CMC (CONTROLLED MODULUS COLUMNS) : POTENTIAL APPLICATION TO CANADIAN SOILS WITH A NEW TREND IN GROUND IMPROVEMENT

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ABSTRACT
Controlled Modulus Columns (CMC) were developed in Europe to meet technical, financial & quality requirements of a constantly more demanding ground improvement market. Classical ground improvement technologies such as Dynamic Compaction, Wick Drains and Stone Columns were frequently pushed to their limits by more and more stringent settlement and bearing capacity criteria and challenging environments. The need of improved quality, tighter schedule and at the same time restricted budget led to the development of ground improvement solutions that were requiring design refinements and increased equipment productivity never experienced before in ground improvement. CMC are one of these new technologies. They are a vertical semi-rigid inclusion system that is designed to obtain a composite material (soil + inclusions). The CMC process has been subject to intense research programs in France in conjunction with Bureau Veritas in order to define a design manual, design codes and a construction procedure. CMC are created using a lean sand-mix or very fluid mortar injected through a hollow stem displacement auger with low pressure in a continuous way during extraction creating a semi-rigid column. This paper will present details on the installation method, equipment, design philosophy as well as several case studies with examples of FEM analysis. The potential of CMC in Canada will also be discussed

RÉSUMÉ
Les Colonnes a Module Contrôle ont ete développees en Europe afin de répondre a des demandes croissantes techniques, financières et de qualité d'un marche de l'amélioration de sols de plus en plus exigeant et compétitif. Les techniques d'amélioration de sols classiques telles que le Compactage Dynamique, les Drains Verticaux ou les Colonnes Ballastées étaient de façon fréquente poussées dans leur retranchement par des critères de tassement et de portance de plus en plus exigeants et par des environnements de plus en plus difficiles. La nécessite d'amélioration de la qualité du produit fini, des plannings de plus en plus condenses et en même temps, des budgets limites ont amene au développement de nouvelles solutions d'amélioration de sols qui demandaient des raffinements dans les methodes de dimensionnement et d'améliorer la productivité des matériels. Les CMC sont une de ces nouvelles technologies. Le procede CMC a ete l'objet de nombreux programmes d'études en France en participation avec le bureau Veritas afin de publier des méthodes de dimensionnement, d'exececution et des procédures de contrôle qualité. Les CMC sont installées en utilisant un mortier très fluide et a résistance généralement réduite qui est injecte a faible pression par l'âme d'une tarriere a refoulement a la remontée de manière a créer de façon continue une colonne semi-rigide. Cet article présente les détails sur les méthodes d'installation, le matériel et la philosophie de dimensionnement ainsi que plusieurs études de cas réels avec exemples de calculs aux éléments finis. Le potentiel de cette technique au Canada est aussi discute base sur les conditions de sols et les critères de réception en vigueur.

1. INTRODUCTION

1.1 Generalities

In recent years, construction of buildings or embankments on uncontrolled fills and/or compressible soils has been a growing problem for construction engineers and designers in most of the industrialized countries. When loads are relatively moderate, ground improvement techniques usually provide the best solution in terms of cost efficiency and quality of the end-product.
The Controlled Modulus Columns (CMC) technology has been developed with these two constraints as main objectives and represents one of the best ground improvement technologies to date in terms of speed of construction, quality-control, reliability, range of application and costs. The term "Controlled Modulus Columns" has to be understood as "Columns installed to obtain a Controlled Modulus ground". Basically, the design of a network of these semi-rigid inclusions is performed to obtain a composite material (soil + columns) within which the macroscopic or global deformation modulus is controlled.

1.2 A new trend in Deep Foundations

The CMC belong basically to the same class of deep foundations as the stone columns or the more recent vibro-concrete columns. More exactly, CMC are bridging over the gap between the so-called rigid deep foundations

(RDF such as piles, caissons...) and deformable foundation systems (DFS such as stone columns, rammed aggregate piers, dynamic replacement…). While for RDF systems, a rigid vertical element is directly connected to the structure through caps and grade beams to form a hyper static foundation system, DFS usually utilize comparatively deformable inclusions made of compacted granular material linked to the structure through a distribution mat and slab-on-grade without a structural connection between the columns and the structure. For RDF, the load of the structure is completely transmitted by the rigid inclusions through end bearing and/or side (skin) friction. For DFS, the load transfer is somewhat more complex with a load distribution between the columns and the surrounding ground which results usually in larger settlements of the overall foundation and reduced cost due to a much simpler transfer platform.
The CMC technology somewhat realizes the engineer's dream of bringing together the advantages of both rigid and deformable inclusions into one hybrid technology which offers efficient settlement control and at the same time does not rely on the necessity of a structural transfer platform and expensive connections with the structure.

