Settlement Analysis of EPCOR Tower in Edmonton

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ABSTRACT

Settlement of tall buildings founded on dense, overconsolidated soils is predominately elastic. For such cases, foundation settlement can be analyzed using the theory of elasticity if representative deformation moduli of foundation soils can be determined. This paper presents results of settlement analysis and measurements obtained during the construction of EPCOR Tower at Station Lands in Edmonton, Alberta. The EPCOR Tower is a 28-storey building founded on spread footings over glacial till and sand deposits. The foundation settlement was computed using elastic theory with deformation moduli derived from historic laboratory data and in-situ pressuremeter tests on foundation soils of similar deposition. Results of settlement prediction and measurement during the EPCOR Tower construction are comparable, indicating the applicability of elastic theory in the settlement analysis of large buildings founded on dense, overconsolidated soils.

RÉSUMÉ

Le tassement d'immeubles de grande hauteur sur des sols de dense consistance et surconsolidés est majoritairement de nature élastique. Pour ces cas, le tassement des fondations peut être analysé en utilisant la théorie d'élasticité s'il est possible de déterminer un module de déformation représentatif des sols de fondation. Cet article présente les résultats de l'analyse du tassement et des observations faites pendant la construction de la *EPCOR Tower* à Station Lands, Edmonton, Alberta. Il s'agit d'un immeuble de 28 étages fondé sur des semelles rectangulaires reposant sur des dépôts glaciaires de till argileux et de sable. Le tassement des fondations a été déterminé en utilisant la théorie d'élasticité et un module de déformation obtenu par la combinaison de données de laboratoire historiques et d'essais in-situ au pressiomètre réalisés sur des sols similaires à ceux des fondation. Les tassements mesurés lors de la construction de la *EPCOR Tower* sont comparables avec les prédictions théoriques ce qui indique l'applicabilité de la théorie de l'élasticité dans l'analyse du tassement d'immeubles de grande hauteur fondés sur des sols de dense consistance et surconsolidés.

1 INTRODUCTION

Settlements of foundations typically consist of time-dependent consolidation and instantaneously elastic deformations of soils underneath the foundations. Conventional practice for the foundation design is to select soil design bearing capacities that will limit both total and differential settlements to certain amounts which structures can tolerate without suffering substantial distresses. For buildings founded on soft soils, deformations due to consolidation are predominant and settlement analyses are typically based on consolidation theory. Consolidation tests are often carried out to determine compression index. Compared to the soft soils, dense, highly overconsolidated glacial till deposits often encountered in Western Canada are relatively incompressible and strong soils. For buildings founded on strong soils, foundation settlements will be predominantly elastic and can be analyzed successfully based on elastic theory (DeJong and Harris 1971; DeJong and Morgenstern 1973; and Clark 1998). The accuracy of the settlement analyses for foundations on strong soils therefore heavily depends on the reliability of the soil elastic parameters which are often developed from calibrated field and laboratory tests (Klohn 1965; Eisenstein and Morrison 1973).

The EPCOR Tower is an office tower currently under construction in downtown Edmonton, Alberta. The building is located on the north edge of the Edmonton central business district and is adjacent to a 26-storey building, the CN Tower. The EPCOR Tower consists of a 28-storey concrete reinforced structure with 4 levels of underground parkade. In addition, the proposed north extension of the Edmonton Light Rail Transit (LRT) from downtown Churchill Station to the Northern Alberta Institute of Technology (NAIT) will pass under the EPCOR Tower site. The City of Edmonton decided to build a 180 m long LRT box tunnel under the EPCOR Tower at the same time as the tower's four-storey underground parkade.

The EPCOR Tower is mainly supported on spread footings at depths ranging between 16 m and 21 m below the ground surface. The tower has a central core structure founded on a single raft foundation at the depth of approximately 20 m. The raft and spread footings were constructed by excavation into the dense till. Along the LRT alignment the EPCOR Tower footings were incorporated into the pre-constructed LRT box tunnel. The relative locations of the EPCOR Tower, CN Tower and LRT box tunnel are shown on Figure 1.

