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Load Transfer Mechanism of Group of Floating Soil-Cement Column In mproving Soft Ground

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Abstract. Soil-cement column by deep mixing method as ground improvement was proven effective enough to improve soft soil for foundation of structure, earthen embankment, rafts foundation, and where a relatively large settlement is permissible. However, the load transfer mechanisms between the column and the surrounding soil especially for a group of floating soil cement column is still lack of investigation. This paper presents the stress sharing mechanism under rigid footing supported by a group of floating cement column. This paper focuses on the development of stress distribution and stress concentration ratio, η under instant loading. Thus, a series of laboratory experiments were carried out to measure the stress of the column and the surrounding soil. For comparison, finite element analysis was performed using PLAXIS 3D with Undrained analysis. Generally, it was found that a group of floating soil cement column shared 1 to 4 times more loads than the surrounding soil with the range of applied stress of 14 kPa to 20 kPa. Moreover, in all cases, it can be seen that the stress measured in lab and predicted by PLAXIS 3D showed a small discrepancy between the results. In addition, good interpretation and understanding on the load transfer between the column and the surrounding soil was obtained by the used of finite element analysis.

1. Introduction

The installation of floating soil-cement column by deep mixing method is an effective ground improvement solution as it is able to reduce the construction time and costs as well as the environmental impacts. Floating soil-cement column is also a proven in increasing the bearing capacity and reducing the differential settlement of the improved soil. The important parameters that affect the improved ground by a group of floating soil-cement column are area improvement ratio (a_p), column height (H_c), soft soil thickness (H), column strength (c_{uc}), strength of surrounding soil (c_{us}), stress concentration ratio (η) and load intensity (P) ([4 – 5], [6- 8], [9], [12], [18]). The a_p is obtained as Equation 1. The ratio of column height to total soft ground thickness is referred as improvement depth ratio, β.

$$a_p = \frac{\Sigma A_c}{d_1 \times d_2} \tag{1}$$

Where A_p is the cross sectional area of a soil cement column, d_1 and d_2 are the dimensions of the improvement area by single cement column in plain view [4].

In a composite ground (i.e the matrix floating soil-cement column and soft soil), the stress distribution of the column and the surrounding soft soil can be interprete using the stress concentration ratio, η that defined as the ratio of stress in column, σ_c to the stress in soil, σ_s, as shown in Equation 2

$$\eta = \frac{\sigma_c}{\sigma_s} \tag{2}$$

The concentration of stress in soil cement column higher as compared to the surrounding soil due to the higher stifness material of the column than that of the native soil [1]. In-soil cement column, there is still no rigorous solution available to estimate the stress of both treated and untreated soil. However, the method developed by Aboshi et. al. (1979) adopting unit cell concept in ground improvement by stone column is still

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reliable to be used in cases where large group of columns are used to improve the soft soil [1]. The relationship of simple equilibrium for an average stress of composite ground was showed as Equation 3 in term of the area replacement ratio, a_p.

$$\sigma = \sigma_C \alpha + \sigma_S (1 - \alpha) \quad (3)$$

where, area replacement ratio, α is ratio of total area number of column to the area of improvement.

The value of stress ratio for column type improved ground depends on different factors such as column's stiffness and strength, surrounding soil's stiffness and strength, load intensity, q and area replacement ratio ([6-7], [11]). For soil-cement column, the η can be highly varied as the columns can be chatagerized as flexible, semi rigid and also rigid depends on amount of cement addition during mixing. For instance, Ishikura (2007) measured the η in between 4 to 20 using stress control method with loading of 40 kPa and 80 kPa uder oedometric testing condition [10]. Another study conducted by Horpilbulsuk et al., (2012) gave η value between 1 to 40 for q = 1200 kN [3]. Raftari (2014) reported that stress concentration ratio decreased as the pre-consolidation pressure increased due to the increase in elasticity of improved ground during the consolidation process [14].

The objective of this paper is to examine the load transfer mechanism for a group of floating soil-cement column. The stress concentration ratio, η was examined in a small scale laboratory work and the findings was compared with three dimensional (3D) numerical method.

