Validating Ground Improvement Performance Using InSAR: A Case Study on Controlled Modulus Columns (CMC)

Trevor Bruce, Simon Bunieski, Houman Soleimani Fard, Samuel Briet, Julien Egron, & Rachid Bennis
MENARD Canada Inc., Canada

Sebastian Amherdt & Andrea Garmendia
SIXENSE Satellite, Spain

ABSTRACT
Controlled Modulus Columns (CMC) are a ground improvement technique used to enhance soil stiffness and control settlement beneath structures built on compressible ground conditions. This study evaluates the long-term performance of CMC-treated sites using satellite-based Interferometric Synthetic Aperture Radar (InSAR), a non-invasive method capable of measuring millimetric ground displacements over time. An InSAR Historical Study was conducted using SIXENSE Satellite's Atlas processing chain to monitor seven buildings across Ontario and Quebec, Canada, where CMCs were installed prior to construction. Monitoring periods began approximately one month after construction and extended from 8 to 60 months. The analysis produced cumulative deformation maps and displacement time series, enabling the identification of settlement trends and seasonal variations. Results indicate that most sites remained stable throughout the observation period, with only minor localized deformations detected, all within acceptable limits. Variations in data density were influenced by surface characteristics and intermittent conditions such as snow cover and construction activity. Overall, the findings confirm that CMC ground improvement is effective in mitigating settlement and ensuring long-term stability of supported structures. This study also highlights the value of InSAR as a practical tool for validating ground improvement performance and supporting engineering decision-making.

RÉSUMÉ
Les colonnes à module contrôlé (CMC) sont une technique d'amélioration des sols utilisée pour augmenter la rigidité du terrain et limiter les tassements sous les ouvrages construits sur des sols compressibles. Cette étude évalue la performance à long terme de sites traités par CMC à l'aide de l'Interférométrie Radar à Synthèse d'Ouverture (InSAR), une méthode non intrusive permettant de mesurer des déplacements du sol de l'ordre du millimètre au fil du temps. Une étude historique InSAR a été réalisée à l'aide de la chaîne de traitement Atlas de SIXENSE Satellite afin de suivre sept bâtiments situés en Ontario et au Québec, Canada, où des CMC ont été installées avant la construction. Les périodes de suivi ont débuté environ un mois après la fin des travaux et se sont étendues de 8 à 60 mois. L'analyse a permis de produire des cartes de déformations cumulées et des séries temporelles de déplacement, facilitant l'identification des tendances de tassement et des variations saisonnières. Les résultats montrent que la majorité des sites sont demeurés stables pendant la période d'observation, avec seulement de faibles déformations localisées, toutes inférieures aux seuils admissibles. Les variations de densité des mesures sont principalement liées aux caractéristiques des surfaces ainsi qu'à des conditions ponctuelles telles que l'enneigement et les activités de construction. Globalement, les résultats confirment l'efficacité des CMC pour limiter les tassements et assurer la stabilité à long terme. Cette étude met également en évidence l'intérêt de l'InSAR comme outil pertinent pour valider la performance des techniques d'amélioration des sols et appuyer la prise de décision en ingénierie.

1 INTRODUCTION

In this study seven ground improvement projects utilizing primarily Controlled Modulus Columns (CMC) across Ontario and Quebec, Canada, are presented. These projects involve the construction of various structures on subsoils that were unable to safely support the imposed structural loads or meet serviceability requirements. As part of these projects, building settlements were monitored using a satellite-based surveying technique known as Synthetic Aperture Radar (SAR), which provides near real-time measurements of surface displacement, particularly those occurring at building rooftops. This monitoring approach enables direct comparison between observed settlements and predicted values derived from design calculations.

One project in Casselman, Ontario was selected for in-depth analyses, whose subsurface conditions at the site consist of soft, sensitive clays of the Champlain Sea Basin in Eastern Ontario and Quebec, necessitating effective ground improvement measures to control settlement and enhance bearing capacity.

The primary objective of this paper is to evaluate commonly used calculation methods for the design of ground improvement using the CMC technique; although, one dynamic compaction project is also presented in this study. This evaluation is carried out by comparing predicted settlements with post-construction monitoring data from the case study building, with the aim of assessing the reliability of the design procedures and their potential applicability to similar projects and ground conditions.

It should be noted, however, that the findings of this study are specific to the conditions of the project site and may not be directly transferable to other locations. Independent, project-specific assessments remain essential to account for variations in subsurface conditions, loading requirements, and construction constraints.

