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Laboratory model study of newly deposited dredger fills using improved multiple-vacuum preloading technique

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ABSTRACT

Problems continue to be encountered concerning the traditional vacuum preloading method in field during the treatment of newly deposited dredger fills. In this paper, an improved multiple-vacuum preloading method was developed to consolidate newly dredger fills that are hydraulically placed in seawater for land reclamation in Lingang Industrial Zone of Tianjin City, China. With this multiple-vacuum preloading method, the newly deposited dredger fills could be treated effectively by adopting a novel moisture separator and a rapid improvement technique without sand cushion. A series of model tests was conducted in the laboratory for comparing the results from the multiple-vacuum preloading method and the traditional one. Ten piezometers and settlement plates were installed to measure the variations in excess pore water pressures and moisture content, and vane shear strength was measured at different positions. The testing results indicate that water discharge–time curves obtained by the traditional vacuum preloading method can be divided into three phases: rapid growth phase, slow growth phase, and steady phase. According to the process of fluid flow concentrated along tiny ripples and building of larger channels inside soils during the whole vacuum loading process, the fluctuations of pore water pressure during each loading step are divided into three phases: steady phase, rapid dissipation phase, and slow dissipation phase. An optimal loading pattern which could have a best treatment effect was proposed for calculating the water discharge and pore water pressure of soil using the improved multiple-vacuum preloading method. For the newly deposited dredger fills at Lingang Industrial Zone of Tianjin City, the best loading step was 20 kPa and the loading of 40–50 kPa produced the highest drainage consolidation. The measured moisture content and vane shear strength were discussed in terms of the effect of reinforcement, both of which indicate that the multiple-vacuum preloading method has a better treatment effect not only in decreasing the moisture content and increasing the bearing capacity, but also in increasing the process uniformity at different depths of foundation.

1. Introduction

China is one of the countries with unique topographic and geomorphic conditions and complicated engineering geology, resulting in extremely complex technical problems in building transportation infrastructure. Key researches have been conducted recently on soft subgrade treatment, paving bituminous pavement in extremely cold areas with frozen soil, constructing long and large tunnels in mountainous areas, and building bridges with great span and high piers. Among all of these key researches, soft subgrade treatment is one of the most important issues, especially in coastal regions of China. With the development of economics, the conflict of rare land source is marked as part of the urbanization process. Therefore, newly deposited dredger fills from a harbor basin or a sea channel are hydraulically placed in seawater for land reclamation in recent years. The newly deposited dredged soil is usually a new hydraulic mud, which contains a large number of fine soil particles and has high moisture content. These properties indicate that the dredged soil is ultra-soft and highly compressible.

Studies have been conducted on properties of this kind of ultra-soft soil both in laboratory and field tests (Masse et al., 2001; Chu

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et al., 2008; Bo et al., 2011; Cai et al., 2012; Ye et al., 2012; Lei et al., 2013, 2016a,b). Among all the ground treatment methods, vacuum preloading method firstly introduced by Kjellmen (1952) has become most popular because it is capable of mitigating the unacceptable differential settlements caused by the heterogeneity and high compressibility of soft soil deposits. Literature and engineering projects both indicate that the vacuum preloading method is an effective technique for the treatment of soft soil deposits, especially for the new dredger fill deposits (Qian et al., 1992; Cognon et al., 1994; Chai et al., 2005; Shen et al., 2013; Wu et al., 2015; Wang et al., 2016).

The basic technical principle of this method is that, instead of increasing the effective stress in the soil mass by increasing the total stress using conventional mechanical surcharging, the vacuum preloads the soil by reducing the pore water pressure while maintaining a constant total stress (Wang and Vu, 2010). In comparison with the conventional surcharge preloading, the vacuum preloading has some remarkable advantages, e.g. the increase in effective stress is isotropic, the lateral surface is therefore compressive, no shear failure happens, and the preloading can be applied at a rapid rate. No surcharge loading is necessary and the requirement for other construction activities is greatly reduced (Qian et al., 1992).

Nevertheless, engineering problems continue to be encountered concerning preloading by vacuum consolidation in field, especially during the treatment of those new dredger fill deposits. The dredger fill is usually a new hydraulic mud, which contains a large number of fine soil particles and has high moisture content. These properties indicate that the dredger fill is ultra-soft and highly compressible. These slurry-like, ultra-soft soils are very difficult to be improved during the vacuum preloading and are very different from the normal sedimentary soil.

