Effect of vibro stone column installation on the performance of reinforced soil

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Abstract—Empirical design methods for stone column foundations are often on single stone columns or as a homogeneous medium of soil/column. These methods underestimate the capacity of the composite system because they do not take into account the increased confining stress acting on the stone column or the increased stiffness of the soil. This study used Plaxis 2D to study the effect of the installation method on the confining pressure and soil stiffness around a single column by assuming the installation of the column could be modelled as an expanding cavity followed by consolidation of the surrounding soil. The mean stress and stiffness generated during installation between two, adjacent columns was used in Plaxis 3D to compare the settlement of circular foundations on estuarine deposits reinforced by stone columns at a site in Santa Barbara, California. Good agreement was found between the predicted and actual settlement of the trial foundations on three column arrangements. The predictions gave a better estimate of the settlement compared to those using a unit cell or homogeneous medium showing that improvements to the soil should be taken into account when assessing stone column performance.

Keywords— Bearing capacity, Design, Installation, Numerical analysis, Settlement, Stone Column**.**

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1. Introduction

The majority of methods to design stone columns, according to Sexton and McCabe (2012), are based on a unit cell (e.g. Aboshi et al., 1979; Balaam and Booker, 1985; Hu, 1995; Priebe, 1995; McKelvey et al., 2004) in which a settlement improvement factor is related to the area replacement ratio of the cell. This was shown by McCabe at al (2009), using case studies, to be an acceptable method. However, a method to install a stone column, the bottom feed method, expands the stone column increasing the confining stress on the stone column and, because of the increase in stress in the surrounding soil, increases the stiffness of the soil. Kirsch (2006) showed that, in sandy soils, the increase in stiffness was permanent to a distance of four to eight times the column diameter, which exceeds typical column arrangements; that is the stiffness of the composite system of soil and stone columns exceeds that of the unit cell. Al Ammari and Clarke (2012) showed that the settlement of a rigid foundation on a unit cell (single column) was reduced by 55% if the increases in soil stiffness and confining stress due to the expanding stone column (Hughes and Withers, 1974) were taken into account. The increase in stiffness is due to the dissipation of excess pore pressures generated during installation (e.g. Castro and Sagasta, 2009; Debats et al, 2003; Gab et al, 2007, Guetif et al, 2007 and Kirsch, 2006). Killeen and McCabe (2014) suggested that the increase in stiffness is offset by the remoulding of the soil around the column though Kirsch (2006) suggested that the increase in stiffness would be permanent.

Therefore, rather than model a stone column as an independent unit, it would be better to model the stone columns and surrounding soil as a system to take into account the increase in confining stress on the columns and the increase in stiffness of the soil. Sexton and McCabe ((2015) suggested that most numerical studies of stone column capacity were based on full replacement columns with an arbitrarily assigned value of confining stress. Kirsch (2006) and Sexton and McCabe (2015) modelled displacement columns by starting with a full replacement column to represent the probe to determine the increase in confining stress in a unit cell analysis using cavity expansion.

In this study, the installation of the stone columns started with a full replacement column to model the probe. This was converted to a displacement column to model the installation of the stone column using cavity expansion to estimate the improvement in the stiffness of the soil, which, together with the stone column, created a composite system. The increase in stiffness of the surrounding soil due to the installation of a stone column was modelled using PLAXIS 2D and the stiffness of the composite system was modelled using PLAXIS 3D.

2. The Field Case – the Santa Barbara waste treatment plant

The field case selected to validate the results of the numerical model was a waste water treatment plant in Santa Barbara, California, US (Figure 1), which had been studied by Mitchell and Huber (1985), Elshazly et al. (2006), Elshazly et al. (2007), Elshazly et al. (2008) and Killeen (2012). The Santa Barbara Wastewater Treatment site is about 2.5m above the sea level. The site stratigraphy (Figure 2) is formed of:-

- 1- 3m of recent fill formed of clayey sand containing a mixture of anthropogenic wastes including asphalt, masonry, wood, glass, and metals;
- 5-16m of estuarine deposits that increase in thickness from northeast to southwest across the site. They consist of layers of silty and sandy to clayey and silty sand, with some local lenses of sand or gravel;
- Older marine deposits that extended up to 19.4m beneath the ground surface comprising cohesive and cohesionless layers of clayey sand, silty sand and lesser amount of sandy clay and sandy silt;
- Ground water level was at 1.5 m below the ground surface.

