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Technical note

Experimental study on the improvement of marine clay slurry by electroosmosis-vacuum preloading

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ABSTRACT

Laboratory tests were conducted on marine clay slurry to investigate the feasibility and effectiveness of a combined electroosmosis-vacuum preloading method in tideland reclamation. This method consists of two main systems: the vacuum preloading system and the electroosmosis technique. In the vacuum preloading system, integrated prefabricated vertical drains (PVDs) are connected to the vacuum pipes directly through a new airtight cap to minimize vacuum loss. In this combined method, the electroosmosis technique is applied towards only the final stage of vacuum preloading, where both the dissipation of excess pore water pressure and the development of settlement have become slow. The test results show that the overall effect of this treatment on marine clay was enhanced significantly when electroosmosis was applied at the final stage of vacuum preloading, and the energy consumption in electroosmosis was only approximately 8% of the energy consumption in vacuum preloading.

1. Introduction

The demand for land has increased prominently due to the booming economic development and dense population in coastal areas of China. Tideland reclamation has been adopted as the best way to solve the land crisis in the coastal cities of China, with more than 300 km^2 of new land being reclaimed from sea belts annually. Due to the lack of granular fill in coastal belts, marine clay slurry dredged from the nearby seabed has served as the main fill material, which is hydraulically placed in seawater in the reclamation area. The dredged soil is typically characterized by high water content, high compressibility, low undrained shear strength, low coefficient of consolidation, low permeability and so on (Chu et al., 2000).

The most common and effective approach to increase the consolidation rate of extremely soft soil foundations is the vacuum preloading method, which was first introduced by Kjellman (1952) in the early 1950s. Since then, it has been used in numerous soil improvement projects worldwide (Bergado et al., 1993, 2002; Song and Kim, 2004; Chu et al., 2004, 2009; Chai et al., 2005; Seah, 2006; Chai et al., 2010; Rujikiatkamjorn and Indraratna, 2013; Chu et al., 2014; Long et al., 2015). The mechanism of vacuum preloading has been analysed extensively in the literature (Holtz and Wager, 1975; Kjellman, 1952; Qian et al., 1992; Chu and Yan, 2005). A notable explanation is the spring analogy described by Chu and Yan (2005), who suggested that the reduction in excess pore water pressure would directly increase the effective stress in soil due to dewatering by vacuum preloading. In practice, different vacuum preloading systems have been employed for different specific applications. In most coastal cities of China, due to the lack of sand supply, a direct vacuum preloading method has been adopted. In this approach, PVDs are tied directly to the vacuum pipes (Fig. 1) in lieu of the sand blanket that is normally employed in the conventional vacuum preloading method (Chu et al., 2000; Chu and Yan, 2005; Chai et al., 2008). However, the performance of the direct vacuum preloading method (i.e., without sand blanket) is not

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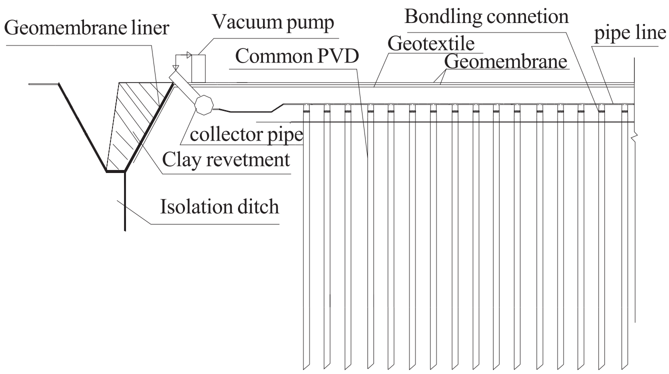

Fig. 1. Direct vacuum preloading method without sand blanket.

always satisfactory due to clogging of the PVDs, bending of the PVDs, smearing near the PVDs, vacuum loss between the PVDs and the vacuum pipes, and insufficient consolidation in the deep soil layer. Thus, a combination of different ground treatment methods would be a better choice for coastal cities that require higher bearing capacity (Mohamedelhassan and Shang, 2002; Indraratna et al., 2012). In the case of newly dredged marine fill, the hydraulic conductivity is too low and the soils too soft to achieve a considerable improvement in a short time. An alternative approach to overcoming these deficiencies is the combination of vacuum preloading and electroosmosis, which has been investigated extensively in recent work (Shang, 1998; Burnotte et al., 2004; Indraratna et al., 2005; Wang and Vu, 2010; Karunaratne, 2011; Mahfouz, 2013).

