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Settlement evaluation of soft ground reinforced by deep mixed columns

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Abstract

According to the similitude theory, a 1-g physical model test for soft ground with deep mixed columns was conducted. The effect of column length, area replacement ratio and surcharge load on foundation settlement was investigated. The column length was varied from 40 cm to 100 cm while the area replacement ratio was changed from 0.023 to 0.093. Test results show that the foundation settlement will decrease with the increase of column length when area replacement ratio and surcharge load are certain. There is a trend of increased settlement difference between foundation with longer column and shorter column as the increase of surcharge load. For the same column length, smaller foundation settlement will be generated by bigger area replacement ratio.

Keywords: Foundation settlement; Deep mixed columns; Column length; Area replacement ratio

1. Introduction

The Yellow River alluvial plain takes up about 1/3 of the whole area of Shandong Province in China, which is formed by silt, silty clay and silty sand. Silt is the main constituent of soils in this area, which is a kind of soft soil with high water content, high compressibility and low shear strength [1]. This kind of soft ground will cause big settlement for expressway foundation or differential settlement in the connection between bridge and freeway without reasonable ground improvement [2,3]. The deep mixed column foundations have been widely used for ground improvement to decrease the settlement and increase the bearing capacity of foundation. The technology of deep mixed columns will mix soft soils with cement, lime or a combination of both in situ to form hardened columns with a certain machine [4–6].

Numerous studies have been done in the past on the deep mixed column foundations, many of which focused on the properties of cement stabilized soil, bearing capacity or stability of the composite foundation. Chew et al. (2004) evaluated the microstructure and engineering properties of cement-treated marine clay. Their test results showed that the treated clay has a higher void ratio than the untreated clay at the same effective vertical stress, which could lead to higher permeability of cement-treated soil. It was also found that the permeability of cemented soil will decrease with an increase of curing period as hydrated calcium silicates and calcium aluminates are deposited onto clustered

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clay particles [7]. Lee et al. (2005) examined the effect or water-cement ratio and soil-cement ratio on the strength and modulus of cement treated Singapore marine clay [8]. Jamsawang et al. (2016) performed a three-dimensional numerical analysis of a field case study on an instrumented deep mixed column-supported embankment along the Bangbo-Klongdan highways. They concluded that it is necessary to consider the bending failure evaluation in the design of embankment supported by deep mixed columns so that field lateral load test was suggested to determine the moment capacity of the deep mixed columns, whereas it is not so necessary to conduct a field axial load test for the ultimate bearing capacity of one single column [9].

In terms of the settlement of deep mixed column foundations, a simple equation was suggested by Alamgir et al. (1996) to calculate the elastic settlement of a foundation improved by columnar inclusions [10]. Broms (1999) proposed a design procedure to estimate the deformation of a foundation reinforced by lime, lime/cement or/and cement columns [11]. Chai et al. (2010) presented a settlement prediction method for soft ground improved by floating deep mixed columns [12]. Jiang et al. (2013) did detailed parametric study by Plaxis to analyse the consolidation behaviour of soft soils fully-penetrated by deep-mixed columns [13]. However, there are still many uncertainties in the settlement calculation or prediction for deep mixed column foundations as the limitation of current theory and complicated mechanisms associated with this issue. Moreover, the design parameters of deep mixed column foundations should be based on quite many factors, such as the soil type and surcharge load [14–17]. As the in-situ test is not very cost-efficient or easy to control for parametric study, a physical model was made in this study for testing the factors influencing foundation settlement, including column length, surcharge load and area replacement ratio (which is defined as the ratio between the area of cross-section of stone column and the area of soil surrounding it) [18]. Fig. 2(a)–(c) show three kinds of area replacement ratio 0.023, 0.053 and 0.093, respectively.

