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Numerical Evaluation on the Different Shapes of Gravelly Sand Columns to Increase the Loading Capacity of Soft Clay

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Abstract. Improvement on soft clay by the installation of stone column is one of the most popular methods followed worldwide. Different analytical and numerical solutions have already been developed for understanding the load transfer mechanism of soft soil reinforced with stone column. This study investigated a bearing capacity of the gravelly sand column, installed in soft clay bed at 15kpa of undrained shear strength. The column variable of length and diameter ratio at 7, 8 and 9 were evaluated. On top of that, the combination of two diameters in single column was tested and the uniform diameter was used as a control. In the numerical analysis, Mohr-coulomb model was adopted in the idealization of the behaviour of the gravelly sand column and soft clay materials. The results revealed that the optimum design that gave the highest loading capacity of the combination l1=l2 of column diameter was the length and diameter ratio of 8.

1 Introduction

There are a numerous amount of methods for ground improvement were developed throughout the world. Amongst the wide range of ground improvement methods is stone column, which is often considered as cost-effective and environmentally friendly comparing to other types of stiffening column techniques [1]. The stone column technique of ground improvement has been proven to be successful in improving slope stability of both embankments and natural slopes, via increasing ground bearing capacity and accelerating the period of settlement. The stone column length has been always designed to be reached at stiff layer [2]. In cases of very deep weak soil, which has shear strength below 30 kPa, the application of stone column is not economics [3]. In recent years, the stiffening column technique has been adopted the floating stone column, when the soft ground is too deep. The bearing capacity was remained constant for the floating stone column at length to diameter ratio (L/D) of 10 [4-6]. According to Sivakumar et al [7] and Tekin and Ergun [8], the effective length to diameter ratio of the column was between 7 and 9. However, longer

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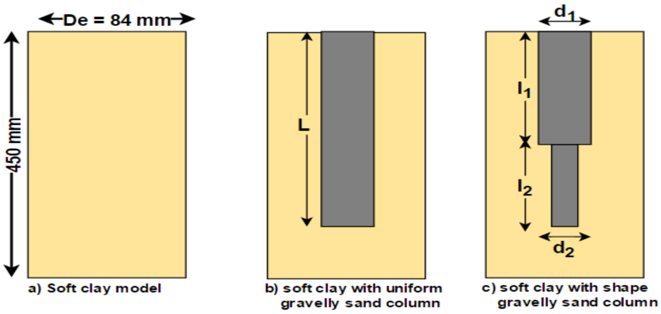
*Corresponding author: aziman@uthm.edu.my column may be needed to reduce the settlement. The ultimate bearing capacity, settlement, and general stability are the parameters to identify the stone column performance.

Numerical analysis enables the resolution of complex problems where the combination of the analytical solutions and experimental measurements can be established. The numerical models were developed using the finite element analysis software such as plaxis. Regardless of the development of more selected constitutive models for soil, the Mohr–Coulomb yield criterion remains a popular choice for geotechnical analysis due to its ease and simplicity to be used by practising engineers [9]. However, Mohr-Coulomb model is the most common constitutive laws used in finite element methods [10]. Al-Saidi [11] studied the behaviour of stone column using the axisymmetric single stone column using (unit cell) concept in the finite element programs. The result showed the failure depth, where the bulging zone occurred between 2 to 3 times the diameter. Gunduz [12] used the plaxis software and adopted a hardening soil and Mohr-coulomb models to analyse the deformation for 50 years period. Both model analyses showed similar results. Shien [13] used Mohr-coulomb model which indicated that the plastic zone was at 0.6 times of the length. Mats [14] indicated that the Mohr-Coulomb material model is inadequate to predict the primary consolidation of soft clay, and thus needs to refer to actual deformation measurements. Meanwhile, Ruben [15] investigated the behaviour of single stone columns via adopting Mohr-Coulomb and modifying Drucker-Prager models which resulted the column diameter influenced the loading capacity and the optimum length to diameter ratio was between 7 and 9. Therefore, this study has considered the design of the floating stone column at length to diameter ratio between 7 and 9. On top of that, the combination of two diameters in single column was tested and the uniform diameter was used as a control. In the numerical analysis, Mohr-coulomb drained and undrained model materials were adopted in the idealization of the behaviour of the gravelly sand column and soft clay materials.

