Embankment Construction Using Controlled Modulus Columns for Nouvelle Autoroute 30 Project in Beauharnois (Qc)

2011 Pan-Am CGS Geotechnical Conference

Rémi Chatte, Marc Lauzon
GEOPAC Inc., Boucherville, QC, Canada

ABSTRACT
The new Autoroute 30 project consists of the completion of the western portion of A-30 over a distance of 42 kilometres, between Châteauguay 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 were used to improve the bearing capacity of the underlying soft soil and to reduce post construction settlements.

RÉSUMÉ
Le projet Nouvelle Autoroute 30 consiste à achever la partie Ouest de l'autoroute A-30 sur environ 42 kilomètres, entre Châteauguay et Vaudreuil-Dorion. Le tracé de la route passe par-dessus le fleuve St. Laurent et le Canal de Beauharnois. À cause de mauvaises conditions de sols au droit des remblais d'approche Est du Pont sur le Canal Beauharnois, des Colonnes à Module Contrôlé ont été mises en œuvre afin d'améliorer la capacité portante des sols sous-jacent et de réduire les tassements résiduels.

1 GROUND IMPROVEMENT WITH 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, ground with rigid inclusions is called 'composite foundations' in some countries.

1.2 Rigid and Deformable Inclusions

Vertical inclusions have typically been placed into two distinct categories: deformable inclusions (such as stone columns) and rigid inclusions (such as steel, concrete and auger-cast piles). Stone columns being considered as a deformable foundation system, 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.

The method of rigid inclusion is similar to the use of piles. They perform their function by having direct contact with the surface loads and transmitting these loads either through end-bearing, 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 usually 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 performs somewhere between rigid deep foundation and deformable foundation systems. The CMC solution reduces the global deformability of soil mass by using of 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 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 by using of a displacement auger which laterally displaces the soil mass 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, which allows for construction in more sensitive areas. The auger is advanced into the soil to the required depth or the preset drilling torque. During the auger extraction process, a highly workable grout-cement mixture is pumped through the centre 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 possibility of handling contaminated in-situ material.

Quality control of the CMC's is insured by laboratory compressive strength tests of 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 and it reaches equilibrium over the full length of the CMC inclusion with 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 CMC by a load transfer platform (LTP). Figure 1 shows a typical load distribution diagram between a soil and an inclusion network.

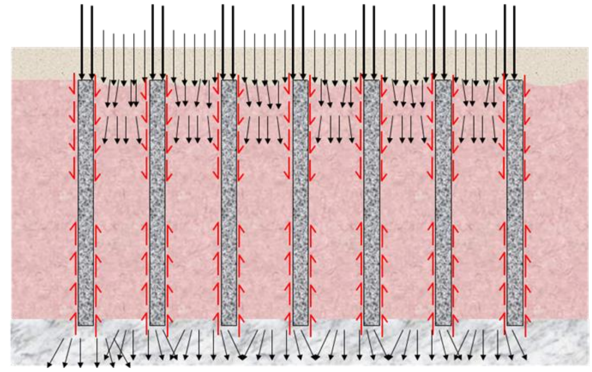

Fig. 1: Load distribution between soil and a CMC network

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 remain 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

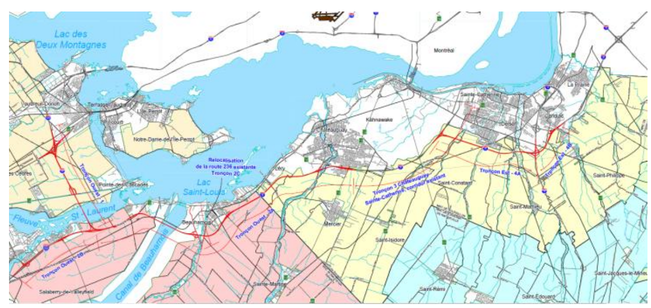

Fig. 2: Alignment of Autoroute 30 (red line)

The Eastern section begins at the existing Autoroute 30 in Châteauguay, and extends to the Jean-Leman interchange in Candiac. The Eastern section will not be connected to the local network, no interchanges are 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 metres;
- 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 is being 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 will cross the St. Lawrence Seaway to Valleyfield. To accomplish this, a 2,550 metre long bridge will be built. It will be erected 38 meters above water level so that ships can pass beneath.

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

For the temporary condition related to the operations on the launching pad, an embankment height of 5 meters above ground level is required at the abutment, reducing to near ground level at CH. 170. The permanent embankment following completion of the launching operations will be 10 meters high at the bridge abutment location, reducing to 7 meters high at CH. 170.

The launching platform will be subjected 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. The load per leg is 2,400 kN. Skids are placed on a 2.5 metre 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 loading from the road traffic of 10 kPa over the entire road surface.

