A DSM WALL FOR EXCAVATION SUPPORT

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Abstract

Excavation for a cut and cover highway tunnel underpass was designed and constructed using deep soil mixing. Several historic mansions located close to the tunnel alignment required special attention to restrict construction induced ground movements that could damage them. Design procedures for this excavation support wall were developed considering the different properties of soil, soil-cement and steel. Both design and construction practices followed procedures intended to limit ground movements. Results from a program of instrumentation and monitoring demonstrated that the approach implemented on this project succeeded in meeting the stringent requirements to limit ground movements.

Introduction

The Pennsylvania Department of Transportation (PennDOT) planned to connect a new bridge crossing the Susquehanna River to State Route 54 and by-passing the Danville, Pennsylvania business district. The new route passes through the historic district, characterized by spectacular old mansions and a narrow right of way. The new connector, an underpass, replaces Factory Street and extends under Market Street, which before construction, consisted of an at-grade crossing, see Figure 1.

The underpass extends from Front Street, continues beneath Market Street and ends at Mahoning Street, for a total length of 186 meters (610 feet). The ground surface along the center of Factory Street increases from Front Street to Market Street and then decreases to the elevation at Mahoning Street. The underpass alignment descends from Front Street to Market Street and then rises to meet the Mahoning Street elevation.

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The historic mansions are 0.9 to 1.2 meters (3 to 4 feet) from the pre-construction location of the sidewalks. These 3-story mansions are constructed of brick, stone or stucco, notoriously brittle materials that crack from small movements. PennDOT's designer, Gannett Fleming, Inc., recognized that the excavation for the underpass needed to limit ground movements to preserve the appearance of the adjacent historic mansions and therefore specified an excavation support system consisting of either a concrete slurry wall, a secant pile wall or a deep soil mix (DSM) wall. These systems eliminate sloughing of cohesionless soils during excavation, which could result in lateral movements of the adjacent structures. Driving soldier piles or steel sheet piling was not permitted, due to the potential for vibration damage to the adjacent structures.

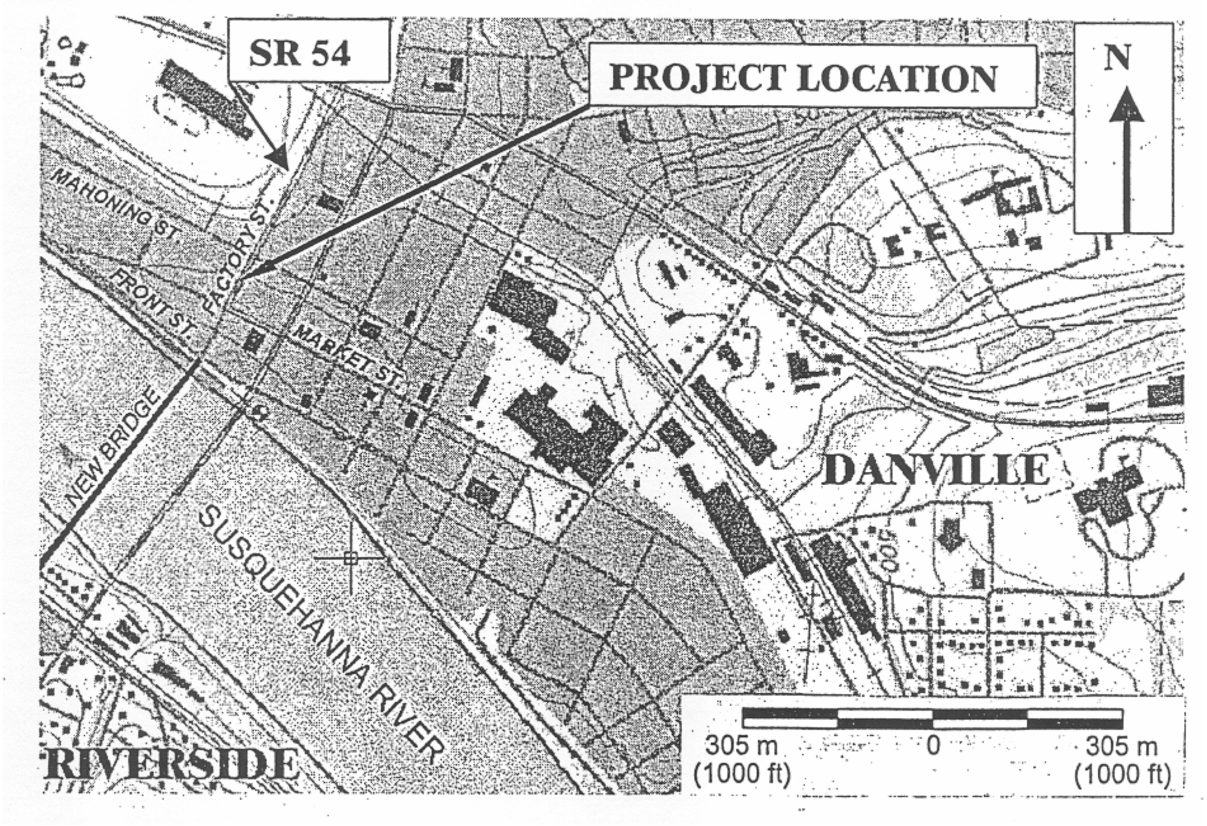

Figure 1. Project Location

PennDOT awarded the construction contract to G.A. & F.C. Wagman, Inc. who subcontracted Geo-Con to construct the deep soil mix wall and McMahon & Mann Consulting Engineers, P.C. to design the excavation shoring.

