An Owners Guide to Immersed Tunnels

ITA Working Group 11
for Immersed and Floating Tunnels

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1 >> Objective Of The Guide

The objective of this Guide is to answer the following question:

What does an Owner need to know and document for the planning, construction and operation of an immersed tunnel?

The Guide will give owners confidence to consider an immersed tunnel as a realistic alternative for crossing waterways and help them achieve the quality and standard of construction they are accustomed to or desire. While an immersed tunnel is a specialist field within civil engineering, its planning, construction and operation follow the same established procedures for any major infrastructure project. This Guide is written with the intention of demystifying the complexities of an immersed tunnel and to help an owner identify the aspects of an immersed tunnel that need particular attention. As such, the Guide is immersed tunnel specific and does not discuss routine construction practices.

The concept of instrumentation, documentation and verification (IDV) is also introduced as a means of reliably documenting parameters of importance. In addition, the Guide has been written as a general aid and as such is neither site nor material specific. Various ground conditions are however discussed and distinctions made between steel tunnels and concrete tunnels where necessary.

The objective of the guide is to enable Owners to determine the important characteristics of their project which require particular attention over the life of the tunnel. Hence a number of themes are summarised to serve as a check list of items to be considered. This does not replace the need for expert advice during planning, design or construction, but should give owners a tool for understanding what their key risks and issues are, and to implement a mechanism to control these risks and address the project specific issues. It will enable Owners to create a framework whereby their input can be provided where necessary, and to allocate responsibilities to others where appropriate.

The main material of the Guide is located in the annex. Here individual themes are treated one by one in a standard template. The theme is discussed generically but without specific reference to individual projects. It is difficult to cover all types of construction and specific project circumstances with a generic approach, but by selecting a broad range of themes, the important characteristics and project constraints can be identified for any project. The approach proposed can be adapted on a project by project basis to suit the parties involved and the particulars of the scheme.

The themes are not categorised into planning, construction or operation phases as many of the themes are relevant to all three phases. For example, soil investigations performed during the planning phase, plays a vital role during design and construction and will still be important in interpreting long-term settlement data.

2 >> Introduction To Immersed Tunnels

Before looking at the individual themes, it is beneficial to give an overview of the immersed tunnel method of construction and the forms of structure that are involved. The following overview draws from the previous WG11 publication "Immersed Tunnels - a better way to cross waterways (Tribune - special edition, May 1999)". Reference should also be made to other WG11 publications – the State-of-the-Art Report and the Glossary of Terms.

2.1 WHY CHOOSE AN IMMERSED TUNNEL?

Immersed tunnels do not suit every situation. However, if there is water to cross, they usually present a feasible alternative to bored tunnels at a comparable price, and they offer a number of advantages, such as:

1. Immersed tunnels do not have to be circular in cross section. Almost any cross section can be accommodated, making immersed tunnels particularly attractive for wide highways and combined road/rail tunnels, see Figure 1.

2. Immersed tunnels can be placed immediately beneath a waterway, often with no more than 2 m of protective cover on top. In contrast, a rule of thumb for bored tunnel construction is for the crown (top of the tunnel) to be one diameter beneath bed level. Because the immersed tunnel is so shallow, approaches can be shorter and/or approach gradients flatter – an advantage for all tunnels, but especially so for railways, see Figure 2.

3. Immersed tunnels can be constructed in ground conditions which would preclude bored tunnelling or render it prohibitively expensive, such as the soft alluvial deposits characteristic of large river estuaries. They can also be designed to deal with the forces and movements under earthquake conditions.

4. Bored tunnelling is a continuous process in which any problem in the boring operation threatens delay to the whole project. Immersed tunnelling creates three operations - dredging, tunnel element construction and

