Construction of Highway Embankment Using Controlled Modulus Columns

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Paper prepared for presentation
At the Advancements in Stabilization and Reinforcement of Soils and Unbound Granular Layers Session

Of the 2015 Conference of the
Transportation Association of Canada
Charlottetown, PEI

ABSTRACT

The new Autoroute 30 project consists of the completion of the western portion of A-30 over a distance of 42 kilometers between Chateauguay and Vaudreuil-Dorion (QC). The road alignment crosses over the St. Lawrence River and the St. Lawrence Seaway at Beauharnois. Due to poor soil conditions at the eastern approach of the Beauharnois Canal Bridge, Controlled Modulus Columns (CMC) were used to improve the bearing capacity of the underlying soft soil, ensure slope stability and to reduce post construction settlements. This part of the project was critical as the embankment was used to launch the bridge spanning the canal. This article presents the specifics of this particular project and the CMC technology. Design considerations and calculation concepts are explained including finite element analysis and verification of resistance of the rigid inclusions in a seismic event.

1 GROUND IMPROVEMENT USING SEMI-RIGID INCLUSIONS

1.1 Introduction

The concept of using semi-rigid inclusions to stiffen a soil mass is fairly old. Deep foundations have been used for support in construction projects for hundreds of years. Ancient structures and bridges are still in use today because networks of wooden piles were driven below their shallow foundations for support.

Semi-rigid inclusions provide required support for the structure above. They are used to reduce the total and differential settlements by reducing the loads sustained by the soft soil (usually between 60% and 90%). For this reason, soils supported with rigid inclusions are sometimes referred to as 'composite foundations'.

1.2 Rigid and Deformable Inclusions

Vertical inclusions have typically been divided into two distinct categories: deformable inclusions (such as stone columns) and rigid inclusions (such as steel, concrete and auger-cast piles). Stone columns are considered a deformable foundation system as the materials used for such columns (sand, granular pit run or crushed rock) are not self-supporting and are not able to stand without the lateral support of soil.

Rigid inclusions are similar in principle to piles. They perform their function by having direct contact with the surface loads and transmitting these loads through end-bearing resistance, skin-friction, or a combination of both. They are designed to support the load with minimal settlement. The strength and stiffness of rigid inclusions are typically much less than those of piles. Predicted settlements for ground improvement methods are typically greater than that of rigid deep foundations by factors ranging from 2 to 10 or more. In this case, the division of stress between the soil and the inclusions determines the magnitude of settlement resulting from loading the improved ground.

1.3 Controlled Modulus Columns (CMC)

The CMC method was developed and patented by Menard in 1994. This technology's performance lands somewhere between rigid deep foundation systems and deformable foundation systems. The CMC solution reduces the global deformability of a soil mass by installing semi-rigid soil reinforcement columns. These columns create a network of elements that effectively distribute loads uniformly throughout the soil mass.

An intermediate load transfer platform (LTP) is used in conjunction with CMC's under uniform loads such as slabs and embankments. CMC's are not intended to directly support the loads imposed by the structure above, but are meant to improve the soil as a composite material, with an equivalent vertical modulus depending on the soil properties and the specific characteristics of the inclusion network as to spacing, column diameter, soil and column modulus, thickness of load transfer platform, etc..

CMC technology can be adapted to almost any type of compressible soil (clay, silt, peat, organic chalk, loose sand, and fills) and permits construction of projects that could not normally be handled by the use of a non-rigid deep foundation solution, most notably:

- Loose to soft soils for non-rigid solutions
- Organic soil, peat, or mixed backfill
- Applications with very high loads
- Applications with stringent settlement criteria

1.4 Means and Methods of CMC construction

Controlled Modulus Columns are constructed using a displacement auger which laterally displaces soil without generating spoils. The CMC displacement auger is powered by equipment with high torque capacity and high static down thrust. CMC's do not generate vibrations during installation allowing for construction in more sensitive areas. The auger is advanced into the soil to the required depth or until the predetermined level of drilling torque is reached. During the auger extraction process, a highly workable grout-cement mixture is pumped through the center of the hollow auger. Unlike jet-grouting, the grout is injected under moderate pressure, typically less than 500 kPa, maintaining a positive head relative to overburden stresses to ensure achievement of full and consistent minimum CMC diameters.

The entire process operates without air or water jetting and without spoils, which provides for cleaner project sites. The elimination of spoils also removes the necessity of handling contaminated in-situ material.

