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Challenging Design of a Strutted Sheet Pile Shaft for the Highway 401 and 409 Rail Tunnels, Metrolinx Project

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ABSTRACT
A deep strutted sheet pile shaft (26m x 10m x 9.8m) was designed to facilitate the construction of support pipe canopy required for tunnel construction in the soft ground between the Highway 409 eastbound ramp and Highway 401 eastbound express lanes. The unbalanced loading on the shaft has been considered due to the grade difference between the Highway 409 ramp and Highway 401 eastbound lanes. The presence of the existing rail tunnel adjacent to the shaft excavation and existing skew of the rail tunnel relative to the Highway resulted in unique design challenges. This paper will provide a comprehensive overview of the challenges encountered during detailed design, analysis techniques adopted, and a summary of the settlement profile observed on the ground surface around the shaft.

RÉSUMÉ
Un puits de palplanche blindé (26 mx 10 mx 9,8 m) a été conçu pour faciliter la construction de toit-abris en tuyaux requis pour la construction de tunnels en sol meuble entre la bretelle en direction est de l'autoroute 409 et les voies express en direction est de l'autoroute 401. Les charges mal équilibrées sur le puits ont été prises en compte en raison de la différence de niveau entre la bretelle de l'autoroute 409 et les voies en direction est de l'autoroute 401. La présence du tunnel ferroviaire existant adjacent à l'excavation du puits et le biais existant du tunnel ferroviaire par rapport à l'autoroute ont entraîné des défis de conception uniques. Cet article fournira un aperçu complet des défis rencontrés lors de la conception détaillée, des techniques d'analyse adoptées et un résumé du profil de tassement observé à la surface du sol autour du puits.

1 INTRODUCTION

As a part of GO Expansion, Metrolinx will provide faster, more frequent, and more convenient GO rail service across the Greater Toronto and Hamilton Area. Two new rail tunnels are being constructed adjacent to the existing rail tunnel crossing below the Highway 401 & 409 interchange consisting of 21 live vehicular lanes. The new tunnels will increase the capacity of the Kitchener Corridor and allow for two additional tracks in the future, supporting two-way, all-day rail service.

A key part of the project was the installation of a shaft structure near the middle of the Highway in a narrow median space between live traffic lanes. This paper focuses on the design and construction of this 26m long, 10m wide and 9.8m deep strutted sheet pile shaft structure.

2 PROJECT OVERVIEW

The Highway 401 and 409 Rail Tunnels project is being constructed by Toronto Tunnel Partners (TTP), a joint venture between Strabag Inc. and EllisDon Civil under a design-build-finance contract to Metrolinx and Infrastructure Ontario. The project primarily consists of the construction of two 180m long tunnels with an excavated cross-section of 8.5 m x 10 m. The tunnels are being advanced in soil utilizing the sequential excavation method (SEM). The contract value for the project is $116.9M (CAD). The engineering design team for the project consists of Dr. Sauer & Partners, WSP Canada Inc., and Wood PLC. After project award, R.V. Anderson was added to the team to provide design services to assist with various construction related structures and temporary works, including the shaft design discussed in this paper.

