



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.

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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 of 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).

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

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]:

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

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

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

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

$$\begin{aligned} C_M &= 1, C_m = 1, \frac{C_{E_{ss}} C_H^2}{P} = 1, \frac{C_{E_{ps}} C_H^2}{P} = 1 \\ C_M &= \frac{M_{\text{model}}}{M_{\text{real}}} = 1, C_m = \frac{m_{\text{model}}}{m_{\text{real}}} = 1 : 100, C_H = \frac{H_{\text{model}}}{H_{\text{real}}} = 1 : 10 \\ C_P &= \frac{P_{\text{model}}}{P_{\text{real}}} = 1 : 100, C_{E_{ss}} = \frac{E_{ss\text{model}}}{E_{ss\text{real}}} = 1, C_{E_{ps}} = \frac{E_{ps\text{model}}}{E_{ps\text{real}}} = 1 \end{aligned} \quad (4)$$

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/cm³. 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,

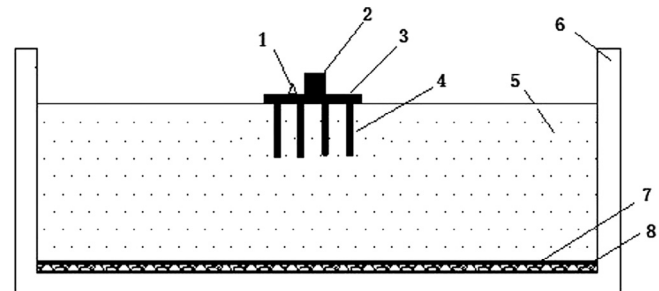


Fig. 1. Set up of experiment. Note: 1. Dial indicator 2. Jack 3. Plate 4. Column 5. Silt 6. Tank 7. Geotextile 8. Gravels.

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