Stone columns were chosen by the design engineers because the site preparation time was limited to 6 months; to avoid any damages that might occur to the adjacent light industrial structures if the ground water table was lowered to form conventional foundations; and to prevent liquefaction in this seismically active area (Mitchell and Huber, 1985). Over 6500 stone columns were constructed using the top feed installation method in which a current of water is jetted from the nose of the vibrator to aid the penetration in to the soft soil creating 0.50m to 0.75m diameter boreholes. When the vibrator reached the desired depth, well graded gravel (12-100mm) was introduced into the annular space between the probe and the borehole wall and was pushed down the borehole by the action of the probe. The probe was moved up and down in the borehole to compact the gravel thus expanding the walls of the borehole. The final diameter of the stone columns varied between 0.81m and 1.22m (Mitchell and Huber, 1985). Three different stone column arrangements were used: (1.2m x 1.5m) for a bearing pressure of 145kPa limiting the settlement to 6mm; (1.75m x 1.75m) for medium loads; and (2.10m x 2.10m) for a bearing pressure of 60kPa. The stone columns were founded in the older marine deposits resulting in 9-15m long stone columns in the overlying estuarine deposits (Mitchell and Huber, 1985).

Twenty eight field loading tests were performed with 1m, 2m and 2.2m diameter, 1.2m deep concrete footings centred on the columns that corresponded to the three cases of stone column arrangements. Load increments of 45kN were applied up to a maximum load of 350-400kN, maintaining each increment for 6hr until the settlement was less than 0.25mm/hr to produce the settlement curves shown in Figure 3. The average time between the installation of the stone columns and the load tests was 18 days.

3. The modelling framework

Stone columns have been analysed as either:-

- A uniform layer of a soil with a stiffness equivalent to the volumetric stiffness of the composite system (homogenised model)
- Or as axisymmetric studies of a single column surrounded by soil with adjacent columns modelled as a thin cylinder of stone (unit cell model).

Neither of these methods take in to account the increase in stiffness of the surrounding soil nor do they model the arrangement of the columns. A three dimensional analysis, in this case, Plaxis 3D, can model the stone columns but is unable to model the undrained cavity expansion and large strains associated with that expansion (McCabe et al., 2009). Therefore, Plaxis 2D was used as a first step to estimate the improvement in both the coefficient of lateral earth pressure and stiffness of the different estuarine soil layers using an axisymmetric model of a single column. The process was as follows:

1. The installation of a single stone column was asymmetrically modelled in Plaxis 2D as a displacement column using the principle of cavity expansion (Clarke, 1994) similar to Stage 1 of the numerical modelling used by Sexton and McCabe (2015). This produces a variation in stress and stiffness in the surrounding soil for a single column.
2. The installation of the adjacent columns also increases the stress and stiffness of the surrounding soil. This was modelled in Plaxis 2D by installing a second column in a soil with the mean stress and stiffness produced from the first stage.
3. The mean stress and stiffness from the second stage was used in Plaxis 3D to model the stone column arrangements at Santa Barbara, comparing the predicted settlements with those observed in the field tests.

The hardening soil model was considered the most appropriate model for simulating the relevant features of the fine and coarse grained soils because it takes into account the stress dependency of stiffness moduli and accounts for shear and volumetric hardening. The properties of the four main groups of soils and stone column materials are given in Table 1.

3.1 Stage 1- axisymmetric analysis of a single column

A dummy elastic, low stiffness material was used to form a replacement column (Figure 4a); that is the creation of the borehole using a vibroflot. This column was then expanded to model a displacement stone column (Figure 4b); that is the compaction of the stone to create the stone column. The axisymmetric model used for the first stage had a 30m diameter boundary which proved sufficient to reduce boundary effects to a minimum. 6 node and 15 node triangular elements were used with a local fineness factor of 0.5. The final diameter of the stone column was assumed to be 1.06m based on field observations of Mitchell and Huber (1985). Strictly speaking creating the stone column is an infinite expansion. This implies the soil around the probe is at the limit state. Observations (e.g. Kirsch, 2006) show that this is not the case since the increase in stress and stiffness reduce with distance from the stone column. Therefore, it was assumed that a stone column could be modelled as the expansion of a cylindrical cavity though the initial diameter is unknown. Kirsch (2006) used a 0.6m diameter dummy material to model the probe; Sexton and McCabe (2012) a 0.5m diameter dummy material. Cavity diameters from 0.56m to 0.96m were considered in this analysis by applying five prescribed displacements (Δr = 0.05, 0.10, 0.15, 0.20 and 0.25m) to study the effects of cavity expansion on the settlement of the composite system. The mesh was updated to account for the change in soil stiffness matrix.