Quality control of the CMC's is ensured by laboratory compressive strength tests of the grout and load testing on isolated columns. All phases of installation are closely monitored by an on-board computerized recording device which records the following installation parameters:

- Speed of rotation and rate of advancement of the auger.
- Torque and down-thrust during advancement.
- Pressure and volume of injected grout, from which the in-situ profile of the columns are determined.

1.5 CMC Design Principle

The behavior of an individual inclusion is predicated on reaching equilibrium under loads (Combarieu, 1988). Stress distribution occurs when it reaches equilibrium over the full length of the CMC inclusion considering the four main components of acting forces:

- The vertical load Q on the head of the CMC
- The resultant Fn of negative skin friction acting on the upper portion of the CMC
- The resultant Fp of positive skin friction mobilized on the lower part of the CMC
- The tip resistance Qp in the anchorage layer

The load of the structure is usually distributed to a network of CMCs through a load transfer platform (LTP). Figure 1 shows a typical load distribution diagram between soil and an inclusion network.

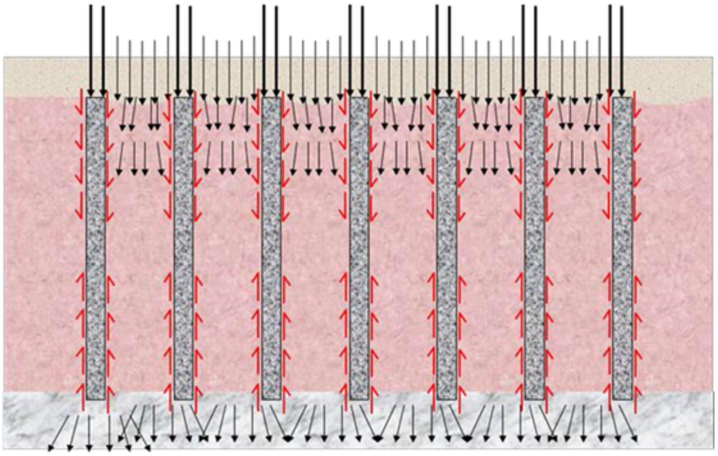

Fig. 1: Load distribution between soil and CMC

2 PRESENTATION OF THE PROJECT

2.1 New Autoroute 30 – Chateauguay / Vaudreuil-Dorion

The new Autoroute 30 provides a convenient direct route for through-traffic between Toronto and Ottawa on the west side and Quebec City on the east side, avoiding the urban areas of Montreal Island. The completion of Autoroute 30 comprises two sections totaling more than 42 km of four-lane divided highway (i.e. two traffic lanes in each direction). Only two sections of Autoroute 30 remained to be completed:

- The Jean-Leman segment of the Eastern section in Candiac
- The Western section, between Châteauguay and Vaudreuil-Dorion

Figure 2 shows Eastern and Western sections alignment of the Autoroute 30

Fig. 2: Alignment of Highway 30 (red line)

The Eastern section begins at the existing Autoroute 30 in Châteauguay, and extends to the Jean-Leman interchange in Candiac. The Eastern section was not to be connected to the local network, and no interchanges were planned in order to limit urban sprawl.

The Western section begins at Autoroute 20 in Vaudreuil-Dorion, including the redesign of Autoroutes 20, 30, and 540. The highway is 35 km long, and connects with Route 138 at the boundary of Châteauguay and Mercier. This section of the project also includes two major structures that will make it possible to cross two large waterways:

- The bridge crossing the Beauharnois Canal, spanning close to 2.5 km, with a vertical clearance in excess of 38 meters;
- The bridge spanning the St. Lawrence River, close to 2 km in length.

Construction of the four-lane highway was scheduled to begin in spring 2009 and finish in 2012, completing a highway link begun in the 1960s.

The Autoroute 30 project was delivered as a Public Private Partnership (PPP). The PPP agreement between the Ministère des Transports du Québec and Nouvelle Autoroute 30 (NA30) for the design, construction, financing, operation, maintenance and repair of the Autoroute 30 completion for a period of 35 years was signed in September 2008.

2.2 Eastern Approach to the Beauharnois Canal Bridge

Autoroute 30 crosses the St. Lawrence Seaway to Valleyfield. To accomplish this, a 2,550 meters long bridge was to be built, erected 38 meters above water level so that ships can pass beneath.