1.3 Overview of CMC challenges

The development of the Controlled Modulus Technology has led to the resolution of three main challenges:

- the need of new design methods and tools in-between the structural approach of pile foundations and the "plane equal-strain" hypothesis of the ground improvement technologies
- the need of improved equipment and tools to maintain the cost efficiency of most ground improvement solutions
- Develop an adequate quality-control program that would satisfy the current quality and safety requirements.

These three axes of research and development have been successfully achieved in the mid-90's in France with the cooperation of several geotechnical consulting firms and equipment manufacturers and have led to the development of a design and construction manual as well as new equipment with improved designs. In the following, we will briefly describe the construction method and emphasize two major aspects of the design (vertical deformation and horizontal / stability analysis). Finally we will present selected case studies. The conclusion will discuss the potential applications to Canadian grounds and infrastructures.

2. METHOD OF CONSTRUCTION

Controlled Modulus Columns are installed by use of a hollow stem displacement auger coupled to a high torque – powerful pull-down pile rig. The displacement auger is composed of three different parts :

- the bottom part of the auger with its constant-volume flight which will evacuate the cuts upward during penetration
- The middle part which is the displacement part itself has the same diameter as the auger and the hole and prevents the spoils from being evacuated and pushes them laterally, thus displacing the surrounding ground
- The upper part is a classical auger with flights in the opposite direction compared to the lower part of the auger. As a result, it brings any remaining spoil caused by potential collapse of the hole down to the displacement section, improving the efficiency of the tool and the overall quality and continuity of the column.

The installation rigs necessary to achieve the displacement effect are usually extremely powerful with very high torque and strong down-thrust. First the auger is introduced into the ground and the auger is advanced while turning. No grout is injected at that point. When the required depth is achieved, the grout is pumped through the hollow stem auger with moderate pressure to provide sufficient column head to overcome the gravity and sufficient lateral reaction at the tip of the auger. The auger is extracted while the rotation is maintained in the same direction as during the descent in order to avoid loss of grout along the shaft of the hole and along the Kelly bar thanks to the displacement auger.

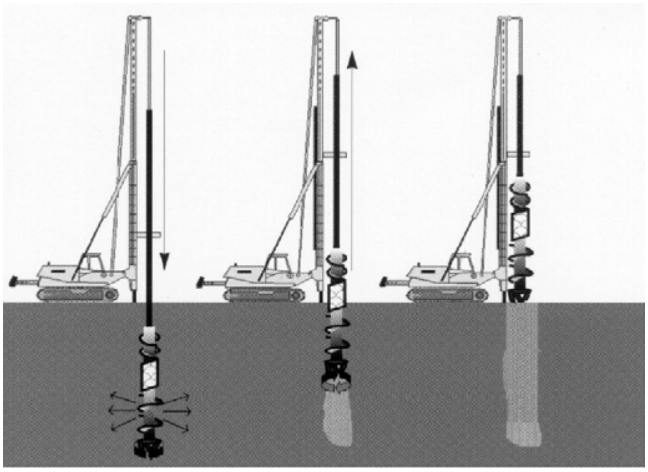

Figure 1. Performance of Controlled Modulus Columns

The grout is usually a lean sand-mix mortar or pea-gravel concrete depending on the required resistance with slumps in the range of 8 to 12. It is important to notice that the grout in pumped without significant high-pressure and the overall process is controlled more by the volume of grout inserted in order to preserve a continuous constant-diameter column than by the injection pressure.
During installation, in addition to the quasi-absence of spoil at the surface, the process is completely vibration-free. The use of CMC is thus recommended for sites with challenging environments that cannot tolerate vibrations or contaminated in-situ spoils. The quality control is insured by laboratory compression strength tests on the grout as well as isolated load tests. The process being closer to ground improvement than piles, it is in our opinion not necessary to carry out expensive load tests at

twice the design load as per ASTM D1143. Load tests at 1 to 1.5 the service load are completely sufficient as the process main purpose of the process is to improve the ground in the overall mass. The European practice in the building codes is to test these elements to 1.5 times the working load. In addition to that, a real-time continuous monitoring of the installation parameters is performed by an on-board computerized quality-control system installed in the rig :

- Speed of rotation and of advancement of auger
- Torque, pull-down, down-pressure, drilling energy
- Pressure and volume of grout

The integration of these parameters allows visualisation in real-time the profile of the column. All the parameters are recorded on flash-memory card and are downloadable daily.

