SHALLOW CONVENTIONAL TUNNELLING UNDER A LIVE 21-LANE HIGHWAY

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ABSTRACT: The expansion of Toronto’s Kitchener rail corridor necessitated the construction of two new rail tunnels beneath the Highway 401/409 junction, the busiest highway in North America. This project was uniquely challenging due to the extremely low soil cover, ranging from only 2.5 to 4m, while the 21 lanes of highway traffic remained fully operational above the excavation site. To address these risks, the Toronto Tunnel Partners utilized the Sequential Excavation Method (SEM) in conjunction with a robust pre-support system consisting of 80cm diameter steel pipes. The design phase involved sophisticated 3D Finite Element (FE) modeling to simulate all construction steps and predict the response of the underlying embankment fill and glacial till to tunnelling. Execution required the interception of existing structural foundations, including the sequential cutting of retaining wall piles and the foundation of a high mast lighting pole, all while maintaining strict settlement limits. Completed in 2021, the project demonstrated that advanced design and execution techniques could successfully deliver large-diameter mined tunnels in a very constrained environment, with negligible impact on existing infrastructure.

1. PROJECT OVERVIEW AND OBJECTIVES

The Highway 401/409 Rail Tunnel Project in Toronto was a critical component of a larger regional initiative by Metrolinx to enhance the capacity of the GO transit Kitchener Corridor. The project involved the design and construction of two new 176m to 180m long mined tunnels to accommodate additional tracks under the highway. The alignment crossed directly below 21 operational traffic lanes and immediately adjacent to an existing live rail tunnel (Figure 1).

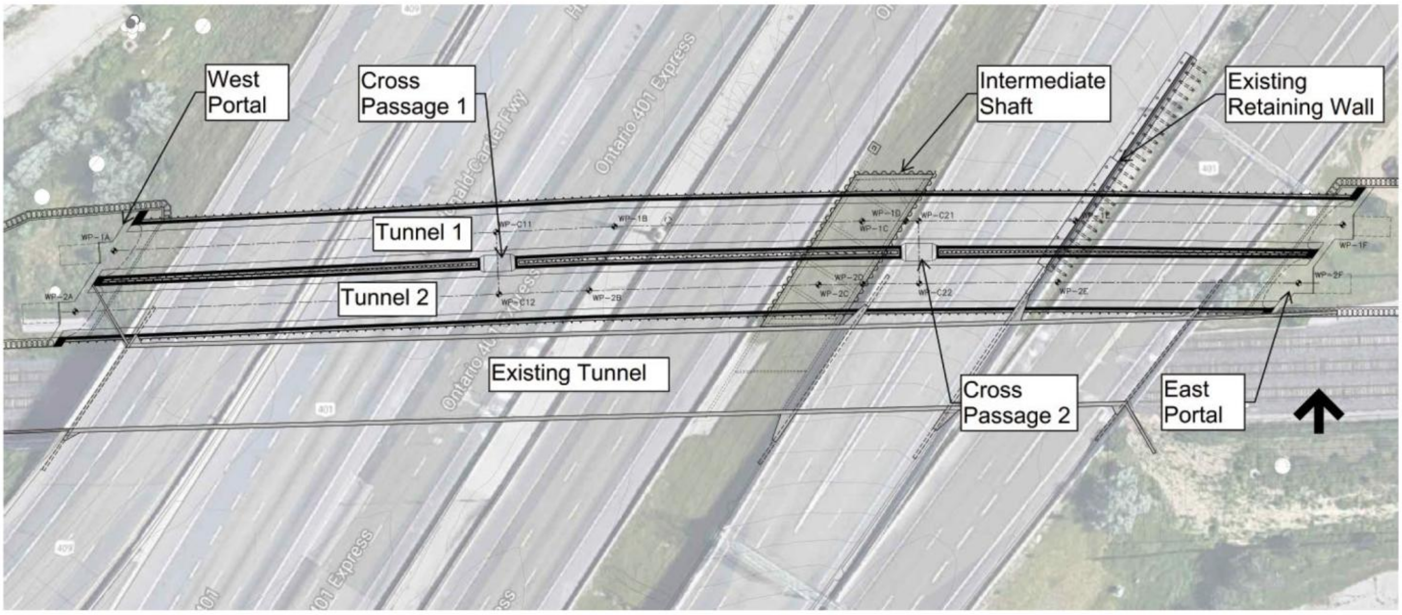

Figure 1: Main elements of the project.

