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Design and Monitoring of an Embankment on Controlled Modulus Columns

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The controlled modulus columns (CMC) foundation is one technique of ground modification for support of light structures such as highway and railway embankments. In this technique, a specially designed auger, powered by equipment with large torque capacity and high static down thrust, displaces the soil laterally without vibration. During the auger extraction process, a column is developed by pressure grouting to achieve a pre-determined stiffness ratio with the surrounding soil. Because of the combined effect of densification and reinforcement, the properties of soft soil are improved because of composite action. The design and monitoring of a column-supported embankment project are presented; 2,193 CMC columns were installed up to a depth of 12.5 m to control settlement. The main challenges were construction on soft ground and the need for an accelerated construction technology for timely delivery of the project. Various alternatives, stability analysis, design considerations, construction challenges, quality control, and monitoring system were evaluated.

Embankment construction is an essential element of any highway and railway infrastructure system. The problem arises when the highway embankment is expected to pass through marginal ground conditions such as soft clay, bay mud, organic soil or peat, chalk, or loose fine sand. In these cases, the ground is subject to settlement or stability problems caused by lack of bearing capacity. The sites with loose saturated fine sand also are subject to liquefaction caused by strong ground shaking. To overcome these difficulties, a wide range of deep foundation systems has recently been developed for construction of embankments on soft soils (1, 2). These techniques take advantage of various ground modification concepts, such as densification, reinforcement, solidification, and so on. Figure 1 illustrates the load transfer mechanisms in a conventional piling system and vertical columnar system, such as controlled modulus columns (CMC) foundation, to control settlement.

This paper presents the case history of an embankment on vertical columns using CMC. The details of analysis, design, and construction monitoring are discussed.

CMC SYSTEM

CMC, originally developed in France, 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 the properties of the soft ground caused by composite action. The CMC system uses a displacement auger powered by equipment with a large torque capacity and high downward thrust, which displace the soil laterally with virtually no spoil or vibration. When the auger is screwed into the soil to the required depth, the compression resulting from the lateral displacement increases the density and load-bearing capacity of the surrounding soil. When the required depth or a preset drilling criterion (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 close to sensitive structures. The grout is injected under low pressure, typically less than 10 bars (145 psi), and no soil mixing takes 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 as follows:

- Material is grouted in place with the use of a displacement auger without spoil.
- Deformation modulus is 100 to 3,000 times that of soil.
- Soil properties are improved around the columns by compression resulting from the lateral displacement.
 - Diameter is determined on the basis of size of the auger (usually in the range from 350 to 500 mm).
 - Common installation practice is based on square grids with center-to-center spacing in the range of 1.2 to 3 m.
 - Maximum length of treatment is 25 m.

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

PROJECT DESCRIPTION

The project consists of improving the ground under the access embankment of a road covering 17 km of railway construction. The embankment height ranged up to 7.5 m and a live load of 20 kPa because the road traffic was taken into account. The main design requirement for the ground improvement was to limit the postconstruction settlement of the embankment to 10 mm per decade.

SUBSURFACE CONDITION

The geotechnical data for this project are derived from the cone penetration tests (CPTs) performed along the axis of the anticipated embankment from station 0+420 to 0+600. The CPT results are presented in Figure 3.

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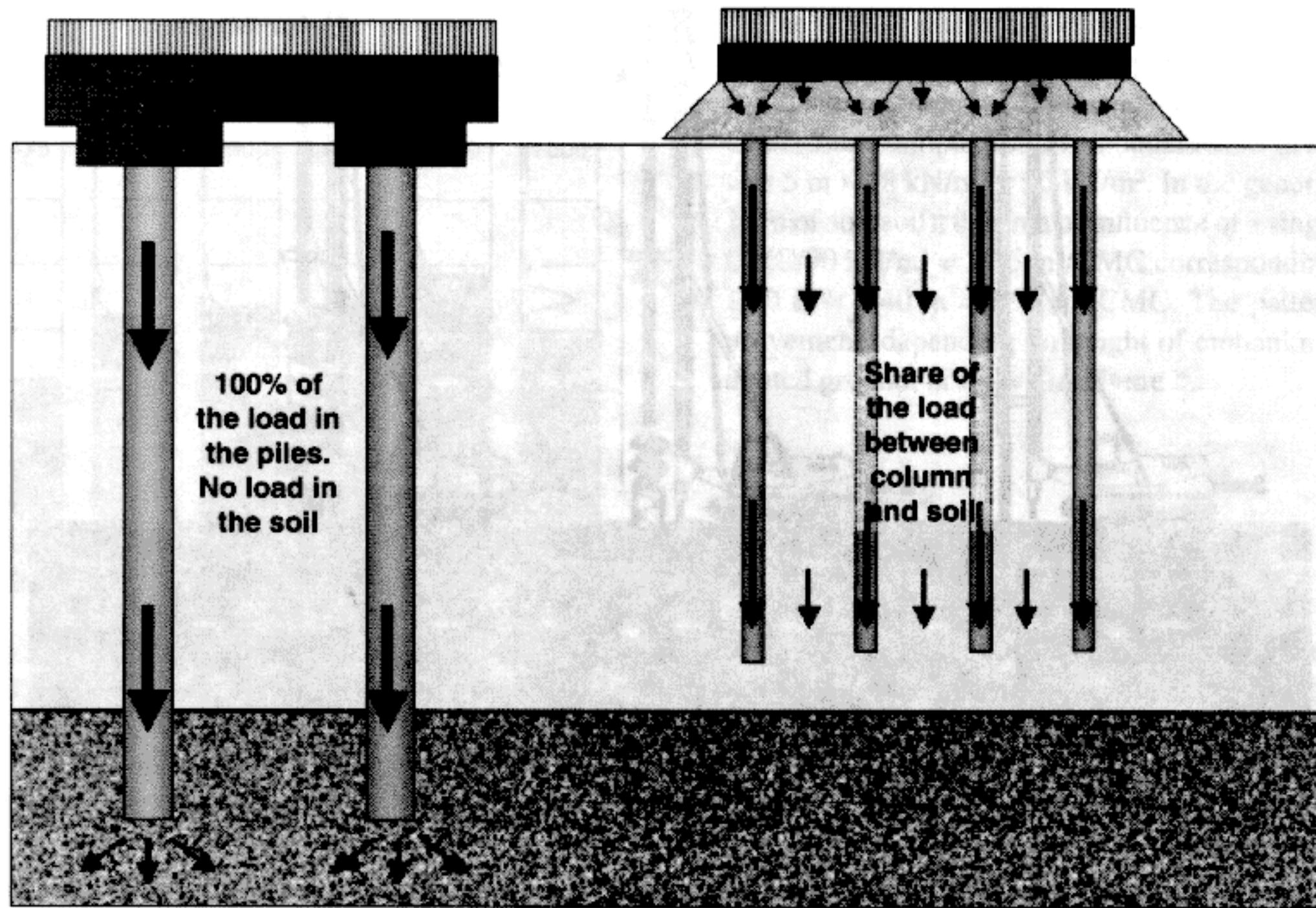


