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3 SEM Stations on ECLRT: Design and construction challenges mastered

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ABSTRACT
For 3 out of 13 underground stations on the new Eglinton Crosstown Light Rail Transit, the Sequential Excavation Method was chosen over Cut & Cover by Project Co. Crosslinx Transit Solutions. The inhouse costing and scheduling during tender showed a clear advantage at 3 locations for SEM as the more cost and time efficient construction method. SEM subconsultant Dr. G. Sauer & Partners provided tender to detailed (IFC) design to the construction arm of CTS called CTS-C with tailormade solutions for each location. Based on the team's mutual experience, highly competitive design solutions have been developed.

A multidisciplinary effort was necessary to change the Reference Concept Design (RFP) from Cut & Cover boxes under Eglinton at busy intersections to the ovoid shaped SEM caverns. These were temporarily and permanently accessed by the much smaller headhouse shafts off-street. Architects, M&E, Systems, Fire-Life Safety and Operations worked closely with the SEM designers to provide new and unique solutions never before applied in Canada.

Laird station posed a logistical challenge with its size (19m span, 15m height, 490m length), housing a full station platform and a double track crossover. At Oakwood, 10m of overburden above the 19m wide platform cavern and single construction access got the design-builders thinking. Avenue station offered up some of the most challenging ground conditions, with extensive sandy deposits below water table to be dewatered by expert firm WJ providing bespoke dynamic designs and execution of dewatering.

The paper will focus on 3 of the most important aspects making this section of the ECLRT project such a success story:

- FE design of caverns and cavern & cross-cut intersections
- Dewatering and pre-support design and execution allowing open face mining in the Avenue Sand-box
- Integration of construction team with designer's personnel for extensive SEM know-how on site.

1 PROJECT OVERVIEW

The new Eglinton Crosstown Light Rail Transit (ECLRT) provides a new 19 km East to West connection in Midtown Toronto from Kennedy to Mount Dennis. It features a dedicated route for LRT vehicles and 25 stations 13 of which underground in its 10km tunnelled core section between Laird and Keelsdale stations. The project was procured by Metrolinx (MX) using two advance TBM tunnel contracts for the running tunnels, cross passages and emergency evacuation buildings (EEBs) in an East and a West section meeting at Yonge Street with two TBMs each. In a third contract, procured by MX and Infrastructure Ontario using an alternative financing procurement model including Design – Build – Finance - Maintain in the contract format covered the at grade guideway sections, track work, signalling, communications and the procurement of the LRT vehicles, the design and construction of all 25 stations.

Figure 1. Eglinton Crosstown LRT map (source Metrolinx)

A Reference Concept Design (RCD) was provided with the Request for Proposal (RFP), identifying all 13 underground stations as Cut & Cover (and Top Down) design. Based on the sheer volume of design work to be done during the RFP phase in this contract the RFP period provided by MX was originally 9 months (February to October 2014) and was eventually extended to 11 months.

2 SEM RFP DESIGN PROCESS

Project Co. Crosslinx Transit Solutions (CTS), a Joint Venture of Dragados, Aecon, EllisDon and SNC Lavalin, employed SEM (Sequential Excavation Method) consultant firm Dr. G. Sauer & Partners (DSP) to provide design services during tender support and subsequently including up to detailed design. Members of this team have previously worked together on SEM solutions in Canada and overseas. Based on the team's mutual experience, highly competitive and innovative design solutions have been developed. The tunnelling team used the RFP period to look for the most efficient way to provide the underground station structures at the predefined locations and depths the advance tunnel contracts had provided. An assessment process was started that lead to the following matrix for the feasibility of SEM (see Figure *2*).

This initial phase 1, high level assessment subjected 15 station location to a simple qualitative rating using the traffic light colors considering criteria such as geology, hydrogeology (dewatering effort), overburden, entrance connections and station geometries and layout for SEM feasibility.

The high-level assessment identified 4 station locations where SEM seemed possible from a technical point of view. These 4 locations were subjective to a more detailed phase 2 assessment including additional aspects such as avoidance of utility relocation and traffic lane closures as well as SEM specific constructability aspects. For each location a more detailed summary sheet was produced (see Figure *3*). The results of the individual phase 2 assessment were entered into a matrix for comparative rating as shown in Figure *4*.