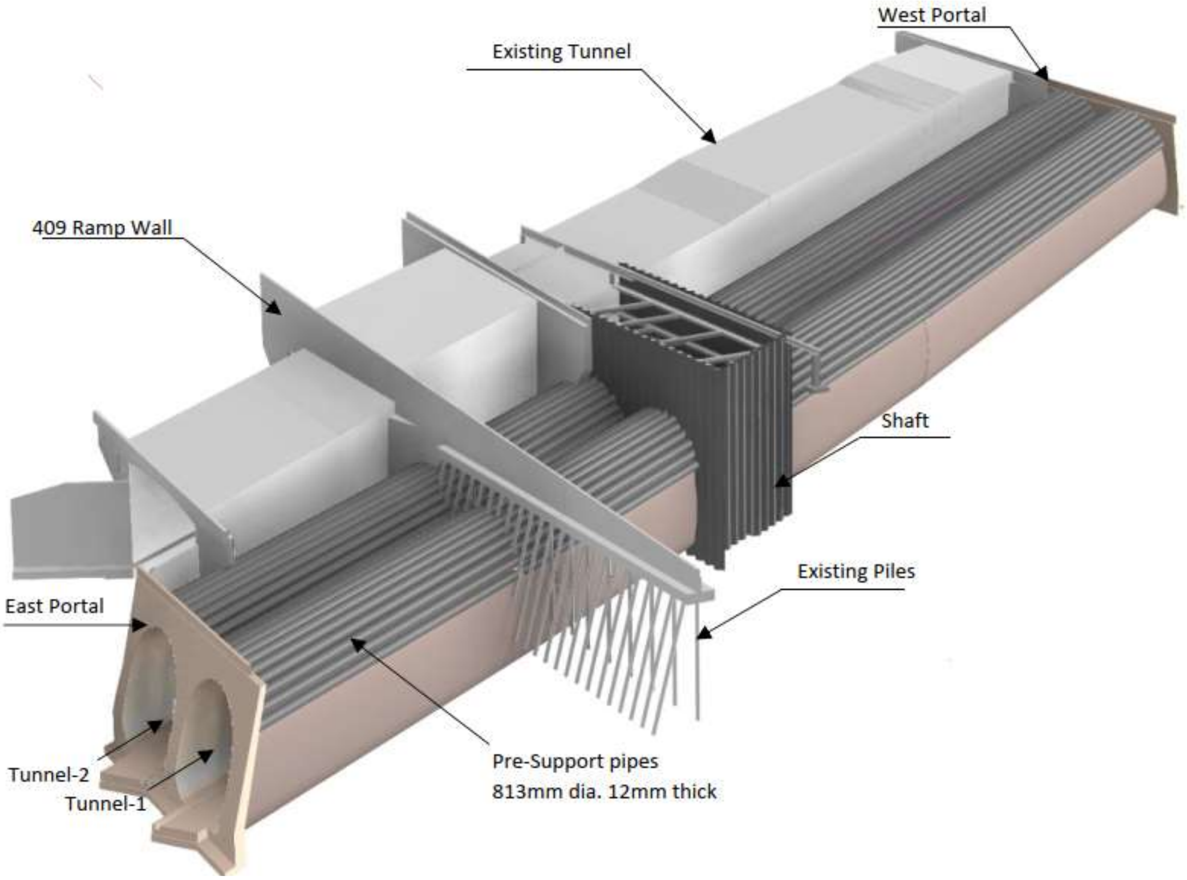

Figure 1: Overview of shaft and tunnel pre-support pipes

2.1 Requirement for intermediate shaft

The design for the SEM tunnel requires pre-support to be installed in the ground prior to tunnel advancement. Early concept designs for the project included two main types of tunnel pre-support. The first type of tunnel pre-support consisted of a series of 813mm diameter steel pipes forming a pipe canopy above the tunnel crown which would be advanced by auger boring in the soil from either side of the Highway. The second type of pre-support consisted of smaller diameter steel pipes installed from within the tunnel excavation by forepoling to create an umbrella arch ahead of the tunnel advancement face.

To mitigate risks of settlement from the forepoling method, the design was changed to utilize the auger-bored pipe canopy for the full length of the tunnel. Due to the length of the auger boring drives from the west side, and obstruction from pile foundations on the east side, a shaft needed to be constructed near the middle of the Highway crossing to allow for the pre-support pipes to be installed in four drives, one drive from each tunnel portal, and two drives from the middle of the Highway. Figure 1 depicts the final arrangement of the tunnel pre-support pipes and the location of the temporary shaft.

