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Soldier Pile Tremie Concrete Walls As Part of the Final Tunnel Structure

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Summary

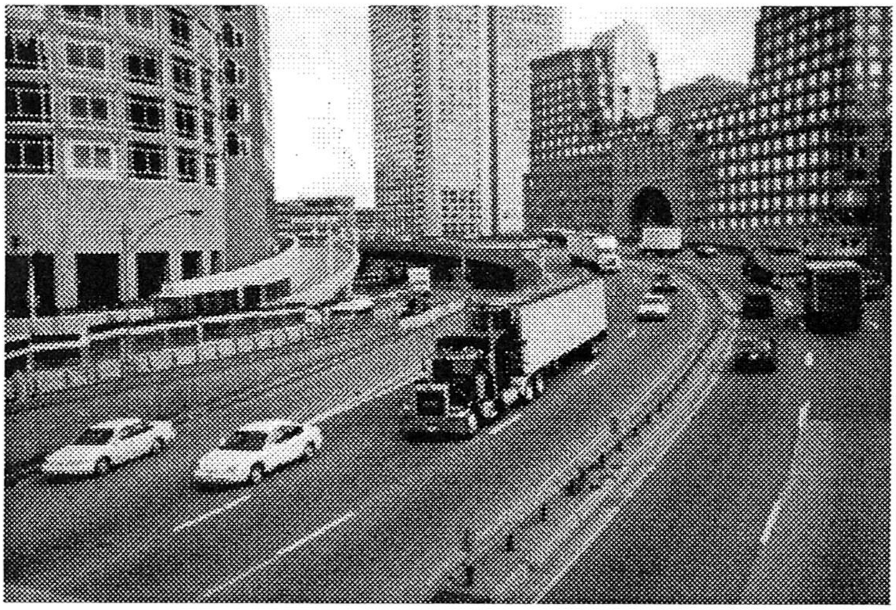
This paper discusses the use of Soldier Pile Tremie Concrete (SPTC) Slurry Walls as permanent tunnel walls on the Massachusetts Highway Department (MHD) Central Artery (I-93)/Tunnel (I-90) (CA/T) project in Boston, U.S.A.. It describes design considerations for choosing the SPTC walls as part of permanent tunnel structure as well as methods of analysis, design and evaluation of construction staging.

1.0 Introduction

The I-93 portion of the Central Artery (I-93)/Tunnel (I-90) project includes over 6.1 kilometers (20,000 feet) of slurry walls. Most of the walls are to be constructed as Soldier Pile Tremie Concrete (SPTC) walls. Steel wide flange soldier piles are installed at 1.2 meter to 1.8 meter (4 to 6 feet) spacing in a slurry trench and tremie concrete is placed to form the concrete wall. The steel wide flange piles form the primary reinforcement. In most areas, the concrete is designed to act as "lagging" spanning between structural steel piles. During construction, the walls are used as an excavation support system. After excavation is completed, the tunnel concrete base slab is moment-connected to the SPTC walls. Steel composite roof beams are connected to the walls in a pined connection to form the tunnel.

Many SPTC wall panels need to be built under the low headroom constraint imposed by the existing Central Artery viaduct. This six lane expressway viaduct must remain in service; thus using the SPTC walls as the foundation to underpin the existing viaduct during excavation and tunnel construction.

Figure 1 shows the existing Central Artery looking North. The tunnel will include three or four SPTC walls along its cross section. The west wall of the proposed tunnel and the most of the middle wall will be built below the existing viaduct. Special equipment is necessary for construction under the low head restriction of the existing viaduct, in some places as tight as 4.3 meters (14 feet). Since the soldier piles are 24 meters (80 feet) to 30 meters (100 feet) long, the piles need to be spliced using bolted splice connection.



Figire 1. Existing Central Artery Viaduct Looking North

For low head room construction, SPTC walls have an advantage over a heavily-reinforced conventional concrete slurry wall. The piles are easier to assemble and splice than multi-layer reinforcement bar cages. This ease of construction was an important consideration in downtown Boston, considering difficult soil conditions and tight construction work zones. Another benefit was that the SPTC walls are stiffer than a conventional concrete slurry walls of the same thickness, leading to improved performance for protection of existing buildings adjacent to the site.