Nr.	Station		SEM appears to be: (*)	Notes
1	Mount Dennis		Not favorable	Too shallow with current alignment
2	Keele		Partly favorable - For the Station: + For the proposed Crossover:	 - Station Configuration would need adjustment; very soft ground + Favorable
3	Caledonia		Possible, from a technical point of view, but:	Station is off-street so most likley no significant cost savings possible

Figure 2. Excerpt of Phase 1 assessment matrix

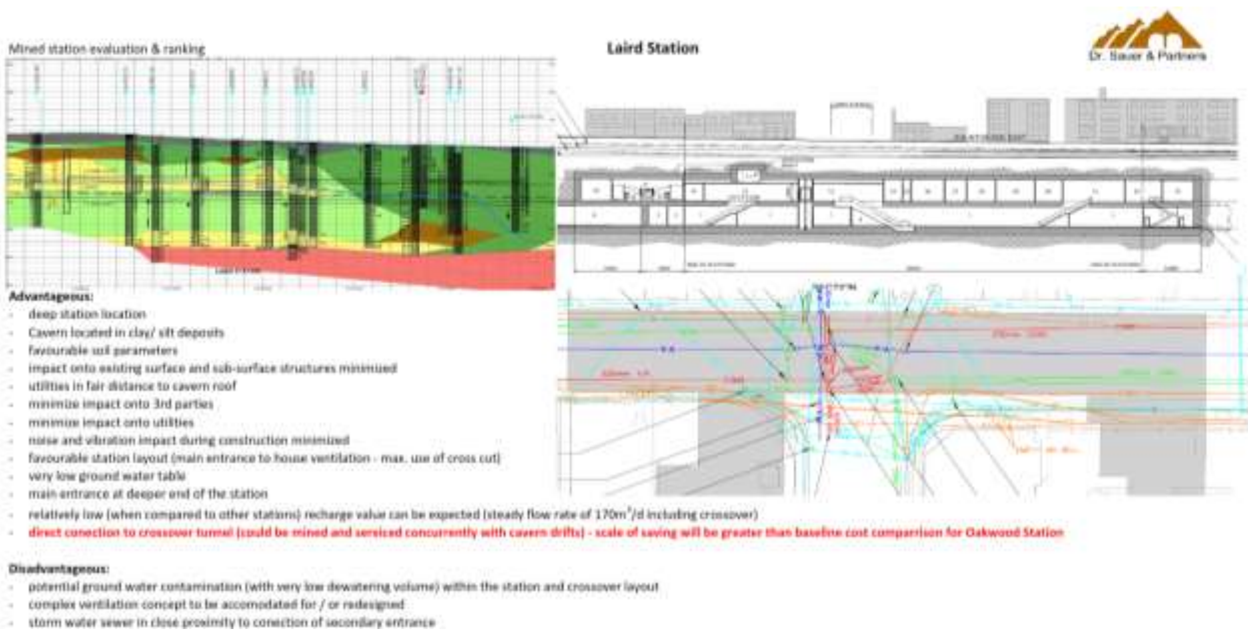

Figure 3. Phase 2 assessment, example Laird station

Subsequently, CTS proceeded with a further commercial, schedule and labor market assessment exercise and decided to advance with SEM for 3 stations and one crossover namely. Laird station and crossover, Avenue and Oakwood where an SEM cavern provided the required platform and mezzanine space.

CTS decided to go ahead with a 70% SEM design for approximately 125m of Oakwood station to have enough information to support a fully detailed cost estimating process and compare the SEM cost with the cost for the traditional and prescribed Cut & Cover solution. The 70% design provided details on the overall SEM construction sequence, presupport elements such as pipe roofs and spiling, face subdivision for the cross-cut, platform and crossover caverns, Ventilation adits, and running tunnels as well as primary and secondary lining thickness, probe drilling and monitoring requirements. It was supported by FE modelling to confirm the lining thickness and construction impact assessment for the utilities above, which wouldn not have to be relocated. The chosen lining system is a double shell system, consisting of a primary/initial lining and a secondary/final lining, separated by a compartmentalised PVC waterproofing system.