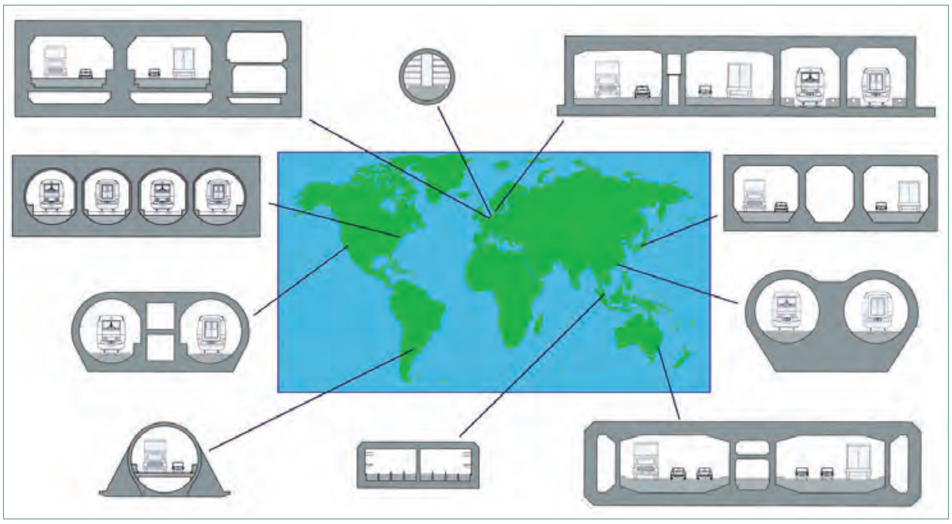


Figure 1: Worldwide examples of immersed tunnels

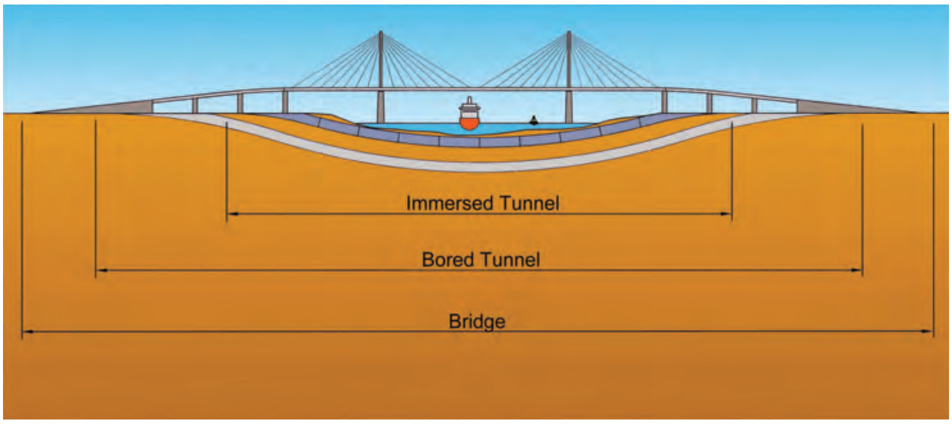


Figure 2: Immersed tunnels are frequently the shortest route for crossing waterways

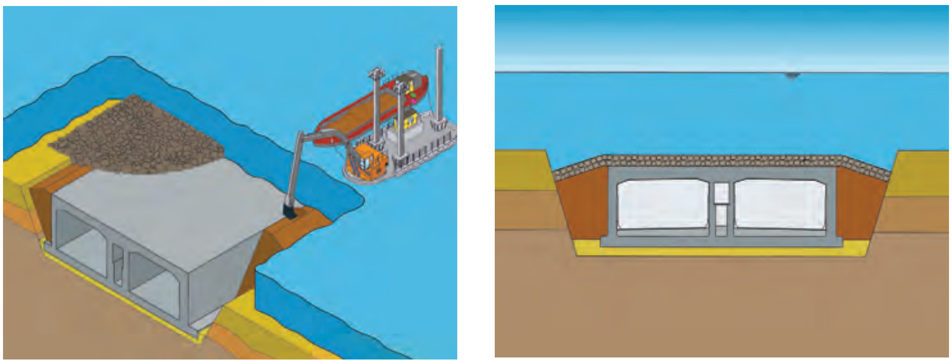


Figure 3: Backfill material is placed beside and over the tunnel to fill the trench and permanently bury the tunnel, as illustrated above.

2 >> Introduction To Immersed Tunnels

tunnel installation, which can take place concurrently, thus moderating programme risk considerably. Tunnel installation can also take place on multiple fronts. Partly for these reasons, an immersed tunnel can generally be completed in a shorter time than a corresponding bored tunnel.

2.2 IMMERSED TUNNEL - DEFINITION

An immersed tunnel consists of one or more prefabricated tunnel elements that 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 terminal structures that are constructed in the dry.