The project has approach sections at each end, and a rigid frame underpass at the deepest portions of the project. The excavation depth ranges from 0 to about 6.7 meters (22 feet) in the approach sections to about 9.4 meters (31 feet) at the deepest point in the rigid frame section.

The excavation width was restricted by the location of the historic mansions along Factory Street. The mansions range from 1.5 to 4.9 meters (5 to 16 feet) from the edge of the excavation. The outside of the rigid frame is 10.4 meters (34 feet), but the approaches are 11.4 meters (37.5 feet) wide. The rigid frame walls are 0.6 meters (2 feet) thick.

Geologic Setting

The project is located along the north banks of the Susquehanna River in Central Pennsylvania. A ridge exists along the north bank, approximately parallel to the river. Factory Street is approximately perpendicular to the ridge and Market Street is parallel.

Test borings made along the project alignment show that the ridge consists of a deposit of silt, sand and gravel. Based on Standard Penetration Test results, the density of the deposit appears to range from loose to dense. Boulders are present in this deposit.

Ground water level measurements made in piezometers installed in some of the test borings indicate that the ground water elevation is below the bottom of the proposed toe of the deep soil mix wall.

Design Issues

Deep soil mixing (DSM) involves the use of an auger to mix in-situ soil with cement grout to create a soil-cement column. Steel beams are inserted within selected holes to offer reinforcement. The soil-cement columns are overlapped along the alignment to create a continuous soil-cement wall. The wall design considered construction aspects of the DSM process. The drilling equipment is built such that DSM holes are spaced at 0.69 meters (2.25 feet) center to center. Therefore, the soldier pile spacing needed to be a multiple of 0.69 meters (2.25 feet). A soldier pile spacing of 1.37 meters (4.5 feet) was selected.

Soil-cement exhibits properties similar to very weak concrete, and is thus stronger than most soils. It was expected to be stronger than the on-site soils unless significant confinement existed. The project contract specified the minimum unconfined compressive strength of 1380 kPa (200 psi) for the soil-cement.

Several conceptual issues faced the shoring designers. First, the designers had to select a reasonable model for the wall. A DSM wall doesn’t conform to the characteristics of a continuous wall, such as a sheet pile or concrete diaphragm wall, or of a segmental wall, such as a soldier pile and lagging wall. Issues of relative soil strength, stiffness and degrees of confinement must be resolved to understand the behavior of the soil-cement wall. An important consideration for the design is the behavior of the soil-cement wall below the excavation subgrade, since this affects the required depth of embedment for the stability of the wall. Secondly, the designers needed to consider the proximity of the mansions located along the excavation. The support system needed to restrict horizontal and vertical movements resulting from the excavation.

Earth Pressures

Above the excavation subgrade, the shoring system designers considered the wall as a segmental wall because the steel soldier beams are significantly stiffer than the soil-cement. This disparity in stiffness causes soil behind the wall to arch, similar to a soldier pile and wood-lagging wall. Thus, the soldier beams need to be designed to carry the entire soil and surcharge loads.

The project specifications presented two earth pressure diagrams for the design of the excavation support system, one appropriate for a multiple level bracing system and one for a single brace or cantilever wall. The rectangular earth pressure diagram presented by Terzaghi and Peck (1967) was specified in areas where multiple bracing levels were used. An active Rankine pressure distribution was specified for zones requiring a single row of bracing and the cantilever wall areas.

The project designers also specified the soil properties for design of the support system. Specifications required use of a “deflection reduction factor” of 1.4. That is, the lateral earth pressure, including that from a surcharge must be increased 1.4 times for the design of the excavation system structural members. The “deflection reduction factor” did not apply to the passive earth pressure calculations.

The strength of the soil-cement exceeded the passive strength of the soil below the excavation subgrade by a factor of at least 8 to 10. Therefore, the DSM wall behaved as a rigid element in a deformable soil. Although the stiffness disparity between the soil-cement and the soil was less than that for a sheet pile in soil, it was appropriate to model the DSM wall below the excavation subgrade as a continuous wall. The embedment length was calculated following accepted procedures for a sheet pile wall.

Deflections

Although the contract documents specified the lateral earth pressures and their distribution to be used in the design of the earth retention system, the specifications did not specify the methods to control construction induced ground movements. The specifications required the computed lateral earth pressure to be inflated by a “deflection reduction factor” of 1.4. This merely increases the size of the support members, but does not necessarily restrict ground movements associated with the excavation and corresponding sequence of construction.

