CMC Foundation System for Embankment Support - - A Case History[1]

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ABSTRACT:A wide range of deep foundation systems has recently been developed for construction of embankments on soft soils. Controlled Modulus Columns (CMC) is one technique of ground modification, developed in France, for support of light structures such as highway and railway embankments. This paper presents the case history of a column supported embankment project in which 2193 CMC columns were installed up to a depth of 12.5 m to minimize settlement. Main challenges were soft ground condition of the site, and the need for an accelerated construction technology for timely delivery of the project. Evaluation of various alternatives, design considerations, construction related issues and monitoring system are discussed in detail.

INTRODUCTION

Embankment construction is an essential element of any highway and railway construction. The problem arises when the embankment passes through soft ground conditions such as soft clay, bay mud, organic soil/peat, chalk or loose fine sand. In that case the soil is subject to settlement or stability problem due to lack of bearing capacity; and/or in case of loose saturated fine sand subject to liquefaction due to ground shaking. To overcome these difficulties, a wide range of deep foundation systems has recently been developed for construction of embankments on soft soils (Porbaha et al, 2002a and b). These techniques take advantages of various ground modification concepts such as densification, reinforcement, solidification, etc. (see Figure 1).

The purpose of this paper is to present a new deep foundation system, namely Controlled Modulus Columns (CMC), for support of embankments. The detail of design, construction, and monitoring of an embankment project supported by the CMC system is outlined here.

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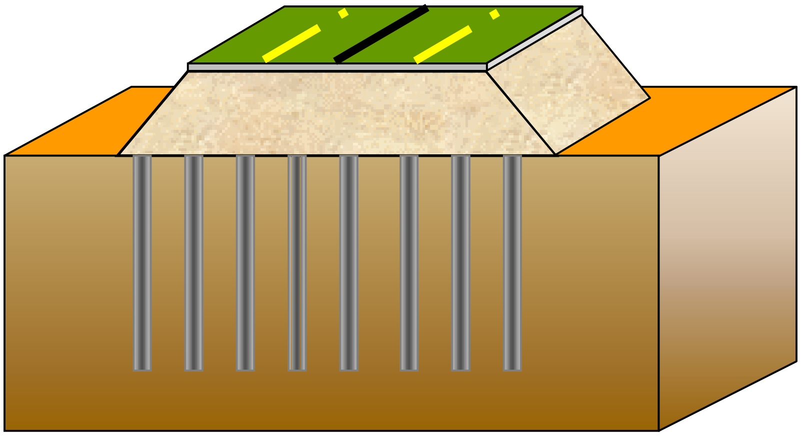


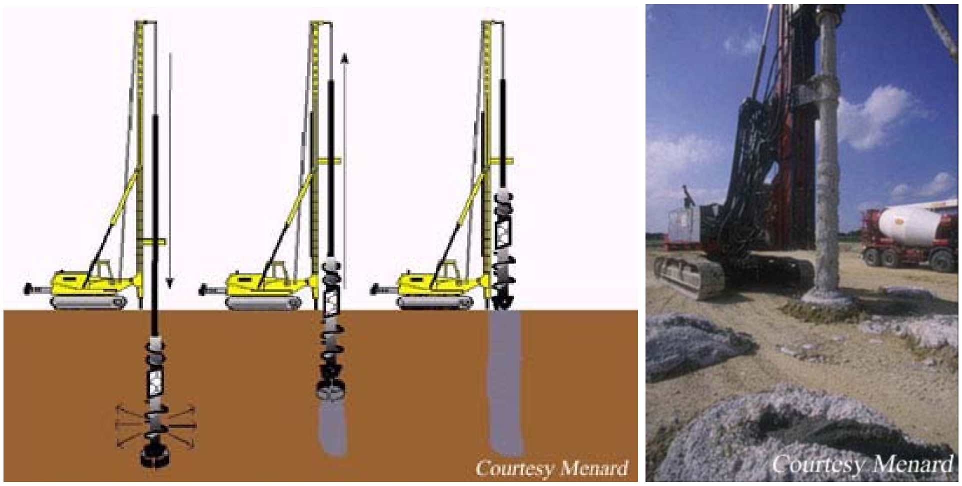
Figure 1: Concept of column-supported embankment