FIGURE 1 Load transfer mechanisms in conventional piling system (left) and columnar foundation system (right).

A very soft alluvium layer, made of a succession of very soft clay [the plastic limit (w_p) = 60%, the liquid limit (w_L) = 150%, 60% < water content (w) < 150%] and fibrous peat [w_L = 480%, 250% < w < 450%, the undrained shear strength (C_u) = 33 kPa], extended 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 values 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 chalk layer with silt fragments between station 0+420 and 0+500, mixed with a medium dense sand and silty sand layer between station 0+500 and 0+600. In those layers, the CPT cone resistance q_c was greater than 3 MPa. As a consequence, according to the anticipated loads and subsequent design requirements, those layers were considered competent for the CMC. At certain locations, a 1- or 2-m 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 to be a suitable competent layer because of its limited thickness.

ALTERNATE FOUNDATION SYSTEMS

Three foundation systems considered for this project included conventional vertical (wick) drains, stone columns, and the CMC system. 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 column solution for the following reasons:

- Predicted settlement. The predicted settlement for stone column 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 column.

- 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 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 from this project. The design parameters needed to define the CMC reinforcement system were as follows:

- The depth of the columns and their possible anchorage length in the competent layer,
- The diameter of the columns,
- The pattern and configuration of the columns grids, and
- The modulus of the grout used to make the CMC.

The modulus of the grout used to make the CMC is adapted for each new project, but for practical reasons, it is constant for a particular project. The complete design of the CMC includes estimation of bearing capacity of single columns, checking predesign parameters by a numerical procedure, performing stability analysis, and developing the final design, as discussed in the following sections.

