A New Concept for Designing & Constructing Immersed Tube Tunnels Without Using Ballast

Using caissons in immersed tube tunnel construction offers distinct advantages over the current method of installation that requires the use of ballast.

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The two important construction phases for installing immersed tube tunnels (ITTs) are:

- Flotation (transporting the tube from the casting basin to the site); and,
- The tube placement operation.

Accordingly, the tubes must satisfy two general requirements:

- The tube weight must be less than or equal to the weight of the displaced water during the first phase; and,
- The tube must considerably exceed this weight after final placement for the second phase.

After the tube is lowered into place, the final factor of safety against uplift varies from 1.12 to 1.2, depending on the criteria for the specific project. In order to achieve the required negative buoyancy, thousands of cubic yards of concrete are usually pumped as additional ballast into the tube after it has been placed into the position onto a dredged area underwater. The extra space used to contain the ballast usually exceeds ten to 12 percent of the tube's total volume. Eliminating the ballast from the tube would result in a reduction of tube dimensions and, therefore, could lead to construction cost savings.

Reducing tube dimensions is particularly important for an ITT that must be constructed above an existing tunnel. In most of these cases, a height restriction exists that mandates that a minimum depth of water above the tubes would have to be maintained for navigation.

In addition to the tight vertical restriction, another situation must be considered during ITT design: the possibility of accidental flooding of the tunnel after construction. Should flooding occur, the resulting loads would be imposed on the soil or any structure located below the tunnel. Once the tube was flooded, its load would be 4.0 to 4.5 times its service load. Therefore, the ITT must be supported by a substantial number of caissons in order to avoid excessive settlements and to protect any structure located beneath it from being crushed.

An additional complication to ITT design development is the goal of protecting any existing structure located beneath the ITT from the accidental dropping of a flooded tube during its immersion.

Such challenging design circumstances are not uncommon for construction in urban areas. The proposed I-90 Seaport Access Road Tunnel at Fort Point Channel in Boston provides an excellent illustration of these concerns. The proposed tunnel, consisting of separate tubes for the eastbound and westbound lanes of the Seaport Access Road, crosses the Fort Point Channel just above the existing Red Line subway tunnel (see Figure 1). This ITT is part of the Central Artery Depression/Third Harbor Tunnel Project.

The existing Red Line subway tunnel, constructed in 1908 of unreinforced concrete, must remain in operation during and after construction. The design of the new tunnel was further complicated by tight vertical clearance constraints. To maintain sufficient clearance above the ITT for navigation and water flow, the vertical gap between the ITT and the existing subway tunnels decreases to 3 feet at the closest point (see Figure 1). Because the ITT is at the lowest point of the Seaport Access Road alignment, the possibility of accidental flooding needed to be considered in the design. This enormous loading would induce considerable settlements of the ITT. In addition, tunnel design had to take into account possible dropping of a flooded tube during immersion.

Tube Tunnel Construction Without Using Ballast

One method of constructing ITTs consists of replacing conventional tube ballast with caissons located below and attached to the tube. The caisson gravity load and skin friction developed between the soil and caissons together serve to resist the tube uplift. This concept is particularly applicable to concrete immersed tubes with a rectangular cross section. The rectangular design ITTs are becoming increasingly popular in the construction of multilane road tunnels.

ITTs can be installed without ballast by following these construction steps:

1. Caissons are installed in the field along the future center lines of the immersed tube walls.
2. The immersed tube is floated to the site, sunk into position and connected to an adjacent tube unit by typical immersed tube construction methods. At this stage, the ITT temporarily rests on jack supports located at both ends of the tube.
3. The immersed tube is "pinned" to the caissons by heavy steel bar cages that are placed into the caissons through 18-inch diameter vertical openings (wells) prefabricated in the tube walls.
4. The vertical wells and caissons are filled with tremie concrete (see Figure 2).

The connection of the ITT to the caissons (Steps 3 and 4 above) is provided directly from the working barge.

