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Immersed Tunnels

Richard Lunniss and Jonathan Baber



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Foreword

Faced with having to cross a waterway, an engineer must decide whether to use a bridge above it or a tunnel underneath. If for whatever reason a bridge is not feasible or desirable, the next decision to be made is what type of tunnel should be used. The key parameter is the depth required for a safe tunnel. This is key, because the depth largely determines the total length of the tunnel and, thereby to a large degree, the cost. There are three basic alternatives of depth, listed here in ascending order: (1) bored, (2) immersed, and (3) submerged floating.

The bored tunnel is most likely the deepest as it generally requires an overhead cover of a full diameter or more below the sound bottom of the waterway. The immersed tunnel requires only a 2–3 m cover below the natural waterway bottom to protect it from dragging anchors or sinking vessels. The submerged floating tunnel is the shallowest alternative as it only needs to be located at a safe navigation depth. The latter has great potential advantage in crossing the deep, wide fjords of Norway. The submerged floating tunnel concept has been studied extensively in that country and others, but no project of that kind has actually been built as of yet.

What this all leads to is the fact that the immersed tunnel has emerged more and more as the most efficient way of crossing under a waterway. In addition, this method offers other very real advantages over bored tunnels. The factory-style production in a dry dock of prefabricated elements that can be floated to the site, lowered into a trench, and joined with watertight immersion joints to very accurate alignment is a construction method with little of the inherent risk or contingency of a bored tunnel.

The first immersed tunnel ever constructed was a sewer tunnel under Boston Harbor in 1893, and the first transport tunnel was a two-track rail tunnel between Detroit, Michigan, and Windsor, Canada, in 1910. The first transport immersed tunnel constructed in Europe was the Maastunnel in the Netherlands that was completed in 1943, being built during the time that spanned the occupation of Holland during World War II. The latter tunnel was designed as a concrete box-type tunnel. That configuration

started immersed tunnel construction in Europe and is still used exclusively to the present day. Immersed tunnel design in the United States, until just recently, was largely that of single and double-shell steel acting compositely with concrete. As immersed tunnel technology grew in acceptance for both service and transport tunnels, its use became worldwide. Other countries, such as Japan and China, adopted both concrete box and steel shell technologies and added some refinements of their own.

In recent years, some truly outstanding projects have been or are currently being constructed involving immersed tunnels. The Øresund Link between Denmark and Sweden with its 4-km-long Drogden Tunnel; the 3.7 km Busan-Geoje immersed tunnel in South Korea; and the Bosphorus rail tunnel, the deepest immersed tunnel in the world at 58 m, are examples of successful milestone projects. Currently, the Hong Kong–Zhuhai–Macao Crossing, with its 5.7 km immersed tunnel, and the 19 km Fehmarn immersed tunnel between Germany and Denmark are the longest immersed tunnel projects proposed to date.

I became involved in the design of my first immersed tunnel in 1954. It was the first Hampton Roads Bridge Tunnel (HRBT). At the time, it seemed like science fiction to me that you could put a tunnel together underwater. Later, in 1970, I went to Virginia to help supervise construction of the parallel second HRBT. Working through the construction of that immersed tunnel was, for me, a marvelous learning experience that led to a lifelong career in this special niche of civil engineering. While in Boston in the 1990s, at work on the Central Artery/Tunnel Project, I joined Working Group 11 (Immersed and Floating Tunnels) of the International Tunnelling Association (ITA). The working group was preparing a “State-of-the-Art Report” on immersed and floating tunnels, and I spent a lot of time at the Massachusetts Institute of Technology Engineering Library researching all existing published papers on all the immersed tunnels constructed to date. From this research, plus much support and help from Dr. Nestor Rasmussen, a world expert in the field, we jointly produced the ITA catalogs of immersed service and transport tunnels.

During this research in Boston, I was surprised to find how little was available in the way of papers on immersed tunnel projects. These were major public works using very innovative technologies still in development, but little seemed to be available that documented them. Beyond this, I found that there also was little available in the way of manuals or technical books to help engineers undertake the design of immersed tunnels. There were a few books that devoted a section, or a chapter or two, to the subject, but they tended to reflect a rather narrow range of experience. The ITA State-of-the-Art Report came closest to a useful design guide with its second edition in 1997, but this is now 14 years old and the technology has moved on considerably since then.

Thus, this comprehensive book on all aspects of developing an immersed tunnel project is a very much needed resource and should be welcomed by planners and designers worldwide. It is written by two fine engineers whom I got to know while I helped to prepare a proposal for the construction of the Marmara project in Istanbul, Turkey. I enjoyed working under their direction and was greatly impressed by their breadth of knowledge and experience, which included key roles in the design and construction of the Drogden Tunnel of the Øresund Link and other important immersed tunnel projects. Although ours was not the winning proposal, it happened that I was later asked by the Turkish Ministry to oversee the construction of the immersed tunnel portion. During the period I worked on the project (2005–2007), I sometimes found myself wishing that some of the construction methods proposed earlier by Richard and Jon had been used by the contractor on the job.

This book covers all the aspects of planning and designing an immersed tunnel project. Early in the project, one must come to grips with the environmental impacts of dredging and dredge spoil disposal, impacts on fishes and their migration, casting basins, water table drawdown, and so on. The basic cross section of the tunnel is determined by the traffic envelope, to be sure, but just as important are the space requirements for ventilation, fire and smoke control, emergency evacuation, service piping, and so on. These considerations, and many others, not purely the mathematics of structural design, are carefully described in this book.

I therefore believe that this book will be found to be a very useful reference for civil engineers in the process of developing an immersed subsea tunnel project for the first time or even for those engineers already experienced in some of the immersed tunnel methods, but who are facing a new project with unusual site conditions or constraints.

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We also show our appreciation to colleagues at the ITA Working Group 11 for sharing their experiences and expertise over the years in the interests of furthering knowledge about this fascinating construction technique. This book has been written in the same spirit of sharing knowledge.

Thanks also to Brendan Moore who kindly assisted with the preparation of a number of figures. Photographs have been included with kind permission from many colleagues, individuals, and organizations, to whom the authors are most grateful.