	Oakwood	Avenue	Mt. Pleasant	Laird	Notes
Traffic Impact Reduction	2	2	2	2	set equal for all stations;
Station Arrangement	3	4	1	2	Avenue & Oakwood leveled entrance box; Mt. Pleasant & Avenue East entrances connected at an angle;
Geology	3	2	1	4	Laird Station in its majority located in clay - **highly favorable;** Oakwood Station's cavern roof is located in the dense to very dense clay layer; Avenue Station's cavern roof is covered by a thick, dense to very dense clay layer; Mt. Pleasant Station's cavern roof is close to a dense clay and silt layer;
Hydrology	3	2	1	4	Laird Station in its majority located in clay, hence the steady flow rate is very low (170m^3/d incl. the cross over)- **highly favorable;** Oakwood Station has the third lowest steady flow rate (800m^3/d); Avenue and Laird, since located in interstadial sand layers have similar, when compared to other two stations, high steady flow rates;
Utility benefit	1	2	4	3	Amount of utilities present at each station.
Pockettrack/ Crossover	0	2	0	2	Avenue and Laird Stations have direct access to crossovers. These two stations are deepest of the Eglinton alignment. The crossover tunnel can be mined with the site set-up and equipment used for the stations. Mining works on crossover can continue or occur concurrently to station works - **very favorable**. **Direct access from the stations to the crossover results in the scale of savings being greater than the baseline comparrison.**
Entrance arrangement	2	4	2	2	Avenue Station allows for double advance as entrances are located at very ends of the station; Laird, Oakwood and Mt. Pleasant Stations are to be accessed from the main entrance (using a cross cut).
Utility proximity	2	4	1	3	Proximity of existing utilities to the cavern roof are evaluated and ranked when four stations are compared. The closer the utility is located to the cavern roof, the more reliance lies on the pre-support to contain the zone of influence due to mining operations and prevent damages to utilities.
Total	**16**	**22**	**12**	**22**	

Figure 4. Comparative rating matrix – 4 stations

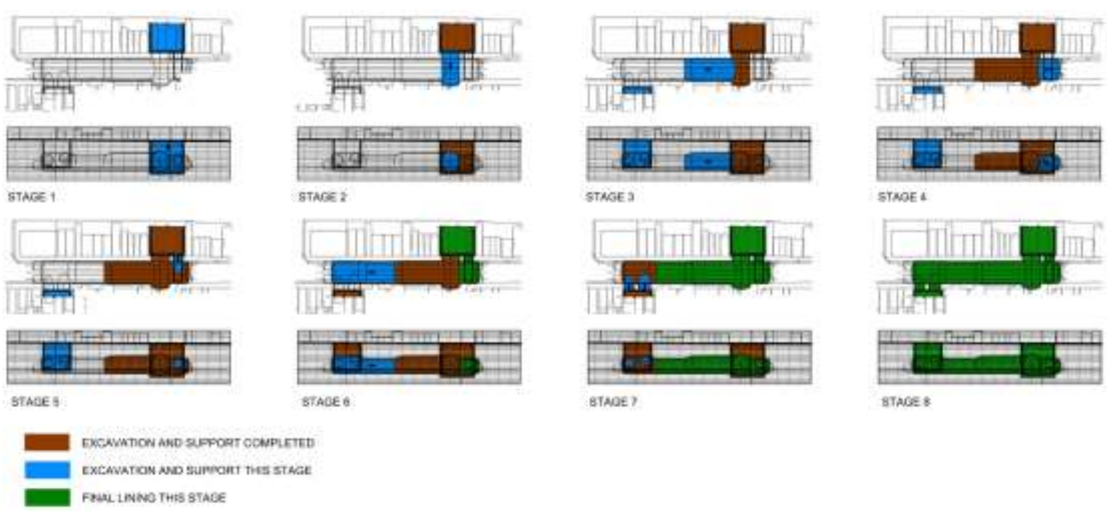

Figure 5. 70% design during RFP providing general SEM excavation sequence, example, Oakwood station for detailed scheduling by CTS

3 SEM DETAILED DESIGN PROCESS

3.1 General Station Layout

In order to simplify and streamline both the design and the construction process, all three SEM stations used the same cavern and tunnel cross sections for the various elements in the stations:

- A large cross-cut cavern (see Figure *6*) connecting the off-street access shafts/headhouses with the caverns located under Eglinton Avenue.