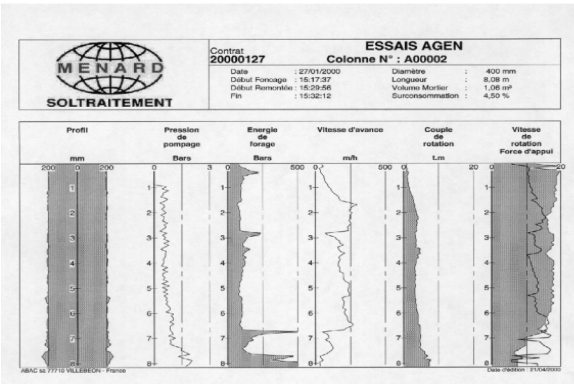

Figure 2. Example of monitoring log of recorded parameters

3. PRINCIPLES OF THE DESIGN OF A NETWORK OF CMC

When designing a CMC solution, two parameters are to be taken into consideration :

- For structures such as buildings the governing factor is usually vertical deformations or settlement
- For column supported embankments, it is necessary to also verify the global stability of the system

3.1 Determination of the deformations of a CMC-supported system

The design of a network of CMC is based on the optimum distribution of loads between the inclusion, the distribution mat or load transfer platform and the surrounding ground. Once these intimate relations have been understood, it is usually possible to determine the total and differential expected settlements of the structure as well as the stresses inside the inclusions. These values have to remain compatible with the deformability of the structure and the resistance of the grout used to build the columns. For stone columns or similar technologies the main hypothesis is that both ground and columns are intimately inter-related and settle together on a plane equal-strain basis which means that at any time and in any given plane section, the settlement of the inclusion is the same as the settlement of the surrounding ground. It is possible to make this assumption because the ratio of deformation modulus between the soil and the columns remains relatively small in the range of 1/10 to 1/100. It is then straight forward to determine the distribution of the load between the columns and the soil and then deduce the elastic settlement of the composite material (soil + column) based on its equivalent modulus of deformation. But as far as CMC are concerned, even with a lean mix, this ratio can be easily between 1/1,000 to 1/10,000 and the plane equal-strain hypothesis is no longer valid. The process of load distribution is extremely more complex and it is necessary to consider that the vertical deformation of a point inside the inclusions at a given initial depth will be different from an adjacent point at the same depth in the ground : there exists a differential field of vertical deformation between the inclusion and the surrounding ground. As a result, the following parameters must be taken into account in the final design of a network of CMC :

- Column top : the ground settles more than the column. As a result, the column head is penetrating inside the transfer platform
- Column tip : the column settles more than the ground. As a result, the column tip penetrates into the competent bottom layer
- In between, there is a differential settlement between the inclusions and the ground leading to friction between the column and the ground. Theoretically, there exists one neutral section which remains plane during the settlement process and thus where the ground and the column settle of the same amount.

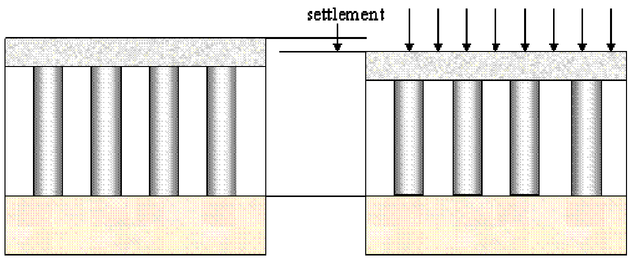

Figure 3. Load distribution concept in the “plane equal-strain” hypothesis used for stone columns design

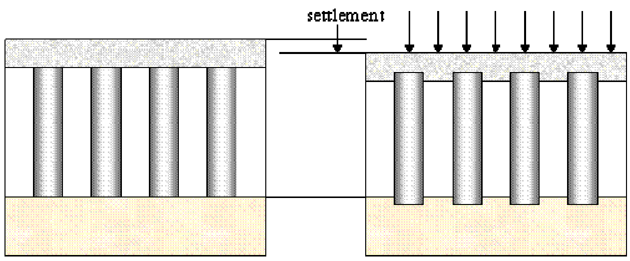

Figure 4. Load distribution concept in the “differential field of settlement “ concept for CMC design

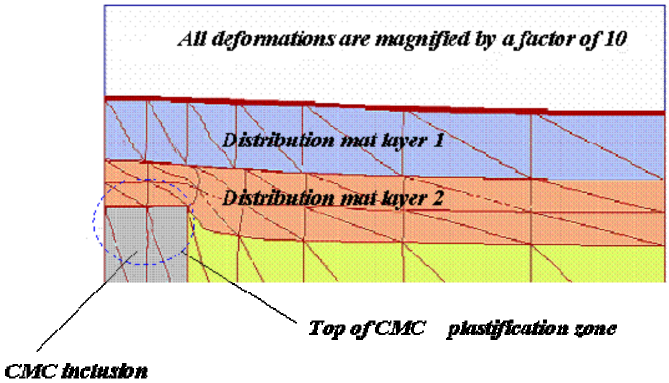

Figure 5. Principle of interaction CMC – distribution mat

As a result, displacement and stresses are given by the following conceptual charts.