2.2 Shaft Geometry

Due to the size requirements for the auger boring machines that were used to advance the pre-support pipes, the shaft needed to maximize the available median space between the Highway 401 eastbound express lanes and the 409 eastbound ramp lanes, with less than 0.5 m between the vehicular barriers and the sheet pile walls of the shaft (Figure 2). The orientation of the rail tunnel to the highway lanes was skewed by about 35 degrees, which complicated nearly every aspect of the design and construction details for the project.

3 SUBSOIL CHARACTERISTICS

The soil at the location of the shaft consisted of clayey silt with sand fills for the top 8 m of depth underlain by a glacial till. The extensive depth of fill was present at the site due to the Highway embankment built up surrounding the existing rail crossing. The glacial till comprised of a heterogeneous mixture of clayey silt, sand, and gravel. The till varies from compact to very dense consistency. The ground water table was observed to be at approximately 152.5m elevation.

The close proximity of the existing rail tunnel also had an influence on the subsoil conditions encountered, as it had sand backfill against the walls that was looser than the surrounding Highway embankment fills.

Table 1. Soil Parameters for Design

Soil	γ [kN/m^3]	c' [kPa]	φ' [°]	E [kPa]	v
Fill- Sand and Gravel	19	0	35	50,000	0.3
Fill- Clayey silt	19	0	28	45,000	0.49
Clayey silt till	21	15	34	225,000	0.49
Sand and silt till	22	0	35	195,000	0.3
Silt till	22	0	36	195,000	0.3

Figure 2: Shaft and Highway 401

4 SHAFT DESIGN

4.1 Loading Key Constraints

The project specification required tight tolerances on allowable settlement to the Highway surface. The cumulative vertical settlement around the work zone, including settlement induced by tunneling, was limited to 25 mm total. To reserve allowable settlement for the tunnel construction, the design targeted a 12 mm settlement limit for the shaft excavation.

The existing rail tunnel is located within 1.5 m of the new rail tunnel which required the excavation of the shaft to expose east side of the existing concrete structure. This exposure of the existing rail tunnel wall created an unbalanced lateral load on the existing structure that needed to be resisted by the temporary shaft.

The existing rail tunnel has an approximately 35-degree skew from the Highway alignment. The Highway 409 ramp is located on the east side of the shaft where the grade is approximately 1.5m higher than the grade on the Highway 401 side. The 409 ramp side also included a wing wall where the ramp crosses the existing rail tunnel which caused an asymmetrical loading on the shaft structure. The design of the temporary shaft had to account for this asymmetrical loading as well as the unbalanced loading from differing soil depths and Highway skew angle, as shown in Figure 3.

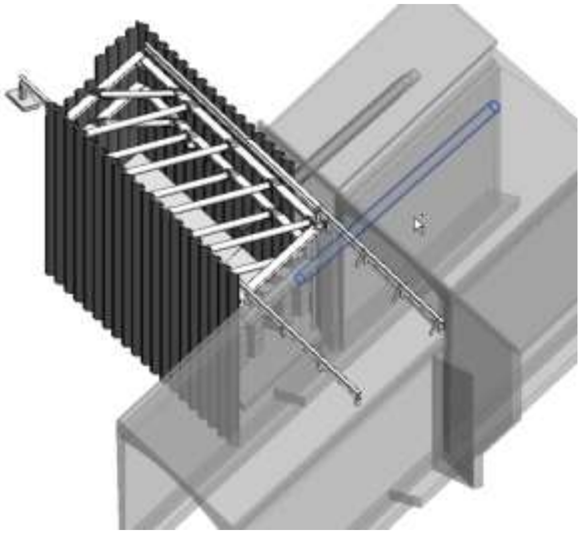

Figure 3: Shaft and existing rail tunnel 3D model

The tunnel pre-support pipes needed to be installed through the wingwall of the Highway 409 ramps. The shaft needed to be designed to prop the wingwall to allow for partial removal during construction to facilitate the pipe installation.

