Design And Construction of A 9-Meter-High Embankment Over Champlain Sea Clay

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ABSTRACT
Construction bearing on normally, or minimally over-consolidated, sensitive clays of the Champlain Sea deposit in Eastern Canada has traditionally forced the implementation of diverse engineered solutions. The present paper reflects on a case study where a 9-meter-high embankment required a comprehensive geotechnical investigation campaign, and the ensuing engineered solutions. The embankment, located in the Canadian National Capital Region, is part of a multi-billion-dollar transit project executed using a fast-paced P3 delivery model. As such, firstly the project required a particular emphasis on schedule optimization. Secondly, a right of way constraint on the northern face entailed the implementation of a retaining structure to limit the footprint of the embankment. Finally, a contractual performance criterion dictated that total post construction settlements, and deflections during operations be limited to under 5mm.
The subsurface encountered at the site mainly consisting of a silty clay deposit underlain by Till and resting on bedrock, was subjected to a multi-phased investigation campaign. Though the baseline geotechnical data provided by the client suggested that the silty clay deposit's OCR ranged between 3.4 to 4.5, supplemental investigation carried out by AtkinsRéalis identified a much lower OCR of about 1.9 – which translated to a governing over-consolidation margin of about 60 kPa. Following a series of analyses and design iterations the retained design solution was able to address the project constrains. This included the implementation of accelerated consolidation of the silty clay deposit using vertical wick-drains and surcharging to meet tight deadlines. Consequently, the resulting ground improvement through consolidation strength gains provided adequate resistance to support the retaining structure. And finally, the targeted use of lightweight EPS embankment fill allowed the mitigation of settlements to adhere to the strict threshold. This was supported by data from a network of geotechnical instrumentation and monitoring systems with near perfect correlations with predicted behaviors.

1 INTRODUCTION

In present day Eastern Ontario and Quebec region, known as the Ottawa River and St Laurence Valleys, laid a vast shallow sea over thousands of years ago Geologically recognized as the Champlain Sea. This vast area has since seen the sea parted and deposits of the Champlain Sea Clay, or colloquially known as Leda clay occupy a considerable portion of the overburden stratigraphy.

This deposit is infamous for its high sensitivity to remolding and its rather low pre-consolidation pressures. Leda Clay has been deemed responsible for numerous infrastructure failures, and some of the most devastating landslides in the region's history. While it would be preferable avoid such geology all together, it is however important to understand, master its defining geotechnical characteristics to better inform and optimize the design and construction of infrastructure bearing overtop it.

The primary objective of this paper is to present a case study detailing the geotechnical design and construction approach undertaken by AtkinsRéalis for the Trillium Line Extension Project in Ottawa, ON. The paper seeks to address the challenges posed by the presence of Champlain Sea Clay and highlights innovative and efficient solutions applied to optimize the project's schedule and accommodate right-of-way constraints. Specifically, the objectives are as follows: 1) To provide a detailed analysis of the subsurface conditions, particularly the consolidation characteristics of the silty clay deposit, through a comprehensive geotechnical investigation campaign. 2)To outline the design process, including the application of accelerated consolidation techniques using vertical wick-drains and surcharging, coupled with the strategic use of lightweight EPS embankment fill to manage settlements effectively. 3) To validate design assumptions and predict ground response during construction using Finite Element modeling (Plaxis2D) and a comprehensive geotechnical instrumentation and monitoring program (GIMP).

2 PROJECT BACKGROUND AND SETTING

AtkinsRéalis was retained to carry out the geotechnical design for the Trillium Line Extension Project (the Project) in Ottawa, ON. The project consists of 5 segments, as shown below in Figure 1.