The eastern approach embankment to Beauharnois Canal Bridge was used temporarily as a launching pad for the precast deck segments of the bridge. These elements were manufactured in the vicinity of the proposed bridge and gantry cranes carried the units from the casting yard to the launching platform. The precast units will be placed on a support sliding on tracks. The 170 meters long bridge abutment and launching pad arrangement is shown in Figure 3.

A temporary embankment with a height of 5 meters (which reduced to approximately the existing ground level at CH. 170) was required at the abutment in order to facilitate the initial launching operations. The permanent embankment following completion of the launching operations was to be 10 meters high at the bridge abutment location, sloping down to a height of 7 meters at CH. 170.

The launching platform was subject to the following loading conditions:

- Weight of embankment fill (5 meters at the abutment)
- Two pairs of skid legs for each precast unit over the embankment fill having a load per leg of 2,400 kN.
- These skids are placed on a 2.5 meters wide concrete slab. The ground pressure at the base of the slab is 300 kPa.

In addition to the applied loads from the launching platform (fill + skid legs), the permanent embankment after the launching operations will apply the following loading:

- Weight of embankment fill (10 meters at the abutment)
- Live loads of 10 kPa due to the road traffic over the entire road surface.

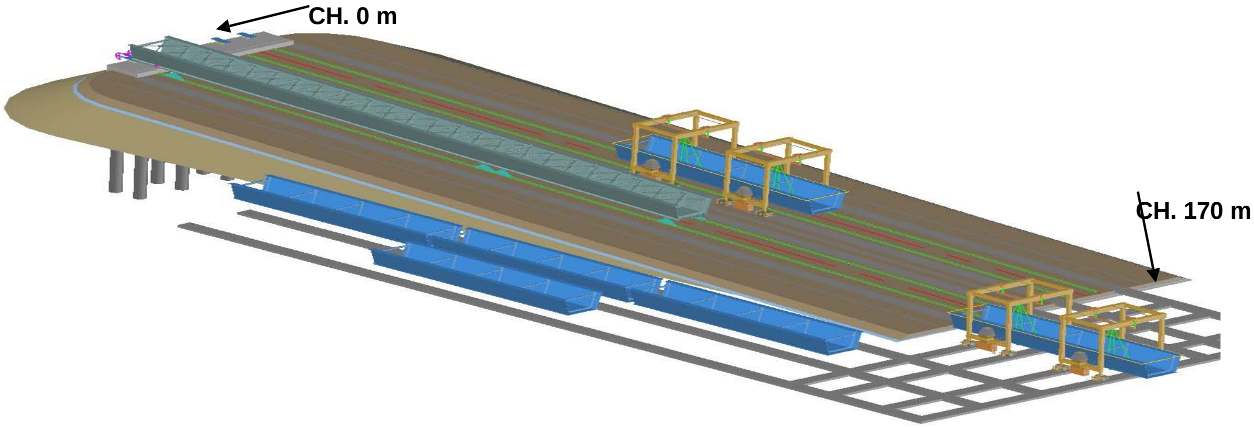

Fig. 3: Launching Platform
(Source: Nouvelle Autoroute 30 – CJV 2010)

2.3 Ground Conditions

The existing geotechnical conditions had been identified through several soil investigation programs. The soil conditions summarized in Table 1 were reasonably consistent over the entire CMC treatment areas.

Soil Layer	Thickness (m)	N_{SPT}	Cu (kPa)
Clayey fill Embankment	5.7	20	-
Granular fill Embankment	4.9	30	-
Made ground Brown silty clay	6.0	-	30
Champlain deposits Clay	10.0	-	22
Glacial deposit Sand and gravel	6.0	55	-

Table 1: Characteristics of the soil layers

Champlain deposits are composed of soft grey silty clay. Shear strength for this layer varies between 20 and 50 kPa, and standard penetration test N values vary between 0 and 4. Ground water level was identified at a depth of about 6.2 meters during site investigation but is known to fluctuate seasonally and can rise near the surface during peak river levels.

3 DESIGN OF THE GROUND IMPROVEMENT

3.1 Description of the CMC Treatment

The design, which was calculated according to soil and loading conditions, used a variable grid designed according to the backfill height. Columns with a 420 mm diameter anchored into the competent till layer were proposed for all areas of the project. The average length of the CMC was 17 meters.

For each defined height of embankment, two separate calculations were made:

- An elasto-plastic axial-symmetrical finite element analysis was carried out.
- Following those calculations, a model of the cross section was set up using a 2D plane-strain model.

