Installation Effect of Controlled Modulus Columns on Nearby Existing Structures

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Abstract: Controlled Modulus Columns (CMC) ground improvement technique is a novel approach to reduce ground settlement. To install CMC, a rotary displacement auger is used to form a vertical cylindrical cavity, by displacing the surrounding soils laterally, followed by grout injection. While the method reduces spoil generation, excessive lateral soil displacement may damage the adjacent structures and freshly-grouted CMCs. Although there has been growing interest in quantifying such effects, only a handful of studies have been attempted. This paper presents results of a numerical investigation on the CMC installation effect on an existing bridge pile using the three-dimensional finite difference software package FLAC3D. The bridge pile response to the lateral soil movement induced by the CMC installation are presented and discussed.

INTRODUCTION

Ground improvement using Controlled Modulus Column (CMC) is an innovative method that uses rigid inclusions to reinforce soft ground, typically for projects having a tight construction schedule or concern related to contaminated soils. The Gerringong Upgrade project is one recent project where CMC have been successfully utilised for bridge and road construction (Fulton Hogan 2013). The solution consists of installing non-reinforced concrete columns in the ground, followed by the construction of a load transfer platform prior to the construction of the fill...
embankment and bridge abutments. The column installation process involves penetrating an auger in the ground under torque and thrust provided by a drilling rig, followed by grout injection through the hollow stem while raising the drill tool. The auger shown in Fig. 1 is purposely designed and built to enable lateral soil compaction during drilling operation and prevents the soils from moving upward when raising the auger.

![Menard’s patented displacement auger](image)

**FIG. 1.** Menard’s patented displacement auger.

When construction sites involving CMC are located in close proximity of existing sensitive structures, proper installation sequence is to be considered, as the risk of damaging adjacent structures due to lateral soil movement can be high (Plomteux et al. 2004, Brown 2005, and Hewitt et al. 2009). Hence, careful construction planning and risk assessment prior to CMC installation is required. Although these tasks have become a routine for piling contractors, assessing installation effects, especially the lateral soil movement due to installation, is still a serious challenge. Current assessment methods for installation effects include cavity expansion theory (Carter et al. 1979), strain path method (Baligh 1985) and more rigorous analyses using numerical modelling. The cavity expansion theory, which is the most common method, studies the changes in pore water pressure and stresses due to the creation or the expansion of a cavity. Current contributions to CMC application include a cavity expansion based numerical study by Rivera et al. (2014) using PLAXIS-2D and a field investigation of installation effects on the surrounding soils by Suleiman et al. (2015). However, assessment of the CMC installation effects to the adjacent existing structures has not been reported in the literature because of a number of reasons. Firstly, the modelling of pile installation process involves large mesh distortion and can be time consuming. Secondly, the existing analytical methods are unable to capture complex three-dimensional soil-structure interaction and construction sequence. This paper presents a 3D numerical model to investigate the response of an existing bridge pile subjected to loading due to the lateral soil movement induced by the installation of nearby CMCs.

**NUMERICAL MODELLING**

To simulate the CMC installation process, three dimensional numerical modelling using **FLAC** (Fast Lagrangian Analysis of Continua) v.5.01 was carried out.
FLAC\textsuperscript{3D} can accommodate large soil displacement, and model pile-soil interaction accurately. A 3D grid, which comprises 89,600 zones and 91,143 grid points, was created to represent a soil profile consisting of a 4.8 m thick homogeneous soft clay layer, overlying bedrock (Fig. 2a). An existing bridge pile and six proposed CMC are located in the middle of the 3D model (Fig. 2b). The radial cylindrical mesh represents CMCs and piles, while the cubical meshes form the outer soil regions. The lateral boundaries were extended 20 times the CMC diameter, from the outmost CMC or pile to minimize the boundary effects. The existing bridge pile is 0.75 m in diameter, and 4.8 m long and is located at 1.8 m centre to centre (c/c) from the nearest CMC. The construction of two rows of CMCs next to the existing bridge pile was simulated in this study. Each row has three columns oriented in the x-direction. CMCs have a diameter of 450 mm, are 4.8 m long and spaced at 1.6 m c/c in a square pattern, which represents a replacement ratio of 6.25\%, the high end of the acceptable range for CMC installation.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2}
\caption{(a) FLAC\textsuperscript{3D} finite difference grid (b) the central portion of the grid.}
\end{figure}