2. Research Methodology

In this study, soft soil that improved by a floating soil-cement column to support a load from rigid footing were investigated by experimental and numerical analysis. A set of six column groups with area improvement ratio, a_p of 21.7% were tested for two different column height, H_c of 50 and 100 mm, thet denotes as T1 and T2 respectively. Firstly, the experimental work started with the undrained bearing capacity test for the soil-cement groups to obtain the working load, W_d Subsequently, the working load was applied instantly as a dead load to a new set of samples. Stress distributions in columns and soils were measured and the results were compared with the numerical analysis performed in three dimensional (3D) finite element method.

2.1 Experimental Programmed

A soft soil laboratory model was constructed in a testing chamber having a dimension of 400 mm x 150 mm x 430 mm in width, long and height respectively. The rigid footing was made of stainless steel with rectangular shapes by 80 mm x 150 mm in width and long respectively. In addition, the loading device consists of two different systems which are first equipped with driving unit (i.e motor and gear to provide an undrained loading) and the other just used a simple dead load system as shown in Figure 3. The column that installed into the soft ground has a dimension of 23 mm in diameter and a spacing of 20 mm. The installation process was conducted by the use of stainless steel template that comprise of six (6) hole which represented of a_p = 21.7%, steel thin tube, easy soil remover and extruded as shown in Figure 1. The sequenced of installation processed was showed in Figure 2. Furthermore, for a measurement method, three (3) transducers were used which are Linear Vertical Displacement Transducer, LVDT, Load cell and Miniature Soil Pressure Transducer, MSPT that used to measure the displacement, the applied load and the soil/column pressure respectively. The MSPT was installed at the surface of the surrounding soil and the column as well as the bottom of column. The location of the instruments is shown in Figure 4.

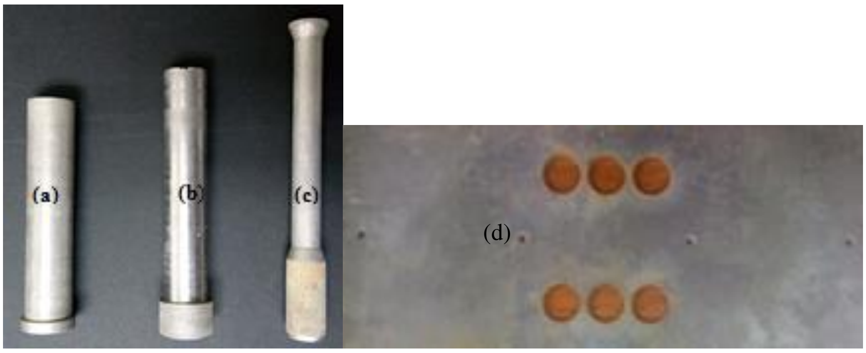


Figure 1. Equipment for Column Installation (a) Steel thin tube (b) Easy soil remover (c) Extruder (d) Template.

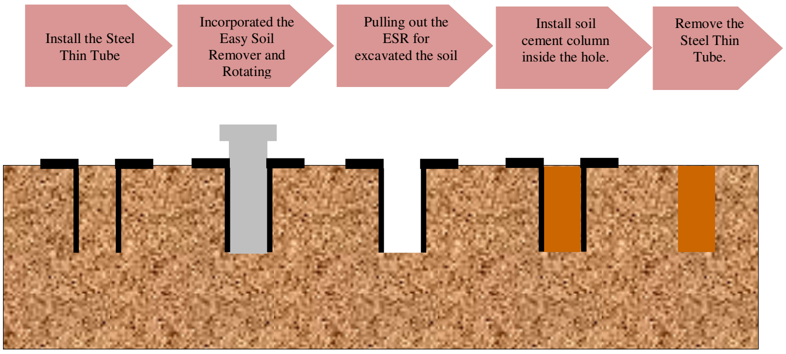


Figure 2. Schematic Diagram of Column Installation.

