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Economic Design of Controlled Modulus Columns for Ground Improvement

P. K. Wong[1] and T. Muttuvel[2]

[1]Senior Principal, Coffey Geotechnics, 8/12 Mars Road, Lane Cove West; NSW Australia, 2066, PH (61) 299111000; email: patrick_wong@coffey.com
[2]Senior Engineer, Coffey Geotechnics, 8/12 Mars Road, Lane Cove West; NSW Australia, 2066, PH (61) 299111000; email: Theva_Muttuvel@coffey.com

ABSTRACT

Controlled Modulus Columns (CMC) may be classed as a form of rigid or semi-rigid inclusions depending on their design. If the columns are founded on rock or a sufficient distance into firmer ground, and designed to take nearly all the vertical loads, they become rigid inclusions. The advantage of this design approach is that settlement will be limited, but the disadvantages are that the columns will attract greater load, including bending moment and shear force in situations where non-uniform loading or ground conditions exist. In some cases, steel reinforcement may be required and project owners or authorities may require the CMC to be designed as structural elements in a similar way as structural piles. For such situations, the design of the CMC would have to satisfy traditional structural design requirements such as load factors, strength reduction factors, concrete strength and durability. If the CMC are designed to share load with the surrounding soil affected via a combination of (a) compressibility of the columns (b) yielding of the column toe, and (c) load sharing via a load transfer platform such as a gravel mattress, they can be more economically designed as semi-rigid inclusions. In order for CMC to be designed economically and be a sustainable ground improvement option in a competitive market, they should be designed as geotechnical elements. This paper proposes an economic design procedure. Issues such as the need for load transfer platform, sharing of loads between the CMC and the soft soil, and design of CMC for bending and shear for the purpose of ground improvement, are discussed.

Keywords: Controlled Modulus Columns, design, case studies,

1 INTRODUCTION

In recent years, the use of controlled modulus columns (CMC) has gained popularity in the support of rail and road bridge approach embankments on soft soils in order to accelerate the construction program. Although many other less costly ground improvement solutions are available, such as preloading, they are usually more time consuming. CMC are rigid or semi-rigid inclusions constructed using grout, concrete or a combination of cementitious materials including waste products such as fly ash and slag. Unlike pile supported structures, there is a sharing of load between the CMC and the surrounding soil. Rigid columns made of concrete or grout may also share load with the surrounding soil by founding their toes only a limited amount into the underlying stiff soils, or by installing them partially penetrating in the soft soil layer. Typical diameter of CMC ranges from 300mm to 500cm installed at a spacing ranging from 1.3m to 2.5m. These columns are typically 10m to 20m length with larger diameter columns installed to 30m depth.

2 TRADITIONAL DESIGN APPROACH

Most CMC designs are similar to piled embankments, with the columns designed to practically carry the entire embankment load. A load transferred platform (LTP), usually in the form of geosynthetic reinforced gravel mattress, is used to transfer the load onto the columns. Most design guides associated with column supported embankments, including the piled embankment design described in the British Standard, BS8006 (1995) recommend that the columns be designed to carry the entire embankment load via arching action and also the catenary loading from the LTP. A single layer of high strength geosynthetic, or multiple layers of geogrid, is usually embedded within a gravel layer to form the LTP. The soft soil between the piles is assumed to carry no load due to concerns regarding long-term consolidation which may cause the soil to separate from the base of the soft soil.

In addition to axial load and settlement limits, the traditional design of CMC requires that the structural strength of the columns is not to be exceeded. In this respect, the CMC are designed such that there are no negative bending stresses at any point along their length (Plomteux & Lazacedieu 2007).

Bending of columns most commonly occur beneath embankment batters, or at transition zones between CMC treated ground and non-treated ground behind the CMC zone due to non-uniform loading. Excess bending and tensile stress can also occur during installation of the columns due to displacement effects and these may cause cracking of the CMC. Alternatively, steel reinforcement may be incorporated to allow the columns to carry negative bending stresses.

In order to design CMC to satisfy the normal design requirements described above, closer spacing columns, larger diameter columns, or reinforcing the columns with steel bar or cage may be required.

3 NEW DESIGN APPROACH

The traditional design approach described above, which treat the CMC as structural elements, could make CMC uncompetitive when compared to other forms of ground treatment solution. In the following sections, the need for load transfer platform, load sharing between CMC and the soft soil to limit post-construction settlement, and designing the CMC for bending and shear are discussed in the quest of making the design of CMC more economical.