Material Model

Soil properties were derived from site investigation and laboratory testing data from the highway upgrade project at Gerringong, a town located approximately 130 kilometers south of Sydney. The modified Cam-Clay (MCC) material model was adopted to represent the behaviour of the soft clay. The adopted parameters include the slope of normal consolidation line (NCL) $\lambda = 0.29$, and the slope of elastic swelling line $\kappa = 0.073$. The NCL line is defined by a reference pressure $p'_{ref} = 74$ kPa and a specific volume $v_{ref} = 2.55$. Based on the oedometer results, an overconsolidation ratio OCR of 1.6 was adopted for the entire depth. The pre-consolidation pressure therefore varies linearly with depth. The adopted effective friction angle $\phi'$ is 28° and the frictional constant of the critical state line is $M = 1.11$. The lateral stress coefficient $K_0$ for lightly overconsolidated clay can be related to that of the normally consolidated clay via OCR and was estimated to be 0.75. Other typical properties for soft clay including a dry density of 1300 kg/m\textsuperscript{3}, a porosity of 0.5 and an effective Poisson’s ratio $\nu' = 0.3$ were also adopted.
Both pile and CMC are considered impermeable and are modelled using solid elements. The pile is assumed socketed into the bedrock or stiff ground and characterized by an isotropic linear elastic law, described by a Young’s modulus of 20 GPa, a Poisson’s ratio of 0.2 and a density of 2400 kg/m³. The Mohr Coulomb (MC) material model was used to represent CMC behaviour. In this study it was assumed that the CMC grout set quickly after injection. Hence, a grout density of 2400 kg/m³, bulk modulus $K = 3.23$ GPa, shear modulus $G = 2.42$ GPa, the cohesion $c' = 300$ kPa, the friction angle $\phi' = 5^\circ$, and a tensile strength $\sigma'^t = 520$ kPa were adopted for CMC simulation. The stiffnesses and the tensile strength of CMCs were estimated according to Eurocode 2 (BSI 2004) using a typical characteristic cylinder compressive strength of sand concrete $f_{ck} = 10$ MPa. The ground surface profile adopted in this study is horizontal. It is noted the topography of a given site has great influence on soil deformation and needs to be accounted for.

**Interfaces, Boundary and Initial Conditions**

To allow gapping or sliding between the soft clay and CMC/pile, interface elements with negligible tensile strength were employed. The interface behaviour is determined by the friction angle and cohesion, which were set equal to those of the soft clay. The interface normal and shear stiffnesses are estimated using Eq. 1 as recommended by Itasca (2012).

$$k_n = k_s \approx 10 \times \frac{K + \frac{4}{3}G}{\Delta z_{\text{min}}}$$

where $K$ and $G$ are the maximum values of soil bulk and shear moduli, respectively; and $\Delta z_{\text{min}}$ is the minimum mesh size in the elements adjacent to the interface.

The bottom soil boundary in Fig. 2a is restrained vertically. The soil at the side boundaries is fixed against the displacement normal to the boundary planes. The top boundary is free and is considered permeable (free draining). The initial conditions include the initial hydrostatic pore water pressure assuming groundwater table at the ground surface; and initial effective stresses due to soil self-weight, assuming a gravitational acceleration of $9.81$ m/s². Once the in-situ stresses are established, the bridge pile is installed by simply changing material properties in the pile zones, from those of soil to concrete and the system is brought again into equilibrium.

**Modelling CMC Installation**

The simulation of the CMC installation process is executed in two stages: (i) creating a cylindrical borehole and (ii) backfilling the borehole with CMC grout.
Cavity creation is most easily modelled numerically by expanding a pre-existing cavity of initial radius \( r = r_i \) to a new cavity of radius \( r = r_f \), as recommended by Carter et al. (1979). Assuming undrained expansion, the radius \( r_f \) at end of the expansion can readily be estimated using a simple relationship: \( r_f = (r_i^2 + r_{CMC}^2)^{0.5} \) where \( r_{CMC} = 225 \) mm. It is important to determine an optimal initial radius, which has to be sufficiently small to maintain reasonable numerical accuracy. At the same time, this radius should not be too small, to avoid excessive mesh distortion. Parametric studies indicate that \( r_i = 65 \) mm (i.e. approximately \( \frac{1}{4} \) of \( r_{CMC} \)) is adequate for the adopted geometry and mesh. The first step of creating a cavity was to turn the soil within the initial cavity of \( r_i = 65 \) mm into “null” material (i.e. material removed). In the next step, outward normal velocities were applied to the cavity wall so that, upon mechanical stepping in a large strain mode, the wall displaced in the radial direction until achieving the final cavity radius of 234 mm. It is noted that, during expansion, the tangential velocity at the wall was fixed to zero.

