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Numerical Investigation of Soft Clayey Soil Improved by Soil-Cement Columns under Harmonic Load

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***Abstract*—**Deep soil mixing is one of the improvement methods in geotechnical engineering which is widely used in soft soils. This article investigates the consolidation behavior of a soft clay soil which is improved by soil-cement column (SCC) by numerical modeling using Plaxis2D program. This behavior is simulated under vertical static and cyclic load which is applied on the soil surface. The static load problem is the simulation of a physical model test in an axisymmetric condition which uses a single SCC in the model center. The results of numerical modeling consist of settlement of soft soil composite, stress on soft soil and column, and excessive pore water pressure in the soil show a good correspondence with the test results. The response of soft soil composite to the cyclic load in vertical direction also compared with the static results. Also the effects of two variables namely the cement content used in a SCC and the area ratio (the ratio of the diameter of SCC to the diameter of composite soil model, a) is investigated. The results show that the stress on the column with the higher value of a, is lesser compared with the stress on other columns. Different rate of consolidation and excessive pore pressure distribution is observed in cyclic load problem. Also comparing the results of settlement of soil shows higher compressibility in the cyclic load problem.

***Keywords*—**Area ratio, consolidation behavior, cyclic load, numerical modeling, soil-cement column.

I. Introduction

DEEP SOIL MIXING (DSM) has been used for soil improvement in practical projects for the last decades. In this method, cement or other material is used to increase soil's strength and stiffness, therefore cement grout is entered the soil body and mix with it by a rotating tool [1], [2]. Nowadays this method is adopted all over the world and is used in different applications such as improving soil permeability, stress properties, and strength [3], [4]. Also this method is used as retaining wall in deep excavations in soft saturated clay, which has more advantages than sheet pile or diaphragm wall [5]. Using sheet pile walls in saturated soft clay, causes water leakage from connectors between sheet piles, and also using diaphragm wall causes instead of sheet pile, is not economical [5]. Therefore, DSM method has overcome the problems due to applying the last methods.

There are several experimental and field studies for investigating the soil strength obtained from DSM method. Lee et al. [6] investigated the effect of soil-cement ratio and cement-water ratio in unconfined compressive strength of SCCs. Lee et al. [7] simulated SCCs and process of DSM method in centrifuge apparatus. Shen et al. [8] studied the effect of installation of SCCs on sensitive clay properties in the field by cone penetration test (CPT). They applied CPT test before and after the installation to study the change in strength of clayey soil with time. Sukpunya and Jotisankasa [9] performed large simple shear test on Bangkok soft clay improved by SCCs, wherein three different layouts for columns were used.

There are also several numerical studies on determining ultimate strength of improved soil with SCCs [10]-[13]. Oliveira et al. simulated the consolidation behavior of a soft soil improved by SCCs under construction of an embankment. The results are given as settlement, change in vertical effective stress and excessive pore pressure with time. Voottipruex et al. [11] simulated a new version of deep mixing columns improved by reinforced cement, called stiffened deep cement mixing (SDCM), in Plaxis 3D and compared SDCM with SCC operationally. Horpibulsuk et al. [12] implemented experimental and numerical studies on consolidation behavior of soft soil improved by SCCs in axisymmetric state. These researchers reported their results as settlement, excessive pore pressure and stress on soil and column of soil-cement system. Ignat et al. [13] compared a 2D model of excavation with sheet pile wall interacting with deep mixing columns with 3D model. The results consist of comparing the failure load, failure mechanism and displacements.

Behavior of soil-cement systems under seismic or harmonic loads among the previous experimental and numerical studies has not observed. In this study, consolidation behavior of soft soil improved by SCCs which was investigated in the study of Horpibulsuk et al. [12], is simulated and verified in a finite element program, Plaxis 2D. Afterwards, the numerical model simulated under cyclic load, and the results of settlement of soil-cement system in two condition of loading are compared together.

II. Properties of Experimental Model

Horpibulsuk et al. [12] study divided into two parts: experimental test and numerical modeling. In the experimental test, Bangkok soft clayey soil with water content of 80% and specific gravity of 2.68 is used. Liquid limit and plastic limit of the soil is 81% and 34%, respectively. As it is seen in Fig.

