

Reinforcement of Soft Soils by Means of Controlled Modulus Columns



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ABSTRACT

Ground improvement techniques can offer economical alternatives to conventional deep foundation and structural slab solutions. Controlled Modulus Columns (CMC) is a ground reinforcement technique developed in France and recently introduced into Canada. The CMC process reduces the compressibility and improves the bearing capacity of soils by means of semi-rigid grout columns installed into the ground with a specially designed and patented hollow stem auger. This paper describes the underlying principles and the installation procedures of CMCs. The experience gained on 2 projects is briefly summarized.

RÉSUMÉ

Les techniques d'amélioration des sols peuvent offrir des alternatives économiquement intéressantes aux systèmes traditionnels de fondation profonde et de dalle structurale. Le système de fondation de Colonnes à Module Contrôlé (CMC) est une technique de renforcement des sols par inclusions semi-rigides développée en France et introduite depuis peu au Canada. L'inclusion des CMC dans les sols, à l'aide d'une tarière évidée brevetée spécialement conçue, permet de réduire leur compressibilité et d'augmenter leur capacité portante. Cet article décrit les principes de base des CMC et de leur installation. L'expérience acquise dans le cadre de 2 projets est présentée.

1 INTRODUCTION

1.1 Ground improvement with semi rigid inclusions

The concept of semi-rigid inclusion is not new. In medieval ages, networks of wood piles were often installed under ancient churches to stabilize soft grounds. The concept is to globally improve the soil using semi-rigid soil reinforcement columns.

The main idea behind the design of Controlled Modulus Columns is to optimally distribute the loads between the columns and the soil. Column diameter, spacing and properties are selected to reduce the anticipated settlements to acceptable levels (Liausu et al, 2001). Once improved with CMCs, the soil behaves like a composite material, with an equivalent vertical modulus depending on the soil properties and on the characteristics of the inclusion network:

- Spacing
- Column diameter
- Penetration depth into the bearing stratum
- Thickness of the load transfer platform placed above the CMCs
- Ratio of Column and soil modulus

The behavior of an individual inclusion is predicated on reaching an equilibrium under loads (Combarieu, 1988) as shown on Figure 1. While the inclusion is being

compressed by the load, negative skin friction is acting in its upper part and positive skin friction in its lower part. When the equilibrium is reached, the stresses acting on the inclusion can be divided in 4 components:

- The vertical load, Q at the top of the inclusion
- The negative skin friction acting on the upper portion of the inclusion
- The positive skin friction acting at the lower portion
- The vertical reaction at the tip

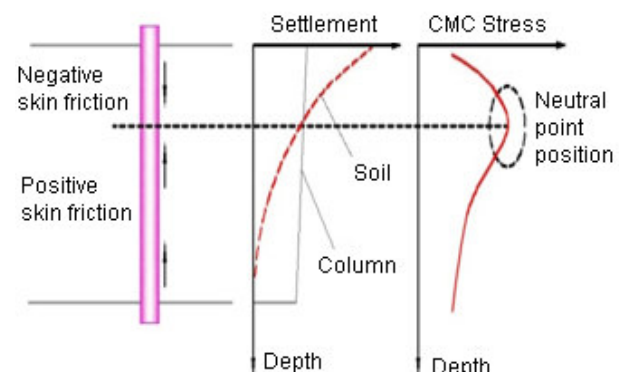


Figure 1: Settlement distribution between soil and an isolated inclusion

The load of the structure is usually distributed to a network of inclusions by a load transfer platform (LTP). Figure 2 shows how the load is distributed from the structure to the bearing layer.

The load distribution between CMCs and surrounding soil is based on reaching an equilibrium between deformations of the CMCs and the surrounding soils. The design of a network of inclusions is thus based on a good knowledge of the distribution of stresses and deformations in the soil and the inclusions.