Due to the limited working area at the temporary shaft location, a gantry crane was required to be installed on top of the shaft structure to service the shaft during construction. The running rails of the gantry crane extended over top of the existing rail tunnel to minimize construction traffic loads on this structure. The gantry crane was used to deliver materials to the shaft, remove excavated spoil, and lower the auger boring machines used to install the tunnel pre-support pipes. The shaft walls were designed to resist the vertical loading from the gantry crane.

One of the most unique and challenging aspects of the shaft design was the requirement to install the tunnel pre-support pipes, which require the sheet pile wall to be continually cut along the top of the new tunnel profile. The shaft was designed to allow for the cutting of the wall to facilitate placement of the pipe, then reconnected with special connections to partially restore continuity of the cut sheet pile.

4.2 Loading on the shaft

The fill close to the existing rail tunnel consisted of granular non-cohesive sands transitioning to a more cohesive fill as it gets away from the rail structure. The cohesive fill was found to be soft to firm consistency. The apparent earth pressure distribution (CFEM 2006) in granular soils and soft to firm cohesive soils were compared and granular distribution was used in design as it provided the highest lateral force in the areas that were critical for the strut placement. In addition, the shaft wall on the east side had an approximately 1.5m cantilever due to the higher soil elevation at the 409 ramp. The granular pressure distribution provided a conservative horizontal deflection of shaft near the surface. In addition, due to the stringent settlement requirement of the project, the at rest pressure coefficient was used to design the walers, struts and the sheet pile. The assumed soil pressure distribution is shown in Figure 4.

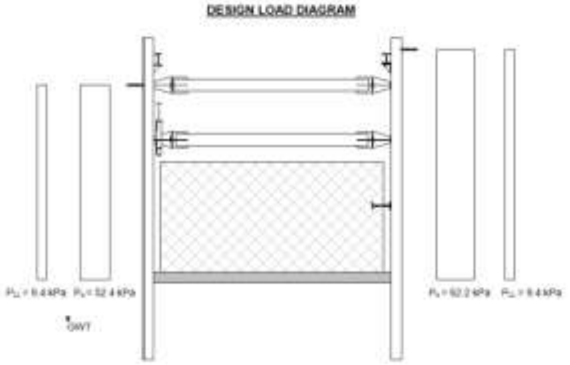

Figure 4: Apparent earth pressure distribution

The live load surcharge on the shaft wall was calculated based on CSA S6-14, *Canadian Highway Bridge Design Code (CHBDC)*. The ground water table was located below the excavated depth of the shaft, so no hydrostatic pressures was applied to the structure walls.

In addition to the soil and traffic loading, the shaft walls were designed to resist a maximum of 200 tonne thrust force from the auger boring operation.

4.3 Base heave and sheet pile embedment depth

The sheet pile was embedded in hard silty clay. The factor of safety against basal heave was calculated based on CFEM 2006 and verified to have a safety factor above 2.

The embedment depth was calculated based on CFEM 2006, assuming free earth support since the ground is clayey in nature and the excavation location had almost 8 m of mixed fill. While considering the overall stability of the anchored system, the moment capacity of the embedded sheet pile is neglected in determining the required embedment depth for the sheet pile. The toes of the piles extended into the existing groundwater table and had to account for effective soil stresses when calculating the required embedment depth.

4.4 Numerical Modelling

The temporary shaft was analyzed using 2-D plane strain finite element program RS2 by Rocscience. The geometry of the model is shown in Figure 5. The materials were assumed to be isotropic. In the initial condition, field and body forces were considered in estimating the lateral force on the sheet pile. Plastic, Mohr-Coulomb material model was used to model the soil behaviour. The material parameters used in the finite element model is tabulated in Table 1. A graded, 6-noded triangular mesh was used to discretize the model. The piezometric line was assumed to be 1.4m below the base of the excavation. The model had multiple phases to depict the shaft construction sequence and are listed below.

