two-ply bituminous membrane system was specified for the sides at top. Steel plate was used for bottom and collars. Waterproofing was protected with concrete. Tube was cast in six sections of 20 m each.

PLACEMENT METHOD:
Transverse barges with survey and control towers were used.

FOUNDATION METHOD:
Sand-flow method, using pipes previously cast in the bottom of the tunnel elements; accessible from the outside.

VENTILATION TYPE:
Longitudinal system.

ADDITIONAL INFORMATION:
OWNER: Kaohsiung Harbor Bureau.
DESIGNER/CONTRACTOR (Turnkey): Retired Serviceman Engineering Agency (RSEA).

TUNNEL NAME /LOCATION/ DATE COMPLETED:
Fort McHenry Tunnel; Baltimore, Maryland, U.S.A.; 1987

File No. 70

TUNNEL TYPE AND USE: Vehicular; two double-shell steel binocular tunnels.

LANES/TRACKS: Two parallel tunnels, each with two tubes and two lanes in each tube, for a total of eight traffic lanes.

NO. OF ELEMENTS: 32 (16 elements for each tunnel)

LENGTH: 104. 8 m

HEIGHT: 12.7 m

WIDTH: 25.1 m

TOTAL IMMERSED LENGTH: 1,646 m

DEPTH AT BOTTOM OF STRUCTURE: 31.7 m

UNUSUAL FEATURES: Two parallel immersed tunnels, only 3 m apart, mostly on a curve. Overall largest vehicular immersed tunnel project in the world. Elements were placed alternately from the northbound tunnel to the southbound tunnel. An 11-m-deep ship wharf was removed during construction and later replaced as a float-in caisson on top of the twin tunnel. Scheduling of element placement depended on the relocation of a 122-cm critical city watermain, which crossed the alignment. This relocation involved a deep cofferdam in the middle of the river, to make the changeover. First use of remotely controlled wedges for horizontal alignment adjustment.

ENVIRONMENTAL CONDITIONS: Very mild currents and tidal conditions, except for storm effects. Flow of bottom sediment was a problem affecting several elements. Three elements required rescreeding.

FABRICATION METHOD: Shipyard at Port Deposit, Maryland about 65 km from tunnel site. Uncontrolled side launch.

OUTFITTING: At dockside in Baltimore, a short distance from the site. Up to six elements were being outfitted at one time.

JOINT TYPE: Double rubber gasket. Welded, grouted liner plate.

WATERPROOFING METHOD: Continuous steel shell.

PLACEMENT METHOD: Catamaran barge system.

FOUNDATION METHOD: Option was provided for either jetted-sand or screeded bedding. The contractor opted for the screeded method. A special taut moored rig was used, with the flotation tanks fully submerged to prevent tidal effects.

DREDGING METHOD: Virtually all dredging was done by a large cutterhead suction dredge (69-cm-dia. pipe) pumping via a submerged pipeline to a disposal site 4 km away. A booster pump was mounted on a barge.

VENTILATION TYPE: Fully transverse ventilation, shared by a ventilation building located at each end of the pair of immersed tunnels.

COVER AND TYPE: 1.5 m of ordinary backfill.

ADDITIONAL INFORMATION: Disposal site for dredged material was segregated into two areas. One area contained the highly contaminated near-bottom materials behind a sealed cofferdam and clay-lined dikes. The other area was used to contain the better, more granular materials; it has since been developed into a major container port facility.

OWNER: Interstate Division Baltimore City (IDBC).
DESIGNER: Joint Venture: Sverdrup Corporation and Parsons Brinckerhoff Quade and Douglas, Inc.
CONTRACTOR: Joint Venture: Peter Kiewit & Sons, Inc., Raymond International, Inc. and Tidewater Construction Corp.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Second Downtown Tunnel; Norfolk to Portsmouth, Virginia, U.S.A.; 1988

File No. 71

TUNNEL TYPE AND USE: Vehicular; double-steel-shell horseshoe element.	LANES/TRACKS: Single tube; two lanes.

NO. OF ELEMENTS: 8	LENGTH: 101.5 m	HEIGHT: 10.5 m	WIDTH: 12.2 m

TOTAL IMMERSED LENGTH: 765 m	DEPTH AT BOTTOM OF STRUCTURE: 13.7 m

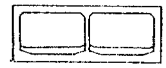
UNUSUAL FEATURES:	Horseshoe shape was used for economy because of the ventilation method adopted. Elements were fabricated in Texas and shipped in pairs on a semi-submersible ocean-going barge.
ENVIRONMENTAL CONDITIONS:	Current 1.0 m/s (2 knots) max. Tide 1.2 m.

FABRICATION METHOD: In shipyard in Corpus Christi, Texas, 3,500 km from tunnel site.	OUTFITTING: At dockside near site.	JOINT TYPE: Double gasket system.

WATERPROOFING METHOD:	Continuous steel shell.
PLACEMENT METHOD:	From catamaran barge system. Tube was brought out almost fully ballasted to reduce the time in the river channel. Remotely controlled wedges used for horizontonal alignment.
FOUNDATION METHOD:	Screeded gravel bedding.
VENTILATION TYPE:	Semi-transverse, using ceiling exhaust air duct. One ventilation building.
COVER AND TYPE:	1.5 m of ordinary backfill.
ADDITIONAL INFORMATION:	OWNER: Virginia Department of Highways and Transportation. DESIGNER: Parsons Brinckerhoff Quade & Douglas, Inc. CONTRACTOR: J.A. Jones Construction Co. and Schiavone Construction Co.

TUNNEL NAME AND LOCATION/ DATE COMPLETED:
Guldborgsund Tunnel; crossing the sound between the islands of Lolland and Falster, Denmark; 1988

File No. 72



TUNNEL TYPE AND USE:
Vehicular; reinforced concrete box sections.

LANES/TRACKS:
Two tubes, each with two lanes.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
2	230 m	7.6 m	20.6 m

TOTAL IMMERSED LENGTH:
460 m

DEPTH AT BOTTOM OF STRUCTURE:
13.8 m

UNUSUAL FEATURES:	230-m-long-, vertically curved elements are some of the longest ever produced. Computer-controlled dynamic ballasting was used. Elements were floated out under water.

FABRICATION METHOD:
The two tunnel elements were cast one at a time in a dry dock located in the future tunnel ramp at Lolland. The elements were cast in 15-m to 15.3-m segments to prevent cracks. When cracks occurred in the first segment, cooling was used in the second element, and no cracks were found.

JOINT TYPE:
Between tunnel elements: Gina gasket supplemented with flat rubber interior gasket. At shore ends of tunnel: Temporary tightening by rubber lip gaskets, allowing ramps to be emptied of water, whereupon the permanent rubber Omega gaskets were installed between the tunnel and the portal structures. The tunnel was made monolithic by casting reinforced concrete in the temporary gap between the two tunnel elements.

WATERPROOFING METHOD:	The elements are waterproofed with a 6-mm steel membrane on the bottom and sides. On the top, a bituminous membrane was installed and protected with 15 cm of reinforced concrete.
PLACEMENT METHOD:	Each of the tunnel elements was provided with bulkheads at the ends and equipped with six ballast tanks with a total capacity of 4,000 cu. m of water. After flotation, the elements were moved to their final position and sunk onto temporary supports approximately 1 m above the bottom of the excavated trench.
FOUNDATION METHOD:	Sand-jetting.
DREDGING METHOD:	A cutterhead suction dredge was used.
VENTILATION TYPE:	Longitudinal ventilation by means of jet fans.
COVER AND TYPE:	The eastern part, where the tunnel is located above the seabed, is protected with 1 m of gravel. No cover is provided for the remaining part of the tunnel.
ADDITIONAL INFORMATION:	The tunnel ramps are located in low water areas in the sound, and surrounded by dikes. Within the dikes. dewatering is performed by relief wells: the collected water is pumped out into the sound at the tunnel portals. The tunnel is designed to be unmanned, with automatic and remote controls. OWNER: Road Directorate. DESIGNER: Christiani & Nielsen A/S. CONTRACTOR: Guldborg Sound Consortium: Armton A/S/, and E. Phil & Son A/S.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Emstunnel; Leer, Germany; 1989

File No. 73

TUNNEL TYPE AND USE:
Vehicular; concrete box elements.

LANES/TRACKS:
Two tubes; two lanes plus one emergency lane/tube.

NO. OF ELEMENTS: 5

LENGTH: 127.5 m

HEIGHT: 8.40 m

WIDTH: 27.50 m

TOTAL IMMERSED LENGTH:
639.5 m

DEPTH AT BOTTOM OF STRUCTURE:
19 m below mean water level

UNUSUAL FEATURES:
An unexpectedly high rate of sedimentation (approx. 15 cm per tide change) filled the trench immediately after each element was placed. Special equipment was developed to remove the siltation under the element a few meters in front of the sand jetting operation.

ENVIRONMENTAL CONDITIONS:
Mean tide 2.61 m. Mean current 1 m/s. Siltation was a problem.

FABRICATION METHOD: The elements were built together in a graving dock adjacent to the tunnel trench. Each element was cast in five 25.5-m-long segments. To prevent cracks, a cooling system was installed. The segments were post-temsioned for placing, after which the post-tensioning bars were cut.

OUTFITTING:
After all of the elements were finished, the dock was flooded and the dike was removed using a dredge. Before floating each element, two pontoons equipped with lowering and mooring winches were floated over the elements and connected to them. After deballasting, the element floated with the pontoons on top.

JOINT TYPE:
Gina/Omega system. Elements divided into 25 segments.

WATERPROOFING METHOD:
Impermeable reinforced concrete with a bituminous layer over the roof, prtected with 0.2 m of protection concrete.

PLACEMENT METHOD:
After winching the element to its location, it was placed by ballasting and lowering. It was temporarily supported by primary and secondary supports.

FOUNDATION METHOD:
Jetted-sand foundation. Special equipment was developed to clean the area under the tunnel just in front of the sand-jetting operation.

DREDGING METHOD:
Cutterhead suction dredge and dustpan dredger.

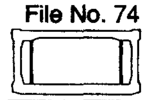
VENTILATION TYPE:
Longitudinal.

COVER AND TYPE:
Approximately 1 m of stone cover on reinforced concrete slab on toof the elements.

BUOYANCY SF: 0.02 for placement.

CONCRETE WORKING STRESS: DIN B35

ADDITIONAL INFORMATION:
OWNER: Autobahn-Beubaumt Oldenburg, Ministry of Transport, Federal Republic of Germany.
OPERATOR: Motorway-Authority Oldenburg.
DESIGNER: IMS Ingenieurgesellschaft mbH, Hamburg.
CONTRACTOR: HBW, the Netherlands: BREWABA; Bauunternehmen Hein; Beton und Tiefbau Mast; Martin Oetken.

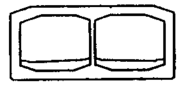
TUNNEL NAME/LOCATOIN/DATE COMPLETED: **Marne Tunnel; under the River Marne, Paris, France; 1989**			File No. 74 
TUNNELTYPE AND USE: Vehicular prestressed concrete box sections.		LANES/TRACKS: Two separate tunnels, with three lanes of traffic in each tunnel.	
NO. OF ELEMENTS: 7	LENGTH: 45–55 M	HEIGHT: 9 m	WIDTH: 17.5 m
TOTAL LENGTH: West Tunnel: 210 m. East Tunnel: 140 m.			
ENVIRONMENTAL CONDITIONS:	Restricted channel area.		
FABRICATION METHOD: In a casting basin at northern ramp site.		JOINT TYPE: Phoenix primary gasket and Omega secondary gasket.	
PLACEMENT METHOD:	Using mooring lines and ballasting. Level control maintained by four corner tanks. Two access shafts, one at each end of element.		
FOUNDATION METHOD:	Jacks and jetted or sand-flow foundation.		
DREDGING METHOD:	Backhoe-type dredge.		
VENTILATION TYPE:	Transverse, using side ventilation ducts.		

TUNNEL NAME/ LOCATION/ DATE COMPLETED: **Zeeburger Tunnel; Amsterdam, The Netherlands; 1989**			**File No. 75**
TUNNEL TYPE AND USE: Vehicular; reinforced concrete box section		LANES/TRACKS: Two tubes, three lanes each	
NO. OF ELEMENTS: 3	LENGTH: 112 m	HEIGHT: 8.125 m	WIDTH: 29.8 m
TOTAL IMMERSED LENGTH: 336 m		DEPTH AT BOTTOM OF STRUCTURE: 14.60 m	
UNUSUAL FEATURES:	Used telescoping pile to element closures. Constructed inside cofferdam for cut-and-cover tunnel. End of last element protrudes into dock, and has a collar around it to permit dewatering and construction in the dry.		
FABRICATION METHOD: Each of the three elements was constructed in sequence in the open construction dock at one end of the tunnel, which was equipped with a specially designed gate. Each element was cast in five 22.4-m-long sections, using a cooling system to prevent cracking.		JOINT TYPE: Gina and Omega gaskets.	
WATERPROOFING METHOD:	To prevent cracking, the elements were constructed of 22.4-m-long sections, post-tensioned together. No exterior waterproofing system was used.		
PLACEMENT METHOD:	A conventional system was used. The element was temporarily supported at the outboard end on two piles while the permanent pile connections were made.		
FOUNDATION METHOD:	Supported on piles driven to a depth of 46 m. Eight piles were used along the outer walls of the tunnel for each 22-m section. The piles are equipped with telescoping inflatable forms, which can be post-grouted to complete the closure between the top of the pile and the underside of the tunnel. 120 steel tubular injection piles 0.5 m in diameter were used to support the elements.		
DREDGING METHOD:	Barge-mounted crane and bucket.		
COVER AND TYPE: Gravel was placed on top of the tunnel. The trench was filled to -10 m, with the rest to be filled by natural siltation.		CONCRETE QUALITY: B25	
ADDITIONAL INFORMATION:	Bad soil conditions to -28 m.		

TUNNEL NAME/LOCATION/ DATE COMPLETED: Hong Kong Eastern Harbour Crossing; Hong Kong Harbour; 1990			File No. 76
TUNNEL TYPE AND USE: Vehicular and railway; reinforced concrete box.		LANES/TRACKS: Two rail tubes; two two-lane highway tubes; one tube for ventilation.	
NO. OF ELEMENTS: 15	LENGTH: 10 @122 m; 4 @128 m; 1 @126.5 m	HEIGHT: 9.5 m	WIDTH: 35 m
TOTAL IMMERSED LENGTH: 1,859 m		DEPTH AT BOTTOM OF STRUCTURE: 27 m	
UNUSUAL FEATURES:	Very large elements with 40,000- to 42,000-ton displacement. Use of waterfilled inflatable rubber bag "jacks" to hold element at grade until sand could be jetted in place under it. The Cha Kwo Ling Ventilation Building was built as a floating structure with the last five elements.		
ENVIRONMENTAL CONDITIONS:	Very busy harbour. Typhoon weather.		
FABRICATION METHOD: Elements were constructed in a rock quarry on the alignment. Gates were constructed in place before first flooding. Five elements were constructed at a time. Cycle times were 27 weeks, 25 weeks and 22 weeks, respectively.		OUTFITTING: Installation of control and survey towers and pontoons equipped with winches. Special telescoping towers were used for the last three shallower elements.	JOINT TYPE: Gina and Omega gaskets.
WATERPROOFING METHOD:	Concrete was poured in three stages—base, walls and roof—in successive bays up to 18 m long. Reinforcement was designed to limit crack width to prevent seepage. Heat of hydration was limited by replacement of 20% of cement with flyash. This also limited sulphate attack. The sides and roof were externally coated with sprayed-on epoxy rubber membrane. Visible cracks were grouted with epoxy resin prior to float-out.		
PLACEMENT METHOD:	Pontoons, mounted transversely over the element and controlled from the tower, lowered the element in place. Waterfilled inflatable bags were used as temporary (6 mos.) support element. Sand was jetted under element using slurry nozzles on each side of the element, fed from a barge.		
FOUNDATION METHOD:	Jetted sand.		
VENTILATION TYPE:	Fully transverse.		
COVER AND TYPE: 1.5 m of backfill.		BUOYANCY SF: 1.02 with no backfill; 1.15 with backfill	
ADDITIONAL INFORMATION:	OWNER: New Hong Kong Tunnel Company. DESIGNER: Freeman Fox. CONTRACTOR: Kumagai Gumi Co. Ltd.		

TUNNEL NAME/LOCATION/ DATE COMPLETED:
Conwy Tunnel; North Wales, United Kingdom; 1991

File No. 77



TUNNEL TYPE AND USE:	LANES/TRACKS:
Vehicular; concrete box elements .	Two tubes; two lanes each tube.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
6	118 m	10.4 m	24.1 m

UNUSUAL FEATURES:
The first immersed tunnel in the U.K. Due to the traffic requirements in the U.K., the tunnel is approximately 2 m higher than usual. The tunnel is skewed to the river, with an angle of less than 45 degrees.

TOTAL IMMERSED LENGTH:	DISPLACEMENT:	DEPTH AT BOTTOM OF STRUCTURE:
710 m	30,000 MT	±17 m

ENVIRONMENTAL CONDITIONS:
Sensitive scenic area. River crossing. Required relocation of small boat anchorages.

FABRICATION METHOD:
Elements were constructed together in a graving dock located next to the trench. Before casting, exterior waterproofing plates were placed on the bed. Each element was cast in segments, although continuous reinforcing was used. No cooling system was installed for the wall pours.

OUTFITTING:
After all of the elements were completed, the dock was flooded and the dike was removed by dredging. Before float-up, two pontoons with lowering and mooring winches were floated over each element to be placed and hooked up to it. After deballlasting, the element floated with the pontoons on top.

JOINT TYPE: Gina/Omega joint with six separate shear keys. Continuous shear keys of concrete not provided at joint. Joint covered with stainless steel joint covers on inside of tunnel.

WATERPROOFING METHOD:
The underside and walls are waterproofed with steel plate with a passive cathodic protection system and a concrete protected bituminous waterproofing membrane is provided on the roof.

PLACEMENT METHOD:
After winching the element to its location, it was placed by ballasting and lowering onto temporary footings.

FOUNDATION METHOD:
Jetted-sand foundation. Restrictions on ability to start sand-jetting caused sedimentation to occur under the tube. This was removed by airlifting.

