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Effect of vacuum removal on consolidation settlement under a combined vacuum and surcharge preloading

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ABSTRACT

The combined vacuum and surcharge preloading technique is extensively used to accelerate the consolidation process of subsoils. The effect of vacuum pressure is often considered as a loading/unloading cycle of mean effective stress, such that elastic rebound occurs after vacuum removal, which cannot explain the observed postconstruction settlement in the field. In this study, the stress state of subsoils subject to vacuum and surcharge preloading is analyzed and decomposed into two components: (a) geostatic consolidation at a different depth, and (b) loading/unloading in the minor principal stress direction. A series of consolidated drained triaxial tests is conducted to simulate the soil behaviour after vacuum removal. Results show that the contribution of unloading in the minor principal stress direction outweighs the magnitude of elastic rebound after vacuum removal, and hence continued settlement dominates. A field case for highways is provided to further demonstrate the proposed mechanism.

1. Introduction

Soft clayey soils are widely distributed in the southeastern coastal plain or in the alluvial plain deposited by large rivers from highland regions in China. Land reclamation projects are also rapidly developing in coastal cities in China, where dredged clay slurry is extensively employed to form reclaimed lands using the hydraulic fill technique. Soft (dredged) estuarine or marine clays could cause geotechnical problems for infrastructure above them due to their undesirable properties, such as high water content, large void ratio, high compressibility, low strength, low permeability, and low bearing capacity (Indraratna et al., 2010). Hence, ground improvement needs to be implemented on the site before any construction can be carried out. The purpose of ground improvement is two-fold: (a) increasing the bearing capacity of subsoils, and (b) allowing the site to experience consolidation settlement prior to construction to minimize further settlement or differential settlement for infrastructure.

Preloading is the most widely used ground improvement technique, which can help to accelerate the consolidation process for soft soils. Different types of approaches have been developed to exert preloading to subsoils, such as surcharge preloading (Guo et al., 2018; Mei et al., 2018; Ni et al., 2018b; Wang et al., 2018b; Yao et al., 2018), vacuum preloading (Shang et al., 1998), wellpoint dewatering, and electro-osmotic treatment (Liu et al., 2014), or any combination of these methods. Based on the field experience in Japan, Chai et al. (2006) indicated that the combined vacuum and surcharge preloading technique was the most effective approach in terms of reducing lateral displacements in subsoils, increasing the effective stress of subsoils, and reducing the consolidation time. Similarly, the advantages of combined vacuum and surcharge preloading over other techniques based on a single preloading approach have been observed in ground improvement projects at the Port of Tianjin, China (Rujikiatkamjorn et al., 2007), at the Port of Brisbane, Australia (Indraratna et al., 2011) and at the Suvarnabhumi Airport, Thailand (Voottipruex et al., 2014).

Fig. 1 illustrates the schematics of the combined vacuum and surcharge preloading method. In the soft soil zone, vertical and horizontal drains are introduced to allow radial and vertical drainage of excess pore water pressure. A pump is used to exert vacuum load (suction) to the zone within the impervious membranes. After a period of vacuum preloading (e.g., several weeks), embankment surcharge can be applied in stages to further accelerate the consolidation of subsoils (Yan and Chu, 2005). This technique has been used commonly in the field for soft ground improvement. For example, Chu and Yan (2005) suggested to measure pore water pressures in the field to interpret the average

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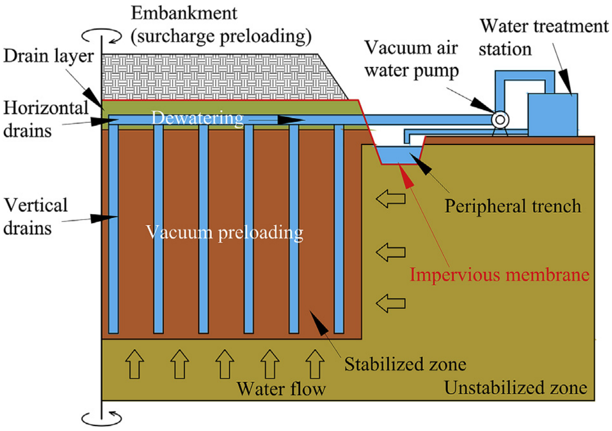

Fig. 1. Schematics of the combined vacuum and surcharge preloading method.

degree of consolidation rather than using settlement data. Long et al. (2015) emphasized the importance of implementing airtight membranes for vacuum consolidation. Wang et al. (2016) proposed to connect all prefabricated vertical drains (PVDs) to a horizontal vacuum pipe directly to increase the efficiency of vacuum preloading. Distributed horizontal sand caps can be employed to save aggregates without causing delays in the construction schedule (Chen et al., 2018; Ni et al., 2018b; Yao et al., 2018). Cai et al. (2017) suggested a new type of integrated PVDs with adhered filters, and similar improvement for vertical drainage paths can be achieved by using permeable pipe piles (Ni et al., 2017, 2018a) or pervious concrete piles (Suleiman et al., 2014). The slurry can also be pretreated with sand to avoid clogging of vertical drains (Wang et al., 2018a).