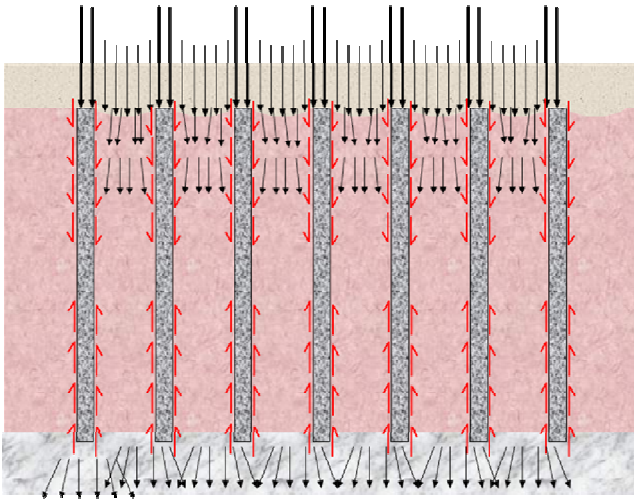


Figure 2. Load distribution between soil and an inclusion network

1.2 Controlled Modulus Columns and design methods

Controlled Modulus Columns (CMC) are inclusions installed using specially designed means and methods. The principle of the Controlled Modulus Columns soil improvement system is to create a composite material with improved geotechnical characteristics. The CMC diameter, spacing and material strength properties are designed to provide a composite soil that will have bearing capacity and settlements adapted to the specifications of each project. Depending on soil conditions and CMC design, an improvement ratio of 2 to 10 times of the initial compressibility can be obtained.

A load transfer platform (LTP) made of well compacted granular material is usually required above the CMCs to distribute the loads through arching between the CMCs and the surrounding soils as shown on Figure 2.

The design of CMCs also takes into consideration the load transfer through friction along the sides of the CMC as well as the compressibility of the soil and the CMC. Computations are usually performed with a Finite Elements Method software. A complete geotechnical investigation giving reliable geotechnical properties is essential to perform an accurate design.

1.3 Means and Methods of CMC construction

CMCs are installed with a specially designed auger, powered by equipment with large torque capacity and high static down thrust, that displaces the soil laterally with virtually no spoils or vibrations.

When the required depth or preset drilling torque criteria is reached, a column is developed by pumping a highly workable grout-fly ash-cement mix through the center of the hollow stem auger. The grout flows under moderate pressure (typically less than 500 kPa) through the tip of the auger while it is extracted to create a grout, high capacity column. Because no vibration is generated, this system can be used in close proximity to sensitive structures. Minimal disturbance of the surface layer is generated during the installation process with virtually no spoils. No soil mixing takes place during the low-pressure grouting. Figure 3 shows the installation process.

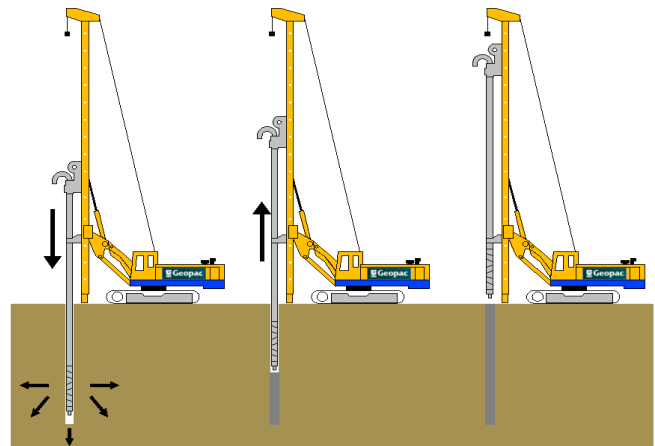


Figure 3. Installation process with hollow stem auger drill rig

All phases of installation are closely monitored by an on-board computerized recording device. As the auger is advanced, its penetration speed, the torque, down thrust and the depth reached are recorded for each column. During the withdrawal phase, the speed of extraction, pressure and volume of the grout injected are also recorded. This real time monitoring ensures that CMCs are installed per design.

2 HOME DEPOT STORE, ST-JEAN-SUR-RICHELIEU, QUEBEC

2.1 Project

The project consisted of the construction of a new Home Depot store in the city of Saint Jean sur Richelieu (Québec). A system of pile and structural slab foundation was foreseen for this project considering the low bearing capacity of the soils. An alternate solution, using the CMC inclusion

system, was offered to the owner's consulting engineers. The requirement for the ground improvement was to achieve a net bearing capacity of 30 kPa under the slab and 150 kPa under the isolated footings and peripheral wall footings. The computed post-construction total settlement had to be less than 25 mm and the differential settlement less than 20 mm.