Required Number & Length of Caissons

After construction, with the roadway wearing course and the protective backfill installed, the ITT will have between six and eight percent negative buoyancy. The caisson gravity load and skin friction would be mobilized only at short periods of time when additional uplift forces may occur due to an accidental loading condition or due to a significant change in water density. Furthermore, the skin friction forces would be mobilized only after all downward gravity forces (including caisson gravity)

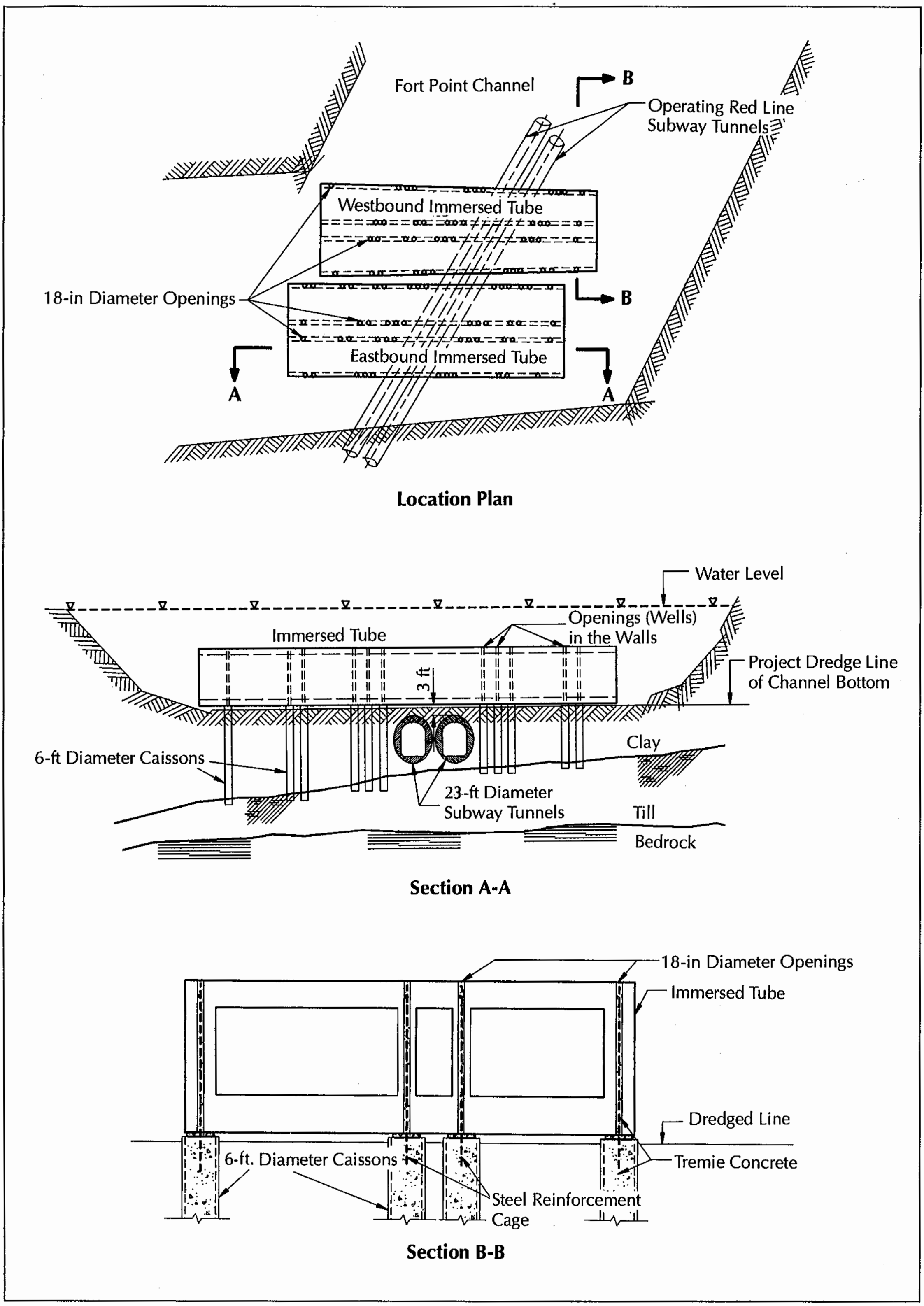

FIGURE 1. The Fort Point Channel crossing showing the tunnel configurations.

have already been exhausted and the ITT develops a tendency to move upward.