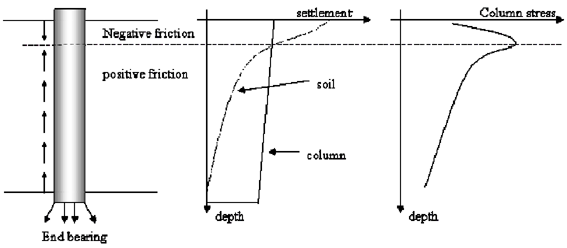

Figure 6. Load transfer, settlement and stress for CMC design

As a result, as far as stresses are concerned, above the neutral point, the column is subject to negative skin friction : the load is transferred from the ground to the column and the stresses inside the column increases to reach a maximum at the neutral point. Below this point, the column is subject to positive skin friction : the load is transferred from the column to the ground and the column is progressively discharged with a decrease of the internal compression stress. This scheme is valid assuming a deformable distribution platform which will allow the punching of the column to occur. In case of a rigid slab, the infinitely-rigid beam hypothesis is governing the stress distribution and the neutral point is directly located under the slab. The deformation of the column and the platform are equal at that point by definition and the stress in the columns is maximal just under the slab. In that case CMC are functioning like friction piles.
Although hand calculations are possible given a certain number of approximations and assumptions, the finite element analysis has proven to be the most reliable method to accurately predict the behaviour of the structures founded on CMC. FEM and finite difference analysis models can take into account :

- the behaviour of the column top and bottom with plastification into the mat and into the competent layer
- strain-stress relation for the CMC grout
- strain-stress relation for the ground depending on the type of soils
- load transfer between columns and ground both ways (from column to ground and ground to column)

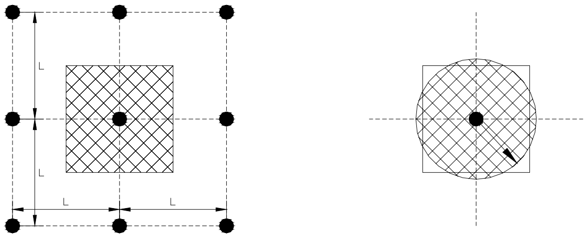

Figure 7. Definition of influence zone of single column

Usually, the calculations are performed in two steps. In a first step, an analysis if performed at the level of a unit cell of the installation network (single column model) using an axysymmetrical hypothesis for the model.

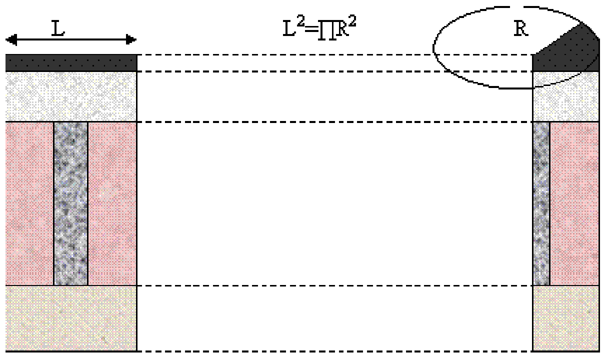

Figure 8. Axysymmetric analysis of a unit cell

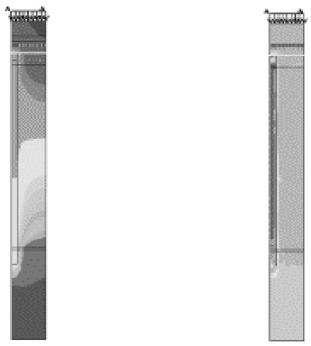

Figure 9. Example of axysymmetric calculation using Plaxis

This axysymmetric calculation is usually performed using PLAXIS and allows to design the grid of installation, the necessity of reinforcement by geotextile in the transfer layer as well as the stresses in the ground and in the column resulting of the stress distribution model. It is thus possible to refine the design parameters such as diameter of the columns, grid of installation, thickness of the transfer layer compression strength of the grout and thus optimize the total cost of the solution. Once the design parameters have been chosen at the "microscopic" level of a single column, a global macroscopic elasto-plastic calculation can be performed using a true FEM program such as Cosmos or Flac in order to take into account specific boundary conditions : examples :

- variable height of fill along the same section or non-symmetric loading conditions
- horizontal loads due to train braking friction on tracks for a railway embankment
- rapidly varying thickness of compressible ground along a given section
- variable CMC grid of installation

This second calculation usually allows the confirmation of compliance with the deformation criteria for the structure and allowable stresses inside the columns.