The site is located east of Toronto’s Pearson Airport, a high-traffic zone where the highway handles approximately 450,000 vehicles daily. The tunnels were designed to be 10.5m high and 9m wide to accommodate rail clearance envelopes and emergency walkways. The two portals were temporarily supported using soil nailing and sprayed concrete, whereas an intermediate shaft was constructed to allow for the partial installation of the pre-support.

From the outset, the project was governed by a single overriding requirement: the highway and the adjacent rail line had to remain fully operational throughout construction. This constraint eliminated open-cut solutions and demanded an excavation method capable of maintaining strict control of ground deformation.

The contract was awarded in December 2017 to Toronto Tunnel Partners (TTP), a joint venture between Strabag Inc. and EllisDon, under a Design, Build, and Finance (DBF) model.

This paper presents the adopted design, construction approach and observed performance.

2. PROJECT SETTING AND GROUND CONDITIONS

The tunnelling site is located within an engineered highway embankment overlying glacial deposits. The upper portion of the tunnel alignment passes predominantly through loose fill materials, locally including construction backfill associated with the existing tunnel and retaining structures, while the lower part of the excavation encounters the in-situ glacial till (Figure 2). These materials exhibit low stiffness and limited cohesion, providing little stand-up time and exhibiting high deformability (Table 1).

The crown of the new tunnels lies only a few metres below the highway, with cover locally as low as 2.5 m. The two SEM bores were driven almost in contact with one another, leaving only a narrow soil pillar, and passed less than 2 m from the existing operational rail tunnel. In addition, several existing structural elements, including retaining walls and deep foundations, intersected the alignment.

Under such conditions and with exceptionally stringent settlement criteria defined, precise control of the sequential excavation was essential to minimising the impact to the operational assets.

Table 1: Geotechnical parameters

Parameters	**Units**	**Fill**	**Till**
Saturated Unit Weight, γ_s	kN/m^3	21	22
Young's Modulus, E_0	MPa	10	35
Elastic Modulus, E_{ur}	MPa	35	150
Effective friction angle, φ'	deg.	35	33
Effective Cohesion, c'	kPa	0	5
Coefficient of lateral in-situ stresses, k_0	-	0.5	0.5

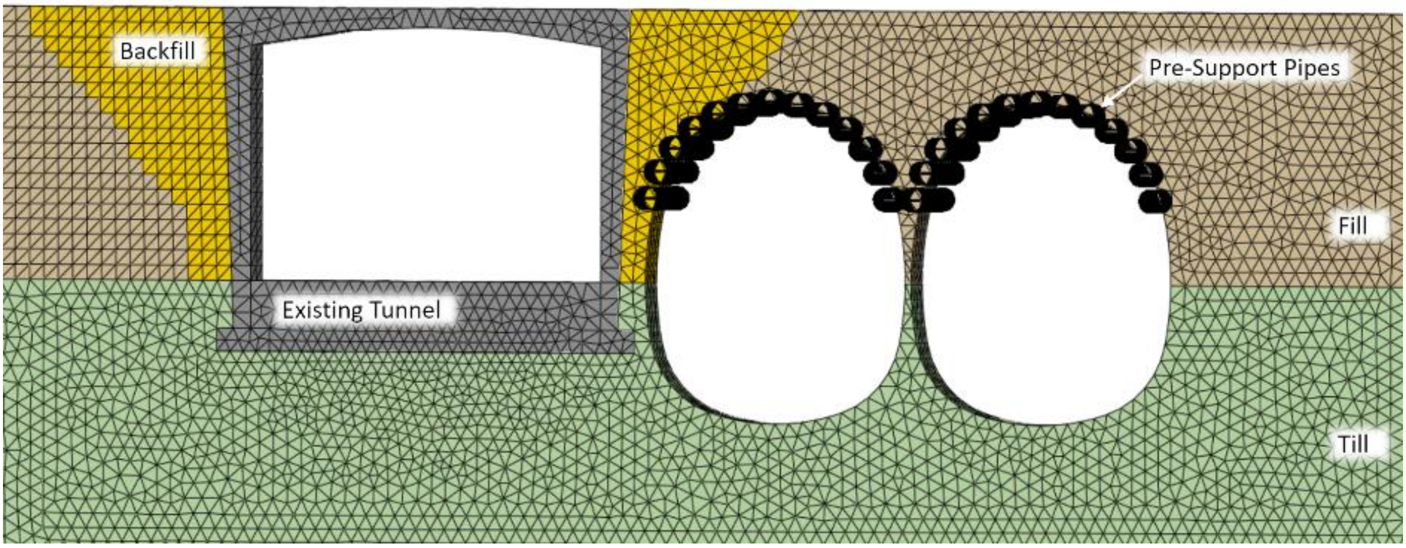

Figure 2: Numerical analysis section indicating the new tunnels with the pre-support pipes, the existing tunnel and the main soil units.