DREDGING METHOD:
Cutterhead suction dredge. Spoil used for project embankment construction.

VENTILATION TYPE:
Longitudinal jet fans.

ADDITIONAL INFORMATION:
OWNER: Government of North Wales.
DESIGNER: Travers Morgan & Partners in association with Christiani & Nielsen A/S.
CONTRACTOR: Joint venture with Constain-Tarmac.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Liefkenshoek Tunnel; under River Schelde, Antwerp, Belgium; 1991

File No. 78

TUNNEL TYPE AND USE:
Vehicular; reinforced concrete box elements.

LANES/TRACKS:
Two tubes; two lanes, each with shoulders.

NO. OF ELEMENTS: 8	LENGTH: 142 m	HEIGHT: 9.6 m	WIDTH: 31.25 m

TOTAL IMMERSED LENGTH: 1136 m

DEPTH AT BOTTOM OF STRUCTURE:

UNUSUAL FEATURES: Specifically designed to carry vehicles with hazardous cargoes. Designed to be fire- and explosion-resistant. Funded under a concession contract. Separate escape passageways provided for each tube. A simulation was done of an anchor dropping on the immersed elements, by impact tests on the in-situ tunnel. Dynamic responses were measured.

ENVIRONMENTAL CONDITIONS: Strong currents.

FABRICATION METHOD:
All eights units were built at the same time in a casting basin located in the harbour area. Each element was cast in six 23.65-m-long segments. A cooling system was used to prevent cracks.

OUTFITTING:
After all elements were finished, the dock was flooded and the dike was removed by a dredge. Transverse floats were used. A temporary post-tensioning system was used. The elements had to pass through a lock before entering the river.

JOINT TYPE:
Gina and Omega gaskets.

WATERPROOFING METHOD: The elements were divided into six 23.7-m-long segments. Longitudinal prestressing was provided in the floor and roof. Carefully designed concrete was used: 1140 kg 4/28 gravel; 730 kg sand 0/5; 270 kg blast-furnace cement HL30; 80 kg flyash; 130 l water; and 3 kg superplasticiser.

PLACEMENT METHOD: A complete river and placement modelling study was carried out. The study showed that placement should be restricted to periods of neap to average tides to limit holding forces. A layer of trimming concrete was placed to reduce the freeboard without water ballast to 50 mm. Alignment towers 30 m high and other placement equipment was installed. The units were towed using four 3,000-HP tugs. Other tugs were on standby. The element was supported on two support points on the tunnel in place, and on two jacks at the outboard end. Support pads 6 x 6 x 1.2-m were used.

FOUNDATION METHOD: Sand-water mixture was pumped through sandfill valves. To avoid siltation, this operation was started within one hour after the sinking operation was completed.

DREDGING METHOD: A cutterhead suction dredger.

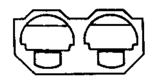
VENTILATION TYPE: Full transverse was used because of the hazardous cargo criteria.

COVER AND TYPE: Special asphalt mattresses were incorporated in the tunnel cover design to protect the tunnel.

ADDITIONAL INFORMATION: The interior of the tunnel was protected by 50 mm of insulation as a result of testing for a four-hour fire exposure. The tunnel design required some 50–60 Kg of additional reinforcing to cope with a 5-bar explosion overpressure.
OWNER: Ministry of Public Works and Transport.
DESIGNER: Haecon NV.
CONTRACTOR: Joint venture of De Meyer-Van Laere-Betonac.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Interstate 664 Tunnel; Hampton Roads, between Newport News and Chesapeake, Va., U.S.A.; 1992

File No. 79



TUNNEL TYPE AND USE:
Vehicular; double-steel-shell binocular section

LANES/TRACKS:
Two tubes; two lanes in each tube.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
15	95 m	12 m	24 m

TOTAL IMMERSED LENGTH: 1425 m

DEPTH AT BOTTOM OF STRUCTURE: 36 m

UNUSUAL FEATURES:
Extends between man-made peninsula and a man-made island, where it joins a trestle. At 6 miles long, it is one of the longest subsea crossings. This is one of the few immersed tunnel projects in the U.S. for which a drydock was used. The navigation channel was so narrow that it had to be closed during placement of the elements.

ENVIRONMENTAL CONDITIONS:
Very strong tidal currents around the point where the James River meets the open water of Hampton Roads required heavy anchor lines and special precuations during maneuvering and placement of the elements. Very active ship channel, with much pleasure-boating.

FABRICATION METHOD:
Elements were fabricated in Baltimore at the Sparrows Point Shipyard of Bethlehem Steel Co. The elements were assembled in a drydock, and all interior concrete (except walkways) was installed before closing the ends with bulkheads. The elements were then floated out with approximately 7.5 m draft. An additional 2,700 cu. m was added at a pier prior to towing the element to Newport News (draft was about 10 m).

OUTFITTING:
Interior concrete was placed at a shipyard. Final concrete was placed at jetty in Newport News, Va.

JOINT TYPE:
Standard double gasket and closure plate detail used in the U.S. for many years.

WATERPROOFING METHOD:
Steel shell and liner plate.

PLACEMENT METHOD:
Remotely controlled weges used for horizontal alignment. Conventional catamaran barge system was used, with a laybarge consisting of two railroad car barges with support beams between them.

FOUNDATION METHOD:
Screeded foundation. Screed rig designed to be unaffected by tidal variations.

DREDGING METHOD:
Cutterhead suction dredging and pumping behind dikes to form manmade island and peninsula. Cleanup dredging was done with a clamshell dredge.

VENTILATION TYPE:
Fully transverse ventilation system split between two ventilation buildings.

COVER AND TYPE: A 0.90-m wall was constructed on each element to contain rock ballast. In addition, rock and armor stone were placed on top of the element as protection.

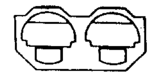
BUOYANCY SF: 1.03
After dewatering, joints, 1.07 without backfill.

CONCRETE WORKING STRESS:
4,000 psi

ADDITIONAL INFORMATION:
OWNER: Virginia Department of Transportation.
DESIGNER: Sverdrup Corporation.
CONTRACTOR: Morrison Knudsen, Inc., and Interbeton Inc. joint venture.

TUNNEL NAME/ LOCATION/ DATE COMPLETED:
Third Harbour Tunnel*; Boston Harbor, Boston, Massachusetts, U.S.A.; U/C (1994)

File No. 80



TUNNEL TYPE AND USE:
Vehicular; double steel shell binocular section.

LANES/TRACKS:
Two tubes; two lanes each tube.

NO. OF ELEMENTS:
12

LENGTH:
98.30 m

HEIGHT:
12.29 m

WIDTH:
24.43 m

TOTAL IMMERSED LENGTH:
1,172.9 m

DEPTH AT BOTTOM OF STRUCTURE:
30 m

UNUSUAL FEATURES:	Much of tunnel trench excavated through hard argellite rock. Immersed tunnel ends incorporated into very deep cofferdams. Depth at cofferdams at bottom of end elements more than 20 m below sea level. First use of Omega gasket in a U.S. tunnel.
ENVIRONMENTAL CONDITIONS:	Many environmental constraints regarding filling in harbor, spawning of fish, blasting, siltation, work around and airside at Logan International Airport, and impacts from harbor celebrations and activities such as "Sail Boston '92."

FABRICATION METHOD:
At shipyard, elements assembled in drydock two at a time and floated out. Each tube floated onto large ocean-going submersible barge (106 x 30 m) for tow to Boston. Tow made using a single 9,000-HP ocean tug direct route between Norfolk, Va., and Cape Cod, Mass.

OUTFITTING:
At pier near tunnel site.

JOINT TYPE:
Double gasket system commonly used in U.S., but with Omega secondary gasket. Joint detail provides for thermal expansion at joint.

WATERPROOFING METHOD:	Steel shell and Omega gasket closures. Closure plate detail not used on this project.
PLACEMENT METHOD:	From catamaran barges. Remotely controlled wedges used for horizontal alignment.
FOUNDATION METHOD:	Screeded foundation.
DREDGING METHOD:	Drill and blast. Used the "Super Scoop", owned by Dutra Corp., with up to 17.5-m^3 buckets for removal of silts, sands, till and rock.
VENTILATION TYPE:	Fully transverse ventilation system. Centrifugal fans.
COVER AND TYPE:	0.6 m of protective rock over .9 m of gravel.
ADDITIONAL INFORMATION:	OWNER: Massachusetts Highway Department. DESIGNER: Preliminary Design: Bechtel/Parsons Brinckerhoff. Final Design: Sverdrup Corporation. CONTRACTOR: Morrison Knuedsen/Interbeton/J. F. White joint venture.

TUNNEL NAME / LOCATION/ DATE COMPLETED:
Willemspoortunnel*; Rotterdam, The Netherlands; U/C

File No. 81

TUNNEL TYPE AND USE:
Railway; concrete box elements.

LANES/TRACKS:
Two tubes; two tracks each tube.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
8	115–138 m	8.62 m	28.82 m

TOTAL IMMERSED LENGTH:
1,012 m

UNUSUAL FEATURES: Unusually difficult, restrictive urban and marine site. Elements placed between cofferdam walls in some areas.

ENVIRONMENTAL CONDITIONS: Very difficult urban and marine constraints on construction. Heavily trafficked waterway. Close to many sensitive existing structures and rail facilities.

FABRICATION METHOD:
Elements were fabricated in five or six 23-m segments post-tensioned together. A cooling system was used. Segments have large triangular shear keys shaped in the vertical walls. Casting was done in an existing basin at Barendrecht, where several other immersed tunnels have been built.

OUTFITTING:
Outfitting for placement was done in the casting basin. Elements were ballasted to keep them on the bottom prior to placement. Each was then floated individually and towed to the site with 20 cm of freeboard. The trip took one day. A catamaran barge system was used for placing.

JOINT TYPE:
Gina/Omega.

WATERPROOFING METHOD: No waterproofing layers were used. Concrete segments were sized and designed to prevent cracking, and careful concrete mix and temperature control were used for each segment.

PLACEMENT METHOD: On the left (northwest) side of the Maas, the elements were lowered from girders. On the right side, across the Nieuwe Maas, floating pontoons were used. The closure joint was made between the last two elements.

FOUNDATION METHOD: Sand-flow foundation.

DREDING METHOD: Backhoe dredging and a cutterhead suction dredge.

COVER AND TYPE: 1.0 m protection.

VENTILATION TYPE: Piston action of trains.

CONCRETE QUALITY: B30.

ADDITIONAL INFORMATION:
OWNER: Dutch Railway.
DESIGNER: Rijkswaterstaat Bouwdienst.
CONTRACTOR: KWT Joint Venture: Dirk Verstoep Rotterdam; Ballest Nedam; Van Hattum in Blankevoort; Strukton Beton bouw.

TUNNEL NAME/LOCATION/ DATE COMPLETED: Niigata Port Road Tunnel*; Niigata, Japan; U/C			File No. 82
TUNNEL TYPE AND USE: Vehicular	LANES/TRACKS: Two tubes; two lanes each tube.	TOTAL IMMERSED LENGTH: 850 m	
NO. OF ELEMENTS: 8	LENGTH: 107.5/110.5 m	HEIGHT: 8.75 m	WIDTH: 28.6 m

TUNNEL NAME/LOCATION/ DATE COMPLETED: Tama River Tunnel*; Tokyo, Japan; U/C			File No. 83 
TUNNEL TYPE AND USE: Vehicular; reinforced concrete box prestressed longitudially for watertightness.		LANES/TRACKS: Two tubes; three lanes each. Escape passageways and utility space for gas, electric and drainage lines in the side ducts.	
NO. OF ELEMENTS: 12	LENGTH: 128.6 m	HEIGHT: 10.0 m	WIDTH: 39.7 m
TOTAL IMMERSED LENGTH: 1,549.5 m		DEPTH AT BOTTOM OF STRUCTURE: 30 m	
UNUSUAL FEATURES:	All of the tunnel was constructed on a curve. Flexible earthquake joints were provided between all the tunnel elements. Piles were driven in casting basin bottom after it was stabilized with soil cement. Liquid nitrogen was used to cool sand during summer concreting. Blast furnace cement was used to reduce thermal cracking.		
ENVIRONMENTAL CONDITIONS: At the mouth of the Tama River.			
FABRICATION METHOD: Fabricated in a graving basin used jointly for the Tama River and Kawasaki Fairway Tunnels. The basin accommodated 11 elements at a time and had a floor area of 107,000 sq. m (592 m x 190 m).		JOINT TYPE: Gina/Omega-type joint. Flexibility is provided by the rubber joint, in combination with the use of post-tensioned rods tightened across the joint. Three vertical shear keys provided in the walls and one horizontal key in the floor provide stability against displacements due to earthquakes and/or settlements.	
WATERPROOFING METHOD:	8-mm steel plate on sides and bottom of elements; concrete protected by 2.5-mm-thick rubberized membrane on top slab. Steel plates are cathodically protected.		
PLACEMENT METHOD:	Catamaran barges. 10-cm freeboard. 500 MT during lowering (1%) and 1500 MT in place (3%) prior to placing final ballast (1.1 SF against flotation, not counting backfill).		
FOUNDATION METHOD:	Mortar pumped over gravel foundation bed.		
VENTILATION TYPE: Longitudinal ventilation.		COVER AND TYPE: 1.5 m of stone cover.	
ADDITIONAL INFORMATION:	Mix proportions for tunnel element concrete: w/c .515; water 155 kg/cu. m; cement 301 kg/cu. m; sand 834 kg/cu. m and gravel 1034 kg/cu. m. OWNER: Metropolitan Expressway Public Corporation. CONTRACTORS: Tamagawa Tunnel Joint Venture: Kajima Corporation; Kumagai Gumi Co. Ltd.; Ohbayashi Corporation; Shimizu Corporation; Nishimatsu Construction Co., Ltd.; Okumura Corporation; Fujita Corporation; Toa Corporation.		

TUNNEL NAME/LOCATION/ DATE COMPLETED:
Kawasaki Fairway Tunnel*; Tokyo, Japan; U/C

File No. 84

TUNNEL TYPE AND USE:
Vehicular; reinforced box concrete elements prestressed longitudinally for watertightness.

LANES/TRACKS:
Two tubes; three lanes each. Escape passageways and utility space for gas, electric and drainage lines in the side ducts.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
9	131.2 m	10.0 m	39.7 m

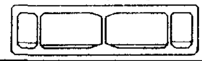
TOTAL IMMERSED LENGTH: 1180.9 m	ELEMENT DISPLACEMENT WEIGHT: 52,000 MT	DEPTH AT BOTTOM OF STRUCTURE: 26 m

UNUSUAL FEATURES:	Flexible earthquake joints were provided between the tunnel elements. Piles were driven in casting basin bottom after it was stabilied with soil cement. Liquid nitrogen was used to cool sand during summer concreting. Blast furnace cement was used to reduce thermal cracking. Part of same roadway as Tama River Tunnel.
ENVIRONMENTAL CONDITIONS:	At mouth of Daishi Canal and entrance to Kawasaki Port.

FABRICATION METHOD:
Fabricated in a graving basin used jointly for the Tama River and Kawasaki Fairway Tunnels. Basin accommodated 11 elements at a time and had a floor area of 107,000 sq. m (592 m x 190 m). Basin was used jointly for Tama River Tunnel.

JOINT TYPE:
Gina/Omega-type joint. Flexibility was provided by the rubber joint, in combination with the use of post-tensioned rods tightened across the joint. Three vertical shear keys in the walls and one horizontal key in the floor provide stability against displacement.

WATERPROOFING METHOD:	8-mm steel plate on sides and bottom of elements; concrete-protected rubberized membrane on top slab. Steel plates are cathodically protected.
PLACEMENT METHOD:	Catamaran barges. 500 MT during lowering (1%) and 1500 MT in place (3%) prior to placing final ballast (1.1 SF against flotation, not counting backfill).
FOUNDATION METHOD:	Mortar pumped over gravel foundation bed.
VENTILATION TYPE:	Longitudinal ventilation.
COVER AND TYPE:	1.5 m of stone cover.
ADDITIONAL INFORMATION:	Mix proportions for tunnel element concrete: w/c, .515; water, 155 kg/cu. m; cement, 301 kg/cu. m; sand, 834 kg/cu. m and gravel, 1034 kg/cu. m. OWNER: Metropolitan Expressway Public Corporation. DESIGNER:: Oriental Consultants Co., Ltd.; Pacific Consultants Co., Ltd. CONTRACTORS: Maeda Construction Co., Ltd.; Hazama Gumi, Ltd.; Tobishima Corporation; Penta-Ocean Construction Co., Ltd.; Sato Koyo Co., Ltd.