3.2 FEM analyses

The 2D plane-strain model allows determination of settlement of the embankment according to the varying loads. The model is composed of four steps:

- Installation of CMCs, the Load Transfer Platform and the initial portion of the embankment (Launching pad – Final level +4.9m)
- Application of the load from the skid legs on the concrete slab
- Installation of the second portion of the embankment (Maximum final level + 10.6m)
- Activation of the live load of 10 kPa

The main results of those analyses were:

- The range of total settlement due to the first portion of the embankment varied from 10 to 31 mm depending on the height of the embankment
- The settlements due to the skid legs' load varied between 38 to 47 mm
- The settlement due to the second portion of the embankment was estimated at approximately 60 mm

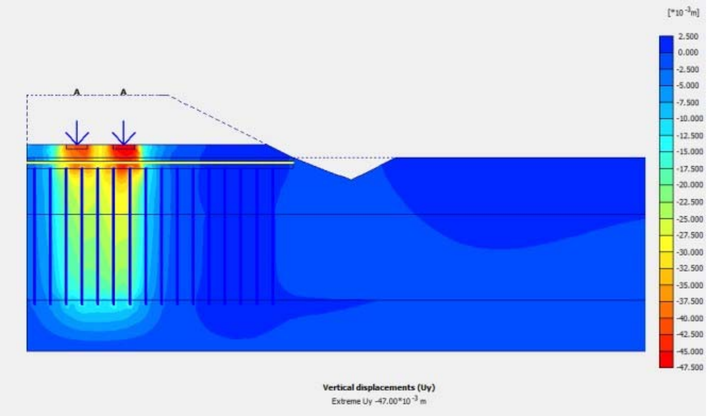

Fig. 5: Result of FEM computations of the soils under the skids legs on the concrete slab

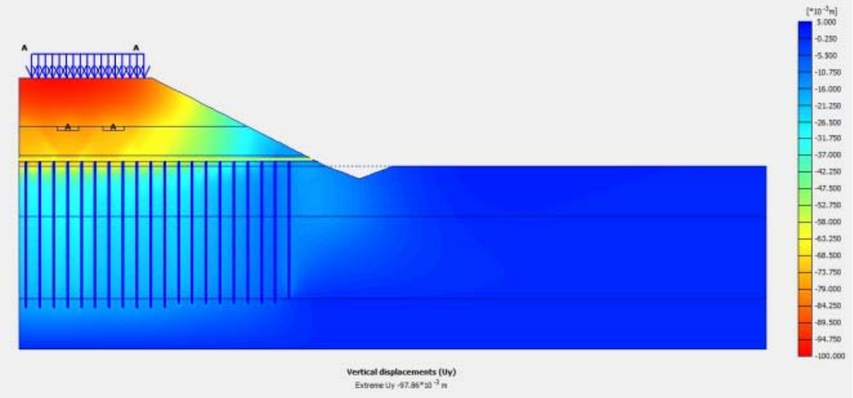

Fig. 6: Result of FEM computations of the soils under the embankment load

The range of long term post-construction settlement (road loading only) varied from 7 to 8 mm.

These performance results demonstrate the efficiency of the CMC ground improvement technique and provide a very favorable range of post-construction settlements, totally compatible with the performance requirements of the road being built.

3.3 CMC Design Under Seismic Conditions

One of the major concerns with this application was the stability of the embankment under seismic conditions. The horizontal displacement could potentially amount to about 5 centimeters. As a result, the CMC inclusions needed to resist horizontal stress and displacement during an earthquake.

Under seismic conditions, the soil displacement influences the behavior of the structure and the structure inertia influences the behavior of the soil.

Shear force T and bending moment M due to the seismic event are determined by studying the cumulative effect of two soil displacements on the CMCs:

- The free soil displacement d_f (this soil displacement would occur without any imposed structure load),
- The inertial soil displacement due to the horizontal earthquake acceleration d_i. This soil displacement is related to the loads imposed by the structure

The following diagram represents the total soil deformation applied on the CMC.