CONTROLLED MODULUS COLUMNS

The Controlled Modulus Columns (CMC) is a ground modification system that reinforces soil by screwing a hollow auger into the soft soil and installing a low-pressure cement-based grout column through the hollow auger (see Figure 2). The combined effect of densification and reinforcement improves characteristics of the soft ground due to composite action. The CMC system uses a displacement auger powered by equipment with very large torque capacity and very high downward thrust, which displace the soil laterally with virtually no spoil or vibration. The auger is screwed into the soil to the required depth and as such it increases the density of the surrounding soil and thus increases its load bearing capacity. When the required depth or a preset drilling criteria (usually rotational torque) is reached, a highly workable grout-cement mixture is pumped through the center of the hollow auger. The grout mixture then flows under low pressure out of the auger base as it is retracting to obtain a high capacity column that can be used in close vicinity of sensitive structures. The grout is injected under low pressure, typically less than 10 bars (145 psi) and no soil mixing take place during the pressure grouting. To ensure that the soil above the auger remains compacted, the top of the auger is equipped with reverse direction flights. The result is a composite system with column reinforcements bonded to the surrounding soil. The main features of CMC technology are:

- Material is grouted in place with the use of a displacement auger without spoil.
- Deformation modulus is 100 to 3000 times that of soil.
- Soil properties are improved around the columns by compression resulting from the lateral displacement.
- Diameter is determined based on size of the auger (usually in range from 350 to 500 mm).
- Common installation practice is based upon square grids with center-to-center spacing in range from 1.2 to 3 m.
- Maximum length of treatment is 25 m.

The case history of a project in which CMC foundation system was used for embankment support is discussed here.



(a) (b)

Figure 2: CMC Foundation system (a) Construction process (b) CMC Rig

PROJECT DESCRIPTION

The project consists of improving the ground under the access embankment of a road crossing over the Channel Tunnel Rail Link (CTRL) covering 17 kilometers of railways construction. The embankment height ranged up to 7.5 meters and live load of 20 kPa from the road traffic was taken into account. The main design requirement for the ground improvement was to limit the post-construction settlement of the embankment to 10 mm per decade. The works have been done in a design and built basis, using a Controlled Modulus Columns solution.

SUBSURFACE CONDITION

The geotechnical data for this project is derived from the Cone Penetration Tests (CPT's) performed along the axis of the anticipated embankment from station 0+420 to 0+600. The CPT results are presented in figure 3.

A very soft alluvium layer, made of a succession of very soft clay (w_p=60%, w_L=150%, 60%<w<150%) and fibrous peat (w_L=480%, 250%<w<450%, C_u=33 kPa), was extending all over the site with a variable thickness ranging from 11 m at station 0+420 to 6 m at station 0+600. In this alluvium layer, CPT cone resistance value q_c were less than 0.5 MPa with typical values around 0.3 MPa. Under this very soft alluvium layer, was a medium density structureless chalk layer with silt fragments between station 0+420 and 0+500, mixed with medium dense sand and silty sand layer between station 0+500 and 0+600. In those layers, the CPT cone resistances q_c were greater than 3 MPa. As a consequence, according to the anticipated loads and subsequent design requirements, those layers were able to be considered as suitable competent layers for the CMC. At certain locations, a 1 or 2 meter thick stiff clay layer (with q_c>20 MPa) was present at the bottom of the soft alluvium layer. Despite being stiff, the clay layer was not considered as a suitable competent layer because of its limited thickness.