The space between the trench bottom and the soffit of the tunnel can be a previously prepared gravel bed, with or without a layer of special grout; alternatively, it may be sand bedding, either pumped or jetted beneath 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 of stone/rock over the roof, see Figure 3.

2.3 DESIGN & CONSTRUCTION OBJECTIVE

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 a 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. Despite different sites and practices, the goal is always the same: to produce watertight and durable immersed tunnels.

2.4 FABRICATION

The terminology “steel or concrete tunnels” relates to the method of fabrication. Once completed, there is no real difference between the two types.

Most concrete tunnel elements are prefabricated inside dry docks 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. Occasionally elements have been fabricated on semi-submersibles or launched using a marine lift. The load-bearing structural concrete is usually complete before launch.

Steel tunnel elements are often fabricated in a shipyard and the keel concrete placed before launch; after the element is launched, the remaining load-bearing structural concrete is installed while the element is floating. Steel shell tunnels have also been fabricated and partly concreted in dry docks.

After launch, completed elements are floated to their destination and placed in the trench.

2.5 JOINTS

All joints are gasketted and tightly closed. The immersion joints between tunnel elements contain rubber gaskets that provide a seal to allow the joint to be dewatered and completed. The immersion joints can remain permanently flexible using rubber compression gaskets, as is often the case for concrete tunnels; these gaskets are pre-installed at one end of each tunnel element and also provide the initial seal. Other immersion joints are made rigid; this is done within the temporary immersion seal by filling the gap with concrete. Steel shell plates can also be made continuous by welding on lap plates. There are a number of ways of making the final joint after the last element is installed. All joints contain seals of some kind.

2.6 WATERTIGHTNESS

Immersed tunnels have few 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, by virtue of the quality of the in situ joints, and the quality of the flexible joints (if they are used). The watertightness of concrete tunnels depends on the quality of the joints, on the absence of full-depth cracks in the concrete, and on the quality of the waterproofing (if it is used).

Figure 4 : Tunnel elements are constructed in the dry, for example in a casting basin, a fabrication yard or in a factory unit.

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

2.7 TUNNEL CROSS-SECTION

In most cases, the selection of the typical cross-section 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 tunnels; in northwest Europe, of selecting concrete tunnels; and in Japan, where both concepts are applied). In some cases, the choice depends upon the available fabrication facilities and cost.

The structure of a steel tunnel consists of structural steel plate acting compositely with concrete. For reasons of weight, the section thickness of most steel and concrete tunnels of the same shape will be similar. The external steel plate provides the water barrier. For a U.S. type double shell tunnel only, ballast tremie concrete is placed outside the inner shell plate in pockets formed between structural diaphragms. Concrete tunnels are monolithic structures in which most of the final weight is incorporated into the structural components.

There is a wide range of cross-sectional 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; how many tracks or lanes altogether are required; 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.

For larger vehicular tunnels, the usual configuration involves one or two main cells, each having two or more roadway lanes and shoulders. Due to the high cost, shoulders in tunnels are usually kept as narrow as possible. Additional cells may be required for ventilation, emergency egress and services. Bidirectional traffic in tunnels is avoided in new tunnels.

2.7.1 Steel tunnels

For all tunnels, a circular-shaped section is the most economical for external pressure loading, since the section is in compression. Hence early tunnels such as the U.S. steel double-shell tunnel type were essentially circular (perhaps with octagonal protection). If two circular tubes are used, the section is described as binocular. 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. The tendency today is to use shallower rectangular tunnels and longitudinal ventilation, so that it is unlikely that further double-shell tunnels will be constructed.

Besides the steel double-shell tunnel, there are two main types of rectangular steel tunnel, single shell and the sandwich. The single shell tunnel has an external structural steel plate that acts compositely with internal reinforced concrete. In some places, an internal plate is also used compositely. Adequately stiffened, all steel tunnels can be launched with little (if any) internal concrete; the concrete is placed in carefully programmed sequences while the shell is afloat. The sandwich type consists of concrete sandwiched between two steel shell plates. Steel webs between the shells are arranged to form closed cells that are filled individually with concrete. Both the inner and outer shells are load carrying and both act compositely with the contained concrete. The concrete is unreinforced and is formulated to be non-shrink and self consolidating. The internal surfaces of the steel shells are stiffened with plates and L-shaped ribs that also provide the connection required for composite action with the internal concrete. The internal concrete, once cured, carries compression loads and also serves to stiffen the steel shells. The steel shells carry the tension loads.