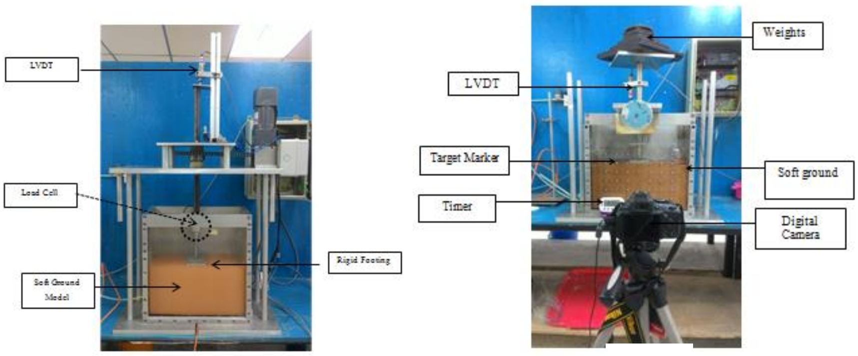
Table 1 shows the properties of the Kaolin Clay used as the improved ground material. The soft soil was prepared in slurry condition after which applied a pre-consolidation pressure to attain undrained shear strength, $c_{us.}$ of 8 kPa to 10 kPa

Table 1 Material Properties of Kaolin Clay

Parameter	Clay
Calssification (USCS)	CL
Specific Gravity, SG	2.64
Atterberg Limit	
PL(%)	57
LL(%)	32
PI(%)	25

The laboratory scheme was started with the clay bed preparation. The slurry soil mix was produced at two times the liquid limit to ensure the soil was workable enough to be pour into the testing chamber. Then, the soil was consolidated under continuous incremental stress by 2.12 kPa, 3.125 kPa, 6.25 kPa, 12.5 kPa and 50kPa. The sequence of the stress was increased after it met 90% degree of consolidation. After that the pressure was reduced to 5kPa to obtain an over-consolidation ratio of 10. Generally, nine days are required to complete all consolidation stages. After that, the soil cement column was inserted by the equipment and method as shown in Figure 1 and 2 respectively. As the installation of columns were completed, the pre-consolidation of 50 kPa was re-applied to the soil in order to have homogeneous contact as well as closing the gap between the installed column and the surrounding soil [15-16]. The gap was considered close when the consolidation was completed. In other words, the columns and the surrounding soil has full adhesion with good bonding.

After finishing the preparation of the ground, the loading test was performed at day-12 of curing period. The sequenced of loading test was initiated with the applied undrained loading until the penetration of 20 mm of displacement was attained as shown in Figure 3(a). As it reached, the undrained behavior of soil was fully developed, which means that the ultimate bearing capacity of model ground was achieved as Figure 3(b). The second stage of loading test was was applied on another set of samples with the measurement of stress distribution under the working load, W_d that applied instantly and kept for 24 hours. The schematic diagram of improved ground for second series or main of this study was shown in Figure 4.



(a) (b)

Figure 3. Schematic Diagram of Loading Test (a) Undrained Loading (b) Instant Dead Load

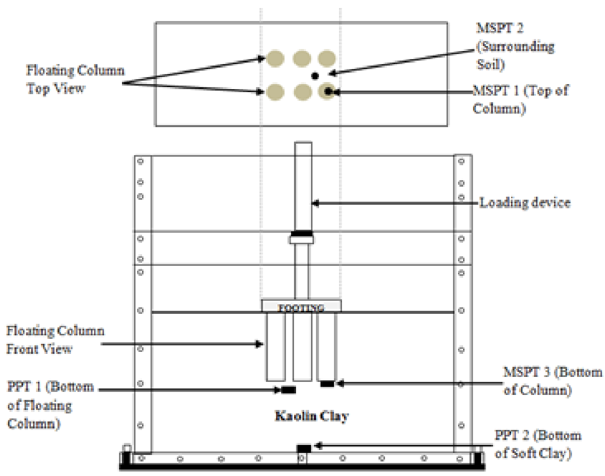


Figure 4. Schematic diagram of MSPT location.