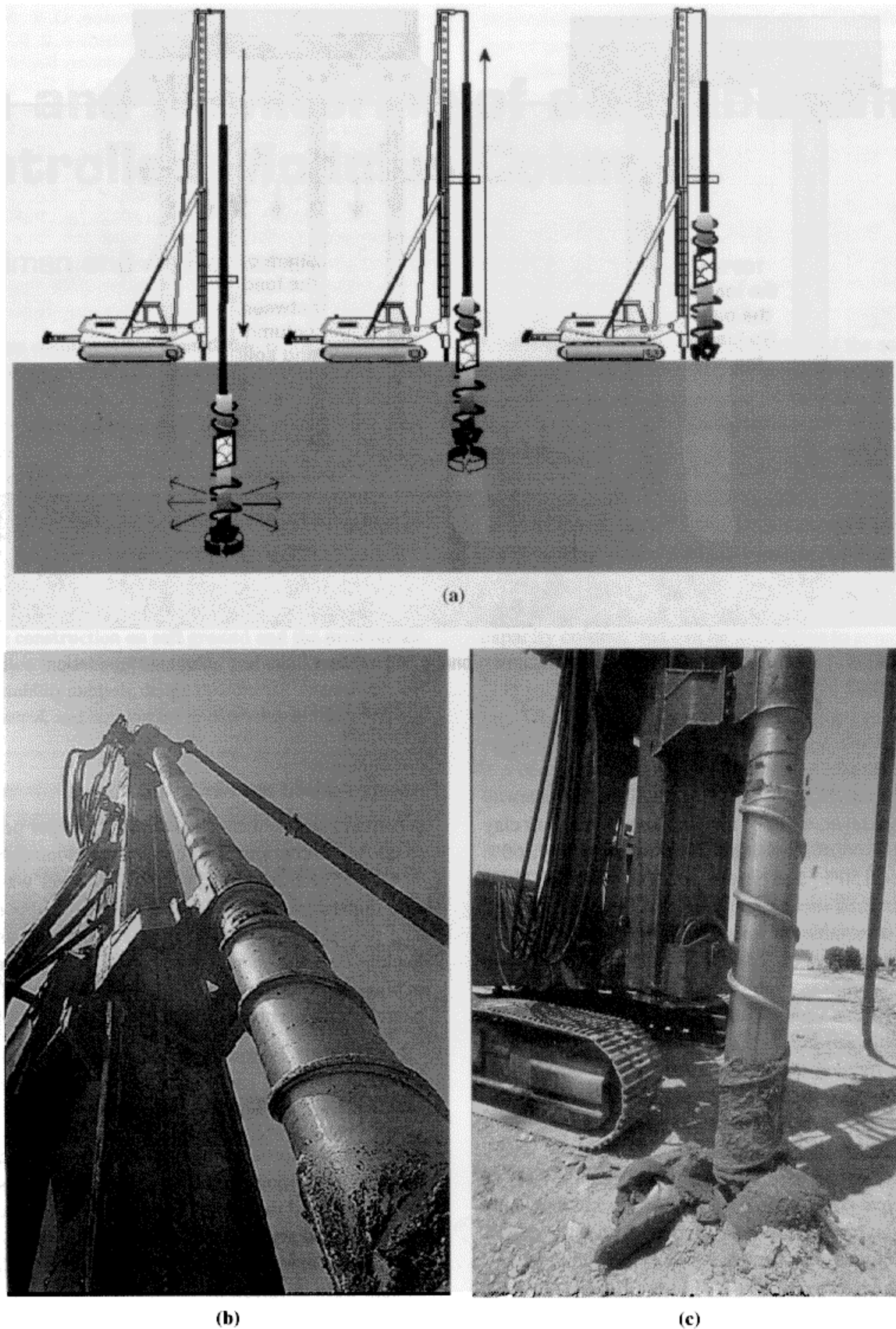


FIGURE 2 CMC foundation system: (a) construction process and (b) and (c) CMC shaft.

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 in Equation 1 (3):

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

where

$$k = 0.5,$$

$$k_1 = 0.5 \text{ (usually } 0.5 < k_1 < 0.9),$$

A = section of the CMC (0.138 m² for diameter 420 mm, 0.101 m² for diameter 360 mm),

q_c = cone resistance,

Z = anchorage length in the competent layer,

FOS = factor of safety, and

ϕ = diameter of the CMC.

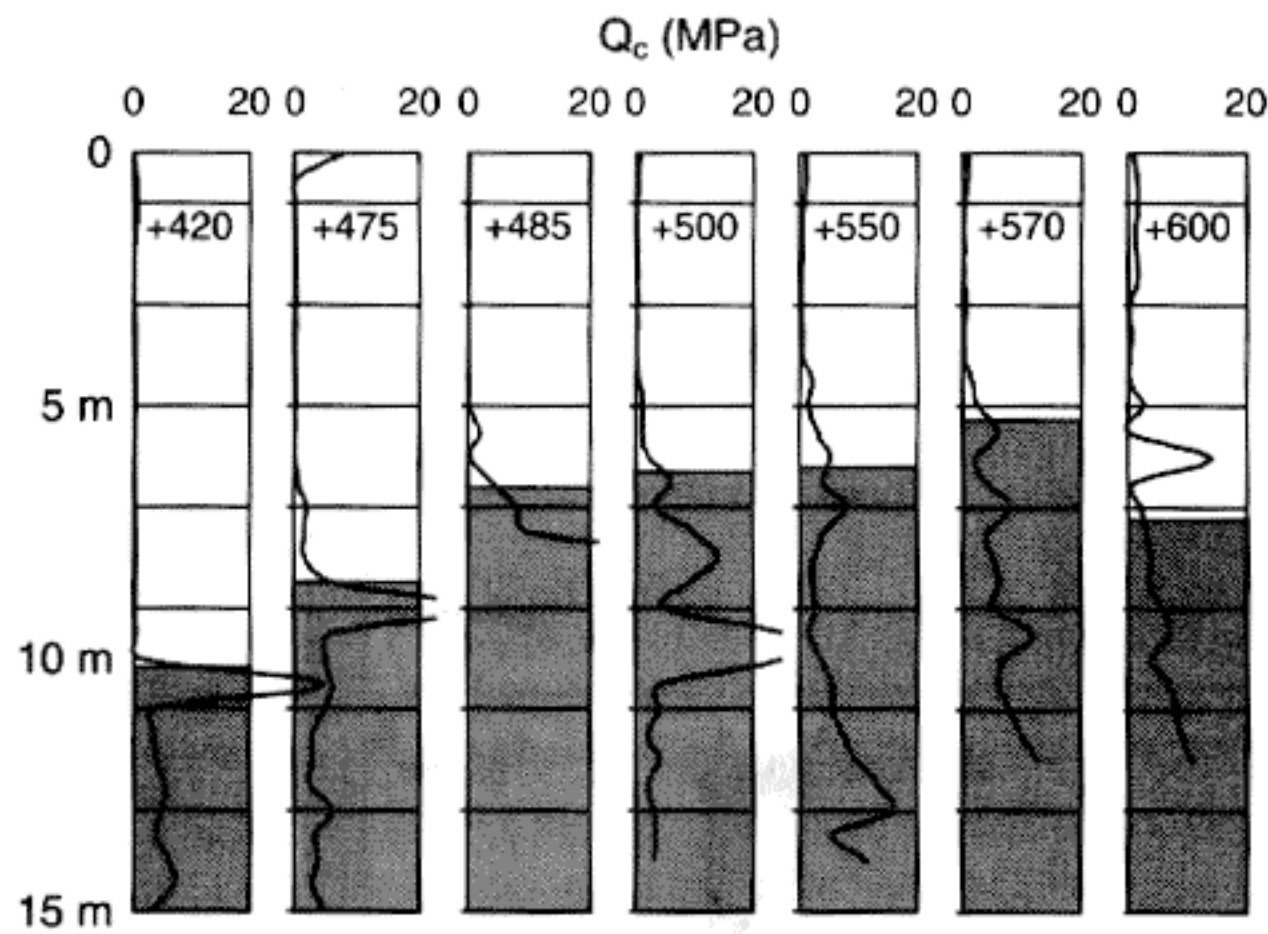


FIGURE 3 CPTs performed along embankment axis at station 0+420 to 0+600.

A FOS of 2 was applied in the bearing capacity calculations.