If the assumed final factor of safety for the ITT against uplift ranges from 1.12 to 1.2 (depending on the criteria for the specific project), the caissons themselves should be designed for an uplift force that is equal only to 0.06 to 0.12 of the tube displacement weight (since the tube and backfill contribute between 1.06 to 1.08 factor of safety).

The total number of caissons can be computed by the following formula:

$$N = (KB - W)/P \qquad 1$$

Where:

N = Total number of caissons
K = Final factor of safety against uplift for the ITT
B = Displacement weight of the tube
W = Dead weight of the tube, including wearing course, protecting backfill, *etc.*
P = Nominal tensile strength of one steel reinforcement cage connecting the tube to the caissons. For the typical steel bar cage made from eight or nine reinforcing bars, the load, P, varies from 150 to 200 kips per caisson.

The minimum required length of the caisson, L, in *cohesive soils* would be computed as follows:

$$L = P/((\pi/4)\gamma_c D^2 + \pi DS) \qquad 2$$

Where:

L = Length of the caisson
D = Diameter of the caisson
P = Nominal tensile strength provided by the steel cage
γ_c = Buoyant weight of the concrete
S = Skin friction

Based on geotechnical recommendations, the design value for the friction of *all cohesive soils* cannot exceed the total resistance of reduced adhesion acting over the caisson surface that is limited to 0.25 to 0.7 kips per square foot (tension and smoothness of steel case are taken into account).

Employing the standard assumption that skin friction for *granular soils* is equal to the total horizontal earth pressure against the caisson surface times the coefficient of friction, *tan* δ, between the caisson and soil, the minimum required length of a caisson, L, in granular soils could be derived from:

$$T = (P - V)/\varphi \qquad 3$$

Where:

V = Buoyant weight of the caisson
T = Ultimate friction force (*i.e.*, a function of L)
φ = Factor of safety

The factor of safety, φ, in Equation 3 is based on the fact that friction forces gain their ultimate value after the upward movement begins.

Solving Equation 3 for the caisson length, L, results in:

$$L = 0.25\frac{\gamma_c}{\gamma_S}\cdot\frac{D\varphi}{K_o\tan\delta}\cdot[(1 - \frac{32PK_o\gamma_S\tan\delta}{\pi D^3\varphi\gamma_c^2})^{1/2} - 1] \qquad 4$$

Some of the components of Equation 4 should be treated as constants for practical purposes:

- γ_c, the buoyant unit weight of concrete is equal to 0.085;
- γ_S, the submerged unit weight of soil is equal to 0.06;
- K_o, the ratio of horizontal to vertical effective stress on the side of the drilled caisson when it is in tension is less than or equal to 0.4;
- δ, the friction angle for steel shell can be taken as 15;
- And the factor of safety, φ, is assumed to be 2.0 (for short-term uplift loading).

Substituting these values into Equation 4, the required length of the caisson can be expressed as:

$$L \cong 6.3D[(1 + 5(P/D^3))^{1/2} - 1] \qquad 5$$

In situations where the caissons are distributed along the walls in groups of two or three, the calculation of the caisson length should be