Ground movements cannot be reliably predicted using a rigorous mathematical approach. The designers attempted to predict the amount of ground movement that could result from the excavation based on the various empirical correlations reported in the literature. Observations of ground deflections next to excavations in sand were reviewed.

As shown in Figure 2, Peck (1969) presented vertical ground movement envelopes, normalized for the height of excavations and the horizontal distance from the excavation face, for supported excavations in various ground conditions. Zone I of Peck's model represent excavations made in sand and hard clay soil where the factor of safety against basal heave was adequate. These conditions fit the description at this site.

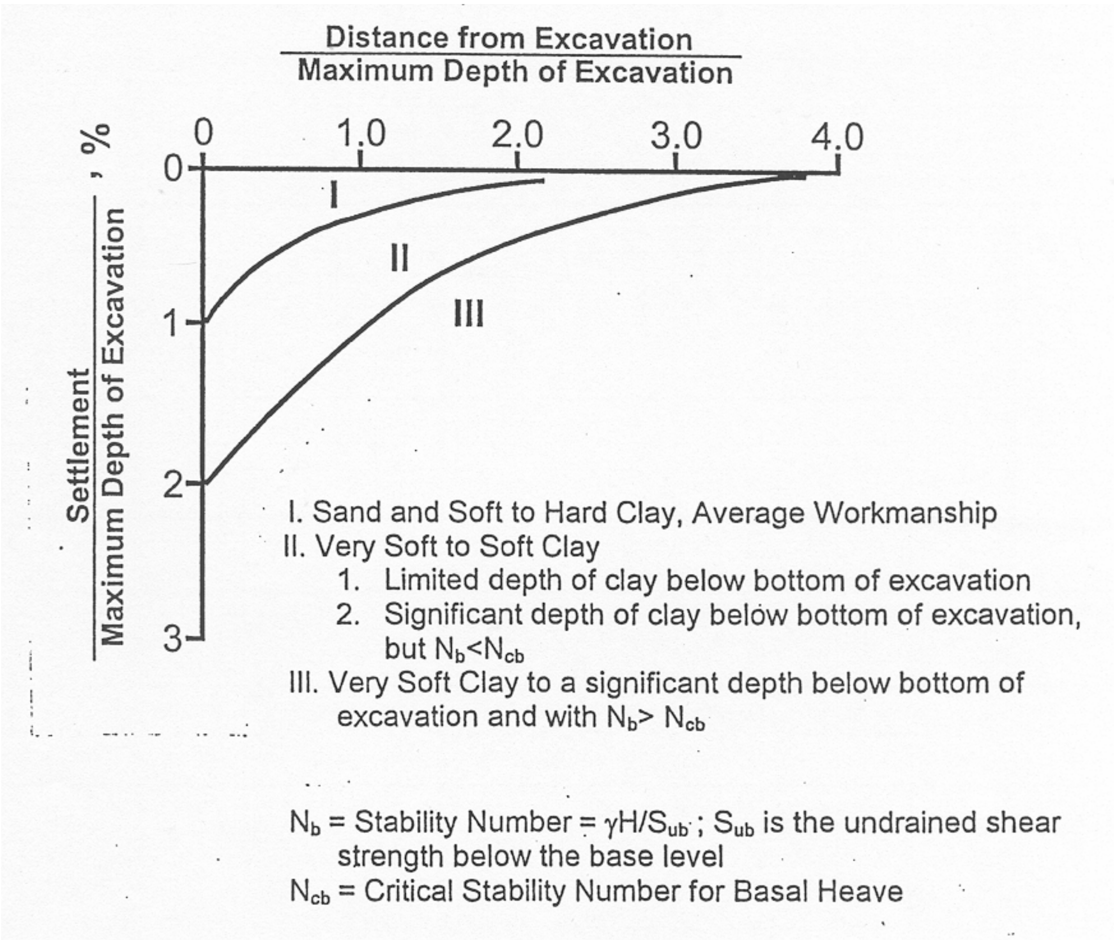

Figure 2. Vertical Ground Movement (Peck, 1969)

Based on this envelope, the vertical movement at the distance from the excavation face corresponding to the location of the mansions, would be about 1 percent of the excavation height for average workmanship. This represents about 102 millimeters (4 inches). Clearly, this amount of movement would generate claims by the mansion owners. The designers and contractor considered this amount of movement intolerable.

O'Rourke (1989) presents normalized vertical ground movement data collected from a variety of wall types constructed in sand (Figure 3). The wall types include soldier piles with cross-lot bracing, soldier piles with tiebacks, sheet piles with tiebacks and a concrete diaphragm wall. The envelope suggests that vertical ground movements corresponding to the locations of the mansions could approach 0.3 percent of the excavation height. This represents about 28 millimeters (1.1 inches). Again, this amount of settlement of the mansions would not go unnoticed and would likely result in a claim.