Based on the success of field applications of the combined vacuum and surcharge preloading technique, extensive investigations have been performed to facilitate the prediction of field settlement. Researchers developed different analytical solutions (Mohamedelhassan and Shang, 2002; Chai et al., 2005; Indraratna et al., 2005; Rujikiatkamjorn and Indraratna, 2007; Tran and Mitachi, 2008; Geng et al., 2011; Lam et al., 2015) under the following assumptions: (a) the vacuum pressure differs insignificantly along the depth of vertical drains, (b) the effect of vacuum load is equivalent to the application of surcharge load, (c) the vacuum load can be simplified as an additional isotropic incremental stress (mean effective stress), and (d) soil deformations in both vertical and horizonal directions are correlated (Mesri and Khan, 2012; Cai et al., 2018). All derived analytical models were solved numerically by introducing equivalent permeability and transformed unit cell geometry for vertical drains and advanced constitutive models for soils (Chai et al. 2001, 2013, 2014; Shen et al., 2005; Rujikiatkamjorn et al., 2007, 2008; Ma et al., 2011; Saowapakpiboon et al., 2011; Voottipruex et al., 2014; Lam et al., 2015; Wu et al., 2015; Zhang et al., 2015; Chen et al., 2016). In addition, consolidation tests have been conducted in the laboratory to simulate the behaviour of PVD improved soft ground under a combined vacuum and surcharge preloading (Saowapakpiboon et al. 2010, 2011).

Most previous studies provided calculations of settlement for subsoils under a combined vacuum and surcharge preloading by assuming that elastic rebound governs (reduced settlement) when the vacuum pressure is removed (due to decreased isotropic effective stress). In reality, further settlement could occur in subsoils after the vacuum pressure is removed, which is dependent on the degree of consolidation at the point of vacuum removal (Shang et al., 1998; Indraratna et al. 2004, 2010, 2011; Mesri and Khan, 2012; Liu et al., 2014; Long et al., 2015; Wang et al., 2016). Without taking into account the continued settlement after removal of vacuum, all predictions will inevitably result in an underestimation of postconstruction settlement upon the completion of combined vacuum and surcharge preloading. Undrained bearing capacity failure could also occur after vacuum removal (Lou and Yin, 2006).

In this investigation, the stress state of subsoils under a combined vacuum and surcharge preloading is systematically analyzed. The mechanism of postconstruction settlement after vacuum removal is explained by a combined action of (a) changes in geostatic stress by moving the soil element to a different depth, (b) loading/unloading the soil element in the minor principal stress direction. A series of consolidated drained triaxial tests is conducted on undisturbed and remoulded soil specimens following different stress paths, being designed to simulate the behaviour of soil consolidation during vacuum preloading/removal and surcharge preloading. At the end, a case history of ground improvement for highways under a combined vacuum and surcharge preloading is presented, and the measurements are compared against calculations from simplified analysis and numerical simulations.

2. Mechanism of combined vacuum and surcharge preloading

2.1. Stress state analysis of soil under surcharge preloading

Surcharge preloading will result in an additional stress field in subsoils, which corresponds to the generation of excess pore water pressure under the undrained condition. Although the permeability of clayey soils is low, the excess pore pressure will dissipate with time slowly, and eventually the effective stress in subsoils will increase. The process of consolidation involves the dissipation of excess pore pressure, the decrease of soil volume (i.e., consolidation settlement), and the increase of soil strength. Vertical drains, such as sand drains, sand bags, and PVDs, are often installed in the field to provide drainage paths to reduce the consolidation time.

As shown in Fig. 2, a uniformly distributed surcharge load P is applied instantaneously on the ground surface within a width L. The subsoil is assumed as a homogeneous infinite isotropic elastic medium, where its compressibility is governed by the reduction of void volume only (i.e., soil particles and pore water are incompressible). The groundwater table is at the surface of the soil medium, such that the subsoil is fully saturated. At an arbitrary point M below the ground surface, the additional stresses can be calculated as:

$$\begin{cases} \sigma_{a1} = \frac{P}{\pi}(2\beta + \sin 2\beta) \\ \sigma_{a3} = \frac{P}{\pi}(2\beta - \sin 2\beta) \end{cases} \tag{1}$$

where σ_{a1} and σ_{a3} are the major and minor principal stresses, respectively; and the term 2β is the angle from point M to both edges of the uniformly distributed load.

In practice, the subsoil has already experienced the consolidation process under geostatic stress σ_{10} and σ_{30}. The additional stress field of σ_{a1} and σ_{a3} will cause the development of excess pore water pressure u,

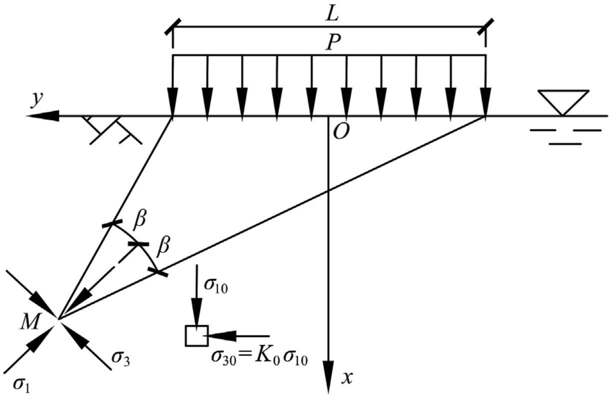

Fig. 2. Stress state of soil subjected to surcharge preloading.