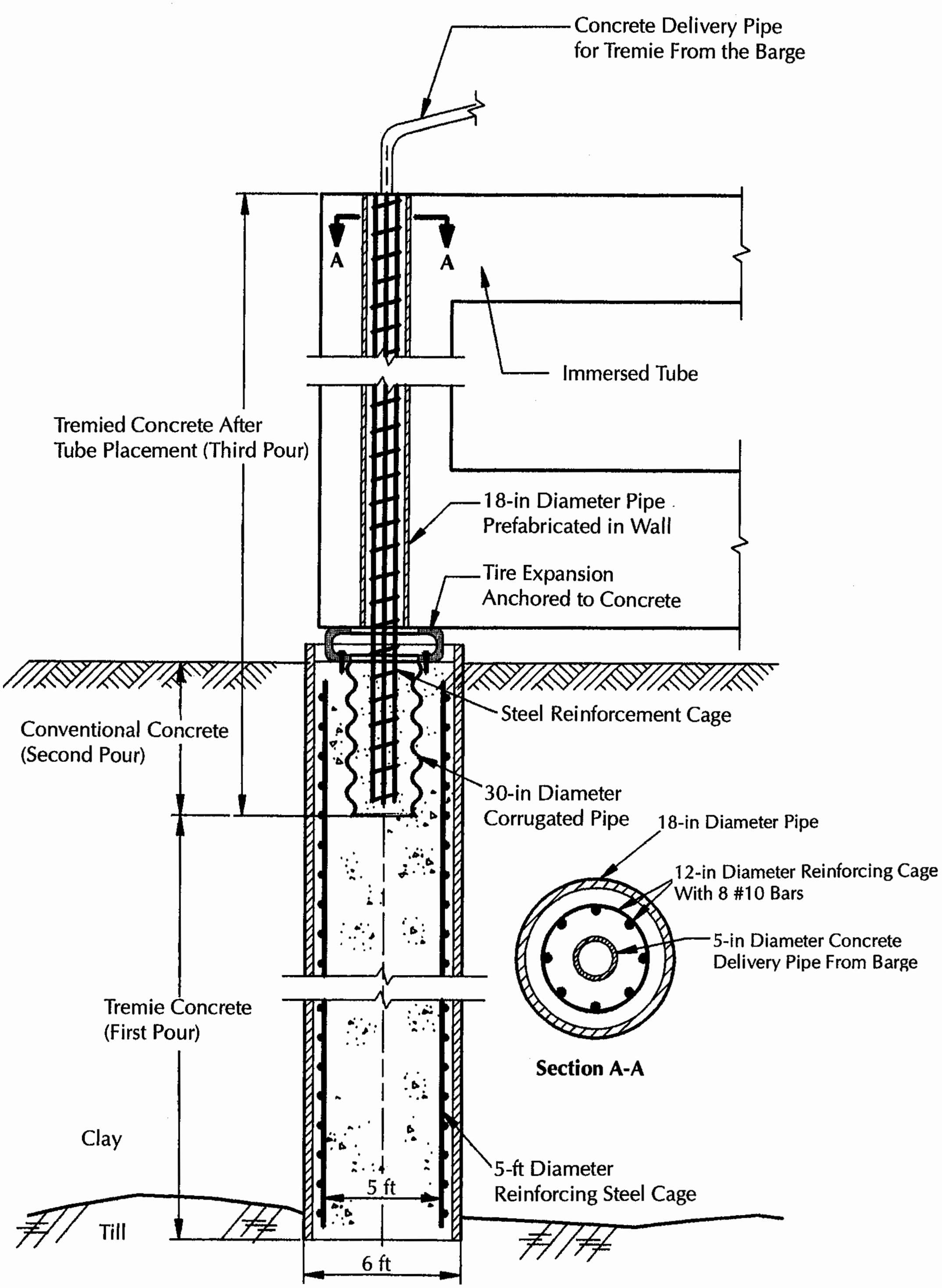

FIGURE 2. Connection of the immersed tube to a six-foot diameter caisson.

modified for the condition of group resistance of the caissons for uplift.

The Location of the Caissons

To protect against flooding effects, the caissons are sited under and along the longitudinal structural walls. The effective (equally loaded) caisson distribution can be achieved by the following two-step procedure. First, the required number of caissons, *N*, should be distributed in the transverse direction among the longitudinal walls by dividing that number on the fragments proportionally to the wall's contributory area (in plan). Then, the caissons of each fragment are distributed in the longitudinal direction along each wall independently.

For tubes with parallel walls, the caissons should be distributed in the longitudinal direction with approximately equal spans.

For the ITT that crosses over an existing tunnel, the caissons should be distributed along the longitudinal walls in groups of two or three caissons. The distance between caissons in these groups should be kept to minimum distances; however, there should be large spans between the caisson groups. The width of the existing tunnel governs the length of the largest span of the ITT. The ideal condition — equally loaded caissons — can be obtained if every caisson group is considered as the single support of a continuous beam. This calculation method yields results that are fairly consistent with results of the finite element method of analysis for the wall-caisson system.

Construction Procedure

Since the stiffness of the existing Red Line subway tunnel, which is supported in till, is much greater than that of the surrounding soil (Boston blue clay), significant reaction forces would be concentrated on the existing tunnel if flooding occurred. To avoid this situation, the preliminary design to support the ITT utilized a number of caissons to transfer the loading to the till and, thus, avoid imposing the loads on the Red Line tunnel.