2 CONTROLLED MODULUS COLUMNS (CMC)

Controlled Modulus Columns (CMCs), also referred to as rigid inclusions (RIs), are a ground improvement technique that has seen increased adoption in the Canadian market in recent years. Their applications include, but are not limited to, the support of residential and commercial structures, industrial facilities, embankments, and wind turbine foundations. The CMC system consists of reinforcing existing soil using a grid of vertical inclusions, typically installed at center-to-center spacings ranging from 1.5 m to 3.0 m, with column diameters generally between 250 mm and 450 mm.

The principal function of CMCs is to transfer a portion of the structural loads from the surface to deeper, more competent soil strata by utilizing a grid of CMC elements below the structure to be supported. In contrast to conventional deep foundation systems, which are designed to transfer nearly the entire load to very stiff bearing layers such as bedrock through limited discrete elements, CMCs rely on load sharing between the rigid inclusions and the surrounding soil. This load-transfer mechanism is facilitated by a Load Transfer Platform (LTP), consisting of a compacted granular layer placed above the tops of the CMCs. Load sharing occurs via arching within the LTP and mobilization of negative skin friction along the upper portion of the columns. The effectiveness of this mechanism depends on several factors, including soil stratigraphy, soil compressibility, LTP thickness, and the embedded length of the CMCs.

Installation of CMCs is typically performed using a specialized displacement hollow-stem auger, followed by low-pressure grouting during auger extraction. The columns are formed using cementitious materials, such as ready-mix concrete or grout, with unconfined compressive strengths typically ranging from 15 to 30 MPa.

3 INSAR SURVEY TECHNIQUE

3.1 SAR Interferometry

Radar satellite interferometry is a non-invasive surveying technique able to measure millimetric motion of terrain structures over wide areas in both urban and non-urban environments. Satellite monitoring techniques are based on the exploitation of synthetic aperture radar (SAR) images. A SAR image is made of complex numbers; it contains amplitude and phase information. Solutions based on radar interferometry (InSAR) use the phase information to compare two SAR images acquired over the same area at different dates, and compute ground displacements information based on the radar waves travel time (Figure 1).

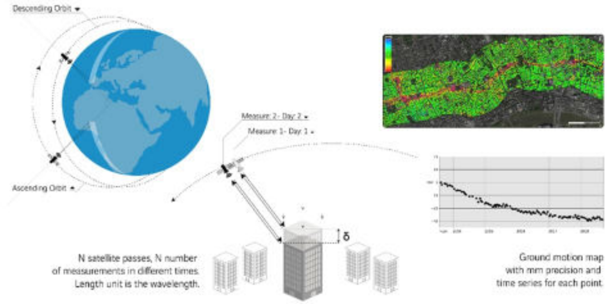


Figure 1. SAR interferometry working principle

Persistent Scatterer Interferometry technique (PSI) takes conventional InSAR a step further to get millimetric precision on the ground motion readings, that is done by correcting atmospheric, orbital and topographic errors. The PSI algorithm identifies common pixels/points (geographical locations) in each image that reflect persistently the radar signal back to the sensor. These locations are permanent reflective targets, whose reflections remain constant over the whole image stack during the duration of a project. They are generally man-made structures or rocky outcrops but can also be other ground features whose surface characteristics allow a perfect reflection of radar waves. The position and density of the measurement points retrieved depends strongly on the characteristics of the studied area.

The InSAR processing was performed using a proprietary processing chain optimized for monitoring geotechnical and structural deformations. Atlas is in constant development to keep up with new opportunities offered by the unprecedent spatial and temporal volume of SAR data.

3.2 Technical Considerations

SAR is an active, side-looking sensor, which emits electromagnetic pulses (microwaves) and detects the reflection of these pulses from targets in the Line of Sight (LOS) direction. The obtained LOS measurement is the orthogonal projection of the real movement vector on the LOS direction, that is, on the line connecting satellite-surface (Figure 2), expressed as movement toward or away from the satellite. The displacement in LOS of a real vector movement is correlated to the incidence angles. Terrain conditions are also a key factor to understand the obtained measurements.

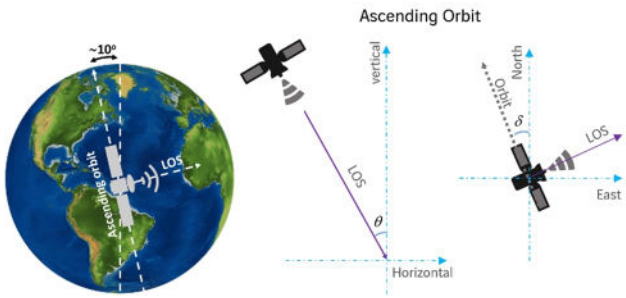


Figure 2. Ascending near-pole orbits (left), and measurements in LOS Ascending orbit (right)

The precision in the displacement measurements and in its positioning depends on the wavelengths of the chosen satellite, often referred to as bands. The wavelength of the microwave determines how the radar signal interacts with the surface and how deep it penetrates the medium of the target. The longer the wavelength the deeper the penetration into vegetation (and soil) but the lower the resolution, and the lower the sensitivity to surface motion.