3.1 Load Transfer Platform

A LTP may or may not be required depending on the embankment height and spacing of the CMC. As it is proposed that the soft soil should share load with the CMC, we can disregard the notion that a LTP must be required to transfer the entire embankment loads to the columns. Instead, the need for a LTP should be governed only by the differential settlement tolerance at the top of the embankment. A LTP is particularly needed for low embankments to avoid the mushroom effect shown in Figure 1 below.

Figure 1. Mushroom Effect on the Surface of a Low Embankment Trial (Photo courtesy of Professor George Filz, Virginia Tech, USA)

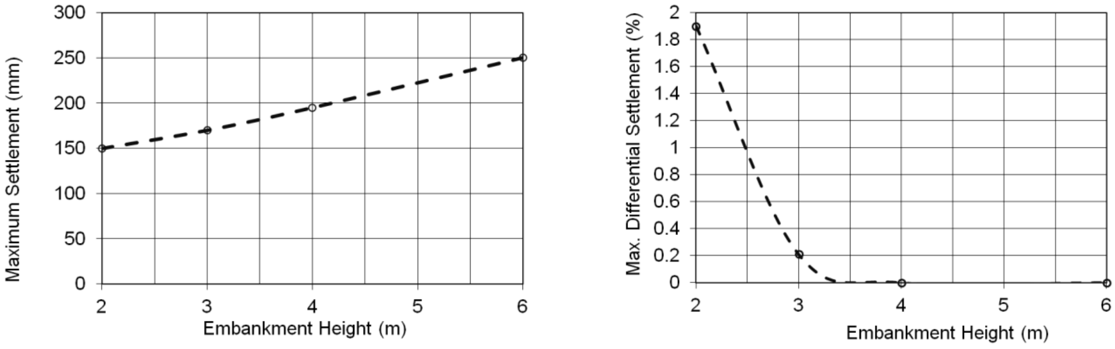
For high embankments, as is the case for most CMC supported embankments at bridge approaches, the compacted fill alone may be sufficient to dissipate the differential settlement at the surface of the embankment without the use of a LTP.

In any case, unless the soft soil is underlain by a relatively thick layer of fill of stiff soil, a working platform comprising a light geotextile and gravel mattress would need to be installed over the soft soil to enable heavy rigs to be used for the installation of the CMC.

By considering the above factors, the use of a heavily reinforced LTP may be avoided. Figure 2 shows the result of parametric analyses carried out for a typical example of a CMC supported embankment having the following parameters:

- **Soft soil**: thickness = 10m, bulk unit weight = 17kN/m^3, long-term Young's modulus (including creep effects) = 1MPa, Poisson's ratio = 0.3, c' = 0kPa, ϕ' = 26°.
- **Underlying stiff clay**: thickness = 10m, bulk unit weight = 20kN/m^3, long-term Young's modulus = 20MPa, Poisson's ratio = 0.3, c' = 5kPa, ϕ' = 30°.
- **Working Platform**: thickness = 1m, bulk unit weight = 20kN/m^3, long-term elastic modulus = 50MPa, c' = 0kPa, ϕ' = 45°. No tensile fabric used.
- **Embankment fill above working platform**: height varies, bulk unit weight = 20kN/m^3, long-term Young's modulus = 30MPa, Poisson's ratio = 0.3, c' = 15kPa, ϕ' = 30°.
- **CMC**: diameter = 0.5m, spacing = 2.0m square grid, length = 11.5m (i.e. 1m through the working platform, 10m through the soft soil, and founded 0.5m below the soft soil), Young's modulus = 10,000MPa, Poisson's ratio = 0.25.

An axi-symmetric finite element analysis was carried out using equal area principle with a radius of 1.13m for the unit cell to model the CMC spacing of 2m, with the total embankment height (including the working platform) varied from 2m to 6m, to assess the total and different settlement. The resulting maximum settlement and different settlement are shown in Figures 2(a) and 2(b) respectively. The maximum differential settlement was assessed based on the maximum gradient of the settlement profile predicted at the embankment surface (i.e. from the centre of CMC to periphery of the tributary area). It can be seen from Figure 2 that while the total settlement increases with increasing embankment height, the maximum differential settlement at the embankment surface actually decreases. The maximum differential settlement at the embankment surface is 1.9% when the embankment height is 2m and decreases to zero when the embankment height approaches 3.5m. This example clearly shows that a load transfer platform with geofabric reinforcement may not required if the embankment fill is of sufficient thickness to even out the differential settlement at the finished level, but may be required for low embankment to meet the design differential settlement criteria.