However, some of the vertical ground movement data presented by O'Rourke show vertical movements as low as 0.1 percent of the excavation height. This translates into about 10 millimeters (0.4 inches) at the distance from the excavation that the mansions are located. The designers considered this to be the maximum tolerable amount for this project. The following measures were implemented to justify the presumption that the retained system is representative of the case studies that exhibited the least amount of deformation.

Clough and O'Rourke (1990) state that wall stiffness and the vertical spacing between horizontal supports have a small effect on the ensuing horizontal and vertical ground movements next to excavations in sands. In spite of this information, the designers considered a large wall stiffness and close vertical spacing of horizontal supports desirable as part of the effort to limit ground movements associated with installation of supports during excavation.

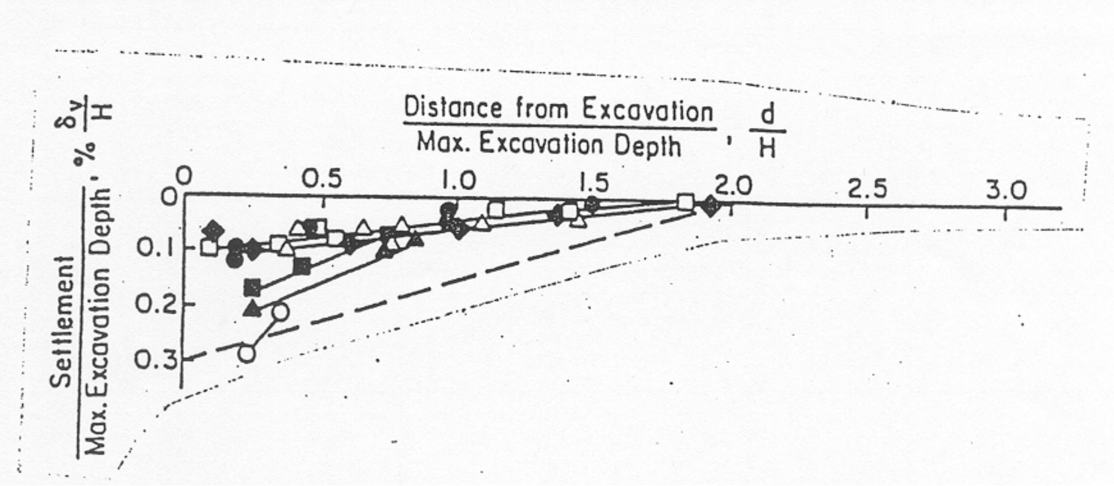

Figure 3. Settlements Next to Excavations in Sand (O'Rourke, 1989)

Attempts were made to make the wall stiff, yet economical for the contractor. Soldier piles were selected to resist the lateral loads calculated using the prescribed earth pressures. Given the choice of several member sizes, the member with the greatest moment of inertia was selected to maximize the wall stiffness. Additionally, the spacing between horizontal braces was minimized to the limit allowed by the excavation equipment used by the contractor.

The designers also realized that controls implemented during construction have the most significant impact on the ensuing deformations.

In summary, the following measures were taken to control ground movements.

1. Design the uppermost bracing level near the top of the excavation to limit ground movements resulting from the cantilever condition during the initial excavation.
2. Limit the maximum vertical distance between supports at any time during the excavation to 3.0 meters (10 feet).
3. Prestress the horizontal supports to 100 percent of the design load (this was specified). Pre-stress loads were applied to struts opposite basement walls only until the soldier pile showed evidence of movement to limit the potential for buckling the basement walls.
4. Extend the excavation below a strut level to a maximum of 0.6 meters (2 feet) before installing the strut.
5. Do not rely on unexcavated earth berms against the retaining wall for horizontal support, i.e., do not make the excavation along the centerline of the underpass before installing the struts.

Figure 4 shows a cross-section view of the excavation configuration near the maximum excavation depth. Soldier piles consisted of wide flange sections, W18x40.

Construction Practice

The design of the earth retention system plays only a part in controlling ground movements. Construction practice has an equal, or even greater, significance. The following describes the construction practice used for the DSM wall.