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

- Case 1 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 could 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/column, taking into account an FOS of 2.
- Case 2 was related to CPT in station 0+420, which showed alluvium thickness of approximately 11 m followed by a stiff layer with a cone resistance q_c of 3 MPa. This case was limited to a small part of the job. However, because of 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 for this limitation, CMCs with a larger diameter (420 mm) were chosen. In those conditions, each of these CMCs was able to support $Q_{allowable} = 153$ kN/column, taking into account an FOS 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 a single CMC. For example, for an embankment 5 m high, the applied load was $5 \text{ m} \times 18 \text{ kN/m}^3 = 90 \text{ kN/m}^2$. In the general case (i.e., less than 10 m of soft soil), the area of influence of a single CMC was $185 \text{ kN/CMC} / 90 \text{ kN/m}^2 = 2.06 \text{ m}^2/\text{CMC}$ corresponding to a square grid of $1.40 \text{ m} \times 1.40 \text{ m} = 1.96 \text{ m}^2/\text{CMC}$. The pattern of the ground improvement, depending on height of embankment and thickness of treated ground, is shown in Figure 4.

Design Check

To check this preliminary design, a finite element method (FEM) calculation was implemented using the PLAXIS program. Figure 5 shows the numerical model under uniform load.

This approach to the problem allows the ability to take 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 (4, 5). 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, to assess the time-related behavior of the improved ground. Table 1 presents the parameters used in the numerical calculation for long-term behavior in correlation with available CPT cone resistance.

For short-term behavior, the geotechnical characteristics of the alluvium layers were assessed with the following equation in which the short-term elastic modulus of 1.7 and 17 MPa was adopted for the alluvium and stiff layers, respectively:

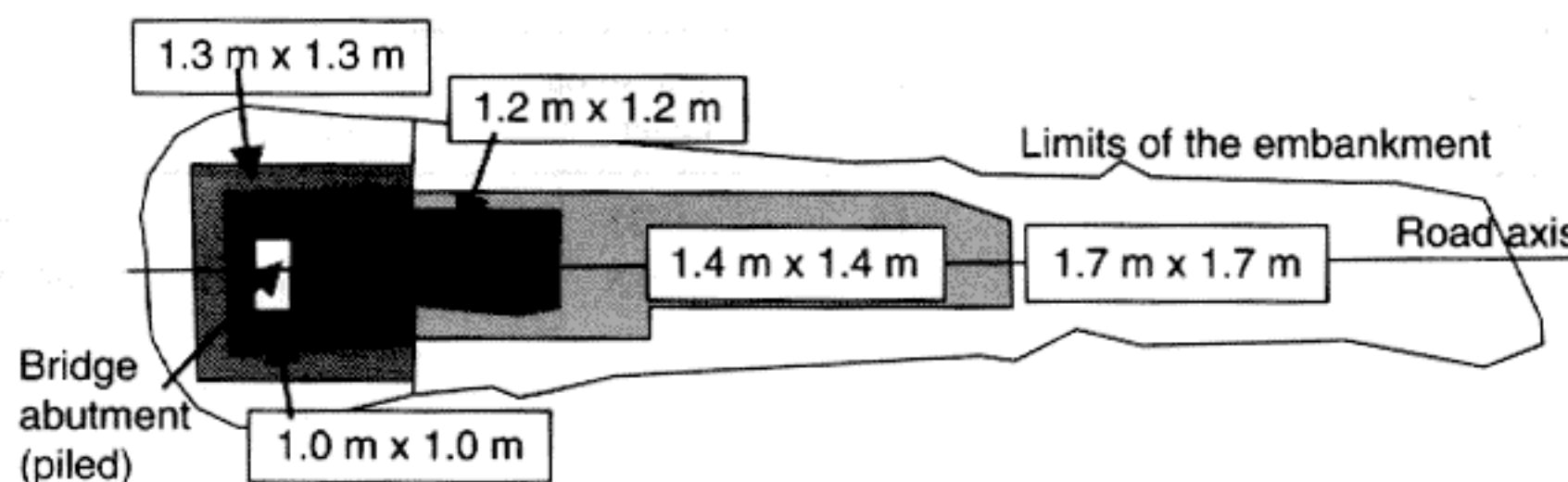
$$\frac{E}{1 + \nu} = \frac{E'}{1 + \nu'} \tag{2}$$

where

- E = modulus,
- E' = modulus for the drained condition,
- ν = Poisson's ratio, and
- ν' = Poisson's ratio for the drained condition.

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

(a)



(b)

FIGURE 4 Layout of CMC.