Introduction

An immersed tunnel is an ideal way of constructing a tunnel across a waterway, as the method relies on water to transport and place the tunnel. The first immersed tunnel was built in 1893, and there are now approximately 180 tunnels of this type that have been built worldwide. This is a relatively low number compared to other forms of tunnel construction, which suggests the field is still in its infancy. In fact, the construction methods draw from many other areas of established engineering practice; it is more the combination of techniques and the marine construction operations that are unusual. With only one or two tunnels opening each year, the knowledge of the technique is restricted to a small community of designers and constructors. With this book, we hope to demystify some of the techniques and broaden the construction industry's awareness of immersed tunnels.

To the uninitiated, it may seem that immersed tunneling is quite a narrow field of engineering, whereas, in fact, it is anything but that. The range of skills and disciplines required for an immersed tunnel project is extremely broad, encompassing structural engineering; complex geotechnical engineering; transport planning; highway and railway engineering; environmental engineering; maritime engineering; mechanical and electrical engineering; building structures; the complex issues of tunnel operation and safety; and of course, a few specialist items specific to immersed tunnel methods. This book attempts to describe how these can all be brought together to create an immersed tunnel crossing of a waterway, recently described by a Dutch colleague as “a most beautiful way of building a tunnel.”

Although there are several different types of immersed tunnels, the following basic principles of their construction are always the same:

- The tunnel is constructed from a series of prefabricated sections, or elements, each typically 100–200 m long.
- The elements are designed to float so that they can be transported to the tunnel location.

- The elements are lowered into a trench that has been dredged in the bottom of the waterway and joined together.
- The trench is backfilled and the tunnel finishes are completed from the inside.

The layout of a typical immersed tunnel is shown in Figure 1.1. It consists of a central section with several immersed tunnel elements that are placed under the waterway. At the banks of the waterway, the type of construction changes to cut and cover tunnel as the alignment rises from beneath the waterway. When the alignment has reached about 5 or 6 m below the bank level, then the cut and cover tunnels end in portal structures, and open approach ramps continue to ground level. There are variations to this general layout; for example, the immersed tunnel could connect directly to a bored tunnel, but in general, these three parts—immersed tunnel elements, cut and cover tunnels, and open approaches—are common to nearly all immersed tunnel schemes.

Immersed tunnels tend to be concentrated in certain geographical areas as a result of the geological and transport infrastructure requirements of various countries. The main areas of construction are the United States, Europe, Japan, and China, with many other countries having one or two such tunnels. Most immersed tunnels accommodate roads or railways but they have also been built as utility tunnels carrying water and power supplies and also as cooling water intakes and outlets for power generation stations. Indeed, the first immersed tunnel ever constructed was a sewage tunnel. Because of this, their dimensions vary enormously, but a typical immersed tunnel carrying a dual carriageway road is about 30 m wide, 9 m high, and generally, approximately 1–2 km long.

The intention of this book is to provide guidance for designers and constructors and explain the wide variety of techniques available to them. It is not to promote immersed tunnels as being intrinsically better than any other form of water crossing, such as bridges or bored tunnels, but rather

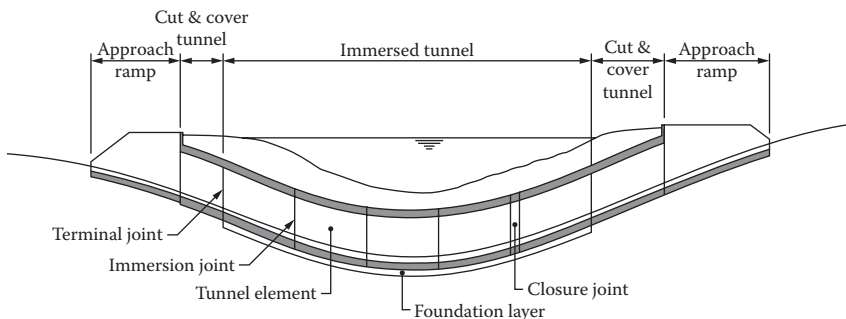


Figure 1.1 General immersed tunnel layout.

to show the merits of immersed tunnels and explain where and how they could be constructed. It gives a general introduction to immersed tunnels from initial planning, through design and construction, to operation and maintenance. We hope that it will promote the use of a technique that is frequently overlooked or misunderstood. Many papers and symposia have been dedicated to immersed tunnels and these cover particular aspects or projects, but this is the first time all aspects of design and construction have been drawn together in a single volume.

There are many different types of immersed tunnel, and practices differ across the world; we have endeavored to bring together the many aspects of current practice. Throughout the text, examples of projects are given where specific techniques have been used or where there are particular issues of which the designer or constructor should be aware. The authors are based in Europe and the majority of their experience is with the concrete immersed tunnels that are used in Europe, so inevitably the book tends to focus on those. We have, however, included sections on steel tunnels to give a complete overview of immersed tunnels. The book provides a general guide for the construction industry, to those engaged in the planning, feasibility, design, construction, or operation of an immersed tunnel, and also to those who have a passing interest in such tunnels. It also provides a broad knowledge base suitable for use in universities.

The book starts by tracing the historical development of the immersed tunnel, leading to the types of tunnel in use today. It then describes the factors that have to be considered when developing an immersed tunnel scheme and in particular, the environmental impact, and the mechanical and electrical systems that are installed, which are a vital part of any transportation tunnel. The second half of the book goes into the details of the design and construction of an immersed tunnel before finishing with operation and maintenance aspects and a review of important contractual issues.

Development of the immersed tunnel

The idea of the immersed tunnel arrived some time before a project was actually realized. The first concepts were developed in England in the early 1800s, at the time Brunel was starting out on his Thames Tunnel in London. The birth of immersed tubes and shield-driven tunnels therefore occurred at around the same time, even though immersed tubes were much slower to be implemented.