Using medium resolution (C-band) satellite images from Sentinel-1 in Interferometric Wide Swath mode (wavelength of about 5 cm), the obtained precision in displacement measurements is about 3-4 mm, and the positioning precision is approximately 10 m in planimetry.

Using high resolution (X-band) satellite images in Spotlight mode (wavelength of about 3 cm), the obtained precision in displacement measurements is about 2-3 mm, and the positioning precision is around 1 m in planimetry.

3.3 Satellite Data Used in This Project

The Atlas InSAR displacement analyses presented in this study have been obtained using mid-resolution Sentinel-1 images for seven buildings and high-resolution TerraSAR-X images for one building, both in Ascending geometry. See Table 1 below for technical characteristics of images.

The incidence angle and the period of analysis used to perform the InSAR study vary for each building depending on the state of construction.

4 PROJECT SUMMARIES

In this study, the InSAR displacement readings from seven different ground improvement projects are presented in Table 2. The markers represent the measurement points, while the colors indicate the magnitude of cumulative displacement, as shown in the color scale. A brief description of each project is provided below. The results were all within the project requirements.

The satellite observations confirmed that the installed ground improvement system effectively controlled post-construction settlement in all projects, with observed total and differential settlements remaining within the project-specified thresholds of 25 mm and 19 mm, respectively.

Project 1: Retirement Facility - St Thomas, Ontario

Project 1 of this study involved the construction of a five-storey retirement facility located in St. Thomas, Ontario. Controlled Modulus Columns (CMCs) were implemented to support the building foundations, providing the required bearing capacity while limiting both total and differential settlements. Soil conditions consisted of heterogeneous fill overlying a native sand layer, underlain by soft to stiff clay extending to approximately 12 m below grade. A dense sand till deposit encountered at this depth served as the bearing and anchorage layer for the CMCs.

Displacement monitoring with InSAR was undertaken between January 2020 and December 2024 shortly following the completion of construction in December 2019.

Project 2: Brewery – Longueuil, Quebec

Project 2 involved the development of a brewery facility founded on ground improved using Controlled Modulus Columns (CMCs), selected as an alternative to deep foundations. The CMC system was employed to support building foundations, loading docks, and raft foundations associated with tank storage. Soil conditions consisted of an upper silty clay crust approximately 2.5 m thick, underlain by soft to sensitive silty clay deposits that increased in stiffness with depth. A dense silty sand till encountered at roughly 8 m below grade provided the anchorage layer for the CMCs.

Displacement monitoring with InSAR was undertaken between October 2020 and December 2024 shortly following the completion of construction in September 2020.

Project 3: Industrial Facility, Beauharnois Quebec

The project involved construction of a distribution centre with a total footprint approximately 39,000 m^2. Due to the soft compressible soils identified on site Controlled Modulus Columns (CMC) were installed to limit total and differential settlements for the north structure's foundations and slab on grade. The ground conditions can generally be described as a silty clay separate in three distinct sections, an upper silty clay crust approximately 2.5 m in thickness overlying a 9 m thick soft sensitive silty clay deposit underlain by a firm clayey silt deposit where CMCs were anchored. It is worth noting that the southern structure captured by the InSAR study is founded on deep foundations not ground improvement.

Displacement monitoring with InSAR was undertaken between September 2022 and December 2024 shortly following the completion of construction in April 2024. The satellite observations confirmed that the CMC system effectively controlled post-construction settlement.

Project 4: Residential/Commercial Development – Toronto, Ontario

This project involved the construction of a 7-storey combined commercial/residential structure with one level of underground parking in Toronto, Ontario. Controlled Modulus Columns (CMCs) were utilized to support the structures foundations in order to provide the required bearing capacity and limit total and differential settlements to within project criteria. Soil conditions generally consisted of an upper layer of heterogenous fill underlain by an upper native sand followed by a soft clay extending up to 10 m below grade before a hard clayey silt glacial till was encountered which served as the anchoring layer for the CMCs.

Displacement monitoring with InSAR was undertaken between May 2024 and December 2024 shortly following the completion of construction in April 2024.

Project 5: Industrial Facility – Welland Ontario

This project involved the construction of a state of the art manufacturing facility on a brown- field site involving the production of large aluminum components for electric vehicles. Controlled Modulus Columns were selected to support the structure's foundations in order to provide an increased bearing capacity and settlement control within project criteria. The project site was a brown-field site with upper fill material overlying a soft silty clay layer extending to approximately 18m below grade underlain by a dense sand till that served as the anchoring layer for the CMCs.