There are a few steel single-shell tunnels based on circular tubes. The 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 compositely with the internal ring concrete. The ballast concrete, which is proportionately less than for a larger steel double-shell tunnel, 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. Steel single-shell tunnels have little spare allowance for internal ducting.

2.7.2 Concrete Tunnels

The shape most often used for double and multi-cell concrete traffic tunnels is the rectangular box, which may have to be widened with extra cells for ventilation air supply or exhaust, and services. The box shape matches best the rectangular internal clearance required for motor traffic, with good conformity between resistance and weight. The box shape also facilitates practical concrete construction practice. When longitudinal ventilation is 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 may be required by the fire department for emergency escape.

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.

2.7.3 Miscellaneous

Low-point drainage sumps have to be provided within the confines of the structure. Draft issues make impractical deeper sections locally, but local widening is possible, if needed. In binocular tunnels, the sump can be placed between the tubes. In other types of tunnels, the sumps have to be placed underneath or to one side of the roadway. The presence of service galleries is helpful in positioning the pumps.

Figure 5: Immersed tunnel element being prepared for immersion. Note the survey towers, one of which is used for interior access.

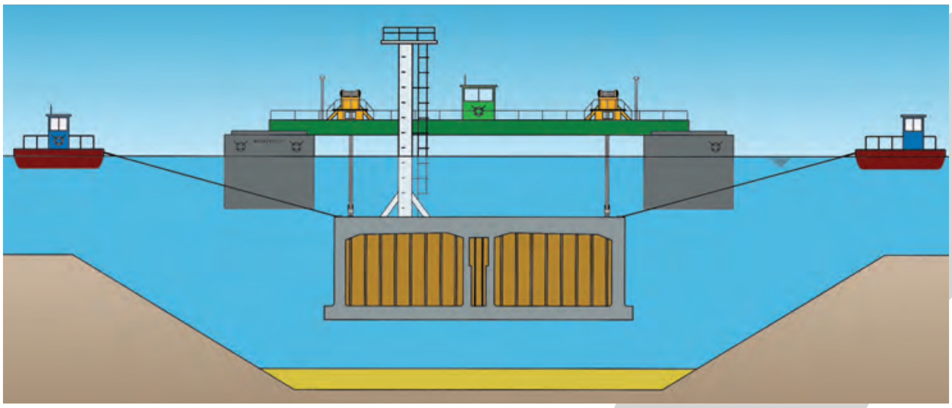
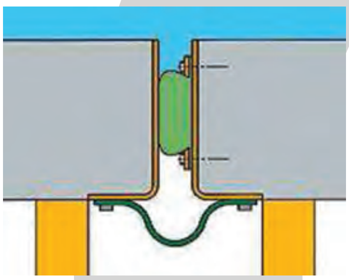


Figure 6: Installation. The tunnel element is lowered to its final place on the foundation at the bottom of the dredged trench. The new element is placed against the previous element under water. Water is then pumped out of the space between the bulkheads and a permanent seal/gasket is installed.



3 INTRODUCTION TO IDV

To help achieve reliable results and to increase our knowledge and understanding of the real behaviour of structures, a quality control method called the IDV method was developed a few years ago (Norwegian 1999). IDV is an abbreviation for Instrumentation, Documentation and Verification. The IDV method is purposely named to indicate that instrumentation by itself has no value, but must be incorporated into an overall plan where the verification objectives are clearly defined, where the requirements for the documentation are specified and where all activities are clearly described. This makes engineers think through the whole process from start to finish. The method does not rely on high level mathematics or theories but on common sense and competent personnel. Design engineers should be involved in discussing and defining:

- Critical phases of construction.
- Vulnerable structural elements.
- Aspects which may affect the durability of the construction.

In addition comes the rather naive but essential demand that the documentation is reliable. This is where redundant measurement systems and competent personnel play an essential role.