In 1803, a British engineer, Henry Tessier du Mottray, proposed linking England and France by an immersed tunnel constructed from cast iron tunnel elements laid on the bed of the English Channel. This was one of a number of similar schemes proposed at the time, but the imminent threat of a French invasion by Napoleon meant that none of these ever progressed. In 1808, another British engineer, Richard Trevithick, proposed a method of construction for a crossing of the river Thames that involved building sections of tunnel within dewatered cofferdams formed of timber piles. Once completed, the brick tunnel sections would be backfilled to the original riverbed level, and the cofferdam removed and reconstructed 50 ft further along the tunnel alignment. By progressing the cofferdam across the river, the tunnel would be formed. Although this was essentially a cut and cover method of construction, it featured many elements of the techniques now employed for immersed tunnels and was an important stepping stone toward the development of the first ideas for building them.

The tunnel was proposed to be of brick construction, although he later suggested the tunnel sections could be cast iron. Trevithick's proposals were submitted to the Thames Archway Company, which was trying to build the first tunnel under the Thames, but were not adopted, and in 1809, the company launched a competition for a new crossing of the Thames. They received 54 proposals, and in 1810, accepted the one from Charles Wyatt. This was to become the first true immersed tunnel concept. Wyatt's idea was to excavate a trench and immerse 50 ft long brick cylinders into it. The ends of the cylinders would be sealed with temporary spherical brickwork

bulkheads to enable them to be watertight and to float. Each would have a simple ballasting arrangement for sinking.

Wyatt's scheme was well engineered; for example, he had considered the possible impact of ships' anchors damaging the tunnel and ensured the trench would be deep enough so that once placed and backfilled, there would be 6 ft of earth covering the tunnel. The Thames Archway Company decided to trial the new technology to test the methods and outcomes, in particular, the method of forming the tunnel joints, the strength of the cylinders, the accuracy of placement that could be achieved, and the disruption to river traffic that would be caused. John Isaac Hawkins was appointed to construct two 25 ft long cylinders with an internal diameter of 9 ft. The trial was carried out in shallow water so that the tops of the cylinders could be inspected at low water, and manhole access was provided to enable internal inspections. The wall thickness of the tubes was 13½ in and each cylinder weighed 52 t, requiring 8–10 t of water ballast for immersion. The cylinders were built on submersible barges and scaffolding was constructed in the river to lower and position the cylinders. Because of the heavy river traffic, there was a frequent need to repair the scaffold following numerous collisions. The cylinders were transported by tying them alongside a barge. Once they were maneuvered into the scaffolding, lowering lines were attached to the cylinders along with masts to control positioning. After immersion, gravel backfill was placed manually around the cylinder to lock it in position. Hawkins's scheme is shown in Figure 2.1.

When the second element was placed, a mixture of mud and gravel was placed around the joint and the tunnel dewatered. Although some leakage of the joint occurred, it was considered that it would be possible to seal the joints with puddled clay. Although the concept was considered technically feasible, undoubtedly the methods of sealing the joints may have proved problematic in the full tunnel construction and would have needed some further engineering development. Sadly, because of the cost of the trials in 1811, the Thames Archway Company decided to abandon the project, but it was the first full-scale use of the technique and was groundbreaking engineering for its time.

The development of ideas continued in the United Kingdom after this, through to the mid-nineteenth century, by engineers such as John de la Haye, who published extensive discourse on the possible applications and construction methods for submerged tunnels in *The Mechanics' Magazine, Museum, Register, Journal, and Gazette* in 1845. He considered the use of cast iron submerged elements to construct tunnels in a number of locations around the United Kingdom and for a Dover to Calais crossing to France. He proposed external ballasting methods and looked closely at the safety benefits and cost benefits the technique would have compared to the new shield tunneling techniques being used beneath the Thames. In fact, a number of new projects were proposed in the mid-nineteenth

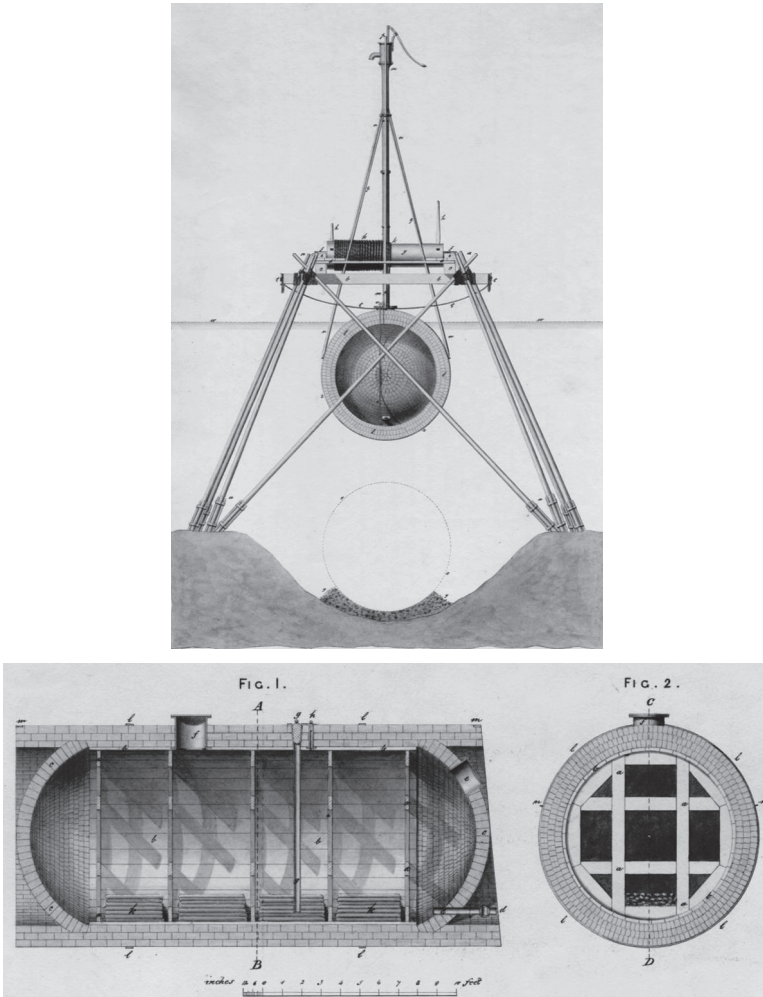


Figure 2.1 Charles Wyatt's immersed tunnel proposals. (Courtesy of Institution of Civil Engineers Library.)

