

# SUSTAINABILITY CONSIDERATIONS FOR GROUND IMPROVEMENT TECHNIQUE USING CONTROLLED MODULUS COLUMNS

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## ABSTRACT

Sustainability is becoming an ever more important consideration for the selection of ground improvement methods on construction projects around the world. When considering this criterion, the controlled modulus column (CMC) technology emerges as one of the relatively novel technologies that are capable to deliver valuable and sustainable outcomes. CMC installation is a vibration free process and produces very limited soil cuttings, making CMC suitable for improvement of soft ground, contaminated sites and ones adjacent to sensitive structures. Besides, CMC uses grout only without the use of steel reinforcement; hence carbon footprint estimated for CMC is generally lower than those for traditional piling techniques. Besides these valuable aspects, it is believed that this technology can still be advanced to contribute more to the sustainable development, owing to ongoing research works and practical experience. This paper summarises the key sustainability aspects of using CMC technology and highlights some potential aspects for further development. Future research directions are discussed to enhance sustainable design practice. These include general discussions on the issues of economic design with trial field tests, the use of recycled industrial by-products for grout mix, improved design, maximising the resiliency of structures and the energy consumption. The CMC installation effects on the surrounding soils and environment are also discussed sensibly in this paper.

*Key words:* Ground improvement, CMC, sustainability, resilience, installation effects, lateral displacement

## 1 INTRODUCTION

The *sustainability* concept has been increasingly accepted to be a key aspect in engineering design and construction, most noticeably in government supported projects. Since geotechnical engineering is one of the key parts of construction, geotechnical engineers have opportunities with power to deliver project outcomes that are not only economical, safe but also sustainable. Ground improvement techniques aim to increase ground bearing capacity, improve stability, and reduce short and long term ground settlements. These techniques have an impact on environment, local ecological systems and ground conditions. Appropriate techniques are increasingly demanded due to decreasing available and favourable land for construction and redevelopment of urban areas. Today a large number of ground improvement methods exist in the industry, with each serving a limited number of purposes. Selection of one or a combination of two or more methods requires deep understanding of various ground treatment methods. Decision making should rely on trials, design requirement, project budget and time restraint, ground and site conditions. Alongside with control of quality, durability, cost and safety, authorities also require design and construction of infrastructure to consider environmental outcomes, forming important aspects of sustainable development.

Although sustainability in geotechnical engineering has been addressed by a number of authors (Abreu et al., 2008; Holt et al., 2010; Jefferson et al., 2007), little attention on sustainable development has been placed during the process of geotechnical design and implementation. The geotechnical community should set out specific sustainability outcomes with tangible results to be achieved within a set time frame. At this stage it will be very likely that any sustainability policies/requirements attached to the contract works may receive mixed responses from businesses.

To target sustainability outcomes in geotechnical engineering and ground improvement works, three major “triple bottom line” Economic, Environment and Social impact proposed by Elkington (1997) should be followed in combination with “financial, social, human, natural and produced” factors. Economic benefits and social reactions should not be considered as barriers for sustainable development. In fact, adoption of sustainable solutions should be considered to enhance the competitiveness in bidding and winning projects. Today sustainability in geotechnical engineering targets (i) reduction in energy consumption, (ii) lower carbon emission during implementation and (iii) decrease in material usage. This should be accompanied with increased use of reused, recycled or green materials and locally available materials instead of importing (Mitchell and Kelly, 2013). Geotechnical engineers should be aware of and equipped with methods of sustainability assessment (e.g. how carbon footprint is estimated).

One way to achieve those outcomes would be through technological innovations. One of the relatively new innovative ground improvement methods is the controlled modulus column (CMC) ground improvement technique. This technology was first developed in France. Today CMC has become a method of choice for many projects having tight construction schedule or with concerns related to soft soils and contaminated ground. CMC possesses several features that are distinct from those of more traditional methods such as prefabricated vertical drains, stone columns, deep soil mixing or piled embankment foundation. CMC has been used considerably in Europe with increasing popularity in the US. The technique has recently been used in a number of projects in Australia, mainly involving construction of bridge approach embankments, port development and warehouse foundation with the aim to reduce both total and differential settlements and to accelerate construction sequence (Fok et al., 2012; Wong and Muttuvel, 2012). The Gerringong Upgrade project is one of the recent projects where CMC have been successfully utilised for bridge and road construction (Fulton Hogan, 2013).

This paper summarises the key sustainability aspects of using CMC technology and highlights some aspects that are potential for development. Future research directions are discussed to further enhance sustainable design practices. These include fuel consumption during operations, economic design with trial field tests, the use of recycled industrial by-products for grout mix, improved design, maximising the resiliency of structures and the energy consumption. The remainder of the paper will discuss the current state of art in assessing installation-induced displacement of the surrounding soils.

## 2 CONTROLLED MODULUS COLUMNS AND SUSTAINABILITY

### 2.1 CMC TECHNOLOGY

CMC technique has been described well in the texts by Plomteux et al. (2004) and Pearlman and Porbaha (2006), amongst others. CMC aims to reinforce soils that are often prone to settlement and having low bearing capacity by using a system consisting of non-reinforced and cement-based grout columns inserted into the ground. Both ground and columns are overlain by a granular layer, which is used to transfer the loading from upper structures to CMC and the surrounding soils. The presence of this layer over isolated columns makes CMC system suitable to support uniform loading applied over a relatively large area. CMC reduces total and differential settlement, better than stone columns and the quality is more controlled than with deep soil mixing techniques.

The CMC installation process involves penetration of a rotary displacement auger into the ground under the torque and downward thrust provided by the drilling rig; which is followed by grout injection through the hollow stem of the drilling tool while the tool is withdrawn (Figure 1). The specially designed auger comprises a short partial flight segment near the tip, the middle segment welded with helically wound blades and the uppermost portion with counter-rotating flight segment (Figure 2), which enables lateral soil compaction during installation.



