

# Immersed Tube Tunnels: Concept, Design & Construction

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*Offering significant engineering and cost advantages, the use of immersed tubes for tunnel construction is growing. Major questions today involve where and how to use the immersed tube concept.*

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**I**MMERSED TUBE is the designation for tunnels composed of prefabricated sections that are placed in a trench that has been dredged in a river or bay bottom. The sections are usually constructed at some distance from the tunnel location and made watertight with temporary bulkheads. They are then floated into position over the trench, and are lowered into place and joined together underwater. The temporary bulkheads are removed, and the trench is backfilled with earth to protect the tubes.

Immersed tubes have been widely used for highway and rail crossings of soft-bottomed, shallow estuaries and tidal rivers. They have occasionally been adapted to sites

with irregular hard rock bottoms, and to sites exposed to ocean wave and storm conditions. In a few cases, they have been used for water supply, and in one case to transport liquefied natural gas.

Immersed tubes have been designed to accommodate both ground shaking and fault displacement resulting from earthquakes. Over many years of service, they have proven to be generally more watertight than other forms of tunnels. For example, the San Francisco Trans-Bay Tube is so watertight that a fire hose needs to be brought in occasionally to spray the concrete-lined inspection gallery in order to keep the dust level down.

## Historical Perspective

The first use in the United States of immersed tube tunnel construction methods — setting long prefabricated elements onto a prepared bed in a subaqueous trench — was for a water tunnel crossing the Shirley Gut in Boston Harbor in 1896. The first transportation tunnel constructed by immersed tube methods in the United States was the Michigan Central Railroad Tunnel under the Detroit River, completed in 1906 under the direction of William Wilgus. Another early immersed tube was the 4-track Harlem River

crossing of the New York Subway, completed in 1914, presently part of the IRT Lexington Avenue line.

The first highway immersed tube in the United States was a concrete tube section, the Posey Tube between Oakland and Alameda, California, completed in 1928. In 1930, the Detroit-Windsor tunnel between Michigan and Canada was completed. This tunnel marked the first use of welded steel shell construction for immersed tubes, and signalled more widespread use of similar construction methods for tunnels, including:

- The Baytown Tunnel under the Houston Ship Channel in Texas
- Three tunnels under the Elizabeth River between Norfolk and Portsmouth, Virginia
- Two parallel tunnels under Hampton Roads in Virginia
- Two tunnels in tandem on the Outer Chesapeake Bay Crossing in Virginia
- The Baltimore Harbor and Fort McHenry Tunnels in Baltimore
- A single 2-track tube used for the Chicago River crossing of the State Street subway in Chicago
- The Orange Line Charles River crossing in Boston, comprising two 2-track transit tubes
- The 4-track 63rd Street transit and rail tunnel in New York City
- The Trans-Bay Tube of the BART system in San Francisco
- The Cove Point Tunnel for unloading tankers at a marine terminal in Maryland
- The Washington Channel crossing on the WMATA Yellow Line in Washington, DC

Although there has been much discussion of concrete box section tubes in the United States, no project using this alternative has been realized here since the Posey Tube, primarily owing to economic constraints of building such a tunnel. The Deas Island Tunnel near Vancouver and the Lafontaine Tunnel at Boucherville, near Montreal, provide two Canadian examples of concrete tube construction.

## Advantages & Disadvantages

For underwater tunnels, the immersed tube concept offers several advantages compared to mined or shield-driven tunnels:

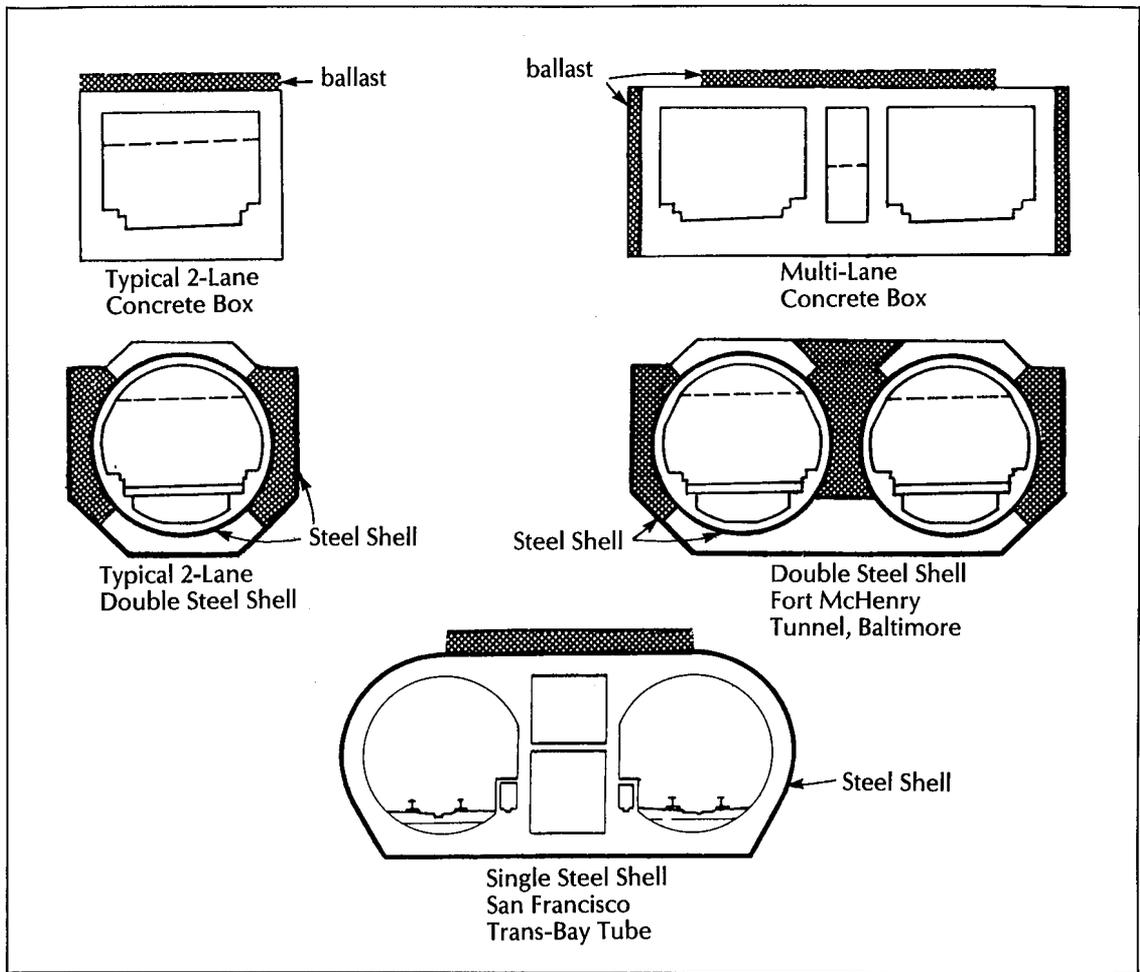
1. The tunnel has the minimum possible depth. For an approach gradient fixed by operating criteria, this usually means minimum tunnel length.
2. Almost all of the construction is accomplished above ground in normal working conditions. This promotes better quality of construction, particularly greater control of water leakage.
3. Most of the construction is similar to ship or building construction, and can utilize readily available labor skills. Relatively small amounts of special labor are required to control the placing and joining operations.

A primary disadvantage of immersed tube construction is the potential for disruption of existing facilities if the trench must be extended past the shore lines. Also, special equipment is required to construct a level foundation for the tubes, and to place and join the tube sections. The disposal of dredge spoil material excavated from the trench may create serious environmental problems.

## Configurations

Figure 1 shows representative immersed tube cross-section configurations. Circular sections are structurally efficient in resisting water pressure, which is the principal design load. Rectangular sections can frequently be made shallower than circular sections, reducing the tunnel depth. For highway tunnels, spaces for ventilation ducts must generally be provided above, below or between the roadway compartments. All sections must provide space for ballast to be added to overcome buoyancy in order to sink the tubes and hold them in place in the trench.

The typical steel shell section has evolved in the United States to combine the structural efficiency of a circular ring section with the economy of shipyard construction. This type of tube can conveniently accommodate a two-



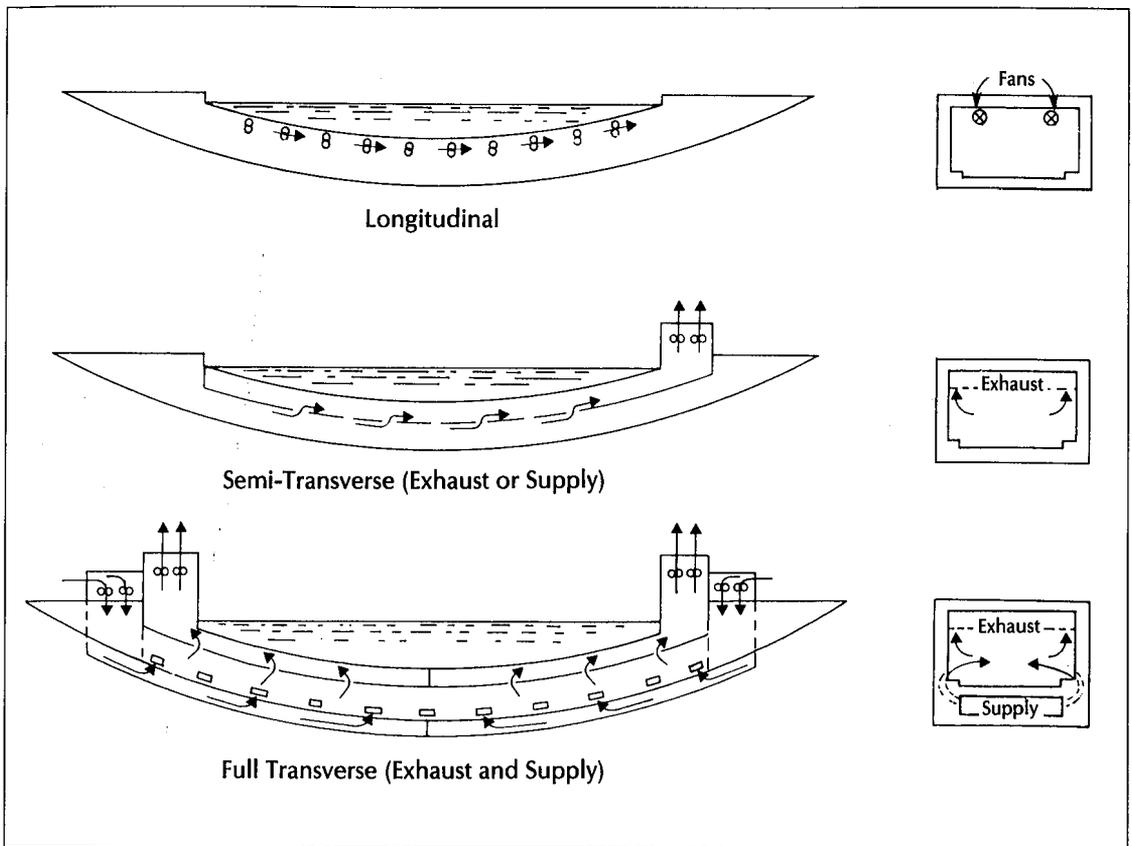
**FIGURE 1. Representative immersed tube cross section configurations.**

lane roadway with a fresh air duct at the bottom and an exhaust air duct at the top. Twin circles can afford sufficient room for four-lane roadways. Double steel shell sections are most common; however, single shell elements have been used. A single steel shell twin-track rapid transit tunnel is represented by the section of the San Francisco Trans-Bay Tube in Figure 1.