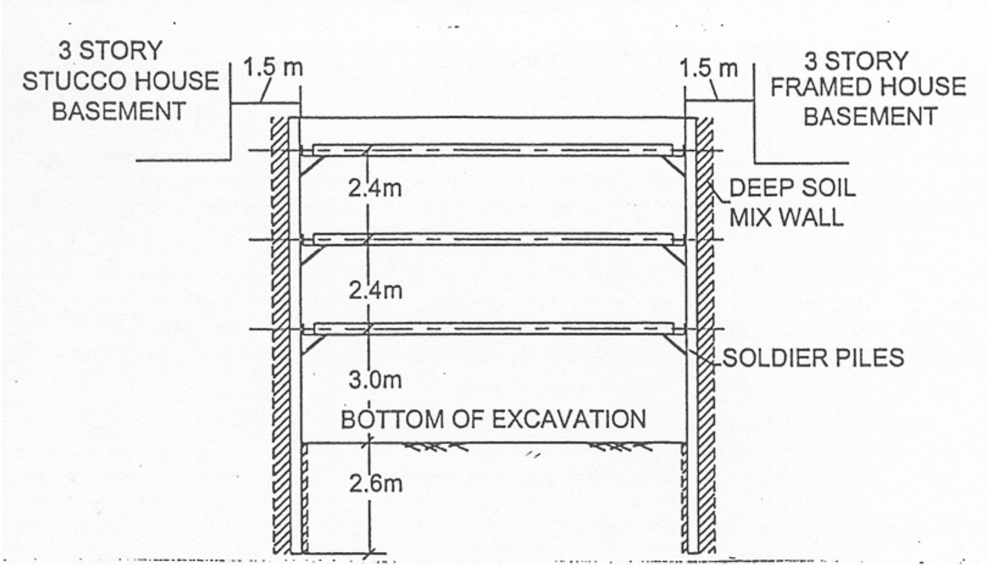

Figure 4. Cross-Section through the Rigid Frame Section

The DSM system utilizes a crane-supported set of leads, which guide a series of multiple, 0.9-meter (36-inch) diameter mixing shafts. DSM allows soil to be treated in place to depths of 36.6 meters (120 feet). As the shafts are advanced vertically into the soil, slurry is injected through the hollow stems of the mixing shafts and then discharged through outlets at the bottom. DSM has been successfully used on numerous earth retention projects throughout the United States.

The DSM procedure blended the in-situ soils with a cement grout to form a continuous soil-cement interconnected wall on each side of the excavation. The walls were constructed so that the minimum effective wall width was 0.61 meters (24 inches). The length of each side of the permanent shoring was 186 meters (610 lineal feet), for a total of 372 meters (1220 feet) of soil-mixed wall. The maximum depth of drilling was 12 meters (40 feet), and the total soil-mixed area was 3480 square meters (37,500 square feet). In addition to the soil-mixed wall, steel beams were placed into the soilcrete, prior to initial set, to provide sufficient stiffness and lateral reinforcement.

Equipment

The equipment used to construct the DSM wall consisted of a set of four mixing tools, top driven by hydraulically powered motors. The motors and the shafts which they turn, run up and down a set of specially designed leads. The leads are supported by a 17,800 kN (200 ton) crane (Manitowoc 4100W). While in operation, each DSM unit has a rated output of 67.8 m-kN (50,000 foot pounds) of torque. A spotter is connected to the front of the crane's car body and also to the bottom of the crane leads. The spotter is used to move the bottom of the leads in and out, and side to side, so that an exact location can be drilled.

The actual mixing tools consist of thick-walled rods, 254 to 305 millimeters (10 to 12 inch) diameter, with 51 to 76 millimeter (2 to 3 inch) diameter center holes for transferring grout to the mixing tool heads. At the bottom of each rod is a cutting head, which is designed to lift the soil into the mixing paddle area where it is blended with the grout. As the rods and paddles penetrate the soil, they continuously rotate and mix the grout and soil together, creating a soilcrete. When the bottom of the column is reached, the augers are retracted using a reduced flow of grout, while continuing to blend the soil and grout mixture.

Construction Procedure

Prior to drilling with the DSM rig, a pre-trench was excavated along the alignment of the DSM wall. The purpose of the pre-trench was to contain the soil cuttings and excess grout as they come to the surface. The spoils from the pre-trench were managed and removed as needed. The dimensions of the pre-trench varied based on the depth of drilling and the space available.

Once the pre-trench and wall layout were complete, the DSM rig was tracked into position, and the mixing shafts were aligned on the centerline. The mixing shafts were then rotated and advanced into the subsurface. As the shafts advanced vertically into the soil, the cement grout was injected through the hollow stems of the mixing shafts and discharged at the head. The action of the overlapping blades and mixing paddles on the shafts lift the soil and blend it with the grout in a pugmill fashion. In order to ensure adequate mixing, the drilling rate was maintained in the range of 0.3 to 2.4 meters (1 to 8 feet) per minute during penetration and withdrawal.

After two primary strokes are completed, a secondary stroke is drilled between them. The secondary stroke overlaps each primary stroke by one auger diameter, as shown in Figure 5. This process continues for the entire length of wall.

After a sufficient length of wall has been mixed, and before the soil-cement began to set, steel beams were lowered into the fresh soilcrete (See Figure 6). The beams were installed on 1.38-meter (4.5-foot) centers using templates, which were preset on the alignment. The beams were marked prior to installation into the soilcrete to verify that proper depths have been reached. Most of the beams were installed under their own weight, with some of the beams needing slight assistance from added weights or small vibrators. Once the beam installation was complete, the templates were left in place until the wall had taken an initial set. At that point, the templates were removed and reset for additional beam placement.

The DSM wall progressed from Front Street over the hill (Market Street) to Mahoning Street for the west wall. Due to schedule and construction practices, the rig was then moved to the top of the hill on the east wall and proceeded north to Mahoning Street. The final section of the east wall was completed from Market Street to Front Street, where the DSM rig was disassembled.