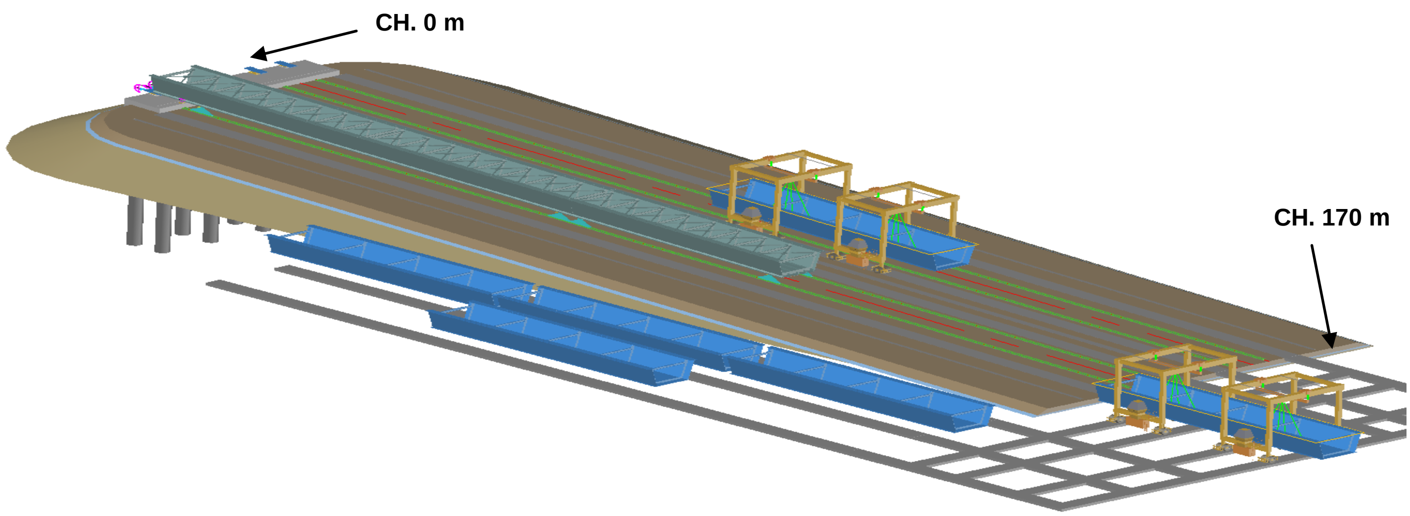

Fig. 3: Launching Platform
(from Nouvelle Autoroute 30 – CJV 2010)

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)**	$\mathbf{N_{SPT}}$	**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 is between 20 and 50 kPa, and standard penetration test N values between 0 and 4.

Ground water level was identified at a depth of about 6.2 meters during site investigation but is known to be seasonal and can rise to near surface during maximum river levels.

3 DESIGN OF THE GROUND IMPROVEMENT

3.1 Description of the CMC Treatment

The design parameter, which has been calculated according to soil and load conditions, was to install one CMC unit for every 600 kN of load, thus a variable grid was designed according to the backfill height. Columns of 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 characteristic 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.

Fig. 4: Construction of the CMCs on the NA30 Project in Beauharnois

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 are:

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

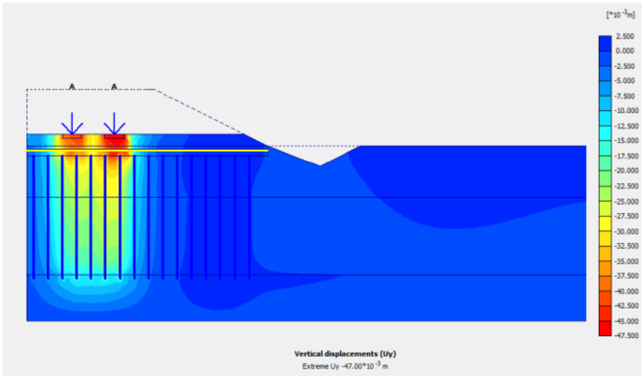

Fig. 5: Result of FEM computations of the soils under the skids legs on the concrete slab

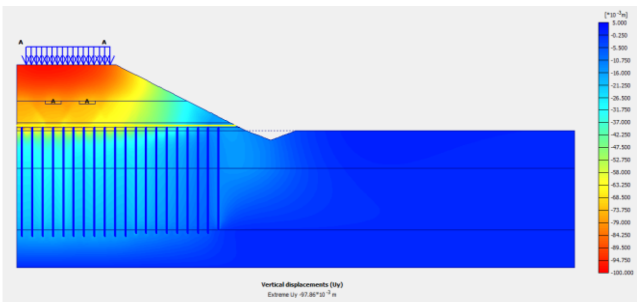

Fig. 6: Result of FEM computations of the soils under the embankment load

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

These performance results demonstrate the efficiency of the CMC ground improvement technique and provide a very favourable 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 on this application was the stability of the embankment under seismic conditions. The horizontal displacement could amount to about 5 centimeters. Hence, the CMC inclusions need 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.

