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

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3

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

16

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

18 1. Introduction

19 The majority of methods to design stone columns, according to Sexton and McCabe (2012), are based on a
20 unit cell (e.g. Aboshi et al., 1979; Balaam and Booker, 1985; Hu, 1995; Priebe, 1995; McKelvey et al., 2004)
21 in which a settlement improvement factor is related to the area replacement ratio of the cell. This was shown
22 by McCabe et al (2009), using case studies, to be an acceptable method. However, a method to install a stone
23 column, the bottom feed method, expands the stone column increasing the confining stress on the stone
24 column and, because of the increase in stress in the surrounding soil, increases the stiffness of the soil. Kirsch
25 (2006) showed that, in sandy soils, the increase in stiffness was permanent to a distance of four to eight times
26 the column diameter, which exceeds typical column arrangements; that is the stiffness of the composite
27 system of soil and stone columns exceeds that of the unit cell. Al Ammari and Clarke (2012) showed that
28 the settlement of a rigid foundation on a unit cell (single column) was reduced by 55% if the increases in soil
29 stiffness and confining stress due to the expanding stone column (Hughes and Withers, 1974) were taken into
30 account. The increase in stiffness is due to the dissipation of excess pore pressures generated during
31 installation (e.g. Castro and Sagasta, 2009; Debats et al, 2003; Gab et al, 2007, Guetif et al, 2007 and Kirsch,
32 2006). Killeen and McCabe (2014) suggested that the increase in stiffness is offset by the remoulding of the
33 soil around the column though Kirsch (2006) suggested that the increase in stiffness would be permanent.

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

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

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

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

- 53 • 1- 3m of recent fill formed of clayey sand containing a mixture of anthropogenic wastes including
54 asphalt, masonry, wood, glass, and metals;
- 55 • 5-16m of estuarine deposits that increase in thickness from northeast to southwest across the site.
56 They consist of layers of silty and sandy to clayey and silty sand, with some local lenses of sand or
57 gravel;
- 58 • Older marine deposits that extended up to 19.4m beneath the ground surface comprising cohesive and
59 cohesionless layers of clayey sand, silty sand and lesser amount of sandy clay and sandy silt;
- 60 • Ground water level was at 1.5 m below the ground surface.

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

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

80 3. The modelling framework

81 Stone columns have been analysed as either:-

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

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

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

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

106 3.1 Stage 1- axisymmetric analysis of a single column

~~107~~
109 A dummy elastic, low stiffness material was used to form a replacement column (Figure 4a); that is the
110 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

111 used for the first stage had a 30m diameter boundary which proved sufficient to reduce boundary effects to
 112 a minimum. 6 node and 15 node triangular elements were used with a local fineness factor of 0.5. The final
 113 diameter of the stone column was assumed to be 1.06m based on field observations of Mitchell and Huber
 114 (1985). Strictly speaking creating the stone column is an infinite expansion. This implies the soil around
 115 the probe is at the limit state. Observations (e.g. Kirsch, 2006) show that this is not the case since the increase
 116 in stress and stiffness reduce with distance from the stone column. Therefore, it was assumed that a stone
 117 column could be modelled as the expansion of a cylindrical cavity though the initial diameter is unknown.
 118 Kirsch (2006) used a 0.6m diameter dummy material to model the probe; Sexton and McCabe (2012) a 0.5m
 119 diameter dummy material. Cavity diameters from 0.56m to 0.96m were considered in this analysis by
 120 applying five prescribed displacements ($\Delta r = 0.05, 0.10, 0.15, 0.20$ and 0.25 m) to study the effects of cavity
 121 expansion on the settlement of the composite system. The mesh was updated to account for the change in
 122 soil stiffness matrix.

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

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

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

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

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

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

148

149 3.2 The effect of two columns

150 Figures 5 and 7 show that the stress and stiffness reduce with distance from the axis of the stone column and
151 the value at any radius depends on the level of expansion. The ratio of column spacing to column diameter
152 varied between 1.1 and 2. Therefore, depending on the soil type and degree of expansion according to Figure
153 5, the increase in stress varied between 1.5 and 3.5; and the increase in stiffness according to Figure 7 between
154 1.5 and 2. Given the distance between the columns, it was assumed that the mean stress and stiffness were a
155 reasonably accurate assessment of the mobilised stress and stiffness. Figure 9 shows the method used to
156 determine the mean stress and stiffness for the 3D analysis.

