Design Aspects of Control Modulus Columns in Ground Improvement Design

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ABSTRACT: Control modulus columns (CMC) with geosynthetic reinforced load transfer platforms (LTP) are commonly used as integrated foundation systems for construction of embankments on soft soils. The performance of this system primarily relies on two mechanisms adopted in design. The load transfer mechanism (LTM) between LTP and CMC, and settlement behaviour of the composite ground. Over the past 20 years several design guides have been published on LTM based on soil arching and membrane theories. A number of expressions have also been published for the estimation of equivalent strength and deformation properties of the clay treated with columns to compute settlements. This paper evaluates the LTM and the settlement behaviour of the composite ground using a series of two dimensional finite element analyses with a soft soil constitutive model. The outcomes of these assessments are presented and the drawbacks of the current design philosophes are discussed.

1 INTRODUCTION

For soft soil ground improvement design, rigid inclusions such as dynamic replacement, vibro concrete columns and continuous flight auger columns are used as settlement reducers as well as to improve stability. Such rigid inclusions are commonly known as control modulus columns (CMC) and are generally incorporated for stability reasons or in scenarios where the construction time is limited to undertake surcharging and in designs where post construction settlements are to be limited to a very small value.

CMCs provide reinforcement to soft soils and lead to increased bearing capacity and reduced compressibility. Research studies indicate that a major portion of the embankment load is transferred to the column by soil arching and the remaining load is supported by the soft ground. This brings about a sequence of interactions between the elements of this integrated foundation system, as the embankment load being shared between the upper weak soils and the deeper stratum through the load transfer platform (LTP) and columns respectively. These mechanisms can be complex and may require numerical techniques for assessment.

A common design practice is to treat the column reinforced soil as an improved soil block and to assess its deformation and shear behaviour with equivalent strength and deformation properties. In such an approach, when columns are closely spaced and are installed in a regular pattern over a relatively large area,it is assumed that they behave like a block within the surrounding soils, instead of acting as individual rigid elements. Further, this approach also helps simplify finite element models, as the composite foundation is treated as a block with equivalent material properties.

1.1 *Equivalent Parameter Method*

Over the past 20 years, numerous theories have been developed, and a number of expressions have been published in the literature to estimate the equivalent strength and deformation properties for ground improved with CMC. The equivalent stiffness is expressed in the form:

$$E_{eq} = E_1 \left[A_r + \frac{E_2}{E_1}(1 - A_r)\right] \qquad (1)$$

where, E_1 and E_2 are respectively the Young's modulus of CMC and soil, and A_r is the area replacement ratio. The primary settlement of the CMC improved ground is estimated using Eq. (2) or using standard consolidation equation but with a settlement reduction factor E_2/E_{eq}.as expressed in Eq. (3).

$$\rho_{prim} = \sum \frac{\Delta h \ \Delta\sigma}{E_{eq}} (2)$$

$$\rho_{prim} = \frac{H \ E_2}{E_{eq}} \left[CR \ log\left(\frac{p_c'}{\sigma_{v0}'}\right) + RR \ log\left(\frac{\sigma_f'}{p_c'}\right)\right] \qquad (3)$$

where CR and RR are compression and recompression ratios, respectively.

One of the key parameters for this approach is the Young's modulus. Undrained modulus (E_u) of soil is generally estimated using empirical correlations based on undrained shear strength, and the drained modulus (E') is then computed through theories of elasticity as per Eq. (4). For typical values of drained and undrained Poisson's ratio, i.e., ν_u and ν', are 0.5 and 0.3 respectively),E_u is around 1.15 times E' and $E'$is 2.6 times the shear modulus (G).

$$E' = \frac{(1+\nu')E_u}{(1+\nu_u)} \quad (4)$$

Published studies (Poulos et. al 2001) suggest that the above relationship generally applies quite well to stiff soils as they behave more like elastic soils, but not for soft soils which exhibit largely plastic behaviour. For soft soils, E' can be 3 to 10 times smaller than would be suggested by elasticity expression from values of E_u as shown in Fig. 1. Hence the equivalent soil stiffness approach has the potential to underestimate settlement for soft soils improved with CMC.