### Ventilation

While ventilation is a consideration for all tunnels, it has special significance for immersed tubes in that it may govern the configuration of the cross section. For highway tunnels, ventilation requirements are of primary importance, especially for long tunnels. The two design requirements for

ventilation systems are the dilution of exhaust gases and the control of smoke during a fire. Figure 2 shows some typical ventilation arrangements. A longitudinal ventilation system has fans mounted directly in the roadway compartment above the vehicle clearance line. This type of system is suited to tunnels with one-way traffic in each roadway compartment. However, the quality of the air decreases progressively toward the exit portal because the polluted air is not removed from the roadway compartment. In past U.S. practice, longitudinal ventilation has been limited to rural tunnels with light traffic or to relatively short tunnels (up to 1,000 feet). Longitudinal ventilation has been used for much longer one-way tunnels in Europe and Japan, and is currently being considered for



**FIGURE 2. Different types of tunnel ventilation systems.**

two U.S. mountain tunnels about 4,000 feet long.

Semi-transverse ventilation systems provide a single ventilation duct separate from the roadway compartment, for either supply of fresh air or exhaust of contaminated air. A supply system provides better air quality in normal operations, but an exhaust system provides better control of smoke. These systems have been used in the U.S. for tunnels up to 3,000 feet long.

For very long or heavily congested tunnels, a full transverse ventilation system is preferred, with separate supply and exhaust ducts. This provides the best quality of control of both exhaust emissions and smoke.

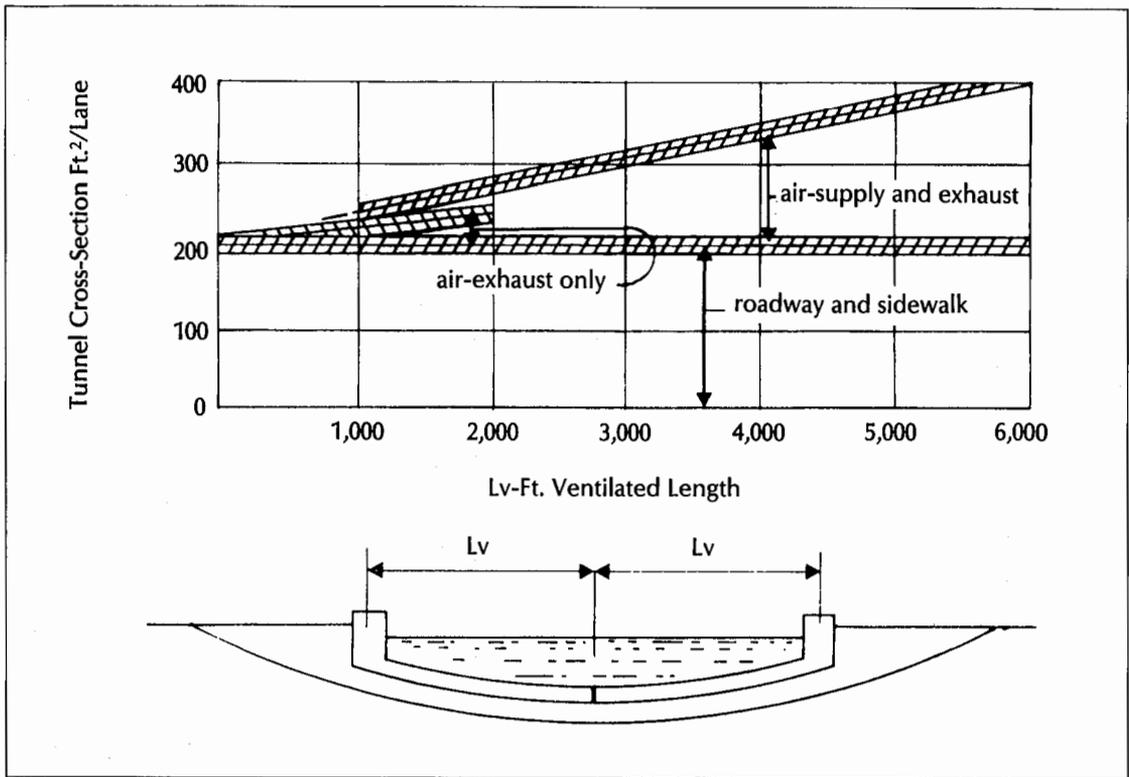
Figure 3 shows the relation between the length of ventilated tunnel and area required for roadway and sidewalk compartments and for ventilation ducts. This figure is based upon data from completed projects. Ventilation considerations may be the primary

factor controlling the selection of the cross-section configuration for long tunnels.

### Construction Methods

The two general construction methods employed for immersed tubes are the concrete box and steel shell systems shown in Figure 1. Most concrete box sections have been rectangular, which are well suited to wide tunnels under relatively narrow and shallow waterways. Concrete box sections depend for watertightness on very careful quality control of the concrete and frequently involve prestressing.

The steel shell system uses a circular steel shell plate as both a primary structural member and as a watertight membrane. The structural concrete lining contributes to the structural strength and provides weight to counteract buoyancy. The double shell system provides a circular structural steel ring and an octagonal steel form plate, and has evolved in



**FIGURE 3. Tunnel ventilation requirements.**

the United States as an efficient form for shipyard construction. The internal structural steel ring is protected by the exterior ballast concrete. Single shell construction, as used for the San Francisco Trans-Bay Tube, minimizes the amount of steel required, but the exposed steel shell must be protected against corrosion.

### Trench Profile

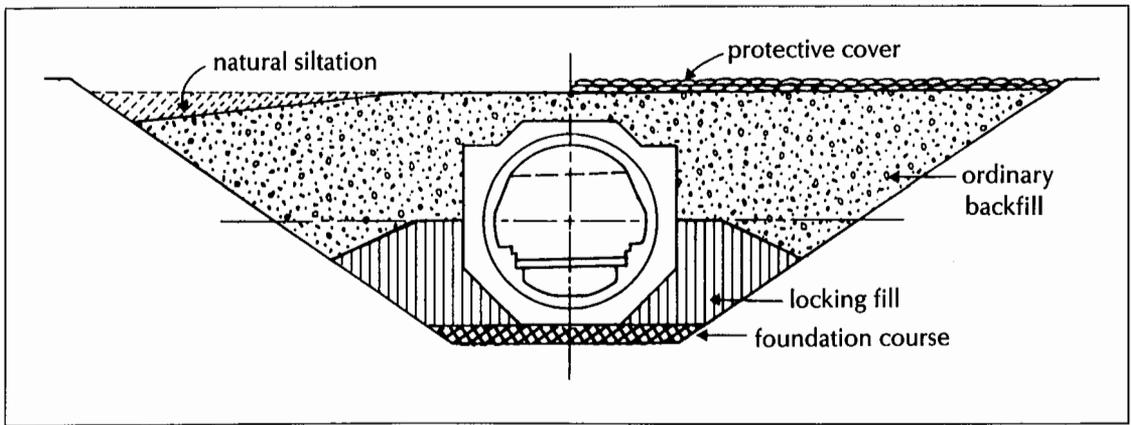
Most immersed tube tunnels have been constructed in soft soils and have been completely buried beneath the existing bottom of the watercourses. However, there are cases where trenches have been successfully blasted into rock, and cases where parts of the tunnel have projected above the existing bottom. Protection must be provided against scour by river and tidal currents, and to distribute concentrated loads or shocks that might arise from sinking ships or dragging anchors.

The buoyant weight of the tube and backfill is not greatly different from that of the original soil. As a result, foundation settlement

is usually not a problem for immersed tube tunnels. The tube sections are relatively flexible in a vertical plane, and can accommodate considerable differential settlement without distress. Very soft soils may have to be removed by dredging and replaced with more suitable materials.

### Foundations & Backfill

Figure 4 shows a typical trench cross-section. The rough dredged trench must be leveled to provide a uniform foundation for the tubes. After the tube section is placed and joined to previously placed sections, a special locking fill is added on both sides to hold the tube in place. This locking fill should be composed of angular crushed rock, so that the particles interlock to resist movement. Rounded river gravels are more suitable for foundation courses, since they can be readily screeded off to form a level bed. The tube is then covered over with ordinary backfill, which usually consists of material excavated from the trench. A protective course of gravel or heavy



**FIGURE 4. A cross section of a typical immersed tube trench.**

stones may be added if required by hydraulic conditions or by possible exposure to dragging anchors or occasional special loads.

### **Dredging**

The side slopes of the dredged trench are determined by the nature of the bottom soils. The bottom of the trench should be kept clear of material that may slough off the trench slopes, or drift in on bottom currents. These conditions usually require clean-up dredging just prior to placing the foundation course.

In the United States, concern for environmental pollution has made disposal of dredged materials a serious problem. At present, it is frequently necessary to construct a diked containment facility to prevent the soft, contaminated bottom soils from spilling out into the watercourse.