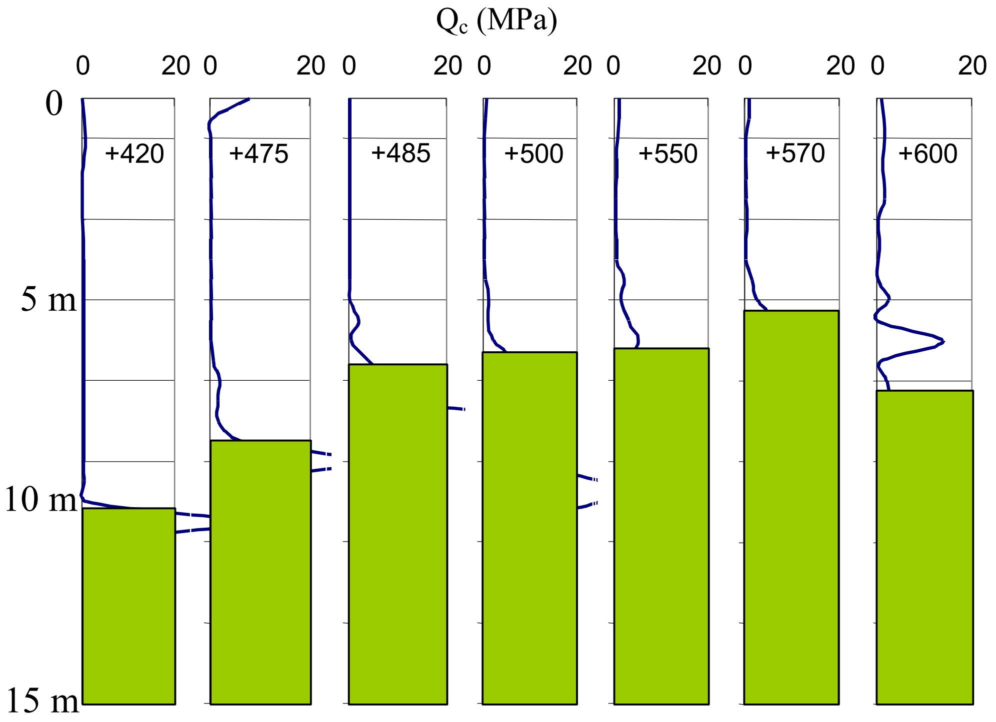


Figure 3: CPT's performed along the embankment axis at station 0+420 to 0+600

ALTERNATE FOUNDATION SYSTEMS

Three foundation systems considered for this project includes: conventional vertical (wick) drain, stone column, and the CMC systems. “Time” was critical for this project, and thus a wick drain and surcharge solution was not acceptable to the project owners. Moreover, a CMC solution was preferred to a stone columns solution for the following reasons:

- Predicted settlement: The predicted settlement for stone columns was more than twice the predicted settlement with CMC. The settlement requirement (less than 10 mm per decade) was too strict to allow an economical solution using stone columns.

- Field performance: The alluvium layer was too soft to allow a safe implementation of stone columns to support the embankment. The presence of critically soft clay and peat, associated with high loading from the embankment (up to 155 kPa), raised the possibility of bulging problems. Indeed, the very soft soil did not provide enough lateral confinement to ensure the lateral stability of the stone columns.

DESIGN OF THE GROUND IMPROVEMENT

The ground improvement solution takes into account the different loading conditions; the settlement tolerance associated with those conditions; and the variability in different soil characteristics. The CMC ground improvement was thus adapted fro this project. The design parameters needed to define the CMC reinforcement system were:

- The depth of the columns and their possible anchorage length in the competent layer
- The diameter of the columns
- The pattern & configuration of the columns grids
- The modulus of the grout used to make the CMC. This parameter is adapted for each new project, but for practical reason, is constant over a particular project.

The complete design of the CMC includes estimation of bearing capacity of single columns, (b) checking pre-design parameters by a numerical procedure, stability analysis, and development of final design, as discussed in the following sections.

Bearing capacity of single CMC column

The bearing capacity of a single CMC column was evaluated according to the equation of the ultimate capacity of piles in chalk proposed by Sanglerat, G. (199?):

$$Q = \left(kAq_c + k_1 \frac{kq_c}{10} Z\pi\phi \right) / FOS \qquad (1)$$

in which, $k = 0.5$; $k_1 = 0.5$ (usually $0.5 < k_1 < 0.9$); A is the section of the CMC (0.138 m^2 for diameter 420 mm, 0.101 m^2 for diameter 360 mm); Z is the anchorage-length in the competent layer; and ϕ is the diameter of the CMC. A factor of safety (FOC) of 2 was applied to evaluate the bearing capacity of the CMC's.