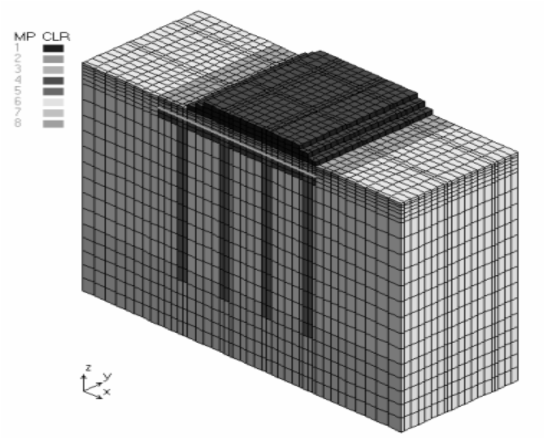

Figure 10. 3D model using Cosmos/M to determine shear stresses in column due to brake efforts under a railway embankment

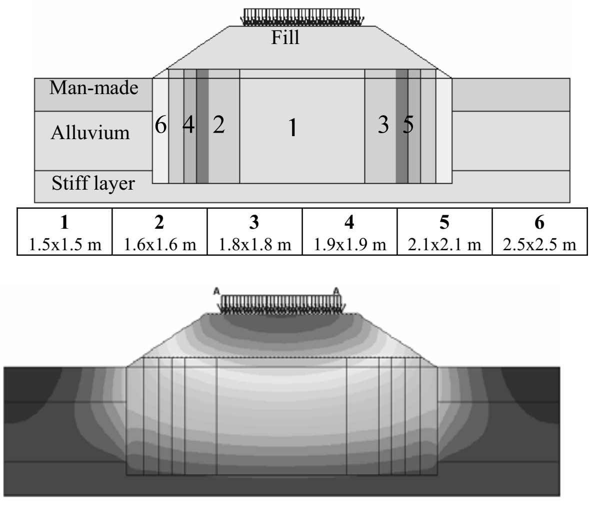

Figure 11. Model of infinitely long embankment (2D) and result of FEM calculation for total settlements.

Additional examples of FEM analysis applied to an actual case history is given in the Case study section of this paper.

3.2 Determination of safety factor against failure in the case of a CMC supported embankment

For soft ground loaded by an embankment, the overall stability of the embankment is usually the critical limiting factor in the design process. Several ground improvement techniques are widely used to improve safety against shear failure under the load of an embankment :

- Wick drains reduce the time of consolidation. Nevertheless, the necessity of stage loading is often incompatible with many project schedule requirements
- Stone columns provide additional shear strength by introducing high friction granular material into a cohesive low-shear strength ground. Nevertheless, in soft clays or peat, the lack of confinement due to the weakness of the surrounding soils is limiting the load that can be carried by each column due to the occurrence of bulging.

CMC is therefore a very efficient solution for column supported embankments and is the solution of choice for embankment under highways or railways.
Basically the main principle governing the design is to reduce the load on the compressible soils by allowing the inclusions to carry most of the load. This results in a dramatic reduction of the sliding moment leading to failure. The network of CMC will transmit most of the load beyond the limit of the potential failure zone. As a result, the CMC inclusions are developing two stabilizing reactions within the soft ground against the appearance of failure lines:

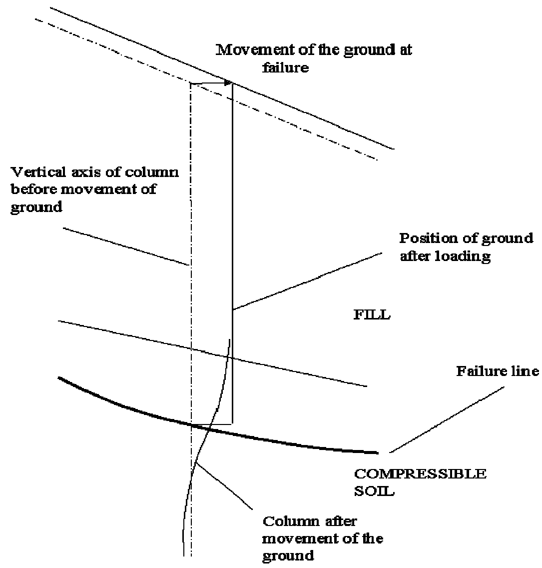

Figure 12. Deformation of ground and column along failure line

- a vertical reaction corresponding to 80 to 90% of the load of the embankment for tight grids and thus "unloading " the soft weak grounds

- a sub-horizontal reaction or lateral force develops an additional shear resistance in the ground as the inclusions create a “hard barrier” against the lateral flow of the compressible ground during failure. This effect directly opposes to the creation of shear failure surfaces. This reaction actually develops because there exists a differential horizontal field of deformation between the column and the soil on each side of the potential failure as shown below.