- A smaller access adit, connecting the secondary entrance boxes with the caverns (Avenue and Laird stations only).
- Two station cavern cross-sections were used for the station platform tunnels depending on the presence of a concourse slab as shown in Figure *6*. The cross section of the cavern without the concourse slab was also used for crossover caverns at Laird and Avenue stations.
- Connection tunnels for ventilation and other secondary access purposes between headhouses and caverns.

3.2 Excavation and Support

The 18.7m wide platform caverns were excavated from the 18.2m high by 15.6m wide cross-cut tunnels post TBM transit, introducing one (Avenue) or two (Oakwood, Laird) $220m^2$ openings in the cross-cut lining. Due to the low overburden and the requirement to minimise the surface impact and increase the face stability, the excavation was staged into several sub-sections utilising double side-drifts using a systematic pipe-roof (Figure *6*).

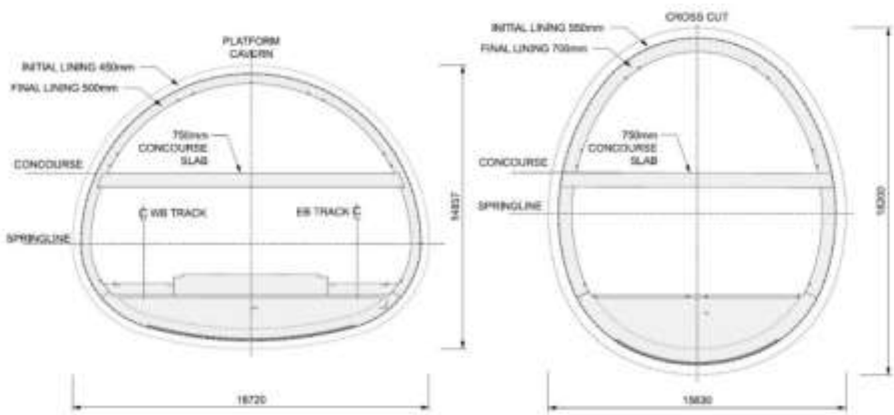

Figure 6. Cross-Section of platform cavern (left) and cross-cut (right)

Due to the complexity and extent of the stations, it was decided to perform detailed 3D FE analyses to simulate the exact excavation sequence. Avenue and Laird station models had to be split into two sub-models to keep the number of elements and subsequently the computational time to a reasonable extent. These analyses were used

- to perform the structural design of the cavern linings (including temporary inverts and temporary middle walls) through the construction process,
- to assess the stability of the advancing tunnel faces and the TBM tunnel lining segments that were removed during the cavern excavation process,
- and to determine surface and sub-surface settlement that formed the basis of the utility assessment process.

3.3 Lining Design

The analyses were performed using Abaqus 0, with the lining simulated with the Abaqus concrete damaged plasticity model (CDP), which allowed a realistic redistribution of stresses and resulted in designing all the initial linings without any reinforcement, even at the intersection of cross-cut and platform cavern with the sizeable openings in the initial lining.

The CDP model (Dassault Systemes 2010 and Lubliner et al 1989) is capable of capturing the stress redistribution behavior assuming a tensile cracking and compressive crushing mechanism following a uniaxial compressive and tensile damaged plasticity response. The stress – strain relationships can be defined manually allowing calibration based on experimental results.

