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Consolidation of composite ground improved by granular columns with medium and high replacement ratio

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Abstract

As pointed out in the Technical Standards and Commentaries for Port and Harbour Facilities in Japan (2009), the consolidation rate of subsoil improved by the sand compaction pile with high replacement ratio tends to be delayed compared to that predicted by Barron's equation (1948). Moreover, the time delay in consolidation becomes greater with an increase in the replacement ratio. This finding cannot be interpreted by the conventional theories. In this context, this paper attempts to interpret this finding by employing two analytical models previously developed by the authors, and by taking the consolidation of column itself into consideration. Moreover, these two analytical models are further extended to predict the consolidation rate under multiple instantaneous loading and multiple ramp loading. Then they are compared to a conventional model with no consideration of column itself. The results show that the conventional model, which does not consider column consolidation, will overestimate the average degree of consolidation, and that the overestimated value increases exponentially with the increase in the replacement ratio. Especially in the case of medium and high replacement ratios, the maximum overestimated average degree of consolidation may increase from 12% to 43% when the replacement ratio increases from 0.4 to 0.8. The time delay observed when using these two analytical models in predicting the consolidation rate is in good agreement with the finding revealed in the Technical Standards and Commentaries for Port and Harbour Facilities in Japan (2009). In particular, a simple relation is derived to calculate the time delay in a simple and explicit way. Finally, the present models are applied to a case study to verify their feasibility in predicting settlement during consolidation.

Keywords: Consolidation; Average degree of consolidation; High replacement ratio; Medium replacement ratio; Composite ground

1. Introduction

As pointed out in the Technical Standards and Commentaries for Port and Harbour Facilities in Japan (2009), a granular column (such as stone column and sand compaction pile, namely SCP) can be categorized according to its replacement ratio α_s, i.e., a high replacement ratio $\alpha_s \geqslant 0.7$; a medium replacement ratio $0.4 < \alpha_s < 0.7$; or a low replacement ratio $\alpha_s \leqslant 0.4$. Various types of granular columns with medium and high replacement ratios have been utilized worldwide to reinforce soft soils by accelerating their consolidation rate and improving their shear strength. Compared to the prefabricated vertical drain (PVD) and sand drain well, the primary characteristics of granular columns with medium and high replacement ratio lie in their much larger diameters (Han and Ye, 2001, 2002) as well as their higher compression modulus (Yoshikuni, 1979). Up till now, most of the analytical theories for the

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consolidation of composite ground improved by granular columns (Yoshikuni, 1979; Han and Ye, 2001, 2002; Zhang et al., 2006; Xie et al., 2009a; Castro and Sagaseta, 2009; Xie et al., 2009b) only took into account the effect of the higher compression modulus by considering the stress transfer from the surrounding soil to the granular column in the process of consolidation. However, because the effect of the large diameter has been given little attention, errors in predicting the consolidation rate are commonplace. As pointed out in the Technical Standards and Commentaries for Port and Harbour Facilities in Japan (2009), the consolidation rate of subsoil improved by the sand compaction pile method tends to be delayed compared to that predicted by Barron's equation (1948), moreover, the time delay in consolidation becomes greater with an increase in the replacement ratio. This issue cannot be interpreted by the above-mentioned theories.

For this reason, this paper attempts to interpret this issue using an analytical approach. The consolidation of the column itself is taken into account and is regarded as the key for the analysis of consolidation of composite ground in the case of medium and high replacement ratios. In light of this, this paper employs two analytical models developed previously by the authors, to consider the consolidation of column itself in two different ways, and extends them to predict the average degree of consolidation under multiple instantaneous loadings and multiple ramp loadings. Moreover, the consolidation characteristics of the composite ground improved by granular columns with medium and high replacement ratios is investigated by comparing them to those predicted by a conventional theory which does not consider column consolidation. In addition, the time delay to attain a certain average degree of consolidation caused by these two analytical models is derived in a simple and explicit way. Finally, these two analytical models are applied to a case study to verify the feasibility of predicting the average degree of consolidation.

2. Theories of consolidation for composite ground improved by granular column with high replacement ratio

The consolidation theories for composite ground improved by granular columns are developed on the basis of that for a sand drain (Barron, 1948). For this reason, some basic assumptions adopted in the sand drain theories are utilized directly with no verification of their feasibility to composite ground improved by granular columns; this is especially problematic for columns with large diameters. For example, the equal flow assumption around the sand drain-soil interface has been commonly used in analytical studies focussed on the consolidation of the sand drain (Zeng and Xie, 1989; Tang and Onitsuka, 1996; Chai et al., 1997; Leo, 2004; Zhu and Yin, 2004; Walker and Indraratna, 2006) by assuming the water flowing into the sand drain along the radial direction is equal to that discharging from it along the vertical direction. This implies the water quantity within the sand drain is held constant, and that deformation will therefore not occur in the sand drain itself during consolidation. This is because deformation is generally regarded as the result of the discharging of water. This assumption is illogical and incompatible with the equal strain assumption that the settlement of the sand drain is equal to that of the surrounding soil at any time. From this point of view, the nature of the incompatibility between these two assumptions can be attributed to the neglect of the consolidation of sand drain itself. In the case of granular columns with medium and high replacement ratios, the effect of consolidation of the column itself is significant and should not be neglected for the sake of its much larger diameter compared to the sand drain. Therefore, the breakthrough to capture the characteristic of consolidation of composite ground improved by granular columns with medium and high replacement ratios lies in considering the consolidation of columns as well as the consolidation of the surrounding soils. Then, the analysis of consolidation can be started by modifying or removing the equal flow assumption at the soil-column interface.

Xie et al. (2009b) modified the equal flow assumption by assuming a difference exists between the water quantity flowing into the column and that discharging from it, and this difference is equal to the deformation of the column. In this way, the incompatibility between the equal flow assumption and the equal strain assumption was compromised; that is, the consolidation and the deformation of the column itself was considered to be compatible. Based on this modification, they developed an analytical model (hereinafter referred to as Model A) for the consolidation of composite ground improved by granular columns.

From another standpoint, Lu et al. (2010) supposed there are not only vertical flows but also radial flows within the granular column. For the sake of columns with a large radius, the water flowing into it was allowed to continue to flow until it arrived at its centerline (served as an impervious boundary condition) along the radial direction. At the soil-column interface, the equal flow assumption was removed and replaced by the continuous conditions of equal excess pore pressure and equal flow velocity. In this way, the consolidation of the column itself with coupled radial and vertical flows was analyzed in the same way as it is for the surrounding soil. Hereinafter this analytical model for consolidation of composite ground with granular columns is referred to as Model B.

By taking into account the consolidation of the column, these two analytical models can be employed to deal with the consolidation of composite ground improved by granular columns with medium and high replacement ratios.

Referred to the studies by Xie et al. (2009b) and Lu et al. (2010), the analytical solutions for the average degrees of consolidation of Model A and Model B is given in a unified form as follows:

$$U(t) = 1 - \sum_{m=1}^{\infty} \frac{2}{M^2} e^{-\beta_m t} \tag{1}$$