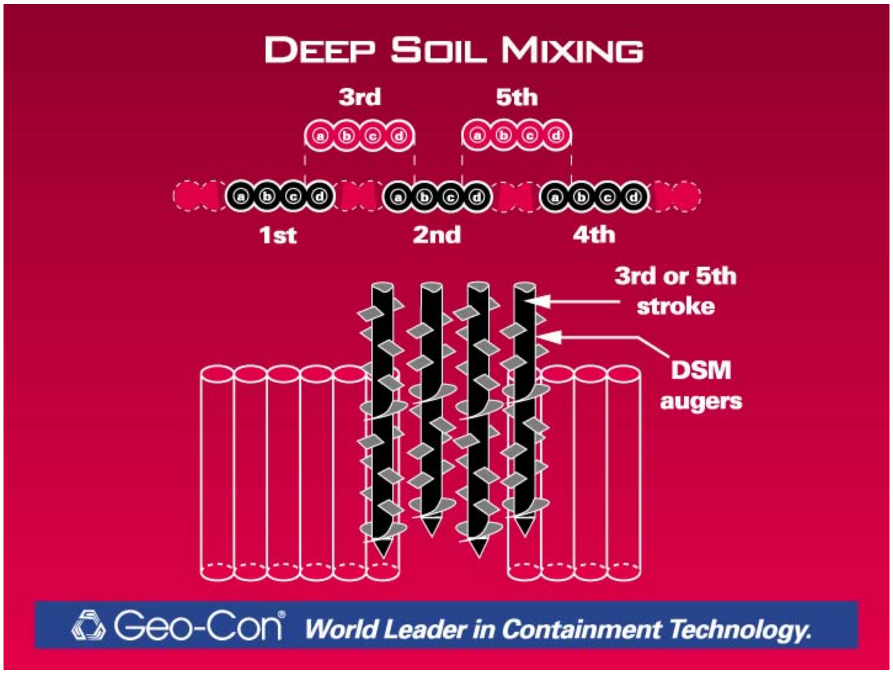

Figure 5. DSM Pattern

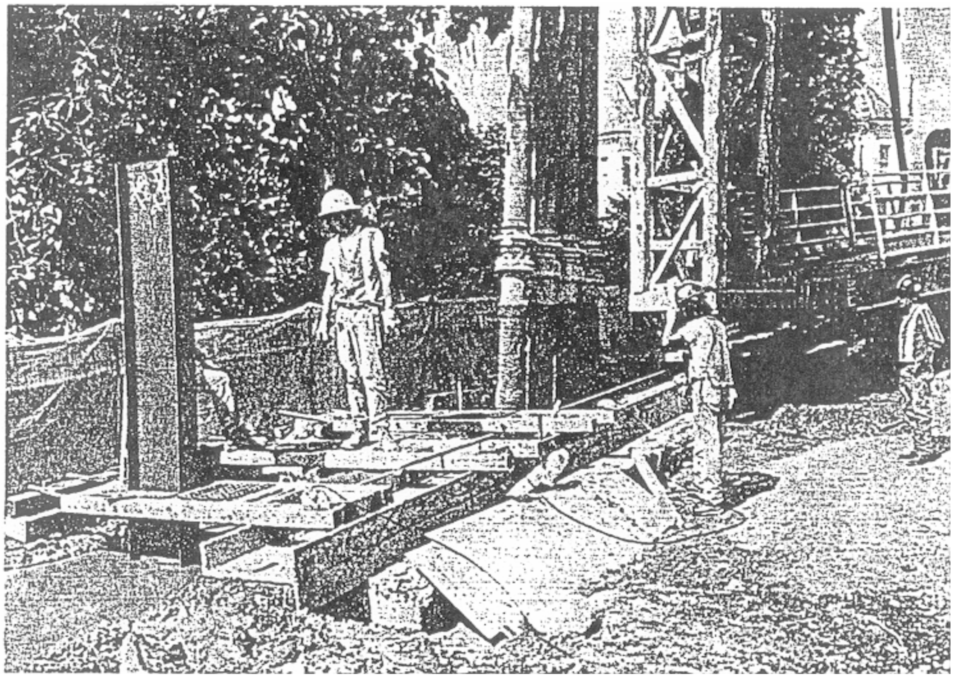

Figure 6. Installation of Steel Beams into the DSM wall

Field Tests During Construction

During construction activities, grout, slurry and soil mix materials were tested for compliance in accordance with the established standard operating procedures.

- *Cement-Water Grout*

For the soil mixed columns, a cement-water grout was mixed. This grout consisted of a combination of 1.5:1 water to cement, by weight. The target density of the grout after mixing was a minimum of 13.5 kN/m^3 (86 pounds per cubic foot); (specific gravity of 1.38). Density was verified using a mud balance, and recorded.

- *In-Situ Sampling*

Unconfined Compressive Strength (UCS) testing was performed on the completed wall to determine the acceptability of the soil-mixed material. One sample per 6.1 meters (20 feet) of lineal wall length was required per the specifications. A specially fabricated sampling tool was used to obtain samples of the "wet" soil mix prior to set. Samples, to be tested, were collected at mid-depth of the soil-mixed columns. These "fresh" soil-cement samples were tested at 7 days and 28 days to measure UCS.

