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Abstract
In the practical design of stone column for soft soil improvement, the stress ratio between stone column and soft clay has been largely calculated based on the surface stresses. The vertical stress and pore pressure changes in the surrounding soft clay have not been adequately measured and compared with column stresses in the past research works. Similarly, the influence of the morphological properties of column particles on these stresses has been largely overlooked in the practice. As part of the laboratory testing programme, onedimensional consolidation tests were carried out on a unit cell which comprised of soft kaolin clay and stone column. A number of tests were carried out by varying the morphological properties of column materials such as the particle size distribution and particle angularity. Miniature pressure and pore-pressure sensors were placed at various locations including in the proximity of anticipated bulging location where the column stress was relatively high. The results showed that stress ratios between column and clay at the same depth within the unit cell were influenced by the morphological properties of column materials. Moreover, it was generally observed that stress ratio of a unit cell under sustained loading did not only vary with time but it also varied with the depth.

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VERTICAL STRESSES IN STONE COLUMN AND SOFT CLAY DURING ONE-DIMENSIONAL CONSOLIDATION TEST

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ABSTRACT: In the practical design of stone column for soft soil improvement, the stress ratio between stone column and soft clay has been largely calculated based on the surface stresses. The vertical stress and pore pressure changes in the surrounding soft clay have not been adequately measured and compared with column stresses in the past research works. Similarly, the influence of the morphological properties of column particles on these stresses has been largely overlooked in the practice. As part of the laboratory testing programme, one-dimensional consolidation tests were carried out on a unit cell which comprised of soft kaolin clay and stone column. A number of tests were carried out by varying the morphological properties of column materials such as the particle size distribution and particle angularity. Miniature pressure and pore-pressure sensors were placed at various locations including in the proximity of anticipated bulging location where the column stress was relatively high. The results showed that stress ratios between column and clay at the same depth within the unit cell were influenced by the morphological properties of column materials. Moreover, it was generally observed that stress ratio of a unit cell under sustained loading did not only vary with time but it also varied with the depth.

Keywords: stone column, soft soil, soft clay, ground improvement, micromechanics.

INTRODUCTION

Reducing long-term settlement of infrastructure and providing cost-effective foundations with sufficient load-bearing capacities are national priorities for infrastructure development in most countries (Indraratna et al 2013). Due to the mounting pressure to develop fast and economically-viable solutions in building the infrastructures, it is becoming necessary to build them over soft soils (McCabe et al 2009). However, the soft soil foundations can cause excessive settlement initiating undrained failure of infrastructure if a proper ground improvement is not carried out (Indraratna et al 2013). Stone columns are a popular technique for improving soft soil over which the infrastructures such as road and rail embankments can be constructed. Stone columns reinforced in soft soil contain non-spherical aggregates which form an inclusion where the stiffness, shear strength, and permeability are significantly higher than that of surrounding soft soil (Castro and Sagaseta, 2009).

A number of analytical methods have been widely-used for the design of stone columns for soft soil improvement (Barksdale and Bachus 1983, Priebe 1975, Balaam and Booker 1985). In those methods, the load transfer between the stone column and the soft clay is crudely represented by a stress concentration ratio (ns) which is a ratio of stress on column to stress on soft soil typically calculated using the stresses occurring on the surface of a unit cell which comprises a single stone column and its surrounding soft soil. Consequently, those methods rely heavily on the assumption of equal strain on the surface of unit cell and ignore the stress distribution within the column and load transfer along the column-clay interface at various depths. Indraratna et al (2012) stated that the nature of embankment loading is neither fully-flexible nor purely-rigid, but

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at an intermediate state between the free strain and equal strain conditions.

In a similar fashion to the piled foundation, a column within its unit cell is significantly stiffer than the surrounding soil. Barksdale and Bachus (1983) proposed empirical correlation between the stiffness ratio of column and soil and the stress concentration ratio. However unlike piles, stone columns consist of coarse aggregates whose morphological properties play a crucial role in redistributing stresses within the column and transferring loads to the surrounding soil. Not only skin-friction can develop along the column-soil interface (Muir Wood et al 2000), but the stresses at various depths within the column also vary (Sivakumar et al 2011). Therefore, the reliance on stress concentration ratio alone without a proper consideration on morphological properties of the particulates tends to generalize and overlook the stresses evolution below the surface of unit cell.