### **Foundation Alternatives**

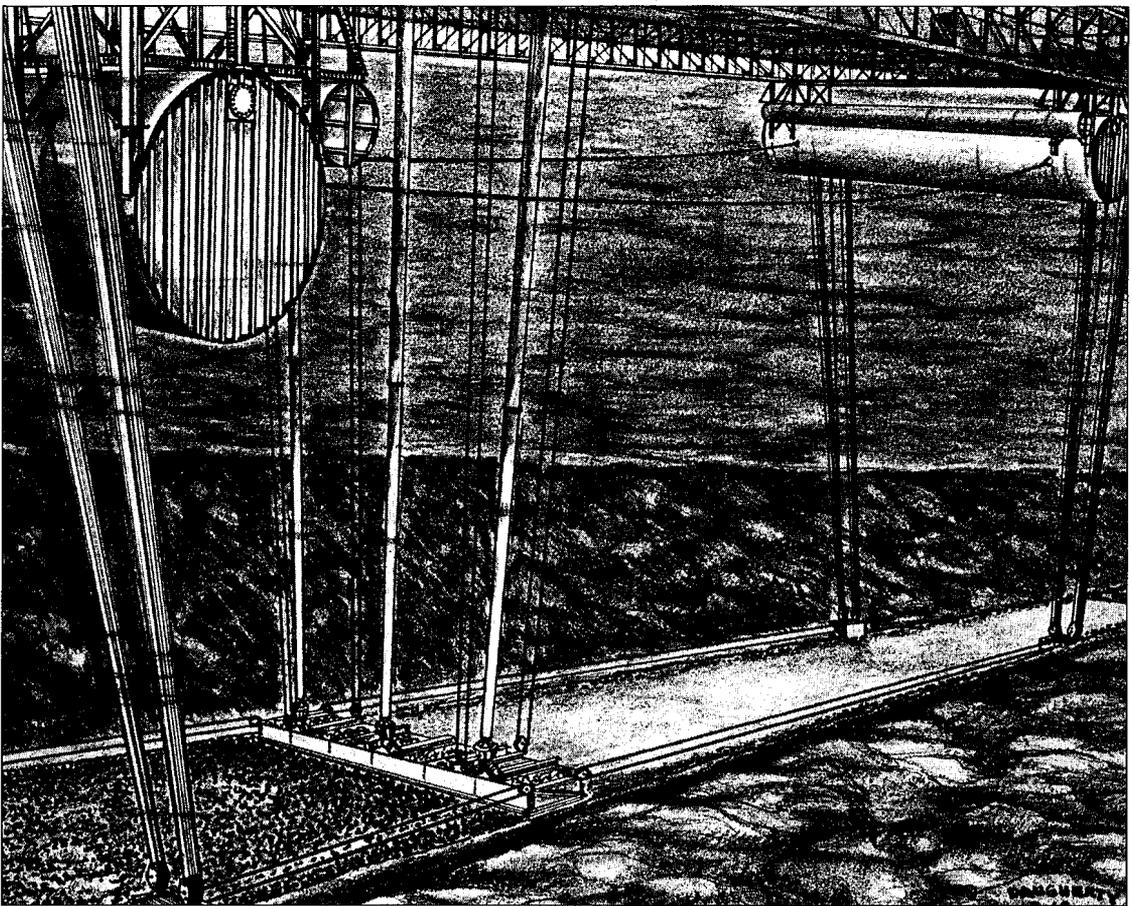
The most common foundation system in the United States is the screeded bed. This system requires a special construction rig for striking off a smooth plane at the desired profile. This is generally accomplished by suspending a heavy screed bar from a carriage that rides on rails set parallel to the trench profile and supported on a pair of barges. Figure 5 portrays the screed rig operation for the BART Trans-Bay Tube. The gravel is fed to a group of hopper bins supported by a carriage that rides on rails on the floating screed rig, which is ballasted so that the rails are parallel to the desired trench grade. The gravel is fed down

three pipes to a spreader box, which is open on the bottom only. As the carriage travels along the rails above, the box releases gravel into the trench, and the edge of the box screeds off a level bed. Screeded beds have been constructed to a width of 180 feet, with a surface accuracy of  $\pm 2$  inches.

The pumped sand foundation has been widely used in Europe. It requires setting the tube section on temporary foundation pads and adjusting its location with jacks. Sand is then pumped in beneath the tube to form a bed. This system also requires special equipment to place the sand uniformly and to verify that the space has been filled. The Japanese have developed a system involving injecting cement grout beneath the tube from the inside, working through holes in the floor. This system is capable of producing a superior foundation, but requires great care to seal up the large number of holes in the floor.

### **Tube Fabrication**

Steel shell sections have generally been fabricated on existing ship-launching ways in shipyards. Occasionally, new shipway facilities have been especially constructed for tube fabrication. The character of steel fabrication work required is similar to that required for ship construction. Double steel shell sections are particularly well suited to shipyard construction. The fabricating facility may be located at a great distance from the tunnel site. Steel tube sections have been towed through the open ocean for distances up to



**FIGURE 5. The screed rig operation for the Trans-Bay Tube Tunnel.**

1,500 miles. An outfitting facility, at which most of the concrete lining and ballast for sinking are added, should be provided. This facility is usually close to the tunnel site, but in one case it was actually 400 miles away.

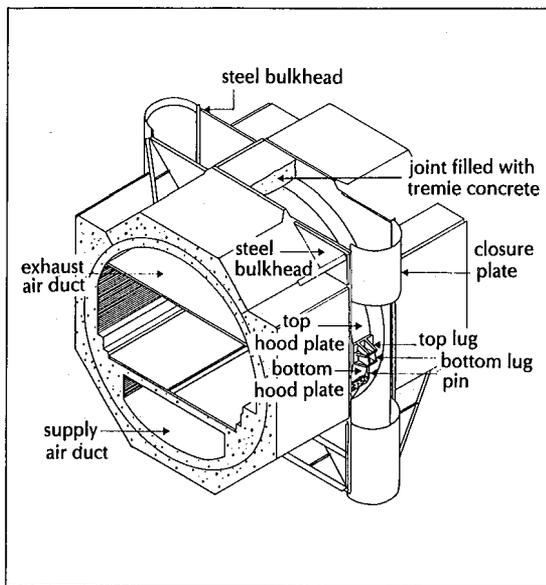
Although concrete box sections may theoretically be constructed in existing dry-docks or graving docks, in practice such facilities have rarely been available for the long duration required for their use in tunnel construction. Therefore, concrete box tubes generally require a construction basin specifically dedicated to their fabrication. The basin usually must be located fairly close to the tunnel site because of the difficulty of maneuvering the large, heavy sections (weighing up to 35,000 tons). Transportation of the sections from the basin to the tunnel site may require dredging to secure adequate depth for flotation. Special control of concrete

materials and their placement is necessary to control the development of shrinkage cracking. If the box section is not prestressed, membrane waterproofing is usually required to assure watertightness.

Records of projects worldwide indicate that the total construction time has generally been one to two years longer for concrete box tunnels than for steel shell tunnels.

### **Joint Connections**

In early U.S. immersed tube tunnels, connections between tubes were made with the tremie concrete joint (see Figure 6). This system permits tubes to be positioned independently, so that tolerances in tube fabrication do not result in alignment errors. More recent tunnels have used rubber gasket joints for temporary connections. These joints are made more quickly and are less costly than



**FIGURE 6. Tremie concrete joint.**

the tremie joint, but require great accuracy in fabrication in order to assure that the ends of adjacent tubes are exactly square to the tube axis and parallel to each other.

For the rubber gasket joint, temporary closure is made by means of couplers mounted on the ends of the tube sections, similar to those used to couple railroad cars. The operation of the couplers is remotely controlled from a surface vessel. The general position of the tube is established from survey towers projecting above the surface and the precise relative location of the sections to be joined is determined by electronic sonar methods. A diver is generally sent down shortly before the closure for a visual inspection to confirm the absence of obstructions, but the actual closure operations are all accomplished by remotely controlled equipment (see Figure 7).

In both methods, after the temporary seal between prefabricated tunnel sections is made, the interior bulkheads are removed and a permanent seal and structural connection between the tubes is made by welding a closure plate from the inside.

## Ventilation

For highway tunnels, as the length between ventilation buildings grows beyond 6,000 to

7,000 feet, both the construction cost and the operation cost of ventilation systems become oppressive. The longest existing ventilated length in the United States is about 7,300 feet for congested tunnels in urban areas. For rural tunnels with light traffic, ventilation of 10,000-foot lengths is practical to a high quality standard. With lower ventilation standards, several European and Japanese mountain highway tunnels have been stretched to 13,000 to 14,000 feet between ventilation shafts. The Mont Blanc Tunnel through the Alps achieves an extraordinary length of 38,000 feet between ventilation buildings by devoting 40 percent of the tunnel cross section to ventilation ducts and by limiting the permitted volume of truck traffic to approximately 100 trucks per hour (sum of both directions).

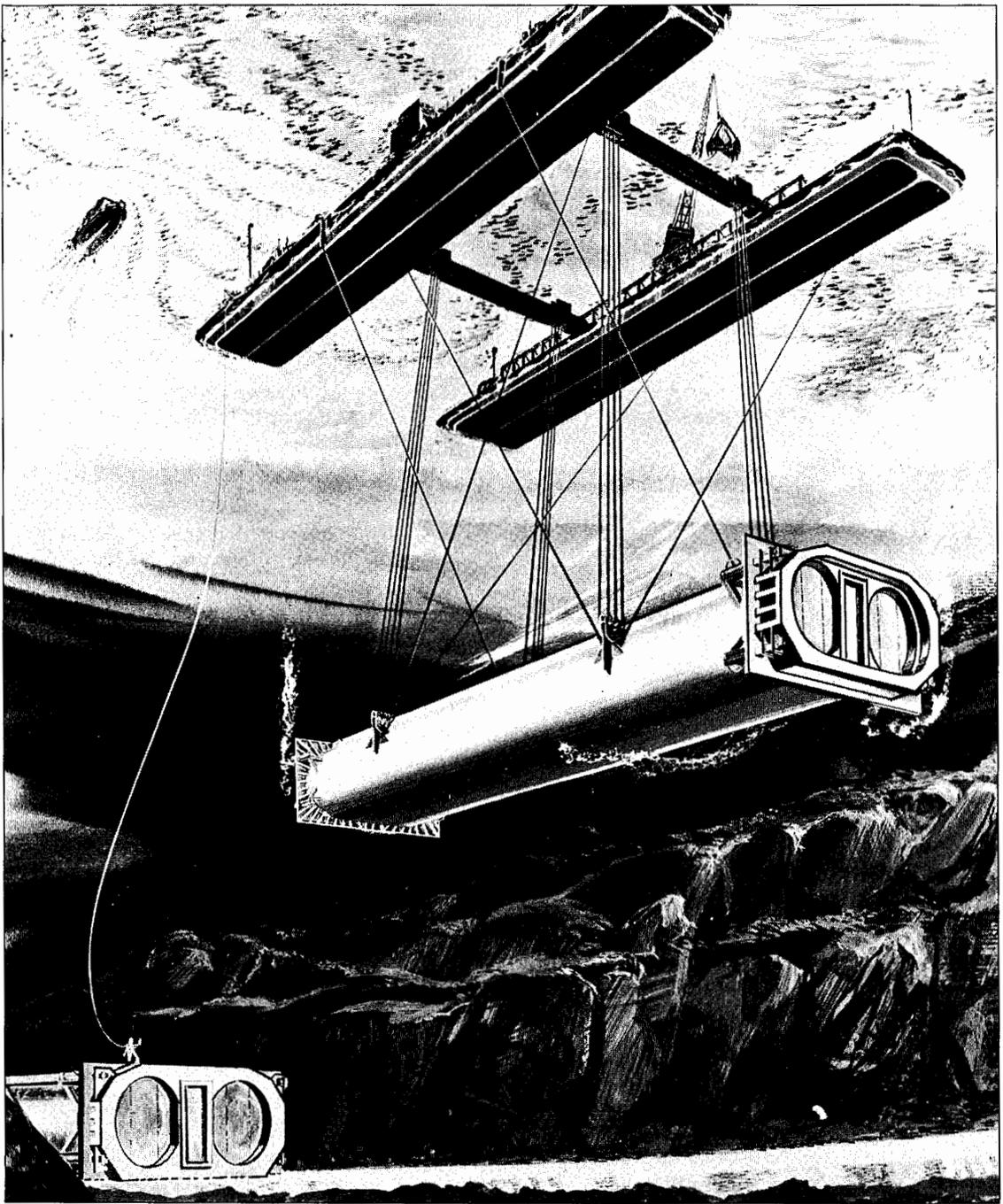
For electric railway tunnels, ventilation is much less serious and essentially places no limit on tunnel length. For rail tunnels using coal- or diesel-fired locomotives, the ventilation problem is intermediate. The Rogers Pass Tunnel in Canada is designed with a rather elaborate ventilation system for diesel operation with a maximum ventilated length of 27,500 feet.