century that used the immersed tunnel idea. These included further proposals for crossing the English Channel by French engineers, but they were not progressed due to continued national security concerns. There were also a number of immersed tunnels proposed on railway projects in various western European countries. At the same time, ideas were beginning to emerge in the United States. However, the next attempt at construction was back in the United Kingdom, when a new immersed tunnel beneath the Thames in London was proposed in 1865 for the Waterloo and Whitehall

Pneumatic Railway. Thomas Webster Rammell had formed a company that envisaged a network of pneumatic subways in London, and the Waterloo–Whitehall line was to be the first section to be built, crossing the river Thames at Waterloo station. This project was abandoned in 1868 following a banking crisis in 1866. Work had progressed to the extent that parts of the riverbed had been dredged and some foundation works had been constructed. One of the tunnel elements had been completed and two more partly constructed. This was, therefore, the first true attempt at building an immersed tunnel, but the works were eventually dismantled. The type of construction was different from Wyatt’s earlier tunnel; the tunnel elements were constructed from $\frac{3}{4}$ in thick iron boiler plate and had an internal and external brickwork lining. They were also much longer cylinders, each 235 ft long, with an internal diameter of 10 ft.

In the United States, momentum was gathering to build transportation tunnels with the method. An engineer named Joseph de Sendzimir was particularly active in this and proposed links between Lower Manhattan and Brooklyn crossing the East River with submerged tunnel elements fabricated from bolted iron boiler plate. This work was published in 1857. He also looked into building a pneumatic railway, following in Rammell’s footsteps in 1866, using submerged iron tubes to connect Manhattan with Brooklyn and New Jersey. There were a number of similar ideas across the United States, but as with the United Kingdom, none ever came to fruition.

The first immersed tunnel project to be built eventually came in the United States right at the end of the century in 1893. It was a rather unglamorous scheme, a siphon beneath a 60 m wide tidal sea inlet called Shirley Gut, which conducted sewage from Boston to Deer Island station. The tunnel was constructed from brick and concrete; it was 100 m long and 2.7 m in diameter. Wooden bulkheads were installed at the end of each tunnel element, and external steel flanges at the ends of the elements enabled them to be bolted together after placing. Its opening marked the birth of immersed tunnels and it was quickly followed by others. In the same year, a twin-tube 200 m sewer scheme was constructed in Paris beneath the river Seine using the same technique, and 7 years later in 1900, a 185 m long culvert and a 43 m long sewer were constructed in Denmark. From these humble beginnings, the construction technique was able to be developed and applied to larger-scale transportation tunnels. The first of these to be constructed was the Detroit River Tunnel that opened in 1910. This was a border crossing railway tunnel built under the St. Clair river between Detroit, Michigan, in the United States and Windsor in Canada, for the Michigan Central Railway. The tunnel was designed by the American engineer W.J. Wilgus and comprised twin watertight steel tubes placed in a dredged trench, which were then surrounded by concrete. The tunnel was made up of 10 elements, each 80 m long with one shorter closure element of 20 m. The floating element can be seen in Figure 2.2.

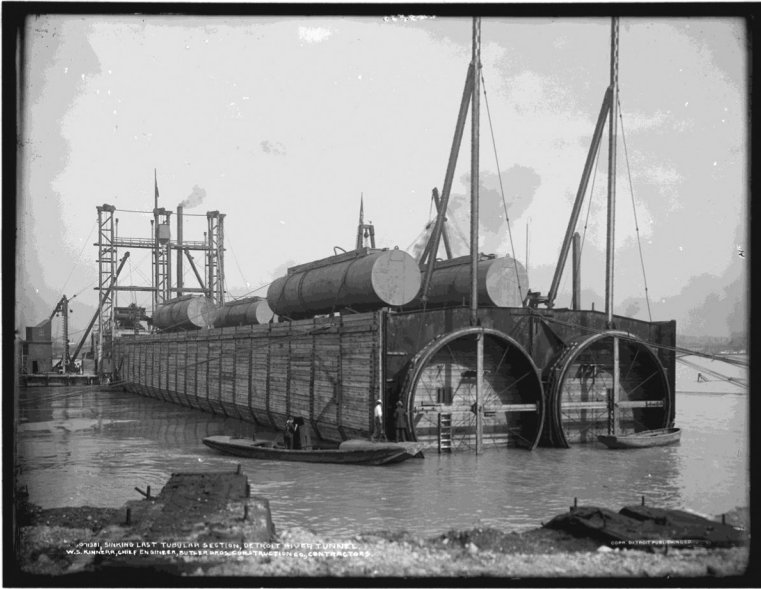


Figure 2.2 Detroit River Tunnel. (Courtesy of Library of Congress, Prints and Photographs Division, Detroit Publishing Company Collection.)

There was a considerable steel shipbuilding industry in the United States, and it made sense to make use of that expertise in the construction of the prefabricated units that formed the tunnel. The tubes were built by the Great Lakes Engineering Works in Detroit. They were used to building freighters for the Great Lakes and so they used a form of construction that was familiar to them. The tubes were constructed in pairs and each tube was designed to carry one railway track. The tubes were circular, 23 ft 4 in in diameter, and built from $3/8$ in steel plate riveted together with lap joints that were caulked similar to boiler construction. They were strengthened by circumferential stiffener angles ($4 \times 3 \times 3/8$ in) riveted to the inside of the plate at 12 ft centers. To provide additional temporary support during the placing operation, internal steel rods, similar to bicycle wheel spokes, were placed at each stiffener. The tubes were fitted with external steel diaphragms, again at 12 ft centers, which in turn supported wooden shuttering on the vertical sides that formed an open box around the tubes. This external box contained the permanent ballast concrete that was poured around the tubes once they had been placed in position in the trench. The minimum thickness of concrete around the steel tube was 3 ft. The ends of the tubes were sealed with wooden bulkheads, and rubber gaskets were used to seal the joints between the elements. All the tube sections were built within 20 months.