Figure 1: CMC auger (Gerringong Upgrade project, 2013)

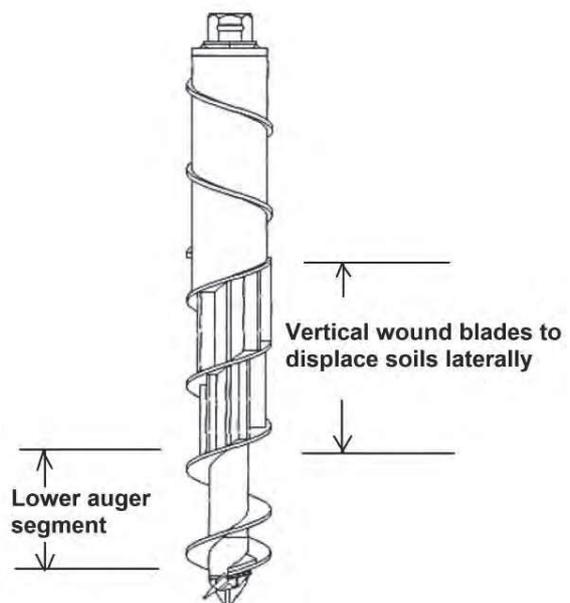


Figure 2: Patented CMC auger (Cognon, 2004)

## 2.2 SUSTAINABILITY ASPECTS OF CMC

The key contribution of CMC technology to the sustainable development is the production of very limited soil cuttings to the ground surface, thanks to the auger that is specially designed to displace soils laterally. This feature is particularly useful for construction projects involving contaminated or landfill sites, making CMC a cost-effective ground improvement technique associated with the reduction of cost for spoil disposal and handling compared to the contiguous flight auger (CFA) piling or bored piles (Masse et al., 2011; Walker et al., 2011). Besides performing well in soft or loose soils, CMC is also suitable for soils with significant organic content or acid sulphate soils. Integrity pile testing by Kirstein and Wittorf (2013) indicated that CMC can also be performed well in very soft soils although additional vertical drains had to be installed in the soft soil surrounding the columns. Environmental benefits can also be achieved through a vibration free and quasi-static installation process, as opposed to dynamic vibratory methods e.g. stone columns or driven piles. This allows CMC to be installed near sensitive structures.

The second advantage of CMC over other traditional methods is associated with a high production rate, which means overhead cost saving and suitable for projects with tight construction schedules. Hole drilling and concrete injection are carried out in one go without risk of hole collapses. Experience shows that many bored piling project suffered extended delay due to the unforeseen ground conditions. CMC column strength develops quickly, does not rely on the surrounding soil strength, and is effective in settlement control. Hence CMC is often selected to support bridge approach embankment, to fast track the bridge construction (Plomteux and Lacazedieu, 2007; Plomteux et al., 2004).

Thirdly, with CMC, saving can be achieved by various ways. Using displacement auger, the risk of necking is minimised leading to saving in the volume of injected grout. The load transfer layer functions in place for a more costly structural pile caps and concrete slabs. Fok et al. (2012) indicated that a 10 to 15% cost saving was achieved by using CMC compared to the deep soil mixing technique. Sometimes up to 30% in saving could be achieved (Angelo, 2007). When making judgement in terms of time, cost and long term performance (Higgins, 2014), it is considered that CMC may be positioned between deep soil mixing and piling with quick results and lower post construction settlement (Figure 3).

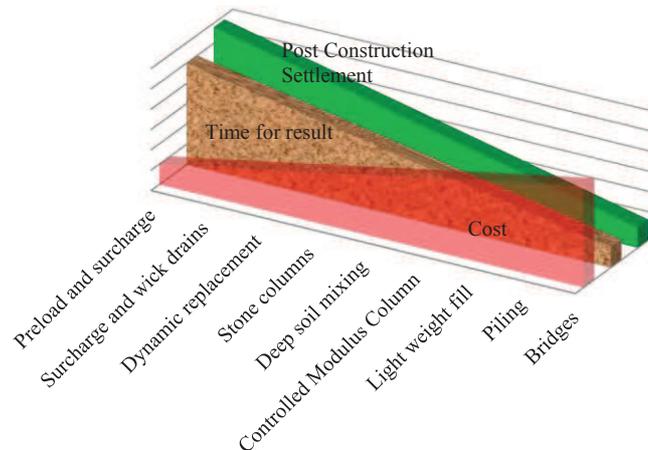


Figure 3: Cost, time for result, and performance considerations (modified after Higgins, 2014)

When scoring sustainability for a ground improvement method, the estimated carbon footprint can often be an important indicator. Carbon footprint is the sum of all emissions of CO<sub>2</sub> in a year, induced by ground improvement activities and by the production of materials used in construction. The estimated carbon footprint from CMC operation and related materials is considered lower than those from traditional piling methods by approximately 25% (Masse et al., 2011; Spaulding et al., 2008; Walker et al., 2011). Those emissions were calculated assuming no steel is used for CMC and that production of steel generally emits more carbon dioxide than cement related products.

Today, access to new tools to assess several environmental indicators for various competing solutions allows for the rapid comparison of ground improvement techniques and assists both contractors and clients in retaining the “best for project” schemes. Figure 4 illustrates such a comparison being performed on a range of solutions in accordance with the European Norm 15804.

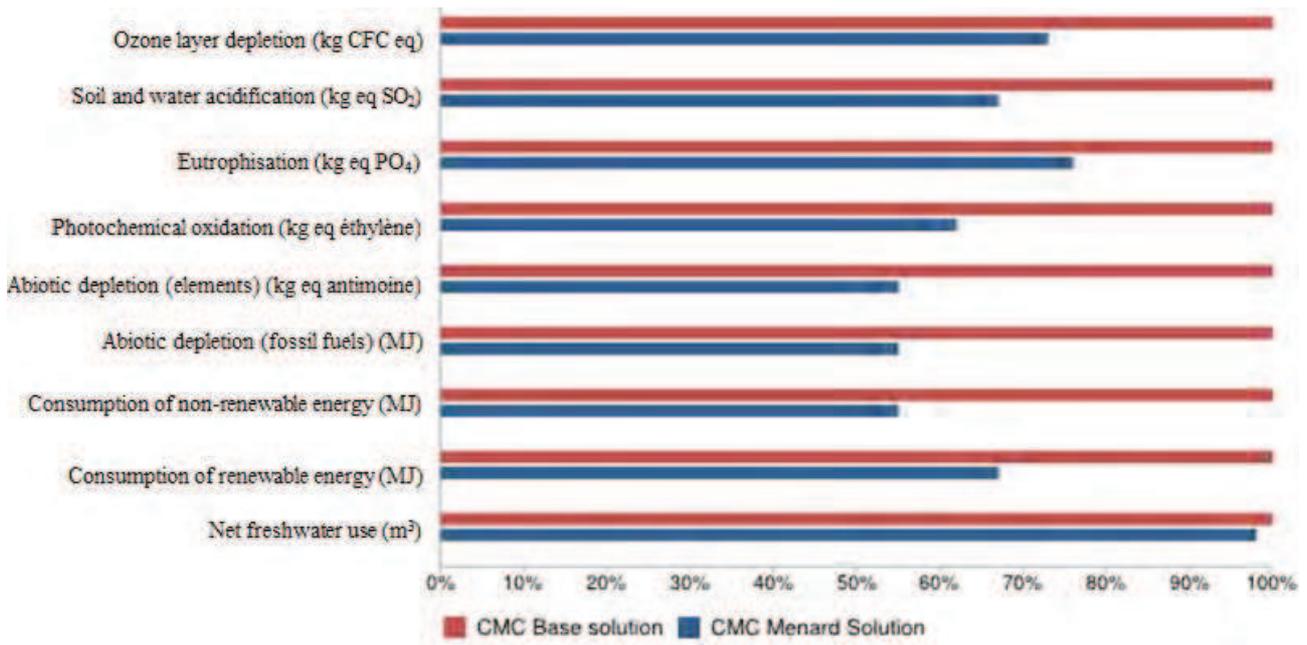


Figure 4: NF EN 15804 Indicators – Comparison of various CMC schemes (Prism solution – Menard Bachy)