The electroosmotic dewatering (EOD) method was first demonstrated by Casagrande (1952). The principle of this approach is that when a Direct Current (DC) field is applied through soft soils with high water content, cations move in diffused double layers towards the cathode and drag water with them. Thus, water is removed at the cathode, and the soils are consolidated accordingly (Burnotte et al., 2004). This technique works effectively in soft soil improvement because the electroosmotic permeability is independent of grain size (Mitchell and Soga, 1976), and the depth disposed by EOD is more than any other foundation treatments (Zhuang et al., 2013, 2014; Zhaung, 2015). Thus, EOD has the potential to enhance the hydraulic flow in fine-grained, low-permeability materials such as sludge and clays. However, its high cost limits its promotion and application, Therefore, the combination of vacuum preloading and EOD has become the most effective way to combine the advantages of each method (Lorenzo et al., 2004). Recently, notable achievements have been contributed by Gopalakrishnan et al. (1996), Fang et al. (2006), Wang and Vu (2010), Shen et al. (2012) and so on. However, the limitations of the aforementioned work cannot be ignored in terms of the size and properties of PVDs, the configuration of electrodes, and energy consumption. As an example (Mahfouz, 2013), performed a comprehensive experimental investigation to assess the effectiveness of vacuum preloading combined with the electroosmotic strengthening of extremely soft soil and achieved some useful results, but the sizes and properties of PVDs in the experiments were different from the ones applied in engineering practice. Similar treatments of PVDs can also be found in the literature (Wang and Vu, 2010). Another criticism addresses the feasibility of the configuration of electrodes in the electroosmosis method, i.e., the typical mode in which electrode plates are installed parallel and perpendicular to the direction of water flow and settlement (Shang, 1998; Micic et al., 2001; Glendinning et al., 2007) is not applicable when dealing with deep soils. In practice, electrode rods are employed and are typically installed vertically. Thus, accounting for the PVDs and the vertical electrode configuration become necessary for the design of electroosmosis-vacuum preloading.

In this paper, a new approach of vacuum preloading combined with electroosmosis was developed to consolidate the dredged marine clay slurry in Wenzhou, China. This method is characterized by integrated PVDs with exactly the same properties as employed in current practice, a more realistic arrangement of cathode (steel tube) and anode (steel bar), and lower energy consumption. Laboratory experiments were conducted to evaluate the effect of this new technique. Marine clay slurry dredged from the seabed was first consolidated by vacuum preloading and then dewatered by the electroosmosis-vacuum preloading technique. The experimental results show that the combined method is more effective in terms of reducing water content and increasing vane shear strength.

2. Experimental apparatus

The apparatus for the electroosmosis-vacuum preloading method is schematically shown in Fig. 2. It consists of a testing cell, an improved vacuum preloading system and a new electroosmosis system. The details of the three main components are described below.

2.1. Testing cell

A testing cell made of tempered glass (10 mm thick) with inner dimensions of 1200 mm in length, 600 mm in height and 600 mm in width was employed in this study.

2.2. Electroosmosis system

As shown in Fig. 3, the electroosmosis system consists of an anode array, cathode arrays and a DC power supply unit, appropriately connected with copper wires. A stainless steel tube with an outer diameter of 32 mm and 1 mm thick is used as the anode, and reinforcement steel bars with a diameter of 10 mm are used as the cathodes, aiming to increase the contact area between the electrodes and soil and also to minimize the cost (Fig. 3c). Both electrodes are 700 mm in length and connected to a DC power supply unit with a maximum output power of 30 V in voltage and 6 A in current. The output power of this DC power supply unit is also adjustable for specific applications when fixed allowable ranges of power are required in laboratory study. The pore water is dragged towards the cathode by the potential gradient simultaneously sucked by vacuum pressure as the cathode array is inserted close to the PVD.

2.3. Vacuum preloading system

The vacuum preloading system consists of a vacuum pump, vacuum pipes, a water–air separation bottle and PVDs, as shown in Fig. 2, which is similar to the direct vacuum preloading system used in practice. Specifically, integrated PVDs are employed in this system. In an integrated PVD, the filter is adhered to the core by heat-melting to form an integrated body (Fig. 3a), which increases its tensile strength by 19% and its discharge capacity by 38% compared with the common PVD (Liu and Chu, 2009). The detailed properties of the integrated PVD are outlined in Table 1. The other improvement of the vacuum preloading system is the use of an airtight connector/cap to connect each PVD directly to the vacuum pipes (Fig. 3b), enabling the vacuum pressure to be transferred directly from the vacuum pipes to the PVDs while minimizing vacuum loss.