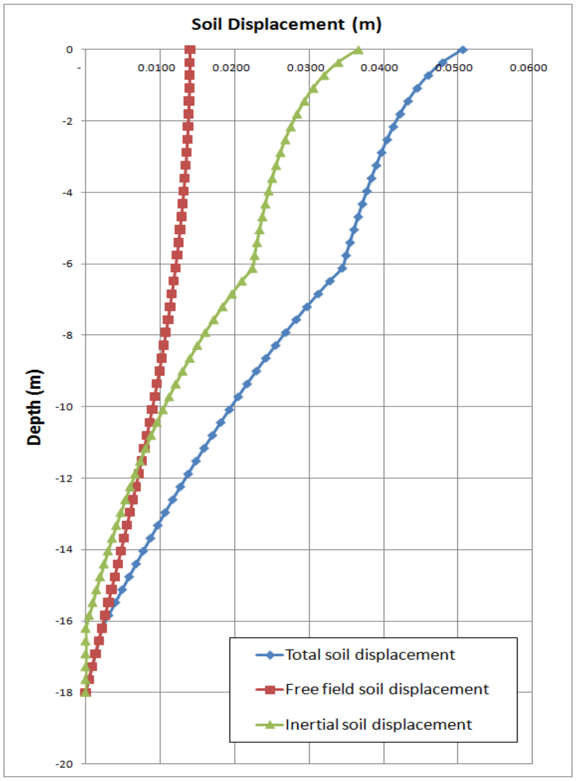

Fig. 7: Total soil displacement

Knowing the value of soil displacement with depth, it is possible to compute the values of the bending moment M, and the shear force T at each depth according to the theory of columns under lateral forces using the following differential equation Eq. (1) :

$$\delta\sigma . B = K_S \times B \times \delta y \tag{1}$$

Where:

$\delta\sigma$: Differential pressure of the soil between each side of the CMC with $\delta\sigma$ limited to creep pressure p_f

δy: Differential displacement between soil and inclusion

K_S x B: Reaction modulus of the soil applied on the width of the CMC (B)

The reaction modulus of the soil against the CMC is calculated with the short-term pressuremeter formula Eq. (2):

$$K_S . B = \frac{12 E_M}{\frac{4}{3} 2.65^{\alpha} + \alpha} \tag{2}$$

Where:

α: rheological coefficient of the soil

CMCs were installed through soft soil and support the embankment load. Depending on the grid, embankment thickness and type of soil, the vertical reaction R may account for about 60 to 90% of the embankment weight. Knowing the axial vertical stress R and the bending moment M, maximum compression and tensile stresses in CMC material are calculated using Eq. (3):

$$\sigma = \frac{R}{S} \pm \frac{M}{I/v} \tag{3}$$

Where:

$$S = \pi \frac{D^2}{4} \qquad I = \pi \frac{D^4}{64} \qquad v = \frac{D}{2}$$

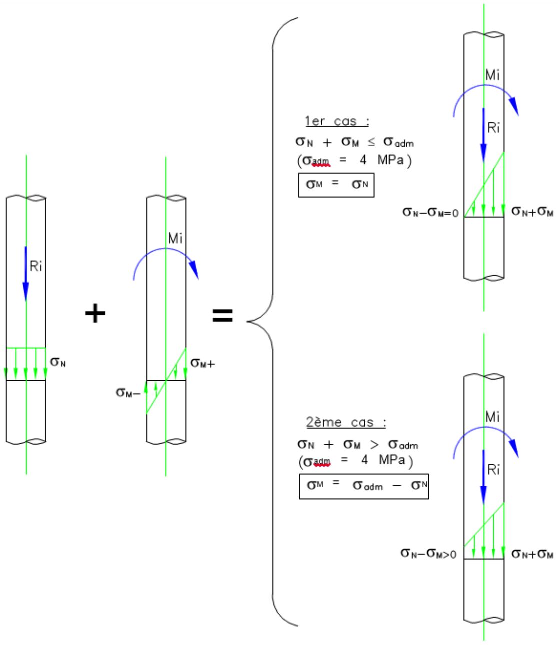

Fig. 8: CMC under combined vertical load and bending moment

The stresses in CMC units must comply with the following specifications:

- Compressive stress limited to a maximum of 5 MPa
- No tensile stresses in the CMC units.

4 CONCLUSION

In order to deal with the difficult soil conditions associated with the launching operations and the permanent future eastern approach embankment to the Beauharnois Canal Bridge, the use of Controlled Modulus Columns has proven to be an economical and technically sound foundation solution when compared to light weight fill or piled embankment options.

CMC foundation soil improvement methods were used to provide the required bearing capacity and to reduce post construction settlement to within acceptable limits for the eastern approach embankment to the Beauharnois Canal Bridge.

ACKNOWLEDGMENTS

The writers would like to acknowledge NOUVELLE AUTOROUTE 30 (NA30) for making the completion of this paper possible.

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