Sustainable development also means design for durability and robustness to maximise the future resilience of a structure. The quality of CMC columns are subject to a real time monitoring system where installation parameters are recorded, allowing the operator to adjust the drill rate and installation depths, in combination with prior column design and drawings. This is particularly important for a site having varying ground profile with depth and/or with heterogeneous soils. Durability of the grout columns within a specific design life also relates to the properties of the mix i.e. the ability of the columns to resist chemic attack and weathering. Although the grout column will somewhat deteriorate with time, addition of fly ash can improve column durability. In fact, grout incorporating high volume fly ash was found to create grout columns with very low permeability and a high resistance to the passage of chloride ions (Bilodeau et al., 1994).

Every ground improvement method serves just a limited number of purposes. Decision making in selection of ground improvement methods will have to rely on the project requirement, local sustainability policies, ground, site conditions and others. Specifically within its functions, there are still areas for future development of CMC, which will be discussed in the next section.

### 2.3 POTENTIAL DEVELOPMENT IN TERMS OF SUSTAINABILITY FOR CMC

Many potential development approaches can be underlined when dealing with sustainability for controlled modulus columns (CMC). They are summarised in this section.

1. Economic design, an important aspect of sustainable development, can be achieved by various ways. In a CMC system, the load transfer layer provides arching effects, allowing structural or embankment loads to be transferred to the columns and to the founding stratum. Wong and Muttuvel (2012) carried out a limited study, indicating that it may be possible to reduce the thickness of the load transfer layer and the use of geotextiles for embankments that are sufficiently high. Similarly, for warehouse building constructions, due to the presence of the concrete floor slabs, geogrid reinforcement was rarely placed within the load transfer layer (Masse et al., 2011). Such economic designs are currently carried out on a case-by-case basis and no standardised method has been proposed. In fact, if the load transfer layer is not provided, the soil arching developed in the embankment fill alone may break due to traffic dynamic loads, seismic effects and flooding. Further rigorous numerical and experimental investigations are required.

In medium to large projects, the economic design proposal can be confirmed by construction of CMC test pads. The purposes of the test pads are not only to optimise the final design but also for design optimisation in future projects. According to Farouz (2014), with every \$1 spent for the rigid inclusion test pads, \$4 of savings could be achieved in the long run.

2. Grout mix design may be modified with further considerations of using industrial by-products such as ground blast-furnace slag, coal ash and fly ash with various contents, depending on the design strength requirements. The most appropriate grout mix for good pumpability is a specially designed lean sand-mix mortar or pea-gravel concrete, often with fly ash to increase workability. Concrete has been considered less costly than grout and has been increasingly used

in the US and Europe for CFA and displacement columns (Brown et al., 2007). Whether concrete or grout, the mix producers should make more use of local materials rather than importing in order to reduce the transport cost and fuel consumption. To increase tensile strength for columns, some recycled fibres such as polypropylene and recycled carpet may be added to the grout mix. The addition of fibres was found to reduce the cement content for stabilising poor clayey soils, particularly for applications associated deformations under seismic loading (Fatahi et al., 2013). Sustainability relates to savings in design and building resilient structures; however, such designs should have sufficient testing and verification to meet strength and durability requirements.

3. The installation effects are rarely taken into account to estimate columns' skin friction capacity. Designers seem to have little confidence in the use of increased soil parameters in actual design and no systematic approach has been established. In fact, most CMC or rigid inclusions in general, are installed through soft or loose soils and founded on stiffer founding stratum. The installation of displacement columns, despite causing compaction effects, usually creates a thin smeared or disturbed zone around the columns, depending on the type of auger and soil types. For column installation in loose sands, soils are densified everywhere immediately after installation. For clayey soils, strength gain and column set-up can be achieved at later stages depending on the amount of generated excess pore water pressure (Carter et al., 1980). A recent numerical study was carried out by Rivera et al. (2014) to study the increase in the radial effective stress  $\sigma'_r$  and the earth pressure coefficients  $K$  in clayey soils due to CMC installation. Figure 5 shows some increase in  $K$  value at the end of construction within a zone of up to 10 times column radius  $r_0$ . Although the results of this study is very useful, field test and performance verification have not been carried out. Further studies should be accompanied with thorough site investigation before CMC design and employing recent technology advancement e.g. the National French ASIRI project by Simon and others (2012a).

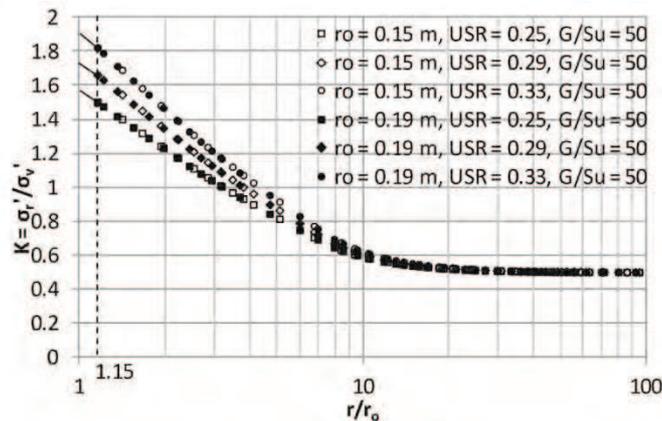


Figure 5: Distribution of radial effective stress in terms of  $K$  at the end of construction with varying CMC radius  $r_0$ , varying undrained strength ratio ( $USR = s_u/\sigma'_v$ ) and a constant soil rigidity index  $G/s_u$  of 50 (Rivera et al., 2014)

4. The performance of CMC installed in expansive soils is unknown. Although deep columns can be designed to bypass such soil horizons, CMC should also be able to resist potential tension and uplift effects. While CMC are non-reinforced and relatively weak in tension, the shaft may fail under excessive tension and the column may move upwards when the clay expands (Manjriker, 2006). In such cases, one of the possible solutions would be to add fibre reinforcement to the grout mix to provide additional tensile strength for the columns. In fact, it was found that the tensile strength of the cement-treated clay increased with the addition of carpet fibres (Fatahi et al., 2012). Figure 6 presents a sample of cement-treated clay with added geofibres.