Before filling the bore hole with the CMC grout, the applied velocities at the cavity wall were removed. After grouting, the soil/CMC interface elements were inserted and the system was brought into equilibrium to complete the CMC installation. The installation of the subsequent CMCs was simulated in a similar manner; according to a sequence shown in Fig. 3, i.e. starting with the rear row (CMCs 1 to 3) and then progressing to the front row (CMCs 4 to 6).

![FIG. 3. The order of CMC installation.](image)

![FIG. 4. Magnified pile head movement during CMC installation.](image)

**RESULTS AND DISCUSSION**

Fig. 4 shows that during CMC installation the pile head moves away from the CMCs as expected. However, the pile head also moves slightly sideways, i.e. in the negative x direction. It is noted that the direction of pile head movement can be different if the installation sequence differs from that described in Fig. 3. The sideways movement of pile head in the x direction is the consequence of the change in the direction of the lateral soil movement induced by the installation of different CMCs.
Fig. 5a illustrates the excess pore water pressure in front of the pile (i.e. along line A-B shown in Fig. 6), due to the undrained cavity expansion. The excess pore water pressure due to the installation of the rear row is relatively small; however, a substantial increase in excess pore water pressure occurs when the front row CMCs are installed. The installation of CMC 5, which is the closest CMC to the bridge pile, causes the most significant excess pore water pressure increase. The normal stresses acting on the pile shaft shown in Fig. 5b indicate a similar pattern to the pore water pressure at the pile shaft. Fig. 6 presents a cross section through the pile centre together with the contour of the excess pore water pressure at the completion of all CMC installations. It is clearly observed that the pore water pressures increase significantly in front of the pile along line A-B, while the pore water pressure behind the pile is less than the static pore pressure, due to the decompression of the soil.

**FIG. 5.** (a) Pore water pressure near pile shaft (b) Normal stress acting on the pile shaft after CMC installation.
FIG. 6. Pore water pressure upon complete installation of the final CMC.

The response of the existing bridge pile foundation to the lateral soil movement induced by the CMC installation process was recorded in terms of lateral deflection in the y direction (Fig. 7a) and the induced bending moment (Fig. 7b). As expected, the lateral deflection increases as more CMCs are installed, with much greater effect due to the front row than the rear row. A maximum pile lateral deflection of approximately 3.5 mm occurs at the top of the existing bridge pile. According to Stewart et al. (1994), horizontal displacement of less than 25 mm is often considered to be acceptable in bridge design. This study considered only a limited bridge pile and CMC lengths and soft soil depth (i.e. 4.8 m). However, when the pile is longer and hence more slender, the pile movement may be more significant. The calculated maximum bending moment in the pile is approximately 200 kNm, which occurs at the bottom of the bridge pile. It is noted that if CMC is shorter than the pile, it is likely the pile behavior may be different. In this study, the soil is homogenous, resulting in a straightforward prediction of the maximum bending moment location. It should be noted that for a stratified soil profile, the location of the maximum bending moment may be positioned elsewhere.
CONCLUSIONS

The installation process of controlled modulus columns (CMC) in soft soil was simulated using FLAC$^{3D}$ and the short term CMC installation effect on an existing bridge pile has been investigated, which shows the feasibility of simulating the installation process numerically. The numerical results show that the undrained excess pore water pressure in front of the bridge pile and the normal stress applied on the bridge pile increase as more CMCs are installed. The lateral pile deflection due to the lateral soil movement induced by the CMC installation process in this study is in the tolerable range. However, the lateral pile deflection could be more significant if the CMCs are longer and the bridge pile is more slender. The results of this study indicate that the CMC installation effects on the existing structures should be assessed carefully.

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