Displacement monitoring with InSAR was undertaken between February 2024 and December 2024 shortly following the completion of construction in January 2024.

Project 6: Industrial Warehouse – Mississauga, Ontario

This project involved the construction of an industrial warehouse in Mississauga, Ontario. Soil conditions consisted of a heterogenous fill material extending up to 12 m in depth underlain by dense till. The heterogenous fill encountered on site only affected one of the two warehouses being constructed with the western structure being supported on native till without ground improvement with the eastern structure was founded on fill material that was improved using Dynamic Compaction.

Displacement monitoring with InSAR was undertaken between June 2023 and December 2024 shortly following the completion of construction in May 2023. Unlike other case studies presented here, this project was not a CMC treatment. This project was studied to demonstrate that InSAR's applicability is not limited to one technique only. The satellite observations confirmed that the Dynamic Compaction performed effectively controlled post-construction settlement, with no discernable difference in performance between the two structures.

5 PROJECT 7: DISTRIBUTION CENTER – CASSELMAN, ONTARIO

The following sections present an in-depth case study of Project 7, undertaken to assess structural performance by comparing design-based performance expectations with displacement results derived from InSAR monitoring.

The project consisted of building an approximate 49,000 m^2 vehicle part distribution center. The facility was design from 15.25 m bays and an approximate building height of 13 m.

The geotechnical investigations undertaken for the project indicated a limited bearing capacity of 75 kPa SLS (110 kPa ULS) for shallow foundations with a maximum width of 4m and a grade raise limitation of 0.75 m.

Civil designs required an average grade raise of 1.5 m, with a maximum grade raise of 2.09 m to achieve Finished Floor Elevation (FFE). The requirements on the slab were up to 35 kPa. Column loads were designed up to 1620 kN.

The CMC system was designed to support the foundations (strip and isolated pad footings) with an increase in bearing capacity of up to 300 kPa SLS, support the grade raise, and the design slab loads to achieve a maximum post-construction settlement of 25 mm and 19 mm differential.

5.1 Ground Condition

Based on the borehole (BH) logs and Cone Penetration Test (CPT) soundings at around the west side of the case study building (for which the InSAR readings are taken into calculation for this study), the subsurface conditions across the site are generally consistent and dominated by fine-grained soils. A thin surficial layer of loose sand or sandy silt is locally present at or near ground surface. This is underlain by a thick sequence of silt and clay, typically described as brownish grey to grey, moist to wet, and soft to very soft, with SPT N-values as low as zero. As shown in Figure 3 the CPT data classify these materials mainly as silt mixtures and clays, with low cone tip resistance and elevated friction ratios confirming low strength and high compressibility. Minor interbedded sand or sand–silt mixtures are identified although discontinuous and with limited in thickness.

At greater depths, there is a transition to significantly stronger material. Several boreholes encounter compact glacial till composed of silt and sand with some clay and gravel-sized stone. The CPT soundings show corresponding increases in cone resistance and, in places, refusal. This dense to very dense unit represents the competent bearing stratum underlying the softer fine-grained deposits. While the depth to till or refusal varies somewhat across the site, no major stratigraphic variations are evident. In summary, the site is characterized by laterally extensive soft silts and clays overlying dense glacial deposits, with the CPTs providing continuous confirmation of soil variability and strength trends observed in discrete borehole data.

In

Table 3 the soil properties estimated based on the performed ground investigations are presented. These parameters have been used in the calculations of the following section.

5.2 Survey Results

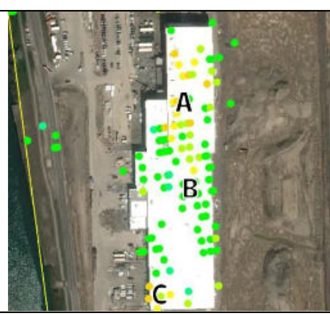
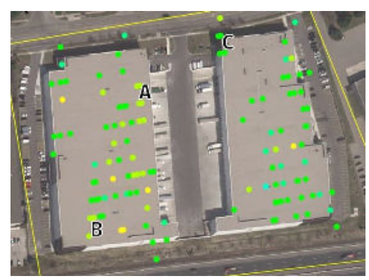
The InSAR monitoring period begins one month after the end of construction. start of monitoring usually coincides with roof completion, when most permanent structural loads had been applied. Measurement points are mainly derived from persistent scatterers located on buildings and associated infrastructure.

In addition, images with the presence of snow were excluded from processing, as they are not coherently stable in time. This is why there are data gaps for some buildings during the winter season.