3. DEVELOPMENT OF THE TUNNELLING CONCEPT

The client's initial reference concept envisaged a single box structure. However, staged open excavation was incompatible with maintaining traffic on such a heavily loaded interchange. During procurement, multiple construction concepts were assessed, including micro-tunnelling variants, box jacking schemes and both single and twin SEM alternatives. Each option was evaluated against risk, programme, direct cost and constructability criteria (Urschitz 2019). The twin SEM solution consistently achieved the highest overall rating, primarily due to the following reasons:

- Dividing the cross-section into two smaller tunnels reduced the open excavation area and improved short-term stability compared to a single large tunnel.
- The method allowed excavation to proceed in short advances with immediate installation of shotcrete support, enabling deformations to be controlled incrementally.
- SEM offered flexibility to accommodate anticipated obstructions such as piles and buried structures.
- The approach was well suited to integration with a pre-support system, considered essential to manage the extremely low cover.

As the design progressed post-award, the tunnel geometry was refined and two short cross-passages were incorporated to satisfy fire-life-safety requirements. The final concept combined twin mined tunnels with systematic roof pre-support installed from both portals and from an intermediate shaft (Figure 3).

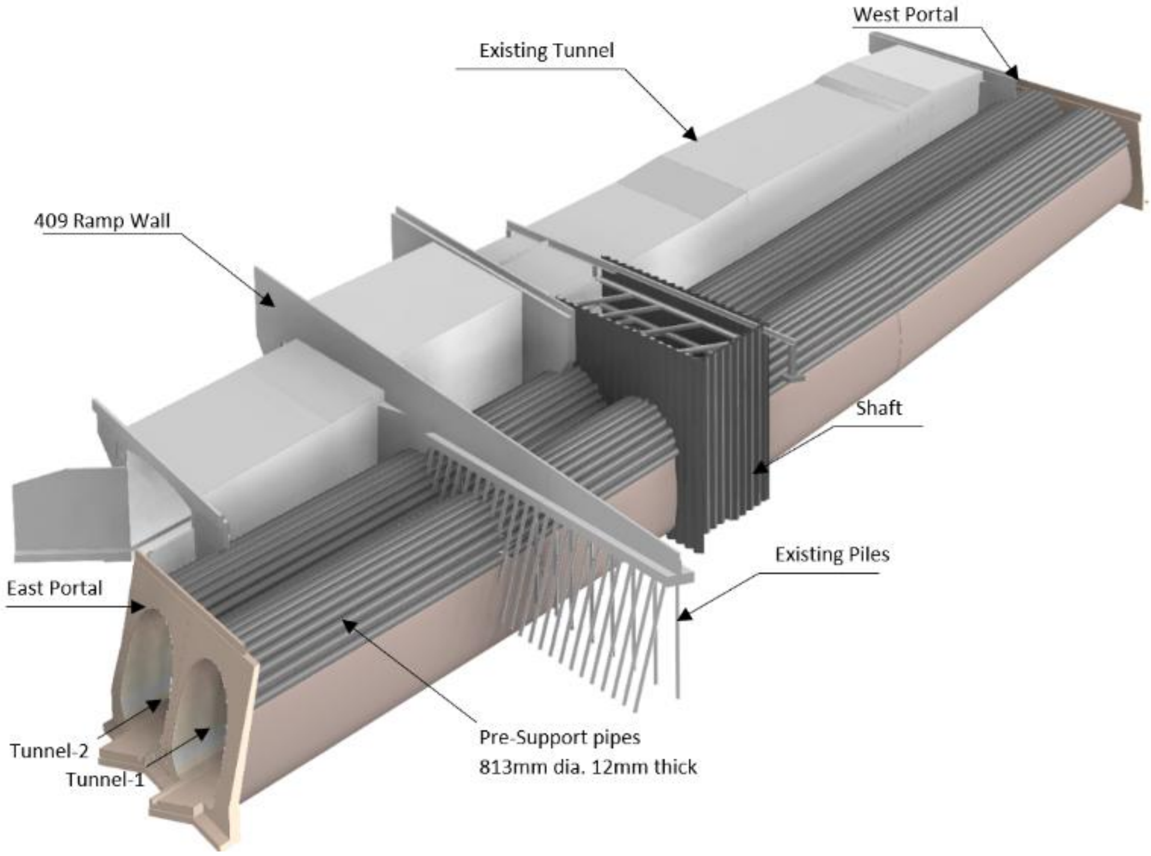

Figure 3: Final layout of the project.