2 Methodology

The compression modelling was performed using the plaxis 2-dimensional program. The model was based on the scaled-down at 25 times similar to Kelly [5]. The model of 84 mm wide and 450 mm high represents the unit cell (De) containing a soft clay as shown in Fig 1(a). It was deemed to represent a field scenario where gravelly sand column was installed in a triangular pattern (De=1.05S) where the spacing (S) at 80 mm. The uniform diameter of the column as a control shape was installed at the centre of the soft clay with a diameter (D) at 44 mm to achieve a replacement ratio in the average (as) between 0.25 and 0.50.



a) Soft clay model
b) soft clay with uniform gravelly sand column
c) soft clay with shape gravelly sand column

Fig. 1. Geometry of models

The various lengths (L) of the column were adopted at 308, 352 and 396 mm according to the ratio of length and diameter (L/D) between 7, 8 and 9 respectively as shown in Fig. 1(b). The combination of two column diameters (d1 and d2) and lengths (l1 and l2) was installed at the centre of the soft clay as shown in Fig. 1 (c). The first diameter (d1) is similar with control shape and for the second column diameter (d2) is smaller at 44 mm and 20mm respectively. There were 9 variables adopted at first diameter column lengths (l1) of 102.6, 154, 205.4, 117.4, 176, 234.6, 132, 198, 264 mm and second diameter column lengths (l2) at 205.4, 154, 102.6, 234.6, 176, 117.4, 264, 198, 132 mm. Table 1 and 2 summarize the parameters adopted in the numerical analysis.

Table 1. Uniform column diameter

No	Length (L), mm	Diameter (D), mm	Ratio (L:D)
1	308	44	7:1
2	352		8:1
3	396		9:1

Table 2. Combination of 2 columns diameter

No	Length (l1), mm	Length (l2), mm	Ratio (l1:l2)	Total length, (L) mm	Diameter (d1), mm	Diameter (d2), mm	Ratio (L:d1)
1	102.6	205.4	1:2	308	44	20	7:1
2	154	154	1:1				
3	205.4	102.6	2:1				
4	117.4	234.6	1:2	352			8:1
5	176	176	1:1				
6	234.6	117.4	2:1				
7	132	264	1:2	396			9:1
8	198	198	1:1				
9	264	132	2:1				

3Material properties

Kaolin from Associated Kaolin Industries was the main material used to form a soft clay bed. This material was used to ensure a high degree of sample control and reduce variability throughout the test program. Its properties were determined during the laboratory tests as summarized in Table 3. The material for constructing the column was obtained by sieving a fine quarry aggregate in the laboratory. The suitable grain sizes were based on the scaled-down prototype grain diameter at 25. For this study, a prototype of the bottom feed technique of constructing sand columns was used with a typical grain size diameter of 10 to 40 mm and thus, the scaled-down grain size diameter was between 0.4 mm and 1.6 mm. Properties of the gravelly sand were determined during the laboratory tests and summarized in Table 3.

4 Constitutive model

The Mohr - coulomb model is widely used in finite element analysis of geotechnical applications due to its simplicity and sufficient accuracy. The Mohr-coulomb model for drained and undrained condition was adopted to model the behaviour of the gravelly sand and soft clay materials respectively. Meanwhile, an Elasto-perfectly plastic behaviour with the Mohr-coulomb failure criterion was adopted for the material response under loading conditions. An elasto-perfectly plastic behaviour with the Mohr-Coulomb failure criterion was adopted for the material response under loading conditions. In terms of the principal stresses (σ1 and σ3), the failure envelope of the Mohr-Coulomb model is defined using (1).

$$(\sigma 1 - \sigma 3) + (\sigma 1 + \sigma 3) \sin\varphi - 2c \cos \varphi = 0 \quad (1)$$

where c and φ are the cohesion and the angle of internal friction of the material respectively.