2.2 Numerical Modelling

In this study, the numerical analysis was performed by using PLAXIS 3D 2016. In the analysis, a group of column as in experimental was modeled. The geometry of numerical analysis was scaled up by 10 times due to the ingenerated mesh inside the soil cement column if the small dimension was used. The global fine mesh was implemented for overall analysis while refine mesh was generated in the area where the concentrated stress occur which is at the area of beneath the rigid footing as shown in Figure 5. The boundary of z direction was unclosed based on the two drainage system used in laboratory experiments.

For the numerical analysis, Mohr Column, MC model was chosen. The MC model is elastic-perfectly plastic models that involve five (5) parameters. However, the analysis was implemented with three (3) important parameters that influenced the analysis which are Young Modulus, E, poison's ratio, υ, and undrained shear strength, c_u. In PLAXIS, the type of analysis that used those parameters known as Undrained (B) type. Table 2 shows the material properties as an input parameter in Plaxis. The rigid footing properties was assigned as Plate with high stiffness of 1.2×10^7 kPa.

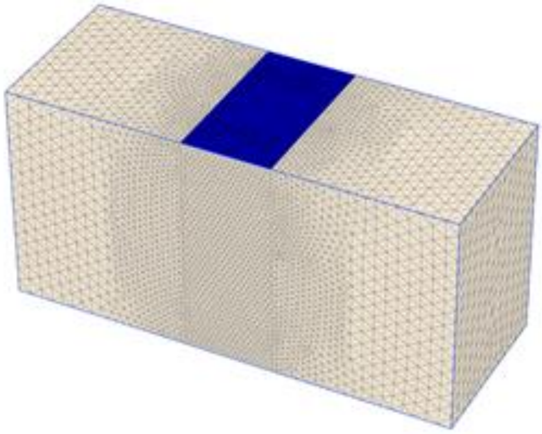


Figure 5. Generated Mesh.

Table 2 Material Properties for Plaxis 3D

Parameter	Name	Kaolin Clay	Soil Cement Column	Unit
General				
Material Model	**Model**	Mohr Coulomb	Mohr Coulomb	-
Drainage Type	**Type**	Undrained(B)	Undrained(B)	-
Unit weight	γ_{unsat}	17	17	kN/m^3
Unit weight	γ_{sat}	18	18	kN/m^3
Parameter				
Young Modulus	**E'**	4000	16,461	kN/m^2
Poisson Ratio,	υ	0.35	0.3	
Cohesion	c_u	7	64.8	kN/m^2
Friction Angle	ϕ	0	0^o	^{0}
Dilatancy	ψ	0	0^o	^{0}
Permeability	**k**	2.229 x 10^{-5}	8.79x 10^{-4}	m/d
Initial				
K_0 determination	**-**	1	1	

3. Results and Discussion

3.1 Ultimate Bearing Capacity, q_u and Design Load, W_d

Table 3 shows the ultimate bearing capacity,q_u obtained from the fierst stage of the experimental study. Obviously, the installations of floating soil cement column with long column (H_c = 100 mm) increase the ultimate bearing capacity of the improved ground. The undrained capacity of the soil-cement group isabout 7 to 8 times of the undrained shear strength of the soils. Numerical results matched the laboratory results quite well, with less than 6% discrepency. The design load, W_d was determined as 1/3 of q_u and will be used in the second stage loading.

Table 3 Ultimate bearing capacity, q_u and design load, W_d

Test	a_p(%)	H_c (mm)	q_{ult}, (kPa)		Discrepancy (%)	q_d, (kPa)	W_d (kg)
			Physical Testing	Numerical Analysis			
T1	21.7%	50	44.8	47.3	5.6	14.9	17.8
T2	21.7%	100	57.5	57.8	0.52	19.2	22.9