2. Experiment

The factors for the settlement of foundation with deep mixed columns include the surcharge load P, the modulus of silt E_{ss}, the modulus of column E_{ps}, column length H, the area of single column m and the area replacement ratio M. The formula for the model test is shown as Eq. (1).

$$f(P, H, M, m, E_{ss}, E_{ps}) = 0 \tag{1}$$

in which, P and H are two basic physical parameters. According to the similitude theory, the other 4 dimensionless π parameters should be as follows [19]:

$$\pi_1 = M, \pi_2 = \frac{m}{H^2}, \pi_3 = \frac{E_{ss}H^2}{P}, \pi_4 = \frac{E_{ps}H^2}{P} \tag{2}$$

Then the Eq. (1) could also be written as:

$$F\left(M, \frac{m}{H^2}, \frac{E_{ss}H^2}{P}, \frac{E_{ps}H^2}{P}\right) = 0 \tag{3}$$

According to the similitude theory, the following equations could be obtained:

$$\begin{aligned}
&C_M = 1, \tfrac{C_m}{C_H^2} = 1, \tfrac{C_{E_{ss}} C_H^2}{P} = 1, \tfrac{C_{E_{ps}} C_H^2}{P} = 1 \\
&C_M = \tfrac{M_{model}}{M_{real}} = 1, C_m = \tfrac{m_{model}}{m_{real}} = 1:100, C_H = \tfrac{H_{model}}{H_{real}} = 1:10 \\
&C_P = \tfrac{P_{model}}{P_{real}} = 1:100, C_{E_{ss}} = \tfrac{E_{ss_{model}}}{E_{ss_{real}}} = 1, C_{E_{ps}} = \tfrac{E_{ps_{model}}}{E_{ps_{real}}} = 1
\end{aligned} \tag{4}$$

The set up for experiment is shown in Fig. 1. The dimension of the tank for physical modelling is 5 m*3 m*2.5 m, which is big enough for avoiding the boundary effect on foundation settlement. Otherwise it will not be easy and efficient to conduct experiment if the tank is too big. The silt for the model test is obtained from the Ji-Le expressway construction site (Northwest Part of Shandong Province) in the Yellow River alluvial plain. For the silt, the optimum water content is 13.6% and the maximum dry density is 1.67 g/cm^3. The height of silt in the tank is 2 m with 10 cm depth of gravels below. The silt was filled by 5 layers with each layer of 40 cm height. TRD-80 vibrator was used to compact the silt. The properties of silt in each layer are shown in Table 1. To make the columns, a 60 cm*60 cm area was excavated after filling of silt. The columns were made of normal portland cement with strength of 32.5 MPa in the PVC moulds with 5 cm diameter. The water to cement ratio of columns is 0.5 and the cement content is 15%. The cement mixture was put into the PVC mould layer by layer with the refilling of the silt around the PVC mould. The PVC mould was also lifted step by step with the filling of cement mixture. The columns were displaced like Fig. 2 for cases of different area replacement ratio.

The whole progress of testing is shown in Fig. 3. After the columns were cured for 7 days, the load was increased slowly by a jack above a plate. There were totally 6 steps of loading (2.8 kPa, 5.6 kPa, 8.4 kPa, 11.2 kPa, 14 kPa, 16.8 kPa), with each increased loading of 2.8 kPa. The settlement of plate was monitored by a dial indicator. When the settlement within 1 hour was less than 0.1 mm and this phenomenon was monitored again in the following 1 hour,

