Hybrid Cutter Soil Mixing Shoring System for a Deep Temporary Excavation in Vancouver, British Columbia

Marina S.W. Li, M.Eng., P.Eng.
Isherwood Associates, Burnaby, BC.

Nadir Ansari, M.E.Sc., P.Eng.
Isherwood Associates, Mississauga, ON.

Brian W. Wilson, B.Sc., P.Eng.
Vice President, Pacific Ground Engineering, Burnaby, BC.

ABSTRACT A hybrid shoring system consisting of cast-in-place king piles with Cutter Soil Mixing (CSM) infill panels was designed and constructed for temporary support of a 19.8 m deep excavation in downtown Vancouver. This temporary excavation is located adjacent to the Cambie Street Bridge off-Ramp with the shoring design required to meet a performance criteria of 20 mm of total lateral displacements. Deep mixing (DM) was completed to a depth of 9.7 m through fill, organic material, wood waste, and overburden consisting of clayey silt to sandy silt, and embedding into dense clayey silt to sandy silt till with the cast-in-place king piles constructed through the dense till extending to below final excavation level. Shotcrete lagging was used to control erosion between the king piles through the till. Two trial CSM panels were installed ahead of production to assist with finalizing the shoring design as well as developing the termination criteria of the CSM panels in the dense till. The constructed depth of the CSM panels was based on interpretation of real-time monitoring data. Inclinometer monitoring data from three CSM panels and two king piles, as well as king pile target survey data was used to assess and monitor the performance of the hybrid shoring system throughout bulk excavation. This paper provides an overview of the design and construction aspects of the hybrid shoring system using the CSM technique, specifically the performance-based shoring design approach; construction challenges encountered during installation of CSM panels through the variable fill containing wood debris and man-made obstructions; and the use of inclinometer and pile target survey monitoring data to assist with fine-tuning of the design. This paper also discusses the results and value of anchor testing, and the merits of using real-time monitoring data as part of the engineering decision-making process for validating CSM panel construction.

Introduction

A hybrid DM shoring design was recently completed for a high-rise development in Downtown Vancouver for temporary support of a five level basement excavation to depths of approximately 18.5 m (south portion) to 19.8 m (north portion). Deep mixing was proposed by the excavation and shoring design-build team as the preferred method to construct infill panels between king piles because of the speed and reduced cost at which the shoring system could be installed in the variable fill, organic material, wood waste and overburden, while meeting tight shoring performance requirements.

Project Information

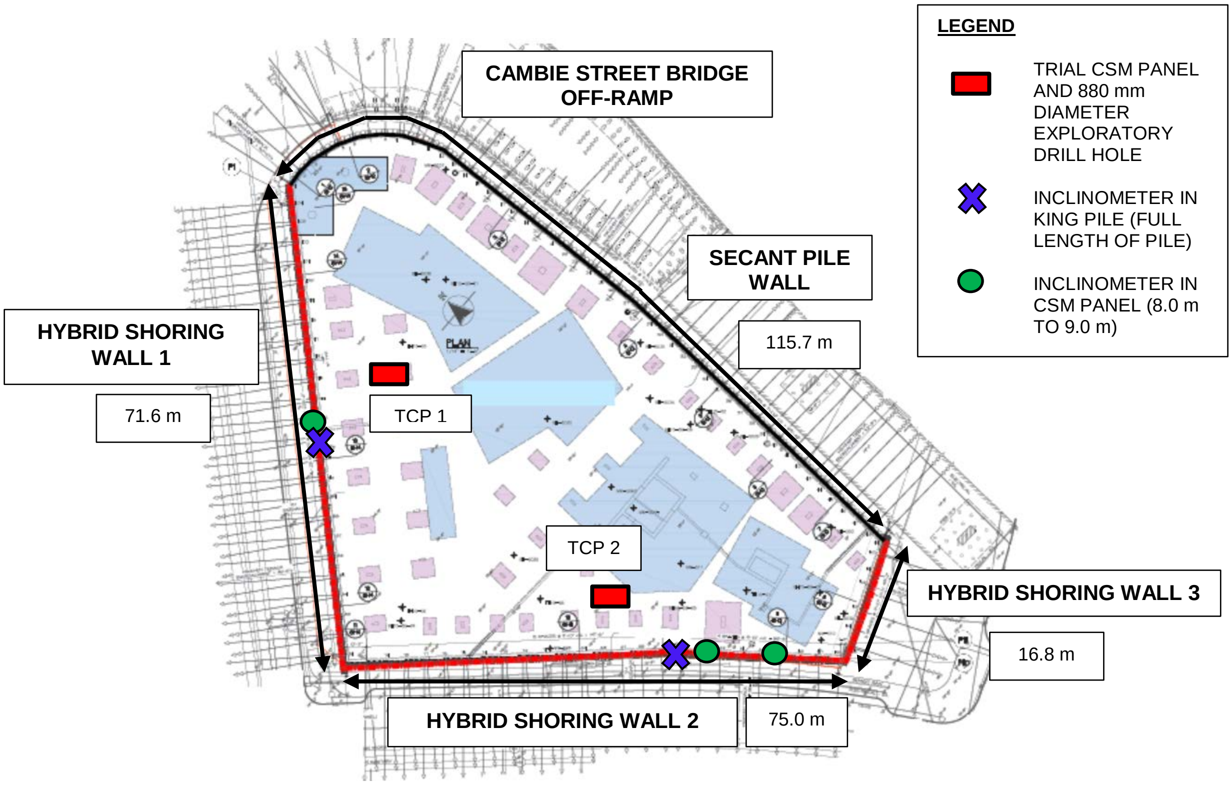
The development site is generally a truncated triangle in plan, with the longest side of the triangle, being approximately 115.7 m long and the two shorter sides, being approximately 71.6 m (Hybrid Shoring Wall 1) to 75.0 m (Hybrid Shoring Wall 2) long. The truncated section is approximately 16.8 m (Hybrid Shoring Wall 3) long. The site is bounded by the existing Cambie Street Bridge Off-Ramp along its longest side, and by city streets on the other two sides, as shown in Fig. 1. Due to project constraints, the hybrid DM and king pile shoring system was only proposed for the two shorter sides of the triangle and the truncated section. Traditional secant piles were installed for the longest side. This paper focusses on the hybrid shoring system.