Table 3. Properties of soft clay and gravelly sand materials

Properties	**Unit**	**Soft clay**	**Gravelly sand**
Specific gravity	---	2.65	2.70
Moisture content	%	42	9
Undrained shear strength	kPa	15	N.G
Cohesion	N/mm2	0.00887	0.000376
Angle of internal friction	o	31.2	47.9
Dilatancy angle	o	10.4	15.97
Permeability	mm/s	$7e^{-6}$	0.012
Young modulus	N/mm2	1.8	40
Poisson ratio	---	0.35	0.30
Unit weight saturation	N/mm3	$1.738\ e^{-5}$	$2.138\ e^{-5}$
Unit weight unsaturation	N/mm3	$1.224e^{-5}$	$2.04\ e^{-5}$

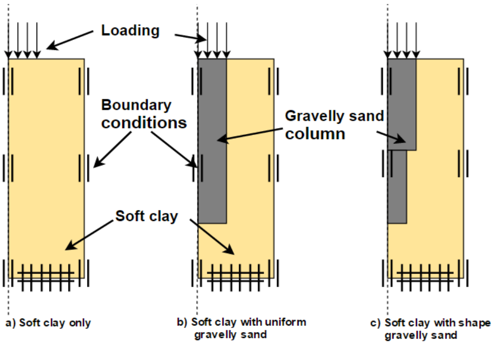
5 Finite element analysis

5.1 Program used

Plaxis as the most used software packages in geotechnical engineering was employed for finite element analysis. Plaxis 2D is a two dimensional finite element program interface but currently restricted to 2D plane strain and axisymmetric problems. The program can deal with undrained and drained consolidation analysis of two dimensions (with axisymmetric loading).

5.2 Finite element geometry, boundary conditions

The problem of axially loaded sand column surrounded with soft clay is an axisymmetric one, because the materials are homogenous. Axisymmetric finite element analysis was carried out for the assessment of the load settlement of the soft clay and gravelly sand column. Due to symmetry, only half of the axisymmetric problem is considered. The boundary conditions of the axisymmetric problem domain are shear free with no radial movement at the lateral sides and prevent the bottom boundary from both radial and vertical movements as shown in Fig. 2. Fifteen nodes elements are used to model the soft clay and gravelly sand column. An example of the domain meshes generated from the analyses is shown in Fig. 3.



a) Soft clay only b) Soft clay with uniform gravelly sand c) Soft clay with shape gravelly sand

Fig. 2. Boundary conditions and loading

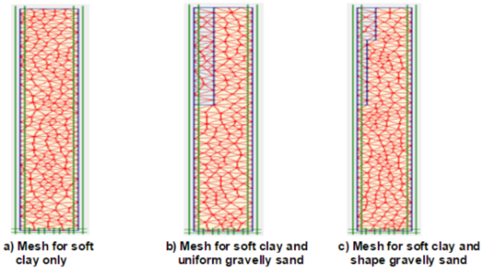

a) Mesh for soft clay only b) Mesh for soft clay and uniform gravelly sand c) Mesh for soft clay and shape gravelly sand

Fig. 3. Mesh of the models

6 Results and discussion

Fig. 4 shows the relation between the load and the displacement for three cases of soft clay only, uniform column diameter, and the combination of two column diameters (l1 and l2) when the ratio of length and diameter (L/D) is 7.