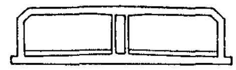
TUNNEL NAME/LOCATION/ DATE COMPLETED: **Sydney Harbour Tunnel*; Sydney Australia; U/C**			**File No. 85** 
TUNNEL TYPE AND USE: Vehicular; concrete box elements.		LANES/TRACKS: Two tubes; two lanes each tube.	
NO. OF ELEMENTS: 8	LENGTH: 120 m	HEIGHT: 7.43 m	WIDTH: 26.1 m
TOTAL IMMERSED LENGTH: 960 m		DEPTH AT BOTTOM OF STRUCTURE: 25 m	
UNUSUAL FEATURES:	Element No. 1 was laid against the ventilation building at the north end of the tunnel. A short stub section of tunnel built into the ventilation building was provided with a sill beam to receive the first element. Element No. 2 was placed next. Element No. 8 was then placed; the connection to the land tunnel was made in a unique cofferdam in order to protect the Sydney Opera House forecourt. A cofferdam was built over and around the end of the element; a tremie seal to the sandstone rock was made at the front. To allow for differential settlement between elements No. 7 and No. 8, a special flexible joint was attached to the end of element No. 7. Temporary bars were cut after the elements were in place. Unique protective stone armour for dragging or falling anchors was used.		
ENVIRONMENTAL CONDITIONS:	Very environmentally sensitive area at scenic Sydney Harbour, with the Sydney Opera House almost in the alignment. These conditions led to the unique use of a bridge pier for vent stack.		
FABRICATION METHOD: The elements were built in two groups of four in a graving dock. The elements have continuous reinforcement, but were cast in sections.	TOWING/OUTFITTING: Elements were cast in Port Kembla, 100 km away. Extensive model studies were undertaken to assure feasibility of tow. A freeboard of 0.5 m was used during tow. At the outfitting pier in Sydney, further ballast and placing equipment was installed, bringing elements to almost neutral buoyancy.		JOINT TYPE: Gina/Omega type of joint. A special prefabricated settlement joint was provided on element No. 7, which was founded on sand. Element No. 8 was connected into a sandstone wall and a tunnel was mined to it.
WATERPROOFING METHOD:	A PVC membrane was used on the bottom. The sides and top were covered with an epoxy resin coating. Low heat of hydration with good impermeability to chloride ion penetration was achieved using a high replacement blend of Type A cement and ground granulated blast furnace slag. Sulphate resistance was also good. Blast furnace slag was not chosen for coarse aggregate because of a 3% lower density than natural basalt aggregate mix.		
PLACEMENT METHOD:	Transverse pontoons.		
FOUNDATION METHOD:	Sand-flow method utilizing pipes installed in the walls from the roof slab to the base slab. Element No. 8 was supported on a foundation of cement-based grout. The other elements were founded on sand.		
DREDGING METHOD:	Alluvial deposits were dredged using a grab dredge. Sandstone deposits were dredged using a cutterhead suction dredge. Provisions made for blasting were not required.		
VENTILATION TYPE:	Semi-transverse, using side ducts. Pier shafts of cable-stay bridge were used as exhaust stacks at one end of tunnel.		
COVER AND TYPE:	A 2-m cover of rock fill with rock armour flanks was provided. The rock fill was designed to absorb the impact of a falling anchor; the rock armour was designed to deflect an anchor dragged across the tunnel.		

TUNNEL NAME/LOCATION/ DATE COMPLETED: **Osaka South Port Tunnel*; Osaka, Japan; U/C**			**File No. 86**
TUNNEL TYPE AND USE: Vehicular and railway; rectangular		LANES/TRACKS: Four-lane vehicular; two-track railway.	
NO. OF ELEMENTS: 10	LENGTH: 102.5 m	HEIGHT: 8.80 m	WIDTH: 34.8 m
TOTAL IMMERSED LENGTH: 1025 m		UNUSUAL FEATURES: Mixed highway and railroad service.	

TUNNEL NAME/LOCATION/ DATE COMPLETED: **Bilbao Metro*; rail tunnel under Bilbao Estuary for Deusto-Olavega section of Bilbao Metro Line 1, Bilbao, Spain; U/C**			**File No. 87** 
TUNNEL TYPE AND USE: Metro railway; reinforced concrete box elements.		LANES/TRACKS: Two tubes; single rail each tube.	
NO. OF ELEMENTS: 2	LENGTH: 85.35 m	HEIGHT: 7.2 m	WIDTH: 11.4
TOTAL IMMERSED LENGTH: 172.2 m		DEPTH AT BOTTOM OF STRUCTURE: 17 m	
FABRICATION METHOD: In casting basin within excavation for cut-and-cover tunnel on Deusto side of river.		OUTFITTING:	JOINT TYPE: Gina/Omega.
WATERPROOFING METHOD:	Steel membrane on bottom and sides. Bituminous membrane on roof.		
FOUNDATION METHOD:	Jetted sand foundation.		
VENTILATION TYPE:	Piston action.		
ADDITIONAL INFORMATION:	OWNER: Basque Government, Department of Transport and Public Works. DESIGNER: Chrisitiani & Nielsen. CONTRACTOR: AGROMAN Empresa Constructuora, S.A.		

TUNNEL NAME/LOCATION/ DATE COMPLETED:
Noord Tunnel*; Alblasserdam, The Netherlands (crossing De Noord River); U/C

File No. 88



TUNNEL TYPE AND USE:
Vehicular tunnel; concrete box elements.

LANES/TRACKS:
Two tubes; three lanes each tube.

NO. OF ELEMENTS:	LENGTH:	HEIGHT:	WIDTH:
4	3 @130 m; 1 @ 100 m	8.30 m	29.95 m

TOTAL IMMERSED LENGTH: 492 m

DEPTH AT BOTTOM OF STRUCTURE: 16 m

UNUSUAL FEATURES:
To avoid dredging of the river to allow transport of the elements, the roofs of the elements were only partially cast. This reduced the draft of the elements enough to tow them to the site. The roofs were then completed.

FABRICATION METHOD:
Th elements were constructed together in a graving dock, at the same time that the elements for the Willemspoor Tunnel were under construction. Three elements were cast in five 26.15-m segements; one element was cast in four 24.85-m segments. A cooling system was installed.

OUTFITTING:
The elements were deballasted, floated, and prepared for a two-day tow over tidal water and rivers. After the elements arrived at the site, the remaining portions of the roof were cast, as well as a portion of the ballast concrete on the bottom slab. This was used as added weight for placing.

JOINT TYPE:
Gina/Omega.

WATERPROOFING METHOD:
No exterior waterproofing was used. Concrete segments were sized and designed to avoid cracking. Concrete was designed to reduce thermal cracking and produce high-density impermeable segments.

PLACEMENT METHOD:
Four small pontoons with hoisting and mooring winches were hoisted on top of the tunnel. Conventional placing methods were used. The closure joint was made in the river between the last two elements.

FOUNDATION METHOD:
Sand-flow method.

DREDGING METHOD:
Cutterhead suction dredge.

VENTILATION TYPE:
Longitudinal.

COVER AND TYPE:
1.0 m of gravel protection.

ADDITIONAL INFORMATION:
OWNER: Rijkswaterstaat, The Department of Public Works.
ENGINEER: Consortium - DHV, Haskoning and Wittenveen & Bos forming Tunnel Engineering Consultants (TEC) to work in kind of Joint Venture with Engineers from Rijkswaterstaat.
CONTRACTORS: Kombinatie Tunnelbouw (KTB), a consortium of four firms: Ballast Nedam, Van Hattum & Blankevoort, Hollandsche Beton & Waterbouw, and Dirk Verstoep.

TUNNEL NAME/ LOCATION/ DATE COMPLETED: **Grouw Tunnel*; Grouw, The Netherlands; U/C (1993)**			**File No. 89**
TUNNEL TYPE AND USE: Vehicular; concrete box tunnel		LANES/TRACKS: Two tubes, two lanes each (two highway, two local roads)	
NO. OF ELEMENTS: 1	LENGTH: 88 m	HEIGHT: 7 m	WIDTH: 32 m
TOTAL IMMERSED LENGTH: 88 m		DEPTH AT BOTTOM OF STRUCTURE: 11.5 m	
UNUSUAL FEATURES:	Supported on the abutments.		
FABRICATION METHOD: The element was constructed in the approach. It was cast in four sections without flexible joints. Reinforcement was continuous and the tunnel was permanently prestressed.		OUTFITTING: After the approach structure was flooded, the element was pulled through it across the channel. Water ballast tanks were in river retaining structures on top of the element.	JOINT TYPE: An inflatable rubber gasket and an Omega gasket.
WATERPROOFING METHOD:	There was no separate exterior waterproofing membrane.		
PLACEMENT METHOD:	The river retaining structures were designed to eliminate the need for additional equipment. Water ballasting was sufficient.		
FOUNDATION METHOD:	The element was supported on both abutments like a bridge.		
DREDGING METHOD:	Cutterhead suction dredger.		
VENTILATION TYPE:	No ventilation system.		
COVER AND TYPE: 10 cm of concrete.		CONCRETE QUALITY: B35	

TUNNEL NAME/ LOCATION/ DATE COMPLETED: Medway Tunnel*; Rochester, U.K.; U/C (1995)				File No. 90
TUNNEL TYPE AND USE: Vehicular; concrete box sections			LANES/TRACKS: Two tubes; two lanes, with shoulder in each tube	
NO. OF ELEMENTS: 3	LENGTH: 126/118		HEIGHT: 9.15 m	WIDTH: 25 m
TOTAL IMMERSED LENGTH: 370 m			DEPTH AT BOTTOM OF STRUCTURE: 18.65 m	
UNUSUAL FEATURES:	First design/construct tunnel in the U.K. The tunnel is designed to withstand possible uplift from water pressures in a chalk layer.			
FABRICATION METHOD: A graving dock for the elements was provided at the eastern portal. On completion of the elements, the graving dock will be opened, and the elements will be removed and placed. The approach structure will then be constructed in the closed dock. The elements were cast in six 21-m segments.			OUTFITTING: The elements will be deballasted, floated and towed out of the dock into the trench and placed. A small catamaran barge system was developed.	JOINT TYPE: Gina/Omega gasket system.
WATERPROOFING METHOD:	A separate waterproofing membrane was used.			
PLACEMENT METHOD:	The elements will be lowered by two small catamarans while the elements are positioned with winches. The closure joint will be made between the last element and the approach structure.			
FOUNDATION METHOD:	Sand-flow method.			
VENTILATION TYPE:	Longitudinal. Fans are located in recesses in the cut-and-cover section. This arrangement reduced the height of the elements considerably.			
COVER AND TYPE:	2 m of stone protection and a seal in the river on top of the dredged area, to prevent river water from entering the chalk.			

TUNNEL NAME/ LOCATION/ DATE COMPLETED: **Schiphol Railway Tunnel*; Amsterdam, The Netherlands; U/C (1994)**			**File No. 91**
TUNNEL TYPE AND USE: Railway; concrete box tunnel		LANES/TRACKS: Two tubes, one track each.	
NO. OF ELEMENTS: 4	LENGTH: 125 m	HEIGHT: 8.05 m	WIDTH: 13.60 m
TOTAL IMMERSED LENGTH: 500 m		DEPTH AT BOTTOM OF STRUCTURE: 9 m	
UNUSUAL FEATURES:	The railway tracks under the airport are being doubled (from two to four). The new tunnel will be constructed directly adjacent to the existing tunnel. Most of the 5.7 km of the railroad tunnels are being constructed by cut-and-cover methods; however, 500 m under a runway will be constructed by immersed tunnel methods to save time.		
FABRICATION METHOD: The construction dock was made in the adjacent cut-and-cover area. Each element consists of six segments with flexible joints.		OUTFITTING: The constructed dock consisted of a sheetpile cofferdam with bracing across the to The elements were fully outfitted in the dock.	JOINT TYPE: Gina and Omega gaskets were used.
WATERPROOFING METHOD:	No exterior waterproofing membrane was used.		
PLACEMENT METHOD:	After the dock filled with groundwater, the elements were floated to a freeboard of 15 cm and pulled by winches under the bracing to their posistion. The elements were lowered from hoists on beams across the top of the cofferdam while they were ballasted with water.		
FOUNDATION METHOD:	Sand-flow method.		
DREDGING METHOD:	Land excavation.		
VENTILATION TYPE:	No ventilation system.		
COVER AND TYPE: 1 m of compacted layers under the runway pavement.		CONCRETE WORKING STRESS: B35	

Chapter 6:

SUBMERGED FLOATING TUNNELS

by

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Chapter 6: Submerged Floating Tunnels

1. Introduction

1.1 The ITA and Submerged Floating Tunnels

In 1989, the International Tunnelling Association (ITA) established a Working Group on Immersed and Floating Tunnels in order to give more worldwide attention to this type of tunnelling.

The task of the Working Group is to present the state of the art for two types of tunnels:

1. *Immersed or Submersed Tunnels*, which can be used in rivers or waterways when it is possible to place the tunnel in the riverbed or seabed. These types of tunnels have been built for many years.

2. *Submerged Floating Tunnels* (SFTs), which represent a new concept for crossing deep waterways. In this case, the tunnel is not an embedded structure, but instead is suspended.

Because both types of tunnels involve many different aspects, a number of subworking groups were established. Each sub-group was composed of specialists in the particular field. The development in recent years of proposals for "floating" sub-aqueous tunnels resulted in the formation of the subworking group on Submerged Floating Tunnels.

In a number of countries, especially Norway, Italy and The Netherlands, extensive research has been done on specific tunnel schemes for crossing deep and relatively narrow waterways.

The solution—a suspended tunnel structure—has passed the preliminary and conceptual design stage, supported by detailed research and hydraulic model tests. It has now reached the stage where an actual project employing this new type of tunnel could be realized in the near future.

The state of the art for this type of tunnel is presented in this chapter. Part Chapter 6 explains the concept of the Submerged Floating Tunnel (SFT) and the opportunities it represents. The second half of the chapter presents relevant technical information about the SFT concept.

1.2 Submerged Floating Tunnel (SFT)

1.2.1 Description

The tunnel structure discussed in this chapter would serve all types of traffic between two shores separated by deep water. The unique feature of this type of tunnel is that it bridges both shores and is not buried in or placed on top of the bed of the waterway.

From the users' point of view, the structure has all the usual characteristics of a tunnel. Because it is closed, it is considered a "tunnel" rather than a "bridge".

The difference between this type of tunnel and a conventional immersed or bored tunnel is that the floating tunnel structure is surrounded by water. That is, the tunnel is neither placed within nor bored through the ground. Instead, the tunnel structure is kept in position by virtue of its own structural capability, though it may be augmented by a support system. The support system may take several forms, such as:

- Pontoons on the surface.
- Tension anchoring to the bed.
- Compression anchoring to the bed.
- Horizontal anchoring.
- Combinations of the above methods.
- Anchoring at the abutments only.

The tunnel is positioned below the water surface in such a way that ships can pass above it without undue interference.

Different types of submerged floating tunnels are presented in Figures 6-1; 6-2, 6-3, 6-4, and 6-5.

The submerged floating tunnel examined herein uses existing technology. The materials, the design methods, and the construction methods are known and conventional, but they are combined in a new and specific way. It

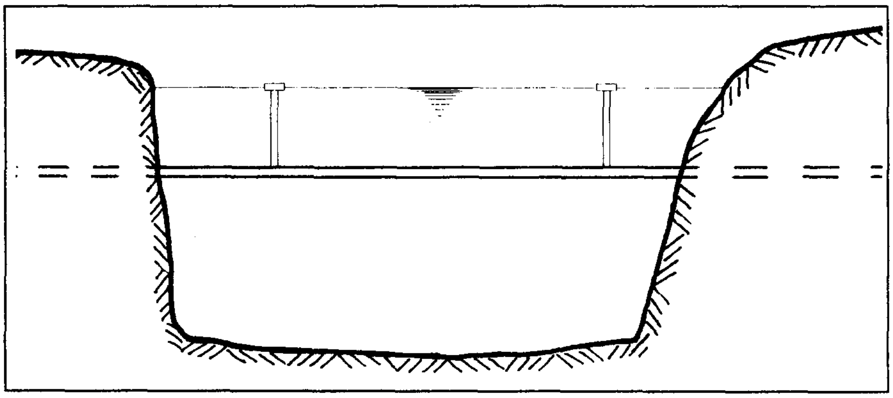

Figure 6-1. Pontoons on the surface.

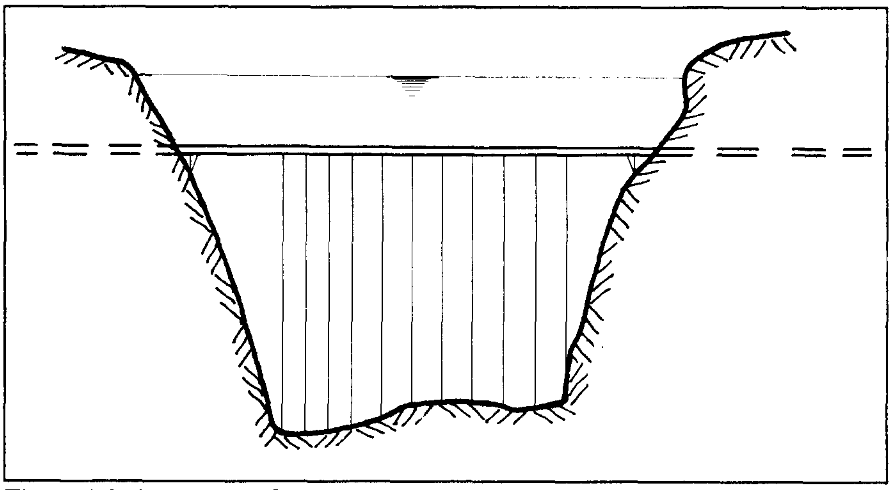

Figure 6-2. Tension anchoring to the bed.

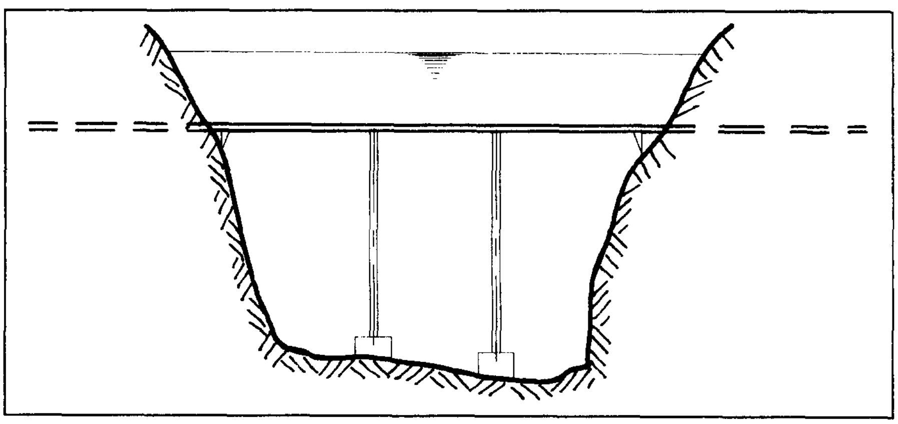

Figure 6-3. Compression anchoring to the bed.