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1, the physical model consists of a metal cylinder with 300 mm diameter and 450 mm height. The clay slurry which is used in the cast is prepared with water content twice the liquid limit. The clay slurry is consolidated under 200 kPa compression loads, until the height of model reaches 200 mm. To build the SCCs, two cement contents of 20% and 40% are used to mix with the soil. The columns are prepared in 50 mm and 100 mm diameter and installed in the clayey soil vertically. Six pore pressure transducers (PPTs) are used for measuring the produced pore water pressure (Fig. 1). Two earth pressure cell (EPC) is used on the soil surface and above the SCC (Fig. 1). Also there are two linear variable differential transformers (LVDTs) in the physical model to measure the deformations (Fig. 1). Two 30 mm sand layers are used above and below the physical model. Table I shows three modes of experiment performed on soil-cement systems [12]. Ratio of improvement area (a) defines as the ratio of SCC diameter to diameter of soil-column system.

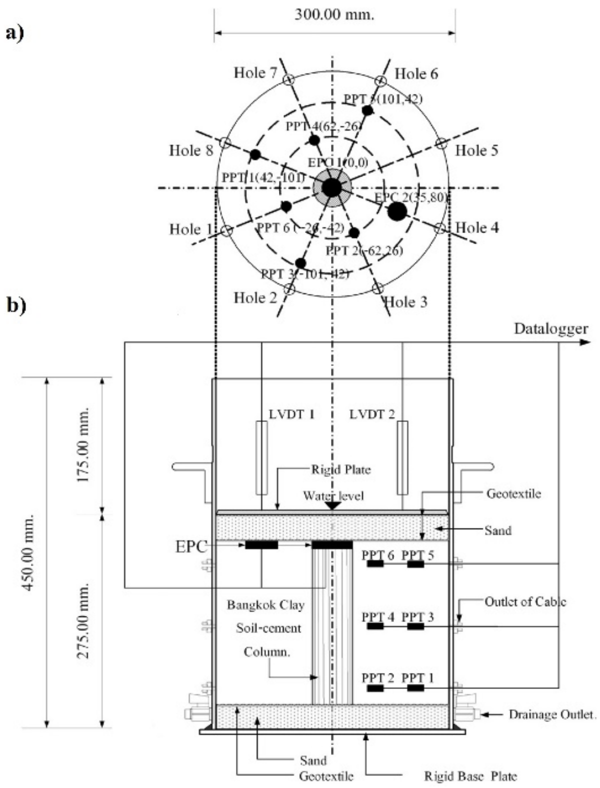


Fig. 1 Physical model of Horpibulsuk et al. [12], a) plan view of the model and arrangement of transducers, b) side view of the model

III. Properties of Numerical Model

The numerical model in this article is identical to the numerical model of Horpibulsuk et al. [12]. As can be seen in Fig. 2, the model is simulated in axisymmetric condition in plaxis 2D. V.8.5. 15-node triangular and 12-node triangular element are used for stress-strain and pore water pressure analysis (Fig. 2 (b)). In static analysis, vertical boundaries are closed in horizontal direction, and horizontal boundaries are closed in both vertical and horizontal directions. In dynamic analysis, absorbent boundaries are also used at side and bottom boundaries, to prevent wave reflection into the soil media. Drainage path is one-way from down to the top of model (Fig. 2 (a)). Table II shows the parameters used in this analysis are identical to the parameters used in the study of Horpibulsuk et al. [12].

TABLE I
Modes of Experiments in Physical Model of [12]

Model number	Diameter of SCC (mm)	Height (mm)	Cement ratio (%)	a	q_u (kPa)
1	50	200	40	1/6	1200
2	100	200	40	1/3	1200
3	100	200	20	1/3	500