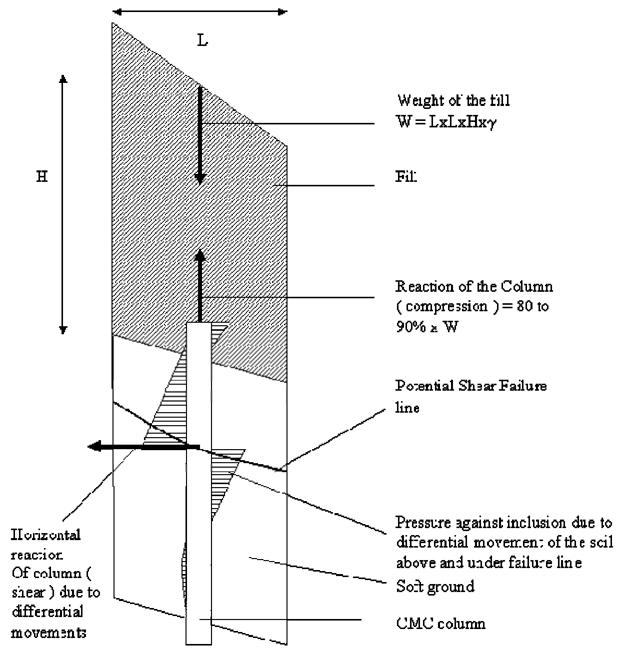

Figure 13. Conceptual lateral resistance mechanism

The resisting lateral reaction T mobilized by the column is directly related to the shear resistance necessary to prevent failure from occurring. The idea is to be able to enter in the slope stability analysis software (Talren or equivalent) a model that is taking into account all the benefits of the CMC. Therefore, in Talren, each CMC is modelized as a nail working with imposed compression (corresponding to 80 to 90% of W in the previous figure) and imposed horizontal shear resistance (horizontal reaction of the column due to differential movement of the ground above and below the failure line). The calculation of the vertical reaction is straightforward given an height and density of fill load as shown in figure 11. The determination of the horizontal reaction requires further analysis. The calculation of this reaction is made in two steps :

- Determination of the maximum allowable bending moment in the CMC column. We, by hypothesis, limit the bending moment using the following assumptions:
  - o The maximum total stress inside the column is limited by the grout compression resistance and approved construction codes
  - o No tension is allowed in the inclusion.

The stress linked to the bending moment is calculated using the previous hypothesis as shown on figure 12 and the moment is given by

$\sigma_M = \frac{My}{I}$; I being the inertia of the column.

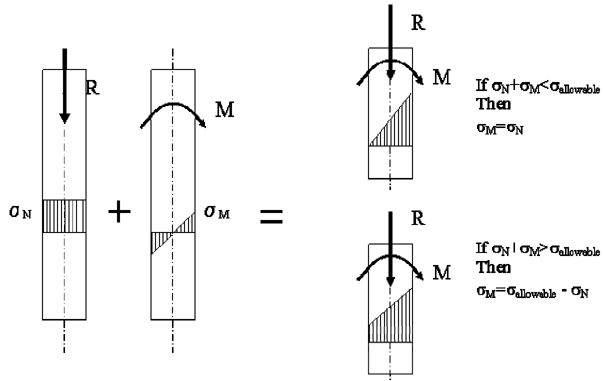

Figure 14. Determination of stresses from bending moment in the inclusion

The maximum allowable bending moment gives us the ability to calculate the lateral reaction T of the column due to the difference in movement between the ground above and below the failure line. It is very important to note that the maximum horizontal reaction is not controlled by the direct shear resistance of the grout itself. If you only rely on the shear strength of the grout, the solution is unconservative (i.e. with the CMC the resistance is bending controlled). This approach would tend to overestimate the safety factor against shear failure and unsafely reduce the overall number of columns. The calculation of the resisting shear reaction T is performed using a finite difference analysis with the following formula :

$\partial\sigma.L = K_s.L.\partial y$ [1]

where

$K_s.L$ is the modulus of reaction of the ground applied on the width of the inclusion

∂s is the pressure difference from each side of the inclusion

∂y is the differential displacement between the ground and the inclusion.