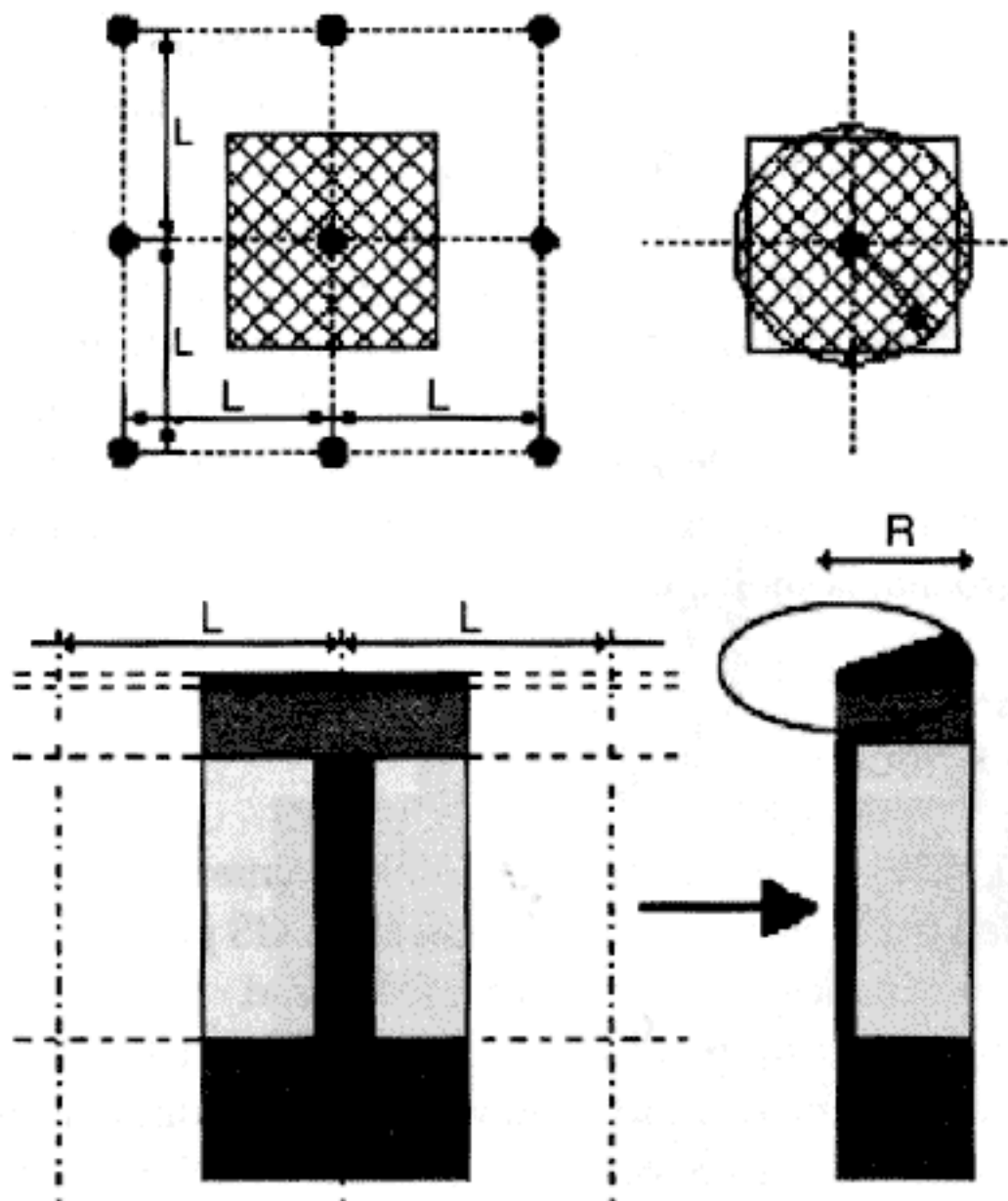


FIGURE 5 Principle of axial-symmetrical calculation.

To address all possibilities, two different cases, corresponding to the worst-case scenarios, were studied (see Figure 6):

Case 1

- 7 m of soft soil
- CMC diameter: 360 mm
- CMC mesh: 1.40 m × 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 × 1.00 m
- Embankment height (including transition layer): 8.00 m
- Road surcharge: 20 kPa

The main results of the numerical calculations are presented in Table 2. The geotextile layer was placed to increase the factor

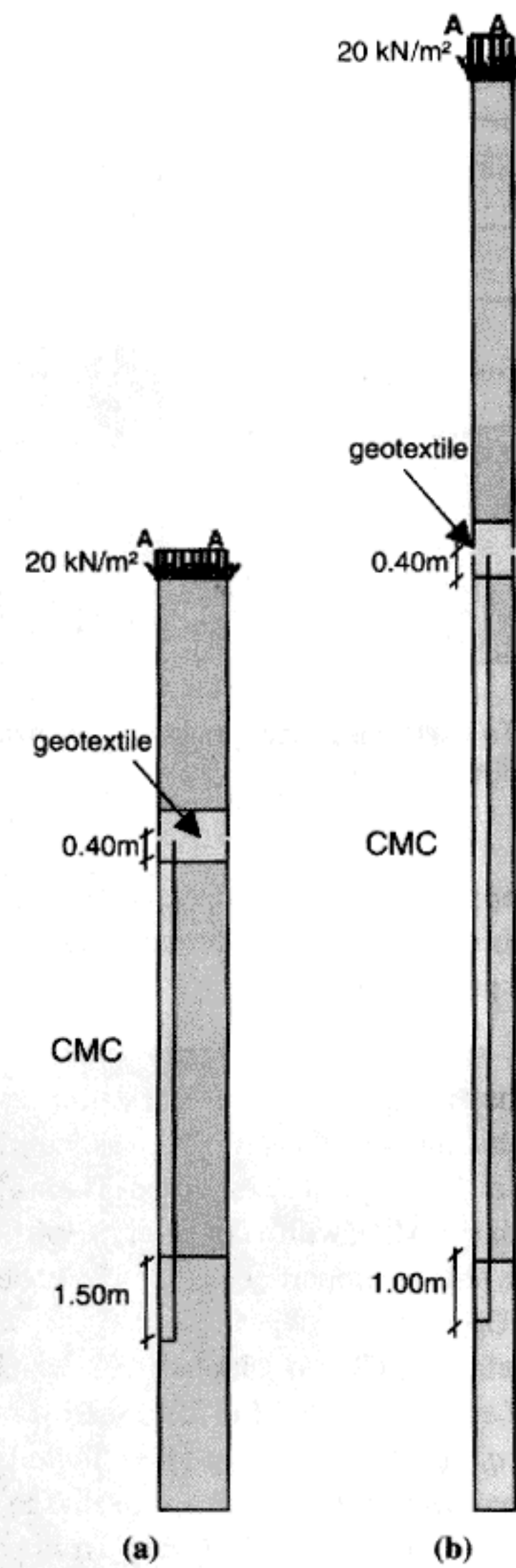


FIGURE 6 Axial-symmetrical finite difference models: (a) Case 1 and (b) Case 2.

of safety against shear failure, although the calculations based on the British Standard method showed small tensile stress in the geotextile.