The dummy material was then replaced with stone (Figure 4c) to allow the soil to consolidate for 18 days, the average time between installation and load tests on site. The increase in stress, expressed as the coefficient of lateral pressure, K, for the five prescribed displacements for the top coarse grained and bottom fine grained layers are shown in Figure 5 with respect to the distance from the column axis expressed as a ratio of the final diameter (D_c = 1.06m). They show an increase in displacement increases the confining stress acting on the stone column and the increase extends to at least six times the column diameter, which exceeds the distance between adjacent columns. Thus, the stresses within the soil between two columns will be affected by both columns.

Figure 6 shows the increase in stress at 1m from the axis of the column for all eight soil layers for a column spacing of 2.1m. Figure 6 shows that the confining pressure acting on the column increases as the expansion increases though there is a limit (c.f. theory of expanding cavities) and, in general, the increase in confining pressure is greater for the coarse grained soils than the fine grained soils. The initial, in situ coefficient of lateral earth pressure was assumed to be 0.5, representing the lightly overconsolidated estuarine deposits.

An increase in lateral stress, after consolidation, leads to an increase in stiffness because stiffness is a function of the effective stress. Janbu (1963) and others suggest that the soil stiffness, E, is related to the mean effective stress, *p'*, by:

$$\frac{E_1}{E_0} = \left(\frac{P'}{P'_0}\right)^m \qquad (1)$$

$$p' = (\sigma'_r + \sigma'_\theta + \sigma'_z)/3 \qquad (2)$$

Where the subscript “0” indicates the initial state and “1” the current state. Brinkgreve and Broere (2006) suggested a value of m of one for soft soils and Brinkgreve and Vermeer (1998) recommended that E_{50} should be used as a reference value for the modulus of elasticity. Figure 7 shows that the increase in stiffness due to installation of a stone column extends to five to six diameters which is consistent with the observations of Kirsch (2006). Thus, a column expansion impacts on the soil surrounding adjacent columns. Figure 8 shows that the stiffnesses of the coarse and fine grained layers increase with degree of expansion with the increase being greatest towards the top of the column.

3.2 The effect of two columns

Figures 5 and 7 show that the stress and stiffness reduce with distance from the axis of the stone column and the value at any radius depends on the level of expansion. The ratio of column spacing to column diameter varied between 1.1 and 2. Therefore, depending on the soil type and degree of expansion according to Figure 5, the increase in stress varied between 1.5 and 3.5; and the increase in stiffness according to Figure 7 between 1.5 and 2. Given the distance between the columns, it was assumed that the mean stress and stiffness were a reasonably accurate assessment of the mobilised stress and stiffness. Figure 9 shows the method used to determine the mean stress and stiffness for the 3D analysis.

- The variation in lateral stress and stiffness were calculated for a single column using a 2D axisymmetric model (Figure 9a).
- The mean stress and stiffness between the existing column and the proposed second column were found from the area under the graph.
- A second stone column, modelling an adjacent column, was inserted into a soil with the mean stress and stiffness derived from the expansion of the first column. The second column is expanded to give the variation in stress and stiffness from the axis of the second column (Figure 9b).
- The mean stress and stiffness between the two columns were derived (Figure 9c) and used in the 3D analysis.

This was undertaken for all layers for the three column configurations. Figure 10 shows the effect of installing one and then two columns in the top coarse grained layer and the bottom fine grained layer for a column spacing of 1.5m. It shows that the mean stress (expressed as the coefficient of lateral pressure) increases after the first column is installed. The installation of the second column reduces the mean stress within the top layer and increases the stress in the bottom layer.