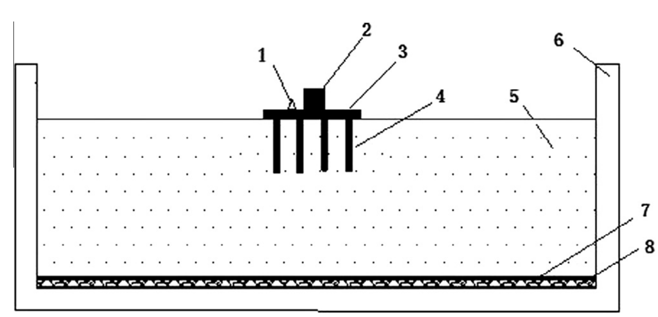
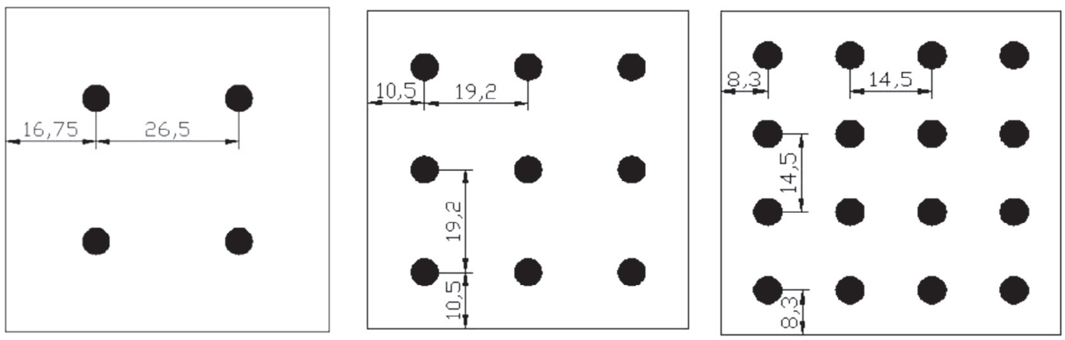


Fig. 1. Set up of experiment. Note: 1. Dial indicator 2. Jack 3. Plate 4. Column 5. Silt 6. Tank 7. Geotextile 8. Gravels.

Table 1
Properties of Silt in the Tank.

Layer	Water content (%)	Wet density (g/cm^3)	Dry density (g/cm^3)	Degree of compaction (%)
1	10.01	1.714	1.558	93.3
2	10.31	1.708	1.548	92.7
3	10.44	1.722	1.559	93.4
4	10.22	1.716	1.556	93.2
5	11.02	1.712	1.542	92.3



(a) area replacement ratio = 0.023 (b) area replacement ratio = 0.053 (c) area replacement ratio = 0.093

Fig. 2. Columns with different area replacement ratio.

Fig. 3. Progress of testing.

it could be defined that the settlement under the loading condition is stable. Then the next stage of loading would be added on the plate.

3. Test results and discussion

The common column length used in site usually varies from 4 to 20 m for deep mixed column foundations. To study the effect of column length and area replacement ratio on foundation settlement, there are 4 cases of column length (40 cm, 50 cm, 60 cm, 100 cm) and 3 cases of area replacement ratio (0.023, 0.053, 0.093) investigated in the physical model test. As the column length ratio for model test and in-situ condition is 1:10, the results of 40 cm column could represent 4 m column in the real construction project.

3.1. The effect of column length on foundation settlement

For each case of area replacement ratio (0.023, 0.053, 0.093), the effect of column length is shown in Figs. 4–6. From Figs. 4–6, it could be seen that for all cases the settlement of foundation will increase as the surcharge load increases. For the cases with area replacement ratio of 0.093 and 0.053, the displacement rate of shorter columns (40 cm and 50 cm) will have a big increase when the surcharge load is beyond 11.2 kPa. With the increase of surcharge load, the difference of settlement between foundation with longer column and shorter column will also increase, which can prove the significance of longer column under higher load. While for the foundation with area replacement ratio of 0.023, the settlement increment with surcharge load seems almost consistent for all the column lengths used in the test. It could also be found that the advantage of longer column for decreasing the settlement will be much more significant for the case with higher area replacement ratio. For different column lengths, the foundation settlement will decrease as the increase of column length at the same area replacement ratio and surcharge load. For the area replacement ratio of 0.093, the settlement of foundation with 10 m column is less than 50% that of foundation with 4 m column.

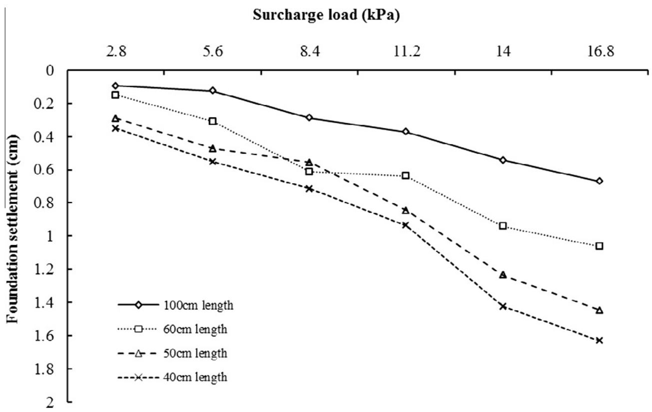


Fig. 4. Foundation settlement-load curve (area replacement ratio = 0.093).