For the purpose of clarity, a distinction is made between IDV-system and IDV-concept. The system refers to the actions (planned or carried out) whilst the concept refers to the governing principles. In this way, the concept defines and guides the system to a reliable result. It must be pointed out that one of the objectives of IDV is to document "good knowledge" and "bad knowledge". Both are equally important, but are useless unless the documentation is reliable.

Another important aspect of IDV is the transfer of knowledge and results to others. This imposes certain demands on the editing and publishing of the documentation. In brief:

- Instrumentation: Record loading, response or condition through field measurements.
- Documentation: Systematize results and describe all instrumentation and verification activities so that reliability can be evaluated.
- Verification: Compare field measurements with calculated and accepted values, and determine the real behaviour of structure.

In addition, the following points must always be achieved:

- Clearly defined objectives
- Data must be kept to a minimum - processing should be planned.
- Data and results must be reliable and be presented in an understandable fashion (engineering values).

The IDV process has benefits at all stages in a projects life as follows:

Planning Phase

The objective during the planning phase is primarily to determine site specific factors which affect the design, construction and operation of the immersed tunnel, such as:

- Ground conditions.
- Polluted or contaminated sediments and their disposal or storage.
- Ship wrecks and undetonated ordinance
- Water conditions: density, turbidity, current velocities and tidal variations.

For the ground investigations, special emphasis is placed on parameters related to settlement and calculations must take the construction sequence into account.

Construction Phase

The objective during the construction phase is primarily to ensure that the structure is built as designed and that excessive loading does not occur. Certain testing is also performed, such as:

- Pressure test of Gina and Omega gaskets.
- Weight of the individual elements.
- Watertightness is monitored.

Note that this phase frequently contains certain tasks related to research and technical development. These are primarily aimed at increasing our knowledge of the real behaviour of the construction, verification that design assumptions concur with reality, and improving the design of future immersed tunnels.

Operation Phase

The objective during the operation phase is to use and update the as-built documentation produced during the design and construction. This incorporates both static information (material parameters, geometry, drawings) and dynamic information (maintenance intervals and routines, settlement measurements). Inspection must also be performed to obtain information concerning the condition of the structure that has consequences for maintenance and repair operations.

A major task in this phase is to keep the documentation alive and accessible. Information technology is changing rapidly and individual data retrieval systems are expensive to maintain. While normal bridge or tunnel management systems may appear restrictive or limiting for a structure like an immersed tunnel, continuous upgrading is more likely to be assured for national systems.

Requirements for Contractor

The contractor has the same function as for other construction projects. Documentation pertinent to immersed tunnel construction will be necessary, e.g. dry dock construction, loading during transportation, installation procedures, etc. The format of all documentation provided by the contractor should also be specified to facilitate the operation phase, i.e. data management system.

Requirements for Design Engineer

The designer has the same function as for other construction projects. However, the designer's role in the I, D and V and the preparation of the as-built documentation must be emphasised.

4 > Owners Guide Themes

The IDV principles can be set out in the individual themes according to the need and desire of the Owners organisation. It should be recognised that different Owners will want differing levels of involvement in the technical decision making process during the planning, execution and operating phases and to a large degree this will be reflected in the selected procurement method and operating philosophy.

Nevertheless some recommendations are provided on the areas where IDV would be of benefit to all Owners in order to ensure that they obtain value for money, to assist them in maintaining their assets over their expected life and to transfer knowledge.

EACH THEME IS PRESENTED BY USING THE FOLLOWING TEMPLATE
Theme: xxx
What (parameter, e.g. settlement …)
When (start-finish & measurement frequency)
Specifications (number, precision, placement, redundancy …)
Documentation (format, deadlines)
Expected values
Analysis (requirements, timescale …)
Behavioural tolerances (limits, deviations)
Remedial measures/Actions (for unexpected behaviour/values)
Links to other processes
Performed by / Responsible : (e.g. 100% contractor …)

ANNEX – THEMES :

00 Glossary of Terms
01 Theme: Concrete – Concrete Construction
02 Theme: Cracks – Concrete Construction
03 Theme: Fire Protection
04 Theme: Tunnel Ventilation and fire
05 Theme: Segment Joints
06 Theme: Immersion Joints
07 Theme: Closure Joints
08 Theme: Steel Construction
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