Figure 6: A typical fibre reinforced cement-treated clay sample

5. Sustainable development also means design to maximise the future resilience of a structure against slope instability and seismic loadings. CMC is typically non-reinforced and often designed to mainly support uniform vertical loading. If CMC columns are located at the batter of embankment, or subject to seismic events, the column capacity to resist negative bending moment may be of particular concern. Under such non-vertical or dissymmetric loading, the excessive shear forces and bending moments may be induced.

To support reinforced soil wall (RSW) blocks at a site near Newcastle, one of the seismically active zones in Australia, the outer rows of CMC were reinforced with steel bars (Wong and Muttuvel, 2011). High strength grout may be required if additional strength is required to resist cracks developed in negative bending resisting elements. In addition to the capacity of CMC columns, quality and thickness of the Load Transfer Platform strongly affect the intensity of shear forces and bending moments in the columns, and therefore the behaviour of foundation, under seismic effects (Simon, 2012b). Similar to design approach using micropiles presented in the French national project on micropiles (Juran and Weinstein, 2008), some CMC columns may be installed symmetrically inclined in small angles to make use of the axial capacity. If implemented, this solution may potentially replace other costly solutions such as using larger and/or reinforced columns. The use of CMC or other rigid inclusions in seismic related projects is still a general concern to the designers, demanding a set of general design guidelines.

6. The amount of carbon footprint from a CMC system is generally less than other traditional piling methods. CMC columns normally have smaller diameters compared to typical bored piles. Also CMC columns are not normally designed to socket into hard stratum. Considering only the diesel consumption of the machinery during installation, however, displacement methods may require larger torque and vertical force than using continuous flight auger methods for an equivalent column diameter. Research by NeSmith and Fox (2009) indicated that the installation effort required to drill a new hole adjacent to the previously drilled hole was higher due to densified soils caused by the installation effects. While CMC auger has been optimised to significantly reduce the soil resistance, future research on auger geometry would further reduce soil resistance and hence the energy consumption.

7. Although CMC is a vibration free method, large displacement caused by the installation process could cause damage to the surrounding built environment (Brown, 2005) if proper installation sequence is not considered during implementation. If the soil deformation is excessive, the shape of the adjacent CMC may not be maintained, leading the reduction in the bending stiffness. This particular concern, relevant to sustainable development, will be presented in the following section. Recommendations for the required improvement in predicting lateral displacement and simulation of the CMC installation are provided.

### 3 DISPLACEMENT EFFECTS ON SURROUNDING ENVIRONMENT

The movement of the CMC auger into the ground causes lateral displacement of the soils surrounding the column. The displacement effects become more apparent in a number of circumstances, e.g. design of closely spaced columns in order to reduce differential settlement at the surface of the embankment. As a result, the installation-induced displacement at a new column could cause damage to freshly grouted surrounding columns. While the long term CMC elastic modulus ranges between 1,000 and 10,000MPa, the fresh grout is often wet, plastic and viscous. If the freshly-grouted columns are subject to soil movement, the verticality of the column may be adversely affected and hence a reduced bending moment capacity can be expected, potentially causing column cracking. Within the first 24 hours of the grout setting time, the grout has not cured to gain sufficient stiffness and could be susceptible when subject to external loading. Similarly, if installation is carried out near a bridge abutment or an existing sensitive structure, the displacement may cause lateral movement and impose additional load on the bridge piles or structures. Such effects can be a major concern for piling contractors and geotechnical engineers (Brown, 2005; Hewitt et al., 2009; Plomteux et al., 2004). As recommended by French National project on rigid inclusions (Simon, 2012a), for inclusions executed with displacement piling technique, the minimum distance between columns is recommended to be approximately four diameters i.e.  $S_{min} = 4D$ . As a comparison, in a much less displacement method like CFA, it is considered risky to install piles within a centre-to-centre distance of less than three column diameters from adjacent piles cast within the previous 24 hours (NSW Roads and Maritime Services, 2010). If ground conditions are unfavourable, then the spacing should be increased. Based on author's experience, the displacement effects of non-displacement type CFA piling can sometimes adversely affect sensitive structures at close proximity. Therefore, it is important for engineers to become aware of the piling displacement effects, especially with displacement installation techniques like CMC.

Plomteux et al. (2004) highlighted the risk involving construction of CMC columns with a spacing of 1m near the bridge abutment piles. The proposed construction method was modified with CMCs installed in two different interleave passes, each with 1.4m x 1.4m grids (Figure 7).

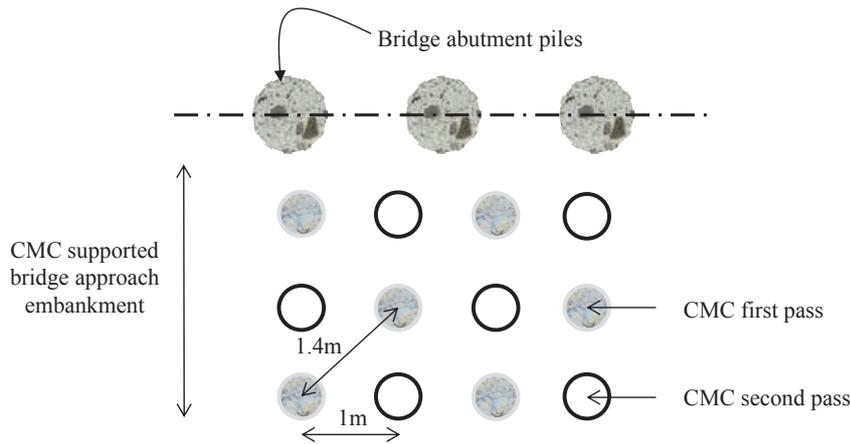


Figure 7: Modified CMC installation layout (modified after Plomteux et al. 2004)

Another installation sequence of displacement columns was reported by Hewitt et al. (2009), where columns closer to the existing embankment were installed first and then the rig worked away from the existing embankment to avoid accumulated installation-induced stresses. Although reported results from these modified installation patterns were positive, there is no solid justification for those selected patterns and how efficient they were in comparison to other possible installation patterns. To date the magnitude of such installation induced displacement remains unclear and, hence, requires further investigation. Optimisation of the CMC installation patterns requires (1) accurate assessments of the lateral displacement of the surrounding soils due to column installation, specific to CMC technique and (2) a good understanding of the soil structure interaction. The assessments should involve rigorous numerical, analytical and physical modelling techniques. Knowing the extent of installation effects on neighbouring structures will contribute to the selection and evaluation process of ground improvement techniques.