A total of 61 wet samples were collected at random wall locations. The average 7-day strengths of these samples were 3.05 MPa (442 psi), while the average 28-day strengths were 4.2 MPa (614 psi).

Two samples of cured soil-cement were collected per 50 lineal feet of wall. From each cored location, one sample was tested at 28 days for UCS and the remaining sample was stored until the underpass construction was completed. All cored sample locations were backfilled with a grout mixture.

A total of 24 cored samples were collected at randomly selected wall locations. The average compressive strengths of these samples were 3.8 MPa (552 psi).

- *Vertical Control*

Verticality was accomplished by visual observation of the augers as they advanced downward, and controlled by the DSM operator. Verticality was checked periodically, using a level on the auger leads.

- *Depth Control*

The augers were pre-measured and marked in the field prior to starting work. The depths are recorded from the shortest auger to assure that the minimum depths were reached. Final depth was recorded from the preset marks on the augers. After completing the soil mixing, steel beams were placed as described above.

- *Mixing Shaft Speed*

The mixing shaft speed was adjusted to accommodate a constant rate of mixing and shaft penetration, based on the degree of drilling difficulty. The speed was optimized to provide the best drilling production.

- *Penetration Rate*

The penetration and extraction rates of 0.3 to 2.4 meters (1 to 8 feet) per minute were monitored in the field and optimized to provide adequate material injection and mixing.

- *Grout Take*

The grout take (or injection rate), per vertical meter of soil-mixed stroke, was adjusted so that the requirements of the mix design were met. A positive displacement pump transferred the grout mix through a manifold located on the DSM spotter. From there, the grout was conveyed to the mixing shafts from the manifold via hoses. Each hose is dedicated to an individual mixing shaft, allowing specific flow control to each shaft, as necessary. A flow monitoring device was used to meter the grout take as it was injected.

Once the wall was complete, it was allowed to cure before the interior face was excavated to the steel beams and the bracing was installed. Figure 7 shows the texture of the excavated soil-cement wall and the soldier piles.

Monitoring Results

Contract documents required the contractor to establish a monitoring system to observe the behavior of the excavation support system. This monitoring system included inclinometers and settlement points along the sides of the excavation and tape extensometer measurements across the excavation.

Data from the six inclinometers installed between the back of the DSM wall and the mansions were consistent and showed maximum horizontal movements ranging from about 5.6 to 6.9 millimeters (0.22 to 0.27 inches). Figure 8 shows a representative deflection profile from inclinometer measurements.

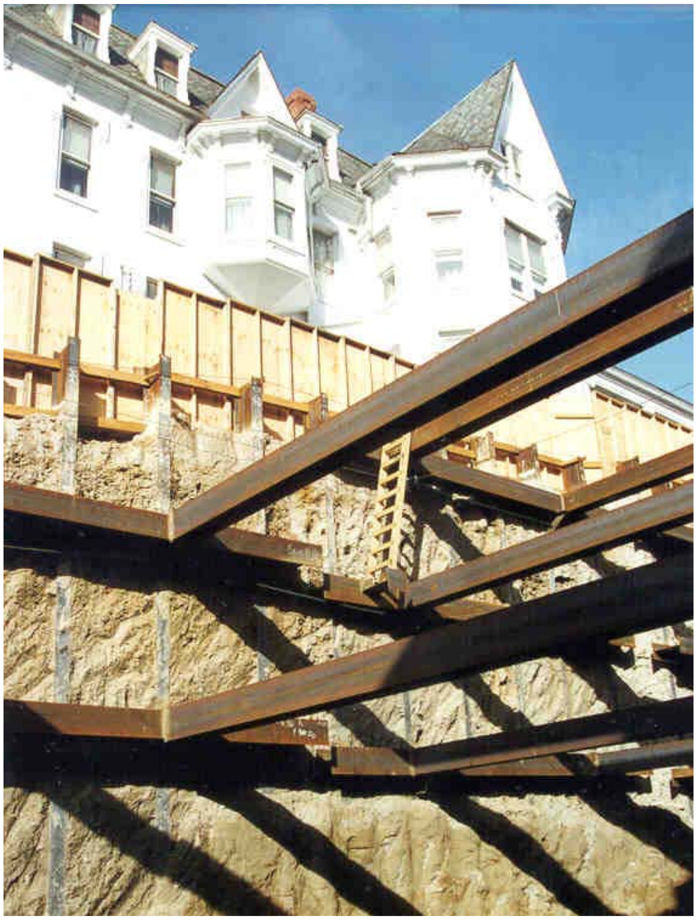

Figure 7. Deep Soil Mix Wall

Of the three instrumentation techniques employed, the inclinometers yield the most accurate and precise data. O'Rourke (1976) compared vertical and horizontal ground movements with distance from the edge of the excavation. For locales close to the excavation, O'Rourke's data show the ratio of horizontal to vertical deflections approximating 0.7. Using that relationship on the data from this project, the settlement is estimated to be about 10 millimeters (0.4 inches) for a horizontal deflection of 6.9

millimeters (0.27 inches). Settlement of 10 millimeters (0.4 inches) relates to 0.1 percent of the excavation height; the lower bound of O'Rourke's (1989) data.