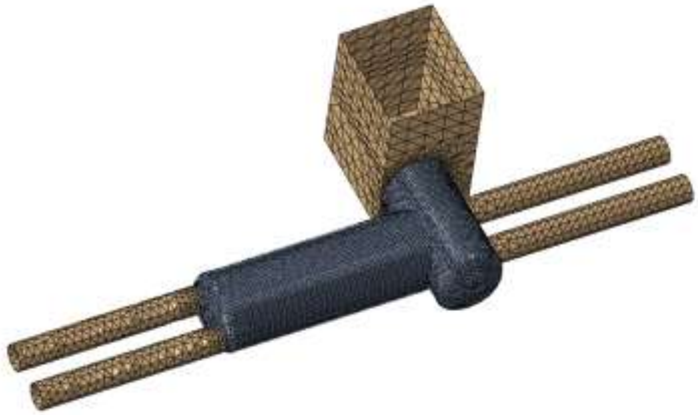

Figure 7. 3D FE model of Avenue station

The concrete parameters were calibrated against laboratory testing curves. One such calibration was performed for the flexural response of the fiber reinforced concrete according to the ASTM C1550 test results. The centrally loaded round panel (75mm thick, diameter of 800mm 3 supports) was simulated using the CDP model and loaded to determine the post-crack flexural toughness. Indicative maximum principal stress plots at 2mm central deformation in a linear elastic and CDP models as well as a comparison between experimental and calibrated force-displacement results are shown in Figure 8. The linear elastic model can only capture the elastic, pre-peak behavior. An estimate of the residual tensile strength based on the energy absorption can be derived according to Bernard 2002.

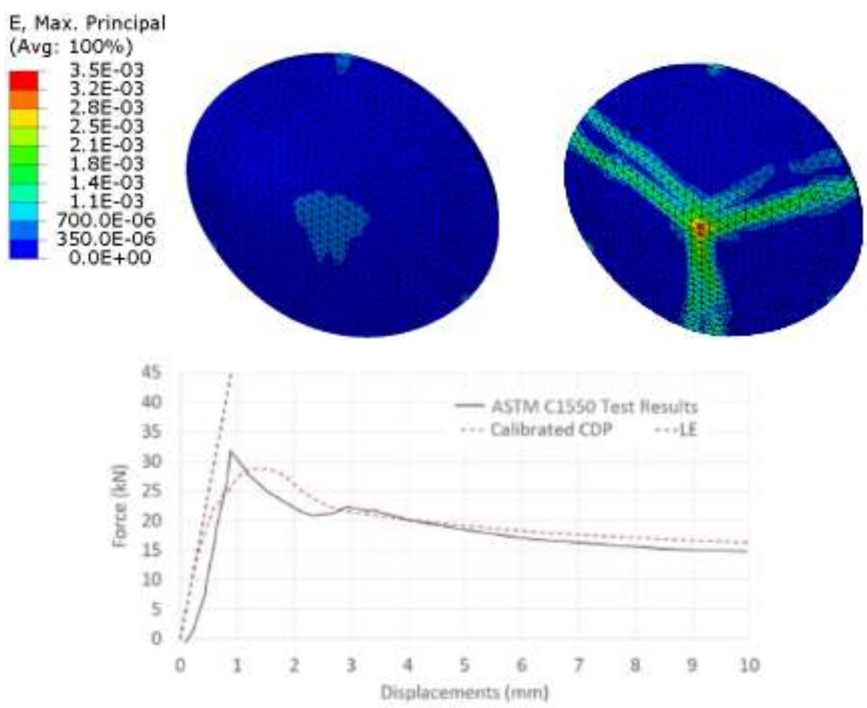

Figure 8. Max. principal strains at the underside of the test panel at 2 mm deflection: top left - linear elastic top right – CDP, bottom – calibration of force-displacement behaviour (Laubbichler et al 2021)

3.4 Surface Deformations

The low-bound estimated settlements due to SEM excavations were 35mm above the intersection between cross-cut and platform cavern at Laird station (and similar at the other two stations) as shown in Figure *9*. The FE prediction was multiplied by a factor of 1.5 to account for additional settlements during pipe-roof installation and other unforeseen conditions and settlements due to station box excavation (5mm) and dewatering (4mm) were added, resulting in an upper-bound of 60mm for asset impact assessment. The monitored surface settlements were about 45mm, which implied a good prediction of the FE analysis as the additional 10mm were contributed to the box excavation and dewatering and no additional settlements occurred during pipe roof installation.