The trench was dredged across the river using a clamshell dredger. The material excavated was clay with layers of sand and gravel and the water depth varied between 20 and 50 ft. The bottom of the trench was checked for depth and width by dragging a steel beam along it. Once the trench had been excavated, a steel grillage was placed on the bottom under each joint between tubes to provide support when they were placed. The grillages placed under the joints were large enough to engage with the end diaphragms of each tube and shims were placed to achieve the required levels. This was an interesting, if perhaps expensive, method of overcoming the problem of obtaining the correct relative vertical position of adjacent tunnel elements, which is still a challenge using modern techniques.

To overcome the negative buoyancy of the tubes, water was introduced through the bulkheads with each of the end bulkheads being fitted with a valve that could be opened from the outside. The inside of the tubes were compartmentalized into three sections by two interior bulkheads, and 60 ft long air cylinders were placed on top of the elements. These external air cylinders were also divided into three compartments. This arrangement enabled the trim of the element to be controlled very accurately during the placing operation. The submerged weight of the whole element during placing was about 500 t. The sinking operation itself was very similar to those of today. Large anchored floating barges fitted with derricks were used, and the time taken to submerge an element was approximately 2 hours. The elements were joined together using bolted flanges at the end of each unit, and these connections were made by divers.

Concrete was then tremied into the open box around the steel shells. At the time, there was no experience of placing such large volumes of concrete underwater and the contractor had to undertake numerous experiments to develop a successful concrete mix and a method of placing it. This operation was controlled by divers who ensured that the concrete surrounded the shells and provided sufficient cover to the top. The trench was then backfilled, first with granular material to about half the tunnel height and then the remainder was filled with clay that had been excavated from the trench. The water in the elements was then pumped out through the previously placed units. This enabled work to continue inside the elements with the removal of the wooden bulkheads and the placing of the inner reinforced concrete lining. The successful completion of the tunnel in 1910 demonstrated the feasibility of large-scale immersed tunnel construction and found practical solutions to the technical challenges it presented. The steel shell immersed tunnel had been born, and many of the techniques used for this first tunnel were carried forward, reused, and developed for the many tunnels that were to follow in the next decades.

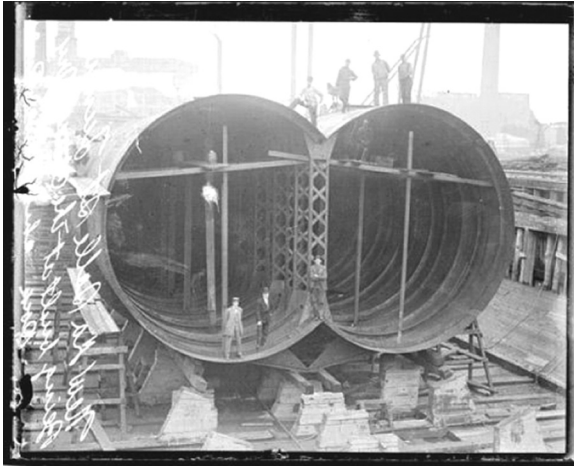


Figure 2.3 LaSalle Street Tunnel.

STEEL SHELL TUNNELS

Following the success of the Detroit River Tunnel, steel shell immersed tunnels became an established method of building tunnels under waterways in the United States. Two more rail tunnels were to follow in quick succession. The LaSalle Street rail tunnel in Chicago was opened in 1912, although this was only one element long. This was a single-shell tunnel and the first of its kind. The steel shell can be seen under construction in the Goose Island dry dock in Figure 2.3. Shortly after this, the Harlem River railway tunnel in New York opened in 1914. The first road tunnel in the world was the Posey Street Tunnel between Oakland and Alameda in California, which was completed in 1928, although this was, in fact, a cylindrical reinforced concrete tunnel.

The first three tunnels were all slightly different in how they were constructed, but from thereon, designs for steel tunnels in the United States developed subsequently into two clear types:

- Double steel shell
- Single steel shell

The original Detroit River Tunnel has been described as being both of these. In fact, it was a kind of hybrid. It only featured one steel shell, but it used the construction methodology that would come to be used for the double-shell tunnel and, in fact, the tunnel is closest to this form. The only difference was that timber shuttering was used to form the outer shell. The first true double-shell tunnel with a steel outer shell was the Harlem River Tunnel. Figure 2.4

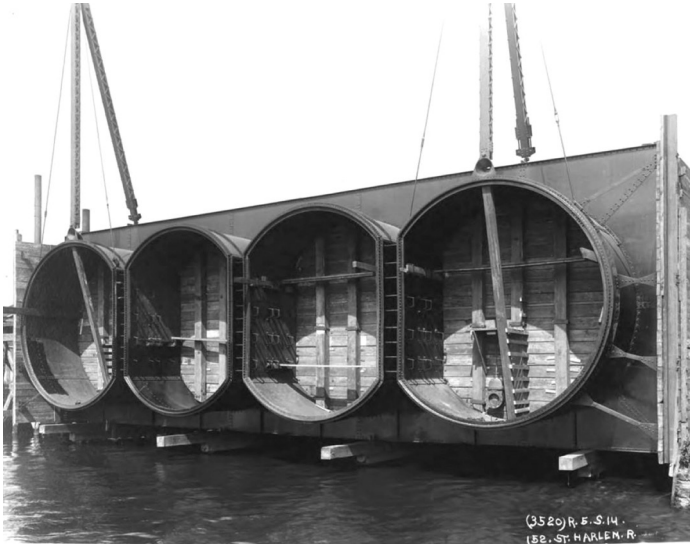


Figure 2.4 Harlem River Tunnel. (Photo Courtesy of New York State Public Service Commission.)

shows one of the tunnel elements for the Harlem River Tunnel supported on a series of flatboats prior to its immersion.