This paper presents the experimental results on a model unit cell loaded during one-dimensional consolidation. These results show conceptually the effects of particle morphology comprising different Particle Size Distributions (PSD) and particle angularities on the stress concentration ratio especially when the clay within the unit cell is loaded below its pre-consolidation pressure.

EXPERIMENTAL PROGRAM

The test setup is shown in Figure 1. Initially, dry kaolin and water were mixed to a moisture content at 1.2 times of its liquid limit. The slurry was then placed into the consolidation cell (see Figure 1).

Miniature soil pressure gauges and pore pressure transducers were installed at various locations. The wet clay was vibrated to ensure that air bubble did not present before it was pre-consolidated under a vertical pressure of 65 kPa. The measured pore pressures and settlement were used to monitor the consolidation. A settlement of 150 mm, which is 20% of the initial sample height, typically occurred once the degree of consolidation of at least 95% was achieved. The kaolin specimen at the end of pre-consolidation was approximately 600-mm high.

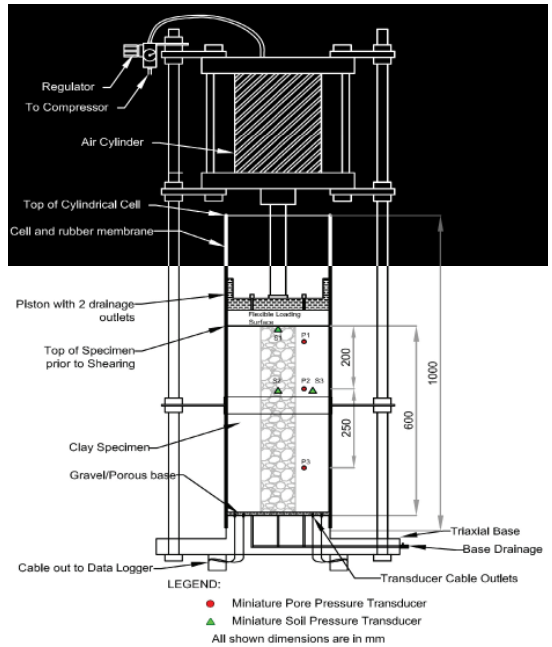

Figure 1. Large-scale (300-mm diameter) Consolidometer

A stone column was then installed by means of replacement method. A thin-walled tube with tapered end was used to extrude a 100-mm diameter hole at the centre of the kaolin specimen. Then the second tube with a smaller diameter was used to carefully remove the clay extruded within the first tube. The column materials were then placed into the hole with gentle compaction on several layers. The materials in each layer were placed in a controlled manner where their weights were continuously measured to ensure that a relative density of 80 – 85% was achieved. A replacement method was adopted to prevent the damage on sensors and remove unwanted installation effect which can influence the properties of column materials. The resulting column diameter was 102-mm which gave an area replacement ratio (A_r) of 11%. Area replacement ratio is the ratio between areas of the stone column and the unit cell. As several tests with similar setups and A_r values ranging from 6% to 20% have been carried out successfully by Ambily and Gandhi (2007), the A_r adopted in the testing program is reasonable.

A flexible rubber membrane with polished internal surface was placed between the cylindrical cell and soil samples to reduce friction between soil and the vertical boundary and prevent slurry from escaping during the initial pre-consolidation stage.

The unit cell was loaded up to pressures which were lower than the pre-consolidation pressure of the kaolin clay. This is to ensure that the soft clay remained lightly-consolidated. Four tests were performed by varying the PSD and angularities of column materials listed in Table 2.

SOIL PARAMETERS

Table 1 shows the compressibility properties of kaolin clay and the properties of column materials. Two types of column materials and three sets of particle size distributions were used. Material type M1 was typically angular in shape and originated from quarried igneous rock while material type M2 was obtained from polished river pebbles which typically were rounded or sub-rounded in shape (Powers, 1953). These material types are illustrated in Figure 2. Three sets of particle size distributions are shown in Figure 3.