(a) Total Post-construction Settlement *(b) Differential Settlement at Surface*

Figure 2. Total and Differential Settlement at Embankment Surface for Example Problem

3.2 Load Sharing between CMC and Soft Soil

Without deliberately using high strength geosynthetic reinforced LTP to span between columns and transfer the entire embankment loading to the columns, the CMC and soft soil can be designed to share the embankment load. The embankment settlement will be greater, but this approach will also result in a more economical solution. The assessment of load distribution with depth along the length of the CMC, and distribution of load between the CMC and the soft soil, together with resulting settlement can be assessed using numerical methods to optimise the CMC spacing. The results of an axi-symmetric numerical parametric analysis reported by Wong and Muttuvel (2011) for a 9m high embankment over 20m of soft clay is presented in Figure 3. In this case study, the soft clay layer was modelled using the PLAXIS Soft Soil model (i.e. Modified CAM-Clay model), with compression and recompression ratios of 0.25 and 0.035 respectively. The over-consolidation ratio profile adopted ranged from 15 at the top of the soft clay to 1.05 at 17m depth. The adopted undrained shear strength of the soft clay for the skin resistance calculation ranged from 35 kPa to 15 kPa over a similar depth range. It can be observed from Figure 3 that the predicted embankment settlement increases rapidly beyond a spacing to column diameter ratio of about 4.

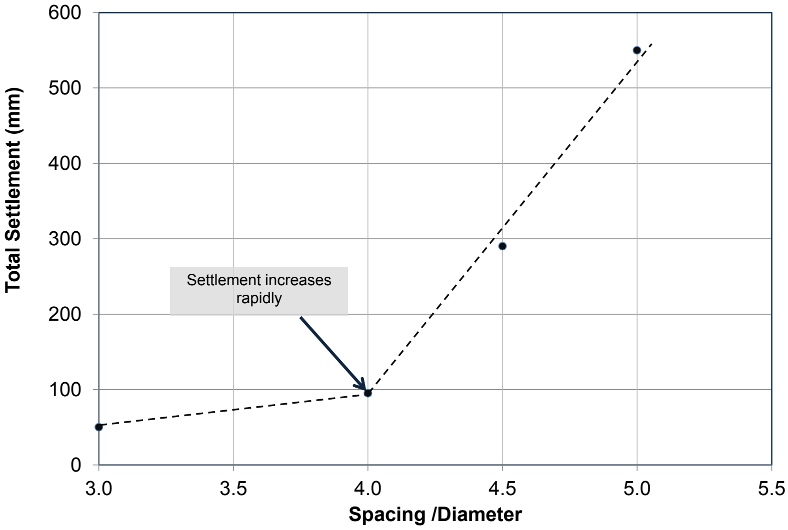


Figure 3. Computed Total Settlement with Spacing/Diameter ratio (Case Study described in Section 4)

3.3 Bending and Shear Impact on CMC Design

For CMC located beneath the batters of the embankment, or at transition zones between the CMC supported embankment and non-treated zone, the columns will be subjected to bending and shear due to non-uniform loading. This problem is similar to embankments supported on deep soil mix columns, where panels are often used beneath the embankment batters to avoid bending failure and provide greater shear resistance against slope stability. Filz (2009) showed the 8 potential failure mechanisms (A to H) described by Kivelo and Broms (1999) as shown in Figure 4. Kivelo and Broms (1999) developed expressions for the equivalent shear resistance for each of the failure modes for the purpose of limit equilibrium slope stability analysis. However, the equivalent shear strength varies with depth and also varies with the potential failure mode, therefore making such assessment cumbersome. Kitazume (2008) developed simplified analytical solutions for embankment stability of deep soil mix column groups, and showed via centrifuge testing that the columns continue to provide support after development of cracks due to bending.