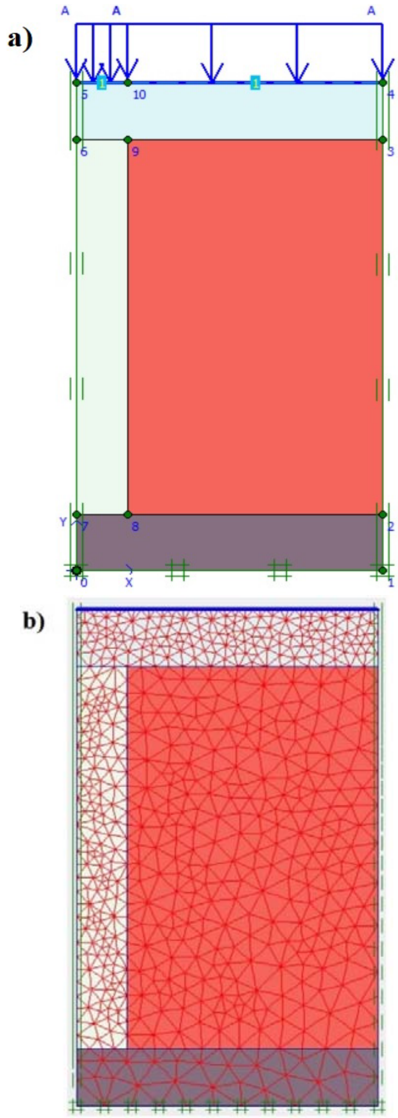


Fig. 2 Axisymmetric numerical model in static analysis, (a) compression loading, (b) mesh sizes in static analysis

TABLE II
PARAMETERS SPECIFIED FOR NUMERICAL ANALYSIS [12]

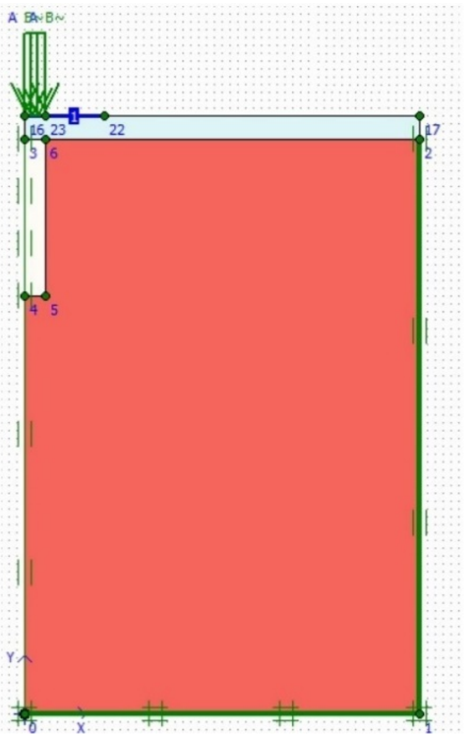
Soil	Sand	Bangkok clay	SCC	Unit
Model	Mohr-Coulomb	Soft soil	Mohr-Coulomb	-
γ_{dry}	17	16	13 (C=20%) 14 (C=20%)	kN/m^3
γ_{sat}	20	18	13 (C=20%) 14 (C=20%)	kN/m^3
k_v	3.43×10^{-4}	1.0×10^{-7}	5.0×10^{-6}	$m/\min$
k_h	3.43×10^{-4}	1.0×10^{-7}	5.0×10^{-6}	$m/\min$
E'	13,000 (top layer) 52,000 (bottom layer)	-	112,000 (C=20%) 120,000 (C=40%)	kPa
ν'	0.3	0.3	0.3	-
λ^*	-	0.095	-	-
κ^*	-	0.0095	-	-
c'	1	1	600	kPa
ϕ'	37	21	25	Degree

IV. LOADING SEQUENCES

At the first step of static analysis, a consolidation pressure of 20 kPa is applied to the soil without SCC, and the load continues to consolidate the soil. Then in mode 1 (50 mm diameter and a=1/6), after installing the SCC with 40% cement, consolidation pressure of 20, 40, and 60 kPa is applied in 1440, 1440 and 4320 seconds, respectively. In mode 2 and 3, (100 mm diameter and a=1/3), consolidation pressure of 20, 40, 60 and80 is applied in 1440 seconds for each load.

In dynamic analysis, harmonic loads due to function of a machinery with stress amplitude of 20, 40 and 60 kPa, frequency of 5 Hz in 2 seconds (10 cycle) is applied on a 200 mm diameter base (Fig. 3).

a)



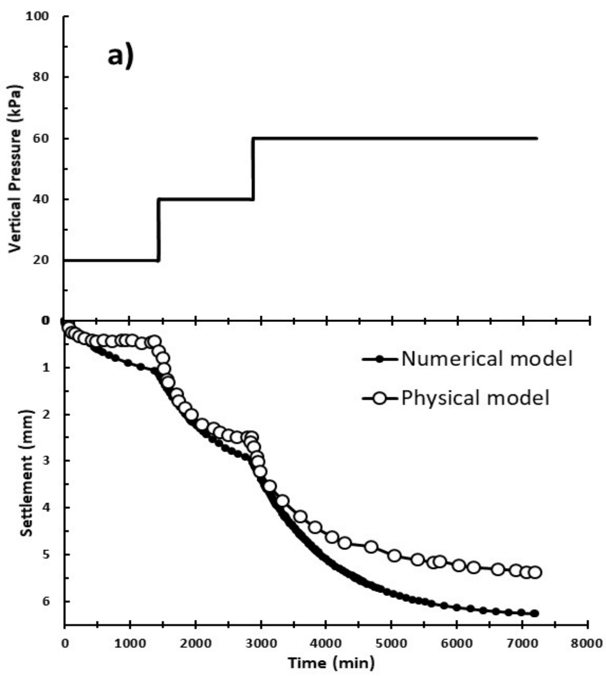
b)