2.2 Geotechnical conditions

The existing geotechnical conditions had been identified through several soil investigation campaigns. The soil conditions summarized in Table 1 were quite homogeneous over the whole site. The Young's moduli presented in Table 1 were selected for calculation purposes based on correlations with available SPT values.

Table 1. Characteristics of the soil layers

Soil Layer	Thickness (m)	Young's modulus (MPa)
Stiff silty clay	2.0	2
Firm silty clay	3.3	5
Compact silty sand	2.7	3
Dense gravelly and silty sand	7.0	3

2.3 Design of the CMC inclusion network

The ground improvement design using CMCs considered the different loading conditions of the project, the allowable displacement associated with each loading condition and the variation in soil characteristics across the site.

2.3.1 Slab-on-grade

The design of the CMC network for the slab on grade is based on elasto-plastic FEM calculations using the software PLAXIS. Design conditions were modeled using axisymmetrical calculations (see Figure 4). The model isolates one single column, the unit cell, which allows transforming, using the properties of symmetry, a complex 3D model into a more manageable 2D model.

For the slab-on-grade, the inclusions were installed on a 2.5 m square grid. The slab was 15 cm thick and was subjected to a uniform load of 30 kPa. The Figure 5 shows the results of FEM calculations in terms of stresses and settlements. The main results of this analysis are summarized in Table 2.

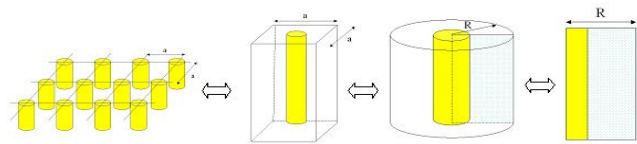


Figure 4. Simplification from square grid to cylindrical unit cell

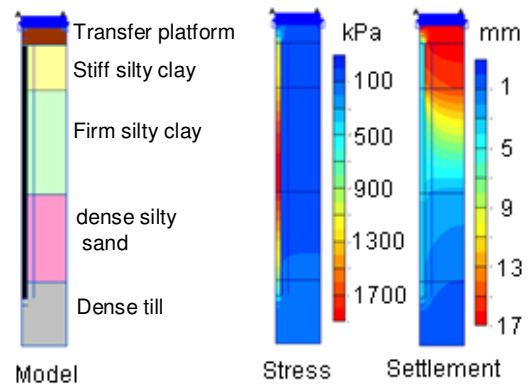


Figure 5: Results of the FEM calculations

Table 2: Main results of analysis for the slab on grade

Grid spacing (m x m)	Column diameter (m)	Settlement (mm)	Column stress (MPa)	Slab moment (kNm/m)
2.5 x 2.5	0.32	17	1.86	4.86

The vertical compressive stress in the CMC was lower than the allowable limit of 8.5 MPa for the selected type of grout. The maximum total settlement was estimated at 17 mm under a maximum load of 30 kPa.

2.3.2 Spread and strip footings

The number of CMCs to be installed varied according to the loads and dimensions of the spread and continuous footings.

The calculation of the anticipated performance of the CMCs installed under footings was based on Combarieu (1988b). This paper provides a calculation method that takes into account the interaction between the footing and the CMCs, modeling the transfer of load from the point of application to the bearing stratum. This computation method has been programmed into a spreadsheet by Menard.

This spreadsheet first checks that the loads supported by the soils and the columns remains within acceptable

limits. It is then possible to calculate the settlement of the individual footings under design loads.

Past experience with this method has shown that the implementation of this computation method is reasonable and provides a conservative upper bound for the expected settlement of the CMC-reinforced soils.

Calculation results for select cases of spread footings supported by 4 CMCs are summarized in Table 3.

Table 3: Examples of results for isolated spread footing

Footing Dimensions (m x m)	Maximum applied load (kN)	Stress in column (MPa)	Computed Settlement (mm)
3.2 x 3.2	940	1.38	4
3.05 x 3.05	810	1.22	4

The results indicated that the anticipated settlements, of 4 mm, were well below the objective of 25 mm. Furthermore, compressive stresses in the inclusion were calculated to remain below 1.5 MPa, which is less than the allowable compressive stress of 6.8 MPa in the grout.

2.4 Special load-transfer-slab over the sewer pipe

An underground sewer pipe was crossing the site of the future building and a solution was designed to avoid moving it to reduce the overall cost of the project. The use of a CMC foundation system allowed to leave the pipe in place.