2.0 Design Consideration

Since the SPTC walls are used both as part of support of excavation and as permanent final structure, it is necessary to consider the construction staging load along with the permanent load condition for the stress and deformation analysis. Construction stages include sequential excavation and strutting with cross lot braces, installation of the base slab, sequential removal of struts, installation of the roof, and placement of backfill. The load on the SPTC wall during the construction stage, which is temporary, is different from that in the final stage. Although the magnitude of total load on the SPTC wall in the temporary construction stage is less than that in permanent condition, it is very important to realize that most lateral deformation of the SPTC wall is associated with the excavation process. The construction induced ground movement, both horizontal and vertical, is of most concern to the project.

A unique aspect of the SPTC wall design is that the maximum lateral deformation occurs at a stage when the total lateral load is relatively small compared with its maximum magnitude. The excavation induced lateral movement will reduce the lateral soil pressure to some magnitude equal to or greater the active soil pressure depending on deflection of wall. Typical tunnel load diagram used for design is shown on Figure 2.

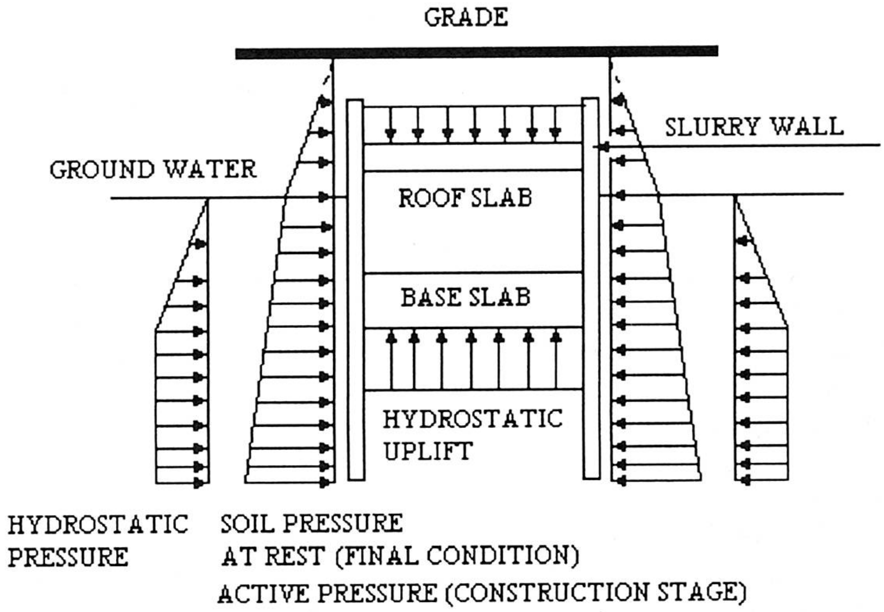


Figure 2. Typical Tunnel Load Diagram

In the final condition, the soil pressure will increase over time and will reach at rest value. This requires the structural design of the SPTC wall to first consider deformation control at the construction stage when the load is relatively small, and then the strength of the wall for the permanent condition. For this purpose, the CA/T project adopted a design approach to use an allowable stress design method together with additional stringent deformation control requirements for design of the SPTC wall during temporary construction stage and Load Factor Design for the final condition.

3.0 Analysis of the SPTC Wall

Two general methods of analysis have been used for analysis and design of SPTC walls. The "structural model" uses frame analysis for structural design and selection of wall members. The material properties of the structural elements in the SPTC wall are assumed to be homogeneous, isotropic, and elastic. Nonlinearity associated with the staged excavation is significant to the stress and strain in the SPTC wall and, therefore, needs to be modeled accordingly. Both linear and nonlinear finite element programs have been used for SPTC wall analysis to achieve acceptable results. The "geotechnical model" considers the overall stiffness of the wall support and soil system, and has been used for evaluation of potential construction-induced effects to buildings along the tunnel right-of-way. This method utilizes the Finite Element Analysis to model soil and use the vertical wall as a boundary condition.

3.1. Structural Model

The wall structural model for the construction phase is nonlinear and requires stress-historydependent soil structural interaction analysis. Prior to tunnel excavation, the newly-installed wall is in a state of equilibrium with the surrounding soil. The first stage excavation on one side of the slurry wall creates different ground elevations and mobilizes soil pressure on the retained side to push laterally against the wall. The soil below the bottom of excavation acts as support to maintain the stability of the wall. To understand the nonlinear behavior of the system, it is important to note that the wall deflects into the excavation some distance below the strut support level, before the strut can be installed. What this implies is that the wall will deflect more into the excavation than would be predicted by a linear model of loads applied to the wall and full-excavated depth strutting levels.