A total of 57 No. CSM panels, approximately 2.8 m long by 1.0 m wide were installed as part of the hybrid shoring system with depths ranging from approximately 6.1 m to 9.7 m. The CSM panels were generally installed to achieve a 0.5 m to 1.0 m embedment in dense till with a target design strength of 2.0 MPa at 56 days. The king piles supporting the CSM infill panels were 880 mm diameter piles, between 18.6 m and 23.9 m long and situated at approximately 3.0 m centres reinforced with W610X101 to W610X113 steel beams in 8.0 MPa strength concrete. The king piles extended through the dense till to between 3.5 m and 4.0 m below the ultimate base of excavation, with reinforced shotcrete serving as lagging between piles below the base of the CSM panels.

Subsurface Conditions

The site is situated in Downtown Vancouver, adjacent to the existing Cambie Street Bridge Off-Ramp, approximately 230 m north of False Creek. Temporary shoring is required along the perimeter of the proposed development for permanent basement structure and shallow foundations construction.

Fig. 1. Site Location Plan showing location of Hybrid Shoring Walls



The ground surface at the site generally slopes from north to south towards False Creek with existing ground elevations ranging from approximately EL. +6.5 m at the north end to approximately EL. +4.2 m at the south end.

Based on various site investigations carried out by others in 1989, 2005 and 2015 for geotechnical and geo-environmental assessments, subsurface conditions at the site consisted of asphalt, overlying coarse to fine grained fill (sand and gravel, silt and sand to clayey silt), overlying wood waste (including sand and organic material), overlying overburden (clayey silt to sand and silt), overlying dense to very dense till (clayey silt till to sandy silt till with interbedded layers of silt). The thickness of the fill and wood waste ranged from approximately 1.5 m to 6.4 m and approximately 0.3 m to 5.0 m, respectively. Along the perimeter of the proposed development, the top of till was encountered from approximately 7.4 m to 8.5 m below existing ground.

Based on the site investigation data, perched groundwater was recorded in the fill, wood waste and overburden, with seepages noted within the interbedded layers of silt in the underlying till.

Design Philosophy

A performance-based approach was implemented for the design of the temporary hybrid shoring system. As part of the design approach, inclinometers were installed at the location of two king piles and three CSM panels to monitor and assess the lateral displacement response of the hybrid shoring system as bulk excavation progresses. King pile target survey data was also collected to verify the overall performance of the shoring walls. Adopting the "Observational Method", the performance of the hybrid shoring walls were monitored using inclinometer and target survey data such that refinements to the shoring design could be made in order to meet project-specific performance requirement of 20 mm of total lateral displacements. Throughout the deep mixing, piling and anchor installation process, a project-specific Quality Assurance/Quality Control (QA/QC) program was implemented, which enabled timely review of data for design verification and construction refinement.

Hybrid Shoring Design Summary

Shoring Design Parameters

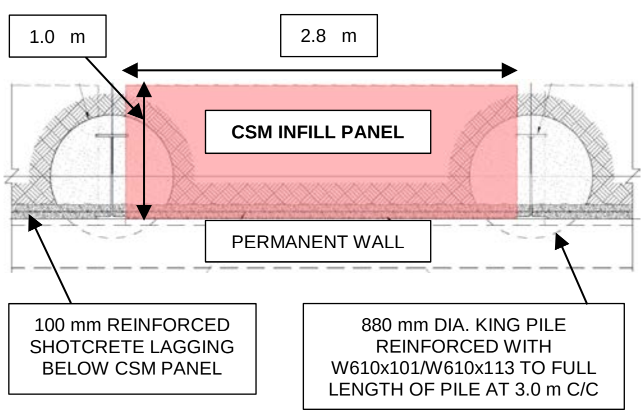
The temporary shoring design for the portions of the site where the hybrid system was implemented was based on meeting the project-specific performance requirement of achieving less than 20 mm of lateral displacements to minimize the impact on buried utilities along the perimeter of the proposed shoring. Factors taken into consideration for shoring design included the lateral earth pressures from the fill and native soils; groundwater pressures; temporary construction loads (e.g. due to crane or heavy plant/equipment placed within the zone of influence of the shoring system); and permanent structural requirements, i.e., final footing elevations and slab elevations of the basement structure. Table 1 presents a summary of the key parameters considered for temporary shoring design.

Table 1. Summary of Parameters considered for Temporary Hybrid Shoring Design

Parameters	Design Value
Unit Weight, γ : • Fill / Wood Waste/Overburden • Till	 • 19.5 kN/m^3 • 21.0 kN/m^3
Active Pressure Coefficient, k_a for: • Fill/Wood Waste/Overburden • Till • At existing structures	 • 0.42 • 0.30 • 0.45
Passive Pressure Coefficient, k_p for till	3.5
Temporary Surcharge, q	12 kPa
Groundwater Conditions in Fill/Wood Waste/Overburden	Perched, from approximately 2.0 m below existing ground.