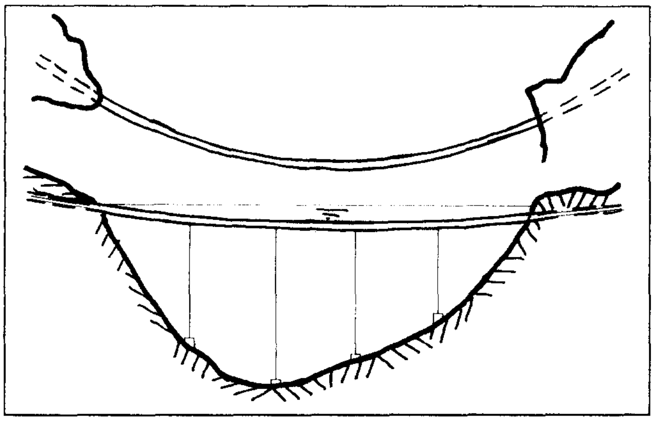

Figure 6-4. Horizontal anchoring.

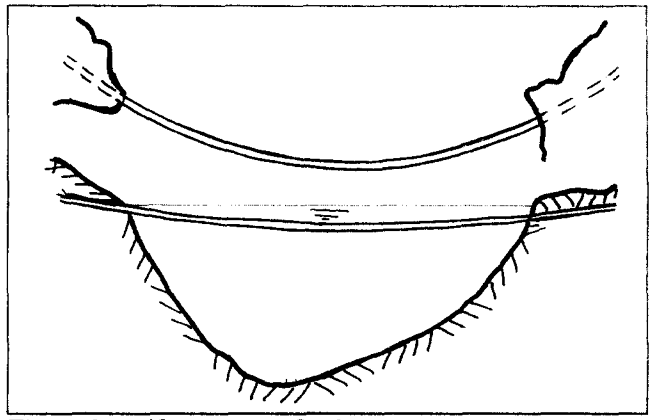

Figure 6-5. Abutment anchoring.

is important to stress that *these structures do not include any totally new features that have not been encountered in tunnelling.*

1.2.2 Name of Structure Type

This type of structure has been called by various names, such as:

- Submerged Tube.
- Submerged Tube Bridge.
- Submerged Floating Tube.
- Floating Tunnel.
- Underwater Bridge.
- Submerged Floating Tunnel

The last of these terms seems to be the most accurate for describing the following main features of such structures:

Submerged: the tunnel is located under water.
Tunnel: it is a closed structure.
Floating: the structure has a large floating capacity and is surrounded by water.

Therefore, this report will refer to this type of structure as a "Submerged Floating Tunnel," abbreviated as "SFT".

2 Feasibility of Submerged Floating Tunnels

2.1 Opportunities for Submerged Floating Tunnels

An SFT can span different types of waterways—estuaries, rivers, fjords, sounds, lakes, etc.—without interfering with shipping.

In some cases, an SFT may be the *only* possible, affordable and acceptable form of fixed crossing because of constraints such as deep water, distance between the shores, or environmental considerations (see discussions below).

The SFT technique offers the opportunity to plan crossings where they have never before been thought possible.

In other cases, an SFT may be an alternative to another type of fixed crossing, such as a bridge, a pontoon bridge, a floating bridge, a bored tunnel or an immersed tunnel. Investigations have shown that the SFT may be highly competitive with these solutions in some situations.

Another advantage of the SFT is that the crossing is invisible, making it attractive from an environmental standpoint. In addition, the gradients are very small and surface waterway traffic is, in principle, not obstructed.

Until now, considerations for SFTs have most often focused on their use for road traffic (e.g., as with the Høgsfjord and Strait of Messina crossing, described in sections 2.6.1 and 2.6.2.). However, the SFT concept can be applied for other purposes, such as:

- *Pedestrian tunnels*: connecting the mainland and a recreation island in a deep lake, for example.
- *Service tunnels*: to guide pipelines and cables.

2.2 Safety

Research has shown SFTs to be technically and economically feasible. But are they also safe? The answer is yes, because *the level of safety required for an SFT will be the same as that required for comparable structures*, e.g., bridges. Comparisons of the probability of failure of an SFT with the probability of failure of other forms of crossings show that the chance of failure is of the same order. This is not surprising, considering that the technologies used for the SFT, notably those concerning materials and design methods, are based on already existing technologies.

There are two particular aspects related to safety of SFTs:

1. *Technological safety*. This will be assured during the design of the total structure and its components, by adapting design rules and knowledge derived from experience (see section 3).

2. *Psychological safety*. Although the expected movements are structurally acceptable, the human interpretation of such movements can be of major importance. It is therefore critical that the movements of the structure be kept below the limits of human observation. Research has shown that this is the case for the two SFT projects currently being prepared (see Section 2.6). In general, it can be said that the psychological interpretation limit of the movements is more critical than the technological limits.

Because the SFT concept is new, extra attention must given to the safety aspects. This means that the first Submerged Floating Tunnel will be based on rather conservative criteria and design assumptions. Research on the Høgsfjord and Messina Strait crossings has shown that all safety regulations can be met.

Measurements can be taken to minimize the risks of ship collision and to bring these risks into a range that is lower than that for comparable risks (see also the discussion in section 3.2.4).

2.3 Costs

2.3.1 Construction Costs

At present, the cost of building an SFT can only be an order of magnitude estimate. Obviously, the construction costs will vary from project to project because they are highly dependent on the local site conditions.

Based on cost experience on projects of similar magnitude and on the preliminary cost estimates of SFT projects studied in recent years, a comparison with the cost of relevant alternatives, such as a suspension bridge, can be made (see Fig. 6-6). The construction costs of an SFT, per meter length, do not increase significantly with the length of the crossing or with the depth of the waterway, making an SFT competitive with suspension bridges having spans greater than 800 to 900 m.

Even in cases where the SFT would be considered the only feasible alternative, the costs are not unreasonably high.

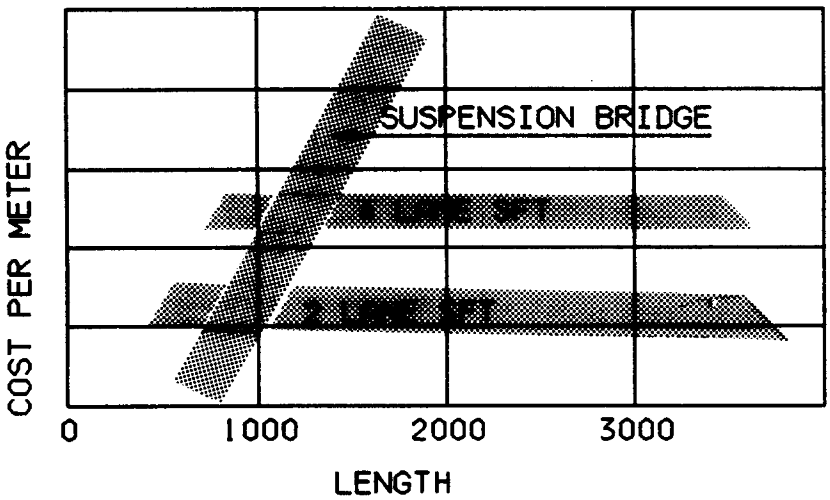

Figure 6-6. Cost comparison for SFT solution vs. suspension bridge.

For an SFT with more than two lanes, the large uplift forces may increase the costs.

2.3.2 Operational Costs

In general terms, the expected operational cost of an SFT will comprise:

- The usual operating and maintenance costs related to tunnels in general, such as lighting, ventilation, interior cleaning, drainage, traffic control, etc.; and
- Costs particular to an SFT structure. The first SFT constructed will carry additional costs, at least during the early years, for instrumentation, monitoring, inspection, reporting and, subsequently, verification of the design.

Maintenance costs for the external surface are expected to be very low. Because marine growth is one of the design criteria, no costs for removal of such growth will arise.

For tunnels that involve separate means of support or tie-down for the structure, external inspection and maintenance will be necessary and will continue throughout the life of the tunnel. This maintenance may require replacing components, although the total cost of such inspection and maintenance is not expected to be high.

2.4 Environment

SFTs have a number of special features, many of which offer good solutions to environmental constraints. As noted above, the use of an SFT may make a crossing possible where planners in the past thought it was impossible. Some examples of the SFT solution are given below.

Case #1: An inland lake having severe traffic problems around the perimeter, especially during tourist seasons. The car and heavy truck traffic has become such a problem that the area is becoming less attractive every year. However, because of the natural beauty of the lake, a suspension bridge or floating bridge is not desirable.

In such a case, only three "invisible" alternatives are possible:

1. A tunnel underneath the bed of the lake.
2. An immersed tunnel.
3. A Submerged Floating Tunnel.

If the lake is very deep, a tunnel underneath the bed might be very long and, consequently, expensive to construct, maintain and use.

If the water depth is moderate, an immersed tunnel may be contemplated; however, if the depth is considerable, this solution must be ruled out.

For such a situation, an SFT could be the only answer. It could be located invisibly at a level fairly near the surface of the water, because the sea state of the lakes is much more than moderate, and the tunnel could take the shortest route across the lake (see Fig. 6-7). Furthermore, an SFT would require only a limited construction area at the side of the lake, thereby minimizing interference with the existing traffic.

Additionally, the SFT solution would have the merit of limited environmental impact.

Case #2: A city or an area of environmental interest alongside a fjord or lake has busy traffic passing through it, and no options to reroute the traffic on land available because of geographical and/or environmental reasons. The solution could be to re-route the traffic through an underwater tunnel parallel with the shore (see Fig. 6-8). An SFT would be invisible and, in comparison with an immersed tunnel, would make fewer demands on the underwater bathymetry.

Case #3: A strait of considerable width to be crossed. Using an SFT anchored to the sea bottom would avoid creating a visible impact on the environment. There are no construction limitations to the length of such a structure. In contrast, a bridge has limitations in its span length; and the piers and anchorages that might be required for a multi-span bridge would pose obvious difficulties in deep water (see Fig. 6-9).

Case #4: A deep fjord or waterway with high mountains directly adjacent to it, and the need for a

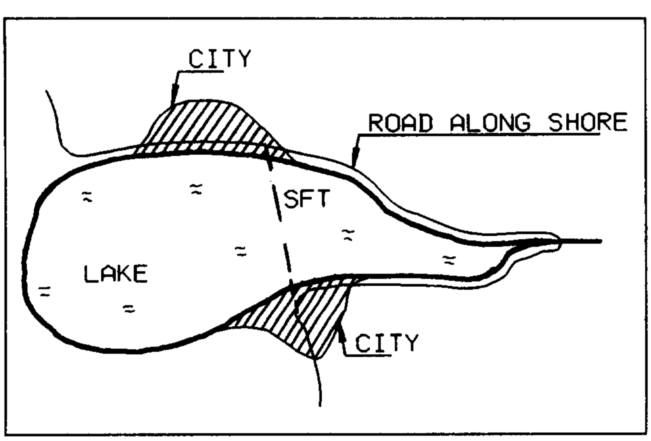

Figure 6-7. SFT used for crossing a lake.

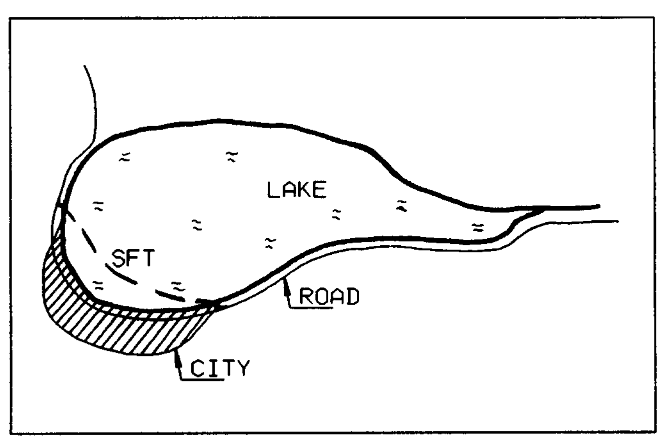

Figure 6-8. SFT used for by-passing a city.

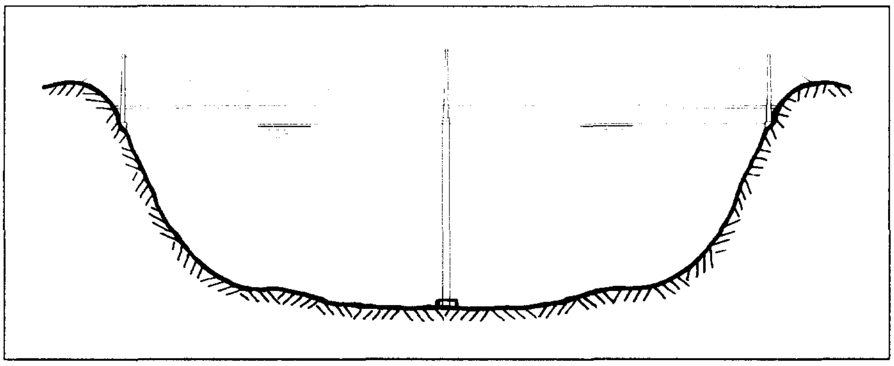

Figure 6-9. An SFT used for a very long crossing.

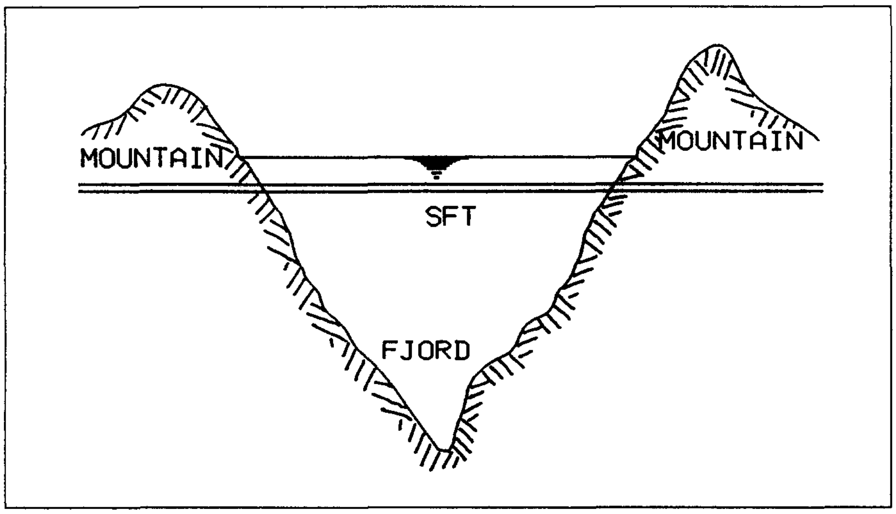

Figure 6-10. An SFT used to cross deep water with mountains adjacent.

fixed crossing as part of the national transportation system. In the past, planners would have considered such a crossing impossible. However, an SFT could be built to connect directly with tunnels at both sides through the mountains, as shown in Figure 6-10. The SFT would make it possible to create a crossing in which no part of the structure is visible—a characteristic that could yield great environmental advantages.

These four examples illustrate possible ways that an SFT may offer a unique solution to important and difficult environmental problems.

In many parts of the world, it is necessary that certain crossings be made invisible in order to avoid interfering with the natural beauty of the surroundings. Structures such as suspension bridges, cable-stayed bridges or floating bridges, no matter how elegant and "high-tech", cannot avoid interfering in some way with the surface environment.

2.5 Possible Locations

As discussed above, a Submerged Floating Tunnel may be applicable in a number of locations where alternative structures are also feasible. In such cases, the SFT will need to be a competitive alternative if it is to be adopted.

In contrast, at some locations an SFT may be the only feasible alternative.

Possible locations for SFTs can be divided into two main groups:

1. Coastal regions.
2. Inland regions.

The technicalities related to each of these locations are discussed below.

2.5.1 Coastal Regions

Coastal regions, which include fjords, sounds, and connections between islands, often pose the greatest difficulties for fixed crossings.

Although there are possible locations for SFTs on all continents, some areas present particularly worthwhile opportunities. Some of these are listed in Table 6-1.

2.5.2 Inland Regions

Large lakes exist in virtually every country. In the past, many of these lakes have been considered impossible to cross, for a number of reasons. In many cases, the lakes have been considered too wide for conventional bridges, and environmental concerns have prohibited a visible structure.

The obvious choice would be to construct a tunnel underneath the bed of the lake. However, these tunnels often become very long and expensive, or the depths are excessive.

The SFT offers the possibility of crossing at very gentle gradients and without visible environmental impact. In addition, some of the increasing road traffic around a number of lakes could be eliminated by reducing the travel distance, as well as removing the traffic from visible view.

Table 6-2 shows a number of lakes throughout the world that are of particular interest for application of the SFT concept. This list, although incomplete, reflects current opportunities perceived by the authors. There are undoubtedly further opportunities in other parts of the world. It will be for local authorities and developers to de-

Table 6-1. Possible locations for SFTs worldwide.

Country	Possible Locations for Submerged Floating Tunnels
Norway	Many fjords
Italy	Strait of Messina
Greece	Mainland to islands
Turkey	In-between continents; between mainland and islands
Spain/Morocco	Strait of Gibraltar
France	Gironde
U.S.A.	Fjords on west coast
Alaska	Bering Strait
Canada	Fjords on west coast
South China Sea	Between islands
Coast of Southeast Asia	Mainland to islands
Japan	Mainland to islands; between islands

Table 6-2. Possible sites for submerged floating tunnels.