The time-related aspect of settlement was considered by comparing the computed settlement for short- and long-term behavior. The difference between short- and long-term settlement was approxi-

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 ($^\circ$)	18	25	—	33	—

NOTE: A grout with unconfined compressive strength at 28 days (f_{c28}) of 11 MPa was chosen; the Young's modulus of the CMC was then assumed to be at least 11,000 MPa.

TABLE 2 Results of Numerical Analysis

			Case 1		Case 2	
			Short Term	Long Term	Short Term	Long Term
CMC data	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: Other cases with similar soft soil conditions were designed so that the load per CMC was comparable to the studied cases.

mately 4 mm, and the typical duration for this settlement to occur was between 5 and 10 years.

Stability Calculations

Stability calculation was performed with a general-purpose slope stability program to check possible slope failure problems during embankment construction. The results of these calculations showed a factor of safety against slip circle failure of 1.39 (Figure 7).

Final Design

Because of the soft ground condition for this project (particularly the chalk layer), a dense column spacing of 1.0 m² grid spacing was initially adopted to correspond with an area replacement ratio of 13.9%. The area replacement ratios for CMC system are typically 2% to 8%, with CMC single columns designed to support loading of 150 to 350 kN. A displacement auger is used for installation of CMC, and thus the high improvement ratio 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 improvement area. The columns were installed in two different interleave passes, each with 1.4 m × 1.4 m grids, as shown in Figure 8, corresponding to an area replacement ratio of 6.9%. The columns were anchored in the chalk or sand layers, which resulted in columns from 7.5 to 12.5 m in length. Two thousand one hundred ninety-three CMC columns were installed in 2 months.

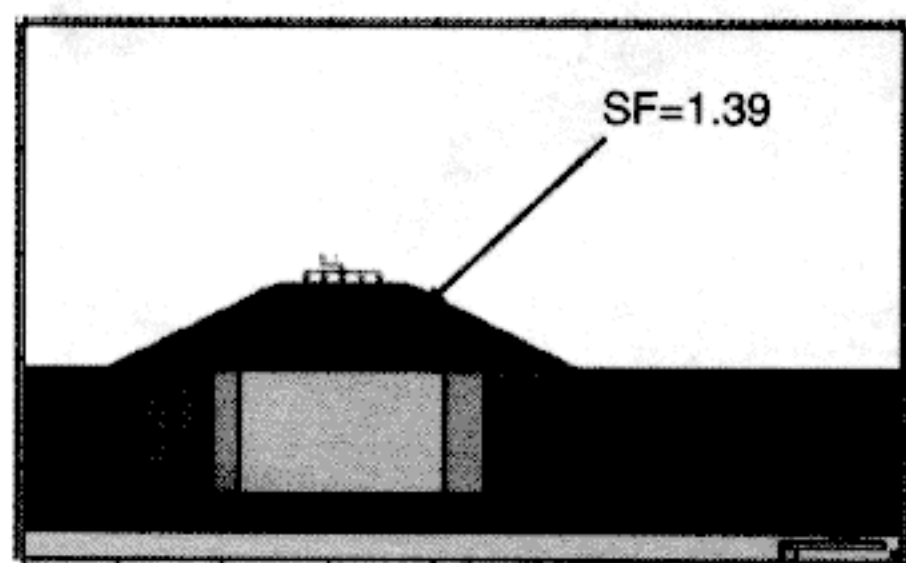


FIGURE 7 Stability calculation.

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 approximately 2 m crossed the working area transversally. The requirement was to protect the existing culvert against differential settlement. The decision was made to install an additional CMC to bridge the culvert and protect it. The strategy to reduce differential settlement was to adapt the grid to have an almost constant area of influence for each CMC even if the square pattern was modified (see Figure 9). With those construction changes, the predicted differential settlement along the culvert was less than 3 mm, completely compatible with the rigidity of the culvert.

Existing overhead electrical cables also crossed the construction site, requiring special attention and safety measures. Equipment modification also was required 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).

QUALITY CONTROL

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

- Speed of rotation and advancement of the auger;
- Torque, down-thrust, and drilling energy applied during advancement; and

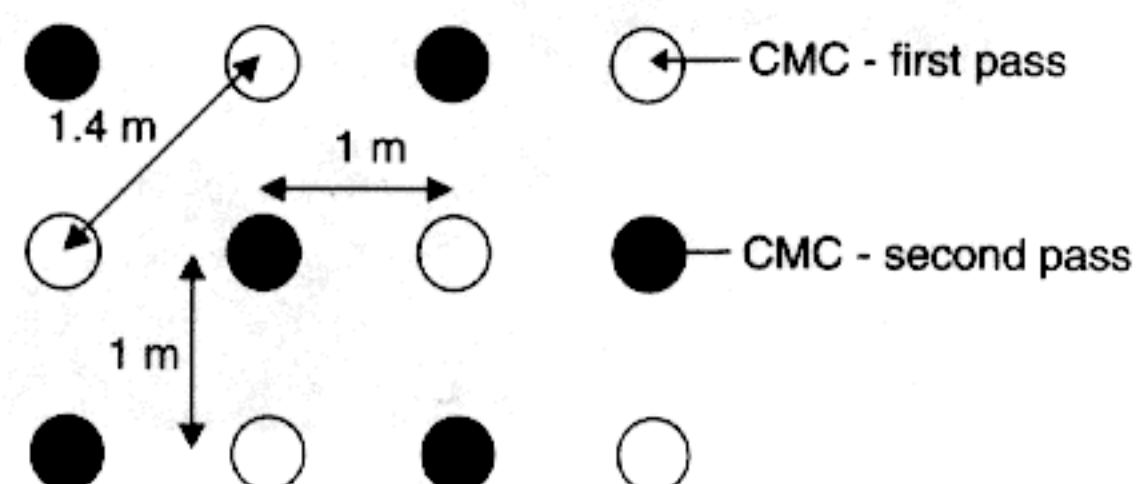


FIGURE 8 Modification of CMC layout.