1. Initial condition with surcharge pressure from Highway applied on the surface
2. Installation of sheet pile.
3. Excavate 1.2m below the first strut elevation.
4. Installation of the first strut.
5. Excavate 1.2m below the second strut elevation.
6. Installation of the second strut.
7. Excavate 1.2m below the third strut elevation.
8. Installation of the third strut.
9. Excavate to base slab elevation.
10. Installation of bottom slab, which acts as a struct.
11. Removal of third strut.

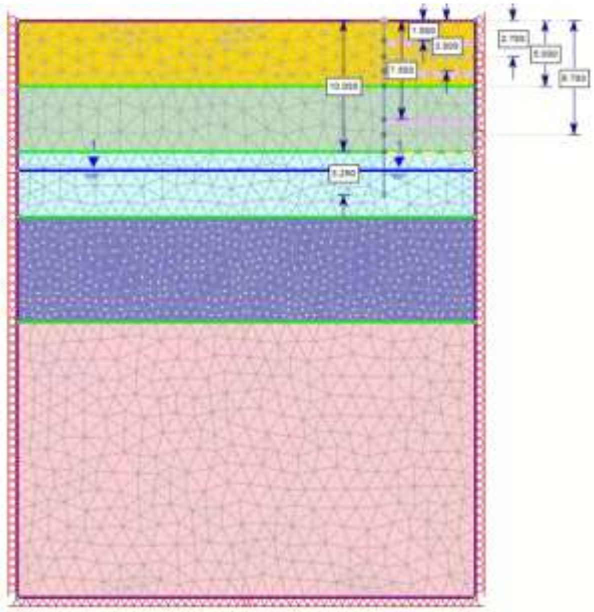

Figure 5: 2D Finite element model

The third level of struts required removal after the base slab was complete because they interfered with the auger boring operation (Figure 12).

The three-dimensional effects of the shaft were captured by analyzing the shaft using SAP2000 finite element software. A 2D finite element model with springs applied on both active and passive side was created in SAP2000. For each excavation stage, a separate model was created in SAP2000. The spring constants in each soil layer was calibrated by comparing the deflection of the 2D SAP2000 model and RS2 model. These spring values were compared against the values recommended in Table 7.1 of CFEM, 2006 for vertical modulus of subgrade reaction and showed close agreement. Although the vertical modulus of subgrade reaction is not directly relevant to this application, it served as a useful reference check for the use of soil springs. The calibrated spring values from the 2D model were then assigned to a 3D SAP2000 model and the forces in the shaft elements due to non-symmetric geometry and loading were estimated at the final stage. The 3D model was also used to evaluate the effects of cutting the sheet pile walls during the tunnel pre-support pipe installation, and the transfer of loading from the adjacent rail tunnel and wing wall structure.

The use of two distinct analysis methods also aided in verifying the behavior of the structure under the unusual loading conditions imparted on the shaft at various stages of construction to provide better confidence in the validity of the design.

4.5 Structural Design of shaft elements

The walers and struts were designed using CSA S16-14, *Design of steel structures.* The sheet pile was designed using European Standard EN 1993-5. The web crippling capacity of sheet pile to resist the forces from the jacking forces were calculated based on EN 1993-5.

4.6 Installation of Pre-Support Pipes

The sheet pile was cut along the profile of the roof of each tunnel to facilitate the installation of the 813mm diameter pre-support pipes as shown in Figure 6. The sheet piles were cut at varying heights along their longest span between the shaft base and the second strut level. These cuts in the sheet pile had to be made when the sheet piles were under full soil load. The opening for each pipe was made one pipe at a time. When each cut was made, the load on the cut pile had to be redistributed to adjacent sheet piles. This resulted in high stresses around the opening which had to be checked against the piles resistance to these moments, shears and web crippling effects. The apparent earth pressure distribution load was used to perform the analysis. Once the sheet pile is completely cut, the pre-support pipe was installed, and the pipe was connected to the sheet pile using small shear tabs along the perimeter of the pipe. It was assumed that the connected ends of the sheet piles are pinned at the new condition and the redistributed sheet pile moment and pipe reactions were calculated. Also, it was verified that the skin friction developed along the pipe is large enough to resist the reaction from the new sheet pile connection.