Country	Location of Lake
EUROPE:	
Italy	Como/Lecco
Italy	Maggiore
Italy	Lugano
Italy	Iseo
Italy	Garda
Switzerland	Neuchatel
Switzerland	Vierwaldstettersee
Switzerland	Zürichsee
France, Switzerland	Geneve/Leman
Germany, Austria, Switzerland	Bodensee
Sweden	Vättern
Portugal	Rio Tejo
THE AMERICAS:	
Canada, U.S.A.	Superior
Canada, U.S.A.	Huron
Canada, U.S.A.	Erie
Canada, U.S.A.	Ontario
U.S.A.	Michigan
Nicaragua	Managua
Peru, Bolivia	Titicaca
ASIA:	
Israel, Jordan	Dead Sea
Japan	Biwa Ko
Ukraine	Azov
OCEANIA:	
New Zealand	Taupo
New Zealand	Wakatipu

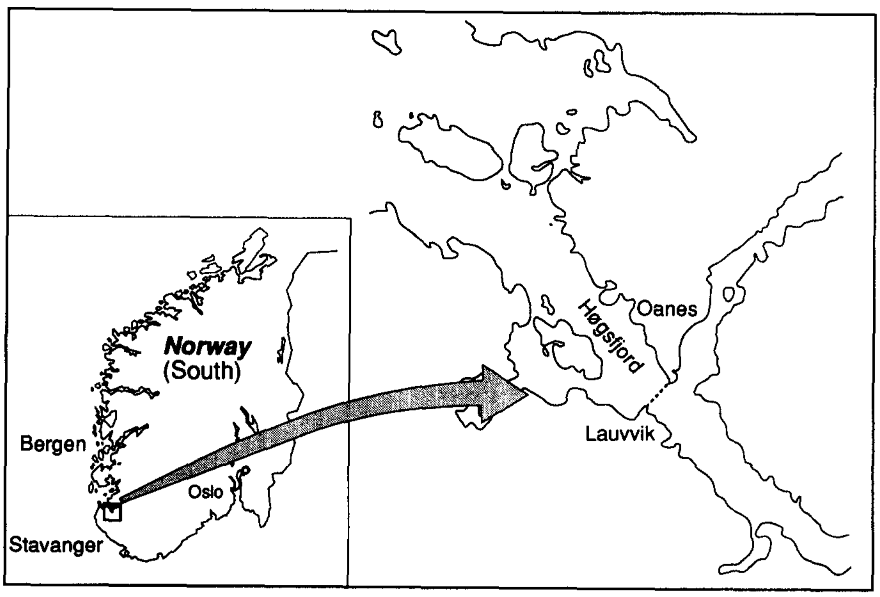

Figure 6-11. Location of Norway's Høgsfjord, for which a submerged floating tunnel solution has been proposed.

termine whether there are lakes in their area that might be suitable for this form of crossing.

2.6 Study and Research to the Present

The development of the principle of an SFT to a feasible concept has extended over approximately a decade. In the context of the development of comparable complex structures in history, this is a short period. However, the brevity of the development period is offset by the fact that those involved have gained experience in comparable technologies in the civil, marine and offshore industries.

Conventional design methods and existing technologies have been used and found sufficient to enable feasible SFT schemes to be developed.

Extensive studies have been carried out regarding the feasibility of an SFT under the Høgsfjord in Norway and at the Strait of Messina in Italy. Conceptual work has been done for other locations in Norway and for Lakes Como and Lecco in Italy, and general desk studies have been done in other parts of the world.

The experience gained through these studies has provided increased confidence in the feasibility of a Submerged Floating Tunnel.

2.6.1 Høgsfjord in Norway

The Norwegian Road Directorate has chosen the Høgsfjord on the west coast of Norway as a pilot project for an SFT. The proposed tunnel will be in a remote fjord area, where a fixed crossing between the villages of Lauvvik and Oanes is needed. The SFT will be part of the Norwegian coastal road system (see Fig. 6-11).

Some relevant site conditions are listed below:

Width of waterway:	1400 m
Water depth:	150 m
Average currents:	0.6 m/s
Water depth above tunnel:	20 m
Significant wave height:	1.5 m
Amt. of shipping traffic:	low

The research and studies on the relevant aspects of this project began in 1987 and were completed at the end of 1991. This work involved both the Norwegian Government and international consultants and contractors.

The work has followed conventional design procedures, the principal stages of which were:

1. Feasibility study.
2. Conceptual design.
3. Hydraulic models tests.
4. Readjustment of design criteria.
5. Tender design.
6. Final design.

The first four stages have been completed. During the first two stages, four classified contractor groups developed the design and construction methods for a Submerged Floating Tunnel at the specific Høgsfjord location.

As promoter of the project, the Norwegian Government has initiated further hydraulic model investigations and has prepared and adjusted the final design criteria. The feasibility design has reached the status of technical approval, which means that no obstructions in the various design disciplines are anticipated.

The necessary documents for the tender for the Høgsfjord crossing are finished, and the owner's requirements and specifications have been worked out. Preliminary approval has been given to four different concepts (shown in Figs. 6-12-, 6-13, 6-14, and 6.15), which will be entered in a final design and construction competition. The results of the competition will be decided by the Norwegian Parliament in the near future.

Some of the most important areas of research for the Høgsfjord project have been:

- Site-specific measurement of environmental loads.
- The development of programmes for calculating dynamic forces and the behaviour of the structure.
- Hydraulic model testing of the dynamic behaviour of several concepts.

Figure 6-12. Design of Norwegian contractors and partners for the Høgsfjord subsea crossing.

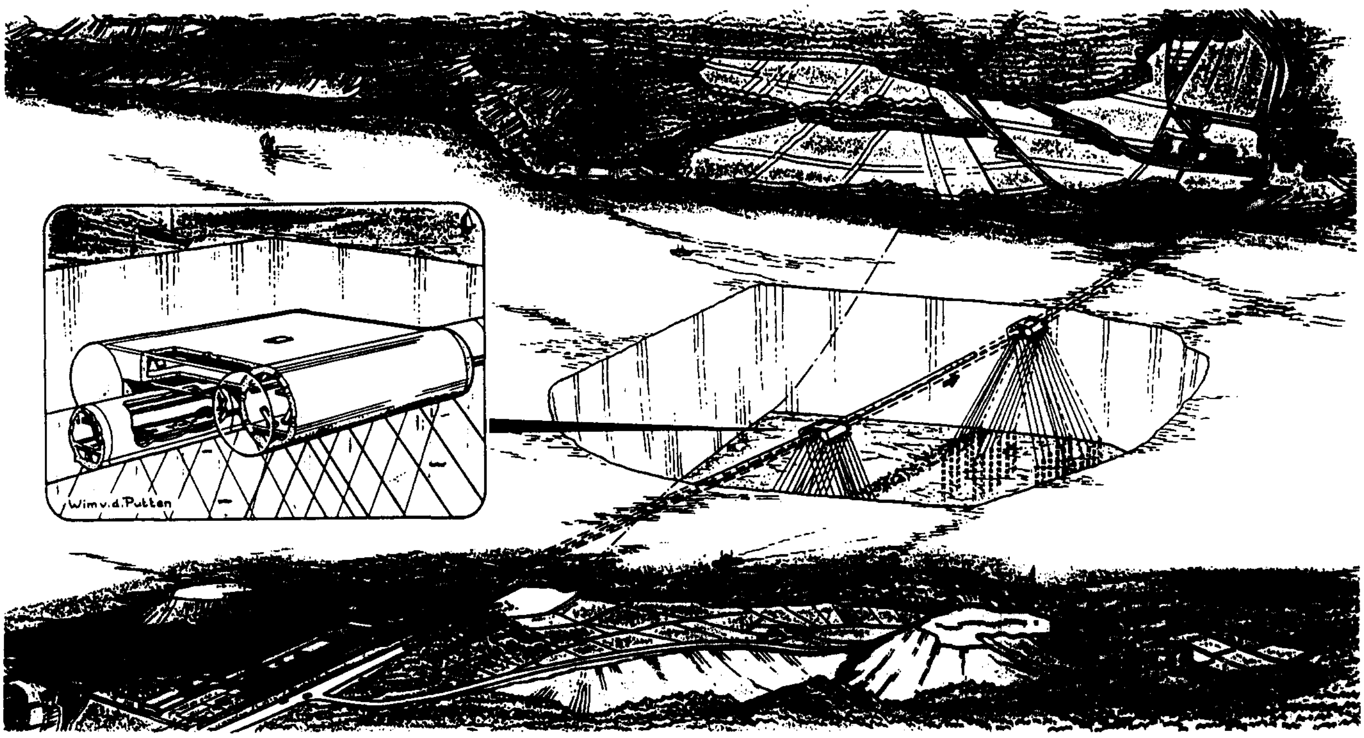

Figure 6-13. Design of Hollandsche Beton en Waterbouw, Veidekke and partners for the Høgsfjord subsea crossing.

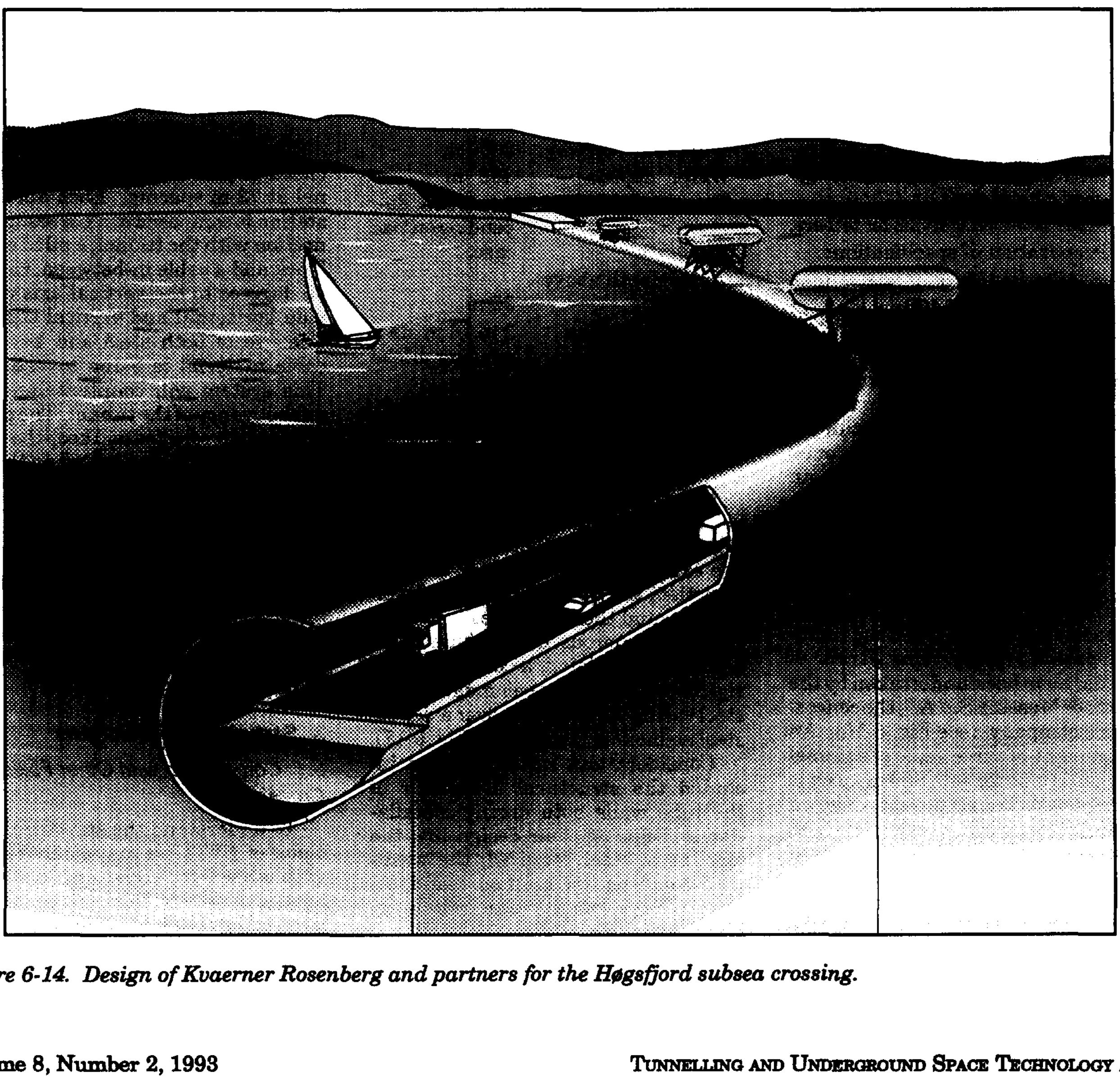

Figure 6-14. Design of Kvaerner Rosenberg and partners for the Høgsfjord subsea crossing.

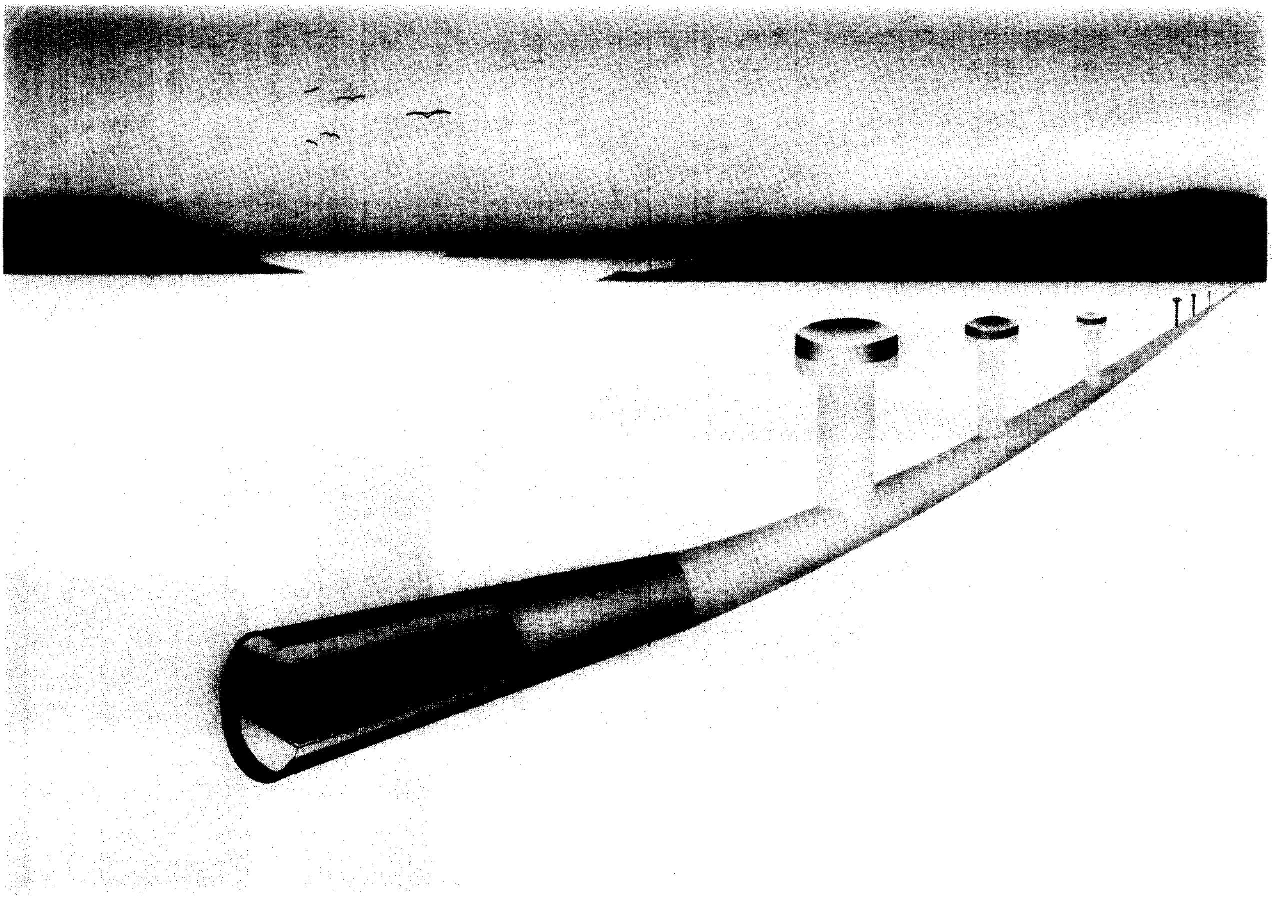

Figure 6-15. Design of Selmer Furuholmen and partners for the Høgsfjord subsea crossing.

- Development of special instrumentation for monitoring dynamic behaviour.
- Material investigations for tethers.
- Preparation of specifications.

The estimated cost of a two-lane SFT, approximately 1400 m long, in the Høgsfjord will be about US$80 to $100 million (1991 level). This cost is comparable with that of alternatives, such as a bridge or ferry, at the same location. This cost estimate, together with previously mentioned aspects of the project, makes an SFT the preferred alternative.

2.6.2 Strait of Messina

In Italy, extensive studies to explore the possibility of an SFT connecting the island of Sicily with the mainland, passing under the Strait of Messina, have been undertaken by the "Stretto di Messina S.p.A.", the concessionaire company (see Fig. 6-16). An arrangement of three separate tunnel alignments (one for rail) 500 m apart is contemplated. The studies have shown that an SFT would be a viable solution, notwithstanding the harsh environmental and seismic conditions existing in the area.

Some relevant site conditions for the project are given below:

Width of waterway:	3000 m
Water depth:	350 m
Currents:	1 to 2 m/s, depending on load case.
Water depth above tunnel:	35 m
Significant wave height:	9 to 16 m, depending on load case.
Amount of shipping traffic:	high

Seismic loading is expected.

Several alternatives have been studied, such as different types and layouts of bridges. Because the preference is to use existing naval docks for the construction, the SFT concept was developed around these facilities.

After numerous alternative studies had been completed, a conceptual design based on concrete elements with a steel casing was selected over a double steel element structure (see Fig. 6-17).

Considerations in the decision included the structural behaviour of the tube walls both during installation and during their design life; the amount of steel required; the available construction methods; and, finally, the durability and reliability of the structure.

The anchoring system comprises anchoring stations located along the tunnel at 72-m spacing. Each anchoring station is composed of a horseshoe connection with the tunnel, a piled anchor block and a cable in-between, running 45 degrees to the vertical axis to provide horizontal and vertical stiffness. The use of both steel and kevlar as cable material is being investigated. This system will counterbalance the net buoyancy of the tunnel. The degree of buoyancy selected will keep the cables from receiving any slack when the tunnel experiences extreme environmental or seismic events.

Each of the three proposed schemes (one bi-directional railway tunnel and two uni-directional road tunnels) is estimated to cost about US$2.5 billion (1991 level). The crossing would be a major project.