A feature of the inclinometer data is the shape of the lateral deflection/depth plots. The location of maximum deflection ranged from 3.7 to 8.5 meters (12 to 28 feet) from the top of the excavation. The shape of the lateral deflection/depth plots has a very shallow curvature and one point of maximum deflection.

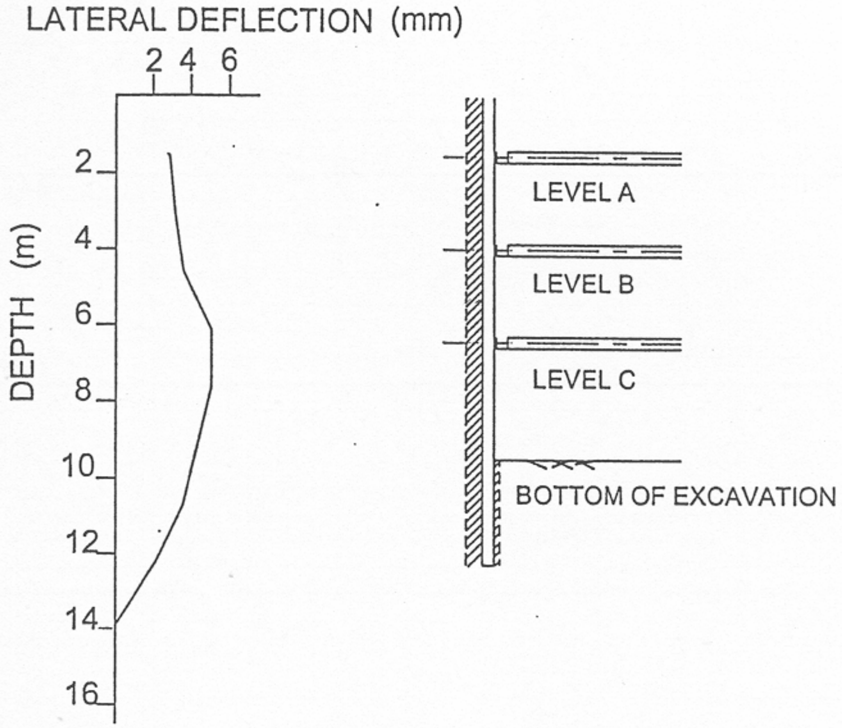

Figure 8. Lateral Deflections with Depth

This shape differs from a soldier pile or a sheet pile wall where the depths of the bracing can often be identified. This suggests that the DSM wall behaves as a rigid support wall, similar to a diaphragm wall.

Summary and Conclusions

This paper presents some of the considerations related to the design of a DSM wall for excavation support. It also presents a description of the techniques used to construct the DSM wall.

The instrumentation data demonstrate that the excavation support system succeeded in limiting ground movements and protecting the adjacent mansions during construction. The project demonstrates the viability of DSM as a technique for constructing an excavation support wall where limiting ground movements is a project objective. Ground movements were restricted to the minimum amount observed in case studies reported by others.

The project demonstrates the importance of good construction control and development of a proper construction sequence in controlling construction induced deformations. It is believed that data points representing the minimum extent of the range of observed behavior can be attributed to construction practice rather than adaptation of an optimal system stiffness based solely on studies of soil-structure interaction.

Acknowledgements

The Pennsylvania Department of Transportation and its designer, Gannett Fleming, contributed to the excavation support system design and construction. The authors acknowledge their contribution to the success of the project. G.A. & F.C. Wagman constructed the underpass and collected the instrumentation data discussed herein. The authors thank it for the opportunity to participate in this project.

References

Clough, G. Wayne and O'Rourke, Thomas D. (1990) "Construction Induced Movements of Insitu Walls," *Design and Performance of Earth Retaining Structures, Geotechnical Special Publication No. 25,* ASCE, 439-470.

O'Rourke, T. D., Cording, E. J. and Boscardin, M. (1976) the Ground Movements Related to Braced Excavation and Their Influence on Adjacent Buildings," Report No. DOT-TST 76T-23 for the U.S. Department of Transportation.

O'Rourke, T. D. (1989) "Predicting Displacements of Lateral Support Systems," *Design, Construction and Performance of Deep Excavations in Urban Areas, Proceedings of the 1989 Seminar,* Boston Society of Civil Engineers.

Peck, R. B. (1969) "State of the Art Report, Deep Excavations and Tunneling in Soft Ground," *Seventh International Conference on Soil Mechanics and Foundation Engineering,* Mexico City, Mexico.

Terzaghi, Karl and Peck, Ralph B. (1967) *Soil Mechanics in Engineering Practice,* John Wiley and Sons, Inc., New York, NY.