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

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

171 Figure 11 shows the effect of the installation of one and two columns on the stiffness of those two layers.
172 The reduction in stress and stiffness in the top layer when the second column was installed is attributed to

173 heave in the upper layers. The increase in stress and stiffness was noted in all the other layers for the three
174 column arrangements with the maximum increase associated with the smallest column spacing as shown in
175 Figure 12 and 13 which show the effects of column spacing on the lateral pressure coefficient and stiffness
176 for the top, coarse grained and bottom, fine grained layers. They show that increasing the spacing, as
177 expected, generally reduces the effect, though, given the assumptions made only general observations can be
178 made. The coefficient of lateral earth pressure increased in depth from between 1.3 and 2.6 in the upper
179 coarse grained layer to between 2.5 and 3.3 in the lowest fine grained layer; and the stiffness between 1.5
180 and 2.2 in the upper fine grained layer to between 1.5 and 3 in the lowest fine grained layer. The increases in
181 the top layers were less sensitive to the degree of expansion, possibly due to heave occurring in those layers.
182 As the overburden pressure increased, the increase in lateral pressure coefficient increased with degree of
183 expansion.

184 4. Numerical analysis of the Santa Barbara site

185
186 Plaxis 3D AE Version 01 was used to simulate the stone columns at the Santa Barbara site using the stress
187 and stiffness derived from the axisymmetric model. The parameters given in Table 1, modified to take into
188 account the effect of installation on the column confining stress and soil stiffness were used in the 3D
189 analysis; the other parameters, including the hydraulic conductivity, were kept constant. The 3D composite
190 model for the 2.1m by 2.1m column spacing is shown in Figure 14 with the test footing at the centre of the
191 cross section. A sensitivity analysis showed that the vertical boundaries had to be at least 11m from the
192 footing axis; 13m was chosen. The base of the model was taken as the base of the marine soils. The global
193 coarseness of the finite element mesh was taken to be fine and the local fineness factor was 0.5 to have
194 sufficient accuracy.

195 Figure 15 shows a comparison between the settlement of the footing for the three arrangements of stone
196 columns and different degrees of compaction, expressed as an increase in radius, Δr . It shows the dramatic
197 effect of stone columns on the settlement of the footings by comparing the settlement for no ground
198 improvement, for replacement stone columns and for displacement stone columns with different degrees of
199 expansion. The settlement improvement factor for a contact pressure of 40kPa varied from about 5 to 12. The
200 ranges of observed settlements from the field trials are also shown in Figure 15. They indicate that the radial
201 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
202 the settlement is to be modelled suggesting that the smaller the spacing the greater the expansion.

203 The final diameter of the actual stone columns varied between 0.81m and 1.22m; the average of 1.06 was
204 chosen to model the installation. The borehole created by the probe varied between 0.5m and 0.75m. Thus,
205 the increase in radius due to the installation compaction could be between 0.03m and 0.36m with an average

206 of 0.2m. The predicted settlement of the trial foundations taking into account the increase in stiffness and
207 confining stress for appropriate expansions based on the field observations are compared with the results of
208 Mitchell and Huber (1985), Elshazly et al (2008) and Killeen (2012). Mitchell and Huber (1985) used a
209 homogenisation method with a K value of 1 and no increase in soil stiffness. Elshazly et al (2008) used the
210 same homogenisation method but increased the K value to 1.7, 1.2 and 0.85 for the fine grained soils and
211 used the hardening soil model. Killeen (2012) undertook a 3D analysis using the hardening soil model with
212 a K value of 1 but did not take into account the increase in soil stiffness. Figure 16 shows that taking into
213 account the characteristics of the composite foundation produces a better prediction of the performance of
214 the stone columns when compared to those models which only take into account the characteristics of the
215 stone columns and increase in confining stress.

216 5. Conclusions

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

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

233

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