Table 1. Technical characteristics of Sentinel-1 & TerraSAR-X studies

Satellite and mode	Band and orbit	Incidence angle [°]	Number images used	Spatial resolution [m]	Absolute precision [mm]	Geocoding precision [m]
Sentinel-1 IWS	C | ASC	36-46	176	20×5	3-4	10
TerraSAR-X Spotlight	X | ASC	26	72	1×1	2-3	<1

Table 2. Survey results for 7 ground improvement projects

Project 1 Retirement Facility St Thomas, ON GI System:CMC		Project 2 Brewery Longeuil, QC GI System: CMC	
Project 3 Industrial Facility Beauharnois, QC GI System: CMC (C,D), Piles (A,B)		Project 4 Residential/Commercial Development Toronto, ON GI Stem: CMC	
Project 5: Industrial Facility Welland, ON GI System: CMC		Project 6: Industrial Warehouse Mississauga, ON GI: DC (C), Native (A,B)	
Project 7: Distribution Facility Casselman, ON GI System: CMC		Scale	

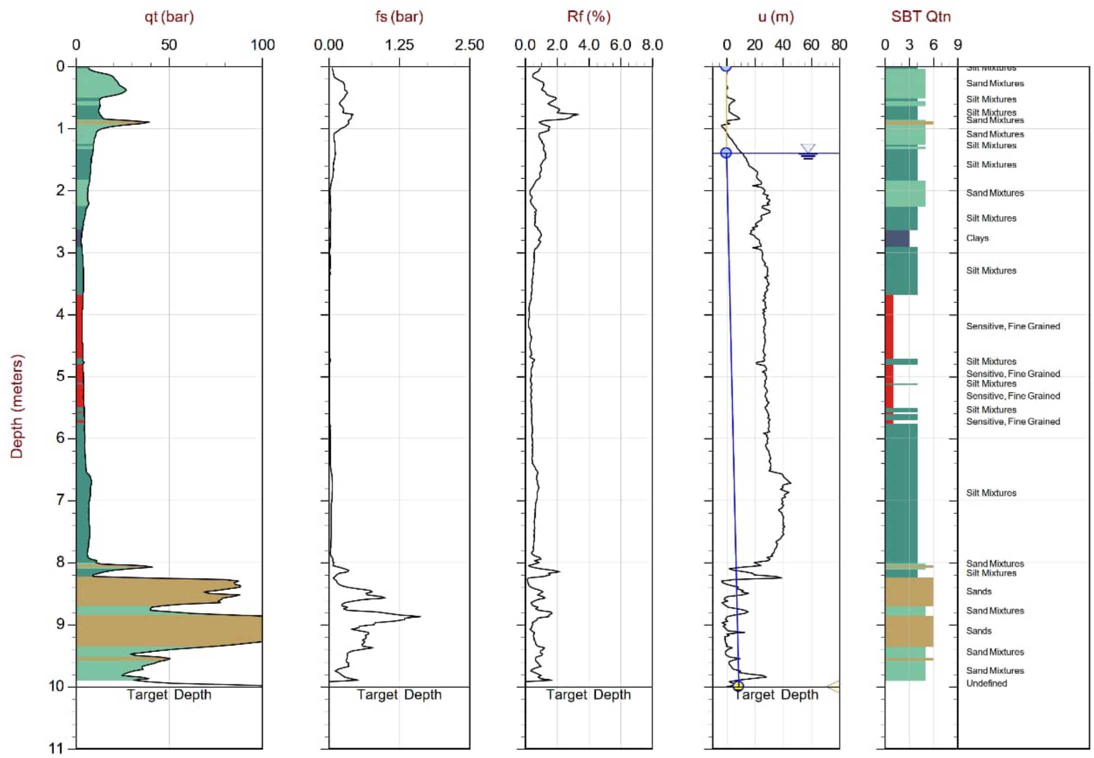


Figure 3. CPT results representing the west side of the building

Table 3. Soil properties used in Plaxis 3D Analysis of Project 7

General soil description	Soil Model	Depth [m]	q_c (ave.) [MPa]	γ_{sat} [kN/m^3]	E [MPa]	c' [kPa]	φ' [°]	k [m/s]	q_s [kPa]	OCR [-]
Dense Sand and Silt	MC	0.0 to 1.1	1.78	17.1	16.5	0	30	3.67E-7	30	-
Dense Silt	HS	1.1 to 2.5	0.71	16.0	6.8	0	30	7.87E-8	30	3.7
Soft Silt and Clay	HS	2.5 to 6.5	0.34	16.0	1.9	1	25	1.47E-8	5	2.3
Soft Silt	HS	6.5 to 8.2	0.83	17.0	6.5	1	26	7.87E-8	5	2.0
Dense Sand	MC	8.2 to 9.4	9.2	18.6	47.8	0	37	3.47E-5	60	-
Very Dense Sand	MC	9.4 to 10.0	4.3	17.7	31.4	0	33	2.80E-6	60	-
Till	MC	10.0 to 20.0	-	19.0	40.0	5	35	1.00E-9	60	-

Where q_s is the ultimate skin friction between the soil and the CMCs.