To determine the value of the modulus of reaction of the ground against the inclusion is calculated using a pressuremeter analysis described in the D.60.A.N manual “ Interpretation and Application of Pressuremeter Results to Foundation design” (paragraph 4.7 & 4.8) :

Long term : $K_s.B = \dfrac{6.E_M}{\frac{4}{3}.2.65^{\alpha} + \alpha}$ [2]

short term : $K_s.B = \dfrac{12.E_M}{\frac{4}{3}.2.65^{\alpha} + \alpha}$ [3]

The loop calculation gives the horizontal shear stress in the inclusions which corresponds to the deformation of the ground and column that gives the maximum allowable bending moment already calculated.

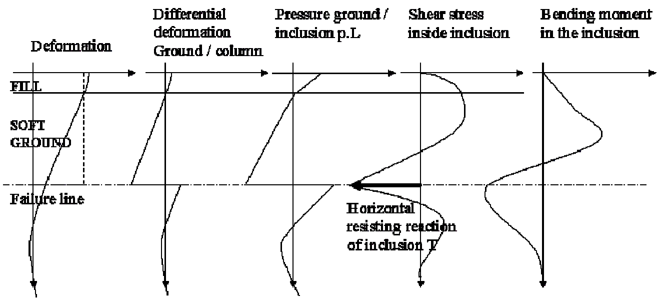

Figure 15. Deformation, stresses and moment in columns

The value of horizontal reaction T and vertical reaction R are then entered into Talren model where each CMC column is modelled as a soil nail with imposed compression and shear.

4. CASE STUDY

4.1 Test section – Agen (France)

4.1.1 Description of the test section

This project is part of the test section program developed jointly with bureau Veritas in France in order to update the building design codes and recommendations to engineers to take into account the recent developments with the CMC technology. The test section procedure is as follows:

- 9 CMC columns diameter 0.40 m are performed on a 3.0m x 3.0m square grid – depth of the column is 8.5m
- Columns are covered by a distribution mat made of roller compacted granular fill of 0.40m thickness
- A concrete slab 15cm thick with no steel reinforcement is then placed on top of the mat
- The area is instrumented with 1 multidepth settlement gage, 4 settlement plates on top of the slab and 9 total stress gages directly under the slab
- A reference test section is also installed adjacent to the CMC area without any treatment to be able to compare the results with the CMC test section
- The CMC test area has been loaded with 3m in a first step then 5m. the top of the embankment was 12m x 12m in order to be as close as possible to an infinite embankment hypothesis. The reference test section was loaded with 3m of fill.

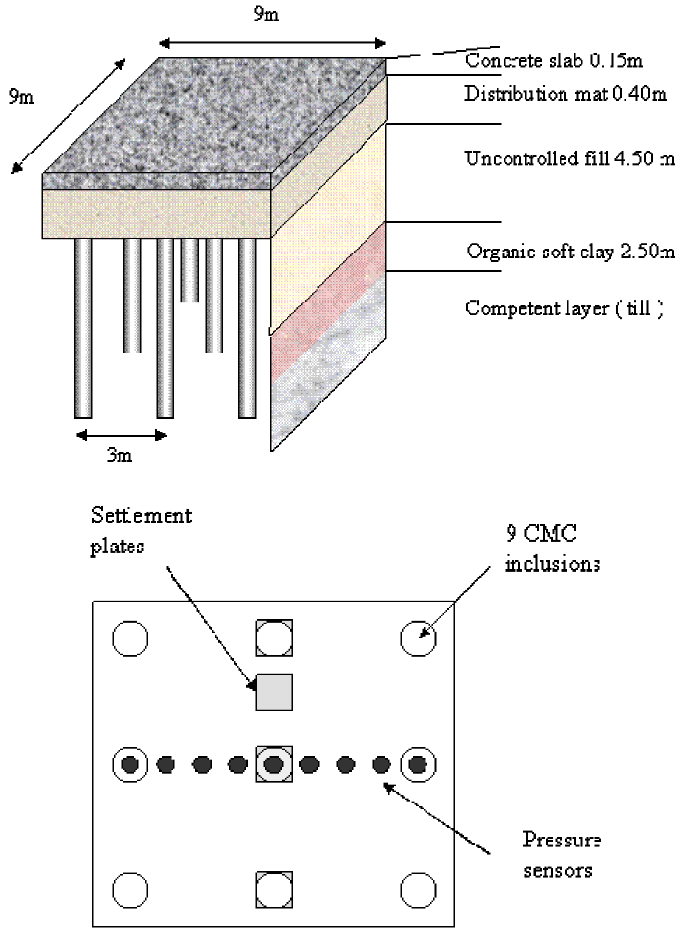

Figure 16. CMC test section set-up

4.1.2 Soil Profile

The soil characteristics were determined using pressuremeter tests in the test section area. The values given below are average values :