Considering the physical dimensions of CSM panels and the inherent potential for "arching" within the dense till, the king piles were designed to be situated at intervals of approximately 3.0 m with the CSM panels acting as infill panels, as shown in Fig. 2.

Fig. 2. Typical detail CSM infill panel with king piles



Hybrid Shoring Wall

CSM panels, approximately 2.8 m long by 1.0 m wide were initially installed between the proposed locations of the 880 mm diameter king piles as part of the hybrid shoring system, with the piles installed following initial curing of the CSM panels to ensure intimate connections. The CSM panels were generally installed to depths ranging from approximately 6.1 m to 9.7 m, with an average depth of 9.0 m to penetrate through the weathered portion of the till and achieve a 0.5 m to 1.0 m embedment in dense till. The CSM panels between the king piles were designed to provide lateral support for the upper 7.0 m to 8.5 m of weak fill and overburden soils, where the inherent "arching effect" is likely to be very small. In the competent, dense till, a 100 mm layer of 35 MPa shotcrete reinforced with a single layer of welded wire mesh was proposed to limit erosion and confine the native soils between the king piles. A target strength of 2.0 MPa for the CSM infill panels was designed based on the geometry of the CSM panels; spacing of the king piles; and the estimated lateral load required to be supported.

The king piles were designed based on the bending moments due to the assumed lateral loading and considering three levels of tie-back anchor supports. King piles assumed a "composite reinforced concrete section" comprised of 880 mm diameter concrete piles with target strength of 8.0 MPa, reinforced with W610X101 or W610X113 steel beams. The king piles were installed to depths of approximately 18.6 m and 23.9 m below existing ground with a minimum 3.5 m to 4.0 m embedment below the ultimate base of excavation.

Tie-Back Anchors

Tie-back anchor supports were designed based on a 3.0 m spacing such that the anchors could be installed adjacent to the king piles. Based on the assumed lateral loads and the required performance of the hybrid shoring wall, design loads of between 845 kN to 1,045 kN per anchor were required. Considering the subsurface conditions, these anchors were designed assuming 150 mm diameter reinforced grout columns with bond lengths of between 10.7 m and 13.4 m in dense to very dense till, at 25 to 40 degrees from horizontal. A typical hybrid shoring section is presented in Fig. 3.

Hybrid Shoring Construction Summary

Trial CSM Panels

The construction sequence of the hybrid DM shoring system comprised installing CSM panels at approximately 3.0 m centre-to-centre spacing, followed by installing the 880 mm diameter king piles. This would ensure intimate contact between the CSM panels and the king piles.

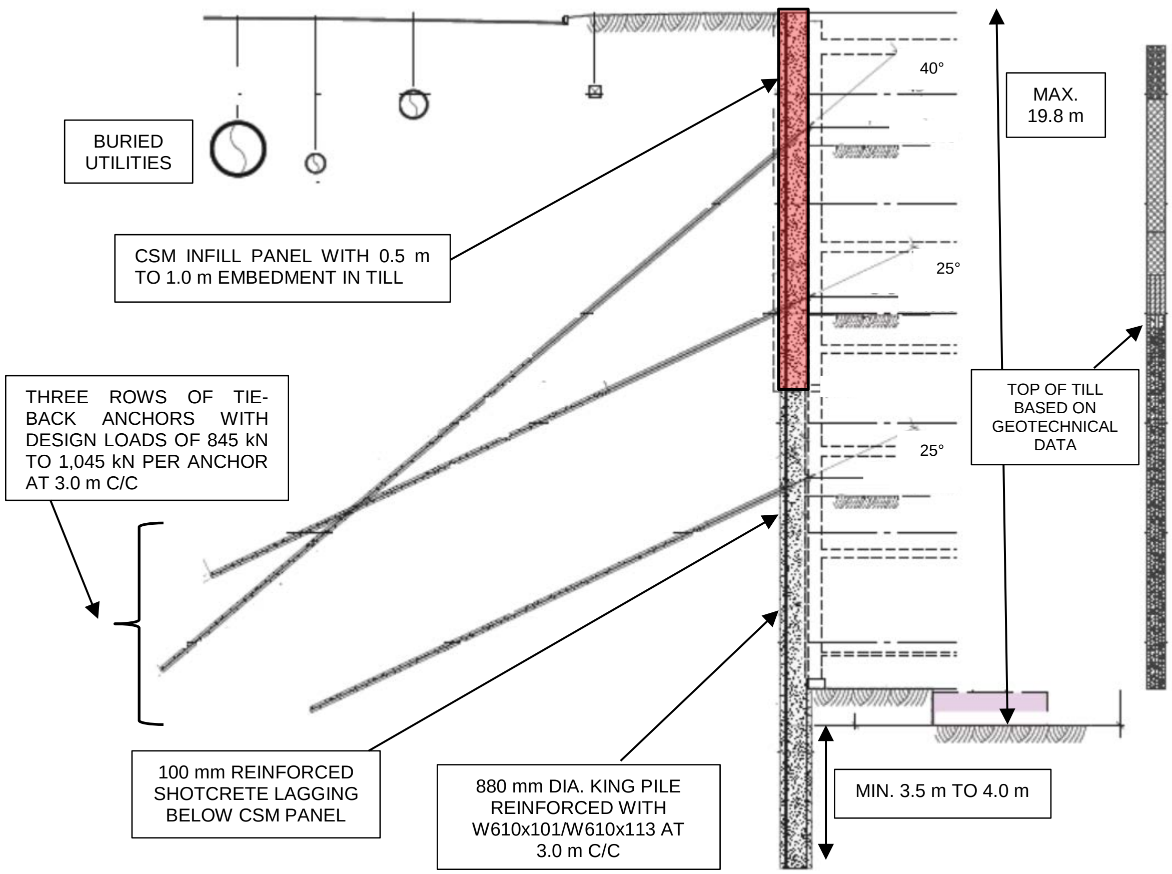
Ahead of the production work, a trial CSM program consisting of two trial CSM panels installed in close proximity to two large diameter holes was implemented. The large diameter holes were used to initially verify subsurface conditions indicated from the available existing geotechnical data, and to establish termination criteria of the CSM panels in dense till. The location of the trial CSM panels and supporting large diameter exploratory drill holes are shown in Fig. 1. Real-time monitoring using the Bauer B-tronic system (Bauer) was carried out during installation of the trial CSM panels.