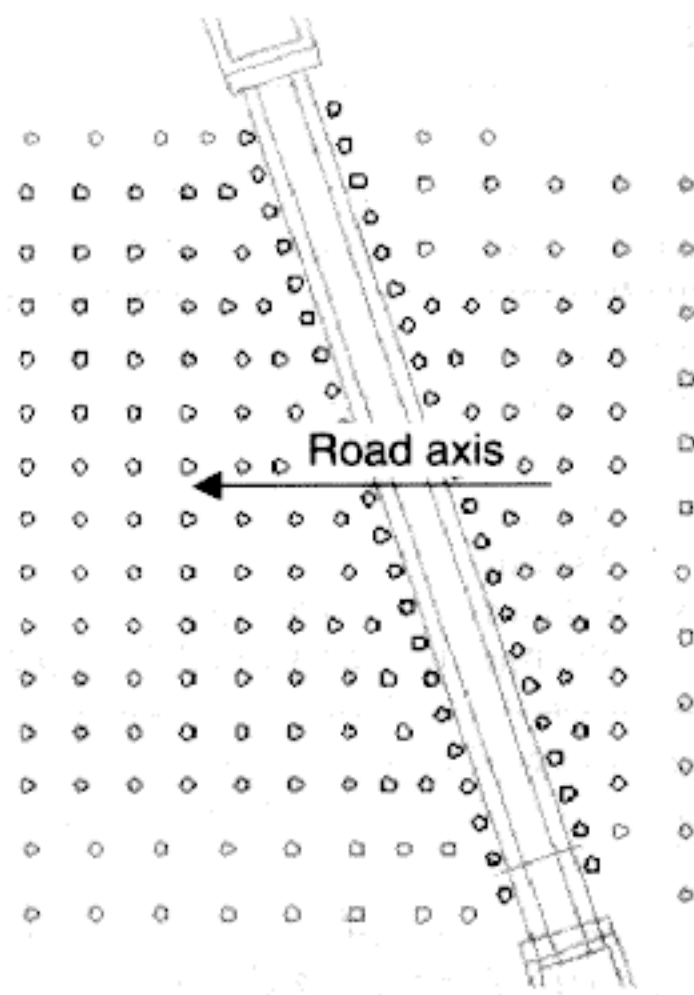


FIGURE 9 CMC grid modification along culvert.

- Pressure and volume of injected grout, from which the profile of the columns is determined.

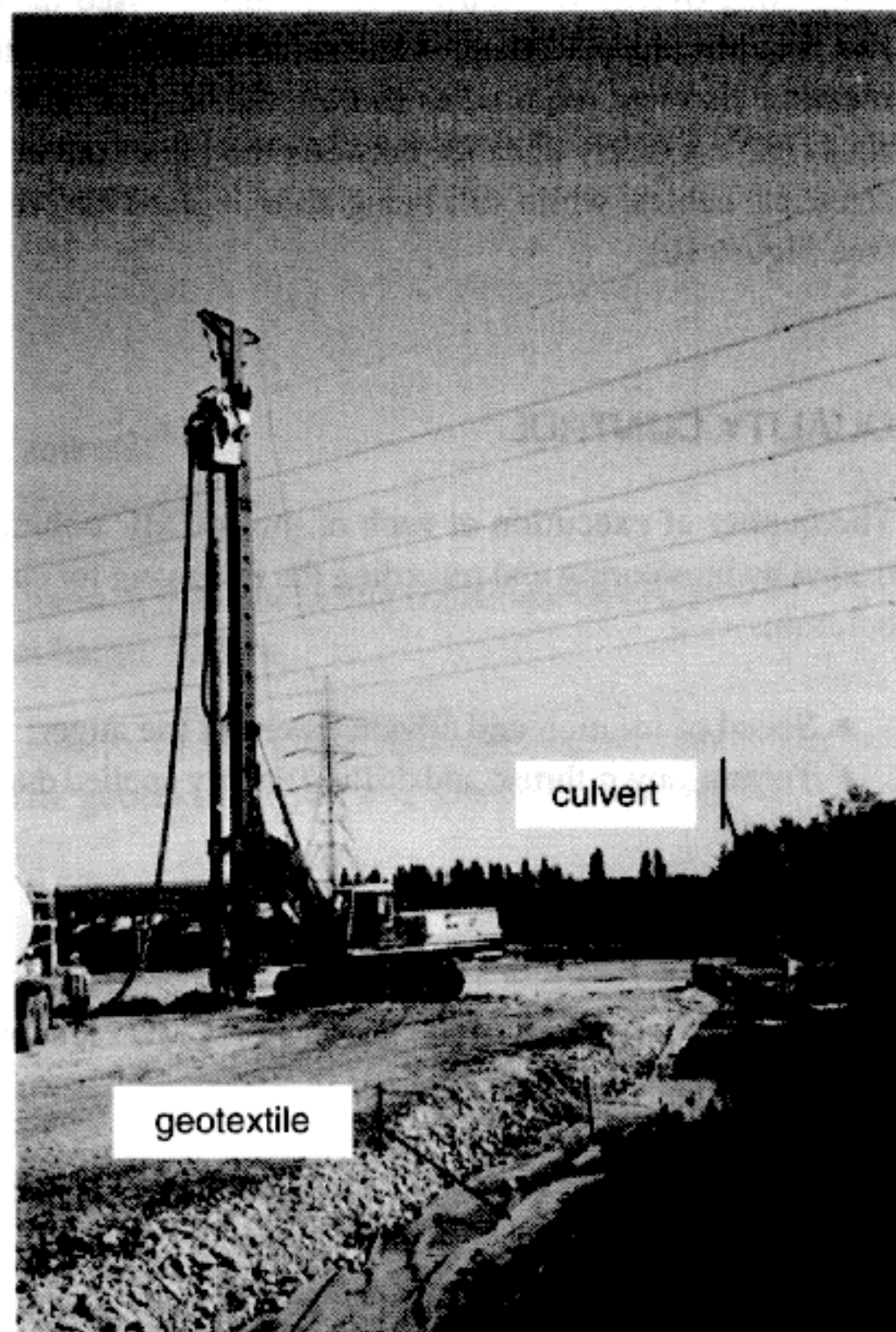
The quality of the grout was controlled regularly by unconfined compressive strength tests at 7, 14, and 28 days. Four samples were taken every 100 m³ of grout for testing. The bearing capac-