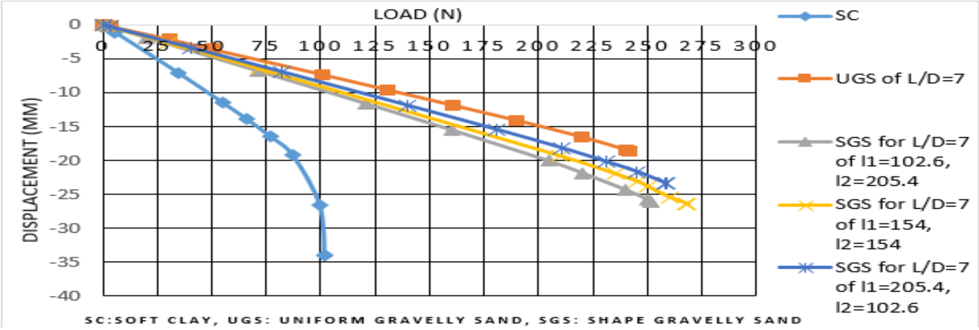


Fig. 4. Load vs. displacement for column at ratio (L/D=7) 7:1

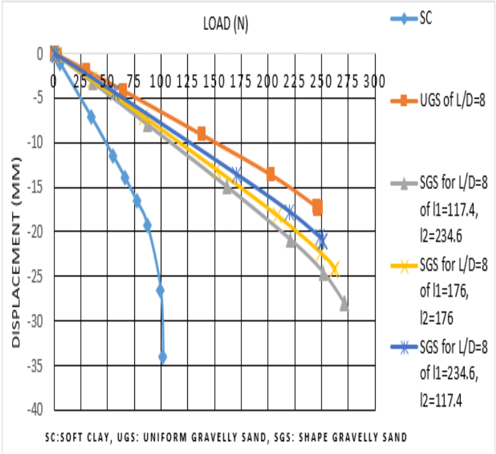


Fig. 5. Load vs. displacement for the column at ratio (L/D) 8:1

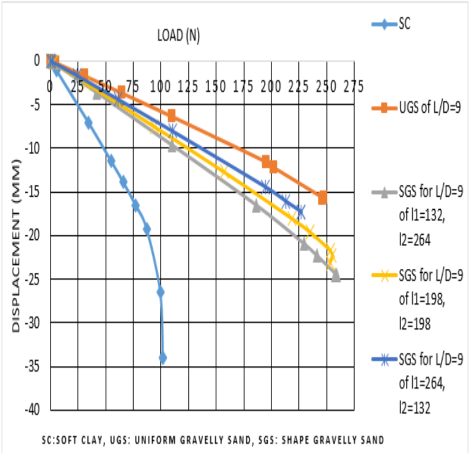


Fig. 6. Load vs. displacement for the column at ratio (L/D) 9:1

The loading capacity increased more than twice with the column installation at uniform and a combination of two diameters. The highest loading capacity for column length at 308 mm was the uniform column diameter and a combination of two column diameters (l1 and l2) at ratio 1:1 of 268.506 N.

In the case of the column length at 352 mm and diameter 44 mm at a ratio (L/D) 8:1 as shown in Fig. 5, the loading capacity increased more than twice with the column installation at uniform and a combination of two diameters. The highest loading capacity for column length of 352 mm was the combination of two column diameters (l1 and l2) at ratio 1:2 of 271.543 N.

In the case of the column length at 396 mm and diameter 44 mm at a ratio (L/D) 9:1 as shown in Fig. 6, the loading capacity increased more than twice with the column installation at uniform and a combination of two diameters. The highest loading capacity for column length of 396 mm was the combination of two column diameters (l1 and l2) at ratio 1:2 of 258.865N.

7 Conclusion

From the finite element analysis, the following conclusions can be drawn:

- The loading capacity without and with the column is more than twice, indicating that column is able to improve the bearing capacity of soft clay.
- The loading capacity of the uniform column and the combination of two column diameters are comparatively equal. However, in many cases, the highest loading capacity was a combination of two column diameters.
- The column ratio length and diameter (L/D= 8) and the combination of two column diameters (l1 and l2) at ratio 1:2 (L/D=8 of l1=176, l2=176) have the highest loading capacity of 271.543N.
- There is unbeneficial to increase the length to diameter ratio more than 8.

The combination of two column diameters, where the larger column diameter at the top is practical to be implemented and able to reduce the volume of aggregate to build the column. It is recommended to explore the laboratory and numerical modelling of bulging and punching for the different column diameters.

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