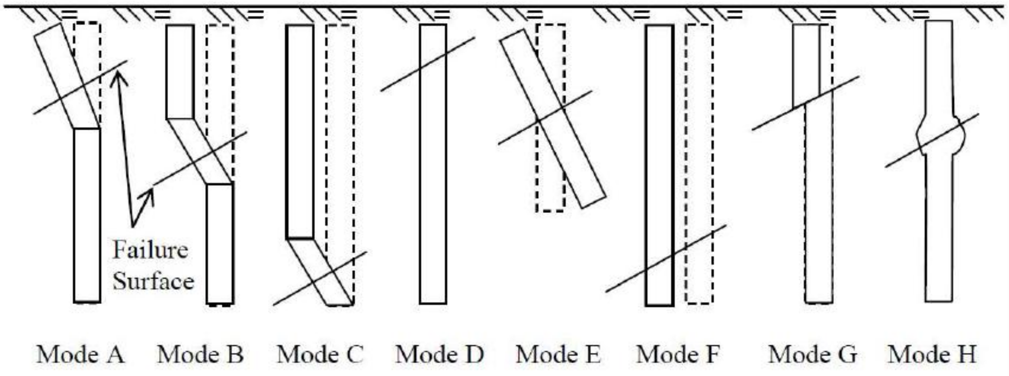


Figure 4. Potential Failure Models (redrawn by Filz, 2009 based on Kivelo and Broms, 1999)

With the advent of numerical analysis, the problem of bending and shear CMC supported embankments can be readily assessed. Filz (2009) showed the factor of safety obtained by limit equilibrium analysis can be over 3 times that obtained by numerical analysis of isolated columns due to bending and shear failure effects. Filz and Navin (2006) showed the greater the shear strength of the column, the greater is the deviation between the factor of safety computed between limit equilibrium and numerical analyses.

Unlike deep soil mix columns, however, CMC cannot be installed in panels. Therefore, it is necessary to assess the stability and lateral deformation of embankments supported by groups of isolated CMC numerically. To assess whether the lateral deformation is acceptable and whether the columns need to be reinforced, the columns may be modelled as fully cracked elements that have no flexural rigidity but retains some of the axial stiffness depending on lateral deformations. As a guide, the full axial stiffness may be assumed if the line of action, after lateral deformation, remains within the middle third of the column. The CMC may be modelled as a vertical plate element embedded within the middle of the CMC material elements described below.

Cracked CMC can be modelled as equivalent finite element strips, having a width of $\sqrt{3}/2$ times the CMC diameter, with appropriate stiffness and strength parameters in order to assess its lateral response. It is important to note that the equivalent properties of the cracked CMC will depend on the extent of deformation and cracking. In most cases, they will retain their axial stiffness, but may exhibit the behaviour similar to that of a jointed rock mass after cracking has occurred. Therefore, designers must use appropriate engineering judgment when assigning equivalent material parameters for the equivalent material strips to model the CMC. An iterative process may be required to finalise the design parameters based on the results of preliminary analysis. As a guide, initial estimates may be based on a long term modulus, E_{eq}, of 1/50 of the column, an effective cohesion of 0.5% to 1% of the unconfined compressive strength of the column, and a friction angle of between 30° and 40°.

4 CASE STUDY

As part of the Roads and Maritime Services (RMS) Pacific Highway upgrade in New South Wales (NSW), Australia, construction of a bypass joining south Kempsey to Frederickton started in late 2010. The northern approach of the Macleay River bridge is founded over alluvial deposits consisting of soft to firm clay with interbedded loose sand, extending down to approximately 6.5m to10.5m in depth followed by extremely weathered siltstone/sandstone. Various ground improvement methods such as stone columns and deep soil mixing were considered but CMC ground treatment was selected to speed up bridge construction and to meet lateral movement tolerance of 30mm in 100 years design life at the bridge abutment pile location. Numerical modelling was carried out using the commercially available computer software PLAXIS 2D (Ver. 8.6), adopting cracked CMC to assess the lateral movement at abutment location. Modelling the cracked CMC has been briefly described in Section 3.3. A summary of material parameters adopted for cracked CMC are summarised below:

- Young's modulus of cracked CMC = 200MPa (2% of uncracked CMC Young's modulus), with a Poisson's ratio of 0.25; cohesion of 50kPa and friction angle of 30 degrees; and
- Plate element inserted in the centre of CMC with axial stiffness, EA of 10,000 MPa x 0.159m^2 = 1590MN (same as uncracked CMC), but with negligible flexural stiffness.