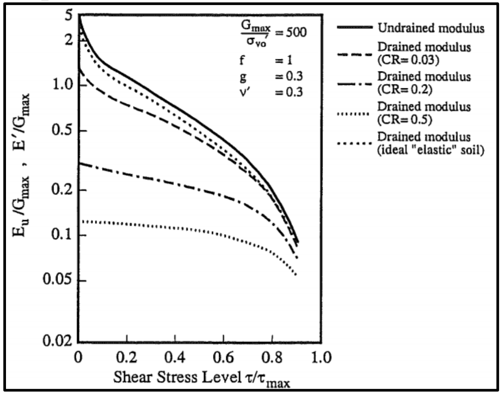

Fig. 1 Computed relationship between normalised drained and undrained Young's modulus (after Poulos 2001)

To overcome the above, constrained modulus (E_{oed}) relevant for the stress range is adopted in designin place of E'. E_{oed} can be estimated by equating primary settlements as expressed below.

$$E_{oed} = \frac{\Delta\sigma}{CR\,\log\left(\frac{p'_c}{\sigma'_{v0}}\right) + RR\,\log\left(\frac{\sigma'_f}{p'_c}\right)} \quad (5)$$

2 EVALUATION OF SETTLEMENT OF CMC TREATED SOFT SOILS

A series of analyses were undertaken by modelling CMCs as follows:

- rigid individual elements (Column Model); and
- a block with the surrounding soil having equivalent properties (Block Model).

The analyses were carried out using the software 2D PLAXIS with a ground model as described in Fig 2.

Analyses were undertaken to assess the total primary settlement at the end of 25 years considering the following:

- 5m thick compressible soft clay overlying a stiff soil layer.
- For the soft clay,E_{oed} value was varied from 0.5MPa to 6MPa.
- 0.35m diameter CMCs with 11GPa stiffness, installed at 1.05m centres in a square pattern, and resting on the stiff soil.
- LTP, 0.5m thick, reinforced with 3 layers of geosynthetics of capacity 60x60 kN/m.
- For the column model, CMCs were modelled as rows of embedded piles.
- Mohr coulomb material model for LTP and the stiff soil layer.
- Soft Soil constitutive model for the compressible clay.
- Embankment load was captured as surcharge over the LTP and the load was varied between 20kPa and 100kPa.

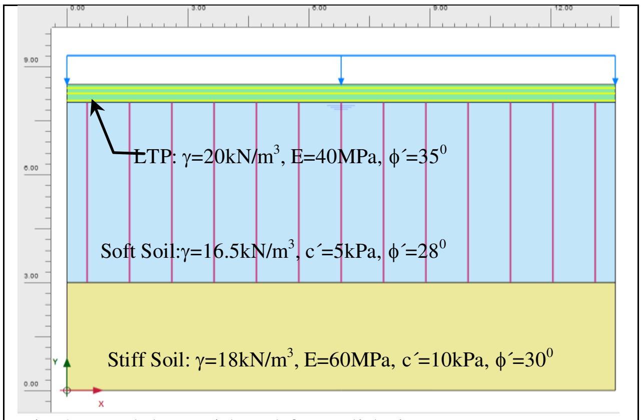

Fig 2. Model considered for validation

The computed settlement ratios defined as Settlement in the Column Model (S_{column})/settlement in Block Model (S_{block}) are presented in Fig 3.

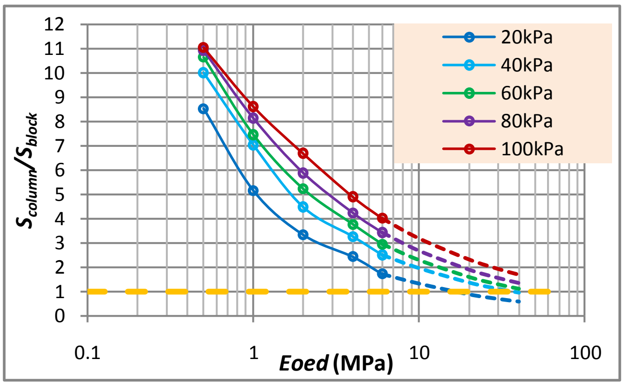

Fig 3. Settlement ratio and constrained modulus

Based on the observed trend the settlement ratio was extrapolated up to E_{oed} of 40MPa. It is evident from the analyses; settlement predicted by block model is many fold smaller compared to the column model.As soil stiffness increase the gap between the predicted settlements by the two models reduce and for soil stiffness greater than 20MPa there is reasonable agreement between the models.

3 EVALUATION OF LOAD TRANSFER MECHANISM

To design CMC reinforced soft soil ground effectively, interaction between the elements involved in the system is essential. The interactions in play include:

- Interaction between the embankment and LTP based on LTP thickness and stiffness;
- Interaction between LTP and reinforced soil block;
- Interaction between soft soil and CMC due to successive negative and positive skin friction;
- Interaction between CMC tip and the bearing layer.