In this paper, geotechnical properties of the foundation soils derived from results of historic laboratory and in-situ pressuremeter tests were reviewed. Foundation settlements were analyzed using the elastic theory and the results were compared with those measured during the period of the tower construction.

2 GEOLOGY AND GEOTECHNICAL PROPERTIES OF FOUNDATION SOILS

2.1 Geology

The general soil stratigraphy in the City of Edmonton area consists of lacustrine clay overlying silty glacial till. The glacial till is underlain by preglacial sand and gravel deposits over very weak clay shale and sandstone bedrock strata (Kathol and McPherson 1975).

The results of the site investigation programs undertaken for the EPCOR Tower indicated that the main soil strata at the project site are typical of the central Edmonton area except for the presence of random fill varying between 1 and 2.5 m in thickness at the ground surface (Wang, Bobey, and Papanicolas 2008). The fill consisted of clay, sand, and gravel. The generalized soil units encountered in the test holes at the EPCOR Tower site are presented on the stratigraphic cross sections in Figure 2 and are summarized in Table 1. The approximate excavation limits and the EPCOR Tower footing base elevations are also shown in Figure 2.

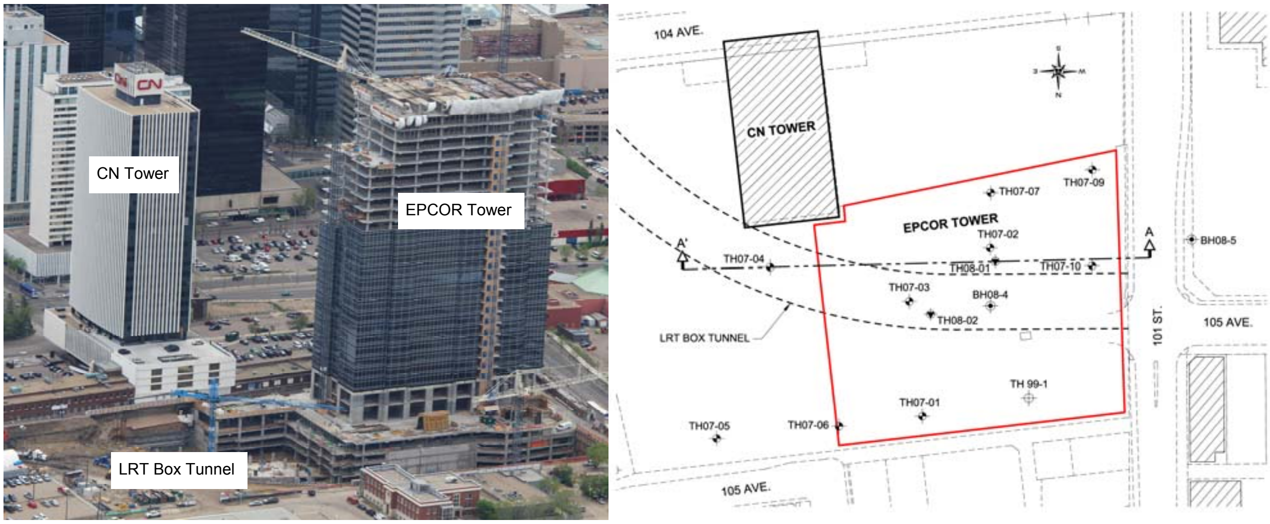

Figure 1. Locations of EPCOR Tower, CN Tower and proposed LRT box tunnel

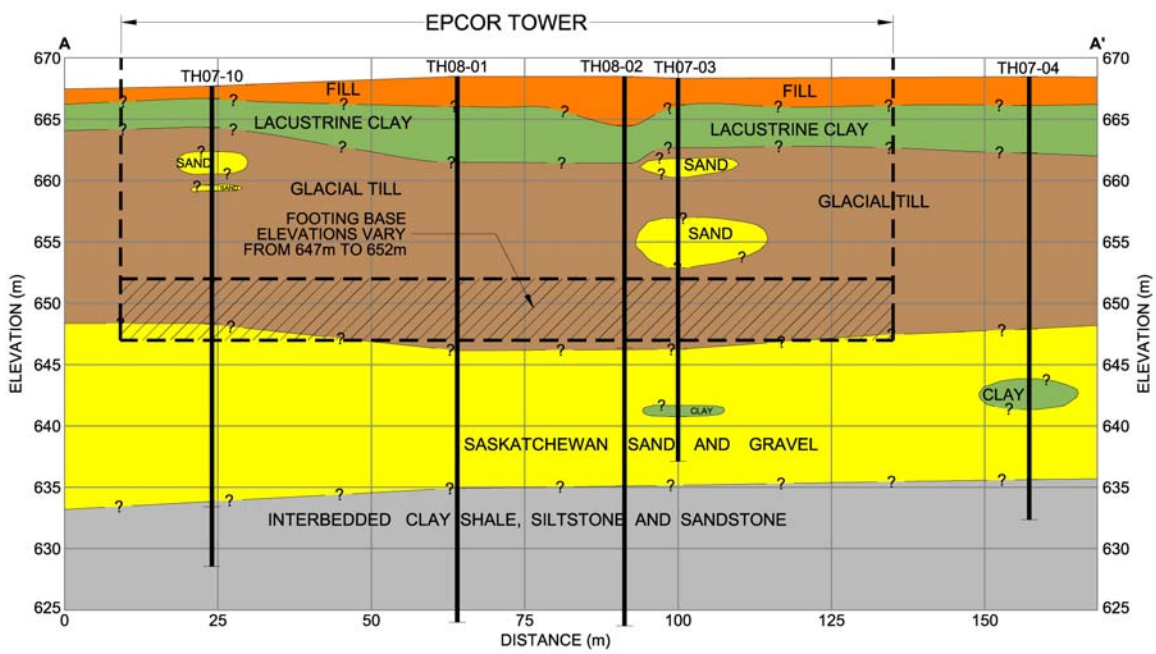

Figure 2. Stratigraphic cross sections A-A’

Table 1. Main stratigraphic units encountered at EPCOR Tower site

Stratigraphic unit	Description	Approximate thickness (m)	Water Content (%)	SPT N
Fill	Clay, sand and gravel	1 – 2.5	2 - 36	—
Lacustrine clay	Silty, containing sand lenses	3 – 4.5	25 - 50	8 - 16
Glacial Till	Sandy, silty clay containing coal, gravels, and sand lenses	14 – 16	10 - 30	40 - 60
Saskatchewan sand and gravel	Medium to fine grained sand, occasional sand and gravel mixture	11 – 15	5 - 15	40 – 100+