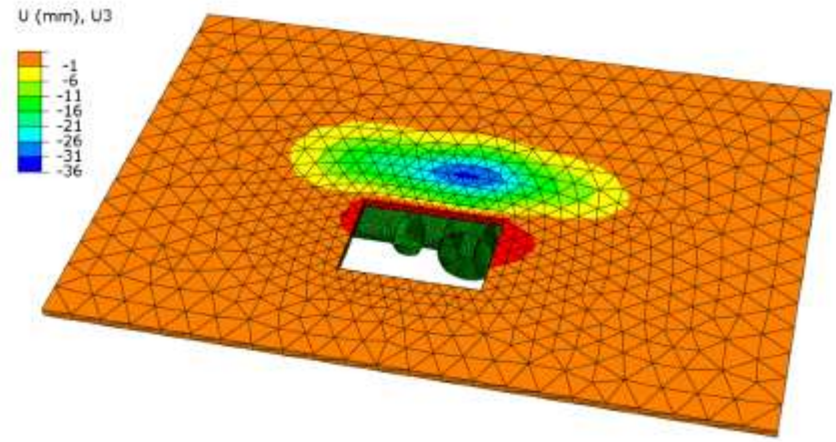

Figure 9 – Predicted Surface Settlements at Laird station

During the detailed design process, the ongoing attempts to further reduce cost and increase efficiencies in the design led to further optimisations in the implemented solutions:

- Hollow core slab to reduce slab thickness/self-weight and reduce required cavern size.
- Introduction of a combined lining system, where the initial/primary lining forms part of the final load carrying lining system.
- Removal of the Lattice Girders in the primary lining as shape control element and replacement by an optical/geodetical shape control system.
- Removal of the bar reinforcement in the arch sections above the hollow core slab and replacement with fiber reinforcement.

4 DEWATERING DESIGN AND EXECUTION

The stakes are high when mining below the standing ground water level in sandy soils; any short comings in the dewatering systems can lead to significant delays, and far worse, instability of the mining face. Executing dewatering requires a combination of engineering design, experience, and a can-do attitude in the field under any conditions the subsurface presents. This was the situation at Avenue station which was constructed below the standing ground water level in a broad range of soil types, including glacio-lacustrine plastic and non-plastic soils (i.e. clay and sand). The layered nature of the soils within the aquifer presented significant challenges to the construction team. The ground conditions featured a low-permeability saturated silty sand overlaying a thick clay layer. The base of the cavern was founded just above the interface between the sand and clay. Sand/Clay interfaces are especially challenging – to halve the depth water above the interface requires having the well spacing and thereby doubling the quantity of wells.

The aquifer held 14 m of water above the clay interface, nearly all of which of which needed to be drained by the dewatering system. As the excavation depth approaches the clay interface, the well count grows exponentially. Multiple ‘stages’ of dewatering systems were incorporated into the dewatering strategy to reduce the overall drilling required. Once the initial stage was installed at ground surface, subsequent stages of wells were drilled at the depth of drawdown that the previous stage of dewatering achieved, thereby reducing the overall ‘drilling meters’ required. Deep wells with submersible pumps were drilled from the ground surface, ejector wells were drilled from the top headings of the mined caverns and then wellpoints were installed from the bench and temporary invert elevations of the cavern (Figure 10).

Further complicating dewatering, excavation unearthed several thin clay horizons within the aquifer, ranging between a few inches and a few feet in thickness. Critically, regardless of the thickness, a continuous clay layer inhibits the downward drainage of water, significantly reducing the effectiveness of the surface dewatering system in achieving the drawdown to the base of the excavation. A contingency plan was implemented comprising arrays of wellpoints targeting the clay interfaces, installed from various locations within the previously bored TBM tunnels and from within the partially mined cavern to dewater the subsequent mining stages.

At the 20 m x 30 m main entrance cross-cut cavern and shaft, 14 deep wells, 20 ejectors and 209 wellpoints were installed. In total, around the 410 m Avenue station project, 107 deep wells, 109 ejectors and 1,282 wellpoints were installed. Working with the other members of the mining team was critical to ensure the successful execution of the dewatering strategy.

Figure 10. WJ Well Drilling Equipment inside SEM caverns

5 CONCLUSIONS

Changing the RCD design from trадidtional intrusive Cut & Cover stations to traffic and utility friendly SEM alternatives was possible by close collaboration between the CJV's engineering team and a specialist tunnel design team developing early on reliable concepts. Through state of the art 3D FE modelling the complex excavation sequences and thin linings could be designed whilst complying with settlement impact criteria to overcome the challanging ground condidtions. Close collaboration between competent dewatering support, hands on design support and experience contractor teams during construction made the 3 SEM stations on the ECLRT a success story.

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