Therefore, more and more studies focus on solving the problems of vacuum preloading method. Dong et al. (2010) conducted field tests of vacuum preloading without sand platform, and the results showed that the sand-less vacuum preloading method was effective in improving the bearing capacity of ultra-soft foundation. Walker and Indraratna (2009) presented a spectral method to incorporate loading changes by considering both the vertical and radial drainages in prefabricated vertical drains (PVDs) zone, and the new method was verified against the selected case studies. Indraratna et al. (2012) investigated the vertical drains and vacuum-assisted preloading using two selected real field cases, and a procedure for the design of vertical drains was presented as well. Later, more studies found that the seepage velocity directly beneath the PVD's tip should be greater than that away from the drain. Li et al. (2012) analyzed the improvement of soft silty clay with electroosmotic vacuum preloading method, and demonstrated that water content, degree of saturation, and electric potential distributions could be used to deduce the electroosmotic drainage process. Wu et al. (2015) presented the effectiveness and applicability of chemico-physical combined methods (CPCMs) for treatment of marine clay slurries. The vacuum preloading method combined with chemical stabilization was verified to have faster consolidation velocity and higher preloading that help to achieve higher mechanical properties of stabilized slurry. Zheng et al. (2017) described a full-scale test on a very soft clay ground with a new method of vacuum preloading. They showed that the improved method was efficient and cost-effective for improving the ground with low bearing capacity and high compressibility. To enhance the efficiency of consolidation, different kinds of improved vacuum preloading methods are elaborated (Yan and Chu, 2005; Chai et al., 2006; Saowapakpiboon et al., 2010; Wang and Vu, 2010; Liu et al., 2012; Peng et al., 2013; Zhang et al., 2015). It should be noted that the PVD mentioned in this paper is a kind of prefabricated drain, which is used with surcharge load to accelerate consolidation by shortening the drainage path during the process of vacuum preloading. Kjellmen (1952) used the vacuum preloading method, considering the atmospheric pressure as an alternative, to fill preload by sealing off the treatment area from the surrounding and making it subjected to a vacuum suction, which was applied through a network of horizontal and vertical drainage systems (drainage blanket and PVDs) placed within the isolated soil mass. When the PVDs are used during the preloading, some factors need to be taken into consideration, for example, the smear effect and the resistance.

Although many kinds of improved vacuum preloading methods have been proposed, studies on high-efficient and environment-friendly vacuum preloading methods are still limited, especially for the new dredger fill deposits. In this paper, an improved multiple-vacuum preloading technique is developed to consolidate the new dredger fills that are hydraulically placed in seawater for land reclamation in Lingang Industrial Zone of Tianjin City, China. With this multiple-vacuum preloading method, the newly deposited dredger fills could be treated efficiently by adopting a certain loading pattern and a novel moisture separator. The moisture separator can automatically regulate the vacuum pressure variation by changing the volume of gas inside it. Therefore, the vacuum pressure could be ensured by the moisture separator during the process of vacuum preloading. A series of model tests is conducted in the laboratory to compare the results obtained from the multiple-vacuum preloading method with different loading patterns and the traditional one with the rapid improvement technique without sand cushion. The membrane and the horizontal drainage system in the sand-less vacuum preloading method are used in the treatment process to secure the vacuum degree without sand cushion. In the model tests, ten piezometers and settlement plates are installed to measure the variations in excess pore water pressures and moisture content, and vane shear strength is measured at different positions. The performance of ground treated by the vacuum preloading method is evaluated and discussed. The results show that better consolidation effect could be achieved using the multiple-vacuum preloading method. The rapid improvement technique enhances the bearing capacity of ultra-soft foundation substantially. Compared with the traditional vacuum preloading method, this method is more environment-friendly and cost-saving, and can shorten the construction periods as well. The testing results and discussion will be useful for overcoming the difficulties of clogging that occurs during vacuum preloading in coastal areas.

2. Vacuum preloading: methodology and design

The basic technical principle of vacuum preloading method is that, instead of increasing the effective stress in the soil mass by increasing the total stress by means of conventional mechanical surcharging, the vacuum preloads the soil by reducing the pore water pressure while maintaining a constant total stress. Vacuum loading develops at any time when there is a negative pore water pressure with the magnitude $|p_v|$ at the drainage blanket and vertical drains. As time elapses, the vacuum penetrates into the soil, resulting in an increase in effective vertical stress, i.e. $\Delta\sigma'_v = |p_v|$, at the end-of-primary (EOP) consolidation.

However, problems continue to be encountered concerning preloading by vacuum consolidation in the fields: (1) the longer construction period; (2) the environmental pollution and high cost of sand cushion; and (3) the clogging of PVDs. To solve these engineering problems and reduce engineering cost, a series of model tests was conducted with improved multiple-vacuum preloading method in the laboratory to compare the results obtained from the