Following installation, in-situ wet grab samples were recovered from the centre and mid-point of the trial CSM panels and cylinder samples prepared for Unconfined Compression Strength (UCS) testing. UCS testing was carried out at 4, 7 and 28 days to confirm strength and strength gain rates that would meet project performance requirements relative to the construction schedule.

Production CSM Panels

During production work, pre-trenching was generally carried out within the upper 2.0 m to 3.0 m to verify the proximity of adjacent buried utilities and/or permit the removal of shallow obstructions (concrete waste, boulder, wood logs, etc.). CSM panels were typically constructed with water or cement-slurry as the cutting agent, with the target cement-slurry injected on mixing out of the panels. At least one

Fig. 3. Typical Hybrid Shoring Section



complete restroke of the cutter head was carried out for the full depth of the panel to promote homogeneous mixing throughout the organic material and wood waste layers. Real-time monitoring was carried out during installation of all production CSM panels. Following deep mixing, wet grab samples were taken from representative CSM panels, typically at two depths (i.e., at mid-point and towards the bottom 1.5 m of a CSM panel) for UCS testing of the soil-cement samples. Wet grab samples were taken from a total of 23% of production CSM panels, consistent with published guidelines (Bruce et al., 2013) and these samples were cured on site for a minimum of 7 days prior to transportation to an off-site facility for continued curing and/or testing. A total of 28 No. sets of samples were taken for UCS testing with strain gauge measurement. Tests were generally completed at 14, 28 and 56 days to confirm that the target strength of 2.0 MPa at 56 days (and greater) had been achieved prior to bulk excavation adjacent to the hybrid shoring system. Selected additional UCS testing was carried out beyond 56 days to demonstrate the long-term strength gain. The representative UCS data are presented in Fig. 4.

Production King Piles

King piles were installed using temporary segmental casings in the fill, overburden and weathered till layers, where groundwater seepages were observed. Localized drilling using a core barrel was required when man-made obstructions e.g., large concrete mass, and boulders were encountered. Concrete sampling and strength testing was carried out periodically as part of the QA/QC program.

The groundwater conditions in the underlying till were monitored during bulk excavation using nested vibrating wire piezometers installed at approximately 11.0 m, 16.0 m and 19.0 m below existing ground. During bulk excavation groundwater seepage was observed at the interface between fill, wood waste, overburden and till. Significant groundwater seepage was not observed during bulk excavation and detailed excavation for shallow foundations.

Tie-Back Anchors

Following completion of the CSM panel installation and secant piling, bulk excavation was carried out in stages to install three levels of tie-back anchors. A total of seven performance tests were carried out on selected, representative tie-back anchors ahead of production work. The design adhesion value of 80 kN/m to 90 kN/m for typical 150 mm diameter reinforced grout columns in dense to very dense till was verified and factors of safety of between 1.5 and 2.2 were achieved. Fig. 5 shows the performance test results for a production anchor installed along Row 2 of Hybrid Shoring Wall 2, where a design adhesion value of 85 kN/m was achieved with a factor of safety of 2. Following performance testing of selected anchors along a row of the hybrid wall, production anchors were installed consistent with the performance test anchors.

All remaining production anchors were proof tested to 133% of the design load (i.e., between 860 kN and 1,390 kN), generally in accordance with industry guidelines (Post-Tensioning Institute, 2006), prior to being locked off. Lift-off tests were carried out on approximately 5% of representative production anchors to verify performance of