For the case study building, InSAR observations began after structural roof completion, covering the period from 07 September 2022 to 07 November 2024. The displacement vs. time graphs show areas with different magnitudes of displacement, mainly during the first months of the study in 2022, followed by a period of relative stabilization.

Figure 4 presents cumulative deformations on the roof of the case study project, and Figure 5 plots the displacement vs. time for three selected points. It is worth noting that a few points in Figure 4 exhibit minor positive displacement. These occurrences are restricted to the perimeter and are limited in magnitude, therefore they have been considered to most likely reflect measurement artifacts within the InSAR dataset and site activities during the measurement period rather than actual uplift or structural distress.

In this study the condition at the west side of the buildings is reevaluated and the calculated deformations are compared with the measured values (read at points A and B in Figure 4 and Figure 5).

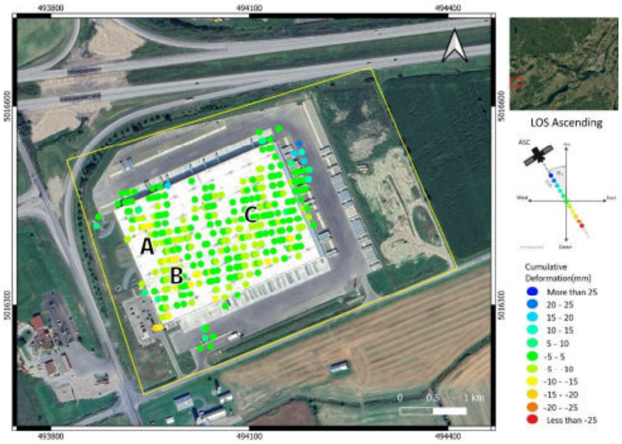


Figure 4. Deformations surveyed at the roof of Project 7

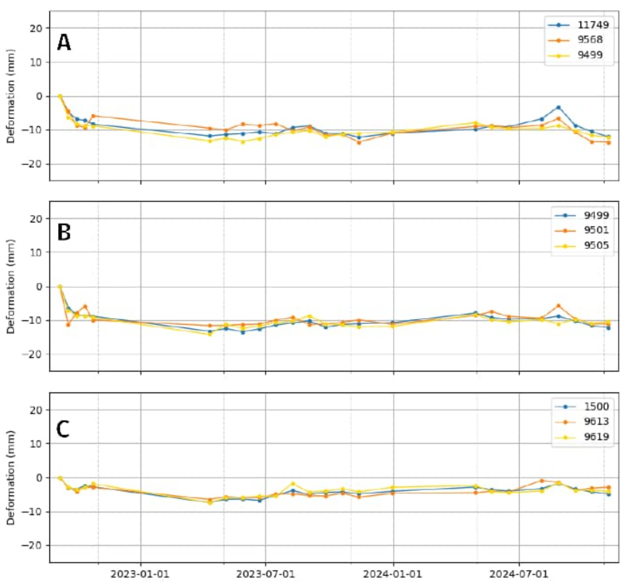


Figure 5. Graphs showing the displacements vs. time for three selected points at Project 7

6 GROUND IMPROVEMENT DESIGN

As specified in the project requirements, the ground improvement design shall satisfy the following criteria:

- Maximum total settlement: 25 mm
- Maximum differential settlement: 19 mm

With respect to the applied loads, the dead load was estimated to be 420 kN per pad foundation and 10 kPa for the Slab on Grade (SoG). This load was applied prior to the commencement of the InSAR surveys. Since the monitoring period extended through the winter of 2022–2023 and beyond, the effects of snow loading must also be considered in the settlement analysis.

During that winter, the maximum recorded snow accumulation in Casselman was approximately 900 mm, corresponding to an estimated load of 1 kPa on the roof. This translates to an additional load of approximately 230 kN per pad footing, based on a tributary area of 15.25×15.25 m (i.e., the spacing between adjacent pad footings). In addition to the snow load, a live load of around 25 kPa was applied on the SoG during the survey period.

As illustrated in Figure 6, three CMCs were installed beneath each 2×2 m pad footing (indicated by red markers). In addition, a uniform grid with 3×3 m spacing was constructed beneath the SoG (indicated by blue markers). All CMCs have a diameter of 280 mm, with lengths varying across the site and averaging approximately 9.0 to 9.5 m.