In this section of the paper, only the interaction between the LTP and the reinforced soil block is discussed. One of the key parameters that evaluate some aspects of this interaction is the load efficiency of the system (η). Load efficiency is defined as the ratio between the load acting on the CMC head (Q_p) to the total vertical load ($Q+W$) within that grid, where W is the dead load of the LTP and Q is the force due to surcharge.

$$\eta = \frac{Q_p}{W+Q} \qquad (6)$$

In routine designs, the loads Q and W are well defined. For a ground reinforced with CMC in a square pattern at a spacing of S, the Q and W are estimated by Eqs. 7 and 8 respectively.

$$Q = qS^2 \qquad (7)$$

$$W = S^2 H \gamma \qquad (8)$$

Where;q is the surcharge, H is the thickness and γ is the unit weight of the LTP.

The portion of the total vertical load shared by the CMC head immediately beneath the LTP is not well defined, although a number of theories have been proposed in the literature. This paper investigates the shear cone approach, one of the common methods adopted in designing CMCs.

3.1 *Load Carried by CMC*

As described in Fig 4, assuming that the vertical load under the cone is transferred to the CMC, the load carried by the CMC head is computed using the Eqs. 9 and 10 for overlapping and non-overlapping shear cones, respectively.

Further, the load between wedges of the cones is transferred directly to the ground beneath the LTP. It is also popularly believed that by reinforcing the LTP with geofabrics, the load on the soft soil can be decreased significantly.

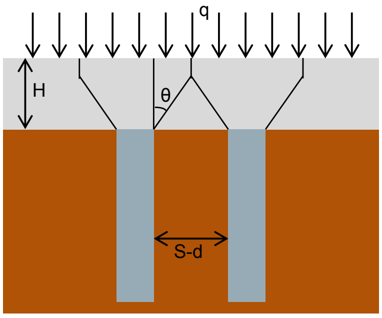

Fig 4 Load transfer model by shearcone

For overlapping cones,$H \tan\theta > \frac{S-d}{2}$

$$Q_p = q\pi\left(\frac{S}{2}\right)^2 + \frac{\gamma\pi}{24\tan\theta}\left[S^3 - d^3\right] + \gamma\pi\left[\left(H - \frac{S-d}{2\tan\theta}\right)\left(\frac{S-d}{2}\right)^2\right] \qquad (9)$$

For non-overlapping cones, $H \tan\theta < \frac{S-d}{2}$

$$Q_p = q\pi\left(\frac{d}{2} + H\tan\theta\right)^2 + \frac{\gamma\pi}{3}\left[\left(H + \frac{d}{2\tan\theta}\right)\left(\frac{d}{2} + H\tan\theta\right)^2 - \left(\frac{d^3}{8\tan\theta}\right)\right] \qquad (10)$$

3.2 *Estimation of Shear Cone Angle*

A series of finite element analyses were undertaken to assess the shear cone angle (θ).The system described in Fig 2 was modelled using PLAXIS2D, for the case of CR=0.27, RR=0.027 and OCR=1.0. Only the friction angle of the LTP(ϕ')was changed during the trial while rest of the parameters were kept unchanged (Section 2). The changes are summarised below.

- Friction angle of the LTP material was varied from 25 to 45 degrees in 5 degree increments.
- Analyses were then repeated to assess the influence of the geofabric reinforcement.

To obtain a better fit between the load on CMC head computed by PLAXIS modelling and load Eqs. (9) and (10), the angle of shear cone was revised. The results for different shear cone values are presented in Fig 5 for LTP with reinforcement. The back calculated shear cone angles and the variation of load efficiency for the system with LTP friction angle are summarised in Fig 6.

3.3 *Vertical Stress beneath LTP*

In such an integrated foundation system, differential settlement may arise between rigid inclusions and its immediate surroundings. It is generally believed that arching of soil within the LTP and embankment above prevents these differential settlements reaching the surface.

The above analyses were also reviewed to understand the order of the applied vertical stress that is transferred to the soft soil beneath the LTP. Owing to the development of negative skin friction on the upper sections of the CMC, portion of the vertical load on the soft soil close to the surface is unloaded to the CMCs. This load transfer mechanism (LTM) diminishes with increasing depth as approaching the neutral plane and away from the CMC. Hence maximum vertical stress is generally observedmidway between the CMCs, beneath LTP.