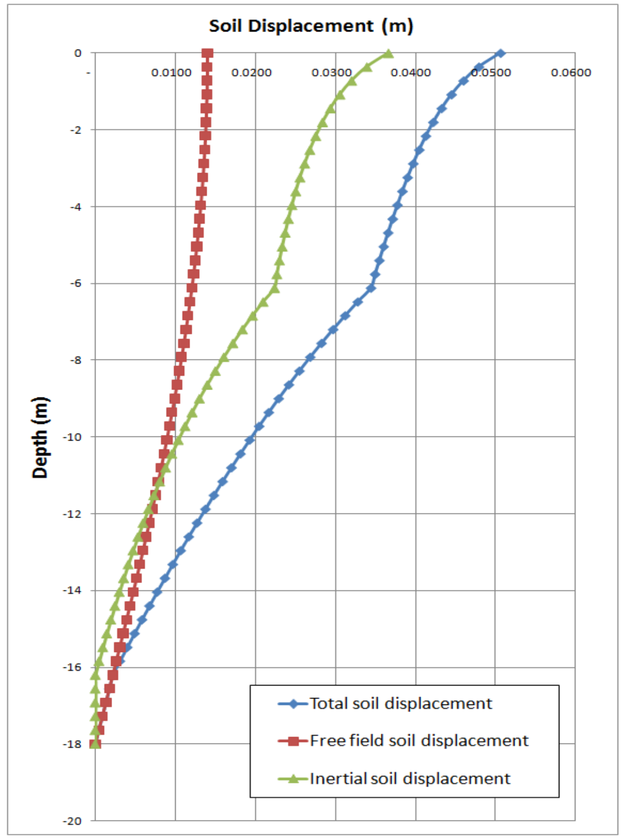

Fig. 7: Total soil displacement

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) :

$$\delta\sigma . B = K_S \times B \times \delta y \qquad (1)$$

Where :

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

δy : differential displacement between soil and inclusion

$K_S \times B$: 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):

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

Where :

α : rheological coefficient of the soil

CMCs are installed through soft soil and support 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):

$$\sigma = \frac{R}{S} \pm \frac{M}{I/_v} \qquad (3)$$

Where :

$$S = \pi \frac{D^2}{4}$$

$$I = \pi \frac{D^4}{64}$$

$$v = \frac{D}{2}$$

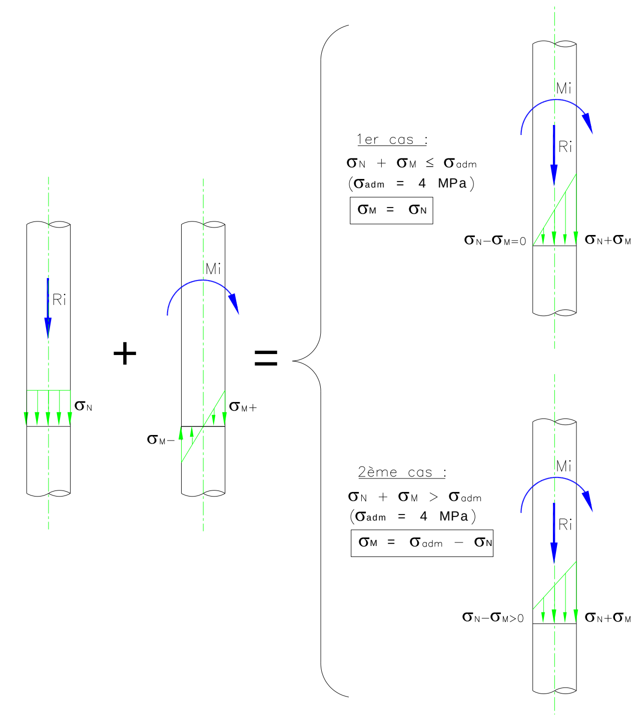

Fig. 8: CMC under combined vertical load and bending moment

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 combined 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 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.

REFERENCES

Liausu, P. and Pezot, B. 2001. Reinforcement of soft soils by means of controlled modulus columns. 15th International Conference of Soil Mechanics and Geotechnical Engineering. Istanbul, Turkey 2:1613-1618

Plomteux, C. and Lacazedieu, M. Embankment Construction on Extremely Soft Soils Using Controlled Modulus Columns for Highway 2000 Project in Jamaica

Combarieu, O. 1988. Amélioration des sols par inclusions rigides verticales – Application à l'édification des remblais sur sols médiocres. *Revue Française de géotechnique* 44 : 57-79

Combarieu, O. 1988b. Calcul d'une fondation mixte semelle-pieux sous charge verticale centrée. *Note d'information technique*, Laboratoire Central des Ponts et Chaussées (LCPC), Ministère de l'équipement et du logement, Paris, France