Bedrock	Interbedded clay shale, siltstone and sandstone	33 – 34*	10 - 30	100+

*depth to bedrock surface

2.2 Soil and Groundwater Conditions

Glacial till and Saskatchewan sand and gravel are the primary bearing media supporting the footings of the EPCOR Tower. Hence, determination of representative deformation moduli of the till and sand is of particular importance to predict the foundation settlements. During the site investigations for the EPCOR Tower development and LRT extension, a number of test holes were drilled within the footprint of the EPCOR Tower. The test hole locations are shown in Figures 1 and 2.

Detailed site investigation revealed that the glacial till of 14 to 16 m in thickness was encountered below the lacustrine clay and extended to depths varying from 19 to 22 m below the ground surface. The till was generally brown, silty, and contained occasional water bearing sand lenses, gravels, pebbles, coal, and stones of a wide range of sizes. The water content of the till ranged from 10% to 30%. Results of the Atterberg limits tests undertaken on the till samples indicated that the till is low to medium plasticity. The liquid limits varied from 26% to 42% and the plastic limits ranged between 7% and 16%. The standard penetration blow counts (SPT N) recorded in the till below the footing level were typically in the range between 40 and 60 blows per 300 mm penetration.

The till was underlain by 11 to 15 m thick Saskatchewan sand and gravel deposits. The sand and gravel extended to bedrock at depths 33 to 34 m below the ground surface. The sand was dense to very dense, brown, silty, fine to medium grained with occasional clay and gravel lenses. Gradation analyses carried out on the sand samples indicated the fines (silt and clay) content in the sand deposits varied from 10% to 25%. The water content of the sand ranged between 5% and 15%. SPT N values recorded in the sand layer ranged from 40 blows to over 100 blows per 300 mm penetration.