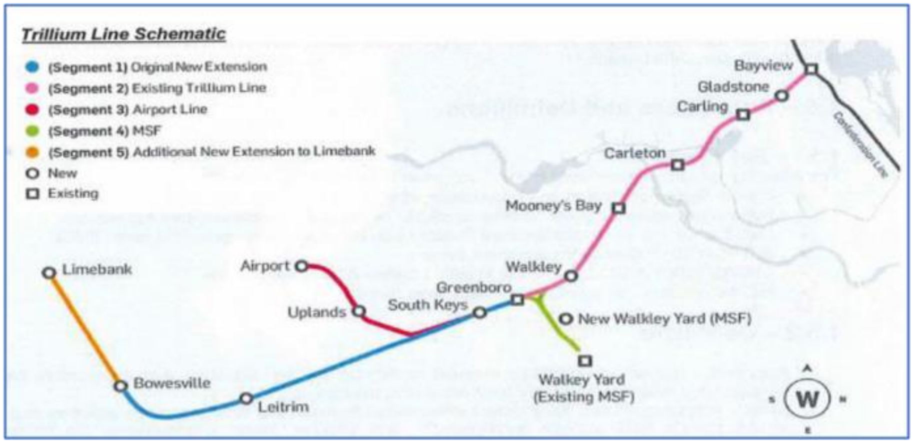


Figure 1 - The Trillium Extension Project

The Trillium Line Extension Project is currently in construction to extend the existing OC Transpo line to the proposed Limebank Station (near the intersection of Limebank Road and Earl Armstrong Road). The total length of the proposed extension is approximately 15 km, which includes an approximate 4 km Airport spur to the existing Ottawa Macdonald-Cartier International Airport (OMCIA).
An approximately 9-meter-high approach embankment – The Embankment at Limebank Road – constitutes part of the East approach to the Limebank rail Bridge. This 9 m high embankment, at the structure, gradually tappers down over about 300 meters stretch to reach the existing grade. The embankment is retained by a Mechanically Stabilized Earth (MSE) wall to the North and sloped to the South.

3 SUMMARY OF SUBSURFACE INVESTIGATION

An initial geotechnical baseline geotechnical data report provided by the project indicated that in general, the overburden encountered at the site consists of a silty clay deposit underlain by a granular till overlaying Sandstone bedrock of the March Formation.
In-situ testing was completed to obtain geotechnical parameters such as undrained shear strength and N(SPT). Similarly, 3 oedometer tests were carried out on samples from three boreholes: RS-20 located 60 m south of the station, RS-17 at 75 m north and RS- 15A at 300 m east of the East Abutment). These boreholes are shown (red marker) in Figures 2 and 3.