3.2 Development of Stress on Surrounding Soil and Floating soil cement column

In the second stage of experimental study, the working loads were applied on a new set of T1 and T2 samples. Stress distribution was examined for 24 hours time. Figure 6, 7 and 8 show the stress against time for the surrounding soil, the top of the column and the bottom of column. From the figures, it can be seen that immediately after the working loads were applied instantly on the top of the soil-cement column, the stress in the column, σ_{col} and the surrounding soil, σ_{soil} increased sharply. After that, the stress in the column, σ_{col} and the stress in the surrounding soil, σ_{soil} increased slowly with time due to consolidation process. In addition, for both T1 and T2, the stresses measured at the surrounding soil is less than the stress measured at the top of columns. This phenomenom is common as the stiffness in columns is higher than the surrounding soil. Another finding is that longer columns attracted more loads than shorter column, as shown in Figure 7. Stresses were found to dissipate from the top of column to the toe as the depth increases, as depicted in Figure 8.

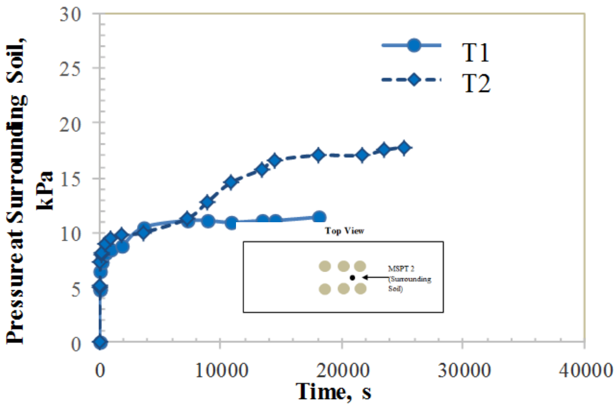


Figure 6. Stress distributions on surrounding soil.

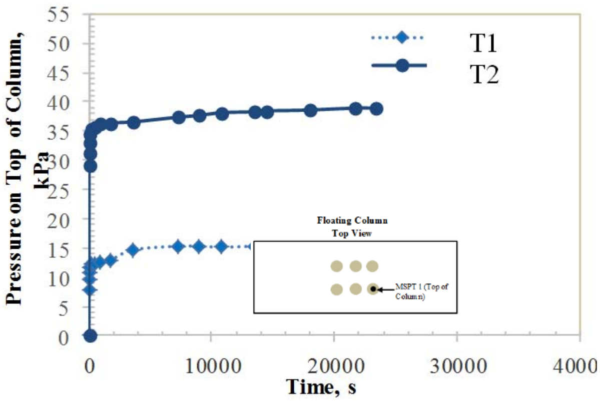


Figure 7. Stress distributions on top of column.

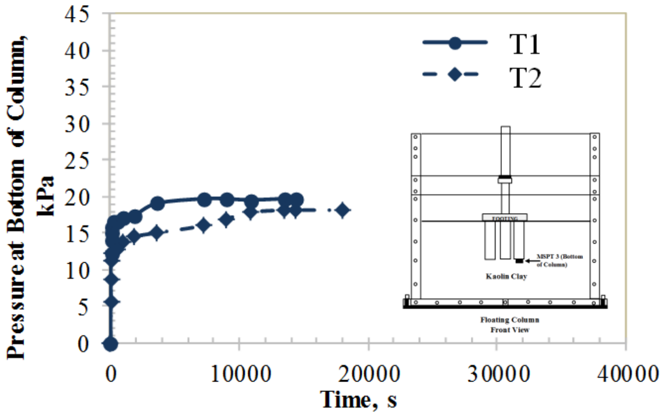


Figure 8. Stress distributions at the bottom of column.

3.3 Stress concentration ratio, η from Experimental and Numerical

Table 4 shows the comparison of stress concentration ratio, η obtained from both numerical and experimental study under working load, W_d, measured at at the top of the column and the surrounding soil (i.e., z = 0 m). From the results, stress concentration, η ratio the range of numerical analysis was around 2 to 3, which in the range of stress concentration ratio, η obtained by physical tests that was in range of 1 to 3. However, numerical analysis produces almost similar stress concentration ratio, η for both short and long column. In addition, in the physical modelling, as the H_c getting higher, the value of stress concentration ratio getting lower. This may be due to the disturbance occurred in the physical test while columns were installed. This effect is not seen in numerical analysis since the wish-in-place adopted for column installation, thus ignoring the effect of installation process.