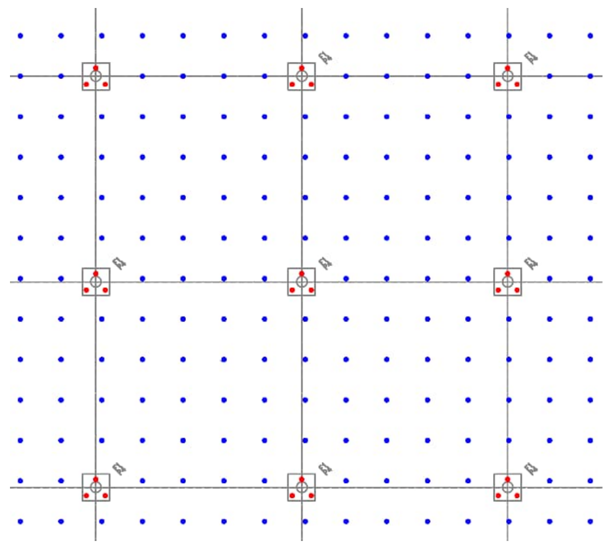


Figure 6. CMC layout under pad footings and SoG

7 CALCULATIONS

To replicate the as-built ground improvement geometry as closely as possible, all numerical analyses were performed using PLAXIS 3D Version 2024.3.0.95. In the model, both pad footings and the SoG were explicitly represented, with loads applied according to their respective construction stages.

The CMCs were modeled as linear elastic embedded beams with a modulus of elasticity of 10 GPa and a diameter of 0.28 m. To properly model the punching of CMCs in the LTP, a rigid plate with an area equal to the cross-section of the CMC was modeled on top of each CMC, as presented in Figure 7.

The soft, compressible soil layers were modeled using the Hardening Soil (HS) constitutive model (Schanz, 1998; Schanz et al., 1999), while the sandy layers and the hard till were modeled using the Mohr–Coulomb (MC) constitutive model. The soil profile and corresponding material properties are presented in

Table 3. Based on the following correlations, the soil parameters were derived from CPTs and BHs representing the western part of the site.

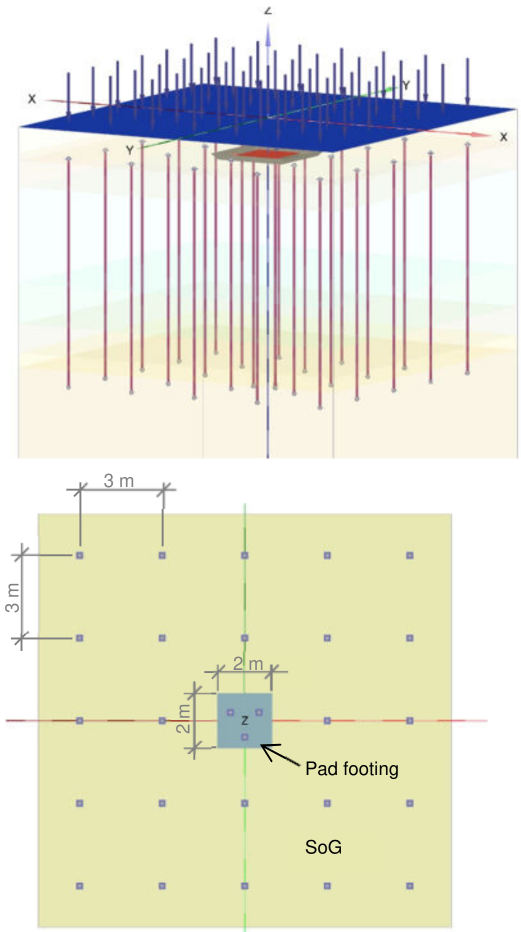


Figure 7. 3D and plan views of the PLAXIS model

Stiffness: Robertson (2010)

$E = \alpha_E \times (q_t - \sigma_{v0})$

$\alpha_E = 0.15 \times 10^{(0.55 I_c + 1.68)}$ max.:10

OCR: Mayne (1992)

$OCR = K \frac{q_t - \sigma_{v0}}{\sigma'_{v0}}$

Permeability: Robertson (2010)

$k = 10^{(0.952 - 3.04 I_c)}$

Friction angle: Robertson and Campanella (1983)

$\tan(\varphi') = 1/2.68 \left[\log\left(\frac{q_c}{\sigma'_{v0}}\right) + 0.26\right]$ for sand

Norwegian Institute of Technology (NTH) method for clay (Ouyang & Mayne 2019)

where:

$K = \left(\frac{{Q_{t1}}^{0.2}}{0.25 \times (10.5 + 7 \log(F_r))}\right)^{1.25}$

σ_{v0} and σ'_{v0}: Total and effective vertical stress

q_t: Corrected tip resistance

α_E: ratio of E over corrected tip resistance

Q_{t1}: Normalized tip resistance

F_r: Normalized skin friction

I_c: Soil behavior index (Robertson 2009)

As noted earlier, the InSAR data used for validation were also obtained from the west side of the building (Points A and B in Figure 4).