3 Structural Principles

3.1 Comparison with Other Fixed Crossings

To understand the structural principles of SFTs, we may compare them with other fixed crossings. SFTs may have a variety of forms, depending on parameters such as distance between the shores, water depth and "sea state"

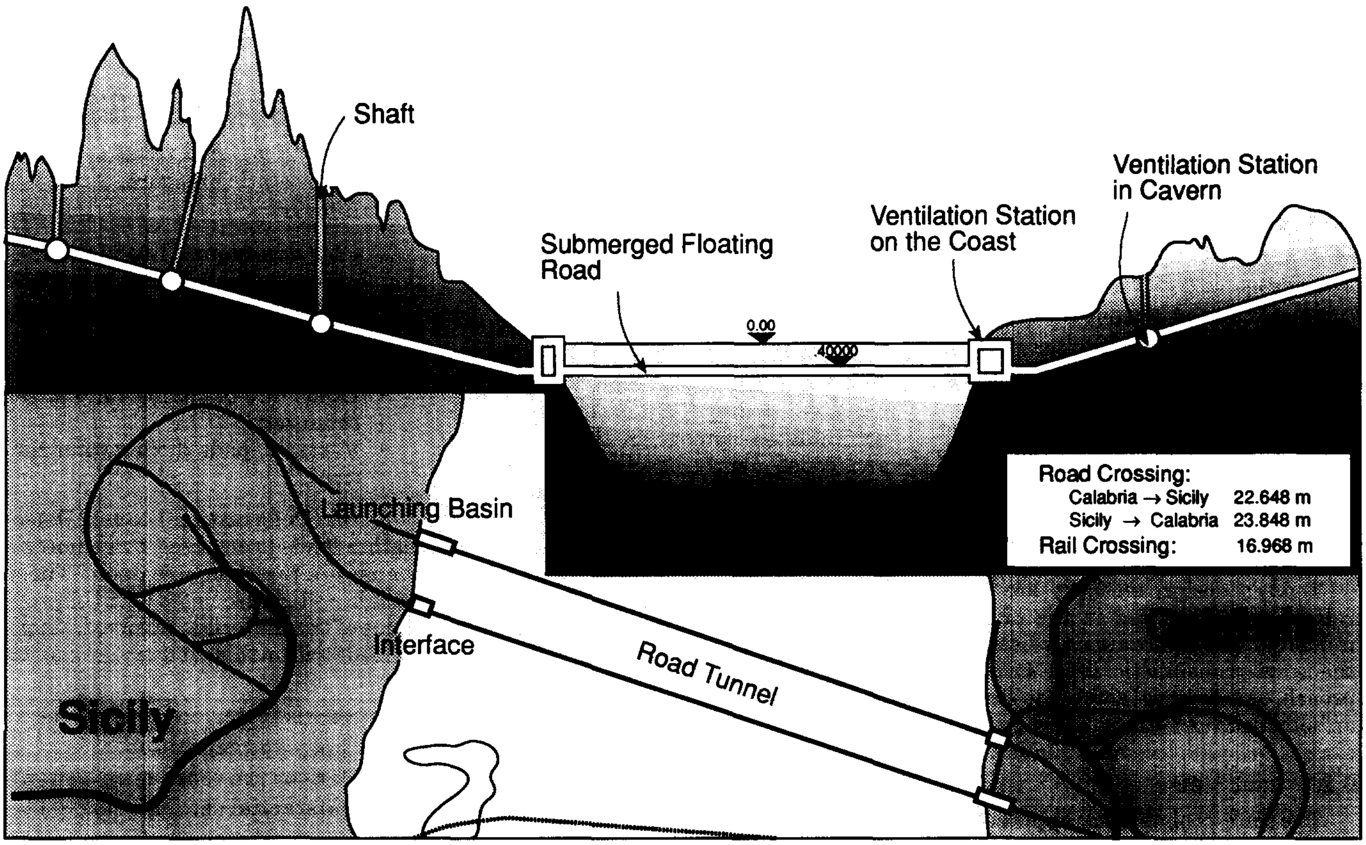

Figure 6-16. Location of the Strait of Messina.

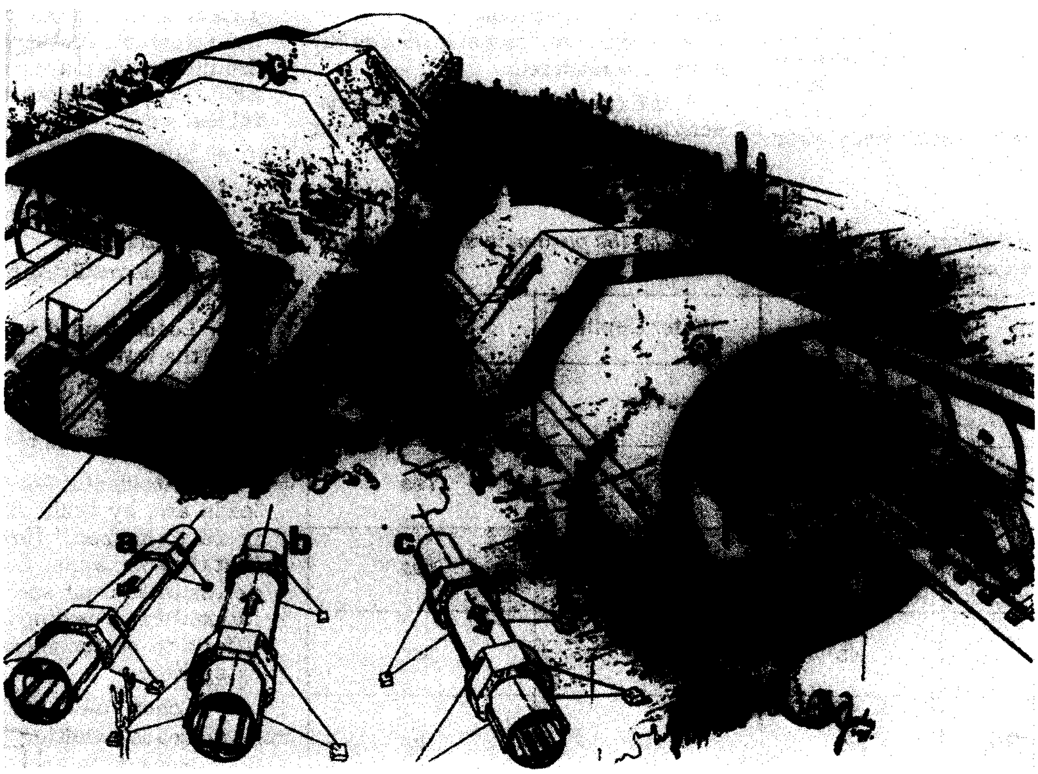

Figure 6-17. Design of Stretto di Messina S.p.A. for the Strait of Messina subsea crossing.

(i.e., waves affecting the structure). Table 6-3 shows whether or not the different structures are affected by these parameters.

The comparison shows that one of the most critical advantages of the SFT is that it opens up possibilities where formerly no fixed connection was considered possible.

3.2 Design Methods

Like every other structure, an SFT must be designed on the basis of expected and possible combinations of loading cases.

The allowable design methods and general criteria are mainly determined by the national codes. Otherwise, the client/owner, together with the designer/contractor, must establish them.

Today's design methods are often related to those used in the offshore industry, and are commonly based on the semi-probabilistic *limit state* approach, using partial safety coefficients on both *loads* and strength of *materials*.

3.2.1 Limit States

The semi-probabilistic approach divides the design into the following design limit states:

SLS (Serviceability Limit State): The SLS conditions are set to ensure that the structure meets practical criteria with regard to deflections, crack widths, factors of safety, accelerations, etc.

ULS (Ultimate Limit State): The ULS conditions are set to confirm that the structure has the necessary strength to survive loads and load combinations at an accepted risk of failure. The structure must be capable of continuing to operate satisfactorily after this design event. The accepted risk level differs among countries.

PLS (Progressive Collapse Limit State): The PLS conditions are designed to preserve human lives in the event of certain loads or load combinations at a very low probability of occurrence. In this case, even if the structure may be severely damaged, loss of lives is still not acceptable. These conditions are often defined at a probability level of approximately 10*(-4) per annum.

FLS (Fatigue Limit State): The FLS is required to account for the fact that some materials lose strength due to repeated loading. By computing the accumulated damage in the material and consequently checking the computed life of the structure against the operational life, the sensitivity of certain components of the structure can be established. A safety factor of 3 to 10 between computed life and required operational life is often adopted, depending on the consequences of failure and the opportunities for repair of the components.

Materials: The safety factors to be used for each type of material are often determined in the national design codes, or they may be specified explicitly by the client.

3.2.2 Loads

The individual loads are combined to give the design loads by using partial load factors. These load factors are generally established in the national design codes, or they may be specified explicitly by the client.

Five different types of loads usually must be considered:

1. *PL* (Permanent Loads): Permanent loads are classified as loads that will be permanently present during the lifetime of the structure. The structure will first be exposed to those loads during the construction period. The most common permanent loads are:

- Structural dead weight.
- Hydrostatic pressure.
- Buoyancy.

2. *FL* (Functional Loads): Functional loads are those loads that will be caused by the usage of the structure. For an SFT, these loads are:

- Loads due to traffic.
- Loads due to changes in ballast conditions.
- Variable loads during construction.

3. *DL* (Deformation Loads): Deformation loads are caused by geometric changes in the structure itself. These loads are often associated with the properties of the materials involved. Typical loads within this category are caused by:

- Shrinkage.
- Creep and relaxation.
- Post- or pre-tensioning.
- Differential settlements.
- Temperature variations.
- Remaining internal loads resulting from the construction method.

EL (Environmental Loads): Environmental loads are caused by the (local) site conditions. Special investigation and study are often required to determine the magnitude of these loads. To assess the effects of such loads on the structure, mathematical and hydraulic models may be needed. For an SFT, the most important environmental loads are:

- Loads due to wave action.
- Static loads caused by current.
- Dynamic loads caused by vortex of current.
- Loads resulting from tidal variation.
- Loads caused by floating ice on the water surface.
- Loads resulting from changes in water density.
- Response due to earthquake.

AL (Accidental Loads): Accidental loads are, by their nature, not supposed to happen. However, the fact that they *do* happen from time to time necessitates their specification and a rational way of dealing with these loads. Effects to be considered in this load category are:

- Loads due to traffic accidents.
- Loads resulting from ship collisions or an anchor dragging.
- Falling ship anchors and other debris.
- Sinking ships.

Table 6-3. How different structures are affected by the parameters of distance, water depth, and sea state.

Type	Distance	Water Depth	Sea State
Bridge	Yes	Yes	No
Pontoon Bridge	No	No	Yes
Floating Bridge	No	No	Yes
Bored Tunnel	No	Yes	No
Immersed Tunnel	No	Yes	No
Submerged Floating Tunnel	No	No	Limited

- Explosions inside or outside the tube.
- Fire from burning cars or fluids.
- Loss of buoyancy.
- Failure within the support system.

3.2.3 Other design methods

The design method used may differ between countries. A more conservative method used in the past employs the elastic and plastic theory. In this case, several levels of acceptable structural behaviour are defined for load conditions based on certain return periods. As an example, for the Strait of Messina crossing, which has a design life of 200 years, the following levels were adopted:

1. *Return period equal to 50 years*: Elastic behaviour of both the main structure and the secondary components, without any damage or need for inspection after the event.

2. *Return period equal to 400 years*: Elastic behaviour of the main structures and local plastic behaviour for the secondary components. Limited damage, if any, must be repairable without any interruption in the use of the tunnel.

3. *Return period equal to 2000 years*: Plastic behaviour with the complete exploitation of the ductility resources of all the structural components. Damage, but not collapse, of the main structure is accepted. Damage and collapse are accepted in the secondary components.

The load cases are similar to those described above. However, there is one special load case associated with the Strait of Messina project that must be taken into account. This load occurs by means of:

1. A slow tectonic slip between Sicily and Italy, occurring in the longitudinal direction of the tunnel, the value of which could reach approximately 0.20 m during the expected life span of the structure.

2. A slow relative movement of the several faults present in the area, which could cause a differential settlement of the foundation blocks.

3.2.4 Ship collision

All of the feasibility studies for SFTs must focus attention on the accidental loading caused by the collision of a ship or submarine.

The safety of an SFT is based on avoiding collision with vessels large enough to damage the structure seriously, as has happened many times to various bridges. Collision of surface vessels can be easily avoided, as the SFT can be positioned at virtually any depth beneath the water surface.

In cases where there is heavy surface traffic, the probability of a sinking ship at that particular location, and the subsequent consequences, must be considered. The energy associated with the impact of a sinking ship (or other object) against the structure must be (partially) absorbed by local and/or global deformation. The magnitude of absorption will depend on the type of ship.

For example, for the SFT proposed for the Strait of Messina, the impact of a 5000-dwt sinking ship must be within level 1, while the impact of a 250,000-dwt sinking ship must be within level 3. The type and size of ship and the appropriate levels will be different for each SFT.

Another form of accidental loading, which is probably more frequent but less sensitive, is the impact of fishing equipment. This type of impact can largely be avoided by adherence to marine regulations.

A traffic regulation system has to be provided for submarine traffic. If necessary, measures must be taken to ensure that both the tunnel and its supports system—especially cables—can be monitored by the submarine navigational equipment. A warning system may be used to ensure the safety of the traffic in the SFT itself.

3.3 Dimensions

Site conditions have an impact on the dimension of the structure, in terms of both criteria for the design of a crossing and criteria for the construction methods.

Conditions to be taken into account include:

- Water depth.
- Length.
- Marine environment: currents, water densities.
- Sea state: long and short waves.
- Geology at the entrances.
- Geology at the foundations of the support system, if applicable.
- Environment.
- Seismic activity in the area.
- Access for bringing marine equipment to the site.
- Surface and subsurface water traffic.

The dimensions of the main body of an SFT are determined by the internal, external and structural requirements.

The dimensions of the secondary components of an SFT are mainly determined by structural requirements and installation methods.

3.3.1 Internal dimensions

The internal dimensions depend on the purpose of the tunnel and, therefore, must be defined by the user. Space also is required for supporting facilities such as ventilation, lighting, signs, ballast, emergency equipment, etc.

3.3.2 External dimensions

The external dimensions are mainly determined by:

- The required internal dimensions.
- The overall structural concept.
- The local structural requirements.
- The influence of external loadings.
- The construction methods.

It has been found that the minimum internal dimensions, which are required to accommodate the required number of traffic lanes and the necessary equipment, result in almost the optimum design. The consequent external dimensions have a significant influence on the behaviour of the tunnel because the most important design loads are related to its volume. Examples of such loads are the circumferential compression load, the buoyancy and the added mass, and the forces of inertia associated with wave motion and seismic excitation.

Recently developed concepts have featured circular-shaped or hexagonal-shaped tunnels. To reduce these loads, in the case of the SFT proposed for the Strait of Messina Crossing, three parallel and independent tunnels are planned.

3.4 Buoyancy

The vertical stability of an SFT is a very important consideration. The concept can best be explained by comparing the SFT with other types of tunnels.

In the case of a *bored tunnel*, the vertical stability is sufficiently ensured by the weight of the soil above the tunnel. This weight is always greater than the buoyancy (in ground water), both during construction and in the final situation.

In the case of an *immersed tunnel*, the vertical stability is ensured by additional ballast concrete, which is added after the element is placed in the trench. There will always be a resultant downward vertical force, equal to the difference between the final structural weight and the buoyancy of the element. The weight of the backfill in the trench will increase the vertical stability. Only during the transport and, in some cases, during placing of the element, when no ballast concrete is present, will the buoyancy exceed the weight of the element.

In the case of a *submerged floating tunnel*, the relationship between buoyancy and self-weight is very important. In general, the weight of the SFT and its buoyancy are almost in equilibrium, even with the large magnitude of each of these loads. Because an SFT will never be covered by soil, the vertical stability has to be ensured by the structure and its support system.

There are two possibilities for accomplishing this:

1. A **tether system**, in which the structure delivers a resulting upward force (more buoyancy than weight), which is taken by the downward force in the support system.
2. A **pontoon system**, in which the structure delivers a resulting downward force (more weight than buoyancy), which is taken by the upward force in the support system.

Because the resulting load in the tether or pontoon system is the difference between two large forces, accuracy in determining these forces is of the utmost importance. The following uncertainties in regard to these forces may arise:

Tolerances in geometry and dimensions. The acceptable tolerances in the geometry and dimensions must be established during the design stage, depending on the choice of construction method. During construction, an experienced contractor with an appropriate quality assurance system is the client's best insurance in keeping the tolerances under control. After construction, this parameter is no longer a variable but, rather, is exactly known. Given sufficient flexibility in the amount of ballast concrete, it is possible to adjust the weight afterwards.

The specific weight of concrete. Although the specific weight of concrete will vary during construction, it can easily be measured. Nevertheless, the acceptable range has to be established beforehand, during the design stage. After construction, this parameter is known exactly; by using ballast concrete, the final weight of the structure can be adjusted.

The "weight" of the structure may alter slightly over time, due to the water absorption of the concrete. However, this alteration is minimal in comparison to the capacity of the support system.

The specific gravity of water. The range in the specific gravity of the water will be particular to the site, and should be obtained at an early stage in the design process. The variation in buoyancy resulting from the change in the specific gravity of water is a permanent variable, and may have special importance in coastal areas, where the amount of river run-off or melting ice or snow can change the value rapidly. The design has to cope with these variations.

The amount and stability of marine growth. Marine growth is known to concentrate at the sea floor and at the surface (see Fig. 6-18). If the SFT is not located in the critical surface layer, the effects of marine growth will be minor. However, where such growth does occur, it will increase the weight and the current resistance. Therefore, accurate predictions of the amount and weight of marine growth are required. The amount of marine growth may differ among projects, depending on the seawater temperature and the depth that the tunnel lies below the water surface.

The range in weight/buoyancy ratio of the tunnel and the support components has to be investigated carefully in order to avoid a net reverse in the resultant forces.

During installation, other conditions may occur, depending on the design and the construction method.

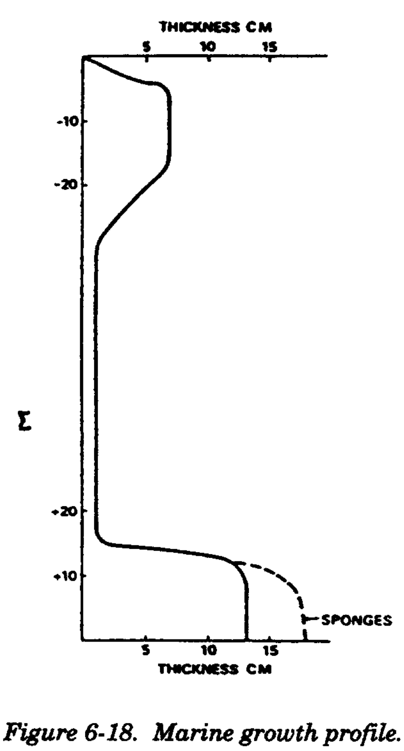

Figure 6-18. Marine growth profile.