Table 4 Values of stress concentration ratio, η

Test	Numerical Modelling	Physical Modelling
	η_N	η
T1	2.67	1.45
T2	2.52	2.11

3.4 Enhancement of Load Transfer Mechanism in Numerical Analysis

Addition findings are obtained for the six floating columns from the numerical analysis. Figure 9 shows the stress concentration ratio, η profile of the column groups. High stress concentration ratio, η was obtained at the top of thecolumn then reduced to unity towards the column toeIn this analysis, the stress concentration ratio decreased non linearly up to the column depth. This implies the effectiveness of longer column in transferring down the stress. Similar stress profile was observed for soft ground improved by fully penetrated stone column ([2]; [11-12]). In addition, Figure 10 shows the distribution shading of the improved ground (cross section taken at 0.01m below ground surface. Outer columns seems to attract higher axial load than the middle columns. Similar observationwas made by Wood et al. (2000)for stone columns in physical testing [17]. Judging from different colour shading, the results also suggested that the soil underneath the footing is nor uniformly loaded, with higher stress concentration near the edge than the middle. The same load transfered mechanism was explained by O' Brian (2002) in pile foundation [13].

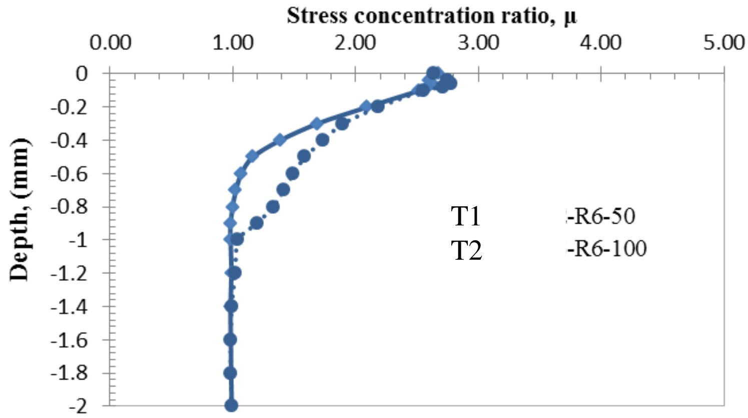


Figure 9. Stress concentration profile.

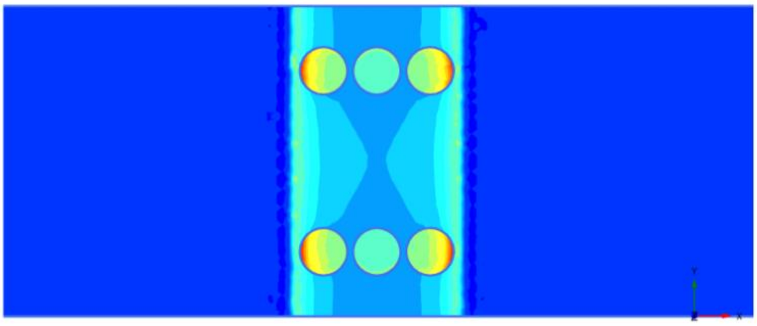


Figure 10. Stress distribution shading.

4.0 Conclusion

Physical and numerical studies have been conducted in this study for the soft soil improved by the floating soil-cement columns. study, The following conclusions can be drawn;

1. Due to higher stiffness in column material, more loads were carried by the soil-cement columns than the surrounding soils. This effect is observed immediately after the dead load was applied and slowly increase in magnitude due to consolidation process.
2. In the experimental study, the stress concentration ratio, η was higher in long columns than in short columns, i.e. 2.7 and 2.5 for T1 and T2 respectively. On the other hand, numerical analysis gave similar observation albeit different slightly in the values.
3. Numerical results showed that the longer columns carried load further down to the column toe.
4. The stress concentration ratio for the outer columns was higher than the inner columns.

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