### 3.1 SOIL RESPONSE DURING AND POST INSTALLATION

CMC installation process involves formation of a cavity by the auger penetration together with simultaneous rotation in a clockwise direction. Soil cuttings at the auger tip are carried upwards between auger flights, towards the auger segments with helically wounded blades, where the soils undergo further destructuration and are displaced laterally. As a result, the surrounding soils are brought into passive state of stress during installation. At the same time, soil elements are also displaced vertically (Ahmadi et al., 2005; Hird et al., 2011). According to Basu and Prezzi (2009), the ratio of vertical and horizontal displacement mainly depends on the ratio of the vertical penetration rate and the rotation speed. Unlike jacked-in and driven piles, CMC techniques involve augering prior to soil compaction by the displacement body. The augering remoulds the soils causing significant soil disturbance. Through numerical modelling, Pucker and Grabe (2012) indicated that the higher ratio of the auger rotation speed over the vertical penetration rate, the larger lateral displacement occurs. In addition, installation induced displacement is quite distinct at different portions of the CMC. Ground heave normally occurs near the ground surface, to depths ranging from approximately 2.5m to 4.0m (Kraśiński, 2014; Larisch et al., 2013). In the middle region of the column, the installation results in a remarkable increase in soil density and stress level. Near CMC column base, the stress increase is insignificant (Kraśiński, 2014). This is in contrast with a jacked or driven pile, where the base is the most influenced portion.

Most current investigations were carried out for cohesionless soils (Basu and Prezzi, 2009; Pucker and Grabe, 2012). During installation sand behaves under drained conditions since the excess pore pressure dissipates quickly. As the auger reaches the elevation of a soil element located in the vicinity of the soil/column interface, the total and effective stresses generally increases. However, as the auger passes that soil element, the soil within 1 diameter (1D) from the column centre is loosened up because of the slight change in auger's cross section, from the displacement body towards the drill rod (Pucker and Grabe, 2012). Outside this very thin zone, the soil generally densified significantly within a distance of 2D. Within this 2D zone, it is noted that dense sand tends to dilate slightly due to strong shear stresses induced by the auger, in addition to the compaction induced by the displacement body (Mahutka et al., 2006). Overall, the extent of densified zone ranges from 6D for dense sand to a greater distance of approximately 8D for loose sand. Long term effects in sand are considered as creep-induced ageing phenomenon (Lim and Lehane, 2014), which has not been thoroughly investigated in the literature.

The behaviour of saturated cohesive soils during installation is often assumed to be undrained due to rapid auger penetration. Little change in the volume is expected with the generation of excess pore pressure. Due to large deformation caused by the installation, the soils closer to the column fail in shear, which forms a region called "plastic zone", extending to a radius  $R = r_0[G/s_u]^{1/2}$ , where  $r_0$  is the column radius,  $s_u$  is the undrained shear strength and  $G$  is

the soil shear modulus (Randolph and Wroth, 1979). Outside the plastic zone is “elastic zone” where excess pore water pressure is assumed zero. Generally the response of clay to cavity expansion depends on the over-consolidation ratio. For normally consolidated clay, there is an increase in both total stress and excess pore pressure  $\Delta u$ , but a decrease in effective stress (Ladanyi, 1964). For over-consolidated clay, the total and effective stress increase everywhere but  $\Delta u$ , after increasing within a narrow zone near the column wall, becomes negative in the next surrounding zone (Ladanyi, 1964). It should be noted that for a structured clayey soil due to increase in the mean effective stress as well as deviatoric stress, cementation degradation may occur influencing the deformation of the ground immediately or long time after the installation (Nguyen et al., 2014).

Immediately after installation, the peak excess pore pressure falls off rather quickly (Randolph and Wroth, 1979). Excess pore pressure decays during consolidation inducing elastic viscoplastic deformation together with soil strength gain. At the end of consolidation, radial effective stresses around the column is greater than the in-situ horizontal effective stresses in the undisturbed ground with decreasing magnitudes with increasing distance from the column centre within a zone of approximately 10 times the column radius (Rivera et al., 2014).

### 3.2 ASSESSMENT METHODS

The response of soils to the installation is time dependent. Compared to installation effects in the long term, short term effects on the surrounding soils and existing structures (e.g. increase in stress and displacement) are more evident, causing more concerns for practitioners. The short term effects due to CMC installation will be discussed here. Since very limited assessment of CMC installation effects has been reported, the existing assessment methods for various piling and ground improvement techniques most relevant to CMC will be discussed herein.

#### 3.2.1 Analytical techniques

Pile jacking or Cone Penetration Testing (CPT) is often simulated using cavity expansion theory. The theory is well described by Yu (2000). Unlike jacked and driven piles, the penetration of CMC auger into the ground includes soil loosening by auger flights in addition to the displacement effects. Therefore, CMC installation is not simply a cavity expansion process, but rather affected by the partial flight auger rotation, significantly reducing the normal stress on the column shaft that would be estimated by cavity expansion theory (Basu and Prezzi, 2009). The cylindrical cavity expansion theory is more applicable for the middle section of CMC. Closer to the column tip the installation resembles spherical cavity expansion. Near the ground surface the confining stress is significantly lower and vertical strain is dominant with the occurrence of heaving effects. Furthermore, since the column is drilled incrementally, the cavity expansion theory cannot simulate the installation process precisely. Despite these limitations, cavity expansion method may be used for preliminary assessment due to its simplicity compared to more complicated methods.

Cavity expansion theory has been applied to assess installation effects of driven piles and other vibratory methods such as stone columns. The predicted lateral displacement due to a closed-ended driven pile reported by Pestana et al. (2002) agreed quite well with the deflection measured using inclinometers. Typical equations used to estimate the radial displacement due to cavity expansion are presented here for illustration.