Fig. 3 Axisymmetrical numerical model in dynamic analysis, (a) Harmonic load on the surface, (b) mesh sizes in dynamic analysis

V. RESULT OF STATIC ANALYSIS

Results of static analysis are given as change in vertical settlement, stress on column and soil and excessive pore pressure with time, in three modes of experiment mentioned in Table I. Also these results are compared with experimental results [12].

Fig. 4 shows diagrams of vertical settlement versus time of applied compression load in three modes of experiment. As it is seen, there is good agreement between experimental and numerical results of this study. By comparing Fig. 4 (a) with (b) and (c), it is clear that increase in improvement area (a) causes the settlements to decrease. Also with increasing cement content, settlements decrease but in slower rate.



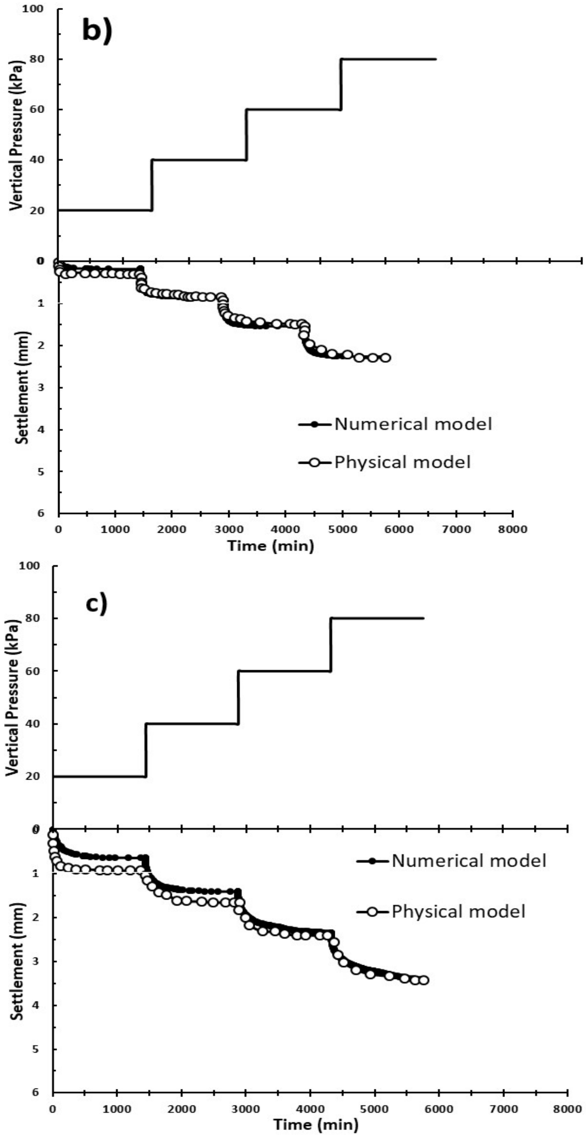


Fig. 4 Results of vertical settlement versus time and comparing with experimental results [12], (a) SCC with 50 mm diameter, a=1/6 and C=40%, (b) SCC with 100 mm diameter, a=1/3 and C=40%, (c) SCC with 100 mm diameter, a=1/3 and C=20%

Fig. 5 displays the results of stress on SCC and clayey soil in numerical and experimental results. As can be seen, stress on column is higher than that on soil. It can be implied that the SCCs have the main role in bearing capacity of these models. This is continued until SCC fails, and after that stress on soil is higher than stress on column [12]. Also, it can be understood from Fig. 5 that in the model with a=1/6, the stress on column is more than two times the stress on model with a=1/3. Also, with increasing cement content, stress on column decreases slightly, and this parameter has a little effect. Also by comparing the numerical and experimental results, a good correspondence between the results is seen especially in modes of 2 and 3.