PLAXIS 2D output showing horizontal displacement shading is presented in Figure 5 and the estimated lateral deformation (excluding long-term creep) at abutment pile location is approximately 16mm. Based on the numerical analysis results, the CMC design included the following:

- 450mm dia. CMC at square spacing of 1.6m with a maximum working load capacity of 407kN;
- relatively low strength, 10MPa concrete used for the CMC except 40MPa was used for the outer two rows around the batter based on advice from the durability engineers;
- no high strength geosynthetic or geogrid reinforcement was used; and
- no steel reinforcement has been provided for the CMC.

CMC installation was completed at the end of February 2011, and the approach embankment was completed at the end May 2011. Within 1 month of embankment construction, the monitoring results indicated that all ground movements had ceased and the site was released for bridge abutment pile construction. Measured maximum settlement and lateral deformation at the bridge abutment location was 27mm (excluding settlement due to the initial 2m of fill placed), and 22mm respectively. All movements ceased after 2 months from placement of filling. Based on the monitoring results, it is expected that post-construction ground deformations (100 years after road opening) at the bridge abutment is likely to be lower than the design criterion of 30mm.

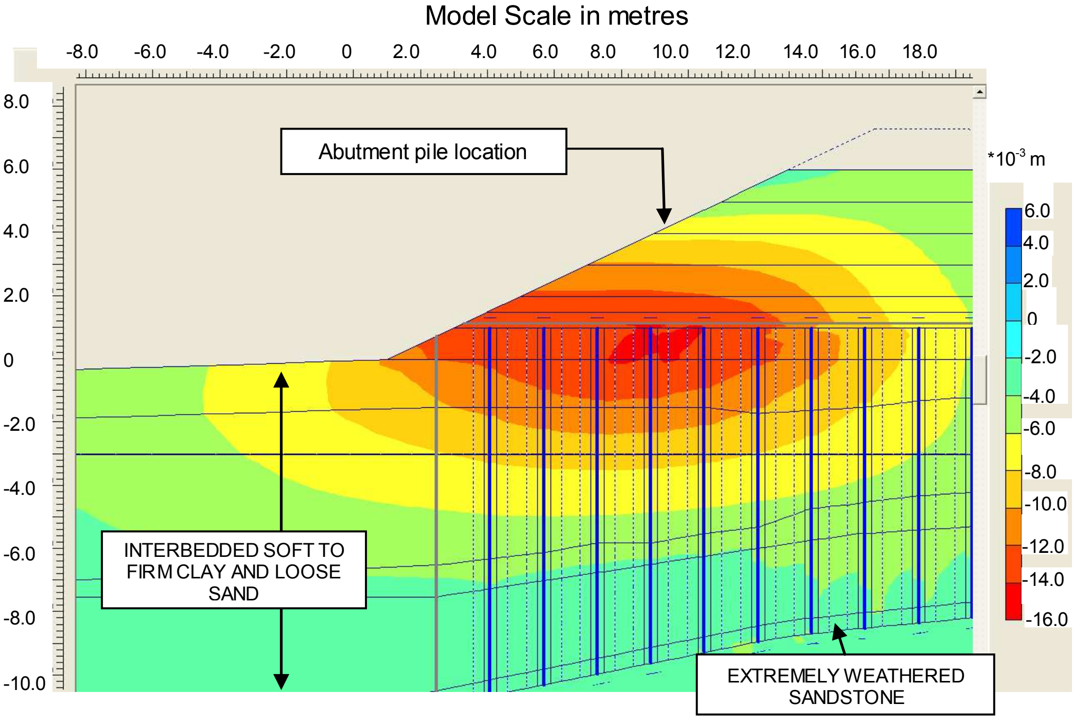


Figure 5. Predicted Lateral Movement Profile for Cracked CMC (Excluding Creep)

5 CONCLUSION

In order for CMC to be designed economically and be a sustainable ground improvement option in a competitive market, they should be designed as geotechnical rather than structural elements. Issues such as the need for load transfer platform, sharing of loads between the CMC and the soft soil, and design of CMC for bending and shear for the purpose of ground improvement, are discussed. Analyses and experience have shown that a load transfer platform is not required if the embankment fill is of sufficient thickness to even out the differential settlement at the finished level. The authors are also of the opinion that yielding of some of the columns in bending is also acceptable provided overall stability of the embankment is maintained and lateral deformation is controlled. An economic CMC design procedure is proposed together with a case study showing its practical application. Further research is required in developing optimum and economical CMC supported embankment solutions.

6 ACKNOWLEDGEMENTS

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