During the excavation of LRT box tunnel, the interface between glacial till and Saskatchewan sand and gravel was clearly observed. As shown in Figure 3, the interface between till and sand was relatively flat and well-defined. It was also observed that the sand underneath the EPCOR Tower raft foundation demonstrated similar deformation behaviours as glacial till, being able to stand as a vertical cut for several weeks following the excavation.

Bedrock was encountered in the deep test holes drilled at the EPCOR Tower site. The bedrock consists of interbedded bentonitic clay shale, siltstone, and sandstone. Coal seams and bentonite layers were found throughout the bedrock to depths greater than 10 m below the bedrock surface.

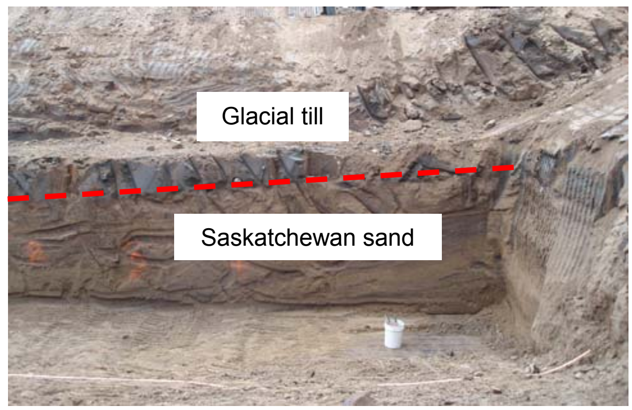

Figure 3. Interface between glacial till and Saskatchewan sand

Groundwater measurements during recent and previous site investigations in the EPCOR Tower area did not show any static groundwater table in the overburden soil layers. Perched water was encountered occasionally in water bearing sand lenses in the glacial till. Groundwater was not a concern and no significant seepage was experienced during the excavation of the EPCOR Tower foundation and LRT box tunnel.

2.3 Deformation Modulus of Foundation Soils

Comprehensive studies of the engineering properties of the till in downtown Edmonton area were carried out in the 1970s during the developments of CN Tower and LRT in City of Edmonton (DeJong and Harris 1971; Eisenstern and Morrison 1973; Madeiros 1979). A series of triaxial compression tests and consolidation tests were carried out on block samples recovered from the glacial till during the CN tower foundation excavation (DeJong and Harris 1971). The moduli of deformation were determined from the results of three unconsolidated undrained triaxial tests (UU), two consolidated undrained triaxial tests (CU), and six consolidation tests. The deformation moduli calculated from the UU tests ranged between 8 and 10 MPa, while the deformation moduli determined from the CU tests varied from 83 to 97 MPa. The calculated deformation modulus based on the consolidation test results ranged from 10 to 21 MPa. DeJong and Harris (1971) also back-estimated the deformation modulus of the glacial till based on settlement data observed during the CN Tower construction. The results of their back-calculation indicated that modulus of deformation determined from field observations was stress dependent, and significantly higher than those obtained from laboratory tests. Comparison of results from the field observations and laboratory tests indicated that deformation moduli of over-consolidated soils determined from the laboratory tests were highly sensitive to sample disturbance. Settlement predictions using consolidation test results could overestimate the actual settlement by an order of magnitude.

The strength and deformation properties of the glacial till in the central Edmonton area were measured by Medeiros (1979). The deformation moduli of the till derived from the unloading and reloading tests ranged from 142 to 165 MPa. A constant deformation modulus of 150 MPa was used for the glacial till to analyze deep excavations in the glacial till.

Pressuremeter tests were carried out in the vicinity of CN Tower building by Eisenstein and Morrison (1973) to determine in-situ deformation moduli of the foundation soils. Results of the in-situ pressuremeter tests indicated a very similar deformation behaviour of the glacial till and Saskatchewan sand and gravel. The measured deformation moduli for the glacial till and Saskatchewan sand and gravel ranged from 120 to 245 MPa. The estimated deformation modulus of the interbedded clay shale and sandstone ranged from 345 to 900 MPa. Moduli of deformation ranging between 180 and 240 MPa were used for the glacial till and Saskatchewan sand and gravel to calculate settlement of the CN Tower foundation. Good agreement was obtained between the calculation and the field observation.