In order to minimize the ground movement, the strut is preloaded between walls. In other words the strut acts as a prestressed spring support to the wall with spring constant equal to the axial stiffness of the strut. Preloading of the strut pushes the wall against the retained soil and generates additional soil reaction on the wall. Each stage of excavation is about 3.66 meters (12 feet). For each subsequent excavation stage, the excavation support structure experiences following changes sequentially:

- Excavation removes the support of subgrade soil to the slurry wall and lowers the wall's soil support down to the bottom of the excavation stage.
- Excavation releases the subgrade soil reaction of the previous stage and causes stress redistribution between the wall and soil below the bottom of the excavation.
- Excavation results in change of lateral soil pressure outside walls.
- Installation of a support strut adds a support point in the model, which is treated as a linear spring in the analysis.
- Preloading of the strut may generate additional soil reactions on the wall by pushing the wall back into the soil.

The final stresses in the wall are accumulated in increments from one excavation stage to the next. As the excavation proceeds, the load on the wall increases while the structural configuration of the wall/support system as well as its boundary conditions change. The final stresses in the wall are not linearly related to the displacements of the structure, requiring an incremental nonlinear analysis.

To use a linear elastic structural software program for the SPTC wall analysis, the structural model assumes that all loads mobilized by excavation will be applied to the wall at once for each excavation stage. The inward deformation of the wall at a strut level prior to the strut's installation is accounted for by introducing a fictitious concentrated load at the position where the strut is to be placed. The fictitious load forces the wall to move inward by a deflection amount equal to the deflected shape prior to strut placement. The subsequent excavation stage analysis can then be run with the new level of strutting in place, and the wall correctly deflected inward. For the computer software program with nonlinear capacity, each stage of excavation may be modeled sequentially from top to bottom. The inward movements and stress in the previous stages of excavation will be accounted accordingly.

The thickness of the SPTC slurry wall varies between 0.9 to 1.2 meter (3 to 4 feet) thick. The soldier piles are spaced between 1.21 meter to 1.83 meter (4 to 6 feet). The structural steel soldier piles are designed as primary load carrying members and the concrete between the soldier piles are considered as lagging between the piles. The flexural stress of the concrete between soldier piles is very small, so no steel bar reinforcement is needed. However, in some locations where the surcharge loading from adjacent building foundations is high, reinforcement may be needed. In most cases, W36 x 393 wide flange sections with 3.45 x 10^5 kpa (50 ksi) yield strength are used as soldier piles. The minimum 28 days strength of the tremie concrete is 2.76 x 10^4 kpa (4000 psi) with a slump between 17.78 to 25.4 centimeters (7 to 10 inches).

The concrete base slab thickness varies between 2.44 to 4.57 meters (8 to 15 feet). The base slab is rigidly connected with the steel soldier piles as shown in Figure 3. The roof structures are simply supported from the soldier piles. The roof structures are composite structural steel plate girders with a concrete roof top slab. Waterproofing material is provided under the base slab and on the top of the roof slab.

3.2. Ground Movement Model

While the structural analysis was performed to size the structural elements in the wall, the geotechnical model was developed as a tool to compare different systems of wall stiffness for predicted performance during the excavation. As excavation proceeds, the wall tends to deform into the excavation, leading to soil movement behind the wall. This movement, along with other factors such as consolidation due to dewatering and construction vibration, is of great concern for protection of existing structures along the right-of-way.

For this analysis, the soil and structure are modeled as a mass. The mass is broken up into discrete elements and assigned elastic or inelastic properties. Typically, the analysis assumes an elastic model for structural elements and an inelastic, hyperbolic stress-strain model for the soil. The model predicts wall and soil movement by simulating the states of stress caused by the construction process. This analysis includes the same stages of construction used in the structural analysis. Unlike the structural model, the geotechnical model includes some stiffness of the unreinforced concrete between piles as part of the overall stiffness of the system. To ignore the stiffness of the concrete, which partially encases the soldier piles, would be over-conservative when trying to estimate movement of the walls during construction.

The geotechnical analysis includes elastic modeling for wall and bracing elements, hyperbolic stress-strain relationships to model the behavior of the soil mass, and a capability of simulating staged construction. For this last capability, the engineer makes assumptions about the sequence of the excavation (similar to the structural analysis), including depths of each cut and installation of bracing. The model sequentially deactivates blocks of soil and adds bracing pre-loads. The soil mass behind the wall reacts to the modeled construction behavior based on the constitutive material properties input into the program. The geotechnical model is analytically more refined than the structural model. It does not require any assumptions regarding lateral load on the wall, but requires an estimation of soil parameters that is difficult to verify.

Therefore, the geotechnical model is good for wall performance comparison, but it has limited ability to precisely predict soil movement behind the excavation support wall.