## Geotechnical Conditions

Exceptionally soft soils may make it difficult and costly to keep the trench open long enough to place the foundation course and tube sections. Isolated pockets of soft materials may be dredged out and replaced. Short stretches of rock may be blasted out for the trench, but this work is slow and costly. If there is a general condition of a rock bottom, immersed tubes should be laid on the bottom and mounded over for protection (if navigation depth clearances will permit this).

## Tides & Currents

The current should preferably not exceed a velocity of 3 feet per second for a minimum duration of two hours to permit maneuvering the tubes into position over the trench and lowering them onto the foundation bed. Somewhat higher currents are not an absolute bar, but indicate a need to investigate the hydraulic drag forces that will be exerted on the tube section and the placing equipment,



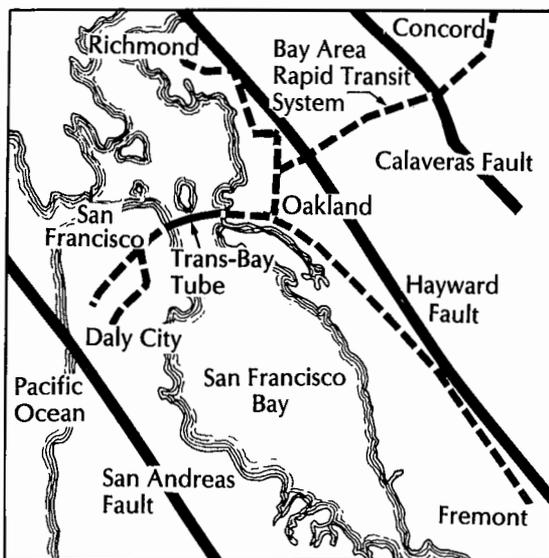
**FIGURE 7.** Divers inspect the area for obstructions prior to closure operations.

the forces on anchor cables, and the ability to develop reliable anchorage in the bottom soils to resist these cable forces.

### **Salinity & Siltation**

The density of the water in the bottom of the

trench at the time of tube placement, and uncertainty regarding the value of this density, are important constraints on the amount of ballast required. Supplemental external sinking blocks and water ballast in internal tanks may be used to overcome



**FIGURE 8. The location of the Trans-Bay Tube Tunnel.**

excess buoyancy during sinking. Generally, a specific gravity of 1.0 to 1.1 for the water in the trench can be handled. Heavy infusions of silt deposited on every tidal cycle may cause serious problems with placing and stabilizing the foundation course and the tube sections.

### **Fabrication Facilities**

The number and size of shipways in the United States have limited the length of steel shell sections that can be fabricated to about 375 feet. However, there is no reason why sections 500 feet long could not be handled if facilities for fabricating them are available.

The construction basin for concrete box sections is generally custom-built for each project, so there are no special constraints on the size of the concrete sections. The availability of waterfront property for use as a construction basin, and the requirements for environmental and other regulatory permits for its use, may impose serious constraints on concrete box construction.

### **Water Depth**

The deepest immersed tube tunnels in the United States have a maximum trench depth of about 135 feet below normal water level. Designs were prepared for an immersed tube tunnel for the English Channel in a depth of

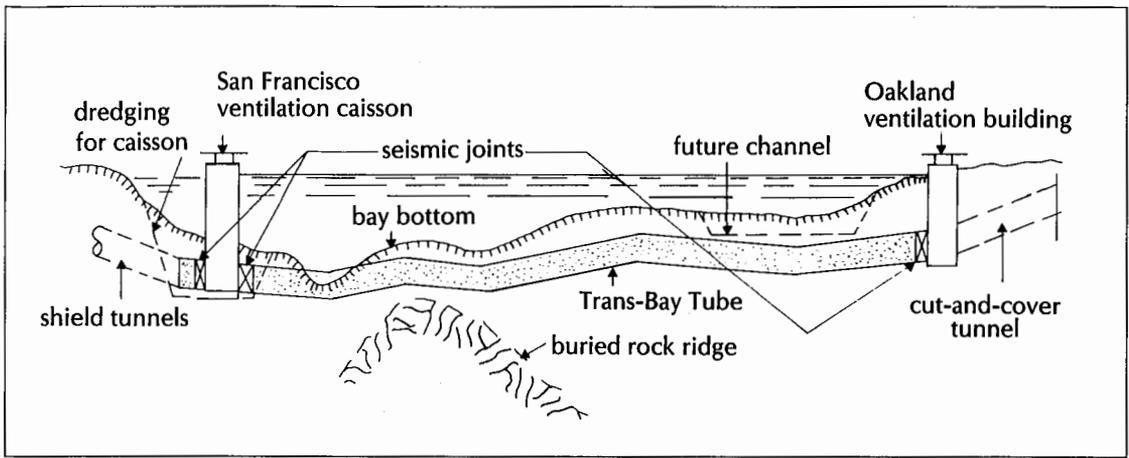
about 200 feet of water. The hydrostatic pressures at 300-foot depth would not impose unmanageable structural problems, but would require further development of joint details and a high grade of quality control in waterproofing. More important than hydrostatic pressure, the length of approach tunnels necessary to reach that depth at an acceptable profile gradient would be very great, so that the economic feasibility of an immersed tube tunnel at 300-foot depth would probably be controlled by the approaches rather than by the actual depth of the tunnel.

The problem of length of approach tunnels leads to the suggestion of founding the tunnel on top of a rock dike established on the bay bottom, in order to raise the tunnel profile line and shorten the approaches. This solution has been proposed for several deep-water crossings, but has yet to be implemented.

### **San Francisco Trans-Bay Tube**

The San Francisco Trans-Bay Tube Tunnel carries two tracks of the Bay Area Rapid Transit (BART) System between San Francisco and Oakland (see Figure 8).<sup>1</sup> The tunnel has a length of 19,113 feet, composed of 57 tube sections, between ventilation buildings. It is by far the longest immersed tube tunnel in the world, and the first to be designed to resist the effects of a major earthquake. It passes beneath the San Francisco-Oakland Bay Bridge and is located to permit future construction of a parallel bridge. The alignment has two horizontal curves, with radii of 8,000 feet and 12,000 feet.

From the San Francisco shore, the tunnel profile descends at a 4% gradient to pass beneath the West Bay with a minimum cover of 5 feet below existing bay bottom (see Figure 9). For a short stretch across a narrow, deep natural trench, the top of the tube is exposed above the bottom and is covered with a rock fill blanket as a protection against scour. The profile rises to pass over a buried rock ridge, descends to pass beneath the Oakland shipping channel, and rises past this onto the Oakland shore. Seven vertical changes in grade are required. The lowest point of the tube trench is 135 feet below low-water level.



**FIGURE 9. A profile of the Trans-Bay Tube Tunnel.**

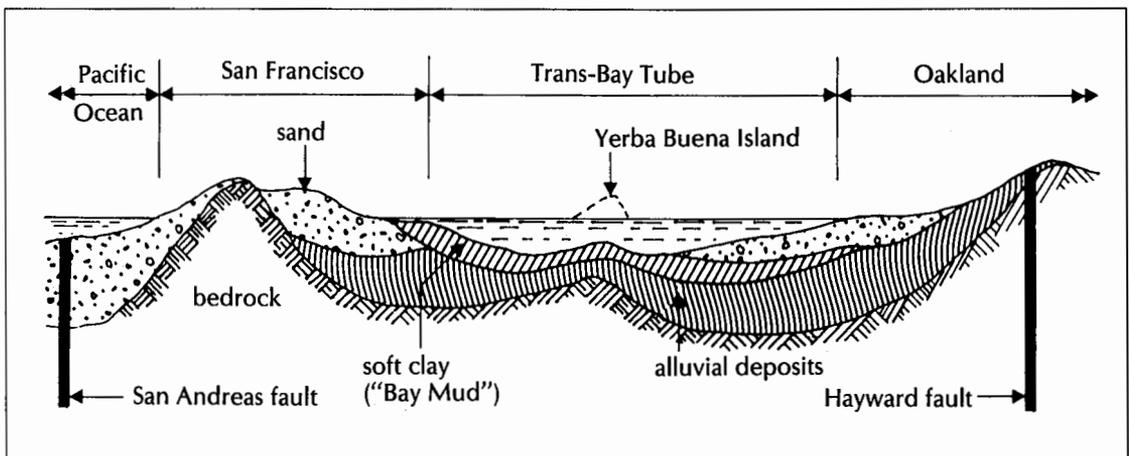
The general geologic conditions of the site are shown in Figure 10. Bedrock is generally at great depth beneath the bay, but a rock ridge rises to about 50 feet below the bay bottom near Yerba Buena Island. The West Bay basin is largely filled with a soft silty clay. The East Bay basin soils are mixed sands and clays.

The tunnel lies between the San Andreas Fault, which passes beneath the ocean west of San Francisco, and the Hayward Fault, which runs through the hills east of Oakland. Both of these faults have produced major earthquakes in the past 100 years. They serve to isolate the intervening block, including the bay and Trans-Bay Tube, in a seismically quiet zone, and no evidence of direct faulting

beneath the bay could be found. Review of the geological conditions indicated that the possibility of direct fault displacement through the tube was so remote as to be negligible, but that the soil surrounding the tube would be subject to severe shaking. The intensity and duration of shaking were established for design on the basis of records of previous earthquakes in California.

After the tube alignment was set, the first important question to be decided was how deep the tube had to be buried. This question devolved into two further questions:

- Would the bay mud fail in shear (a mud slip) during the design earthquake, and if so, to what depth?



**FIGURE 10. The geology of the Trans-Bay Tube Tunnel site.**

- Could any of the bay bottom soils be liquefied during the design earthquake?

Although the samples of bay mud directly at the bottom were very weak, the rigidity increased rapidly with depth. From this analysis of bay bottom soils it was determined that if mud slips occurred (they had been reported in the 1906 San Francisco earthquake), they would be very shallow phenomena at this site, and could not extend deep enough to endanger the tube.