In 1930, the second tunnel beneath the Detroit River, the Detroit–Windsor Tunnel, was completed. The design of this second tunnel developed the hexagonal external shaped double shell section that became the most popular shape for tunnels in the United States. Figure 2.5 shows this geometry and is based on the Second Hampton Roads Tunnel that opened in 1976. The stiffened circular steel shell is fabricated for the whole length of the element. External diaphragms are added at intervals along the length, to which the external steel shell, also known as a form plate, is fitted. Concrete is placed around the outside of the shell between it and the external form plates. This concrete provides the main ballast to prevent uplift and also acts as corrosion protection for the circular structural steel plate. Inside the circular steel shell, an internal reinforced concrete lining is placed, and this in conjunction with the circular steel shell provides the primary structural strength of the tunnel.

The single steel section also developed in the United States. This also has a stiffened outer steel shell that is normally about 1/2 in thick. It is stiffened internally both transversely and longitudinally with the longitudinal stiffening being continuous over the full length of the element. Inside the steel shell, a reinforced concrete lining is placed, which acts compositely with the steel. This design does not use the tremie concrete as ballast but typically uses a ballast container on the roof that is filled

with stone. In this type of design, the structural steel shell remains on the outside and exposed to the waterlogged ground. It is therefore necessary to provide some form of external corrosion protection such as a cathodic corrosion protection system. A typical single shell design is shown in Figure 2.6, which was used for the Bay Area Rapid Transit (BART) Tunnel in San Francisco, California.

A similar method of construction is used for both forms of steel shells, and they both make use of shipyard production techniques. First, the steel shells are fabricated as a series of regular modular subassemblies. Then, several of these subassemblies are welded together to form the continuous element. This is often done directly on a slipway adjacent to the waterway,

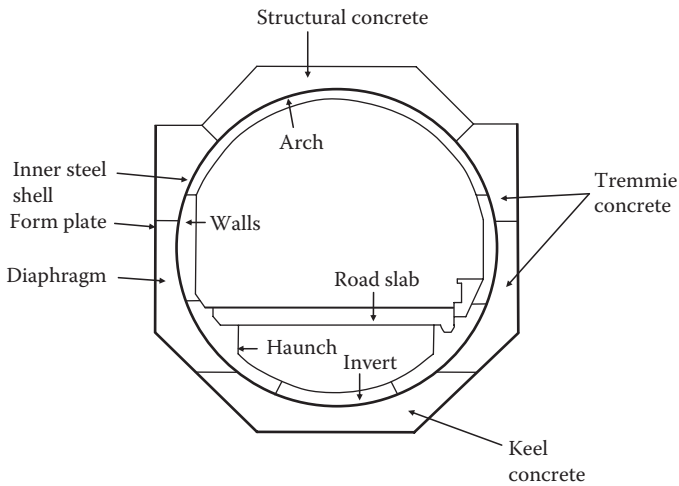


Figure 2.5 Second Hampton Roads double steel shell arrangement.

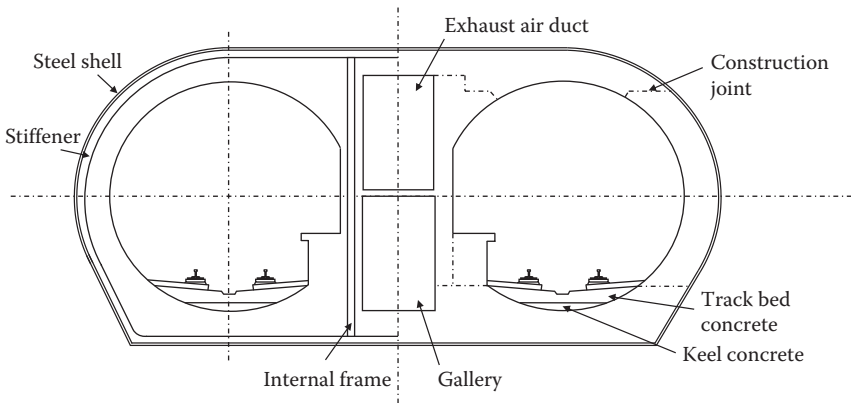


Figure 2.6 BART Tunnel single steel shell section.

to facilitate launching the element. The elements are preferably launched sideways to minimize the stresses imposed, but they can be designed for end launching if required. Before launching, the reinforcement for the inner concrete lining is placed together with other internal equipment and a certain amount of keel concrete is also placed to increase the draft of the element and to give it stability while afloat. The ends of the tubes are sealed with watertight bulkheads and the element launched similar to a ship launching.

It is then towed to an outfitting jetty where the internal concrete is placed while the element is afloat. The outfitting jetty can be some considerable distance from the shipyard and some steel shells have been transported on semisubmersible barges. This concreting operation is shown in Figure 2.7, which shows the draft of the elements increasing as more of the internal concrete is placed. The concreting sequence is carefully programmed so that the steel shell is not overstressed during the operation and also to keep the trim of the element under control. The designer has to take these temporary loading conditions into account when designing the unit and set limits for the contractor to adhere to during construction.

The steel shells are generally founded directly onto screeded gravel foundations. The gravel bed is screeded to the correct levels by dragging a screeding grid or blade over the surface. The base of a steel element section is fairly narrow, so the screeding method produces a sufficiently accurate bed to place the element on.

The advantage of the steel shell is that the fabrication facilities required are not extensive and are generally available in countries with a shipbuilding industry. They can be set up in other countries, but if there is no shipbuilding



Figure 2.7 Ted Williams steel tunnel elements at concreting jetty. (Photo courtesy of W. Grantz.)

tradition, the materials and fabrication skills may not be available and will have to be imported. The shells are also relatively lightweight with a shallow draught of about 2 ft, so they can easily be towed to the outfitting facility without the need for deep navigation channels. It is also possible to tow them considerable distances. For example, the elements for the 63rd Street Tunnel in New York were fabricated in Port Deposit, Maryland, and towed 300 km to Norfolk, Virginia, where the concrete was placed and then towed a further 480 km to the site in New York. Even longer journeys have been undertaken with the steel shells carried on semisubmersible barges. The Ted Williams Tunnel elements were transported from Baltimore to Boston, a distance of about 960 km along the Atlantic coast. In theory, there is no limit to the distance that a steel shell tunnel can be transported on a semi-submersible vessel, which means that a very wide range of fabrication facilities can be considered during the planning stage of the tunnel.