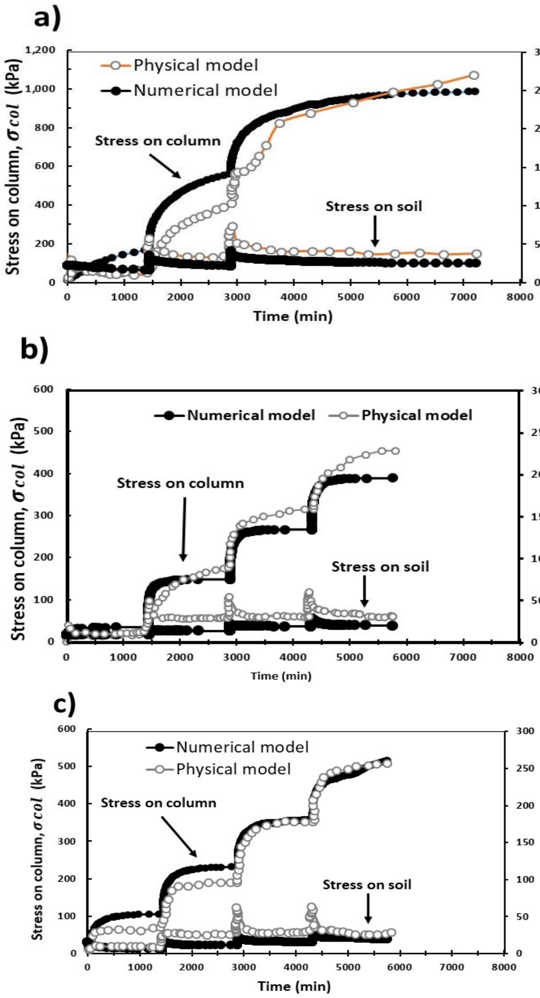


Fig. 5 Comparing the results of stress on column and soil with experimental test [12], (a) SCC with 50 mm diameter, a=1/6 and C=40%, (b) SCC with 100 mm diameter, a=1/3 and C=40%, (c) SCC with 100 mm diameter, a=1/3 and C=20%

Fig. 6 shows the results of excessive pore pressure in numerical and experimental results in three modes of experiment with load of 40 kPa, at the top, middle and bottom of the model, after 1min, 30 min and 120 min. It is seen that, as the time goes on, excessive pore pressure decreases. Decrease is higher at the top of the model, because the drainage takes place from top and the rate of dissipation is more at the top. Also excessive pore pressure in the model with 50 mm diameter of column, is higher than that with 100 mm diameter.

VI. Results of Dynamic Analysis

In dynamic analysis, mesh sizes should be finer than static analysis, which is considered 0.25 mm around the loading area. The absorbant boundaries should be farther than boundaries used in static analysis (Figs. 2 and 3). To model the harmonic load, a sinusoidal harmonic wave which is generated from machinery loading settled is applied on a 200 mm diameter foundation. The harmonic load has a frequency of 5 Hz and amplitude of 20, 40 and 60 kPa, as it is seen in Fig. 7. Duration time of applied load is 2 seconds (10 cycle), and duration time of rest after each loading step is 0.5 seconds to let the soil vibrate freely. To apply material damping, Rayleigh damping is calculated as (1) [14]:

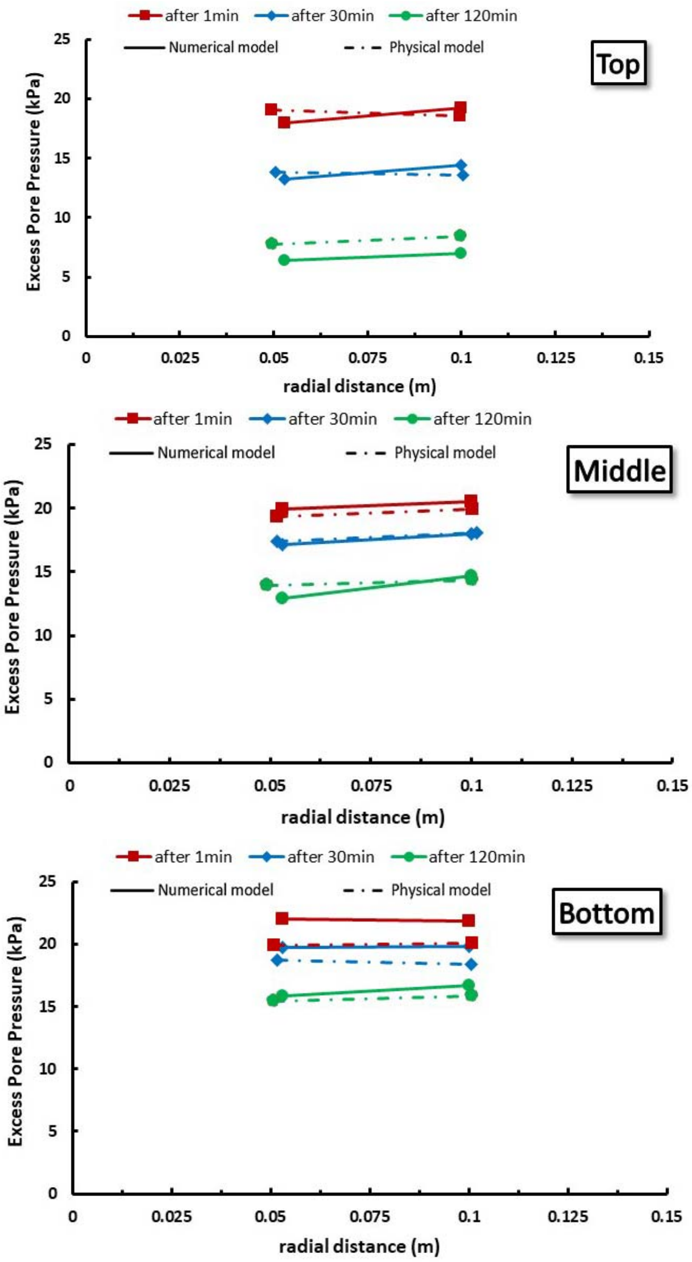
$$C = \alpha M + \beta K \tag{1}$$

wherein, C is the damping matrix, M is the mass matrix, K is the stiffness matrix, α and β are mass and stiffness constants respectively which are calculated as follows:

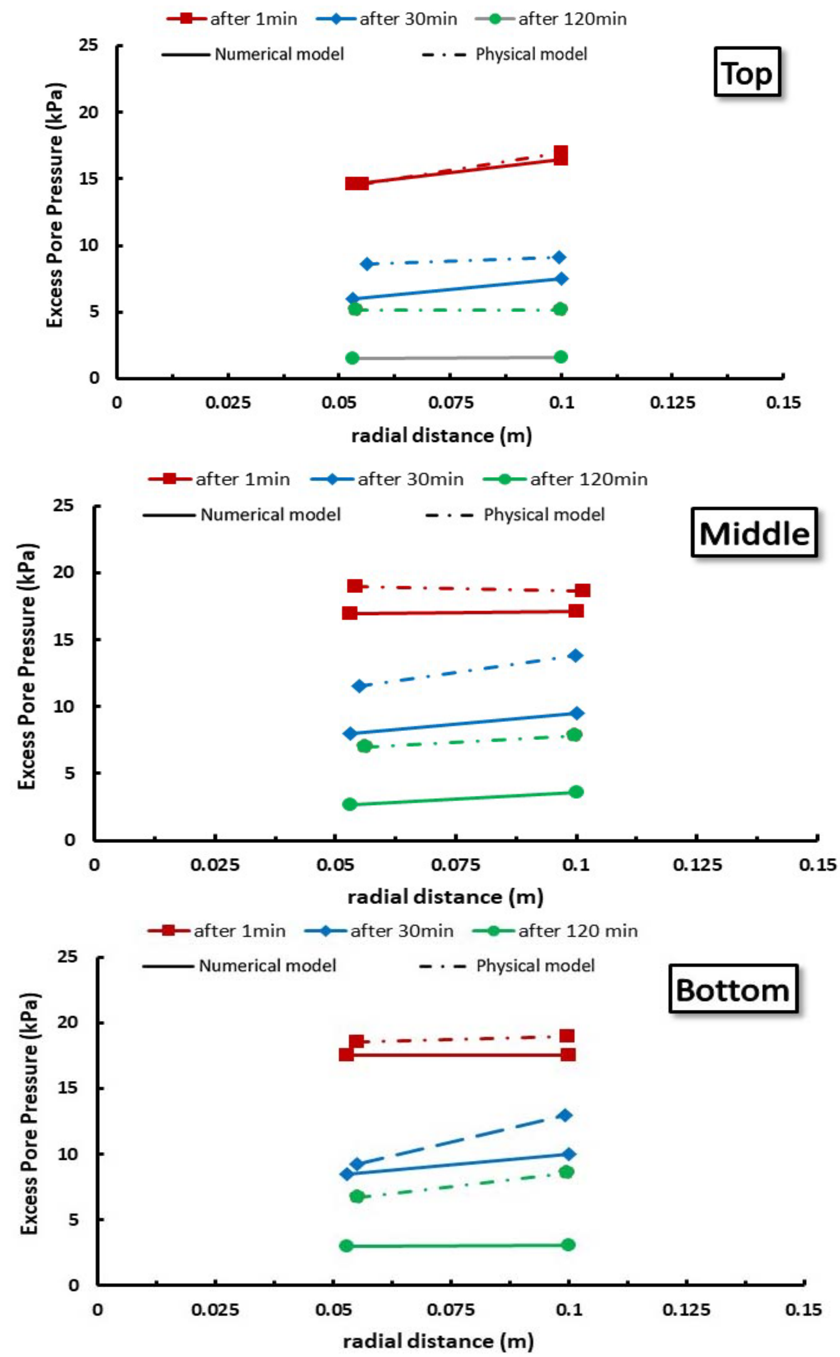
$$\alpha = \xi \omega_1 \tag{2}$$

$$\beta = \xi / \omega_1 \tag{3}$$

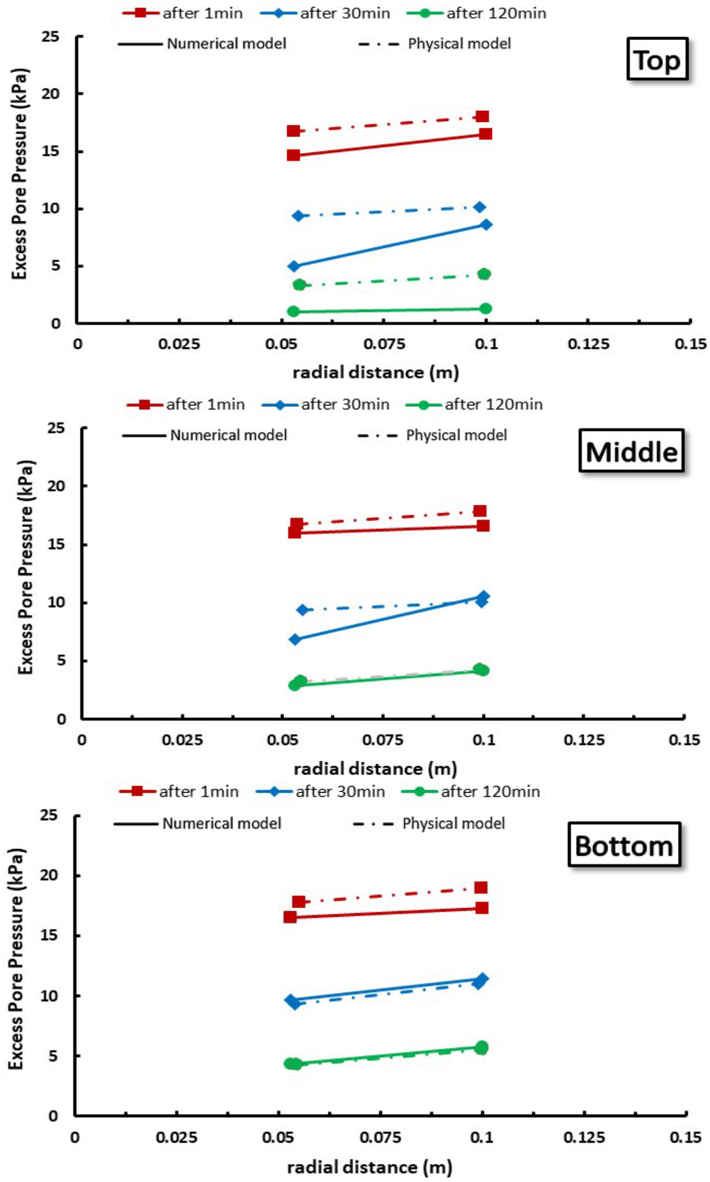
ξ is critical damping and is considered as 0.05, ω_1 is the circular frequency in first mode, which is calculated from free vibration, so, α and β are 8.9 and 0.00079 respectively.