To investigate liquefaction potential, samples of representative soils were subjected to special dynamic laboratory tests. These tests demonstrated that it was possible to produce liquefaction, but that this would require either much larger vibrations or a much longer duration of shaking than would be expected during the design earthquake. Based upon these analyses, it was concluded that there was an ample margin of safety against either mud slips or liquefaction, and therefore no need to bury the tube deeper than the minimum depth profile. The minimum depth was determined generally by keeping the top of the tube structure about 5 feet below the natural bay bottom.

Preliminary estimates indicated that each concrete box section might be about \$1 million less expensive than a steel shell section. However, it was judged to be very difficult to devise a fixed joint between the concrete tube sections that would remain reliably watertight when subject to earthquake vibrations. The alternative of providing a watertight flexible joint between each pair of tube sections was very costly, and was deemed inferior to the fixed, ductile welded steel joint. It was thus concluded that the steel shell design would provide a more ductile structure, better able to absorb the earthquake vibrations.

On the San Francisco shoreline, the tube alignment passes beneath the Ferry Building, an historic structure that had to be preserved. The San Francisco ventilation building was established in a caisson that was floated into place in an enlarged basin at the end of the dredged trench for the tube, 400 feet offshore (see Figure 9). The basin was backfilled with a special clay fill to create an impervious plug,

through which the approach tunnels were driven by shield methods into the caisson. The caisson is protected against ship collisions by a wharf structure that completely surrounds it.

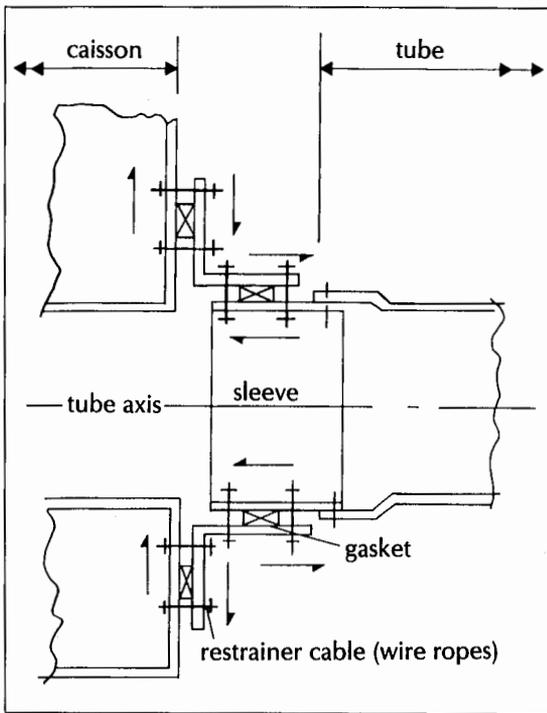
On the Oakland shore, the ventilation building is located on shore within the port facilities. Cofferdam construction was used for the ventilation building. The approach tunnels were constructed using cut-and-cover methods.

Because the center of mass of the San Francisco caisson is considerably above that of the tube structure, it will develop a rocking motion with respect to the tube sections under the vibration of an earthquake. In addition, the earthquake waves imposed on the tube will cause a longitudinal displacement between the end of the tube and the caisson. These combined actions require provisions for longitudinal, transverse, and vertical motions at the joint between the caisson and the tube, and some freedom of rotation about all three axes.

The principle of the seismic joint developed for the Trans-Bay Tube is shown in Figure 11.<sup>2</sup> It consists of two sections which together form a universal joint. The first section is a telescoping sleeve concentric with the tube shell, which permits longitudinal motion and rotation about vertical and transverse axes. The second section is a vertical plane along the outside of the caisson. This part of the joint permits vertical and transverse motion, and rotation about a longitudinal axis. The joints are sealed with neoprene gaskets sliding on Teflon-coated steel plates that are compressed by a series of short wire ropes.

Two such joints were provided on both sides of the caisson, and a third joint at the junction of the tube and the Oakland ventilation building, which is solidly anchored in firm ground.

After investigating several alternatives, the designers settled on the tunnel section shown in Figure 12. This is a single shell steel tube design, with separate compartments for each trackway and a central compartment divided into an upper emergency exhaust ventilation duct and a lower inspection and

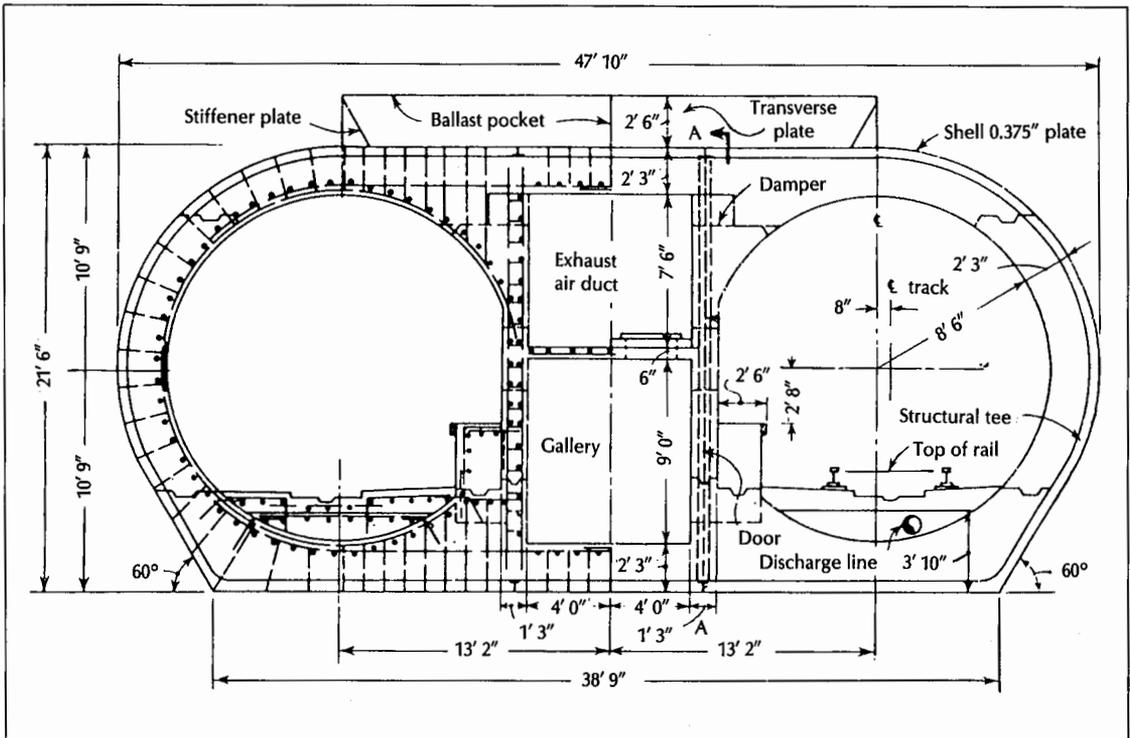


**FIGURE 11. Conceptual design of sliding seismic joint used in the Trans-Bay Tube Tunnel.**

utility gallery. The basic binocular shape is efficient for resistance to the earth and water pressures at a depth of 135 feet. The flat bottom is adapted to fit the screeded bed foundation, and the inward sloping sides minimize the trench width. The top ballast box permits the use of economical stone ballast.

Because of the presence of large stray electric currents resulting from operation of the direct-current traction power system, a cathodic protection system was provided for the steel shell. This system uses sacrificial anodes located on the bottom of the bay and connected to the steel shell through cables.

Figure 13 shows typical sections for dredging and backfill. Although the profile was kept as shallow as possible, the irregular configuration of the bay bottom combined with the maximum operating gradient for the trains resulted in trench depths of up to 70 feet. In these locations, the backfill was placed only to a height of 5 feet above the top of the tube structure, and the remainder of the trench was left open, to be filled by natural



**FIGURE 12. A cross section of the Trans-Bay Tube Tunnel.**

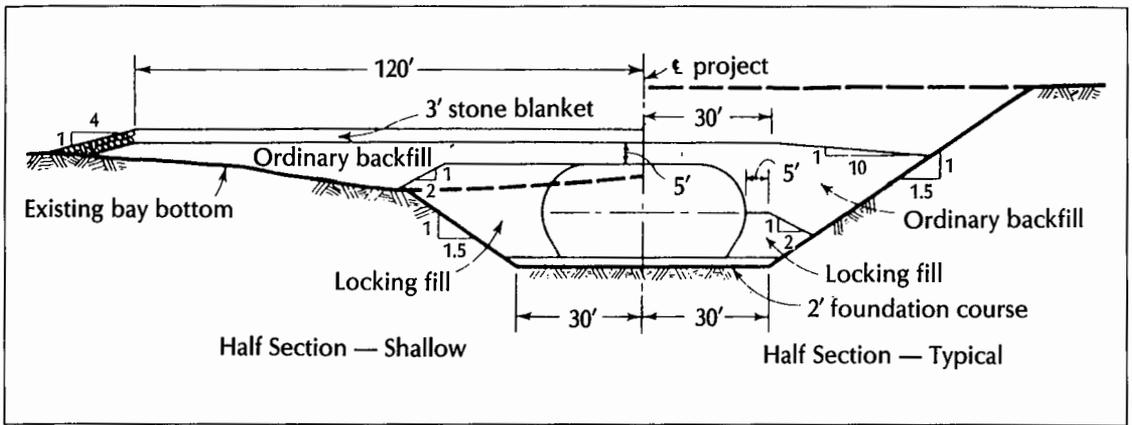


FIGURE 13. Dredging and backfill for the Trans-Bay Tube Tunnel.

siltation. At the other extreme, the top of the tube structure was exposed at or above the natural bay bottom in some locations. A blanket of stone was placed as protection against scour in these locations.

Rounded river gravel was used for the foundation course in order to facilitate the screeding operation. The locking fill was crushed rock, and the ordinary backfill was sand.

At the time of construction of the Trans-Bay Tube, the Port of Oakland was planning a major redevelopment of the Oakland Mole as a port facility. It was arranged that as part of the Trans-Bay Tube project, a dike would be constructed to enclose 140 acres, within which all of the dredged material except for the soft bay mud would be disposed. The total excavated volume was 5,600,000 cubic yards of which about 3,900,000 cubic yards was placed on the Oakland Mole. The remainder was barged out to sea and dumped at a location where prevailing currents would disperse it offshore.

The final design of the Trans-Bay Tube was started in May 1964. Construction for the principal contract, covering all structural work for the 57 tube sections and the San Francisco ventilation caisson, was started in April 1966 and completed in September 1969. Separate contracts for the Oakland ventilation building and for all electrical and mechanical installations followed, and were completed by December 1970. The total construction cost of all of this work was \$110 million.