Some steel shell designs have taken slightly different shapes, but the principles remain the same. In general, steel shells have remained popular in the United States, with most being the double shell type, but not so much in other parts of the world, where concrete tunnels have generally been constructed. There have been exceptions, such as the first Cross-Harbor Tunnel in Hong Kong, but in Europe, concrete tunnels have been used exclusively. This is not due to a lack of shipbuilding facilities, but rather different economic drivers.

CONCRETE TUNNELS

In Europe, even though the immersed tunnel concept had originated in the United Kingdom, the abandonment of the early Thames crossing trials led to the development of shield tunneling, which became the preferred tunneling method there until the 1980s. A number of small utility immersed tunnels were constructed in the early 1900s in Germany, France, and Denmark. These were generally steel pipeline tunnels and culverts. The first concrete immersed tunnel of any significance to be constructed was the Friedrichshagen Tunnel in Germany, a rectangular pedestrian tunnel that was completed in 1927. The first concrete transportation tunnel was finished a year later in 1928 in the United States, the Posey Street Tunnel between Oakland and Alameda in California. Just over a decade later, the immersed tunnel technique was adopted by the Dutch. In response to a growing traffic congestion problem across the bridges over the Maas in Rotterdam, three engineers from the Rotterdam Department of Public Works traveled to the United States in 1929 to study the immersed tunnel construction methods being used there. The result was the letting of a construction contract for the Maastunnel in 1937.

To satisfy an expanding road and railway infrastructure network, the Dutch had to provide many relatively short waterway crossings in their low-lying delta country with its many natural and man-made waterways. The height of the bridges needed to allow ships and barges to pass underneath would require long approach structures. These would be intrusive in such a flat landscape as well as adding to the overall cost of the crossing. In these circumstances, it became economic to construct an immersed tunnel due to its shorter overall length. The soft alluvial sandy soils and high water table present in the Netherlands lent themselves to the adoption of the immersed tunnel technique. The option of using a tunnel shield that had been successfully developed in the United Kingdom would have been very difficult with the high water table and soft permeable ground. The Dutch also had a history and capability in marine construction that could quickly adapt to building an immersed tunnel.

The Dutch, however, did not adopt the steel shell design pioneered in the United States. Steel prices were relatively much higher in Europe than the United States, so the Dutch developed a reinforced concrete section. The overall principle of the tunnel construction is the same, but the tunnel elements were built out of reinforced concrete rather than steel. This is a very adaptable form of construction, more so than the steel shell, and this enabled a rectangular cross section to be developed. The Dutch waterways are not very deep, so the rectangular section was easily capable of resisting the hydrostatic pressures. The rectangular section also matched better the rectangular traffic envelope required for road tunnels.

The use of a rectangular cross section was made possible by the development by the Danish contractor Christiani & Nielsen of a method of injecting a sand foundation into a space below the tunnel element. At the time, the techniques were not available to screed a gravel bed accurately enough to allow a stiff wide concrete box to be placed on it without the possibility of inaccuracies in the bed levels causing unacceptable stresses in the box. The Maastunnel in Rotterdam (Figure 2.8), which was completed in 1942 despite wartime conditions, was the first Dutch tunnel and was the first large transportation immersed tunnel constructed outside the United States.

Subsequently, a few concrete immersed tunnels were built around the world, but the real impetus for concrete immersed tunnels came in the Netherlands in the 1960s as the need for improved transport links grew. The first was the Coen Tunnel, in Amsterdam, built between 1961 and 1966 for the Rijkswaterstaat, the Dutch Ministry of Transport and Water Management, which again involved Christiani & Nielsen both as contractor and designer. Several such tunnels were then built in the area (the Netherlands, Belgium, and Denmark) in the 1960s. There was a similar large building program in the Netherlands in the 1970s.



Figure 2.8 The Maastunnel under construction in 1941. (Photo courtesy of A. Scheel.)

The rectangular concrete section became the standard construction technique for these many European road and rail tunnels. The Dutch and the Danish contractors and designers involved developed considerable expertise and experience, which they subsequently managed to export around the world. Concrete immersed tunnels were also built in Germany and Sweden. Christiani & Nielsen also built two concrete tunnels in Canada in the 1960s with Per Hall as the designer. At this time, the Japanese also showed interest in the technique. Their first immersed tunnel, at Haneda, adopted a different approach with a prestressed concrete design, albeit with a steel outer layer, and was opened in 1964.

The technique spread around the world, and in general, the reinforced concrete section became the preferred option. The United States favored their steel shells, Europe universally adopted reinforced concrete, while the Japanese developed both. The most concentrated development of immersed tunnels is across Hong Kong Harbor, where five immersed tunnel crossings have been built (two road, two rail, and one road/rail combined), and at least two more are proposed. The shallow depth of immersed tunnels is particularly appropriate to somewhere like Hong Kong, where urban development presses in along the sides of the harbor and the approaches to the tunnel have to be as short as possible. In addition, the underlying granite could make it very difficult to bore a tunnel.

As more tunnels were built, the construction methods were refined. For example, initially, the sand foundation material under the tunnel was jetted in place using external plant. A rig was supported on the top of the tunnel and moved along the length of the tunnel. A sand-water mixture was piped down the outside of the tunnel and injected in underneath the tunnel. The use of such plant in the waterway was an obstruction to navigation that would be better avoided. The Dutch developed a method of placing the foundation by

injecting it through ports cast through the floor of the tunnel elements. This enabled the operation to be carried out without obstructing the waterway.

Another major development was the introduction of the segmental concrete tunnel element in the 1960s and 1970s. Before this, the tunnel elements, which were about 100 m long, were built as monolithic reinforced concrete elements. Building such large concrete sections led to early thermal shrinkage cracking, and such cracks go right through the concrete section and provide a path for water to leak into the tunnel. As well as being unsightly and affecting the internal tunnel finishes, the leakage could cause chlorides to penetrate the concrete, jeopardizing the long-term durability of the reinforced concrete. Thus, the early concrete tunnel elements had an external waterproofing membrane to make them watertight. To avoid the need to apply the membrane, which was time-consuming as well as expensive, the Dutch developed the technique of dividing the 100 m long element into a number of individual segments each about 20–25 m long. These segments could be cast without any early thermal shrinkage cracks, so the element did not need an external waterproofing membrane. The effort was put into making the concrete itself watertight rather than surrounding potentially cracked concrete with a watertight membrane. The segments have to be temporarily prestressed together to form a continuous element while it is being towed and placed, but this prestress is then cut after the element has been placed.