Fig. 4. Unconfined Compressive Strength Test Results versus Cure Time Plot

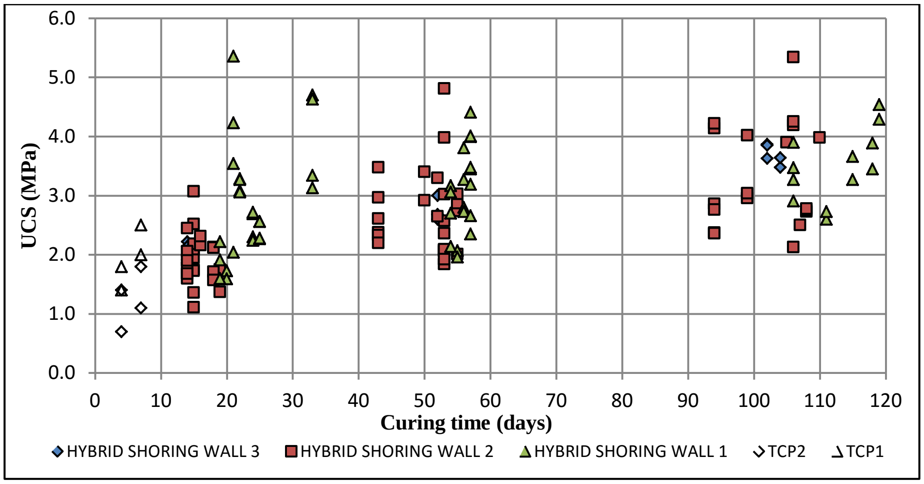
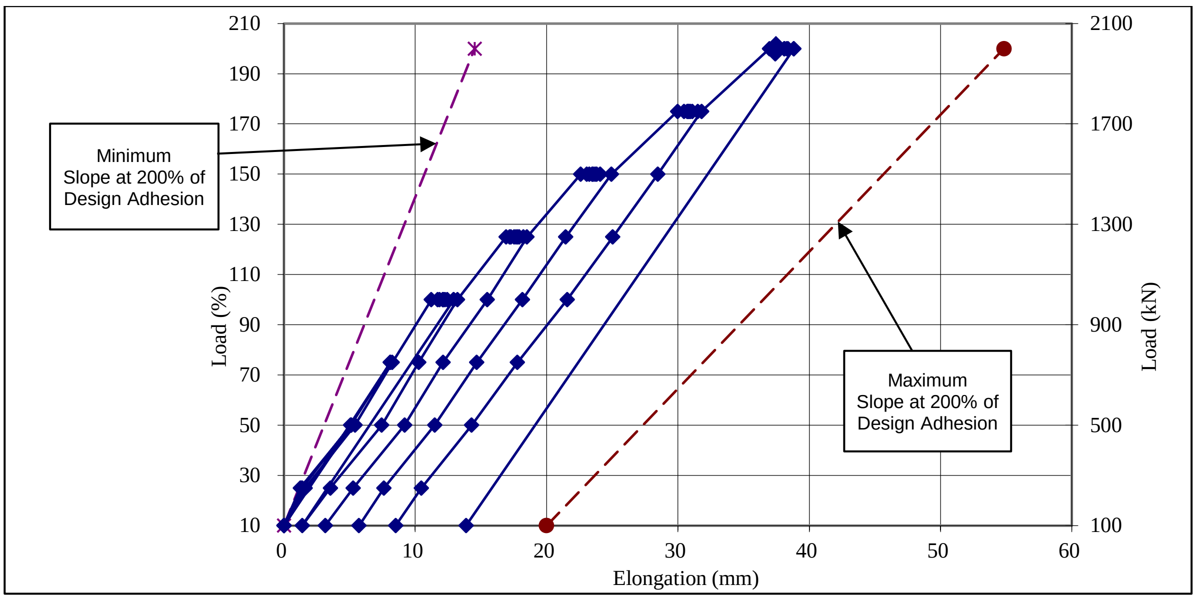


Fig. 5. Performance Test Results for Representative Anchor Along Hybrid Shoring Wall 2



anchors after locking-off generally between three and seven days. Field reviews were regularly carried out during anchor testing, as well as timely reviews of anchor installation and test records to verify consistency of the inferred subsurface conditions and performance of the anchors.

Instrumentation

Inclinometer casings were installed in three CSM panels as well as two king piles for shoring performance assessment. The inclinometer casings were vibrated into the centre of the CSM panel to within approximately 1 m of the bottom of the panel. For the king piles, inclinometer casings were attached to the full length of the steel reinforcements and lowered into the drill holes, prior to concreting.

Throughout the bulk excavation and anchor installation process, inclinometer monitoring combined with king pile target survey monitoring was carried out to assess performance of the hybrid shoring walls. Reflective pile targets were installed within the upper 0.3 m to 0.5 m of all king piles and baseline readings were taken prior to the start of the bulk excavation.

At the time of this paper, bulk excavation had been completed for the northern half of the site with two-thirds of the excavation completed for the southern half of the site. The inclinometer and target survey data presented in this paper is for Hybrid Shoring Wall 1, where excavation had been completed to ultimate base of excavation.

CSM Real Time Monitoring

CSM Parameters

As previously discussed, two trial CSM panels were installed in close proximity to two large diameter exploratory drill holes to initially verify subsurface conditions, and to establish termination criteria of the CSM panels in dense till. The constructed depths of the trial CSM panels were based on interpretation of real-time monitoring data and the knowledge of the actual depth to till identified by the large diameter exploratory drill holes.

The parameters considered for assessment included Rate of Penetration (ROP), pressures at the cutter wheels (pressure), and rotational speed of the cutter wheels (rotational speed), which were compared with available Standard Penetration Tests (SPT) N values from existing geotechnical investigations carried out prior to construction. Consistent trends were observed when comparing all three parameters i.e., ROP, pressures and rotational speed with SPT N values. Consistently, where dense to very dense till was encountered between approximately 8.0 m and 9.5 m below ground, the ROP reduced significantly, while pressures were markedly increased. Changes in the rotational speed were generally less noticeable when passing through variable soils, compared with ROP and pressures.

Based on the trial CSM real-time monitoring data and geotechnical data, the following termination criteria were established to meet project-specific performance requirements of 0.5 m to 1.0 m embedment into dense to very dense till:

- Rate of Penetration ≤ 20 cm/min;
- Pressures at cutter wheels ≥ 200 bars; and
- Rotational speed of cutter wheels ≤ 20 to 25 rotations/min.

Simplified plots showing selected CSM output real-time monitoring data for a representative panel constructed along Hybrid Shoring Walls 1 and 2 are presented in Figs. 6 and 7, respectively.