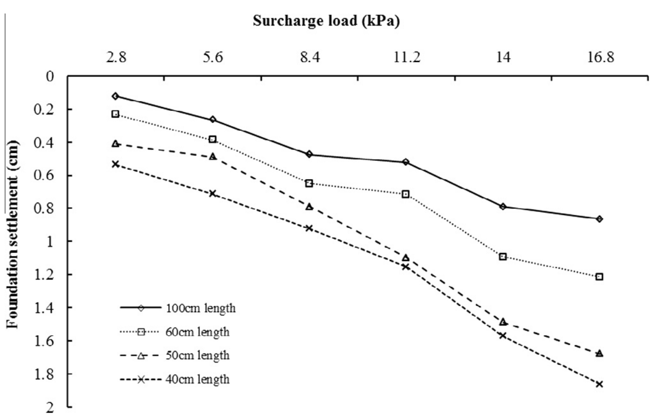


Fig. 5. Foundation settlement-load curve (area replacement ratio = 0.053).

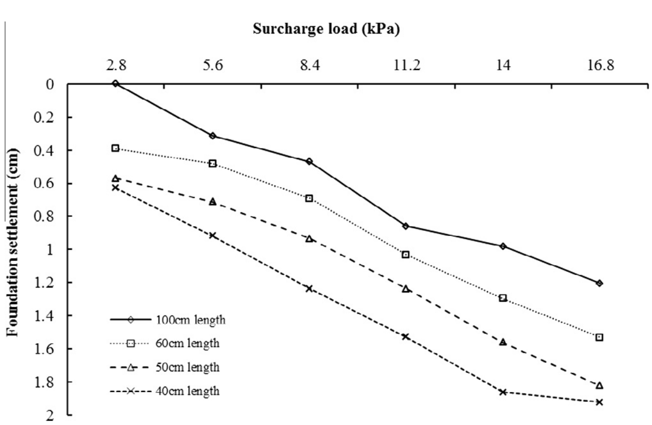


Fig. 6. Foundation settlement-load curve (area replacement ratio = 0.023).

3.2. The effect of area replacement ratio on foundation settlement

Figs. 7–10 show the effect of area replacement ratio on the settlement of foundation with column length varying from 40 cm to 100 cm. It also shows that the settlement

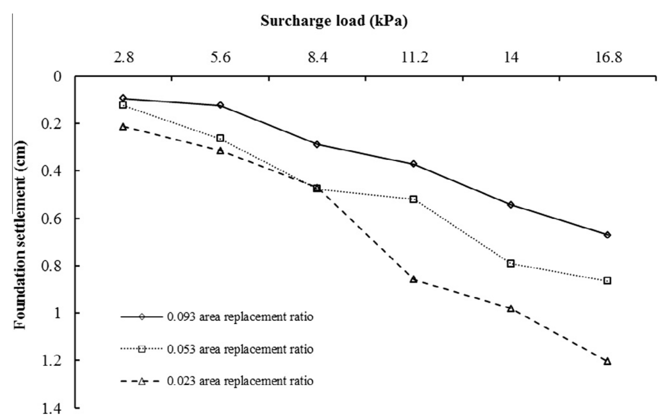


Fig. 7. Foundation settlement-load curve (column length = 100 cm).