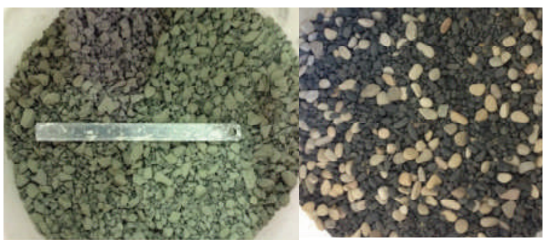

Figure 2. Gravel-sized Materials (M1 – left and M2 – right) used for Model Stone Columns

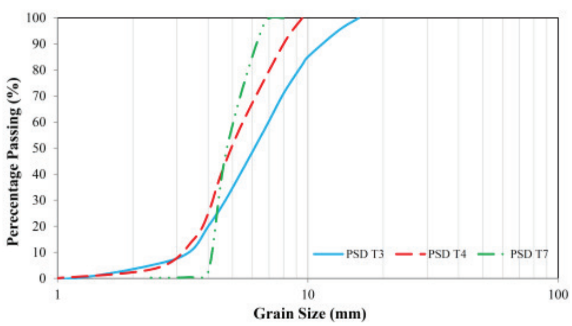

Figure 3. Particle Size Distributions (PSD) for Materials used for Model Stone Columns

Table 1. Properties of Kaolin Clay and Gravel Materials used for Model Stone Columns

Property	Value
Plastic Limit of Clay	27.4%
Liquid Limit of Clay	55.8%
Compression Index (C_r) of Clay	0.365
Recompression Index (C_{rr}) of Clay	0.053
Specific Gravity of Material M1	2.8
Dry Unit Weight of M1 and PSDT4	18.6 kN/m^3
Dry Unit Weight of M1 and PSDT3	17.5 kN/m^3
Dry Unit Weight of M1 and PSDT7	15.6 kN/m^3
Dry Unit Weight of M2 and PSDT4	21 kN/m^3

Twelve large-scale direct shear tests were conducted on stone column materials to obtain the friction angles. On each set of gravel specimen, the normal pressures of 28 kPa, 54 kPa and 78 kPa were applied. The specimens were placed and compacted with the similar compaction efforts to achieve 83% of relative density. The peak friction and constant volume friction angles from direct shear testing are tabulated in Figure 2. Constant volume friction angle was obtained by subtracting the dilation angle (ψ) from the peak friction angle (ϕ_p). It is acknowledged that a difference may exist between friction angles obtained from direct shear and triaxial tests (Rowe, 1969). For the purpose of qualitative comparisons, the friction angles from the direct shear testing are considered reasonable.

Table 2. Friction Angles from Direct Shear Box for all Specimens used for Column Materials in all Tests

Test ID	Specimen	Peak Friction Angle (ϕ_p)	Constant Volume Friction Angle ($\phi_{cv} = \phi_p - \psi$)
3	M1 and PSDT3	57°	40°
4	M1 and PSDT4	54°	35°
7	M1 and PSDT7	52°	34°
5	M2 and PSDT4	49°	30°

The typical inter-particle friction angle (□μ) of typical highly-angular gravels originated from igneous rock could be as high as 36° (Procter and Barton, 1974), while rounded quartz or feldspar with polished surface which is similar to the river pebbles of materials M2 has an inter-particle friction angle of 6° – 8° (Mitchell and Soga, 2005).

RESULTS AND DISCUSSIONS

Variation of Particle Size Distribution (PSD)

The ratios between vertical stress within mid-upper part of the column at 200-mm below the column top and total applied pressure at the surface were plotted in Figure 4 against the axial strain for tests in which the PSD were varied. The results indicate that the intensity of vertical stress within the mid-upper part of the column increased with the increase of applied pressure and the resulting axial strain. The increase is greater in the column with well graded PSD than it was in the column with more uniform PSD. The change in gradient is likely associated with the redistribution of stresses either vertically within the column or radially into the soft clay.

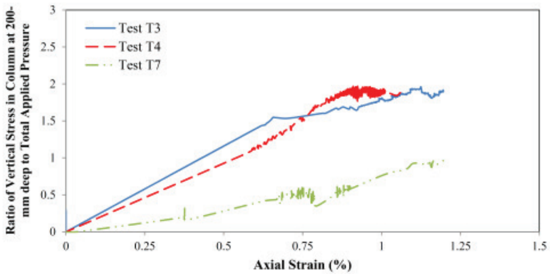

Figure 4. Vertical Stresses within Mid-upper Part of the column as a proportion of Total Applied Pressure at the Surface for Tests with varying PSD

In Figure 5, stress concentration ratios over time within about 200-mm deep below the column top for tests with varying PSD were shown. Despite some differences in the applied axial pressures at any given time, the stress concentration ratios are generally greater in magnitude than those in the column with less uniform PSD.