Construction Modifications

Modifications were made to the DM termination criteria on a "case-by-case" basis to take into consideration areas where significant obstructions were encountered at depth. These

Fig. 6. Hybrid Shoring Wall 1 typical CSM output parameters compared with SPT N values

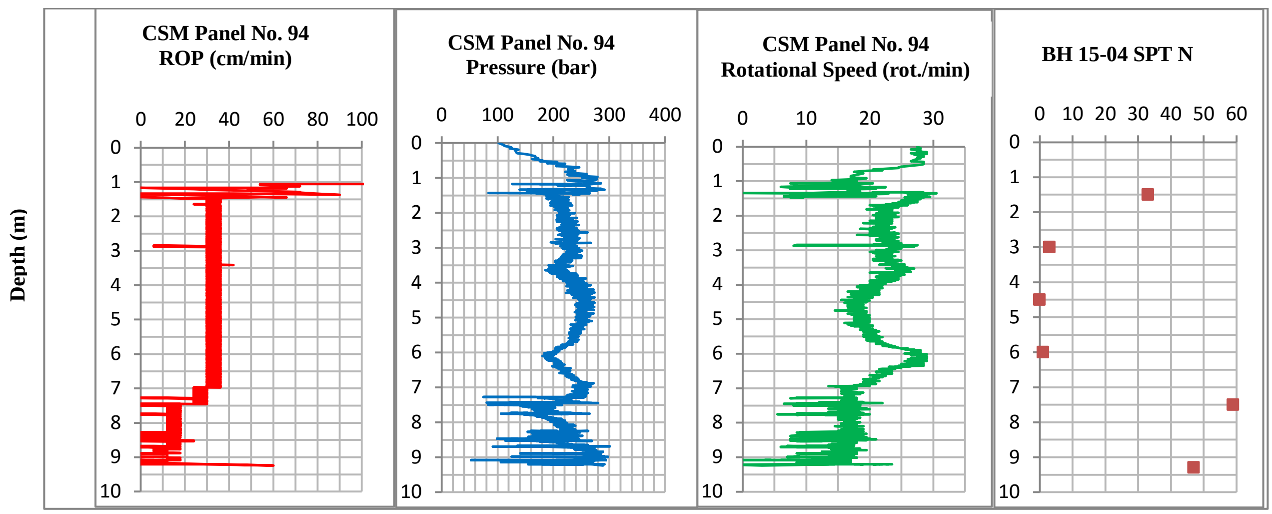
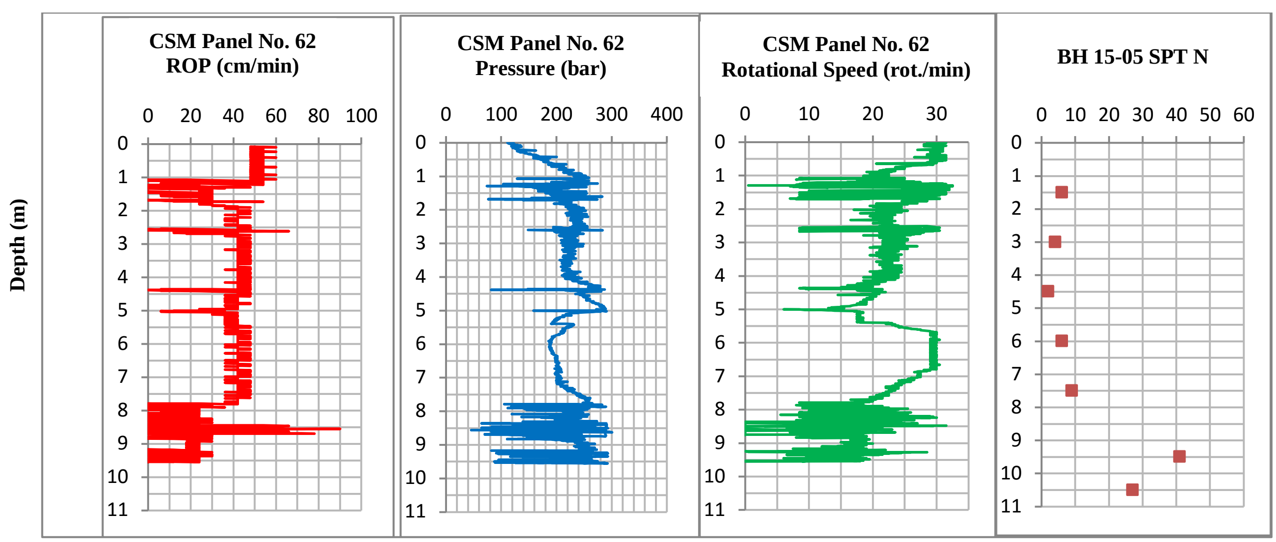


Fig. 7. Hybrid Shoring Wall 2 typical CSM output parameters compared with SPT N values



included buried concrete structures/wood logs in the fill below approximately 4.0 m below ground, and nested cobbles and boulders in the till below approximately 7.5 m below ground, which were beyond the reach of a typical excavator for removal.

Small diameter grout columns (100 mm diameter and typically 9.5 m long) were installed behind CSM panels that terminated above the inferred top of till based on the CSM real-time monitoring data. These grout columns were installed to reduce the potential for significant fines migration and groundwater flow during bulk excavation and shotcrete lagging installation below selected CSM panels.

CSM infill panels were exposed as bulk excavation progressed. Inspection indicated that, generally CSM panels were terminated with an approximate 0.5 m to 1.0 m embedment in dense till, as per design requirements. Fig. 8 presents a portion of Hybrid Shoring Wall 1 exposed to approx. 9.5 m below existing ground with CSM panels fully exposed. Fig. 9 shows welded wire mesh installation in progress in the till, below the CSM panels (impression of cutter wheels left in soil-cement at the top of the dense till).