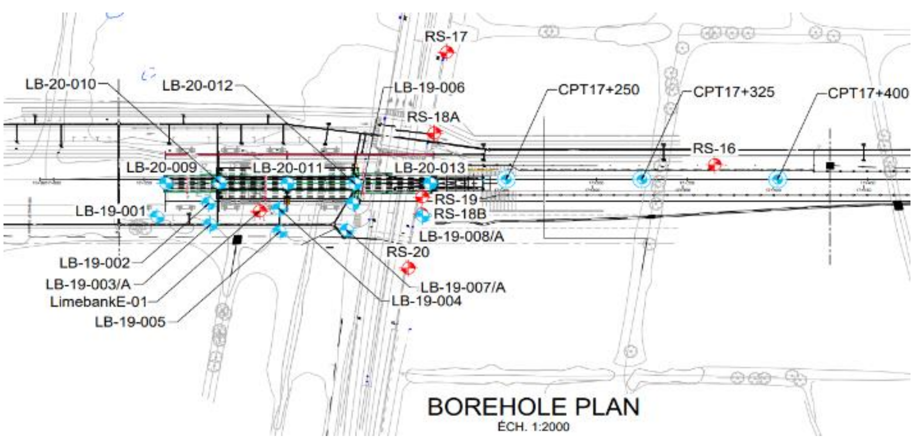


Figure 2 Investigation site plan

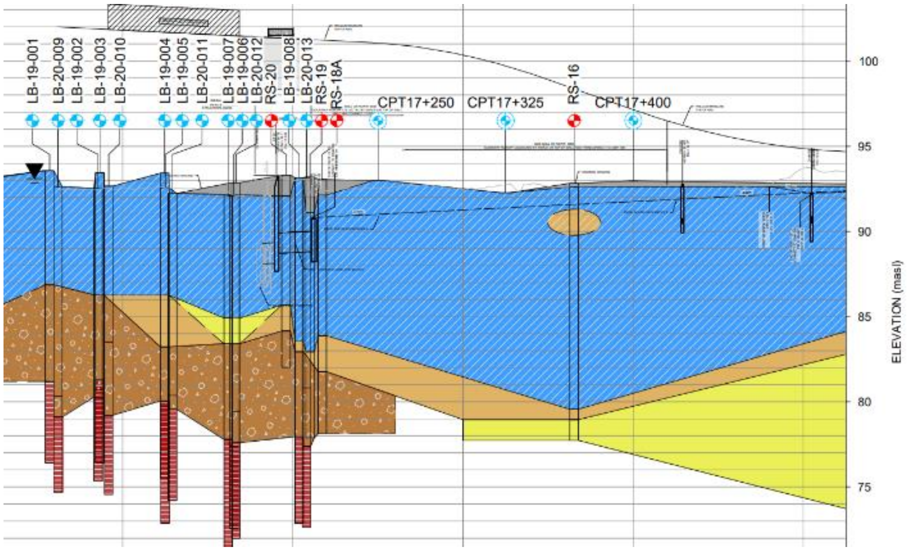


Figure 3 Stratigraphic Cross-section

The Pre-Consolidation Pressures (PCP) obtained from the odometer tests are respectively 160, 285 and 190 kPa. These odometer tests results showed that the clay layer is in an over consolidation condition with ratios ranging from OCR=3,4 to 4,5 - this translates to an over-consolidation margin (OCM) of about 125kPa, as shown in Figure 3, below where a summary of the information interpreted for the site that shows the effective pressure at the site alongside the estimated pre-consolidated pressures are presented.

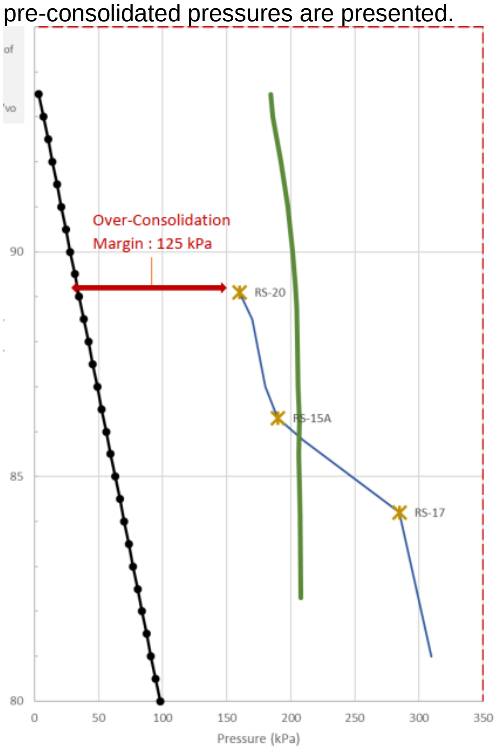


Figure 4 Effective and Pre-Consolidation Pressures Vs Elevation _ Baseline Data

Subsequent supplementary investigation completed by AtkinsRéalis, including sCPTu sounding, higher frequency in-situ undrained shear strength measurements using the Nilcon vane, further uni-axial consolation, and battery of laboratory index testing campaign revealed considerably tighter over-consolidation margins.

Figure 5, below, illustrated the interpreted Effective as well as Pre-consolidation pressures versus elevation.