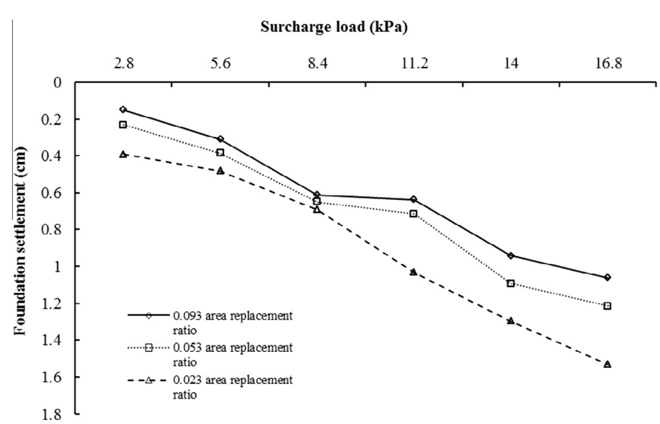


Fig. 8. Foundation settlement-load curve (column length = 60 cm).

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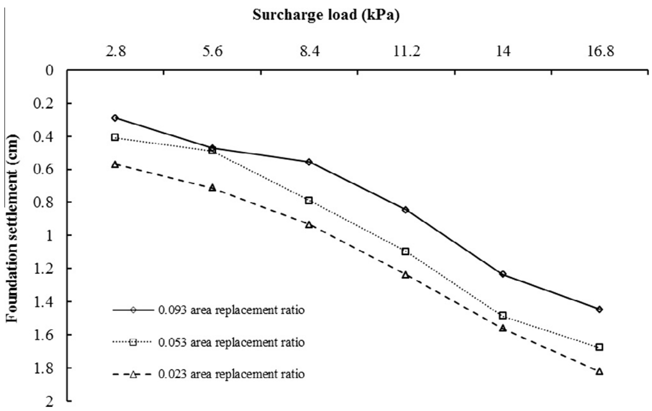

Fig. 9. Foundation settlement-load curve (column length = 50 cm).

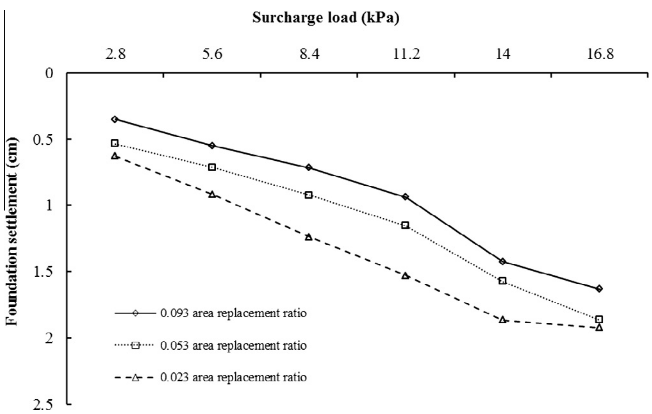

Fig. 10. Foundation settlement-load curve (column length = 40 cm).

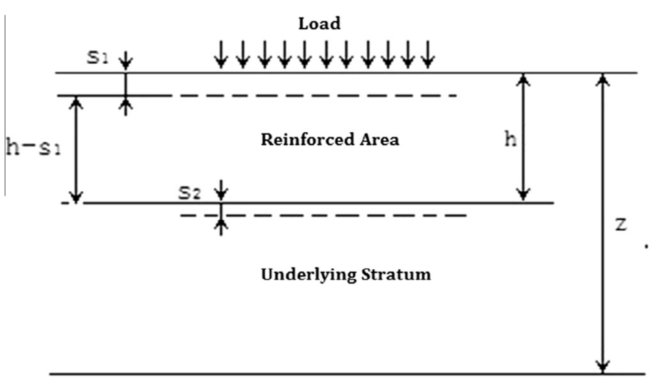

Fig. 11. Theoretical analysis diagram for foundation settlement.

of foundation will increase as the increase of surcharge load. It could also be seen that the foundation settlement will decrease with increase of area replacement ratio from 0.023 to 0.093 with certain column length and surcharge load. For example of foundation with 6 m column, the settlement of foundation with 0.093 area replacement ratio is 30% than that of foundation with 0.023 area replacement ratio. For longer columns (100 cm and 60 cm), the settlement difference between lower and higher area replacement ratios will be more obvious when the surcharge load is larger than 8.4 kPa. It may reveal that the function of area replacement ratio is more significant when the column length is longer. So the two parameters of column length and area replacement ratio should be considered together for a reasonable and economic foundation design.