3 SETTLEMENT ANALYSIS

Calculation of foundation settlement using elastic theory requires representative deformation parameters of the foundation soils and the determination of the stress changes in the soil mass due to foundation loads. Boussinesq method and Westergaard equations are commonly used in engineering practice to compute the stress distribution under the footings. In this paper, Settle 3D developed by Rocscience Inc. was used to analyze the settlement of the EPCOR Tower foundations. Settle 3D is a three-dimensional program developed for the analyses of vertical settlement and consolidation under surface loads such as foundation and embankment. The three-dimensional stress distribution in the soil mass generated by the surface loads can be calculated using Boussinesq method or Westergaard equations.

3.1 Footing Layout, Loads, and Foundation Soil Properties

The EPCOR Tower is founded on a core raft foundation, a number of spread footings and cast-in-place end bearing piles. Similar to the EPCOR Tower core structure, the LRT box tunnel is also founded on a raft foundation. The rafts for the EPCOR Tower and LRT box tunnel are abutting but separate and perform independently. The raft foundation for the EPCOR Tower core structure is about 31.5 m wide, 42.5 m long on the south and about 78 m long adjacent to the LRT box tunnel. The spreading footing dimensions vary from 2.8 m X 2.8 m to 6.8 m X 16.7 m in the area. Soils underneath the raft foundation and a majority of spread footings consist of 1 to 3 m thick glacial till over the Saskatchewan sand and gravel. The raft of the LRT box tunnel is about 18.5 m wide and 180 m long and founded on the top of the Saskatchewan sand and gravel deposits. Several footings of the EPCOR Tower immediately adjacent to the LRT are also founded on the top of the Saskatchewan sand and gravel. A total of 19 cast-in-place concrete piles were installed during the EPCOR Tower construction: one pile at Grid Lines C14, 14 piles along Grid Line J’, and a pile group consisting of 4 piles at Grid Lines D14. Piles located at Grid Lines D14 are founded on the bedrock and the rest piles are founded on the top of the Saskatchewan sand and gravel. Bell sizes of the pile foundations range from 1.1 to 3.2 m in diameter. The layout of the LRT, raft foundation, spread footings, and pile foundations are shown on Figure 4.

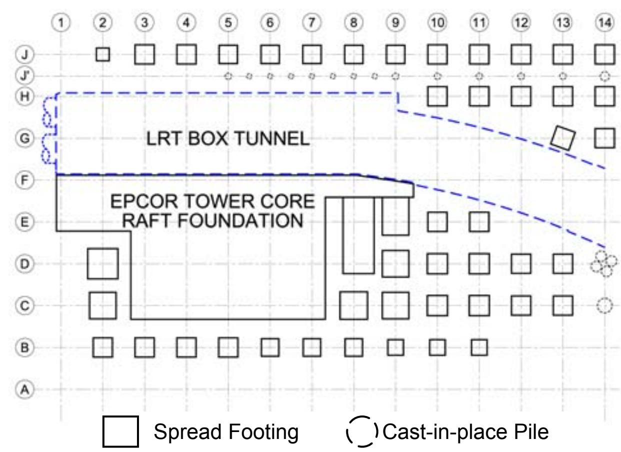

Figure 4. Layout of EPCOR Tower foundations and LRT Box Tunnel

Settlement analyses were carried out using average pressures acting at soil and footing contact upon completion of the EPCOR Tower construction. The footing pressures were estimated from factored structural design loads reduced by appropriate factors. The work by Dejong and Harris (1971) indicated that the footing loads estimated in this manner were close to those determined from the records of delivered concrete quantities during the construction period. The average contact pressures used in the settlement analyses were: 680 kPa for the spread footings; 600 kPa for the EPCOR Tower raft foundation; 135 kPa for the LRT box tunnel raft; and 1100 kPa for the pile foundations.

Previous studies (DeJong and Harris 1971; JeJong and Morgenstern 1973; and Eisenstein and Morrison 1973) indicated that settlement analyses using deformation moduli of glacial till and Saskatchewan sand and gravel derived from the laboratory tests are conservative and tend to overestimate the actual settlement by an order of magnitude. Therefore, the deformation moduli derived from the results of the in-situ pressuremeter test (Eisenstein and Morrison 1973) were used in the settlement analysis. The estimated deformation parameters for the glacial till, Saskatchewan sand and gravel, and underlying bedrock are presented in Table 2.