Fig. 8. Hybrid Shoring Wall 1 exposed during bulk excavation

Fig. 9. Shotcrete lagging installation below CSM panel at Hybrid Shoring Wall 1

Inclinometer Monitoring for Performance Verification

Inclinometer monitoring data from three CSM panels and two king piles, as well as king pile target survey data was used to assess and monitor the performance of the hybrid shoring system throughout bulk excavation. The inclinometers were generally located at the mid-point or at the deepest excavation zone in order to assess the maximum expected movements without "corner effects". Inclinometer readings were taken at intervals of 0.6 m along the length of the CSM panels and along the entire length of the king piles. Pile target survey readings were taken along the top of the hybrid shoring walls at a typical spacing of 3.0 m between targets. Baseline readings of the inclinometers and pile targets were recorded prior to the start of bulk excavation and the frequency at which readings were taken is summarized as follows:

1. Following excavation to the underside of Row 1 tie-back anchors (approx. 3.5 m below ground);
2. After installation and stressing of Row 1 tie-back anchors;
3. Following excavation to the underside of Row 2 tie-back anchors (approx. 6.7 m to 8.9 m below ground);
4. After installation and stressing of Row 2 tie-back anchors;
5. Following excavation to the underside of Row 3 tie-back anchors (approx. 11.3 m to 13.1 m below ground);
6. After installation and stressing of Row 3 tie-back anchors; and
7. Following completion of excavation to final depth (approx. 14.3 m to 19.8 m below ground).

The inclinometer readings and pile target data were compared with expected design performance to assess whether modifications were required to the shoring design and construction to meet project performance requirements of less than 20 mm of lateral displacement of the temporary hybrid shoring walls. The monitoring data indicated an average time-delay response of approximately one week for the hybrid shoring walls in the fill and overburden i.e., additional lateral displacements without further excavation. This was consistent with the expected behaviour of the shoring walls, given the presence of the weak layers of fill, peat, wood waste and clayey silt to sandy silt located within the upper 7.5 m to 9.0 m. Overall, the inclinometer monitoring data obtained during bulk excavation, and as indicated in Figs. 10 and 11, confirmed that performance of the hybrid shoring walls met project performance requirements.

A comparison of the inclinometer monitoring data with the pile target data is presented in Table 2 for Hybrid Shoring Wall 1, indicating good correlation between the two sets of monitoring data.

The inclinometer monitoring data provided a "continuous" profile of the lateral displacements for the full depth of the king pile with excavation. This Information was advantageous in both the monitoring of the hybrid shoring wall performance as well as the assessment of whether design/construction modifications e.g., adjust elevation of tie-back anchors, adjust design load of tie-back anchors, adjust number of tie-back anchors, etc., were necessary to meet project performance requirements. The pile target survey data offered complementary information to supplement areas where increased lateral displacements might be expected e.g., localized over-excavation, changes to surcharge loading etc.