ity 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 tests were carried out until one-and-a-half times the design load of the columns.

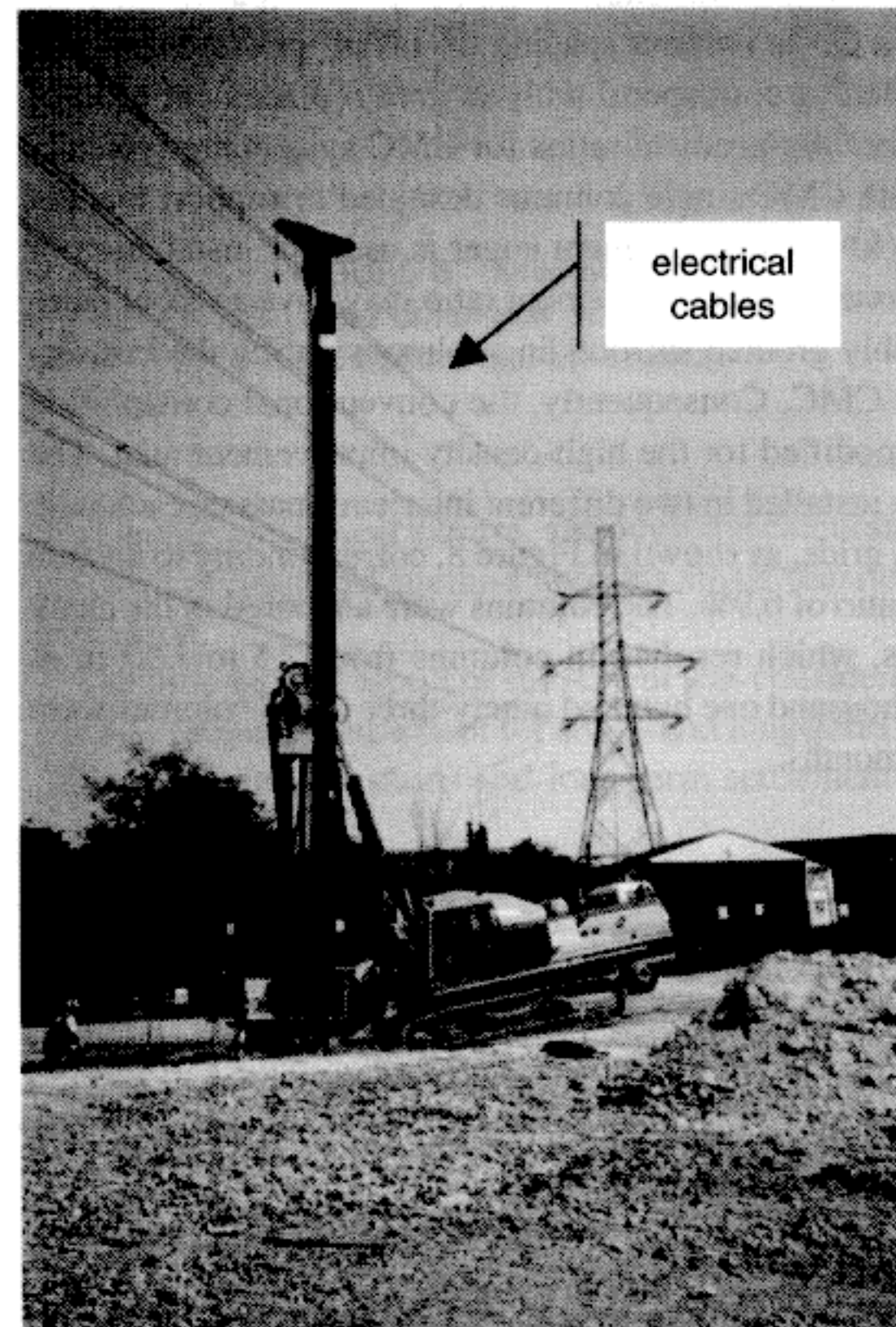
A complete settlement monitoring system, including settlement plates and settlement pegs, was installed over the treated area to record the potential settlement during and after embankment construction. The average settlement measured under the design loads of 185 kN and 153 kN was approximately 10 mm, equivalent to one-third 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 project presented here demonstrates the effectiveness of the CMC foundation system for 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 the evaluation of alterna-



(a)



(b)

FIGURE 10 Construction challenges near (a) culvert and (b) electrical cables.

tives, stone column was not feasible, and the conventional vertical drain solution was not practical because of time constraints.

The CMC foundation system also was used for widening of the Miami-Dade Expressway project in Miami, Florida. The 10 ft of muck at the toe of the slopes could not be removed without destabilizing the existing embankments. In addition, surcharge and wait did not fit the project schedule. Accordingly, for this project, mechanically stabilized earth wall on CMC foundation system was used to maintain stability and to reduce settlement. This project is currently under construction.

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