Designation	thickness meter	limit pressure pl Mpa	Pressuremeter Modulus Ep Mpa	Rheological Coefficient α
Uncontrolled Fill	4.5m	4	0.6	0.5
organic clay	2.5m	2	0.5	0.5
Till		4.5	39	0.5

Table 1. Soil profile – Pressuremeter characteristics

4.1.3 Stress measurement - Settlement Results

The pressure sensors gave an overall distribution of stresses in agreement with the model described above. The sensors were installed just below the slab. The stress measured by the sensors located at ¼ of the grid gave a value of 50% of the full weight of the fill surcharge indicating that the load transfer between the CMC and the soil was efficient. The sensors located at ½ of the grid spacing (in-between two columns) showed a stress ratio of about 80% indicating that the arching effect between the columns was initiated just below the slab and the ratio would probably decrease down to the neutral point. Finally, the stress at the center of the column was about 130 to 150% the weight of the fill. This is a very remarkable result that shows that the differential deformation in the distribution mat (see figure 5) are really occurring. This stress would probably increase until the neutral point is reached.

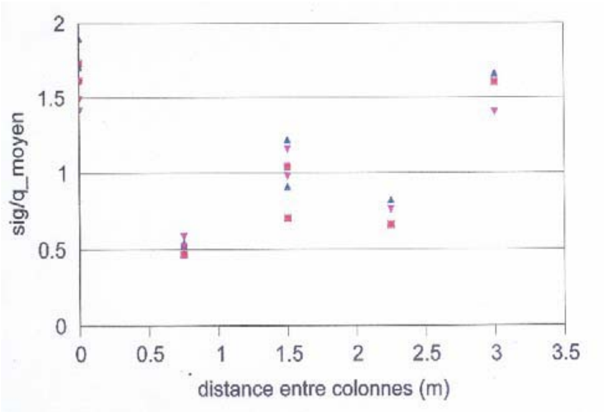

Figure 17. Stress ratio versus distance from center of test section

As far as settlement is concerned, a settlement reduction factor of approximately 3 was measured between the area without CMC and the area with CMC. The settlement was 100% completed 10 days after the placement of the fill.

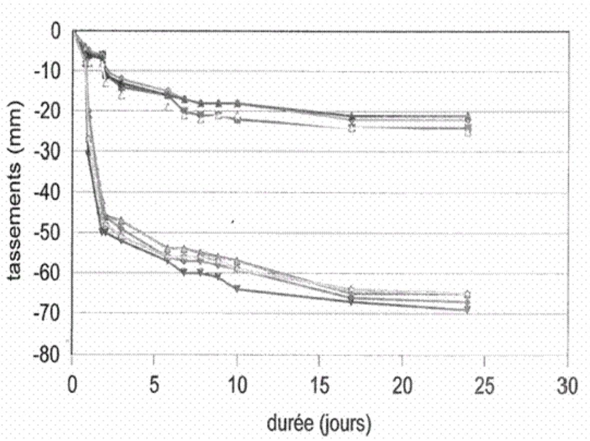

Figure 18. Settlement of CMC test section (above) and reference test section (below) versus time (days from fill completion)

4.1.4 Comparison of model and actual results

A finite element analysis of the test section was performed using Talren and the results were compared with the monitoring data. An axysymetric calculation was used to estimate the total settlement. The calculation gave results within 15% of the actual measurement with a calculated total settlement of 37mm with Plaxis and actual settlement average value of 32mm.

5. CONCLUSION

Controlled Modulus Columns have been successfully used in Europe for about 10 years. Through research and development, partnering between contractors, consultants, engineers and equipment suppliers, the technique is now recognized and accepted as a reliable ground improvement alternative to classical technologies with specific equipment and specific design methods. CMC is a mature technology in the “Old World”. The next challenge is to become successful in the “New World” of North America. The technology is slowly introduced in the USA. The market is tremendous and there is no doubt that North American Engineers and Consultants will progressively become acquainted and comfortable with the technology. The applications are numerous : column supported embankments for highways, railways, airport platforms ; Slab-on-grades Building foundations; slope failure prevention…And the range of applicable soils is the largest among all the ground improvement technologies : from uncontrolled fills to loose sands, from compressible clays to organic peat, there is virtually no limitation to when and where the technology can be applied. Of greatest interest in Canada will be the geographic areas that combine large industrial or commercial land use with soft soils. Areas which fall into this category due to the presence of soft clay includes Edmonton, Sarnia, Ottawa and Quebec City.

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