3.3. Theoretical analysis

As shown in Fig. 11, there are two parts of settlement for the composite foundation (S): one is the settlement of reinforced area (S_1) while the other is the settlement of underlying stratum (S_2). The second part could take up more than 80% of the total settlement, which means that the settlement of reinforced area is quite small compared to the settlement of underlying stratum [20]. Splitting summation method is one common way to calculate the underlying stratum settlement. It will calculate settlement of different layers separately and then summarize all the settlement for getting the settlement of underlying stratum [21,22].

The method of *e–p* curve was adopted in this study and Fig. 12 shows the *e–p* curve for underlying stratum soils. In Fig. 12, *e* represents the void ratio of soil while *p* is the applied stress. Steeper *e–p* curve means higher compressibility of soil as the void ratio will decrease more significantly with the applied stress. The compressibility coefficient and modulus of compressibility for soil could also be obtained from the *e–p* curve. The overburden stress for each layer was also modified for calculation of settlement. Fig. 13 shows that the trend of both tested and calculated settlement is quite similar. The calculated settlement for underlying stratum is smaller than the tested settlement for the total foundation settlement. This is due

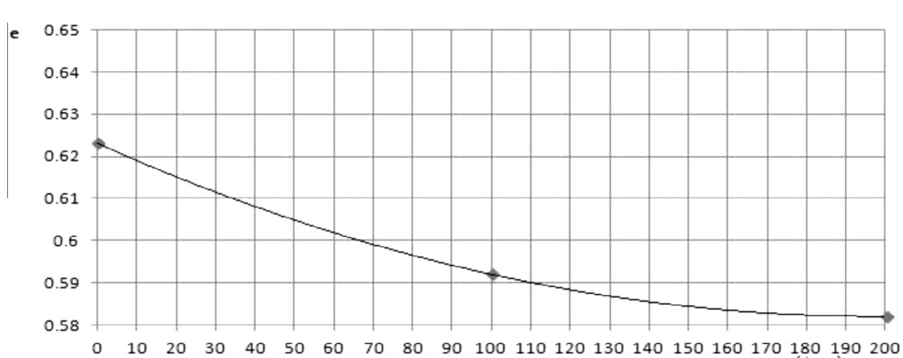

Fig. 12. *e–p* Curve for underlying stratum soils.

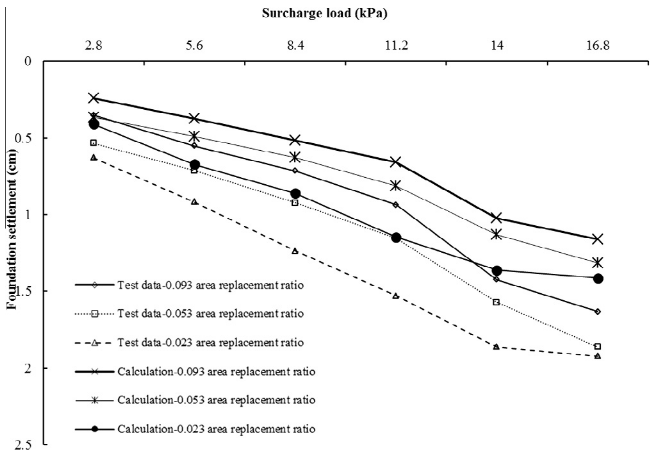

Fig. 13. Calculated and tested foundation settlement (column length = 40 cm).

to that the tested settlement also includes the settlement for the reinforced area (S_1). As there is lack of theory for calculating the settlement for the reinforced area, numerical analysis is suggested for future research about this.

4. Conclusions

It could be seen from the physical model test results that the settlement of foundation will increase when the surcharge load increases. The foundation settlement will decrease as the increase of column length at the same area replacement ratio and surcharge load. As the surcharge load increases, the settlement difference between foundation with longer column and shorter column will also increase. The foundation settlement will decrease with increase of area replacement ratio from 0.023 to 0.093 with certain column length and surcharge load. The trend of tested settlement matches well with calculated settlement. It seems that the advantage of longer column for decreasing the settlement will be much more significant for the case with higher area replacement ratio.

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