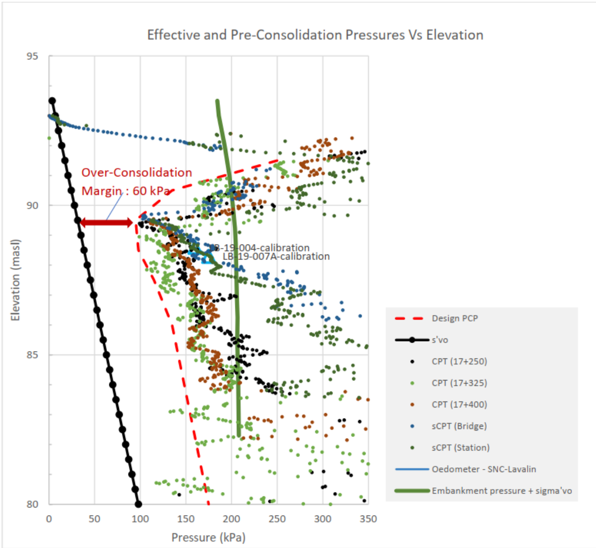
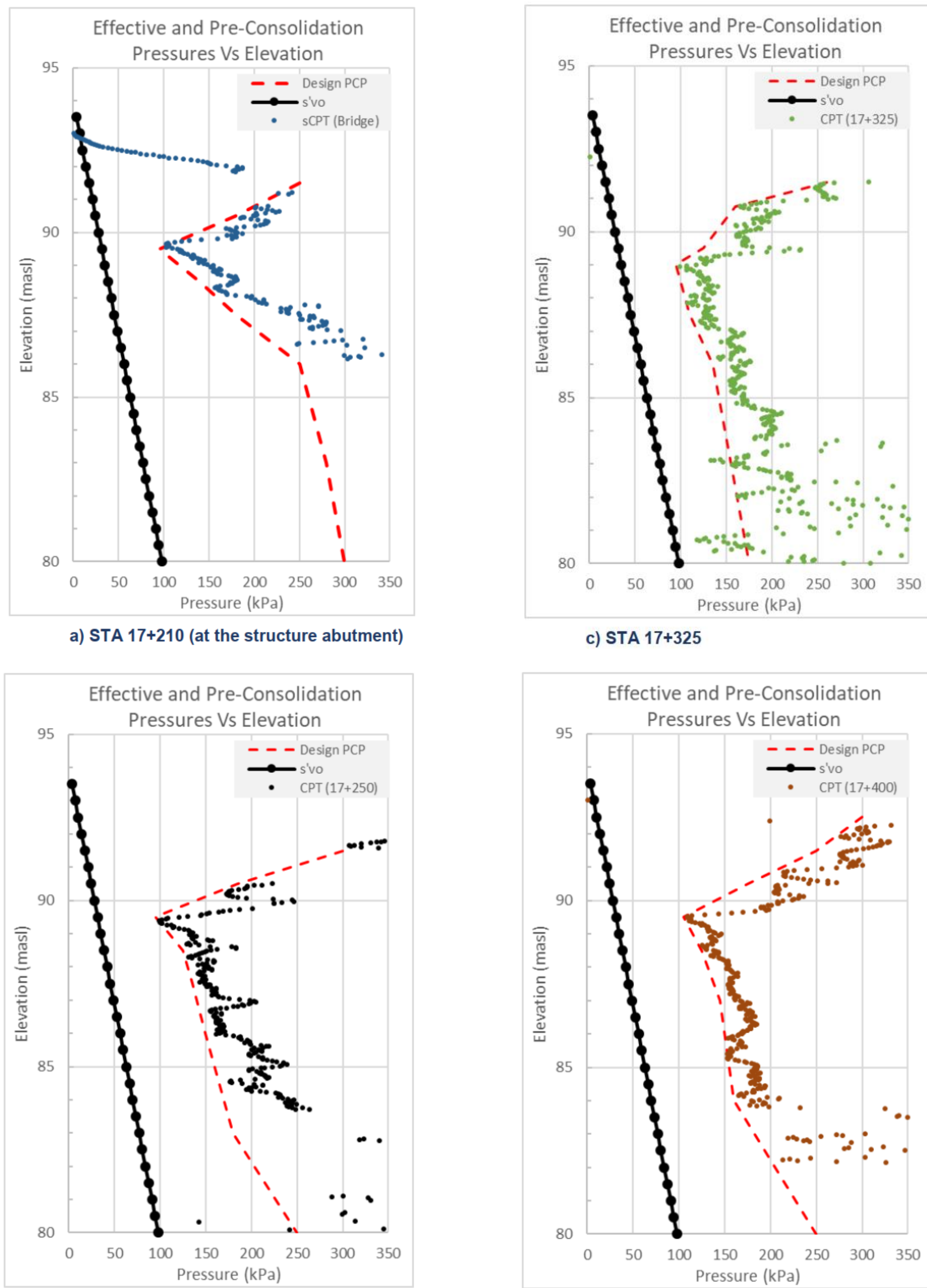


Figure 5 Effective and Pre-Consolidation Pressures Vs Elevation _ Supplementary Data

Pre-consolidation pressure of clay deposit is one of the key properties of Champlain Sea Clay. The state of practice for investigations for such a clay dictates that the minimum value of the pre-consolidation pressure of the clay deposit must be established. For this purpose, the usual state of practice is the provide a clear shear strength profile with values at every 1 m (or less) and then to take a representative intact sample at the minimum shear strength values level to get a sample from such a layer to conduct an Odometer test (Standard Test Methods for One Dimensional Consolidation Properties of Soils). The data obtained in such a process will give us the minimum value of clay's pre-consolidation pressure. The data obtained from this minimum value and odometer test are used to estimate the magnitude of total settlement and also the time of consolidation. These two parameters are essential to design the bridges, buildings and mainly the approach embankment fill to bridges. These parameters are of key importance in the design of engineered structures and the evaluation of their performance. (ASTM D2435)

The data gap identified in the baseline information is that process explained earlier was NOT applied and instead, the shear strength was measured seemingly sporadically, and samples of intact clay submitted to consolidation test were NOT targeted at the governing lowest values as state of the practice dictates it in such a Champlain Sea clay deposit.