Fig. 10. Inclinometer Readings for Hybrid Shoring Wall 1 – King Pile

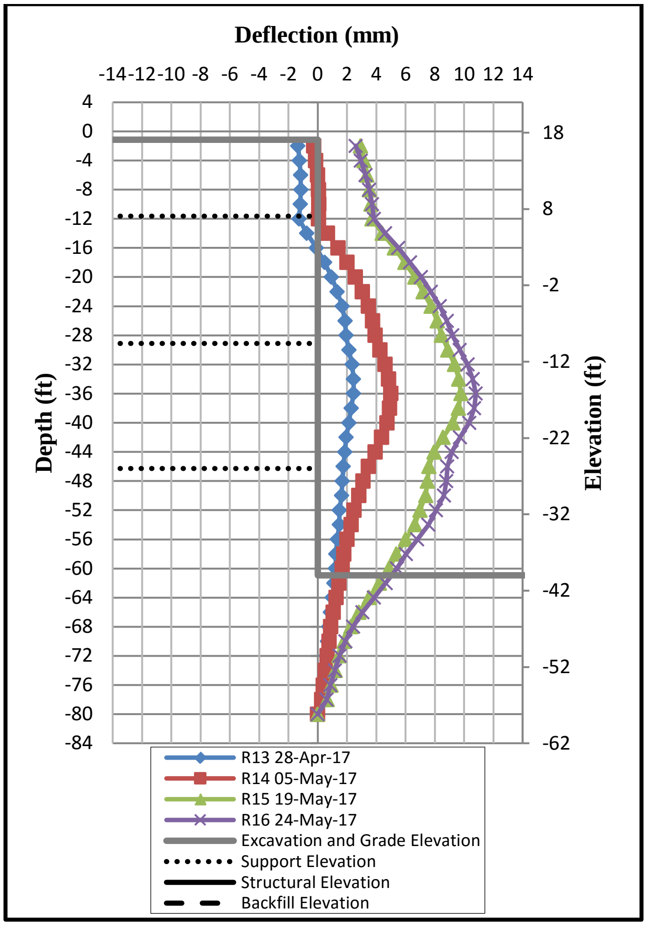


Fig. 11. Inclinometer Readings for Hybrid Shoring Wall 1 – CSM Panel

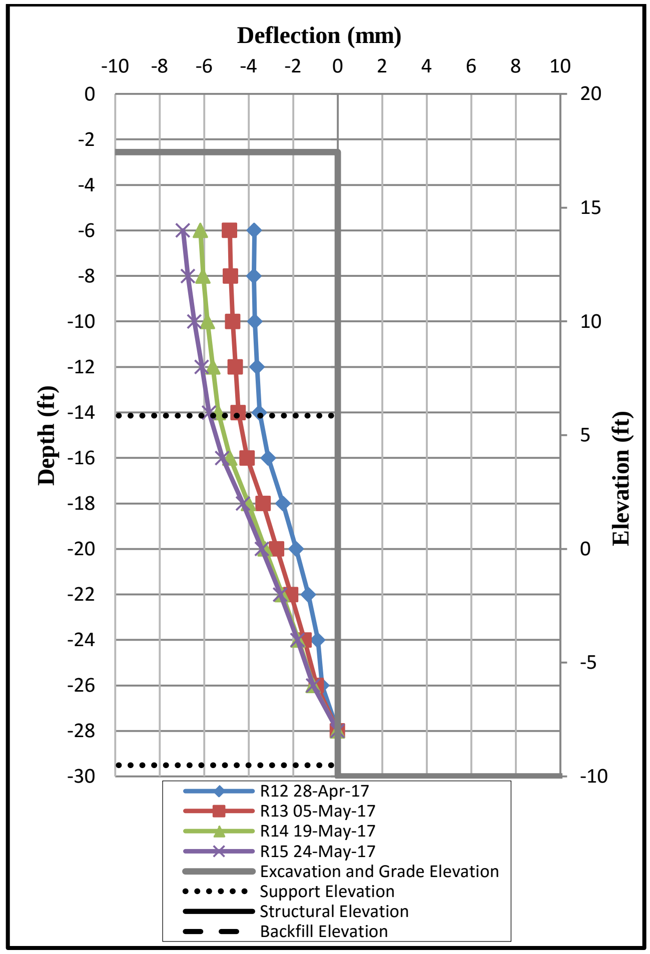


Table 2. Comparison of Inclinometer Monitoring Data with Pile Target Survey Data for Hybrid Shoring Wall 1

Excavation stage	Max. lateral displacements of hybrid shoring wall	
	Secant Pile	Pile Target
Underside of Row 1 anchors	3 mm Into Site	6 mm Into Site
After stressing of Row 1 anchors	1 mm Into Site	2 mm Out of Site
Underside of Row 2 anchors	2 mm Out of Site	4 mm Out of Site
After stressing of Row 2 anchors	3 mm Out of Site	1 mm Out of Site
Underside of Row 3 anchors	5 mm Into Site	3 mm Into Site
After stressing of Row 3 anchors	10 mm Into Site	No readings taken
After completion of excavation	11 mm Into Site	7 mm Into Site

Real-Time Monitoring for Construction Modifications

Based on the real-time monitoring data obtained during the trial, and the comparison of this to the available geotechnical data, associated "signature" ROPs, pressures at the cutter wheels, and rotational speeds for the site-specific subsurface conditions were determined. These "signatures" were then used to guide installation of production CSM panels in similar subsurface conditions, allowing panels to be terminated based on "inferred" conditions rather than a target elevation based on extrapolated geotechnical borehole data.

The real-time monitoring data was also used to identify areas where subsurface conditions could potentially be anomalous and hence where increased wet grab sampling would be beneficial for QA/QC e.g., areas where significant low pressures combined with high ROP and high rotational speed were observed. This allowed for real-time adjustment of the standard operating procedure and included restroking of the cutter head through specific layers such as wood waste or organic soils to promote homogeneous mixing, as well as increased pressures and reduced amount of slurry delivery on encountering obstructions. Cement-slurry was generally used as a cutting agent during mixing in peat, clayey silt and till, whilst water was the preferred cutting agent when mixing through fill, wood waste and obstructions.

Conclusion

Close collaboration within the design-build team enabled timely review of the subsurface conditions encountered during CSM panel and king pile construction, as well as monitoring performance of the hybrid shoring system during staged bulk excavation ensuring project-specific performance requirements were met.

For performance-based design of temporary shoring structures, anchor testing, and inclinometer monitoring combined with pile target survey monitoring enabled the design and construction team to continually monitor and assess shoring wall performance, as well as making timely decisions for modifications to the design and/or construction to meet project performance requirements. The hybrid DM shoring wall constructed in variable subsurface conditions proved to be successful in terms of shoring wall performance, as well as construction scheduling because of the speed and reduced cost at which the shoring system could be constructed in variable fill, organic material, wood waste and overburden compared with traditional secant piling methods.

The B-tronic data provided by the CSM equipment can be used to interpret subsurface conditions in real time particularly when variable subsurface conditions such as fill containing obstructions and soft and loose overburden is encountered overlying dense to very dense soils. Further work is recommended such that interpretation of the real-time monitoring data could be simplified.

Acknowledgements

The authors wish to acknowledge the input from a large team of people who contributed to the success of this project, including the Design-Build project team from Isherwood Associates and Pacific Ground Engineering (including Mr. Jakub Hudler, Mr. Matthew Janes, Mr. Edward Kolakowski, Ms. Jennifer Johnston and Mr. Jim Coull), the Owner, his construction management team and his engineering team, which included Thurber Engineering Ltd.

References

BAUER Maschinen GmbH., 2016. CSM Cutter Soil Mixing Process and equipment, Document No. 905.656.2.

Bruce, M.E.C., Berg, R.R., Collin, J.G., Filz, G.M., Terashi, M. and Yang D.S., 2013. Federal Highway Administration Design Manual: Deep Mixing for Embankment and Foundation Support. Publication No. FHWA-HRT-13-046.

Post-Tensioning Institute, Post-Tensioning Manual, 6th edition, 2006.