Because displacement monitoring commenced at the stage when snow and live loads were applied, the numerical simulations were sequenced to match the actual construction and loading conditions. The adopted sequence is as follows:

- Excavation to a depth of 1.4 m,
- Installation of CMCs, LTP, and footings,
- Backfilling to final grade,
- Placement of the SoG,
- Application of the dead load (420 kN on the footing and 10 kPa on the SoG),
- Application of the snow/live loads (230 kN on the footing and 25 kPa on the SoG), during which the deformation survey was conducted.

It was assumed that all deformation under the dead load occurred during and immediately after construction, prior to the application of snow and live loads and the start of the InSAR survey. Therefore, 100% of the recorded deformations were attributed to the snow and live loads.

7.1 Analyses Results

Figure 8 compares the calculated deformations obtained from the numerical model with the displacements monitored using the InSAR survey technique. The two datasets exhibit a generally consistent trend, indicating good agreement in terms of overall structural behavior.

The numerical analysis, however, was performed using a relatively conservative set of assumptions, resulting in a predicted total displacement of approximately 17 mm at roof (or footing) level, whereas the maximum displacement inferred from the InSAR measurements under snow and live loading conditions is approximately 12 mm. As mentioned earlier, the settlement monitoring started one month after completion of the roof top (i.e., 100% of the dead load). Most of the settlement occurring due to the dead load is expected to have been completed by then; however, in the calculations the actual sequence of the work was modelled with realistic material properties as discussed in section 7. Therefore, if part of the settlement under the dead load is extended to the period when the live and snow loads are applied, a realistic settlement distribution vs. time is reflected in the results.

It should be noted that seasonal effects, variable loading sequences associated with warehouse operations, and other time-dependent influences were not explicitly considered in the numerical model. As a result, the calculated displacement curve does not reproduce the short-term fluctuations and local variability observed in the monitored data, although it captures the long-term deformation trend satisfactorily. It should be noted that such fluctuations are normal for many structures and are not progressive with values remaining within a range of ±20%. In the end the average displacement is around 12 mm. In the numerical calculation the most critical condition was modelled, which is the reason why calculated values are closer to the maximum observed settlements.

Despite the simplified and conservative assumptions adopted in the numerical model, the close agreement between the calculated deformations and the InSAR-derived displacement measurements demonstrates that the adopted design assumptions and calculation framework capture the key mechanisms governing the structural response. This comparison therefore provides confidence in the suitability and robustness of the adopted design and numerical modelling approach.

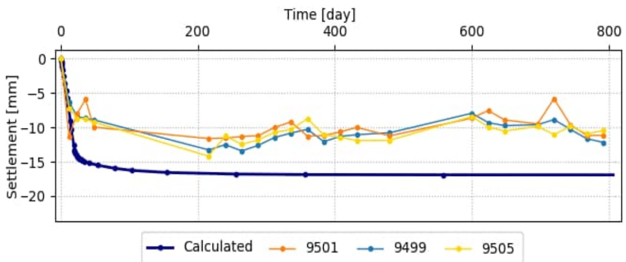


Figure 8. Calculated vs. monitored displacement at the rooftop of the case study project

8 CONCLUSION

This study demonstrates the effectiveness of Controlled Modulus Columns (CMC) as a ground improvement solution for structures founded on very soft and compressible clayey soils, as typically encountered in the Champlain Sea Basin in Eastern Ontario and Quebec. The comparison between calculated settlements from 3D numerical modelling and long-term displacement measurements obtained using the InSAR technique shows good agreement in terms of both magnitude and overall deformation trends. Despite the conservative assumptions and simplifications inherent in the numerical model, the predicted settlements remained slightly higher than the monitored values, which is consistent with sound and safe design practice.

The results confirm that the adopted design methodology captures the dominant mechanisms governing soil–structure interaction for CMC-improved ground, and that the construction process achieved the intended performance in terms of settlement control and long-term stability. The InSAR monitoring further proved to be a valuable, non-intrusive tool for post-construction validation of ground improvement works and other foundation systems, providing confidence in the reliability of both the design assumptions and execution quality.

Based on the outcomes of the case study project and the additional projects reviewed in this paper, it can be concluded that the design and execution approach adopted is appropriate and safe for ground improvement in very soft clayey soils and positive performance over time can be verified using InSAR technology. For future projects with similar geological and loading conditions -particularly in regions characterized by sensitive or highly compressible fine-grained deposits- the methodologies presented herein should be considered a reliable basis for design, provided that project-specific ground investigations and engineering assessments are carried out.

9 REFERENCES

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