The design pre-consolidation pressure (PCP) envelope is further optimized along the guideway covered under the scope of the current design report by utilizing location specific data where appropriate. It is evident that the silty clay layer encountered presents the same governing pre-consolidation pressure of about 60 kPa at an elevation of about 89.25 m to 89.50 m. That said, the pre-consolidation pressure envelop varies slightly as shown in plots a) through to d) of Figure 6.



a) STA 17+210 (at the structure abutment)

c) STA 17+325

b) STA 17+250

d) STA 17+400

Figure 6 Optimized Effective and PCP Vs Elevation

4 PROPOSED INFRUSTRUCTURE AND DESIGN

An approximately 9-meter-high approach embankment – The Embankment at Limebank Road – is planned at the East approach to the Limebank structure. The present report covers the stretch of the guideway from STA 16+900 to 17+500, where the embankment height is at its maximum of about 9 m at the East abutment (~17+210) and decreases to about 0 m around STA 17+500. Due to property limit restraints as well adjacent roads, a combination of MSE walls and slopes are proposed to retain the embankment fill on the north side.

Fill Area	Stations*	Description	Length (m)	Height profile (m)	Proposed side slope
Past Limebank station	16+900 to 17+060	Elevated guideway	160	N.A.	N.A.
Limebank Station and Bridge	17+060 to17+210	Elevated guideway	150	N.A.	N.A.
Diamond track crossing	17+210 to 17+240	Lightweight fill	30	9 to 8.2	Vertical walls
Fill zone	17+240 to 17+500	East approach fill	260	9.0 to 0	1.75H:1V With MSE walls

Soil type	γ_{tot} (kN/m³)	Cu (kPa)	c' (kPa)	φ' (°)
Embankment Fill (Granular B Type II or eq.)	22	--	0	41
Silty clay (crust)	16	>50[1]	7.5[2]	29[2]
Silty Clay	17	35 to 65 55 to 65 [3] 48 to 65 [4]	7.5[2]	29[2]
Silty Sand	18	0	0	33
Till	21	0	0	36

The site at Limebank embankment is characterized by the presence of compressible silty clay layer with minimal margin between effective and pre-consolidation pressures as illustrated earlier.

Figures a) through to d) of Figure 6, presented earlier, allow appreciation of the actual effective ground pressure across the site compared to the pre-consolidation pressure of this silty clay layer. These Figures show that the clay at the site is over-consolidated with governing margins ranging from about 50kPa to 65kPa at an approximate elevation of about 89 masl to 90 masl. The approach fill was expected to induce a peak pressure of about 180 to 200 kPa on the native soils.

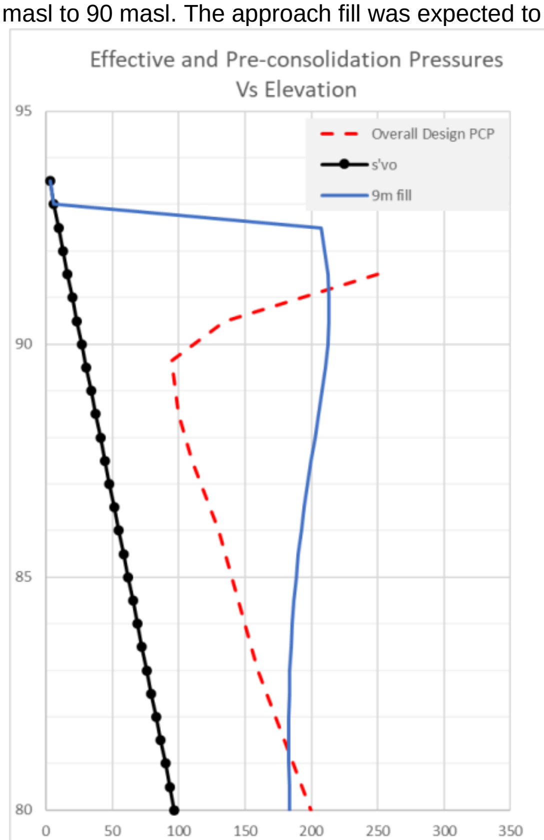


Figure 7 Additional loading as a result of embankment construction

This pressure will stress the silty clay layer past its highest historical stress – the pre-consolidation pressure – thus triggering consolidation settlements, in addition to recompression settlements. This pressure would produce significant long-term settlement in the order of 850 mm to 950 mm primarily due to the consolidation of the clay layer near the highest embankment height. A gross estimation of total settlement under the centerline of the embankment is shown below.