Table 2. Foundation soil properties used in the settlement analysis

Foundation soils	Thickness (m)	Deformation modulus (MPa)	Poisson's ratio
Glacial till	2	150	0.4
Saskatchewan sand and gravel	14	200	0.35
Upper bedrock	10	240	0.3
Middle bedrock	10	585	0.3
Lower bedrock	30	985	0.3

3.2 Footing Settlement Predicted and Measured

Footing settlements calculated from the Settle 3D analysis are presented in the form of a contour plan in Figure 5. As shown on the figure, the EPCOR Tower raft foundation settled in the shape of a dish. The largest settlement calculated was about 51 mm and located near the center of the raft. The amount of settlement decreased constantly from the center towards the edges.

Settlement near the center of the south edge of the EPCOR Tower raft was about 33 mm. Settlement at center of the raft edge adjacent to LRT was about 36 mm. The calculated maximum differential settlement of the raft foundation was approximately 15 mm over a 12.5 m span. The distortion resulting from the differential settlement is considered to be within acceptable limits for the performance of the structure.

Settlement calculated at the centers of the spread footing ranged between 12 and 42 mm. In general, settlement of the spread footing decreases as the increases of the distance between the spread footing and EPCOR Tower raft foundation. The calculated maximum settlement of the spread footings was approximately 41.5 mm and located at Grid Lines E8 immediately adjacent to the EPCOR Tower raft foundation.

Settlement calculated for pile foundations was in a small range between 15 and 17 mm.

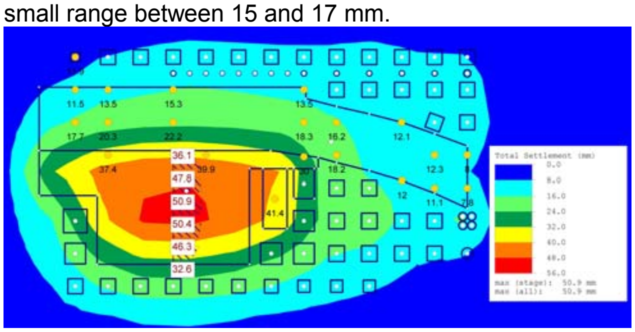

Figure 5. Footing settlement contour plan from Settle 3D analysis

Settlements of the EPCOR Tower raft foundation and the LRT box tunnel were observed by measuring the change in elevations at selected monitoring points. Three settlement points were installed on the north edge of the EPCOR Tower raft foundation along Grid Line F and sixteen settlement points were installed on the roof slab of the LRT box tunnel between Grid Lines 1 and 14. The settlements of the EPCOR Tower raft and LRT box tunnel were monitored on a bi-weekly basis. Two settlement points on the raft foundation were surveyed over the period of time between April 16, 2009 and May 11, 2010 and one settlement point of the raft foundation was monitored from April 16, 2009 to October 4, 2010. Settlement points on the LRT roof slab between Grid Lines 1 and 14 were surveyed between May 22, 2009 and November 16, 2010.

Results of the settlement observations for Tower core raft foundation and LRT box tunnel are presented on Figures 6 to 8. Also shown on the figures are calculated settlements at the corresponding survey points. The time for the calculated settlements shown on the figures was determined based on the date when settlement monitoring started and the date when the EPCOR Tower construction was completed.