The project was divided in two different areas, corresponding to the two main soil profiles of the site:

- The first case was the most general case (from station 0+460 to 0+600). In this area, the thickness of the soft soil was less than 10 m, and anchorage-length of 1.5 m were able to be executed. The stiff layer reached q_c values greater than 4 MPa, with a diameter of 360 mm, each CMC from this area was able to support $Q_{allowable}$ = 185 kN/CMC. (taking into account a factor of safety of 2)
- The second case was related to CPT in station 0+420 which showed alluvium thickness of about 11 m followed by a stiff layer having a cone resistance q_c of 3 MPa. This case was limited to a small part of the job. However, due to the soil profile, the anchorage-length of the CMC had to be limited to only 1 m to avoid penetration into a less stiff layer. To compensate this limitation, CMC's with larger diameter (420 mm) were chosen. In those conditions, each of these CMC was able to support $Q_{allowable}$ = 153 kN/CMC with a factor of safety of 2.

The CMC pattern could thus be estimated from those bearing capacities; simply by dividing them by the applied load. The result is the maximum area of influence that can be associated to one single CMC. For example: for an embankment of 5 m high, the applied load was 5 m x 18 kN/m^3 = 90 kN/m^2 . In the general case (i.e., less than 10 m of soft soil), the area of influence of a single CMC was 185 kN/CMC / 90 kN/m^2 = 2.06 m^2/CMC corresponding to a square grid of 1.40 m x 1.40 m = 1.96 m^2/CMC. The pattern of the ground improvement, depending on height of embankment and thickness of treated ground, is shown in figure 4.

Max thickness of soft soil (m)	CMC diameter (mm)	Maximum allowable load (kN)	Maximum height of embankment (m)			
			1.0	3.0	5.0	7.5
			adopted mesh (m)	adopted mesh (m)	adopted mesh (m)	adopted mesh (m)
11	420	153	-	1.7	1.3	1.0
10	360	185	-	1.7	1.4	1.2

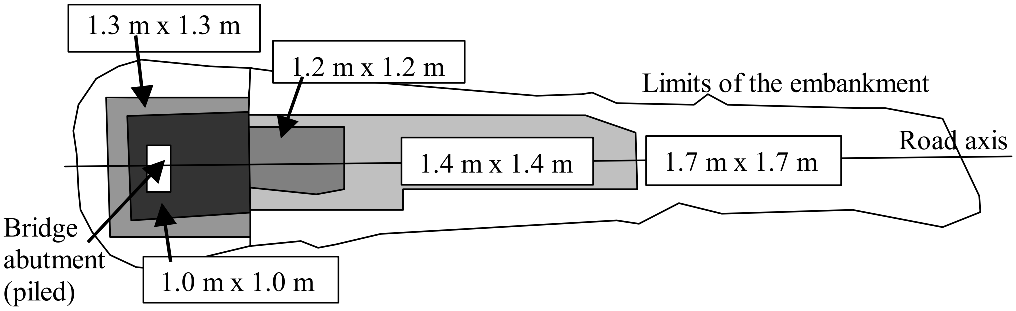


Figure 4: Layout of the CMC

Design Check

To check this preliminary design, axial-symmetrical finite difference method calculations have been implemented with the program PLAXIS. Under uniform loads, the problem can be studied by an axial-symmetrical calculation as shown in figure 5.