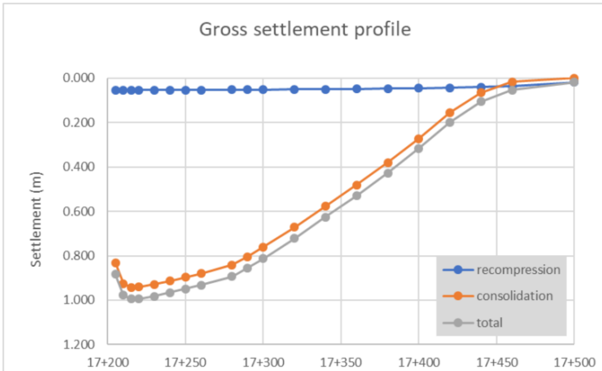
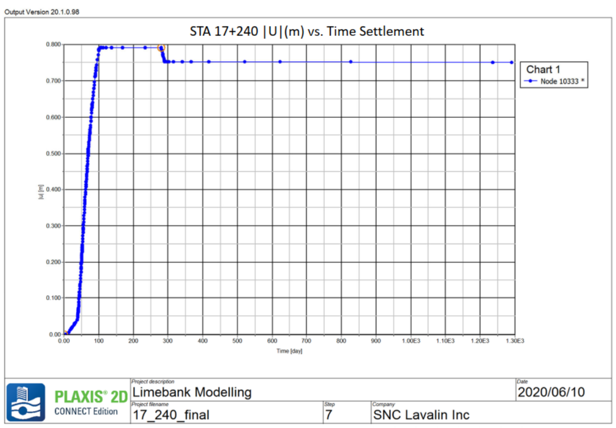
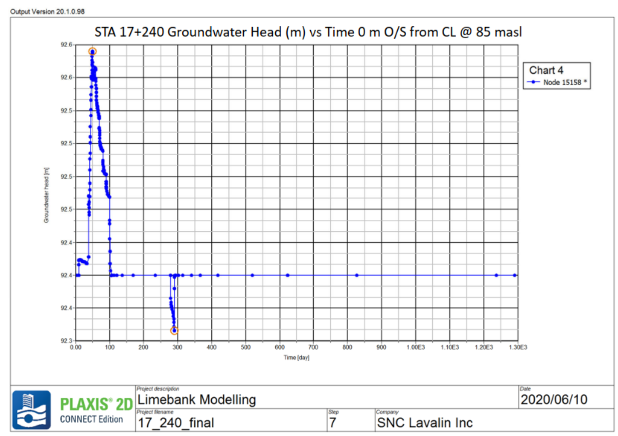
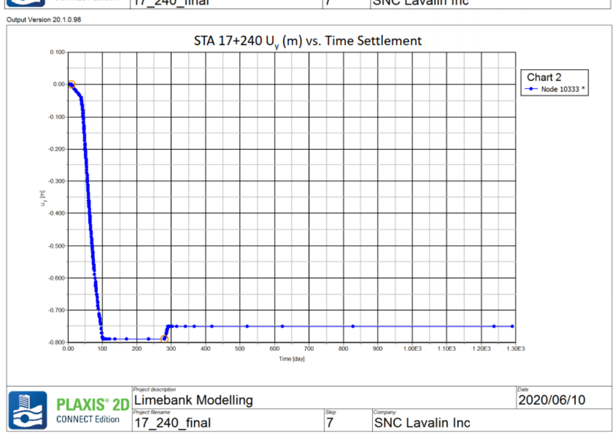


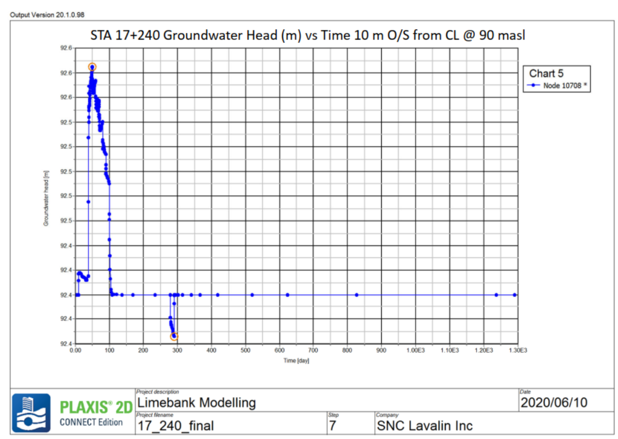
Figure 8 - Gross settlement estimation over time