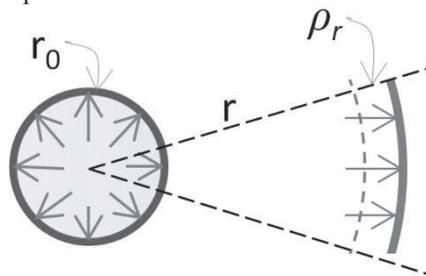


Figure 8: Lateral displacement of a soil element at a radius  $r$  due to cavity expansion

As shown in Figure 8, for an isotropic homogenous soil medium, a soil element located at a radius  $r$  from the centre of the cavity will be displaced a radial distance of  $\rho_r$ , due to undrained cavity expansion from an initial cavity of zero radius to a cylindrical cavity having a radius of  $r_0$ . A radius of  $r_0$  represents the size of a stone column or CMC. The radial displacement  $\rho_r$  can be readily derived by assuming a constant volume of soil before and after undrained cavity expansion, as shown in Equation (1).

$$\rho_r = \sqrt{r^2 + r_0^2} - r \quad (1)$$

From some well-known solutions of undrained cylindrical cavity expansion presented by Yu (2000), Kelly et al. (2011) introduced Equation (2) to estimate soil displacement at various depths due to undrained cylindrical cavity expansion

from zero initial radius in infinite cohesive soil medium. The soil rigidity index ( $G/s_u$ ) can be obtained from the field tests e.g. Seismic Dilatometer testing (SDMT). The undrained finite cavity expansion solution in an infinite soil mass with critical state soils are presented in Yu (2000).

$$\rho_r = s_u / (2G) (1 + \ln(G/s_u)) (r_0 / r)^2 r \quad (2)$$

### 3.2.2 Numerical methods

Installation effects can be assessed more accurately using the finite element method (FEM) or the finite difference method (FDM) including the use of more realistic soil models. Since the soils is strongly affected by the CMC auger rotation, ideally numerical simulation should include augering effect, which becomes very complex and can only be done in a 3D system (Pucker and Grabe, 2012). As illustrated in Figure 1, the auger is asymmetric, making simulating augering effect impossible in a 2D axisymmetric model. Simplified numerical methods have been used by various authors to serve specific research goals. One less complex, yet difficult method, is the numerical simulation of the vertical penetration of a pile/column or other penetrating tools, which is initially positioned above the ground surface. Other less complex studies include the penetration of the tool preinstalled in the soils before simulation starts (Larisch et al., 2013), or the simulation of cavity expansion from a finite cavity using prescribed horizontal and/or vertical displacements e.g. by Castro and Karstunen (2010) and Rivera et al. (2014). Typical outputs of three dimensional analyses simulating horizontal cavity expansion are shown in Figures 9 and 10.

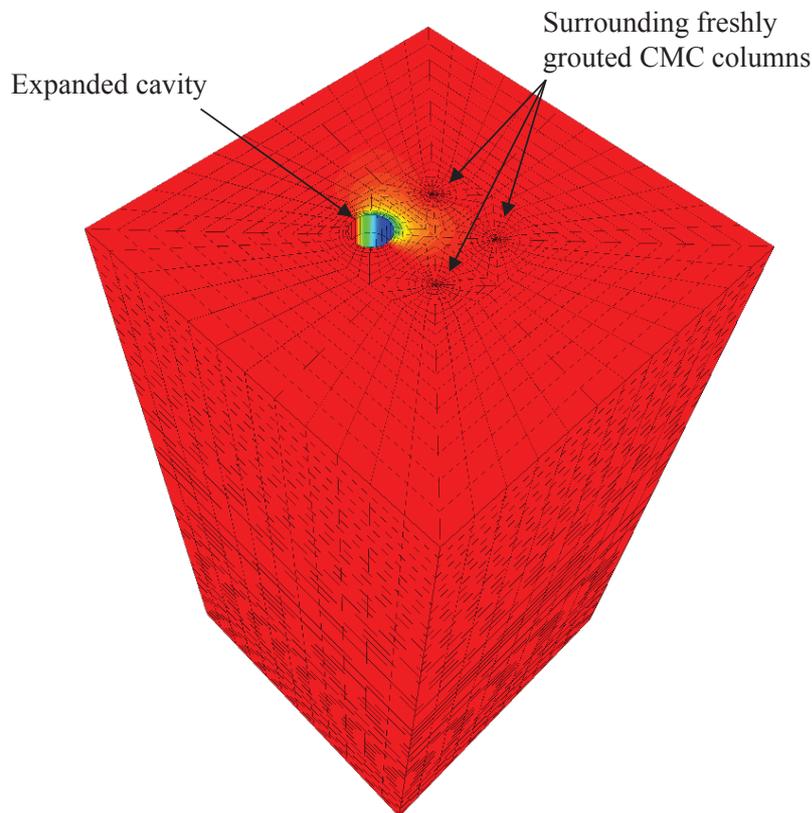


Figure 9: Contour of lateral soil displacement due to undrained cavity expansion performed in FLAC<sup>3D</sup>

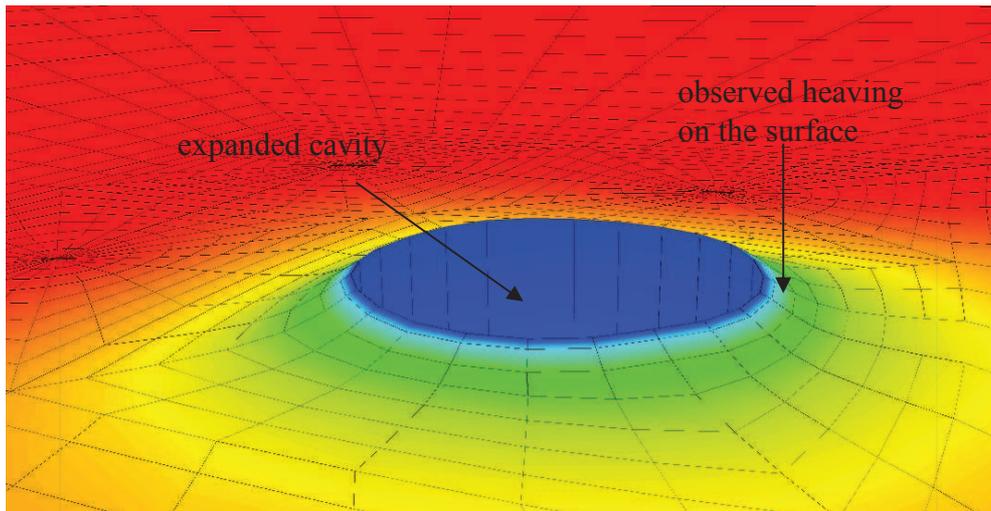


Figure 10: Heaving effects due to undrained cylindrical cavity expansion in FLAC<sup>3D</sup>

*Cavity expansion methods and effects of initial radius on predictions*

Numerically, there are two types of cavity expansion (i) from an existing cavity (ii) from a cavity with an initial zero radius. Although column installation resembles cavity creation from an initial zero radius, numerical expansion must necessarily be modelled from a finite radius rather than from zero radius to avoid numerical difficulties (e.g. infinite circumferential strain). In fact, the restriction of numerical expansion from a finite radius in place for a zero initial radius would cause no inconsistency in the final results (Carter et al., 1979). If undrained cavity expansion is assumed, the required size of the final cavity at the end of the expansion  $r_f$  can be readily estimated using Equation (3), which relates the initial size  $r_i$  of the cavity and the actual column radius  $R_c$  (Figure 11). The initial size of the cavity may have to be adjusted to avoid excessive mesh distortion while maintaining reasonable numerical accuracy.