The required diameter and number of caissons were calculated based, in part, on the bearing capacity of the till. Preliminary calculations have indicated that approximately 36 and 47 six-foot diameter caissons would be required for the westbound and eastbound tubes, respectively. Special procedures for caisson construction and their connection to the ITT were considered as a part of the preliminary design.

The construction sequence for installing caissons for an ITT entails (see Figure 2):

1. A six-foot diameter caisson steel shell is driven to the required position from a working barge.

2. A five-foot diameter cage of reinforcing steel is lowered into the caisson and tremie concrete is placed to within five to six feet from the top of the caisson (first pour).

3. The steel shell, with its top extended above the water level, is dewatered and any debris is removed.

4. A 30-inch diameter corrugated pipe is then installed in line with the theoretical centers established by surveying for every driven caisson. The space between the steel shell and the corrugated pipe is filled with concrete (in the dry) up to the required level at the top of caisson (second pour).

5. A tire is installed and anchored by several bolts to the concrete. The steel shell is then filled with water and a diver burns off the shell exactly to the required elevation.

Steps 1 through 5 must be repeated for each caisson. When the entire procedure has been completed, the caissons would then be capable of receiving the hypothetical loads imposed by accidentally dropping a flooded tube, or by flooding when once in place.

6. After the immersed tube is installed in its final position and it is connected to a previously sited unit, the steel reinforcing cages are lowered into the caissons through the openings in the tube walls. Then, the corrugated pipes in the caissons and the openings in walls are filled by tremie concrete (third pour), thus completing the permanent connection of the immersed tube to the caissons.

However, the construction sequence outlined above should not be implemented if the project meets one or more of the following criteria:

- The ITT does not cross an existing tunnel.