Figure 6: Installing pre-support pipes

4.7 Shaft Settlement

4.7.1 FEM results

The surface settlement and lateral deflection of the shaft were estimated from RS2 finite element model.

The horizontal deflection of the sheet pile from FEM is approximately 16mm as shown in Figure 7. The maximum deflection was observed between the second strut and the base slab at the final stage, when the third and temporary strut is removed.

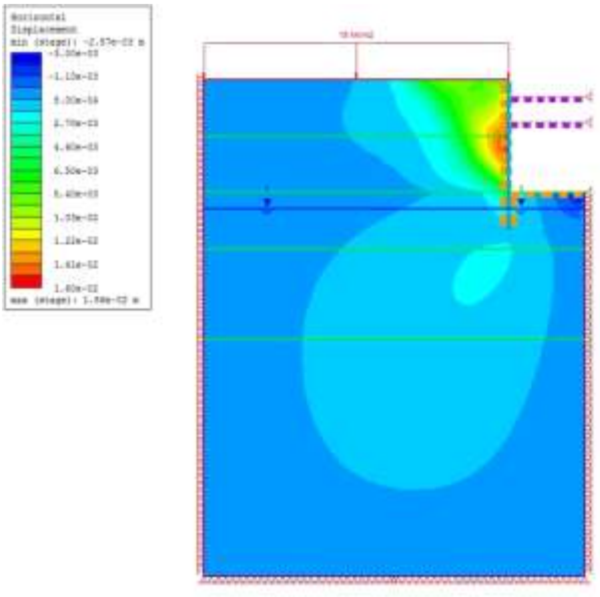

Figure 7: Predicted lateral deformation at final stage

The vertical settlement from the FEM is approximately 12mm as shown in Figure 8 and occurred at the final stage. The settlement was highest approximately 1m away from the sheet pile and settlement shape showed a concaved settlement pattern.

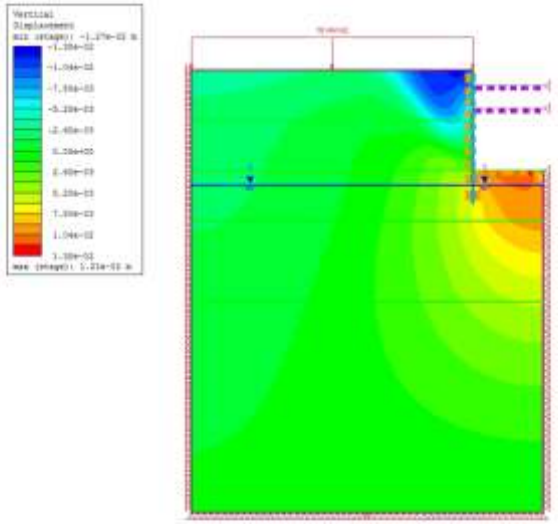

Figure 8: Predicted vertical settlement at final stage

4.7.2 Empirical method Prediction

The maximum horizontal deflection predicted from SAP2000 model was 18mm. The corresponding vertical deflection was predicted to be approximately 12mm at the surface using method described by Hsieh et al. (1998), and the empirical method predicted a concave settlement profile on the surface, as shown in Figure 9.