The technique was developed in stages; segmental construction was used for land tunnels initially on projects such as the Schiphol airport tunnel that was completed in 1966. Short segments were constructed with a waterproof articulation joint between them to prevent groundwater entering the tunnel. The concrete tunnel structure still had an external waterproofing membrane applied because cracking could not be entirely eliminated. This type of construction was first transferred to the immersed tunnel method for the Heinenoordtunnel that opened 3 years later in 1969. The method of temporarily prestressing segments together to create tunnel elements was established for the first time on this project. The final step in the development of the segmental construction method was made for the Vlaketunnel that was opened in 1975. The technique of cooling the concrete during curing meant the cracking could be prevented and the need for a waterproof membrane was eliminated. The technique was successful, and since the 1980s, it has been adopted on all Dutch tunnels and for the majority of the tunnels built in western Europe.

Thereafter both segmental and monolithic concrete designs were used around the world, the choice often being dependent on the client's view of which was the more watertight. Some, like the Dutch, were satisfied that the measures taken to produce crack-free concrete in the segmental method were sufficient. Others were not so convinced and preferred the security of an external waterproofing system. As discussed in Chapter 11, external

waterproofing systems are not problem free and do not always give the watertightness envisaged.

It is worth noting that in the early 1970s, the Dutch were also pioneering techniques for full-section casting of concrete tunnels for their smaller utility tunnels. By constructing short tunnel segments on end, they effectively removed construction joints from the segment structure and prevented cracking from occurring. Segments could then be assembled together to form tunnel elements. This was successfully achieved for the Amsterdam–Rhine canal culvert in 1971 and the Hollandsche Diep and Oude Maas pipeline tunnels in the mid-1970s. This was the precursor to utility tunnels built in Asia, but more importantly fed into the development of full-section casting techniques used for the much larger-scale Øresund and Busan Tunnels.

Concrete tunnels have remained little used in the United States. The two Posey Street Tunnels, built in 1928 and 1962, and the 2002 Boston Fort Point Channel Tunnel are the only concrete tunnels to have been built there. Apart from economic arguments, another reason was that U.S. authorities favored transverse or semi-transverse ventilation. They did not believe that the longitudinal ventilation system used in Europe and elsewhere could provide clean enough tunnels. They also considered their ventilation systems inherently safer in the event of a fire. Transverse ventilation systems are easy to accommodate in the basically circular cross section used in steel shell tunnels because of the spare space above and below the rectangular traffic envelope. This provides space to duct air into and out of the tunnel, so the United States was happy with their approach. In the relatively short Dutch tunnels, which are typically up to 1 km long, longitudinal ventilation was used, with jet fans in the traffic bore assisting the natural piston effect of the moving traffic. Space is at a premium and not having to provide wider or deeper cross sections to accommodate the air ducts was a big advantage.

Worldwide experience and analysis and testing has eventually satisfied U.S. authorities that the longitudinal system is safe in the event of fire and so now concrete immersed tunnels are more acceptable in the United States. Additionally, with the decline of the steel industry, it is becoming more attractive to contractors to construct in concrete as it gives greater flexibility in how they approach a project and a greater pool of labor resources to draw from. The Second Midtown Tunnel project in Virginia is progressing as a concrete tunnel for these reasons, and it is likely that very few, if any, steel tunnels will be constructed in the United States in the future.

COMPOSITE SANDWICH TUNNELS

The use of steel–concrete composite sandwich construction is a more recent development that has mostly been promoted in Japan, although a lot of research and testing has also been carried out in the United Kingdom.

Construction consists of a sandwich of concrete between two steel plates. Typically the steel plates are about 300 mm apart and connected with shear studs. The concrete is placed between the steel plates, so a very fluid self-compacting mix is required. Placing this concrete and ensuring sufficient compaction and complete filling of the void between the plates is one of the main challenges of this method. Because the steel concrete sandwich is very strong structurally, the composite section is a very elegant structural solution. However, in any immersed tunnel, the air space to carry the road or rail traffic requires a fixed amount of ballast to hold it down. So, although the composite design can give thinner structural members, the weight still has to be provided by ballast boxes on the roof or internal ballast under the roadway. The internal steel skin also does not lend itself to the many box outs and openings that are needed in a modern road tunnel.

While research and one-third scale testing of sandwich sections have been carried out in the United Kingdom by the Steel Construction Institute to the extent that design rules have been developed (SCI Publication 132, 1997), the concept has not yet been used on a full-scale tunnel in Europe. It has been left to the Japanese to pioneer the use of steel/concrete composite sandwich construction on the Kobe and Naha Tunnels.

TUNNELS IN JAPAN

Apart from the Netherlands and the United States, Japan has also been instrumental in the development of immersed tunnels and warrants specific mention. The first Japanese immersed tunnel was finished in 1944. This was the Aji River Tunnel and carried both road and pedestrians, but it seems the first tunnel of great significance is considered to be the Haneda Ebitori River Tunnel, completed in 1964 for the Haneda mono-rail. It is a rectangular single shell steel box 7.5 m high and 11 m wide, and the tunnel consists of one 56 m long element. The first tunnels in Japan were all quite short and mostly single shell type construction. Many were built more as underwater bridges than what we would now consider as a conventional immersed tunnel. The first multiple element tunnel was the Haneda Tama River Tunnel built in 1970 beneath the Tama River and the Keihin Channel in Tokyo.

Since then, a number of tunnels have been constructed, generally using the single steel shell construction method or reinforced concrete monolithic tunnel elements. The majority are rectangular in cross section. In recent years, the Japanese have been more innovative in their immersed tunnel designs than any other nation. They have built steel, concrete, and sandwich composite tunnels, developed novel closure joints, and developed seismic-resistant tunnel element joints.