## Second Hampton Roads Tunnel

One of the major harbors of the eastern United States is Hampton Roads, an estuary in southeastern Virginia. Because of the very heavy shipping traffic and the presence of extensive U.S. Navy facilities, the use of a bridge to cross this estuary has long been prohibited. In 1957, the first bridge-tunnel crossing in the world was completed between Hampton and Norfolk. This crossing covers a length of 3.5 miles, including a 7,200-foot two-lane immersed tube tunnel, two portal islands constructed in shallow water, and two trestle bridges connecting the islands to the shore at each end.

By 1970 traffic had grown to such an extent that a second parallel crossing was required. The layout of the combined twin bridge-tunnel facility is shown in Figure 14. The tunnels provide a clear navigation channel 4,500 feet wide by 50 feet deep, but at the deepest point the water depth is 70 feet and the trench reaches 120 feet below sea level. The total length of the precast tube sections is 6,898 feet, and the length between portals is 7,315 feet.<sup>3</sup>

The entire site is underlain with alluvial sediments that extend to a depth of over 1,000 feet. An organic silty clay is found in the trench bottom for a substantial length of the tunnel. This clay lies beneath the entire South Portal Island to a depth of 90 feet. The remaining soils are reasonably firm and offered no design or construction problems.

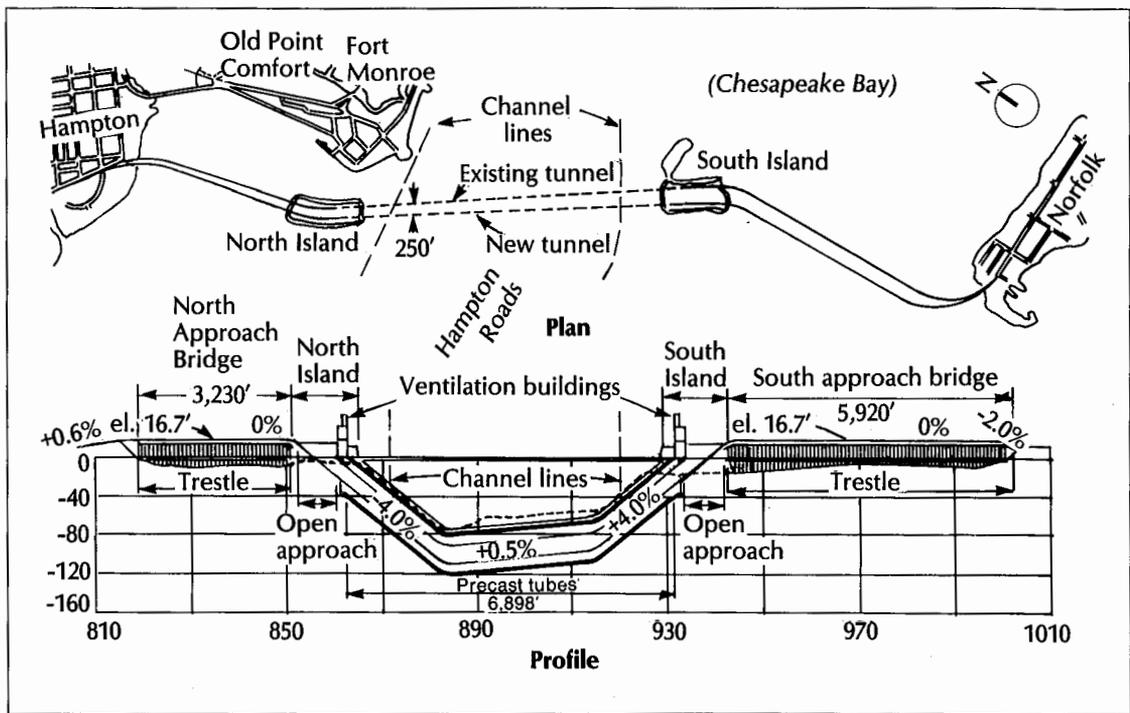


FIGURE 14. The bridge-tunnel layout for the Hampton Roads project.

The most important design question for this project involved the enlargement of the existing South Portal Island in order to accommodate the new tunnel. The original island had been constructed by dredging out all of the soft clay and replacing it with sand fill. Three options were considered for the construction of the new South Portal Island, as shown in Figure 15.

The first option, using a sheet pile cofferdam, would have minimized the extent of the island enlargement, but would have produced unacceptable disturbance to the existing tunnel. The second option for the South Portal Island followed the method used for the original tunnel — removal of all the soft clay and replacement with sand. Concern for stability of the dredged slope in the soft clay, and for lateral movement of the existing structure, would have required a spacing of 500 feet between tunnel centerlines. This layout would have required dredging and disposing of one million cubic yards of unsuitable material. Environmental restrictions would have made this option difficult and costly. The third option proved to be

both technically sound and economical. This option involved consolidating the soft clays in place, utilizing a system of sand drains and surcharge. A finite element analysis indicated that at a spacing of 250 feet between tunnels, the settlements at the existing tunnel would be of the order of 0.5 inch and would cause no damage. This prediction was confirmed by monitoring observations during construction.

Hydraulic sand fill was the most appropriate material for the island and surcharge. However, environmental restrictions prohibited discharging hydraulic fill in the open water, so the entire site had to be enclosed with a rock dike before fill placement could begin. The soft clay was too weak to support the full height of the island plus the surcharge, so a series of berms was established to provide adequate safety against deep-seated slides during construction. All of this work resulted in enlarging the South Island from its original 3.5 acres to 14 acres.

When the island had been built up to about 12 feet above water level, 6,000 sand drains were installed by the jet boring process, and the surcharge was then built up to a

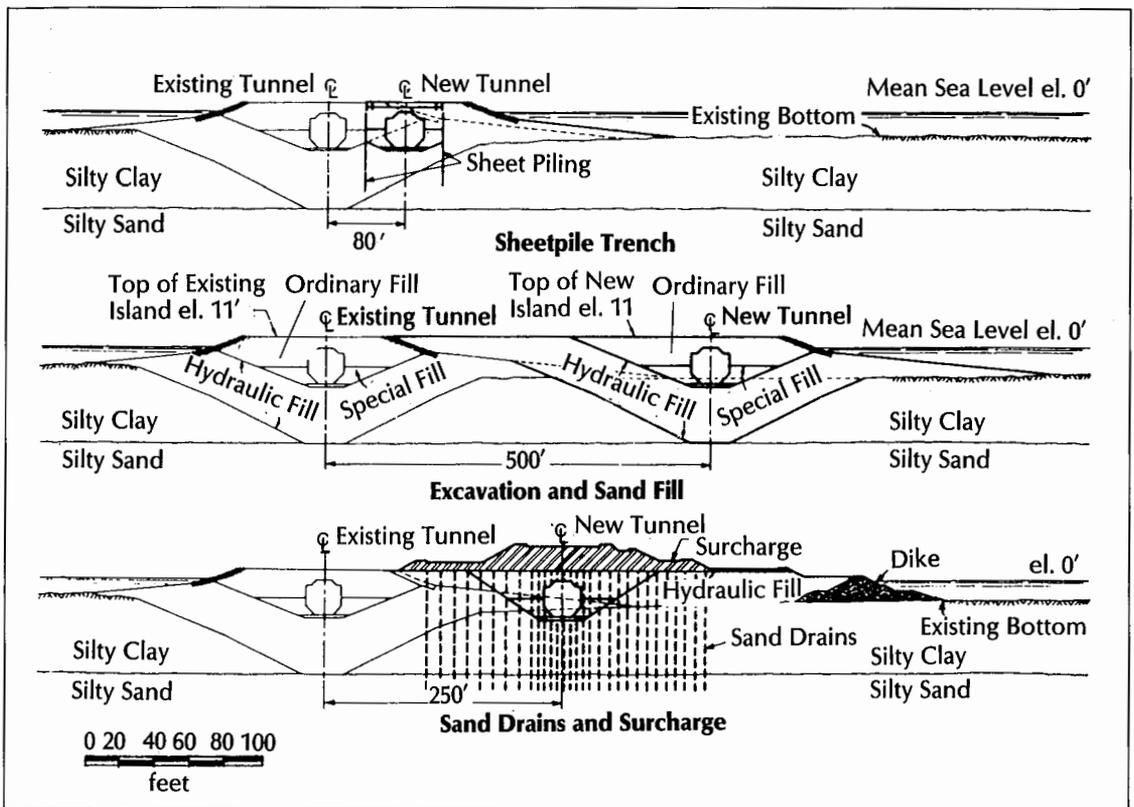


FIGURE 15. South Island design alternatives for the Hampton Roads project.

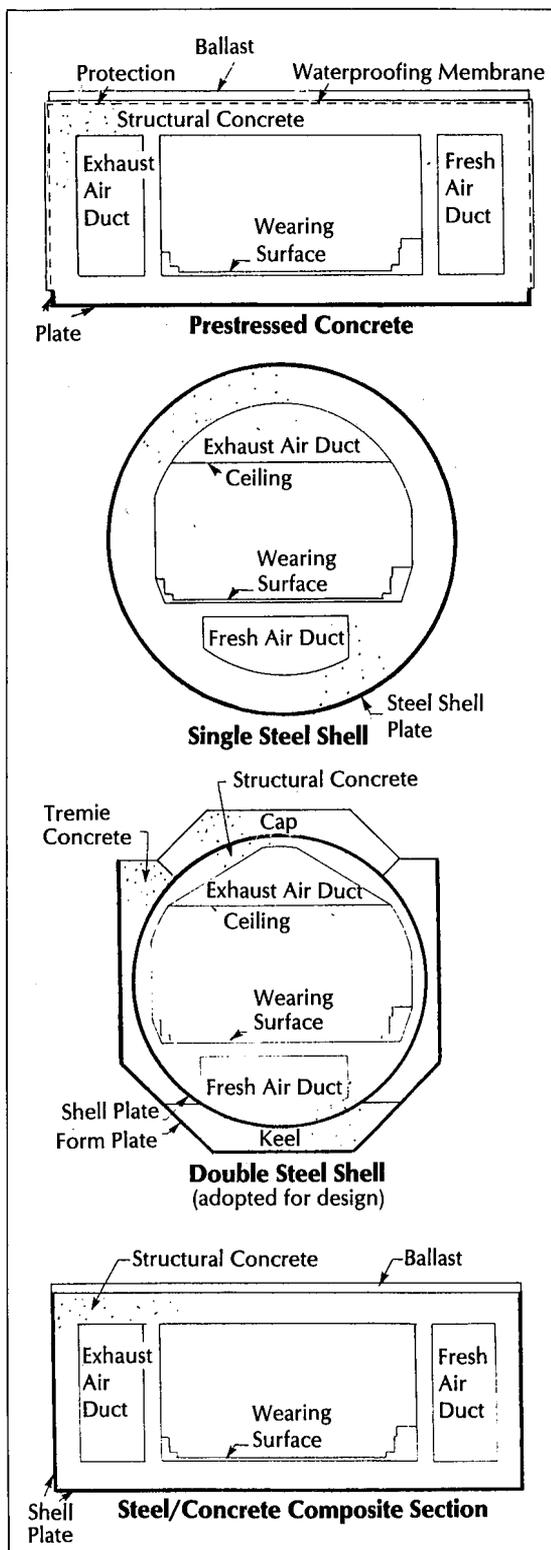
height of 52 feet above the bay bottom. This surcharge remained in place for a year, during which time it was covered with a sprayed emulsion to keep the loose sand from blowing. The island was heavily instrumented to monitor settling. During the year the surcharge remained in place, the settlement amounted to 13 feet. The surcharge was then removed, and subsequent settlements have been small.