4. PRE-SUPPORT STRATEGY

Given the limited cover and low ground strength, the design philosophy relied on pre-support to transform the behaviour of the ground ahead of the face. Rather than allowing the soil to deform prior to support installation, the intent was to create a stiff structural umbrella that would carry loads before significant deformation could develop.

This was achieved using a canopy of 52 steel pipes, 813 mm in diameter with 12 mm wall thickness installed above the tunnel crown. The pipes were advanced by guided auger boring, a technique combining hydraulic jacking with simultaneous soil removal. Drives were executed in welded segments up to 12 m long, with maximum installation length of 78 m and jacking forces of up to 160 tonnes (Ferraro and Lahti 2021). Installation from four launch points (two portals and two sides of the intermediate shaft) allowed continuous umbrellas to be formed along the entire alignment. Pipe segments that deviated from their theoretical alignment were cut and carefully integrated into the lining.

From a structural perspective, the canopy acts as a composite beam-arch system that limits ground relaxation. Sensitivity analyses undertaken during design indicated that the presence of the canopy could reduce surface settlements by up to approximately 50%. After excavation, the pipes were backfilled with concrete, further increasing stiffness and durability.

Figure 4: Installation of 813mm pre-support pipes from the portal (left) and the intermediate shaft (right).

5. EXCAVATION AND SUPPORT

Tunnelling proceeded under the protection of the pipe canopy using conventional SEM tunnelling. Excavation was typically divided into top heading and bench/invert stages. Short advances were adopted to maintain face stability, and a temporary invert was frequently employed to complete the ring and control deformation. The initial lining consisted of 300 mm of mesh-reinforced shotcrete, designed to provide immediate confinement and form part of the composite support system (Figure 5 left). One tunnel was excavated at a time to ensure no adverse interaction would occur and to better control the reaction of the surrounding ground.

Figure 5: Initial shotcrete lining (left) and construction of the final support at the portal.

A double-shell arrangement was implemented, with a waterproofing membrane separating the initial and final linings. The permanent lining comprised a 300 mm cast-in-place fibre-reinforced concrete shell, with conventional reinforcement provided only where required, such as at cross-passages and portal connections (Figure 5 right). This configuration balanced constructability with durability and long-term performance.

Care was required where the alignment intersected existing foundations (Figure 6). In these areas, excavation was locally modified and piles were sequentially exposed, cut and incorporated into the lining while movements were closely monitored. The inherent flexibility of SEM proved advantageous in managing such interfaces.

Figure 6: SEM excavation encountering the foundation of a high mast lighting pole.

6. NUMERICAL MODELLING AND DESIGN VERIFICATION

Because the tight impact thresholds governed the design, detailed prediction of deformations was essential. A comprehensive three-dimensional finite element model was therefore developed in Abaqus to simulate the full soil–structure interaction problem. The model explicitly represented the ground stratigraphy, the new tunnels, the pipe canopy, the intermediate shaft, retaining walls, piles and the existing tunnel.

The analysis incorporated more than one million elements and approximately 459 staged construction steps, reproducing the sequential excavation and installation of support (Figure 7). The soil behaviour was described using the Hardening Mohr–Coulomb model (Doherty & Muir Wood, 2013) to capture stress-path dependent stiffness and plasticity, while shotcrete and concrete linings were represented using non-linear constitutive laws (concrete damaged plasticity model – Lubliner et al., 1989).

Prior to the full analysis, a series of shorter sensitivity models were undertaken to evaluate key parameters, including the influence of the canopy, in-situ stress ratio, soil model selection and the presence of weak backfill zones. These studies confirmed that pre-support stiffness and initial stress conditions exerted the greatest influence on predicted settlements.

The final simulations indicated that maximum highway surface settlements due to tunnelling would remain below approximately 15 mm and that the impact on the existing rail tunnel would be negligible.