$$r_f = \sqrt{r_i^2 + R_c^2} \tag{3}$$

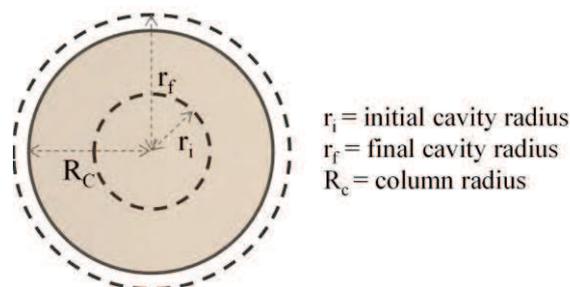


Figure 11: Cavity expansion from an existing cavity with a radius of  $r_i$  to a final radius of  $r_f$

It is quite common to double the size of an existing cavity e.g. Krasinski (2014), Rivera et al. (2014) and Castro and Karstunen (2010). Krasinski (2014) simulated the installation of a screw displacement column using PLAXIS by creating an initial cavity with a radius equal to half column radius, and then doubled that cavity to the full size of column radius in an axisymmetric model. For simulation of the installation of a drilled displacement column as in Basu and Prezzi (2009), a “finite initial radius”  $r_i$  of 0.015m was specified compared to a final column radius  $r_f$  of 0.165m. While a smaller initial radius results in better prediction, a larger amount of expansion  $\Delta r = r_f - r_i$  will be required, which may eventually lead to heavily distorted mesh, especially with the use of fine mesh.

*Heavy mesh distortion and complex soil/auger interface*

One of the simple methods to assess lateral soil displacement is to expand a cavity with the application of horizontal and vertical displacement at the nodes along the existing initial cylindrical cavity (Ahmadi et al., 2005). This method can be performed using several commercially available software packages such as FLAC and PLAXIS, or their 3D counterparts. The packages are equipped with Updated Lagrangian analysis (e.g. “large strain mode” in FLAC and “Update Mesh” in PLAXIS). The analysis allows grid-point coordinates updated at each step. It is noted that the numerical accuracy increases with a fine mesh, but in combination with a large amount of required cavity expansion,

excessive mesh distortion sometimes occurs. For more advanced analyses e.g. numerical modelling of the penetration of a column/pile or a drill tool into the ground, extreme large deformation often occurs, causing mesh to heavily distort. Various authors have used advanced numerical technique to deal with large deformation problem and complex contacts between soils and the penetrating tool. Those methods include the Arbitrary Lagrangian – Eulerian (ALE) adaptive meshing and Coupled Eulerian–Lagrangian (CEL) analysis, both available in commercial FEM software package ABAQUS, with ALE available in ANSYS Multi-Material LS/DYNA program. Compared to ABAQUS/Standard, ALE in ABAQUS/Explicit is more robust and can handle a large variety of problems including severe distorted mesh, hence will be discussed further. ALE mesh is allowed to move independently of material deformation. In the first step, the explicit Lagrangian analysis is performed. The resulted distorted mesh will require a new improved mesh. In the second step, the Eulerian analysis is performed, where variables in the previous analysis is transferred into the new mesh. ALE can deal with large deformation problem; however, since elements and connectivity (i.e. topology) do not change, high quality mesh may not be maintained during extreme deformation.

In contrast, CEL (only in ABAQUS/Explicit) has spatially fixed mesh. Eulerian and Lagrangian bodies within the same model can interact via a contact definition e.g. a Lagrangian auger travelling into Eulerian yielding soil. Chosen portions of a CEL model can be modelled as Eulerian or Lagrangian. Since the Eulerian mesh is fixed in CEL, soil displacement has to be calculated by integrating node velocities of the Eulerian mesh recorded along a predefined path over time (Pucker and Grabe, 2012). The installation of a screw displacement auger into dry sand was numerically simulated using CEL as in Pucker and Grabe (2012), however the results were not adequately verified against field measurements. Overall, although both ALE and CEL seem to be the promising solutions to the very large strain problems, CEL is more computationally friendly since a fixed mesh means no mesh distortion and less solution convergence. These ABAQUS/Explicit analyses, however, seem to offer only single-phase possibility with either fully drained or total stress undrained condition analyses (Elkadi et al., 2014). Also, ABAQUS/Explicit currently only allows total stress or frictionless contact between bodies. The challenge would be to create a user's subroutine into ABAQUS to enable undrained effective stress analysis and frictional contact.

#### *Soil models*

Since soils are subject to complex loadings during installation, constitutive models adopted should capture highly non-linear inelastic behavior, decay of excess pore pressure, loading and unloading paths and density changes. Well-established models such as Mohr Coulomb (MC) and modified Cam Clay (MCC) are incorporated in most of the commercial software packages. Also some consideration should be taken to account for the cyclic effects induced by the action of the drill auger (Pucker and Grabe, 2012). The MC failure criteria if used should account for stress-dependent stiffness. For MCC model, since the soil surrounding the column is likely to be in critical state, this model can be quite representative. It can be noted that above water table, soils may be partially saturated and thus excess pore pressure should be predicted considering coupled flow-deformation behaviour of unsaturated soils.

Compared to MC and MCC, hypoplasticity is a relatively new type of soil model and has been increasingly utilized to solve large deformation problems (Larisch et al., 2013; Pucker and Grabe, 2012). Various hypoplasticity models exist, noticeably by von Wolffersdorff (1996) for sand and modified version by Mašín (2005) for clay. Von Wolffersdorff (1996) model for granular materials incorporates the intergranular strain and dependency of friction angle and stiffness on density changes and compaction. The model requires 13 parameters including critical state friction angle and void ratio. Despite included advanced features, determination of a large number of model parameters may be a challenge. Meanwhile, clay hypoplasticity model developed by Mašín (2005) combines mathematical structure of hypoplasticity models with basic principles of the critical state soil mechanics. This model requires five parameters, similar to those of MCC model; however, it can provide a smooth transition between overconsolidated and normally consolidated states. Unlike MC, this hypoplasticity model correctly predicts the state dependent soil stiffness. Implementation of these models is a difficult task since they are not built-in in most commercial software packages.

#### **3.2.3 Physical modelling**

No laboratory scale simulation of installation effects for CMC has been reported in the literature, possibly due to many challenges associated with preparing auger model, setting up driving tools that can control torque and vertical crowd and complicated on-sample instrumentation. Hird et al. (2011) used an alternative approach to simulate the screw displacement auger without the use of on-sample instrumentation. Transparent artificial soils contained in a chamber with observable window allowed the displacement field to be captured by photographs and analysed using "particle image velocimetry" technique. Such studies indicated that the soil displacement in downward and horizontal direction depends very much on rotation speed of the auger and the penetration rate. Although useful, rigorous scaling is hard to be achieved to translate the results into behaviour of a prototype CMC and artificial soils like glass offers little practical usefulness. Despite expected shortcomings, small scale models may provide roughly similar trends of lateral displacements in full scale field tests.