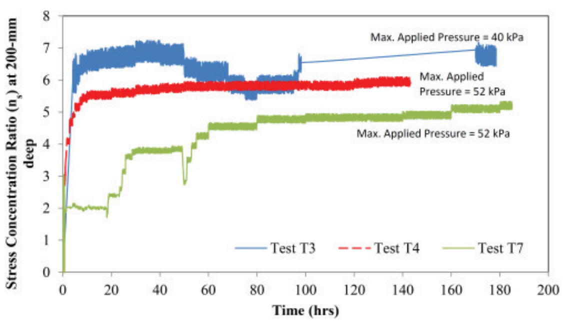

Figure 5. Stress Concentration Ratios (n_s) over time for Tests T3, T4 and T7 where PSD were varied

Due to the absence of pressure sensor in the clay at the surface of unit cell, the stress on the clay surface was back-calculated using the measurement of vertical stress at the column top considering equilibrium equation (Barksdale and Bachus, 1983) shown below:

$$\sigma_a = \sigma_c A_r + \sigma_s (1 - A_r) \quad (1)$$

where σc and σs are the stresses on the column and clay, respectively. σa is the total applied pressure at the top of unit cell and Ar is the area replacement ratio.

Figure 6 shows the ratio between ratios (ns) at the surface and within the mid-upper part of the unit cell. The plots indicate that the ratio in the upper part of stone column is generally greater than those at the column top. The more uniform the PSD was the greater the stresses within the upper half of the column were.

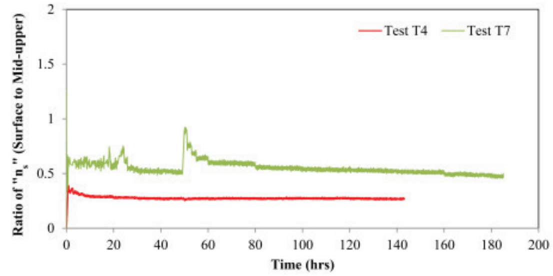

Figure 6. Plot of Ratio of Stress Concentration Ratios (ns) between Surface and Mid-upper (200-mm deep) of the Unit Cell for Tests with varying PSD

Variation of Particle Angularities

The plots showing ratios between vertical stress within mid-upper part of column at 200-mm deep below the surface and the total applied pressure are shown in Figure 7 for Tests T4 and T5. The plots indicate that stress concentration within the mid-upper part of column T5 with sub-rounded to rounded particles was lower than that of the column T4. Furthermore, Figure 8 also shows that the stress concentration ratio over time within the mid-upper part of the column in Test T4 is greater than that in Test T5 at the same location.

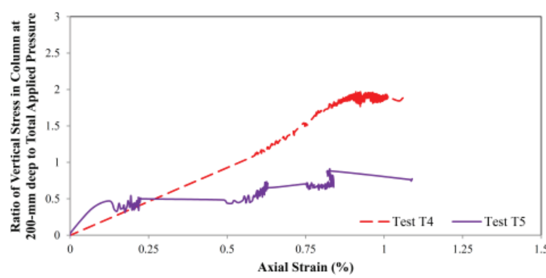

Figure 7. Vertical Stresses within Mid-upper Part of the column as a proportion of Total Applied Pressure at the Surface for Tests with varying Particle Angularities

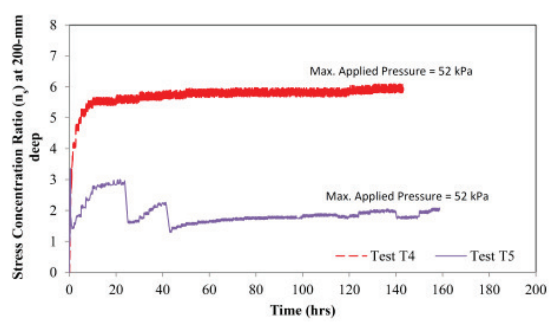

Figure 8. Stress Concentration Ratios (ns) over time for Tests T3, T4 and T7 where Particle Angularities were varied

As shown in Figure 9, the difference between stress concentration ratios at the surface and at 200-mm below the top was smaller in column T5 than that in column T4. The observations from Figure 7 to 9 can be attributed to a more uniform stress distribution within the column with rounded particles. However, this difference reduced with time for column T5 as the stress ratio at the surface approaches 1.0 showing stress in the column is equal to stress in the soft clay.