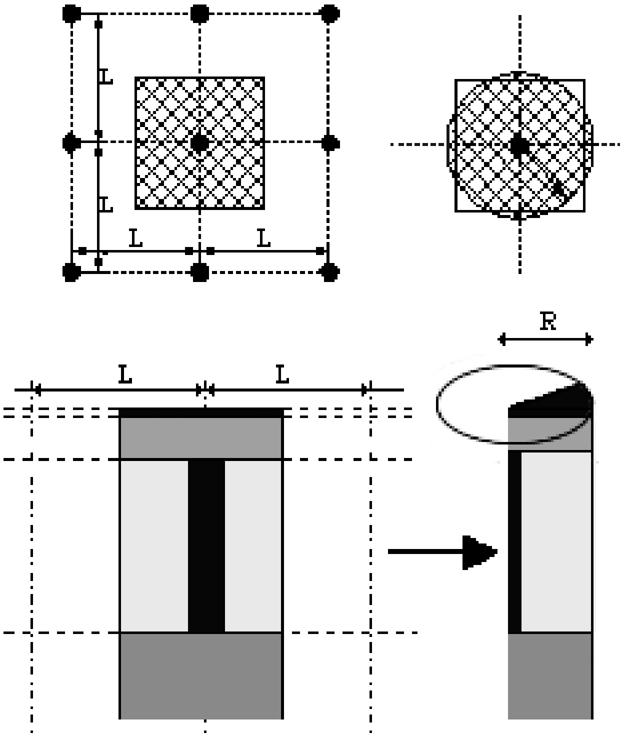


Figure 5 :Principle of the axial-symmetrical calculation

This approach to the problem allows taking into account, under vertical loadings, the reinforced soil as well as the embankment, the geotextile (with ultimate tensile strength 84 kN/m and modulus 630 kN/m) and the transition layer. Thus it gives the strain and stress distribution between the soil and the columns. These FEM calculations were made in short term and long term conditions alike, in order to assess the time related behavior of the improved ground. For FEM calculation purposes, the parameters used in the numerical calculation for long-term behavior in correlation with available CPT's cone resistance are shown in Table 1.

Table 1: Input parameters for FEM analysis

Material	Alluvium	Competent Layer	Transition layer	Embankment	CMC
Modulus,E (MPa)	1.5	15	35	80	11,000
Thickness (m)	7.0 to 11.0	3.0	0.5	0 to 7.5	7.5 to 12.5
Cohesion (kN/m^2)	0	0	-	0	-
Friction Angle (°)	18	25	-	33	-

Note: a grout with unconfined compressive strength at 28 days f_{c28} greater than 11 MPa was chosen, the Young's modulus of the CMC was then assumed to be at least 11,000 Mpa.

For short-term behavior, the geotechnical characteristics of the alluvium competent layers were assessed using the following equation:

$$\frac{E}{1+\nu} = \frac{E'}{1+\nu'} \tag{2}$$

in which the short-term elastic modulus of 1.7 and 17 Mpa was adopted for the alluvium and stiff layers, respectively. To address all possibilities, two different cases, corresponding to the worst case scenarios, were studied:

Case 1:

- 7 m of soft soil
- CMC diameter 360 mm
- CMC mesh 1.40 m x 1.40 m
- Embankment height (including transition layer): 5.00 m
- Road surcharge: 20 kPa

Case 2:

- 11 m of soft soil
- CMC diameter 420 mm
- CMC mesh 1.00 m x 1.00 m
- Embankment height (including transition layer): 8.00 m
- Road surcharge: 20 kPa

The main results of these axial-symmetrical FEM calculation are presented in Table 2.

The geotextile layer has been placed originally to increase the factor of safety against shear stress and was a requirement of the British Standard. However, the calculation showed that the tensile stresses in the geotextile were very limited.

The time related aspect of settlement was assessed by comparing the computed settlement for short and long term behavior. The difference between short and long-term settlement was of about 4 mm, and the typical duration for this settlement to occur was between 5 and 10 years to ensure that the settlement requirement of 10 mm per decade is respected.

Table 2 : Results of numerical analysis

Case #			**Case 1**		**Case 2**	
Studied case			**Short term**	**Long term**	**Short term**	**Long term**
CMC datas	CMC diameter (mm)		360 mm		420 mm	
	CMC mesh (m)		1.4 m		1.0 m	
	Alluvium thickness (m)		7.0 m		11.0 m	
FEM results	Embankment construction	Settlement	29 mm	32 mm	31 mm	34 mm
		Stress in geotextile	1.2 kN/m	1.2 kN/m	0.63 kN/m	0.63 kN/m
	Road loading	Settlement	+ 9 mm	+ 10 mm	+ 5.5 mm	+ 6 mm
		Stress in geotextile	1.4 kN/m	1.4 kN/m	0.72 kN/m	0.72 kN/m

Note: The other cases with similar soft soil conditions have been designed so that the load per CMC was comparable to the studied cases.