3.5 Supports

The SFT is supported by the abutments at the shores and, if necessary, by further supports along the tunnel.

When the SFT reaches a certain length, which will depend on factors such as diameter, shape, material choice, etc., it will be necessary to support the tunnel in both the horizontal and vertical directions.

3.5.1 Horizontal Supports

Usually the static horizontal loads are relatively small in relation to the allowable span length. Currents are the main cause of these horizontal loads. This means that large spans may be used with a minimum of horizontal support.

Some proposed schemes span the total waterway, using the principle of an arch to carry the horizontal loads (see Fig. 6-19).

At a certain span width, the arch shape will not be sufficient to cope with the horizontal loading. A horizontal mooring system is then required.

3.5.2 Vertical Bottom Supports

The requirement of safe vertical stability under all loading cases results in an upward force that is generally larger in magnitude than the forces in the horizontal direction. A support system is therefore required at shorter intervals. The structural principle in the vertical direction involves a continuous beam with intermediate supports.

The principle of the bottom mooring is that the SFT should have sufficient positive (upward) buoyancy to keep the tethers to the bottom under tension at all times, even during seismic events.

A tethered solution is attractive because it can be used in very great water depths.

The tethers or tether groups spacing depends on the weight/buoyancy ratio and the cross-sectional strength of the tube (see Figs. 6-20 and 6-21).

The intervals between the tethers will vary. For example, the intervals in the studies for the Strait of Messina crossing varied between 50 m and 70 m, compared to 400-m intervals for the Høgsfjord crossing.

The tethers can be fabricated of steel wire or steel tubes, similar to those used in the offshore industry for the mooring of tension leg platforms (TLPs). Because the tethers of an SFT are subject to smaller motions and loads than those of a TLP, the tethers and connections for SFTs can be less complex than those used in the offshore industry. Experience has been gained with this type of tether mooring in water as deep as 550 m.

The use of Aramid cables has also been studied. These cables have advantages related to corrosion resistance, stiffness/resistance ratio and low weight in the water, which facilitates installation and avoids catenary effects. A disadvantage is the lack of catenary effect during large motions of the tunnel.

The tethers transfer the upward tension force to the bottom anchor points. The type of *anchor point* used will depend on the soil conditions and installation methods. Both piled anchors and gravity anchor blocks have been proposed for projects. When rock exists in the bottom, drilling and grouting of the anchors may be a solution.

An alternative is the use of *fixed bottom* supports. The height, which depends on the water depth, can range from some tens of meters to about a

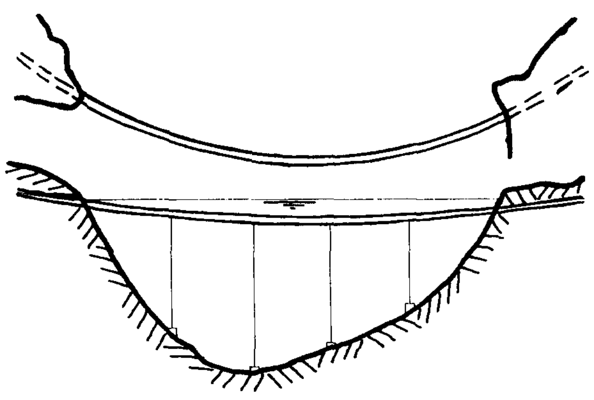

Figure 6-19. Arch shape horizontal support.

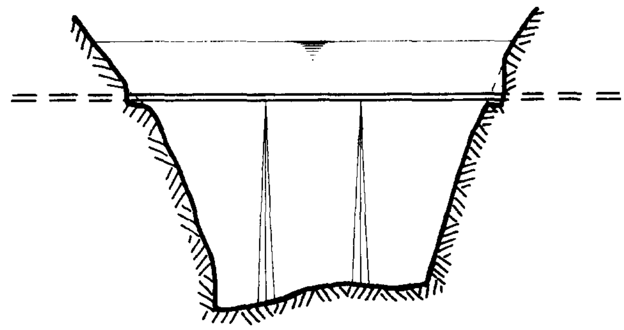

Figure 6-20. Anchor cables in groups.

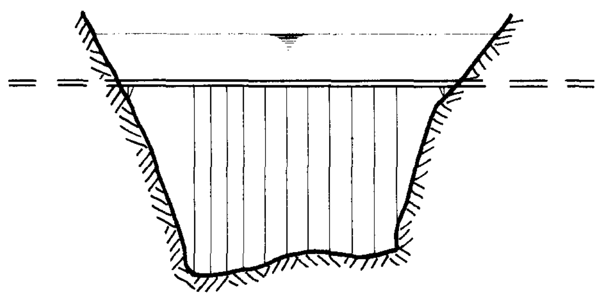

Figure 6-21. Anchor cables along the tunnel.

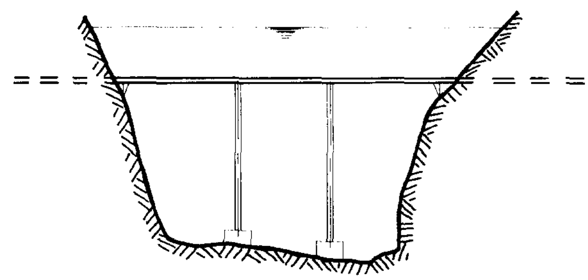

Figure 6-22. Fixed supports.

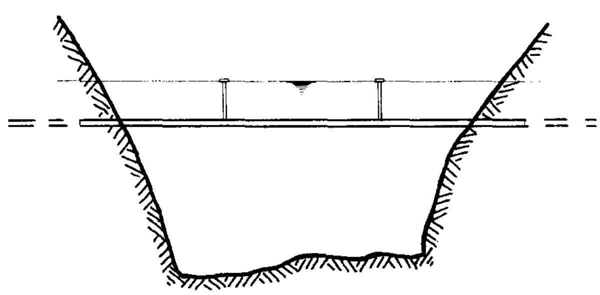

Figure 6-23. Pontoon support.

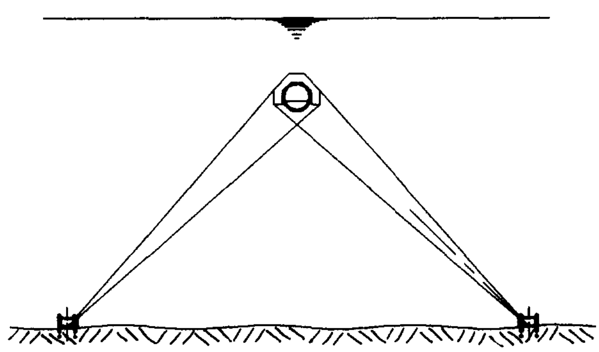

Figure 6-24. Combined horizontal and vertical support.

Figures 6-19 through 6-24. Different types of support systems for Submerged Floating Tunnels.

hundred meters. The base of the support generally will be a gravity structure, which will require good soil conditions. The structural system (see Fig. 6-22) formed by the tunnel and its supports will correspond to a continuous beam with fixed supports. Normally the analysis will be fairly straightforward.

The response under load of such an arrangement may be quite different from the response when a cable arrangement is used.

3.5.3 Vertical Pontoon Supports

In the case of a pontoon support, the SFT will be carried by the pontoons at the surface. This is a more elastic system than the bottom support system (see Fig. 6-23).

Although this solution has the advantage of being independent of water depth, it has to cope with the interaction with ships, waves and ice.

3.5.4 Combined Horizontal and Vertical Supports

If the SFT is long and sufficient horizontal support cannot be obtained from the shore, a combined horizontal and vertical bottom support can be achieved by using an anchor cable configuration, such as that shown in Figure 6-24. The angle of inclination of the cables may be chosen so as to yield an appropriate ratio between the horizontal and vertical forces and stiffness for the particular solution.

3.5.5 Abutments

At each shore a special form of abutments is needed that will contain an axial expansion/structural hinge device. This device will limit the longitudinal and transversal forces induced, for example, by the seismic effects.

It is preferable that the abutments be below water level; otherwise, the SFT may be subject to wave loading. Where such an arrangement is not possible, a protective barrier such as an earth-filled structure is desirable.

The approach structures on each shore may be composed of ramps, bored or cut-and-cover tunnels, or a combination of these. Depending on the construction method, one of the ramp structures may be used as a construction site.

3.6 Static and Dynamic Analysis

As part of the design process, several static and dynamic analyses must be performed, both for the structure as a whole and for certain components.

The SFT must be considered as a long continuous beam that is unsupported or is on fixed or flexible supports. At the ends, however, the road has to be continuous; and, therefore, no significant rotations can be accepted there.

3.6.1 Global Static Analysis

Global static analyses are necessary to investigate the interactions between the components of the structure, and to reach a balanced design following an optimization process.

The global model can begin with a straightforward beam-column model. However, a (three-dimensional) finite element model, which takes the elastic foundations into account, will be needed soon after, in order to achieve a sufficiently accurate analysis.

Displacements of the structure depend on the structural system used. They must be correctly taken into account in order to investigate the consequent geometric changes.

Special software may be required to handle the large number of load cases and the considerable quantity of data. The load cases and the limit states are discussed above, in Section 3.2. The critical load cases will be combined with the results from the dynamic response analyses before the dimensions and stresses are checked.

At this point in the design, the preferred pre-tension in the support system has to be established. This pretension will act together with the loadings, in both the tether system and the pontoon system.

Experience gained in conceptual studies for proposed crossings has shown that the weight/buoyancy ratio is the determining factor in the dimensioning of the structure. All other load conditions are of minor importance.

3.6.2 Local Static Analysis

Local static analyses are normally performed as detailed finite element models, both two-dimensional and three-dimensional, for areas where high stress concentrations are expected. These areas must be studied in detail. Some typical areas requiring study are:

- The joint between the SFT and the abutment.
- The tether connections.
- The pontoon connections.

3.6.3 Dynamic Analysis

A characteristic feature of an SFT is its dynamic behaviour. This behaviour can be analyzed using the same or more specialized finite element software programs that are used for static analysis, and by executing hydraulic model tests in a laboratory.

In the dynamic analysis, considerable care must be taken in selecting the data used and the interpretation of the results. It takes experience to ensure analyses of acceptable quality. Items of importance for these analyses are:

- The mass and expected added mass of the structure and its individual components in relation to each other.
- The stiffness of the structure and its individual components in relation to each other.
- The damping of the structure and its individual components in relation to each other.

Because of the length of the SFT, the highest resonance periods of the tube will be well above the wave period range. However, continuous beams such as an SFT have a large number of eigenperiods, some of which inevitably will be in the wave range. The dynamic amplification of a resonant system is very sensitive and requires careful investigation.

After an SFT has passed the conceptual stage, further analysis can be done with a hydraulic model, simulating certain loading cases. Furthermore, the hydraulic model can be used to calibrate the results from the mathematical models. However, it must be kept in mind that both are only models.

3.6.3.1 Dynamic Response due to Marine Loading

The resonance frequencies in the system cause the structure to be sensitive both to wave frequencies and to structural damping. Therefore, an design wave analyses approach is not sufficient; rather, the analyses should be based on a stochastic approach. Short-term analyses may be acceptable if uncertainty in the wave spectrum period is properly accounted for. The preferable approach for the wave dynamic analyses involves long-term analyses.

Analysis has shown that for both of the SFT projects that have been studied (i.e., the Høgsfjord and Strait of Messina crossings), the response on sea states is well under the acceptable design values.

Fatigue in the different components (e.g., the tunnel, cables and connections), caused by sea states of different magnitudes, is expected to be very low.

Even though the SFT is a slender structure, the possibility of vortex shedding by current needs to be considered. However, the studies mentioned herein have not indicated that this would pose difficulties. For example, at Høgsfjord, where currents are below 1 m/s, no movements are expected.

3.6.3.2 Dynamic Response Due to Seismic Loading

Under seismic disturbance, the response can occur in three directions: transverse, vertical and longitudinal.

A seismic disturbance results in motions with frequencies in the higher and lower ranges. The low frequencies are typical of ground displacements. The SFT has a large number of eigenfrequencies in the high and low ranges.

Analysis indicates that the system filters the high frequencies, but is sensitive to the low frequencies. This may differ from project to project and from design to design.

The *vertical* excitation will cause the maximum accelerations of the SFT. This type of excitation is mainly caused by the seismic pressure waves in the water, generated by the earthquake.

The *transversal* excitation will cause the maximum displacement and, thus, the maximum bending moment in the tunnel section. The maximum axial forces will occur in the anchoring cables, if they are used. Here, again, the excitation is mainly caused by the seismic pressure waves in the water, generated by the earthquake.

The *longitudinal* excitation requires expansion devices at the connections to the shore in order to limit the effects of the earthquake. Otherwise, assuming perfect linear elastic behaviour, very high axial forces will occur. This behaviour could be critical for the connection of the tunnel to the shore. The longitudinal excitation may be caused by the seismic input at each end of the tunnel.

3.6.3.3 Dynamic Response Due to Passing Trains

The effects of a passing train on the global SFT are negligible, compared with the effects of environmental and seismic loads, in the case of the Strait of Messina.

Analyses from the same project have shown that for the case in which a train separates in the tunnel and the individual parts hit behind each other, the dynamic lateral forces caused by this event can be taken by an SFT, assuming the rail support system has been designed for it.

3.7 Risk Analysis

During the design, a probabilistic risk analysis needs to be performed. The possibility of failure of an SFT will be determined by studying the probability of failure of the individual structural components.

The distribution of the possibility of failure of the components can be indicated by fault trees (see Fig. 6-25). If necessary, action can be taken to reduce the local risk.

3.8 Instrumentation

To monitor the SFT for safety and to validate the design, the first SFT will be outfitted with extensive instrumentation. The instrumentation will be specially designed to monitor both the environmental forces and the response of the overall structure and the individual elements. Material behavior, as well as displacements, will be monitored. The instrumentation will be used during construction and will be operational after completion.

It is hoped that the instrumentation results in savings on the design of future SFTs.

3.9 Durability and Maintenance

In a marine environment, the durability of the materials used requires special attention. The tunnel itself should have a design life of perhaps 100 years, although elements such as pontoons, cables, connections and electrical and mechanical plant may have a shorter design life.

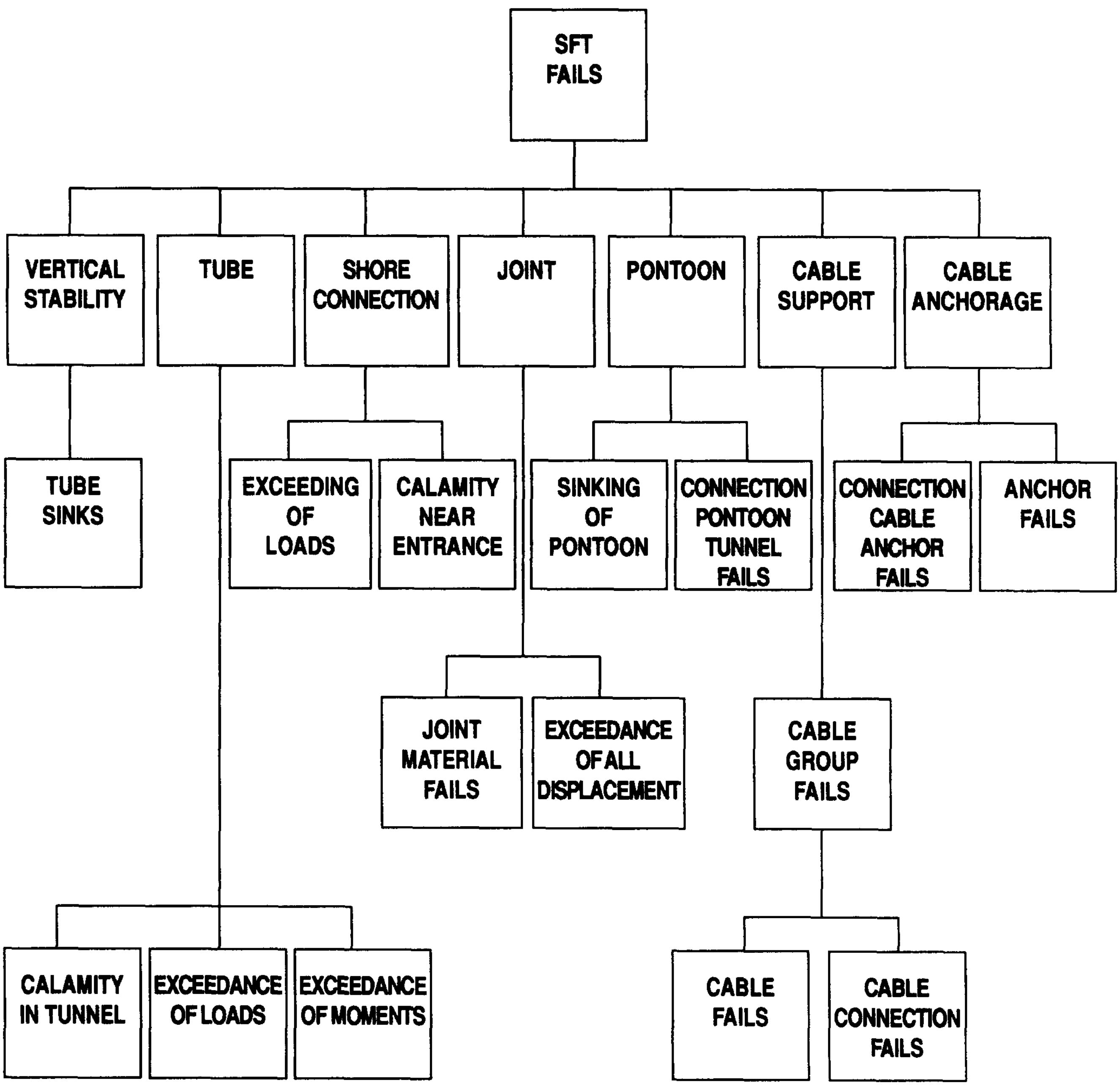

Figure 6-25. Fault tree showing the failure possibilities for SFT components.