To avoid transferring any load to the pipe and protect it from settlements, a load transfer concrete slab resting on CMCs was built on top of the sewer pipe, as shown on Figure 6.

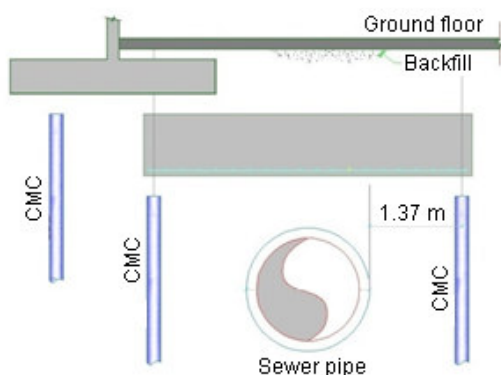


Figure 6. Special load transfer concrete slab supported by CMC inclusions over the sewer pipe

The following Table 4 summarizes the results of the analysis performed for this special slab. It was supported by 2 rows of CMCs spaced 2 metres apart.

The expected settlements of this underground slab supporting the weight of the soil and the loads on the slab on grade, was about 7 mm.

As the installation of the CMCs does not generate vibrations, their installation along the existing sewer was completed without creating distress or damage of the concrete pipe.

Table 4: Computation results for the special load transfer slab analysis

Footing type	Width (m)	Linear load (kN/m)	Stress (MPa)	All. stress (MPa)	Settlements (mm)
Over the sewer pipe	5.18	350	2.39	5.1	7

3 PETROLEUM TANK , PORT OF QUEBEC CITY, QUEBEC

3.1 Project description

The project involved the improvement of the foundation soils of 5 petroleum product tanks on IMTT's property in the Port of Quebec City. The 36.6 metres in diameter tanks were planned to be built on a structural slab supported by a network of expanded base Franki type piles.

To reduce the cost of building the tanks, a ground improvement solution using CMC inclusions was proposed. The requirement for the ground improvement was to achieve a net bearing capacity of 240 kPa. The computed post-construction differential settlement was required to be less than 25 mm between the center and the edge of the tank, which corresponds to an angular deflection of 1:730.

3.2 Geotechnical conditions

Stratigraphy over the site of the 5 tanks was typically composed of a loose surficial fill of silty sand varying to sandy silt about 5 metre thick, covering a layer of wood and organic waste material with lenses of silt and sand. The total thickness of the organic layer varied between 1.5 and 2.5 metres. Natural dense sand with some silt was found underneath this soft compressible layer. The exact total thickness of this natural soil was not indicated in the geotechnical study but was expected to be about 30 metres based on geological data.

Groundwater level was located at a depth of about 3 metres, with tidal influence. At some time of the year, groundwater level could be found almost at the surface.

3.3 Design of the ground improvement

3.3.1 Axisymmetrical unit cell modeling

Settlements and stresses in the CMCs were computed using the FEM software Plaxis and an axisymmetrical model of the unit cell composed of the CMC and its surrounding soils. Soils and CMC properties used in the computations are summarized in Table 5.

Table 5. Characteristics of the soil layers used in the FEM analysis

Material	Thickness (m)	Young's modulus (MPa)
Upper sandy fill	5.0	18
Organic silt	2.5	3
Lower dense sand	±30	30
Load transfer platform	0.6	50
CMC	8.0	17 550

Computation results are summarized in Table 6 and shown graphically on Figure 7.

Table 6. Results of FEM analysis for the unit cell

Grid spacing (m x m)	Column diameter (m)	Settlement (mm)	Column stress (MPa)
1.5 x 1.5	0.32	86	5.2

3.3.2 Modeling of the tank using equivalent soil modulus

In order to estimate the differential settlement due to the tank configuration itself, an axisymmetrical model of the tank and the improved soil was used. The modulus of the improved soils used in the calculations is an equivalent modulus computed from the results of the axisymmetrical calculations.

The equivalent Young's modulus of the composite soil is based on the computed settlement and the stress (σ) applied on top of the CMCs per the following elastic relationship:

$$\frac{\Delta H}{H} = \frac{\sigma}{E_{\text{equivalent}}} \quad (1)$$

Where ΔH is the settlement and H is the total thickness of the composite layer, CMC and the load transfer platform.