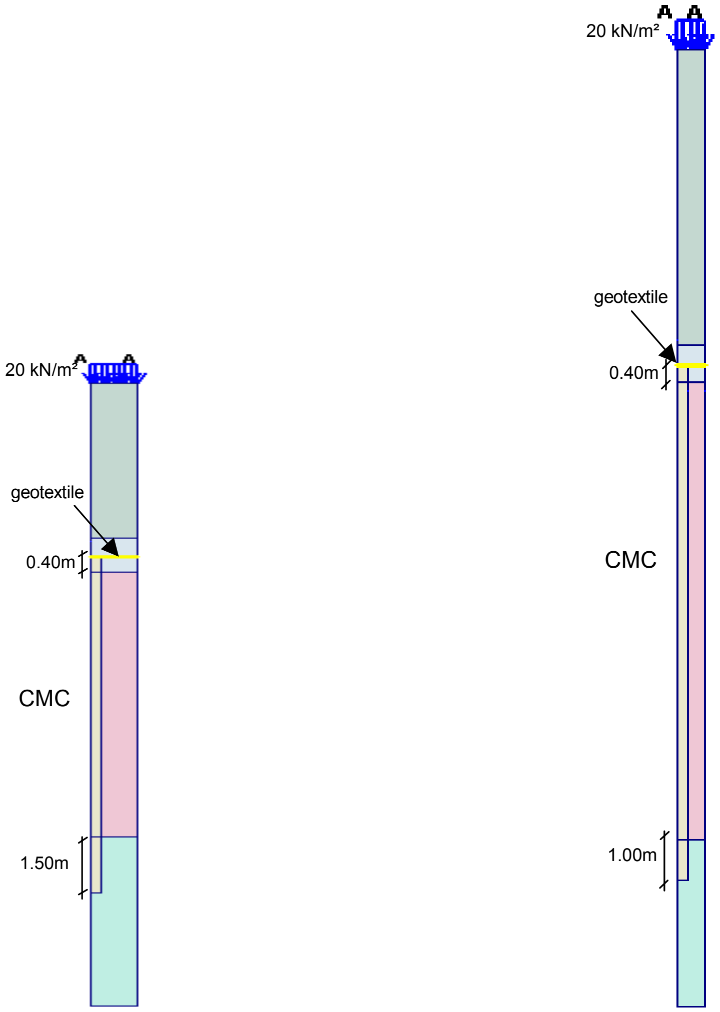


Figure 6: Axial-symmetrical finite difference models, case 1 and 2

Stability Calculations

Stability calculation was performed using TALREN program to check possible slope failure problem during embankment construction. The results of these calculations showed a factor of safety against slip circle failure of 1.39.