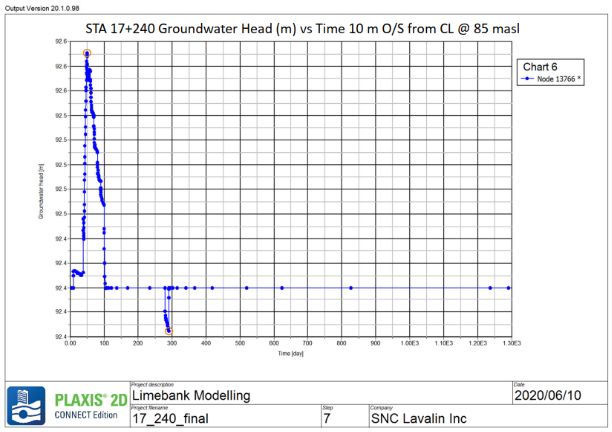
Consequently, an optimized accelerated consolidation surcharging program was designed implemented. This entailed in the installation of vertical wick-drain in a triangular pattern spaced at 1.2m and extending to base of the near normally consolidated silty clay deposit. The ground response in terms of settlement, pore water pressure and strength gains overtime were modeled through Finite Elements using Plaxis2D and later confirmed with a of purpose-built geotechnical instrumentation and monitoring program.











These models were reproduced at set intervals along the embankment stretch to capture the ground response at varying embankment heights, as well as changing ground conditions.

5 GEOTECHNICAL INSTRUMENTATION AND MONITORING PROGRAM

As stated earlier, given that the clay thickness under Limebank is of about 6 m to 10 m, pre-loading the clay with wick drains (installed in the silty clay layer) in order to have a reasonable consolidation time was implemented. The primary purpose of wick drains is to shorten drainage distance and consolidation delays. It is important to plan the embankment construction to avoid sudden over-pressurizing of the area and triggering global instability. As such, Bbar should be limited to 0.8 to ensure stability (Leroueil et al., 1977). Fill placement should be placed such that this threshold is not surpassed. SCs and VWPs are specified to be installed at the following locations.

Consequently, the fill placement was monitored both visually by means of regular survey reports as shown below, and a network instruments.

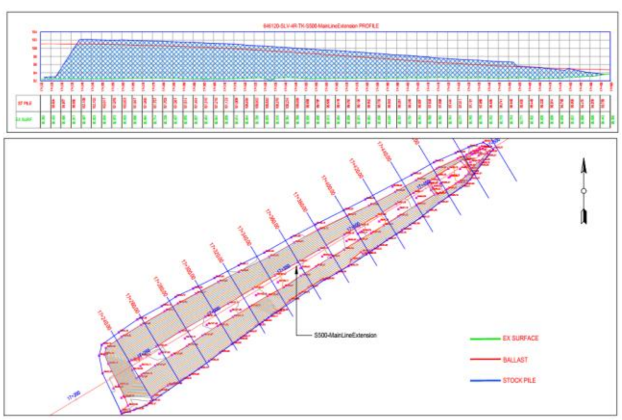


Figure 9 Embankment construction survey monitoring

Figure 10 GIMP instruments layout

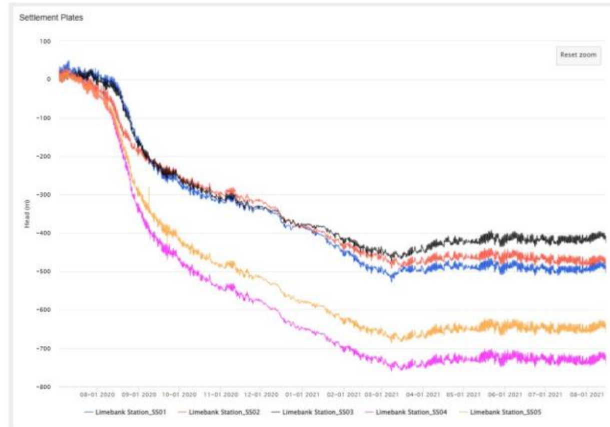


Figure 11 GIMP control unit

Figure 12 GIMP monitoring data

Following the near perfect validation of the FE Plaxis 2D modeling results through the GIMP monitoring data, the design of the final embankment, including the retaining wall on the norther face was confirmed, and constructed.

6 EMBANKMENT AND RETAINING WALL DESIGN

The right of way limitation North of the project alignment dictated that a vertical retaining structure be incorporated into the approach embankment as depicted below. that being said, the less than favorable strength parameters of the soft clay deposit posed challenges to the retaining wall design and required advanced analyses to ensure the requisite Factors of Safety for external stability in particular where satisfied. The final embankment design heavily leveraged the consolidation and settlement analyses discussed earlier and had to further deepened the approach by examining the enhanced strength parameters of the clay deposit as a result of consolidations beyond the PCP limits as detailed by Mesri (1989).