A wide variety of alternative tube cross sections were studied — in rectangular, circular, and octagonal configurations, and using reinforced concrete, prestressed concrete, and composite structural steel and concrete shells (see Figure 16). Owing primarily to the availability of shipyard facilities, the double shell octagonal steel section proved to be most economical and was adopted for design. Twenty-one tube sections, each approximately 350 feet long, were fabricated at Port Deposit, Maryland, approximately 200 miles from the project site. These

sections were towed to Norfolk with only sufficient keel concrete to stabilize them, and the interior concrete was placed at an outfitting dock in Norfolk. The tube sections were then placed on a screeded bed foundation.

Figure 17 shows a section through one of the ventilation buildings. The exhaust air is blown out vertically through the roof, and fresh air is drawn through grilles in the side walls into a plenum beneath the roof, from which the supply fans deliver it to the fresh air duct beneath the roadway.

The Hampton Roads area is subject to infrequent but severe hurricanes, during which the water level may rise above the tops of the islands. A portal tide gate is provided at the end of each ventilation building to permit closing off the tunnel in the event of a catastrophic high tide. This gate is a vertically sliding leaf that fits into a slot in the portal structure, and is equipped with rubber gasket seals. The gate can be operated either by



**FIGURE 16. Alternative cross sections proposed for the Hampton Roads project.**

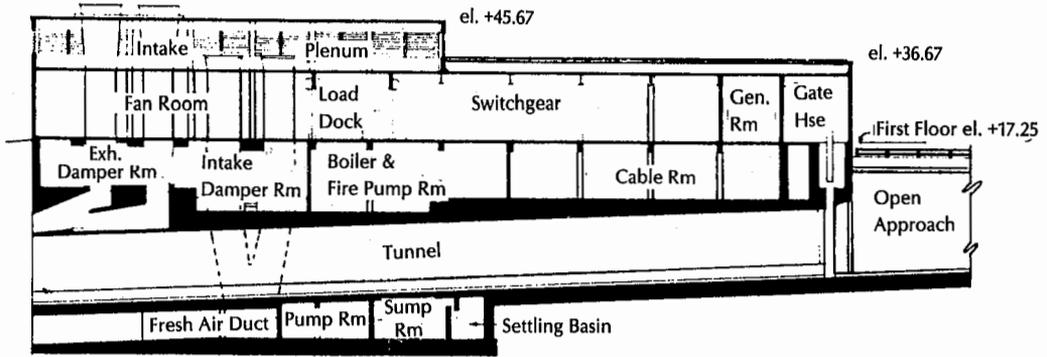
electric drive, or in emergencies by hand crank.

Design of the Second Hampton Roads Tunnel was started in August 1969. The first construction contract, for the South Portal Island, was begun in July 1970. The project was completed in June 1976, at a total construction cost of \$96 million.

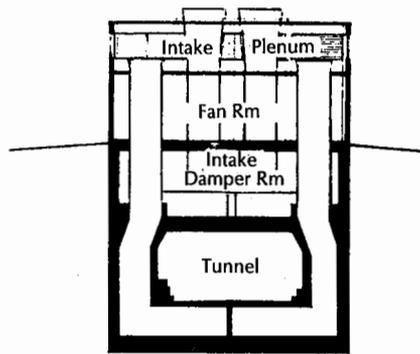
### **Baltimore: Fort McHenry Tunnel**

The Fort McHenry Tunnel is the largest highway tunnel project ever undertaken in the United States. The tunnel carries eight lanes of Interstate Highway 95 beneath Baltimore Harbor (see Figure 18). The tunnel project was selected instead of a high-level bridge primarily to reduce the impact on the historic monument of Fort McHenry, which lies immediately to the north of the tunnel. The total length of the tunnel is 7,150 feet between portals, of which 5,370 feet is composed of immersed tube sections.<sup>4</sup> The cross section includes twin double-bore tubes of double shell steel construction, providing room sufficient for four two-lane roadways. A typical double-bore tube section is 82 feet wide by 350 feet long, and displaced 35,000 tons at the time of placement. Sixteen pairs of these tubes make up the immersed tube portion of the tunnel.

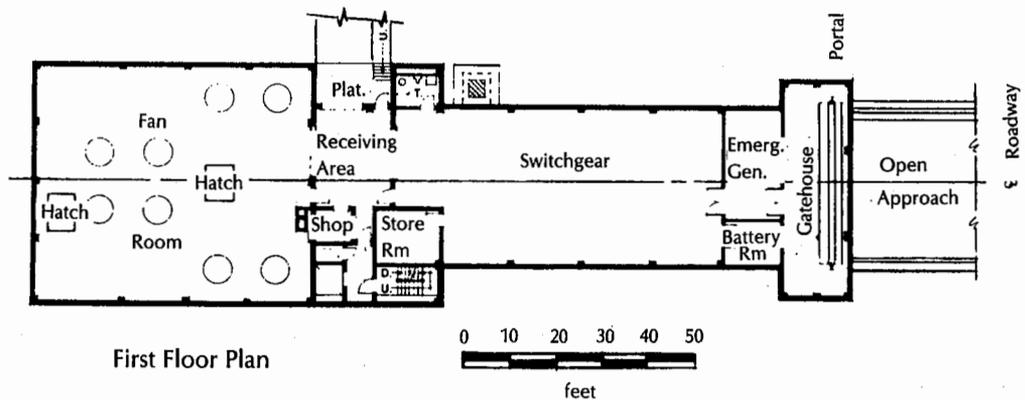
Because the shipping channel is close to the eastern shoreline, the project required dredging a trench 1,300 feet long, 300 feet wide, and up to 70 feet deep into the eastern shore. The first four pairs of tubes were placed in this trench to carry the tunnel down to the depth required to pass under the shipping channel (see Figure 19). The perimeter of the trench was lined with bulkhead walls tied back with soil anchors that protected adjacent industrial facilities. In order to minimize the width of the approach trench and its effect on existing facilities, a careful study was made of the space required for placing the twin tubes in a common trench. The southbound tube sections were placed with the conventional twin-hulled placing barge. Because of the confined space, a special arrangement of heavy cranes mounted on narrow barges was devised to place the northbound tube sections



Longitudinal Section



Cross Section



First Floor Plan

FIGURE 17. Ventilation building for the Hampton Roads project.

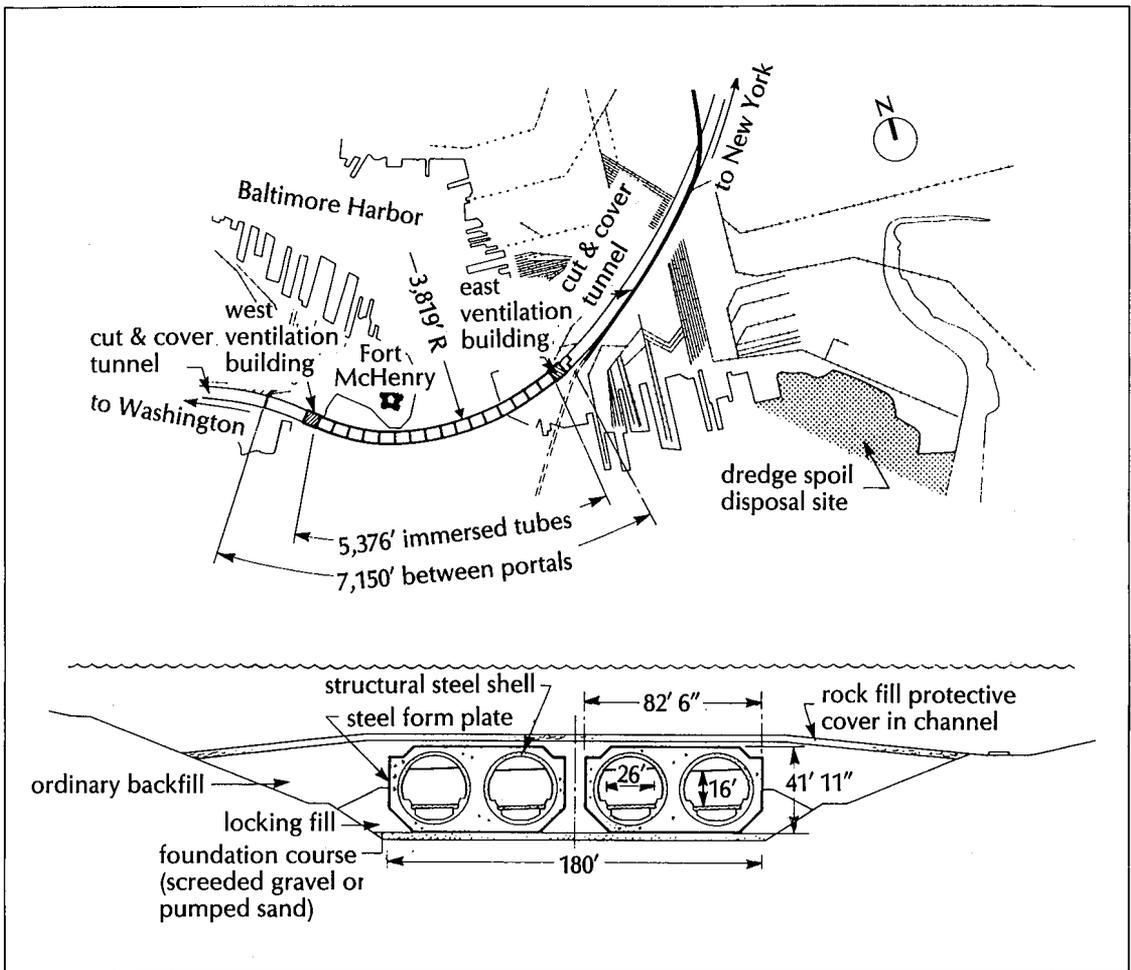


FIGURE 18. Plan and section of the Fort McHenry Tunnel.