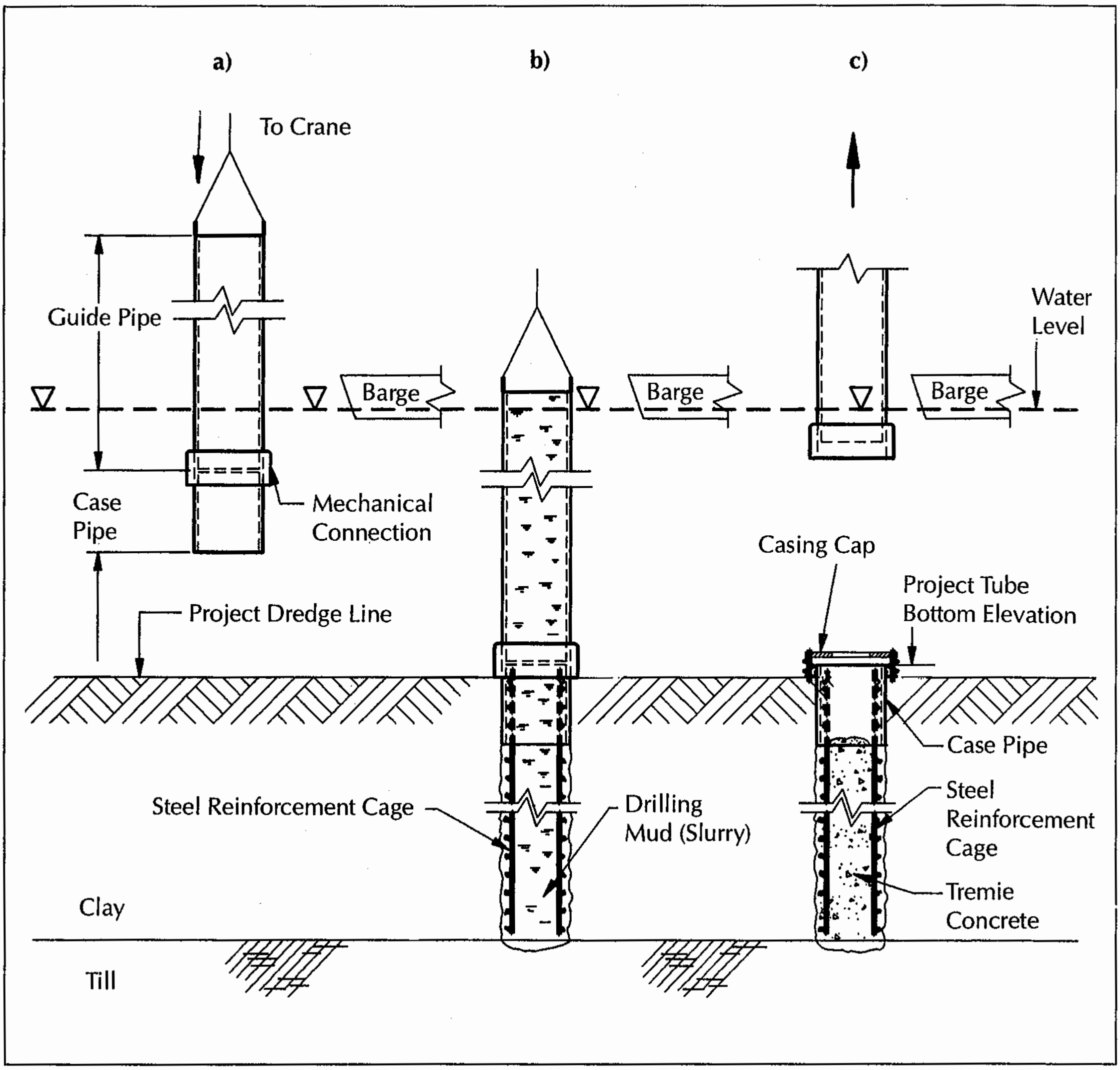

FIGURE 3. An alternative caisson construction sequence.

- The ITT does cross over an existing tunnel, but the accidental flooding of the ITT during its immersion is precluded. The full hermetic seal of all hatches and the bulk heads is provided during this period of time.
- The required caissons have a diameter smaller than six feet and worker access is not available inside the caisson.

In such cases, the construction should proceed as follows (see Figure 3):

*1.*The guide pipe and case pipe, initially mechanically coupled, are installed on a dredged bottom of the river from a working barge (see Figure 3a).

2. Using conventional drilling equipment, the pipe system is lowered into the soil to position the case pipe at the project level (at a minimum of five inches above the dredge line). Then, drilling in soil is conducted to the required depth with the protection of drilling mud (slurry).

3. The steel reinforcing cage is then installed and the caisson is tremied with concrete to above the low end of the case pipe and excess mud is pumped out (see Figure 3b).