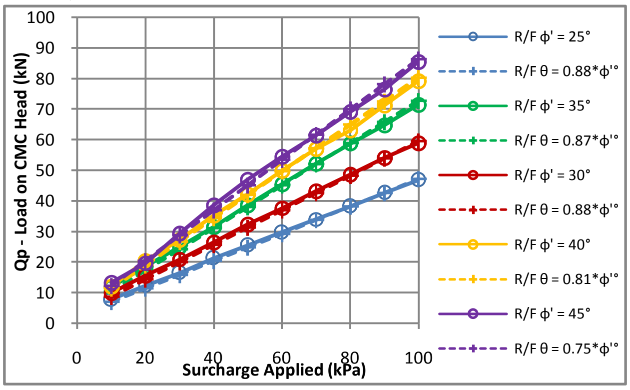

Fig 5. Load on CMC head – reinforced LTP

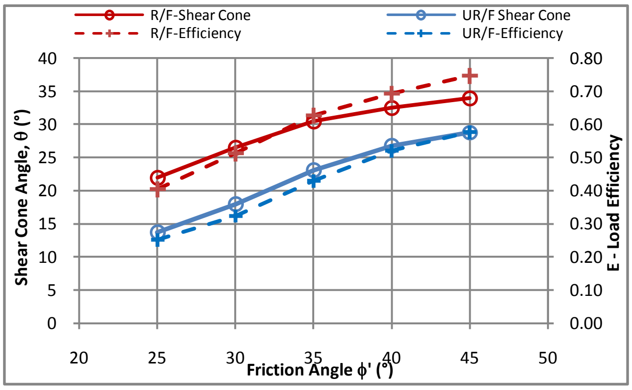

Fig 6. Variation of shear cone angle with ϕ

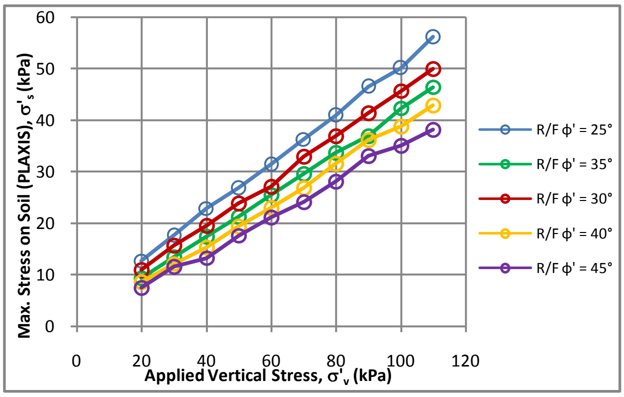

Fig 7. Applied vs Measured stress - R/F LTP

Maximum vertical stress (σ'_s) between the columns assessed from PLAXIS modelling is shown in Fig 7, against the applied total vertical stress (σ'_v) for LTP with reinforcement. The variation of stress ratio (σ'_s/σ'_v) with friction angle (ϕ') is summarised in Fig 8.

As per the adopted shear cone LTM, and by computing the load between the cone wedges, the average stress (σ'_c) on soft soil beneath the LTP was estimated using Eq. (11), for each trial analysed.

$$\sigma'_c = \{(q + \gamma H)S^2 - Q_p\}/\{S^2 - \pi d^2/4\} \qquad (11)$$

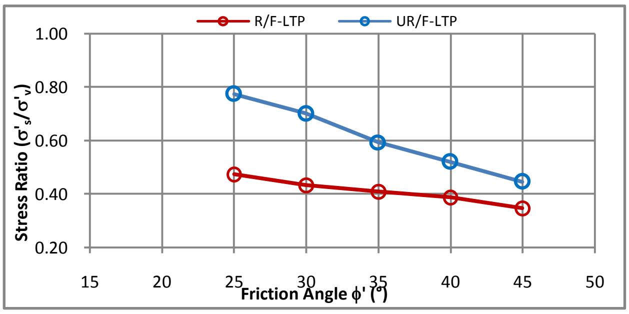

Fig 8. Stress ratio vs Friction angle

The relationship between $\sigma'_c$and σ'_s for reinforced and unreinforced LTP can be approximated by the expressions (12) and (13).

$$\sigma'_s = 0.94\,\sigma'_c - 10.63 \qquad (12)$$

$$\sigma'_s = 0.97\,\sigma'_c - 13.26 \qquad (13)$$

4 CONCLUSIONS

The equivalent soil block model underpredicts consolidation settlement for normally and lightly over-consolidated clays and low modulus values. Hence, this approach is more applicable for over-consolidated soils, where soils exhibit more elastic type behaviour.

Investigation of LTM using shear cone approach indicates that the derived shear cone angles are generally smaller compared to the friction angle of the LTP. The analyses also reveal that load transfer efficiency improves with increasing friction angle of the LTP material.

The low shear cone angle tends to transfer some portion of the design and dead load to the compressible soils beneath the LTP. When the LTP is not adequately thick the compressible clays midway between the CMCs are liable to undergo long term settlement leading to differential settlement in the system.

Presence of geofabric reinforcement does seem to assist in transferring more loads to the CMC and reduce the proportion of the load carried by the compressible soils.

Further investigation of this integrated foundation system, considering varying LTP stiffness, material models and floating CMCs, may provide valuable information to arrive at more conclusive findings.

REFERENCES

Poulos,HG, Carter,JPandSmall,JC (2001).Foundation and Retaining Structures – Research and Practice,Proc.15th ICSMGE, Istanbul, 2001, pp. 2527 – 2606.