The excess pore pressures developed within the soft clay at three different depths in Tests T4 and T5 are shown in Figure 10a and Figure 10b, respectively. Qualitatively, they show that the soft clay located near the surface in Test T5 resisted a greater amount of total vertical stress than that in Test T4. The excess pore pressure in the clay then reduced with the increase of depth.

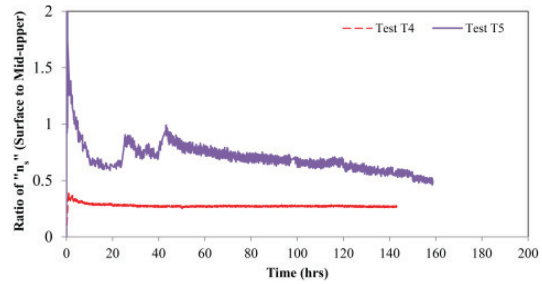

Figure 9. Ratio of Stress Concentration Ratios (ns) between Surface and Mid-upper (200-mm deep) of the Unit Cell for Tests with varying Particle Angularities

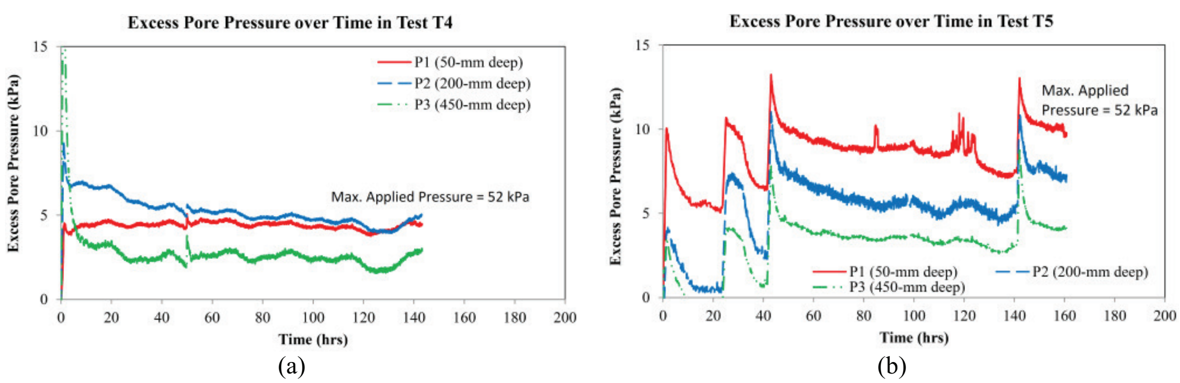

Figure 10. Excess Pore Pressures at Various Depths within Clay Samples in (a) Tests 4 and (b) Test 5

All above observations indicate that the bearing capacity of stone column with angular particles was significantly greater than that of the column with rounded to sub-rounded particles. The ns in columns with rounded to sub-rounded particles is generally smaller than that in column with angular particles due to a more uniform stress. This occurred due to the minimum intensity of particle interlocking within the assembly comprising rounded to sub-rounded particles where the resistance against particle rolling is lower.

These results agree with the numerical predictions presented by Siahaan et al (2014) in which a series of numerical simulations using Discrete Element Method (DEM) were carried out on model stone columns under foundation loading in which particle morphology were varied. The stress concentration ratio measured based on the surface stresses does not necessarily represent the stress distribution along the column length and surrounding clay. It is also influenced by the micro properties of column materials.

CONCLUSION

This paper presents experimental observations of vertical stress distributions within the stone column and soft clay when the unit cell was loaded one-dimensionally within the over-consolidated stress range of the surrounding soft soils.

The results indicated that well graded angular particles within the column contribute to an increase in stress concentration ratio. The stresses generally keep increasing within mid-upper part. However, they were distributed more evenly when more uniform and rounded aggregates were used to form a stone column. The paper demonstrates the significance of morphological properties of column materials in the behavior of stone column used in the soft soil improvement.

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