4. The pipes are uncoupled and the casing cap is assembled on top of the case pipe by

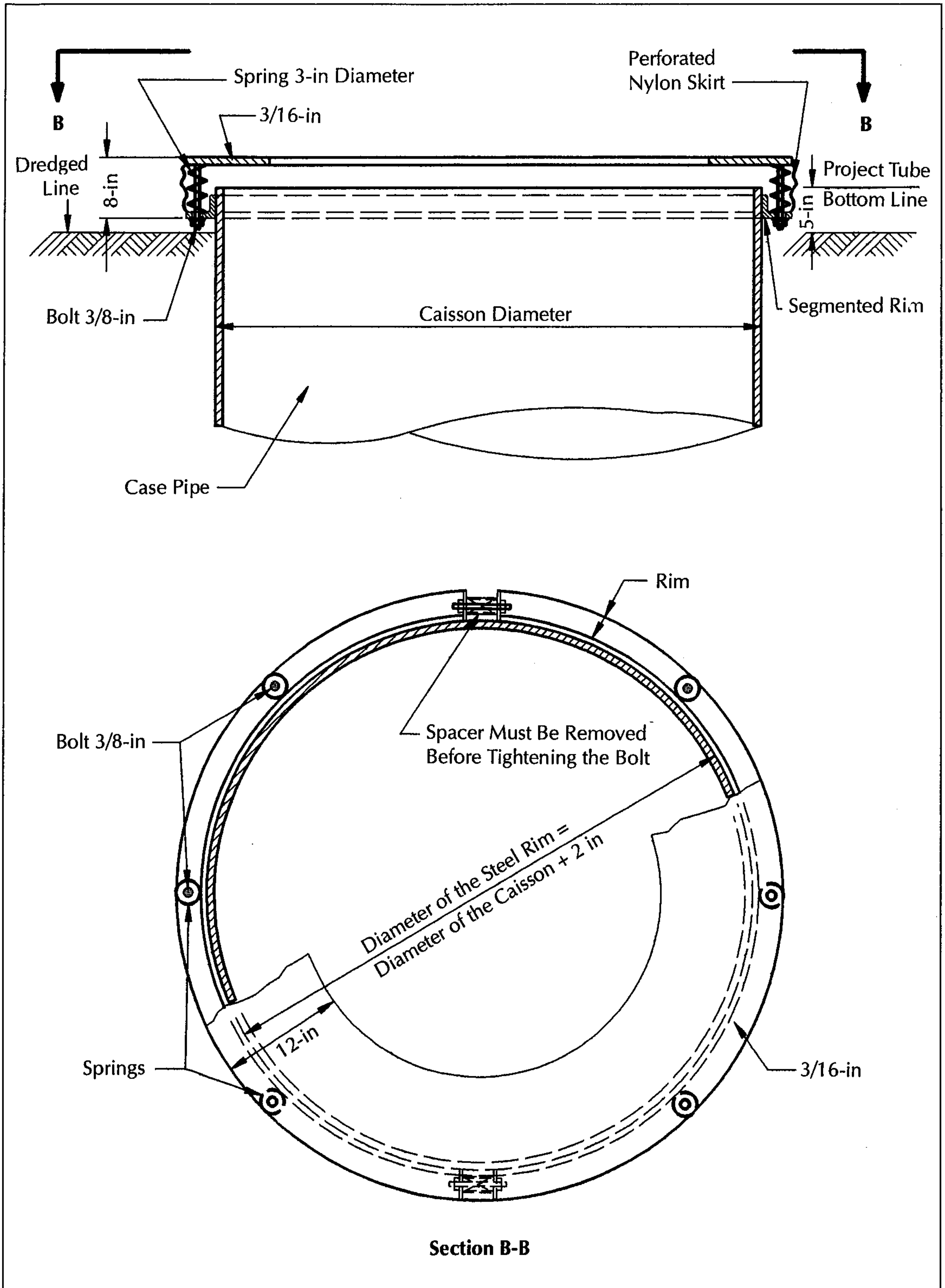

FIGURE 4. The casing cap for the caissons.

a diver. The caisson is now be ready to receive the ITT (see Figure 3c).

5. After final tube installation, the steel reinforcing cages are lowered from the barge into the caissons through the wells in the walls and tremied in place with concrete.

The casing cap (see Figure 4) is intended to account for the tolerances that are possible during the installation of the caissons and the immersed tube. The cap is designed in such a way that it can be easily delivered under water in one piece and quickly connected to the caisson. The cap consists of a circumferential strip and an angular rim, connected to each other by six (or eight) partially compressed springs. The angular rim is broken into several segments that are connected by bolts and spacers. The spacers are used temporarily to increase the diameter of the rim by two or three inches in order to ease installation. The spacers must be removed before the rim segments can be tightened on the caisson.

The nylon perforated skirt surrounds the cap from the outside. The total weight of the cap does not exceed 150 pounds and can be easily manipulated by two divers.

Advantages of Caisson Construction

Connecting an ITT to caissons through vertical wells that are prefabricated in the tube walls has the following advantages:

- A reliable structural connection can be made directly from a moored working barge without any negative impact on the tube waterproofing system.
- The need to place a considerable amount of concrete ballast inside the ITT is eliminated.
- The overall vertical dimension of the tunnel is reduced.
- The need to screed the bottom or to prepare an elaborate sand bedding under the tubes is eliminated.
- The amount of dredging in the crossing area is reduced.
- The amount of structural concrete and reinforcement of the tube is reduced.
- Bending stresses in the tunnel due to potential settlements are eliminated.

Cost Considerations

The proposed method for construction of immersed tube tunnels can be cost-effective when compared to more conventional alternatives. For example, cost estimates made during the preliminary design for the Fort Point Channel immersed tubes on the Central Artery Depression / Third Harbor Tunnel Project indicate that this method may result in a $5 million savings when compared to the previous design, which required the immersed tube to be ballasted.

This method is most efficient for those cases when the caissons serve a dual purpose: protecting an existing tunnel crossed by a new tunnel and eliminating the ballast layer from inside the new tunnel. In conventional situations, when the ITT does not cross an existing tunnel, the proposed method can still be cost-effective.

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