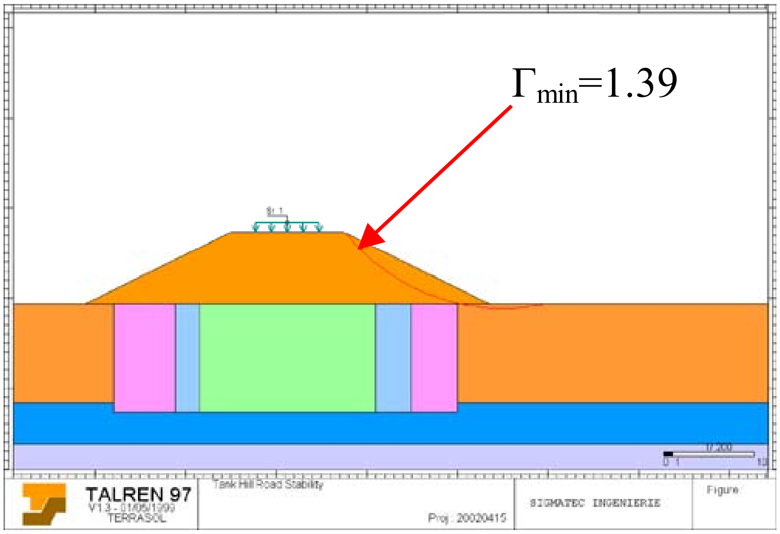


Figure 7: Stability calculation

Final Design

Due to very soft ground condition for this project (particularly the chalk layer), a very dense column spacing of 1.0 m square grid spacing was initially adopted to correspond with an area replacement ratio of 13.9 %. The area replacement ratios for CMC system are typically between 2 to 8 %, with CMC single columns designed to support loading of 150 to 350 kN. The installation process use a displacement auger, and thus the unusually high CMC density may have a risk of damaging the freshly grouted surrounding columns during the installation of a new CMC. Consequently, the conventional construction method was modified for the high density area. The CMC columns were installed in two different interleave passes, each with 1.4 m x 1.4 m grids as shown in figure 8; corresponding to an area replacement ratio of 6.9 %. The CMC columns were anchored in the chalk or sand layers, resulting in columns in length from 7.5 to 12.5 m. 2193 CMC columns were installed in two months for Tank Hill Road South Embankment project.

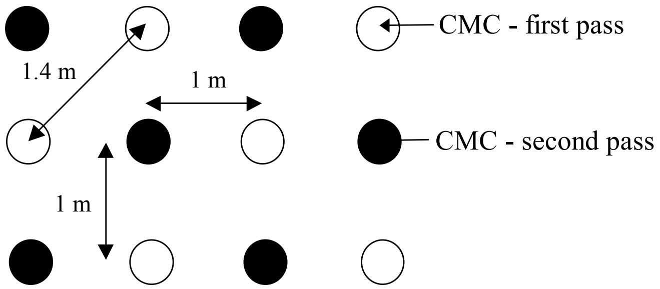


Figure 8: Modification of CMC layout

CONSTRUCTION CHALLENGES

The presence of existing facilities imposed construction changes of the soil reinforcement system in some areas. The main adaptation was related to the existing drainage culvert at the site. This drainage culvert with a total width of about 2 m was crossing the working area transversally. The requirement was to protect the existing culvert against differential settlement. The decision was made to install additional CMC to bridge the culvert and protect it. The strategy to reduce differential settlement was to adapt the grid in order to have an almost constant area of influence for each CMC even if the square pattern is modified (see figure 9). With those construction changes, the predicted differential settlement along the culvert was less than 3 mm, totally compatible with the rigidity of the culvert.

Existing overhead electrical cables were also crossing the construction site, requiring special attention and safety measures. Equipment modification were also required in order to shorten the mast of the CMC drilling rig to leave a safety distance between the top of the rig and the live electrical cables, while still being able to go to the required depths (see figure 10).

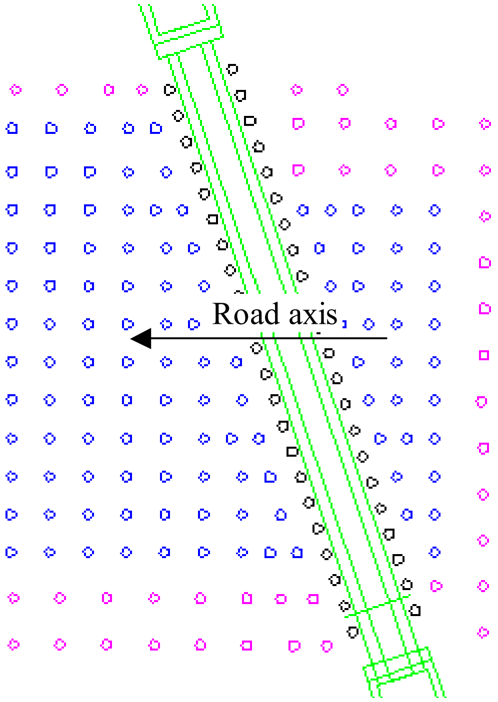


Figure 9: CMC grid modification along the culvert

QUALITY CONTROL

The quality of execution of each of those CMC columns was controlled by monitoring and recording the followings for each individual column:

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

The quality of the grout was controlled regularly by unconfined compressive strength cube tests at 7, 14 and 28 days, four cube samples for testing were taken every 100 m^3 of grout. The bearing capacity of the installed CMC columns was controlled by the execution of 11 vertical load tests on isolated columns (3 on CMC with diameter 420 mm and 8 on CMC with diameter 360 mm). Those test were carried out until one-and-a-half times the design load of the columns.