Field measurement of lateral soil displacement is more indicative although field tests are not often readily available for verification of theoretical analyses. The required field instrumentation and monitoring scheme are often expensive. Also the equipment may be prone to damage during execution.

Rare but limited field tests were carried out by Suleiman et al. (2013), comprising installation of a 320mm-diameter CMC with four surrounding reinforced CMCs acting as reaction piles, instrumentation and one subsequent load test. The CMC was installed in very soft sandy organic soils with a thickness of approximately 6m. The instrumentation included four push-in pressure sensors and four shape acceleration arrays (SAA) to capture stress change and displacement in soft silty soil throughout column installation and testing. Each SAA was inserted together with a PVC casing into a predrilled hole. Two out of the four SAAs did not fit well with the pipes, and hence sand was used to fill the gap. In addition, strain gauges attached to a steel bar were inserted into the freshly grouted column, along the vertical axis, in order to measure the column strain developed during the load tests. The test outputs indicated that the strain gauges located near the CMC tip did not function, which may have been damaged during installation, or also during the steel bar insertion. At the end of CMC installation, an increase in horizontal stress by 2kPa was recorded within 1D (i.e. one diameter) distance from the CMC, by 8kPa within 2D distance, and then with decreasing trend with increasing distance from the CMC. Some stress relaxation by approximately 2 to 3kPa was recorded at the end of the installation. After installation, the stress recorded around the central CMC increased and was greater than stresses recorded at the end of the installation. The maximum soil displacements recorded at radial distances of 450mm, 750mm and 1050mm from the centre of the CMC were approximately 13mm, 8mm and 3mm respectively. The recorded soil displacement showed a clear decreasing trend with increasing distance from the CMC.

Good contracting practice also calls for early trials and excavation of “calibration” columns in order to confirm that the combination of selected design parameters (grid spacing/column diameter for a given type of soil) and retained methodology do not present a risk to the structural integrity of the columns installed. Figure 12 illustrates such trials presenting good quality columns with well-formed shafts and regular diameter. The presence of small and localised cracks is generally acceptable as with most type of unreinforced concrete structures.



Figure 12 : Typical shape of excavated columns presenting sound characteristics

In addition, static load testing is also a routine form of trial to confirm both the integrity and the performance of both calibration columns during initial stages of construction and production columns throughout the works. If appropriately specified, results of static load tests can provide useful information to the practicing engineers about structural and geotechnical capacities. Typical static load test results for CMC columns are shown in Figure 13.

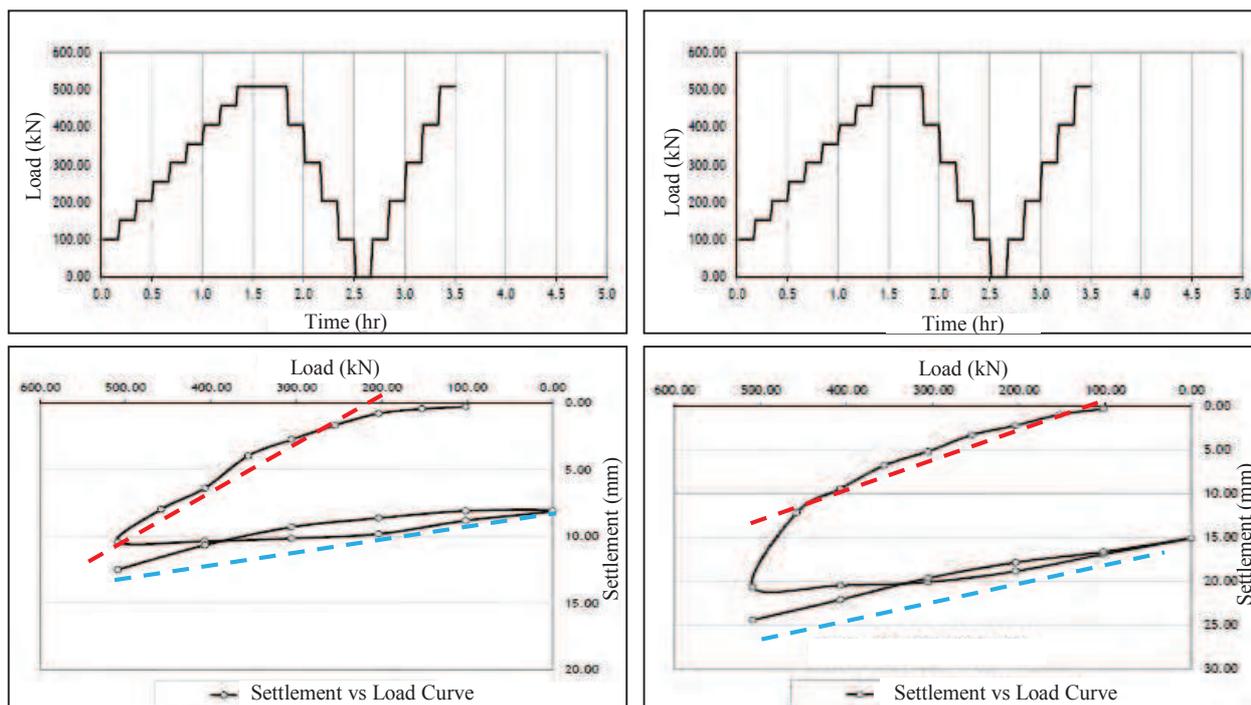


Figure 13: Typical static load test results

#### 4 CONCLUSIONS

The evaluation of controlled modulus column (CMC) technology with respect to the sustainability has been taken into consideration. Evidently CMC provides a sustainable solution to the ground engineering including eliminating cost for spoil disposal, a high production rate, project saving through the use of displacement methods and load transfer layers, controlled quality and durability, and lower carbon emission in comparison to piling. Research directions to improve CMC for sustainable development have also been discussed including economic design with trial field tests, the use of recycled industrial by-products for grout mix, rigorous design, maximising the resiliency of structures and the energy consumption during operations.

The concern over the CMC installation effects on the existing structures and the adjacent columns has also been addressed in this paper. Numerical methods are the most appropriate techniques to assess the resulting stress and displacement fields in the surrounding soils. Selection of a modelling technique and soil model, which are able to account for extreme displacement, are of paramount importance. The results can be checked using preliminary assessment guidelines such as the cavity expansion theory. The other challenge is associated with the verification methods including small and full scale model testing. It is recommended that future CMC projects allow more field measurements as a basis to improve the assessment methods.

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