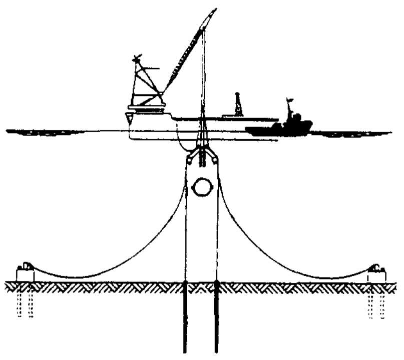

Figure 6-26. Type of installation at site.

A comprehensive maintenance programme should be established to include periodic inspections and the scheduled replacement, as necessary, of individual components.

Special provisions and loading cases arising from replacement operations can be taken into account during the design stage.

It also may be useful to develop special equipment to inspect and maintain the structure and its parts.

Of particular importance is the resistance of the concrete in a chloride environment and the anti-corrosion provisions required for a steel shell, if used.

In the case of a cable support system, the durability of the cables needs to be investigated with regard to both corrosion and fatigue.

Sufficient experience with the maintenance of structures in sea water and in rough environmental conditions has been gained from offshore projects. This experience includes both the structural repair and maintenance procedures and the working methods to fulfill the operations. Special procedures and working methods for both repair and maintenance of the various parts of the tunnel must be prepared as contingency measures.

4 Construction Methods

Experience with similar complex projects, such as those offshore, has proven that design and construction cannot be isolated from one other. Therefore, feasibility studies for SFT projects must consider both design and construction—including, with regard to the latter, the possible methods of construction and the availability of suitable construction sites.

Site-specific conditions, such as marine environment and soil conditions, may affect both the design of the preferred structure and the construction method. It is important that structural analyses of the construction stages be performed early, in order to avoid surprises later on in the project. Additional loading cases must be kept to a minimum to reduce extra costs.

The successful construction of a project of this degree of complexity relies largely on the experience of and equipment available to the contractor. It is therefore advisable to obtain advice from experienced contractors during the feasibility study phase.

Two basic construction methods have been developed:

1. *Construction in elements*. The tunnel is fabricated in elements in a construction dock and coupled to the previous installed elements. The supports can be cables, pontoons or fixed piers.

2. *Incremental launching*. The tunnel is fabricated in sections and pushed out in successive steps. Launching is repeated until the opposite side of the fjord is reached. During launching, a cable-stay system supports the tunnel.

Each of these methods is described in detail below. It should be noted that the suggested methods are generic and must be modified to suit the given site requirements.

4.1 Construction in Elements

The SFT elements are constructed in a dock. After all or a number of the elements have been completed, the dock is flooded and the elements are towed to the site. Bulkheads, used to seal the ends and to maintain positive buoyancy during construction, are joined at the site. The length of each element is determined partly by the structural capabilities of the SFT (the designed distance between the supports) and partly by the available length of existing ship docks, slipways or construction docks. The construction of the elements is similar to construction for immersed tunnels.

Because SFTs and immersed tunnels are designed for different permanent and temporary loading cases, the length of the elements for an SFT is not limited to the 100 to 150 m typical of immersed tunnels. Particularly when permanent prestressing is used, the length of the elements can be increased.

After reaching the site, the installation barge supports the element during assembly and lowering to the intended depth.

At each joint location, a set of tethers is pre-installed and coupled in a horseshoe-shaped support. The element is lowered under the support while temporarily pulling the support aside.

After the element has been fitted into the predetermined tether support system, it is de-ballasted, causing the load to transfer from the installation barge to the tether system. During this process, the length of the tethers is adjusted at the support shoe to prevent unacceptable deflections of both tethers, the position of new element and of previous elements. The adjustments can be made by remote control or by diver or ROV (Remotely Operated Vehicle) assistance. Both forces as displacements are monitored during this process.

Hydraulic couplers located on the previously installed element then pull the new element into place.

An initial watertight seal is provided by a rubber gasket. After de-watering the area between the bulkheads, the permanent joint between the two elements is made and post-tensioned to obtain full structural strength. The rubber gasket has only a temporary function during construction.

This operation is similar in many respects to the placing of immersed tunnel elements. A notable difference, however, is that the support from the cable system is much weaker than that founded by the ground in the case of an immersed tunnel. This must be taken into account in planning the joining operations.

Several solutions may be used for the final connection between the tunnel and the tethers. These connections

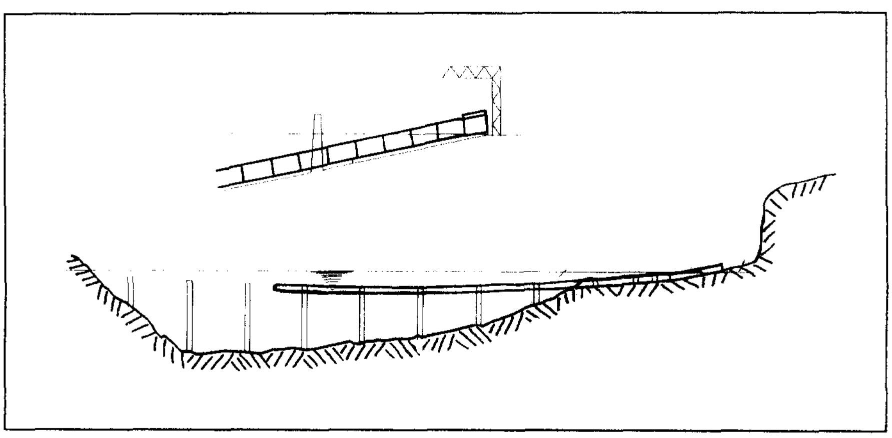

Figure 6-27. Incremental construction and launching of SFT elements.

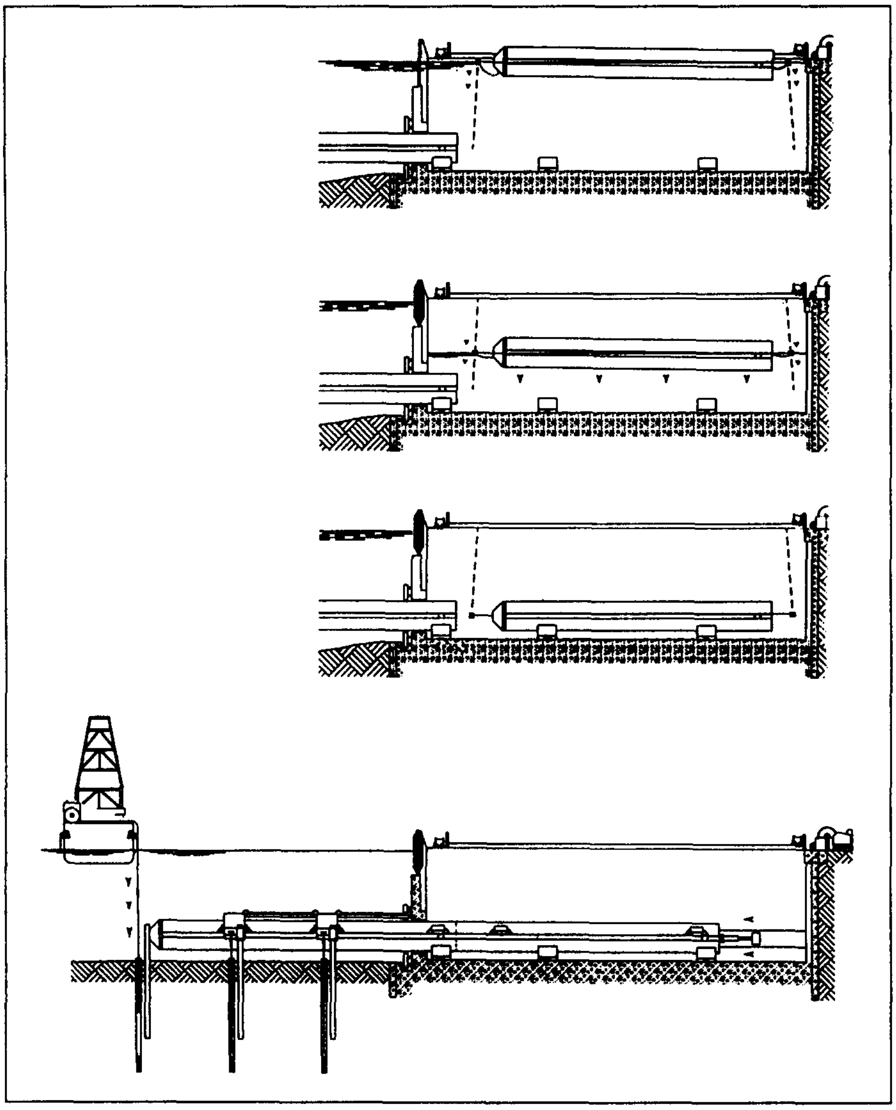

Figure 6-28. Incremental launching.

depend on the location of the connection, i.e., whether they are external or within special chambers added to the tunnel. It also depends on whether the preference is to connect the tethers first to the anchor points on the bed or to the elements before it is lowered. An example showing a possible method is given in Figure 6-26.

Remotely operated vehicles (ROV's) will be used for inspection and for installation assistance.

4.2 Incremental Construction and Launching

In this method, the construction takes place at one of the abutments, which are modified and increased in size to accommodate the construction site and the associated plant, equipment and materials.

The tube is constructed in consecutive sections on an inclined skidway in the abutment. After each section is completed, the tube is moved forward into the water, over the length of one section (see Fig. 6-27) through a gate in the abutment. For this purpose, the segment is constructed on saddles and pushed forward by hydraulic jacks, similar to those used in "No-Dig" technology. Before it is pushed through the gate, the tube is coupled to the previous segments with pretension cables.

The part of the tube pushed out into the water must be kept under control. A temporary cable system and/or a pontoon support system is a likely method for this purpose.

If pontoons are used for the vertical support during push-out, a shore-based cable system may be needed to keep the SFT under control in the horizontal direction. The stiffness of the cable system in relation to the stiffness at the push-out gate will require careful consideration.

New pontoons are connected to the tube as it moves forward. The pontoons, which may be temporary or permanent, follow the structure across the waterway.

An alternative would be to use final tethers, installed in advance and supported by temporary pontoons. To allow the tube to move, a special guidance and support system is needed at the top end of the tethers. Such an arrangement calls for ingenuity. It may be possible to install rollers, guidance plates or hydro-jet bearings in a saddle, which may be temporary or which may become a part of the final construction. As the tube is pushed forward, it meets the guidance structure. The tether tension is then provided by the buoyancy of the tube.

4.3 Element Construction and Incremental Launching

Another construction method involves fabricating tunnel elements in a basin, and then towing them to a specially constructed push-out dock at one of the abutments (see Fig. 6-28). The element is floated into the dock and lowered on a temporary foundation. After the dock is de-watered, the element is pushed forward, coupled to the previous element, and pushed through a launching gate into the water. Support of the tunnel is similar to the arrangement described above.

4.4 Abutments

The construction of the abutments depends on the chosen SFT concept, i.e., prefabricated elements or incremental launching.

In the case of rock abutments, either of two classic methods—the "collection chamber" method or the "concrete plug" method—can be used to connect the tunnel with the abutment. These methods are described below.

Collection chamber method. In this method, the tunnel entrance is made in advance and the joint is prepared to receive the tunnel. In front of the abutment, a collection chamber is made in the rock. After the preparations have been completed and the abutment has been temporarily sealed with a bulkhead, the rock between the abutment and the sea is blasted and is allowed to fall into the collection chamber (see Fig. 6-29). The area in front of the abutment is now clear and the tunnel can be placed and joined to the abutment. This joint is finished in a manner similar to joints between elements. All special facilities can be installed.

Concrete plug method. This method also calls for the tunnel entrance to be made in advance. At the seaside, enough rock is removed under water to allow the tunnel to be placed in the invert. After a tremie concrete plug has been placed over the front end of the tunnel, the remaining rock between abutment and tunnel can be removed from the inside.

If special facilities are required, another separate joint has to be made at some distance from the abutment.

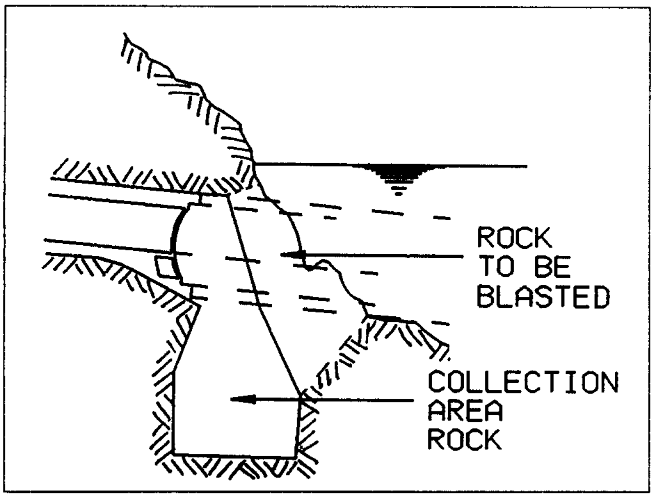

Figure 6-29. Abutment in rock.

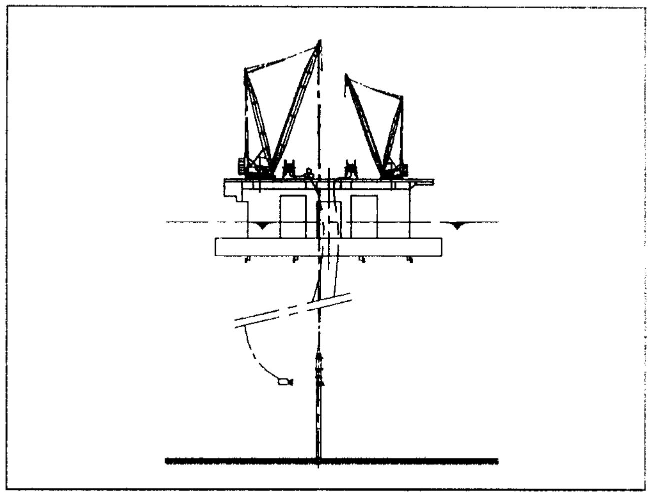

Figure 6-30. Pile driving at great water depth.

For **other soil conditions**, the ramps may be constructed as a concrete structure in a cofferdam. After the ramp is finished, the cofferdam is breached and the first element is joined to the concrete ramp. Finishing can be done similarly to the finishing of the joints between the elements.

For **incremental launching**, one of the ramps is used as a temporary construction site. After the full length of the tunnel has been pushed out, the ramp structure can be completed.

4.5 Anchor Points

Several possible anchorage systems may be used to secure an SFT to the bed of the waterway. These include gravity anchors, driven piles and drilled piles. Selection of the appropriate system will depend on the site geology.

In the case of a cable support system, anchor points are required at the bed, which may be at considerable depth.

As noted above, two concepts are available from the offshore industry:

1. Gravity foundations.
2. Piled templates.

These two types of foundations are described in more detail below.

4.5.1 Gravity Anchors

Foundations based on gravity anchors may be used if the soil conditions are favorable. This type of foundation may take the form of caissons (in concrete or steel), prefabricated in a dock on land or on a floating barge, transported to the site and lowered on the sea bed using a floating crane. Ballast is then placed into the caisson to obtain the necessary weight.

4.5.2 Piled Foundations

Different arrangements may be adopted for piled foundations and the associated tethers. For example, a tether may be anchored by a single pile or by a group of piles; similarly, a group of piles may serve a number of tethers. The latter situation would require a pre-fabricated pile cap, which can also serve as a template for the piles.

Given the technology and experience available in the offshore industry, no specific problems are foreseen during the installation of the templates and piles.

The template can be fabricated in steel or concrete, and incorporates pile sleeves and connection points for the tendons. Additional connection points should be provided to facilitate tendon replacement. The piles are driven from a surface vessel using an underwater pile hammer (see Fig. 6-30). This technique has been used in both the North Sea and Gulf of Mexico, in water depths of up to several hundred meters.

Attention must be paid to the tolerances that may be adopted in installation of the template. These tolerances depend on the adjustment possibilities of the tethers and the allowable tolerances in the tunnel alignment.

4.5.3 Fixed supports

When fixed supports are used for the foundation, the construction method for the piers may be similar to that used for offshore platforms. If the height of the supports is in the range of 50 m to 250 m, the supports could be fabricated afloat in a deep fjord.

After completion, the piers must be outfitted with a temporary extension to reach the water surface, in order to facilitate placing them in position accurately.

4.6 Construction Time

The construction time will depend mainly on the following factors:

- The availability of suitable existing facilities for fabricating the units.
- Suitable space at the abutments, with good access, to allow *in- situ* fabrication.
- An adequate supply of raw materials during production.
- The availability of suitable plant, equipment and manpower during both construction and installation.
- Adequate periods of workable weather, especially during the installation stages.
- The client's requirements regarding the final outfitting.

Obviously the construction time will vary from project to project. The construction times for the Høgsfjord and the Strait of Messina submerged floating tunnels are given below.

Høgsfjord crossing: It is estimated that the Høgsfjord SFT could be constructed in about three years. This period is comparable to that for suspension bridges of similar length.

Strait of Messina crossing: Two studies of existing resources, in naval and in offshore yards, have shown that it would be possible to find sufficient materials, equipment and manpower in Italy to carry out the prefabrication of all of the required components.

It is estimated that construction of the 120 elements would require approximately 1800 man-years over a period of about seven years.

The corresponding estimate for the construction of the templates, piles, collars and cables is 1,600 person-years, also over a period of seven years.

5 Market Expectation

Although there is undoubtedly a market for Submerged Floating Tunnels, it will be necessary to demonstrate the structure in practice. After this has been done, and when the public and politicians have become familiar with this type of structure, many sites around the world could benefit from it.

At present, the market for SFTs is limited to areas where roads have to cross deep waterways. However, SFTs can assist the environment in other locations by enabling traffic to be handled "invisibly"—i.e., out of sight of the surface.

The results of the conceptual studies for the Høgsfjord SFT have been sufficiently promising to give a green light to the technical considerations. A positive political decision is expected soon, thereby opening the way for the actual project to proceed.

6 References

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