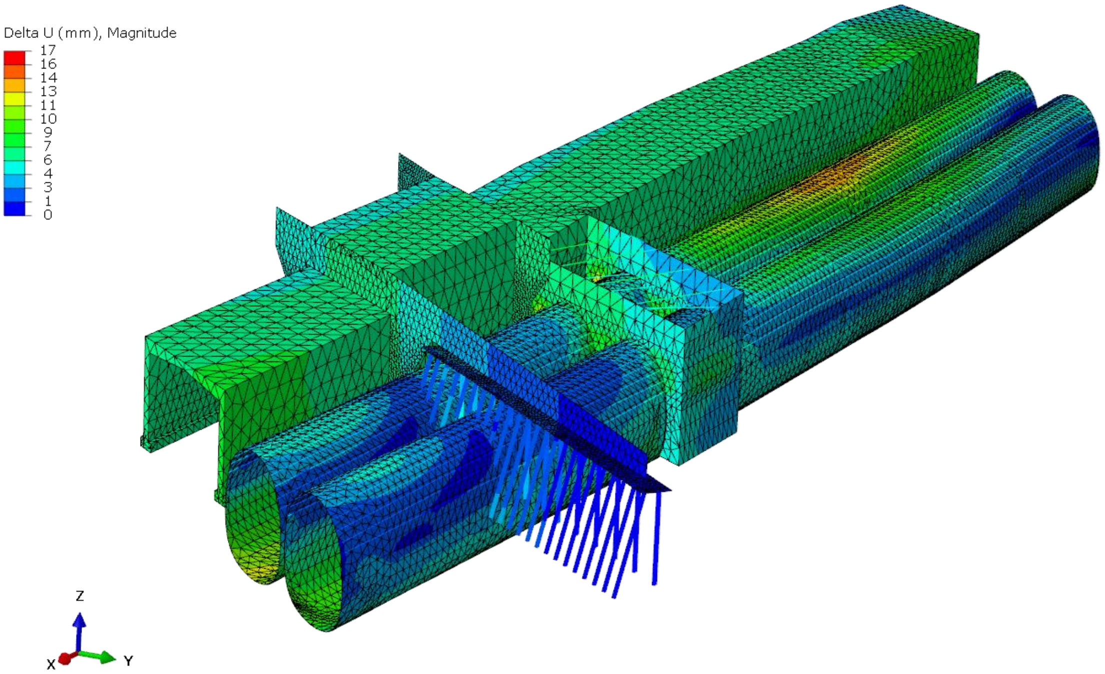

Figure 7: 3D soil-structure interaction FE model – only the structures are highlighted.

7. CONSTRUCTION MONITORING AND PERFORMANCE

Given the consequences of excessive deformation, the project adopted a rigorous observational method, accompanied by an unusually dense monitoring system to enable real-time verification of performance. Four automated motorised total stations continuously surveyed approximately 380 reflector-less surface points together with dozens of targets installed on retaining walls and bridge structures. Within the existing tunnel, 140 track prisms, 59 wall prisms and 95 additional underground targets were monitored, supplemented by inclinometers, extensometers and convergence arrays. Designers and geotechnical engineers remained closely involved during construction, enabling rapid interpretation of data and adjustment of excavation or support measures where required.

Settlement contour plots generated from the automated monitoring system provided near real-time feedback on ground response. Highway settlements due to tunnelling generally remained in the order of 10–15 mm, and movements recorded in the existing tunnel were less than approximately 5 mm. The largest settlements were introduced by the construction of the intermediate shaft.

Isolated construction challenges were encountered, including deviations during pipe installation and interception of foundations. These were addressed through localised measures such as grouting, additional spiling and minor adjustments to excavation sequencing. The ability to adapt the support system in response to observed conditions was instrumental in maintaining control.

8. LESSONS LEARNED

The project provided several practical and technical insights into the execution of mined tunnels beneath critical infrastructure, particularly under conditions of very low cover and continuous high traffic loading.

A key lesson concerned the importance of flexibility in both design and execution, in particular the ability to adapt installation procedures to site-specific constraints. The staged excavation sequence, short advance lengths and immediate support installation enabled the excavation to respond dynamically to observed ground behaviour and to encountered obstructions.

Close collaboration between the contractor, designer and owner was another decisive factor. Designers were embedded within the site team, allowing numerical predictions, monitoring results and field observations to be continuously compared.

Advanced numerical modelling itself played a central role in risk management. Detailed three-dimensional FE analyses provided quantitative predictions of settlements and structural demands, providing the team with necessary data to make informed decisions at each project stage.

Finally, high-frequency automated surveying and subsurface instrumentation provided near real-time confirmation of performance, enabling construction to proceed efficiently without compromising serviceability and safety.

9. CONCLUSION

The successful completion of the Highway 401/409 crossing demonstrates that mined tunnels can be safely constructed beneath heavily trafficked infrastructure with minimal cover, extending the practical limits of mined tunnelling and providing viable alternatives to disruptive open-cut solutions. The combination of carefully designed and installed pre-support, staged SEM excavation, advanced numerical modelling and comprehensive monitoring provided reliable control of settlements and enabled uninterrupted operation of the highway and railway.

LITERATURE

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