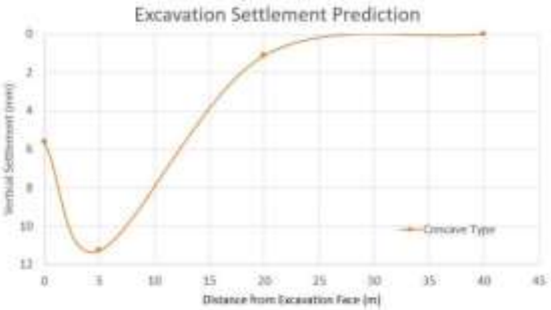

Figure 9: Predicted deformation (Empirical)

5 CONSTRUCTION

5.1 Challenges during installation of sheet piles

The sheet piles were vibrated through fill and granular material with minimal resistance up until approximately 8m below the ground surface when they encountered the native till. Advancing the sheet piles into the till was problematic and resulted in high vibrations and slow productivity. Prolonged vibration into the till layer caused larger-than-anticipated consolidation settlements to occur in the sands immediately adjacent to the existing rail tunnel. These consolidation settlements were beyond the allowable settlements for the project, and a modification to the installation method was required to limit further settlement prior to shaft excavation or tunneling work. Vibration of the sheets through the fill continued for the remainder of the piles but was terminated once the piles were seated on the till. A diesel pile hammer was used to drive the sheet piles to their final depth into the till which minimized the settlements around the shaft structure from pile installation.

Adjustments to the steel structure needed to be made during construction to adapt to the as-built variations on verticality of the sheet piles. Shim plates were used behind the sheet pile to maintain full contact between the sheet piles and the walers, and modifications to the brackets that supported the gantry running beams were made to suit the as-constructed conditions.

5.2 Monitoring

An extensive monitoring program was implemented at the beginning of the project by TTP and forms an integral part of the SEM tunneling approach. A series of instruments continuously monitor the highway surface and subsurface in order to measure the ground deformation which develops as a result of the excavation works. The highway surface and rail infrastructure are measured using a series of automated total stations and the subsurface is measured using shape arrays. Other instruments used to monitor the existing structures in the vicinity of the tunnel include in-place inclinometers, prisms, and tilt meters. The data is accessed via web-based software which allows for data analysis and visualization.

Additional monitoring points were installed specific for monitoring the shaft movements during construction to verify the behavior was consistent with the design during the various stages of the construction project.

5.3 Excavation Settlement

The actual excavation induced settlement measured during construction showed close agreement with the predicted values during design. Figure 10, depicts the settlement near the midpoint of the shaft structure. As indicated, the maximum settlement due to shaft excavation was measured to be 12 mm, which closely matches the 12mm of settlement predicted during design. However, the actual surface settlement followed a spandrel shape and settlement distribution length from the excavation face is less than the empirical prediction. Figure 11 depicts the observed settlement around the shaft

