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An estimation method for predicting final consolidation settlement of ground improved by floating soil cement columns

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Abstract

Ground improvement using floating soil cement columns with shallow stabilization is an effective technique for the treatment of deep soft soil layers under infrastructure embankments. In order to investigate the settlement performance of this improvement technique, model load testing of model column analogues for visualization of ground behavior under plane strain conditions was performed and field observations at full scale test embankments were investigated.

The results of model testing and field investigation show that the ground below an embankment founded on a floating column system can be considered as two separate layers with a confined portion and a consolidating layer which can be related to the degree of improvement used at a particular site such as the improvement ratio and the depth of improvement.

A simplified estimation method for final consolidation settlement is proposed using a stress distribution ratio which considers the contribution from skin friction at the surface of floating columns. The advantage of this method is that is possible to determine the consolidating layer thickness as a function of simple parameters such as the degree of improvement, loading conditions and undrained soil strength. The predicted settlements of the improved ground correspond well to that measured in full scale case studies.

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Keywords: Ground improvement; Soft soils; Floating soil cement column; Shallow stabilization Consolidation (IGC: E02, K06)

1. Introduction

The requirement to reduce both costs and environmental impact have recently become important factors influencing the construction and design of soil structures for utilization in key transport infrastructure. Therefore, it is essential to develop construction techniques aligned with the demands and diversity of current transport infrastructure performance requirements. Ground improvement using cement mixed columns is one effective technique for reducing settlement and stability of deep soft clay deposits under embankments for transport infrastructure such as major highways and rail transport routes. In this form of improvement, firstly, cement mixed columns are installed (a 1 m diameter is typical in Japan) to a specified depth in soft clay deposits. The upper near surface zone (typically 1–3 m in depth) is then excavated and mixed with cement ex-situ before replacement and compacted in the excavation to form a shallow stabilized layer.

Where the column tip interacts with underlying competent layers such as dense sand or rock head, the columns are referred to as end bearing columns, and while these are frequently used, shorter floating columns with shallow stabilization are seeing more frequent utilization due to both construction cost savings and reduced raw material use, as shown in Fig. 1. Furthermore, this combined technology has the potential to be very effective in the treatment of deep soft soil layers where installing extending

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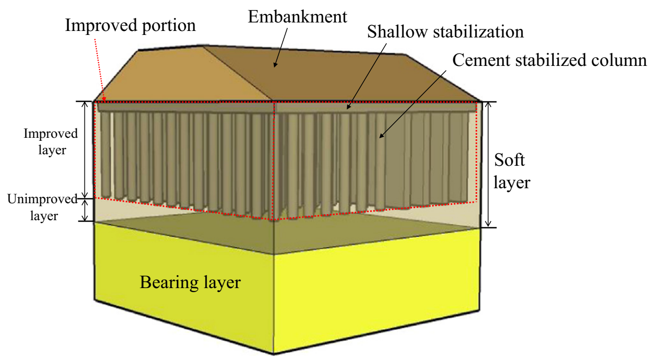

Fig. 1. Schematic representation of shallow stabilization by the floating cement mixed column method.

columns to a bearing layer is neither cost effective or practical due to equipment depth limitations.

Based upon the results from full scale monitoring of case studies, the cement mixed floating column (CMFC) technology has been shown to provide acceptable settlement performance for low settlement tolerance road schemes or large infrastructure embankments on soft ground. In order to allow full utilization of this technique, it is essential to develop a simplified design method to predict settlement reduction related to the degree of improvement and in-situ soil characteristics such as the improvement ratio, depth of column installation and the soils initial undrained shear strength (Ishikura et al., 2009a).

Currently, the calculation of the resulting ground settlement with end bearing columns is based upon a stress distribution ratio approach where the stress is distributed over the soil and columns, and settlement is calculated based upon the ratio of stiffness of the soft clay to the stiffness of the columns, assuming uniform strain below the embankment (Kitazume,2005; Kitazume and Terashi, 2012). While this approach has been investigated in detail (Chow, 1996; Horpibulsuk et al., 2012), investigation of the floating type composite ground has received relatively limited attention (e.g., Jung et al., 1999; Ng and Tan, 2014). Despite this, however, methods for predicting settlement of ground improved by floating soil cement columns have been previously proposed (JICE, 1999; Bergado et al., 1994; Miki and Nozu, 2004). Typically these are based on the settlement of two layers, which are considered improved and unimproved, as shown in Fig. 1. In the method proposed by JICE (1999), an improvement ratio a_p is introduced which is the ratio of the column area to the area of shallow stabilization (or in practical terms the overlying soil structure). If the improvement ratio a_p (%) is more than 30%, the unimproved layer (i.e., that below the columns) is regarded as a consolidating layer; while if a_p (%) is less than 30%, one-third of the improved layer is also regarded as contributing to consolidation settlement. The extent to which the improved layer contributes to settlement (i.e., typically assumed to be one-third depth) is thought to have its origins in the concept of the equivalent raft method for calculating pile group settlement (Tomlinson and Woodward, 2008) where the pile group is assumed to transfer the load to the soft soil layer through skin friction at an elevation corresponding to 2/3 of the pile length below the top of the piles.

Determining the extent of the consolidating layer within the improved layer is key to making accurate calculations of the system settlement. In order to determine the extent of the consolidating zone within that of the improved layer, a unit cell parametric study using FEM was performed (Chai et al., 2010). From the curve fitting of the analytical consolidation settlements, bilinear functions with variables of the improvement ratio and the improvement depth H_1 were proposed to determine the proportion of the consolidating zone within the improved layer. However, this method is still empirical due to the analytical approach and has not been sufficiently validated in relation to the various potential improvement scenarios and other controlling parameters.

Previous work has shown that column skin friction, which is often ignored in settlement assessment, has the potential to be a significant contributor to the behavior of the floating system (Miura et al., 1995, 1998). The magnitude of the skin friction contribution has also been shown to be both time and strain level dependent (Ishikura et al., 2013). As the origins of the position of the consolidating layer seems to be linked to the transfer of stress to the surrounding ground via skin friction, it follows that the influence of skin friction needs to be fully considered and its effect on the position of the consolidating layer needs to be investigated.

Firstly, this study investigates the group effect of the floating column-shallow stabilization composite in a plane strain model soil bed undergoing consolidation with visual observation of settlement. From the results, the influence of improvement variables on the degree of consolidation settlement and the contribution of skin friction are discussed. By applying image analysis to the model test results, the strain distribution in the improved and unimproved zones was used to inform the likely mechanisms for settlement and the extent of the consolidating zone as well as the degree of contribution from the column skin friction.

Secondly, a simplified method to determine the proportion of the consolidation zone for calculating total settlement of the improved ground is proposed which takes account of improvement conditions (column stiffness, improvement ratio and depth), loading regime and soil strength. The extent of the consolidating zone within the improved layer is obtained based upon a stress distribution ratio which considers the contribution from skin friction at the surface of floating columns. Finally, the validity of the approach is shown through comparisons with field measurements at two different case study sites.

2. Visualization of ground behavior under model plane strain conditions

2.1. Outline of model testing

Fig. 2 and Photo 1 shows the apparatus used to perform model tests under plane strain conditions. The apparatus consisted of a rigid walled cell of plan area 250 by 100 mm and 400 mm in depth. The panels of the container were all made from transparent Perspex which allowed observation of deformation of the model soil on the front face during loading/consolidation. The model arrangement allowed drainage from both the upper plate via a clearance gap of 2.5 mm around the outer edge of the upper loading plate and the bottom of the cell via a layer of porous

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