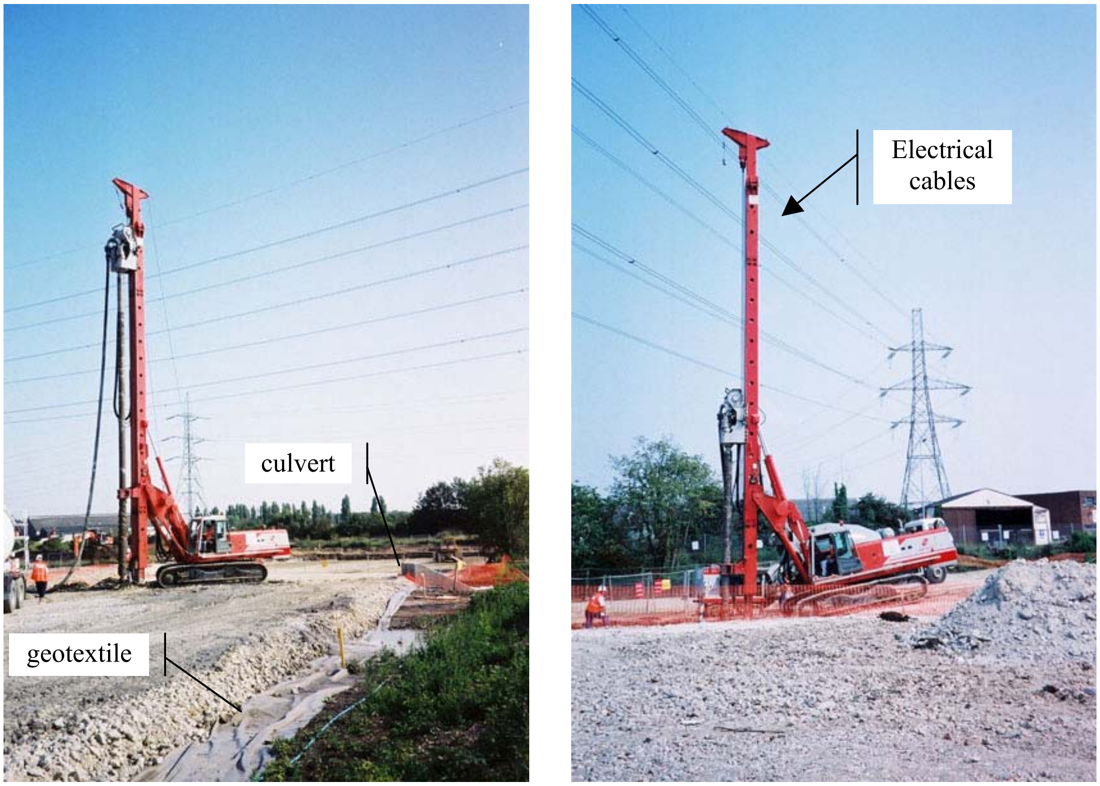


Figure 10: Construction challenges near the culvert and the electrical cables

A complete settlement monitoring system including settlement plates and settlement pegs were installed over the treated area in order to record the potential settlement during and after construction of the embankment. The average settlement measured under the design loads of 185 kN and 153 kN was around 10 mm, equivalent to one third of the calculated settlement. However, the load test on an isolated CMC, in which only the CMC column is loaded, does not mobilize negative skin friction. Therefore, additional downward forces are induced by the differential settlement between the surrounding soil and the CMC column. As a difference, the uniform loading of the ground improvement system by the embankment does mobilize negative skin friction. These additional downward forces may result in additional settlement of the CMC columns.

CONCLUDING REMARKS

The case history of the Tank Hill Road South Embankment project demonstrates that CMC foundation system was an effective solution in timely project delivery and meeting the serviceability requirements of the project. The main challenges were associated with construction time limitation and very soft ground condition of the site. In evaluating the alternatives stone column was not feasible; and the conventional vertical drain solution was not practical due to time constraints.

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