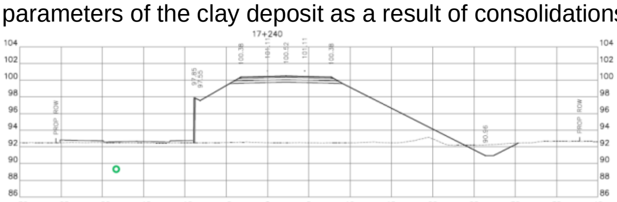


Figure 13 Original conceptual design

Additionally, a design change in the geometry of the embankment as shown below allowed further optimization to “distance” the bearing pressures from the surface of clay deposit by elevating the retaining wall:

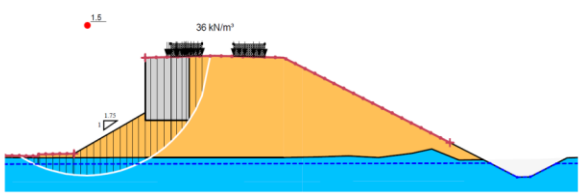


Figure 14 Optimized embankment geometry.

Moreover, an added design constraint at the east abutment was the presence of a diamond rail crossing supported on the approach embankment. Such crossings are known for their stringent requirements as it relates to both settlement, and elastic deflections. As such, the retained design solution for the embankment directly east of the bridge was conceived to virtually eliminate any concern of settlement by incorporating the use of EPS – a lightweight material weighing less than 1 kN/m3. Such innovative design ultimately allowed for a near null net additional loading on the silty clay deposit. A deeper look at the EPS mechanical properties was also completed to ensure the material offered sufficient stiffness under dynamic loading to mitigate deflections during rail traffic. The use of EPS was extended to a comfortable offset from the location of the diamond cross where impacts from settlement of the remainder of the embankment was eliminated, as shown in the below figure.

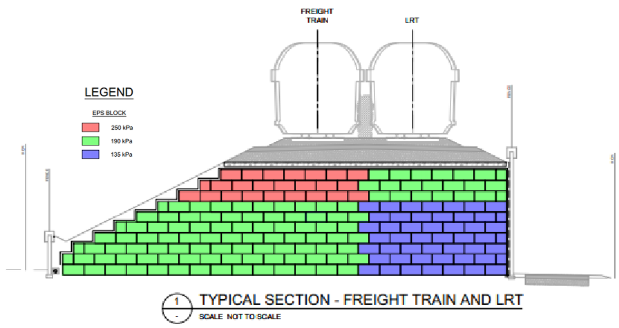


Figure 15 EPS Embankment configuration

7 CONCLUSION

In conclusion, the case study presented in this paper showcases a successful and comprehensive approach to address the challenges posed by construction on sensitive clays of the Champlain Sea deposit in Eastern Canada. The project's location in the Canadian National Capital Region and its association with a multi-billion-dollar transit initiative demanded innovative and efficient solutions to optimize schedule, accommodate right-of-way constraints, and meet stringent performance criteria.

The geotechnical investigation campaign carried out by AtkinsRéalis played a crucial role in providing accurate data on the subsurface conditions, especially the over-consolidation ratio (OCR) of the silty clay deposit. The identification of a lower OCR value than initially estimated required the team to rethink and tailor their design solutions accordingly.

The design process involved a combination of accelerated consolidation through vertical wick-drains and surcharging, complemented along with the strategic use of lightweight EPS embankment fill to manage settlements effectively. The approach successfully mitigated potential long-term consolidation settlements, meeting the specified thresholds. The implementation of a Mechanically Stabilized Earth (MSE) wall and slopes on the northern face of the embankment to accommodate right-of-way constraints demonstrated a balanced and versatile design approach.

The validation of design assumptions and predictions through Finite Element modeling (Plaxis2D) and a comprehensive geotechnical instrumentation and monitoring program (GIMP) provided a robust foundation for decision-making throughout the project. The near-perfect correlation between the monitoring data and the modeling results instilled confidence in the final design and embankment construction, ensuring a stable and safe structure.

The lessons learned from this case study can be invaluable for future projects facing similar challenges involving sensitive clays and time-sensitive schedules. Understanding the defining geotechnical characteristics of the Champlain Sea clay and adopting innovative and adaptive design solutions are crucial to the successful execution of infrastructure projects in the region.

Overall, this case study exemplifies how a collaborative and multidisciplinary approach, coupled with cutting-edge geotechnical investigation techniques and state-of-the-art monitoring systems, can lead to the effective and safe construction of complex infrastructure in challenging geological settings. The successful completion of the 9-meter-high embankment at Limebank Road serves as a testament to the ingenuity and expertise of the engineering team involved in this remarkable project.

Figure 16 Embankment currently under active use (dynamic rolling stock testing)