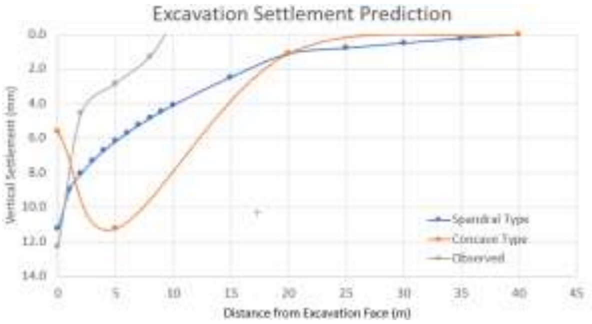

Figure 10: Predicted and observed surface settlement

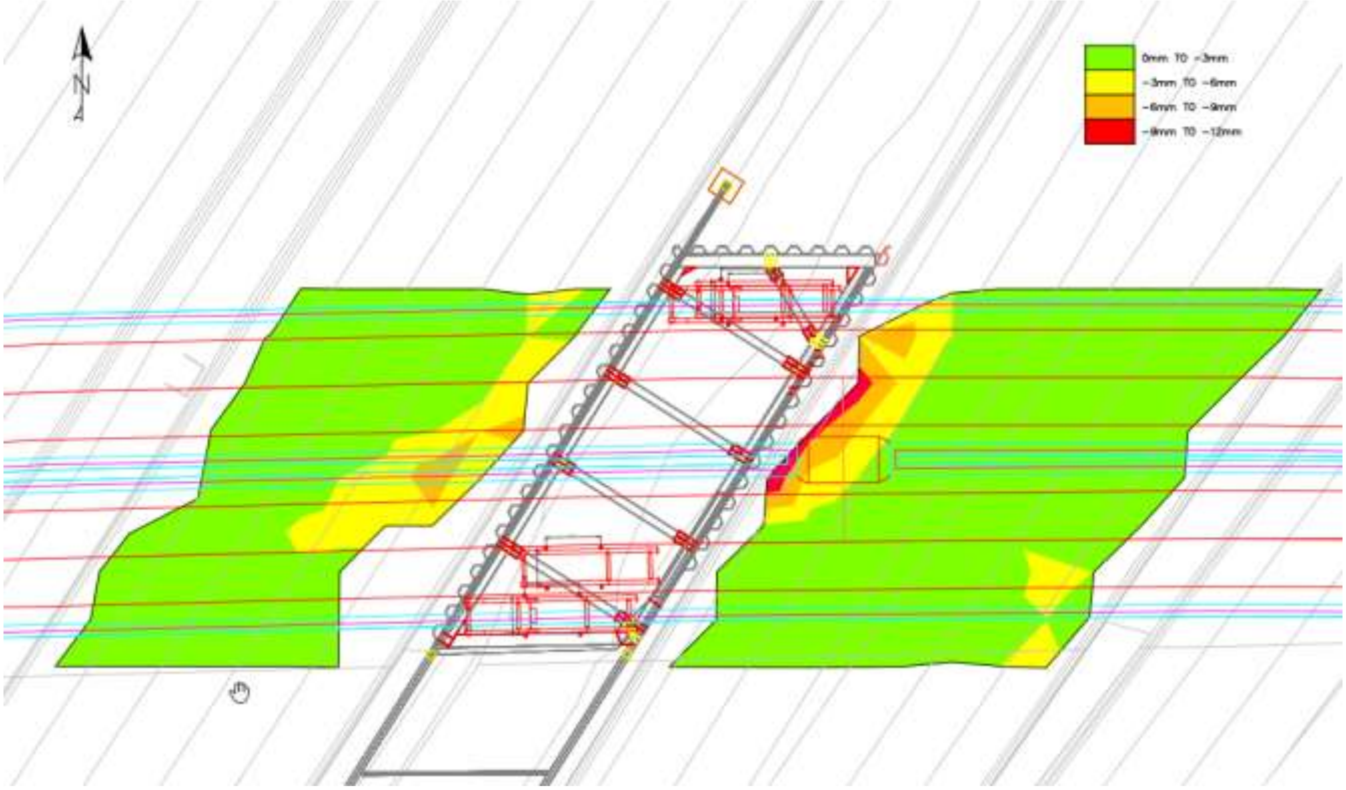

Figure 11: Observed settlement map around the shaft

6 CONCLUDING REMARKS

The design of the shaft structure for the Highway 401 and 409 Rail Tunnels project had to consider challenges caused by the skew angle of the tunnels, the surrounding structures, and the construction staging required to install the tunnel pre-support pipes. The use of various analysis techniques, including geotechnical numerical modeling, structural finite element analysis and various empirical or hand calculations was useful to verify the behavior of the structure during design, but also allowed for grated confidence in the design approach adopted. Settlements predicted during design showed close agreement in total magnitude to the actual settlements measured, but differed in shape. Consolidation settlement caused during the vibration of the first few sheet piles into the hard tills greatly exceeded the values predicted from the effects of excavation. This possibility needs to be considered when installing sheet piles in soils that can be consolidated when using vibratory driving equipment. The switch to hammering in the sheet piles proved effective at limiting these installation induced settlements.

The shaft structure allowed for the successful installation of all the tunnel pre-support pipes. At the time of writing, the shaft has been partially backfilled, and the north tunnel has fully advanced through the shaft (Figure 13).

Figure 12: Shaft and auger boring machine

Figure 13: North tunnel break through into the shaft wall

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