(a) SCC with 50 mm diameter, a=1/6 and C=40%, under compression load of 40 kPa



(b) SCC with 100 mm diameter, a=1/3 and C=40%, under compression load of 40 kPa



(c) SCC with 100 mm diameter, a=1/3 and C=20%, under compression load of 40 kPa

Fig. 6 Comparing the results of excessive pore pressure with experimental test [12]

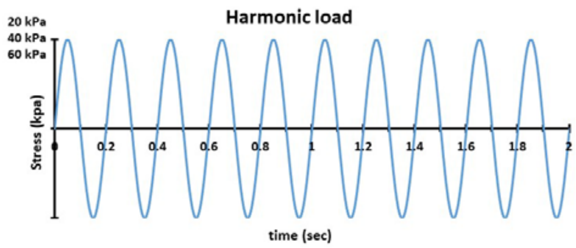


Fig. 7 Harmonic load applied in dynamic analysis for duration of 2 seconds

Fig. 8 displays the results of vertical settlement from harmonic load in three modes of experiment in Table I. As it is observed, pattern of change in vertical settlement under harmonic load is very different from that of static load. In the first mode, column with 50 mm diameter, the final settlement from applying harmonic load by amplitude of 60 kPa, reaches 14 mm, while in static analysis the settlement is 6 mm. it can be inferred that the model shows more compressibility under harmonic load than static load. This has been observed in other models too. Also, by increasing column diameter, vertical settlement increases, this may be due to increase in column stiffness and decrease in natural frequency until it is getting close to harmonic load frequency. Also with increasing in cement content, the settlement decreases slightly, this has also seen in static analysis.

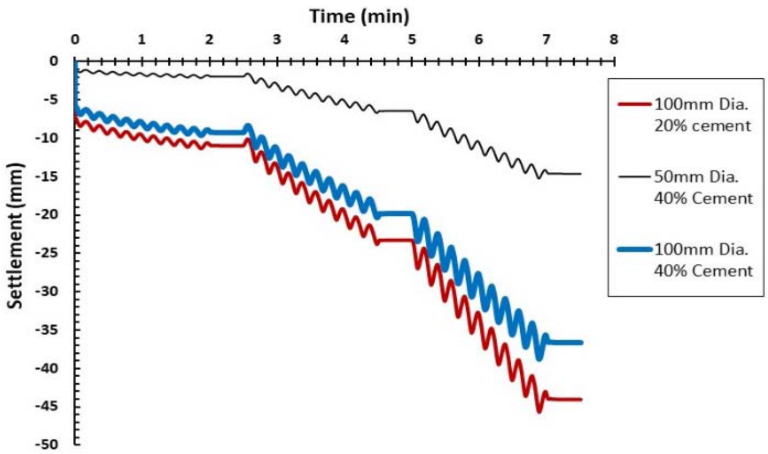


Fig. 8 Results of vertical settlement versus dynamic time under harmonic load

VII. Conclusion

In this study, a numerical model of soft clayey soil improved with SCCs based of experimental and numerical study of Horpibulsuk et al. [12] was performed in Plaxis 2D. The results of static analysis are compared with the experimental results of Horpibulsuk et al. [12]. In dynamic analysis, a harmonic load due to a machinery settled on a foundation on soil surface applied to the model. Conclusions from numerical analysis are as below:

1) By increasing the SCC diameter and also increasing the improvement area ratio (a), vertical settlement decreases significantly. In return, with increasing cement content, settlement decreases slightly.
2) By increasing improvement area ration (a), stress on column and soil decreases. Based on findings of Horpibulsuk et al. [12], stress on column before failure of SCC is higher than stress on soil. Therefore, increase in improvement area ratio (a) which decrease in stress on columns, improves the bearing capacity of the overall system. Also increase in cement content has no significant effect on decreasing the stress on soil and column.
3) By increasing the diameter of SCC from 50 mm to 100 mm, a significant decrease in excessive pore pressure has been observed. Moreover, in all models, excessive pore pressure dissipates rapidly at the top of model. Therefore, it is better in practical works to allow for two-way consolidation in soil to increase the bearing capacity of the system.
4) Results of vertical settlement under harmonic load, shows more compressibility comparing to static analysis. Also it was seen that, by increasing the diameter of SCCs, vertical settlement increases, and by increasing the cement content, settlement decreases.

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