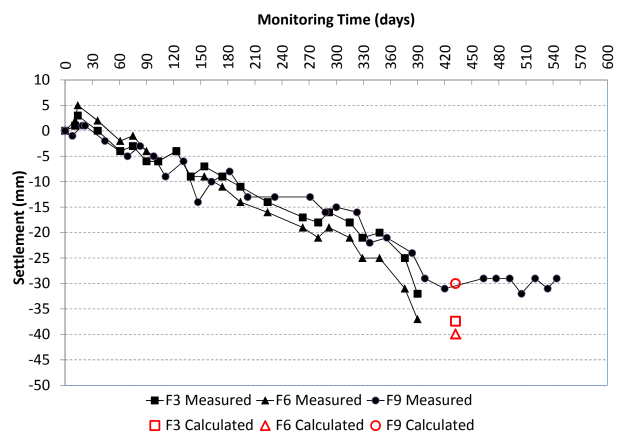

Figure 6. Comparison of measured and calculated EPCOR Tower raft foundation settlements along Grid Line F

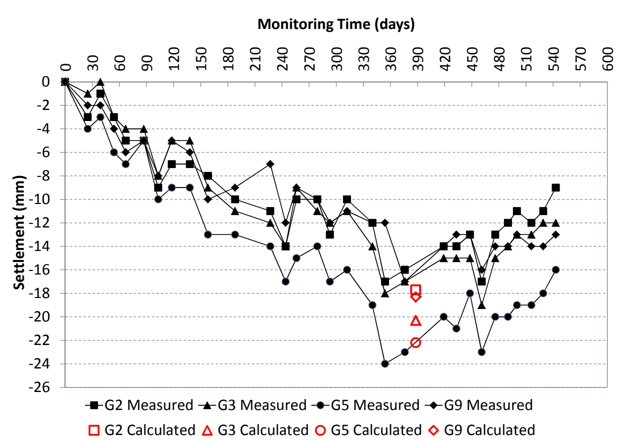

Figure 7. Comparison of measured and calculated LRT box tunnel settlements along Grid Line G

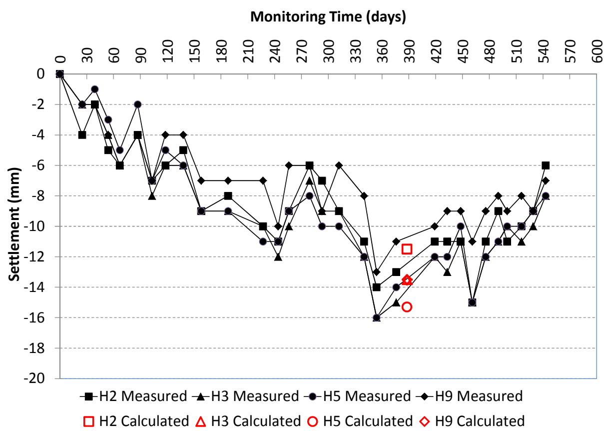

Figure 8. Comparison of measured and calculated LRT box tunnel settlements along Grid Line H

As shown on Figure 6, heave up to 5 mm was observed at settlement points on the EPCOR Tower raft foundation in the first two weeks. Following the foundation soil rebound, the settlement of the raft foundation increased consistently as the construction of the EPCOR Tower proceeded. A near linear relationship between settlement and time of the construction, i.e., footing pressure, was demonstrated on Figure 6. Settlement observation at monitoring point F3 also showed that settlement was almost constant after the construction was completed, indicating a quite rapid settlement response to the footing loading. Results of the settlement monitoring of LRT box tunnel in Figures 7 and 8 showed similar relationship between the settlement and foundation contact pressures.

As shown in Figures 7 and 8, rebound of approximately 4 mm and 6 mm was measured at LRT box tunnel along Grid Lines G and H, respectively, following the completion of the EPCOR Tower construction. The rebound observed was likely the response of foundation soils to excavations carried out at immediately north of the LRT box tunnel during the EPCOR Tower North Parkade construction. In addition, substantially higher contact pressures underneath the adjacent EPCOR Tower core raft foundation might also result in the bulging of foundations soils under the LRT box tunnel.

In general, reasonable agreement was obtained between settlement observations and predictions on Figures 6 to 8. This provided evidence that settlement of footings founded on dense glacial till and Saskatchewan sand and gravel can be predicted within the framework of the theory of elasticity.

4 CONCLUSION

The EPCOR Tower is a 28-story building founded on dense glacial till and Saskatchewan sand. Settlement monitoring during the tower construction indicated a quick response of the settlement to the loads and a near linear relationship between the settlement and the footing pressure. Settlement during the construction stage can be analyzed using the elastic theory and soil deformation parameters determined from the results of the previous pressuremeter test.

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