The movement of the SPTC slurry wall and the adjacent buildings are monitored by extensive instrumentation system to confirm the design assumption and to activate the contingency plan, if the deflection exceeds the threshold values. Threshold Values have been established to provide advance warning of potential problems or detrimental effects related to construction and are typically one half of the Limiting Values. Both Threshold Values and Limiting Values are based on the allowable ground movements the adjacent facilities and utilities can take with acceptable impact. Due to fact that the different facilities and utilities have different sensitivities to the ground movements, the Threshold Values and Limiting Values vary from location to location.

Acknowledgments

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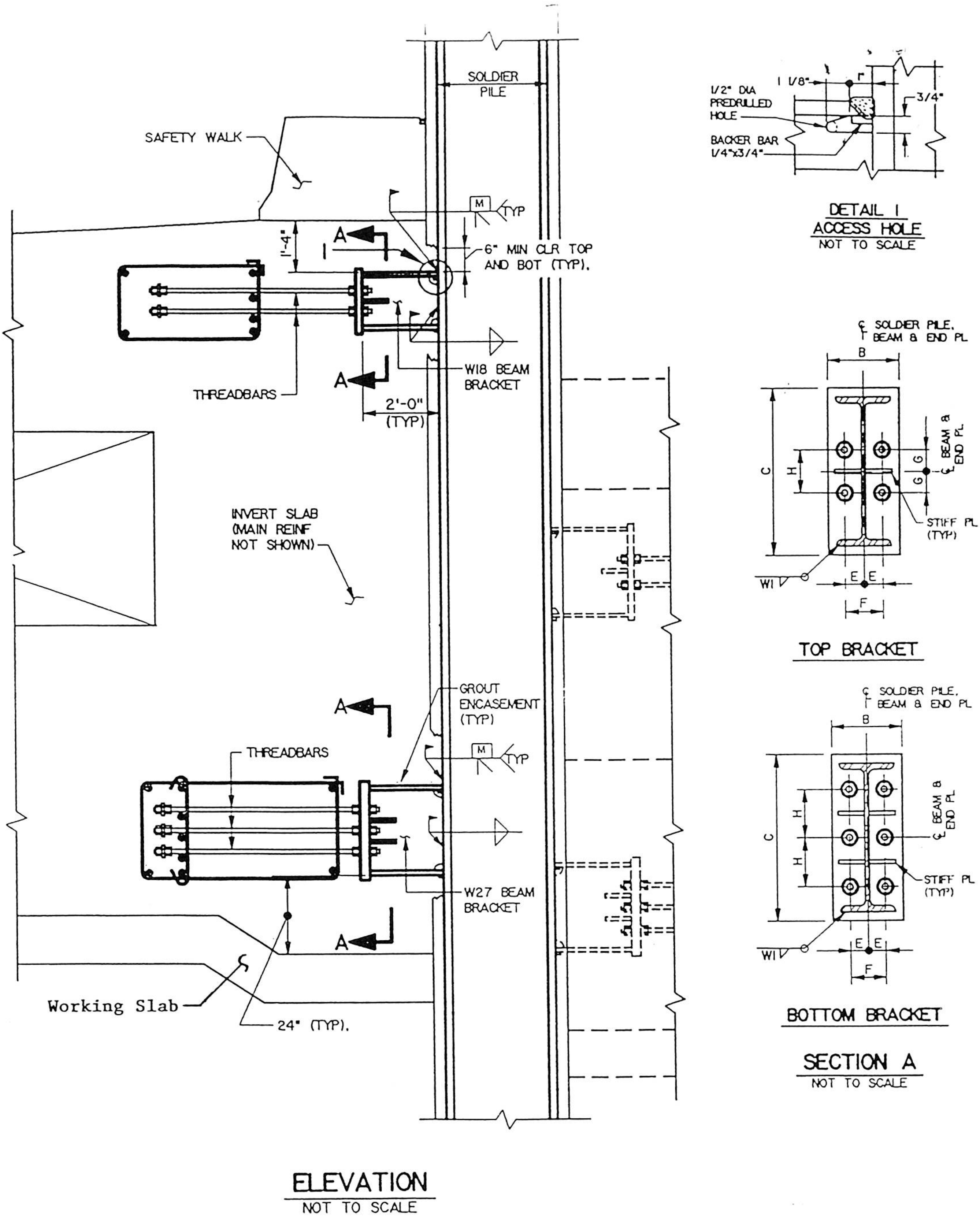

INVERT SLAB TO SPTC WALL CONNECTION

FIGURE 3

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