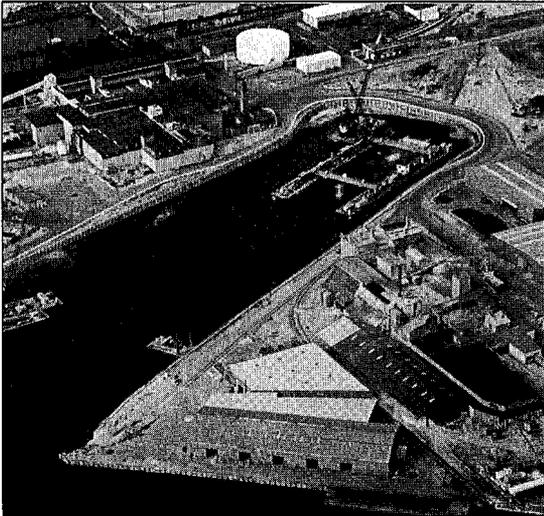


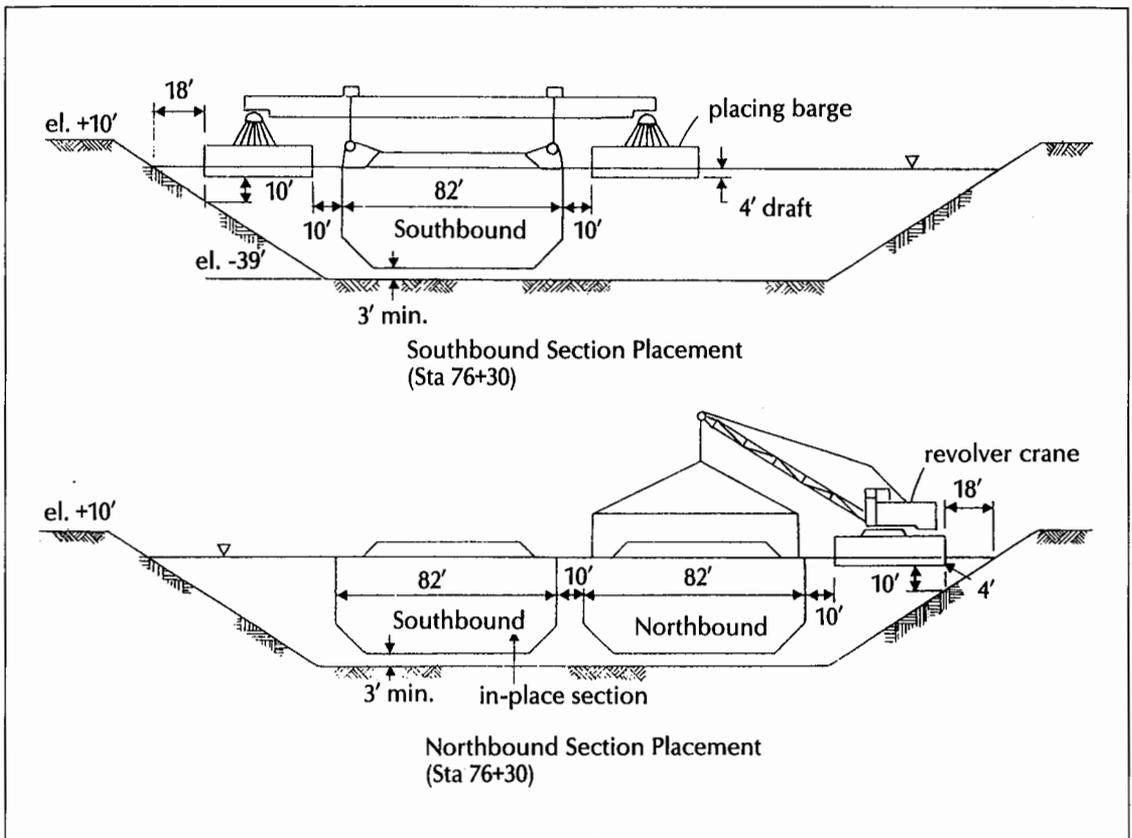
FIGURE 19. The east approach trench for the Fort McHenry Tunnel.

in shallow water at the upper end of the trench (see Figure 20).

The twin-shell tube sections were fabricated in a shipyard about 65 miles from the tunnel site (see Figure 21). One of the most difficult tasks on the project was to move the tubes from the shipyard to the outfitting site. The floating sections had to pass through several existing bridges, with clearances as little as 3 feet in some instances (see Figure 22).

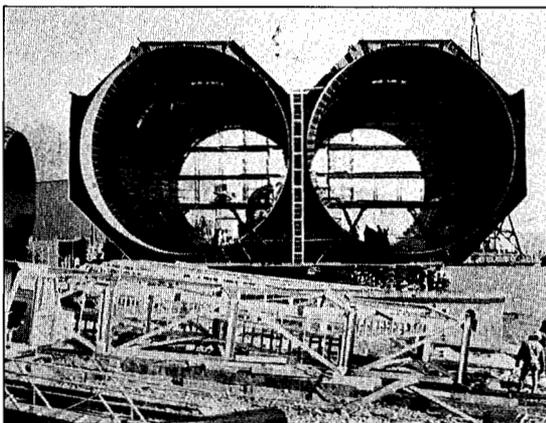
The contract documents provided for alternative foundation construction methods, either the screeded bed or the pumped sand system. The successful bidder selected the screeded bed method.

The project included exceptionally stringent controls on disposal of dredge spoil



**FIGURE 20. Tube placement clearances for the Fort McHenry Tunnel.**

material. Before any dredging could be started, a 145-acre dredge spoil containment facility was required. The containment facility was constructed by enclosing a site about 1.5 miles from the tunnel with a cellular steel

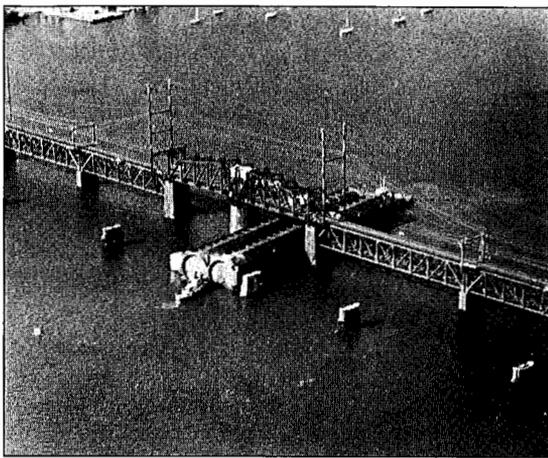


**FIGURE 21. Tube fabrication for the Fort McHenry Tunnel.**

sheetpile cofferdam 5,500 feet long (see Figure 23). The disposal site was divided into two areas. The first area received all the soft, contaminated muck that comprised the top layer of harbor bottom sediments. The second area received the better grade sands and clays dredged up from the deeper parts of the trench. The second area has been stabilized by natural desiccation and is now being developed for a port facility, while the muck area may eventually be reclaimed as a park.

The effluent from both disposal areas was discharged into a treatment basin where chemical flocculents were added to precipitate suspended solids. The effluent then passed over a wier into a settling basin in which a majority of the suspended material settled out. The final discharge into the harbor was cleaner than the present harbor water.

Design of the project began in September 1978. Construction of the main tunnel contract — covering trench excavation, furnish-



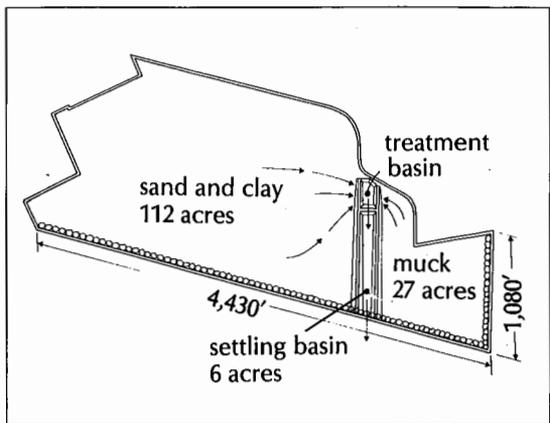
**FIGURE 22. Towing a tube section to the outfitting site for the Fort McHenry Tunnel. Bridge clearances were extremely tight.**

ing and installing the 32 prefabricated tube sections, backfill and the dredge disposal facility — was begun in June 1980 and completed in January 1984. The tunnel was opened to traffic in November 1985. The \$426 million tube contract was the largest ever awarded for a U.S. transportation project. Including subsequent contracts for cut-and-cover work, open portal approach structures, ventilation buildings, and all operating and finish installations and equipment, the total construction cost was \$750 million.

### Alternative Concepts

All tunnel projects involve their own special problems, and no two tunnels are exactly alike. There is a wide range of conditions for which immersed tubes have been found suitable. However, immersed tubes are not invariably the best alternative for all underwater tunnels. Alternative concepts are mined and shield driven tunnels.<sup>5</sup> Although their ranges of application overlap, the following general guidelines are helpful in selecting among these alternatives for any specific project:

1. Immersed tubes are especially suited to sites with moderate water depth (100 to 120 feet) underlain by alluvial deposits or marine sediments, with tidal cycles that provide several hours of slack water or modest current to facilitate tube



**FIGURE 23. The dredge spoil containment facility for the Fort McHenry Tunnel.**

handling and placement.

2. Environmental constraints associated with disposal of large volumes of dredge spoil may preclude immersed tube construction. If an immersed tube is the selected alternative, environmental problems associated with acquisition of a waterfront site for a construction basin may tilt the economic balance away from a concrete tube, towards a steel shell section.

3. The greater ductility of steel compared to concrete makes steel shell sections the favored choice for immersed tubes in seismic areas.

4. Mined tunnels are most economical in a free air construction environment, in dry ground requiring relatively little structural support. If continuous, competent rock is available at a shallow depth beneath the watercourse, a mined rock tunnel may be the preferred alternative. Great depths to sound rock, or extensive water-filled joints, will tilt the balance toward an immersed tube.

5. Shield driven tunnels are best suited to impervious ground. Special measures such as pressurized face machines, compressed air and clay blankets may enable shield tunnels to pass through pervious zones, but if these conditions pervade the site, the cost of a shield-driven tunnel increases sharply. Where existing development makes dredging trenches in from the waterfront objectionable, shield work may

well be appropriate. A number of tunnels have combined immersed tube sections under the water with shield tunnel approaches under the land on either shore.

## Summary

Commonly, tunnel site conditions are not uniform over their length, which may range from less than one to several miles. Project site conditions place their own particular imprint on every tunnel project, posing unique challenges to the designers and constructors. The choice of tunnel concept is frequently a compromise amongst conflicting criteria. A single project may well involve a combination of different methods for different sections of the crossing, each method best adapted to the particular conditions of that section. This type of approach may result in a completed project that best meets engineering and cost criteria. Examples of such hybrid tunnel and bridge-tunnel layouts abound and their use is growing.<sup>5</sup> For underwater tunnels, the immersed tube concept, either alone or as a component of a hybrid layout, is well established and merits consideration for many future projects.



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