Based on the calculated results for the unit cell model, the equivalent modulus of the reinforced soil mass was estimated at 28 MPa.

The load applied by the tank was 240 kPa. All other soil parameters were kept similar to the previous model.

The axisymmetrical calculation results are shown graphically on Figure 8. Based on this model, the settlement at the center of the tank was expected to be approximately 80 mm, and the settlement under the ring wall was about 52 mm with a differential settlement between the center and the edge of approximately 28 mm as shown on Figure 9.

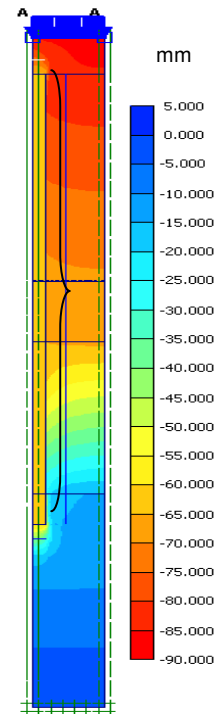


Figure 7. FEM settlement computation results for the unit cell

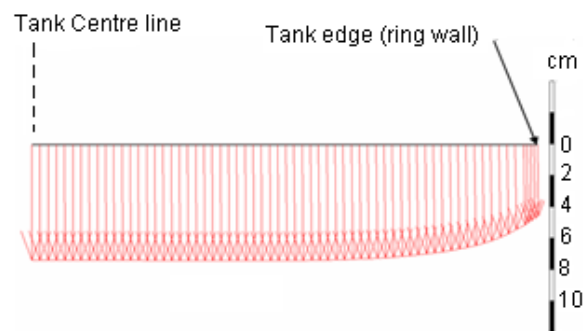


Figure 9. Predicted settlements under the tank load

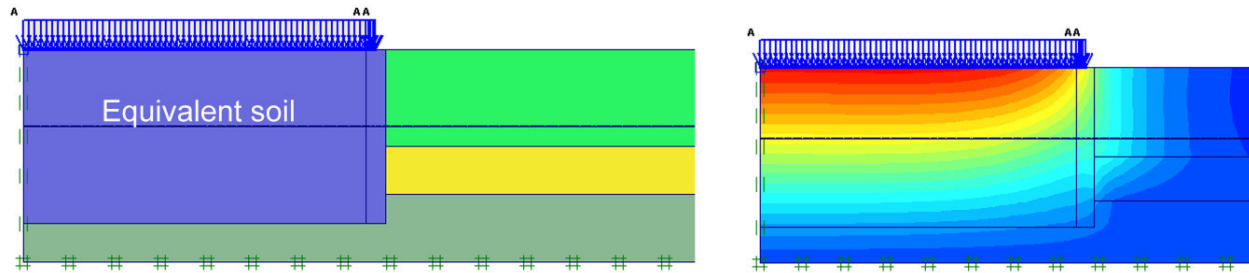


Figure 8. Model and results of FEM computations of the soils under the tank load.

The calculated differential settlement results are on the conservative side since the previous model did not take into consideration the following factors:

- the depth of embedment of the tank; and
- the increased rigidity of the outer edge (ring wall) of the tank.

On this basis, it was considered that the differential settlement between the ring wall and the centre of the tank would be less than 25mm.

3.3.3 Construction and measured settlements

Figure 10 shows the construction of the CMC inclusions on site with the special hollow stem auger system.

During the water test, settlements varying between 25 and 35 mm were measured along the periphery of the tanks. These values, smaller than those computed (52 mm), can be explained by the use of conservative material properties and by the fact that the effect of soil compaction between the inclusions was ignored in the models. Nevertheless, it shows that relatively accurate settlement estimations, with a conservative safety margin, can be obtained with the methods described herein.



Figure 10. Construction of the CMCs on the IMTT's site in the port of Quebec City.

4 CONCLUSION

The case histories presented herein illustrated some of the possibilities of the CMC system. Their use to support heavily loaded tanks founded on soils containing layers of organic wood material proved very cost effective for the owner. Its use to support both the foundation and the slab on grade of a large commercial building is also a good example of the possibilities of this system.

This system is effective in soils that can't be reliably improved with other ground improvement methods. Difficult foundation conditions such as loose/soft fine grained soils, organic soils or foundations applications with high loads and low settlements tolerance are ideal applications.

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