Figure 11 shows the effect of the installation of one and two columns on the stiffness of those two layers. The reduction in stress and stiffness in the top layer when the second column was installed is attributed to heave in the upper layers. The increase in stress and stiffness was noted in all the other layers for the three column arrangements with the maximum increase associated with the smallest column spacing as shown in Figure 12 and 13 which show the effects of column spacing on the lateral pressure coefficient and stiffness for the top, coarse grained and bottom, fine grained layers. They show that increasing the spacing, as expected, generally reduces the effect, though, given the assumptions made only general observations can be made. The coefficient of lateral earth pressure increased in depth from between 1.3 and 2.6 in the upper coarse grained layer to between 2.5 and 3.3 in the lowest fine grained layer; and the stiffness between 1.5 and 2.2 in the upper fine grained layer to between 1.5 and 3 in the lowest fine grained layer. The increases in the top layers were less sensitive to the degree of expansion, possibly due to heave occurring in those layers. As the overburden pressure increased, the increase in lateral pressure coefficient increased with degree of expansion.

4. Numerical analysis of the Santa Barbara site

Plaxis 3D AE Version 01 was used to simulate the stone columns at the Santa Barbara site using the stress and stiffness derived from the axisymmetric model. The parameters given in Table 1, modified to take into account the effect of installation on the column confining stress and soil stiffness were used in the 3D analysis; the other parameters, including the hydraulic conductivity, were kept constant. The 3D composite model for the 2.1m by 2.1m column spacing is shown in Figure 14 with the test footing at the centre of the cross section. A sensitivity analysis showed that the vertical boundaries had to be at least 11m from the footing axis; 13m was chosen. The base of the model was taken as the base of the marine soils. The global coarseness of the finite element mesh was taken to be fine and the local fineness factor was 0.5 to have sufficient accuracy.

Figure 15 shows a comparison between the settlement of the footing for the three arrangements of stone columns and different degrees of compaction, expressed as an increase in radius, Δr. It shows the dramatic effect of stone columns on the settlement of the footings by comparing the settlement for no ground improvement, for replacement stone columns and for displacement stone columns with different degrees of expansion. The settlement improvement factor for a contact pressure of 40kPa varied from about 5 to 12. The ranges of observed settlements from the field trials are also shown in Figure 15. They indicate that the radial expansion has to be at least 0.15m for the 1.5m by 1.2m spacing to 0.1m for the 1.75m and 2.1m spacing if the settlement is to be modelled suggesting that the smaller the spacing the greater the expansion.

The final diameter of the actual stone columns varied between 0.81m and 1.22m; the average of 1.06 was chosen to model the installation. The borehole created by the probe varied between 0.5m and 0.75m. Thus, the increase in radius due to the installation compaction could be between 0.03m and 0.36m with an average of 0.2m. The predicted settlement of the trial foundations taking into account the increase in stiffness and confining stress for appropriate expansions based on the field observations are compared with the results of Mitchell and Huber (1985), Elshazly et al (2008) and Killeen (2012). Mitchell and Huber (1985) used a homogenisation method with a K value of 1 and no increase in soil stiffness. Elshazly et al (2008) used the same homogenisation method but increased the K value to 1.7, 1.2 and 0.85 for the fine grained soils and used the hardening soil model. Killeen (2012) undertook a 3D analysis using the hardening soil model with a K value of 1 but did not take into account the increase in soil stiffness. Figure 16 shows that taking into account the characteristics of the composite foundation produces a better prediction of the performance of the stone columns when compared to those models which only take into account the characteristics of the stone columns and increase in confining stress.

5. Conclusions

Empirical design of stone column installations is based on the concept of compacted columns restrained by the lateral pressure in the surrounding soil. Stone columns also improve the stiffness of the soil creating a composite foundation which is stiffer than the stone columns on their own. It is possible to model this composite foundation by producing a homogeneous system with a stiffness equal to the combined stiffness of the soil and columns based on their volumes. This paper developed that concept by analysing the composite system in which the installation of the stone columns increases the lateral stress and stiffness of the surrounding soil and the increased stiffness of the surrounding soil was used in the numerical analysis. This approach was compared to those based on the single column and homogenized methods and validated against a case study by comparing the predicted settlement with that observed in field tests using a circular foundation. It is concluded that:

- This approach to a composite foundation predicted less settlement than those based on the single column and homogenized methods
- This approach predicted similar settlements to those of the trial foundations on stone columns installed at different centres in estuarine deposits
- The design of a vibro stone column foundations should take into account the increase in lateral stress within the surrounding soil and the increased stiffness of those soils.

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