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Combination of vacuum preloading and lime treatment for improvement of dredged fill

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ABSTRACT

Numerous land reclamation projects that utilise dredged fill are currently being executed in the eastern regions of China to cater to the demands of economic development and address the land shortage problem. However, the dredged fill has high water content, low shear strength, and mainly consists of fine-grained particles. A long period is thus normally required for the treatment of dredge fill by vacuum preloading, and clogging always occurs around the prefabricated vertical drains (PVDs), resulting in insufficient consolidation of the soil. To address this issue, combination of vacuum preloading and lime treatment is proposed in this paper. In this method, a certain percentage of hydrated lime ($Ca(OH)_2$) is added into the dredge fill slurry before vacuum preloading, to enhance the engineering properties of the fill, such as the shear strength and permeability. The added hydrated lime would induce cation exchange on the clay surface and flocculation of the fine soil particles. As a result, this method would significantly mitigate the risk of clogging around the PVDs with the enhanced soil permeability, thereby improving the consolidation efficiency. In this study, dredged slurry with a water content of approximately 187% was utilised. Lime modification optimum (LMO) was first determined using the vacuum preloading method, and a comparison test was then conducted to verify the effectiveness of the proposed method. It was found that, compared to the conventional vacuum preloading method, the proposed method significantly increased the vane shear strength of all the soil layers, especially the deep soil layers, and afforded a higher consolidation rate.

1. Introduction

The Oufei land reclamation project is currently being executed in eastern Wenzhou, China to cater to the demands of urban expansion and infrastructural development. The project utilises slurry dredged from the coastal seabed as the landfill material (Fig. 1). However, the engineering properties of such dredged fills are too poor to support the construction of structures. Even after years of self-weight consolidation, the fills still have a high water content, low bearing capacity, and high compressibility (Chu et al., 2000). Therefore, it is essential to stabilise the soft clayey soil before any construction work is conducted.

One of the methods most widely used for the improvement of soft clay ground is vacuum preloading. The method, which was first proposed by Kjellman (1952), is convenient and economical, and is increasingly being used to improve the mechanical performance of dredged fills in numerous projects (Chai et al., 2010, 2006; Indraratna et al., 2011; Shang et al., 1998; Tang and Shang, 2000; Yan and Chu, 2005). Prefabricated vertical drains (PVDs) are used in the vacuum preloading process to distribute the vacuum pressure and discharge the pore water (Indraratna et al., 2005; Yan and Chu, 2003). However, due to the dredged slurry mainly consists of fine-grained soils, these particles would be moved as the water drainage during the vacuuming and eventually aggregate around the PVDs (Wang et al., 2016b). This leads to the formation of an obvious soil column and clogging around the PVDs, ultimately resulting in insufficient consolidation and limited shear strength improvement (Wang et al., 2016a). There is thus the need for the enhancement of vacuum consolidation.

This paper proposes a method for improving the effectiveness of vacuum consolidation. The proposed method involves the addition of a certain percentage of hydrated lime to the dredged slurry before vacuum preloading. When a hydrated lime is added to a soil, a modification reaction occurs immediately as a result of the substitution of calcium with the existing cations at negative charge sites on the clay mineral surface. Consequently, the interparticle repulsive forces between clay particles are decreased, which induced soil particles aggregate and flocculation (Le Runigo et al., 2009; Salehi and Sivakugan, 2009). The change of soil particles from the initial dispersed orientation state to flocculation increases the void ratio, thereby enhancing the permeability of the soil (Brandl, 1981; Rajasekaran and Narasimha Rao, 2002). These behaviours are beneficial to water flow and drainage of the soil.

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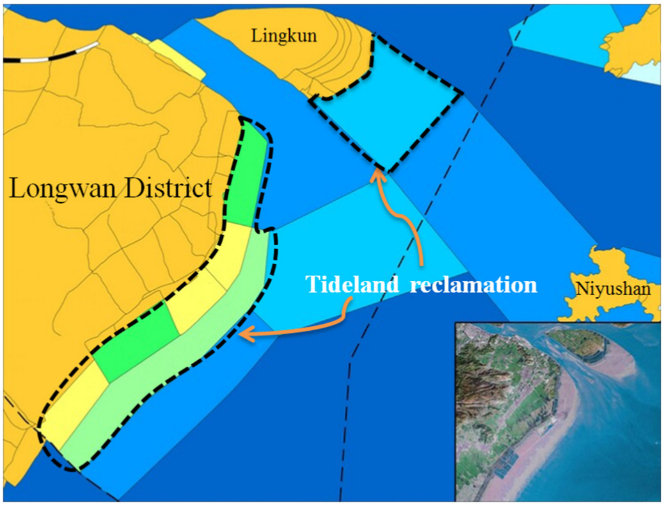

Fig. 1. Layout of the tideland reclamation site in Lingkun (Longwan District), Wenzhou, China.

This approach can also reduce the occurrence of clogging around the PVDs by retarding the formation of soil columns, thereby improving the efficiency of vacuum consolidation.

However, the permeability does not indefinitely increase with increasing lime content, but begins to slowly decrease beyond a threshold value. This decrease is due to the flow channels being blocked by the precipitation of cementitious compounds generated by the lime-soil reactions, resulting in reduced water flow (Le Runigo et al., 2009). Hence, it is imperative to determine the threshold for subsequent vacuum preloading. This threshold was also known as the lime modification optimum (LMO), which was first introduced by McCallister and Petry (1992) through leach tests conducted on lime-treated clay. They reported that the maximum permeability occurs at the LMO. Eades and Grim (1966) first developed the pH method for determining the LMO, and Rogers and Glendinning (1997) subsequently improved the method by considering the change in plasticity. Salehi and Sivakugan (2009) also determined the LMO for dredged mud based on the permeability and void ratio. However, these methods only consider the changes in the permeability or pH without directly assessing the efficiency of the vacuum preloading process.

In the present study, a determination test was firstly conducted to identify the LMO by vacuum preloading with the purpose of quantifying the changes produced by the use of hydrated lime. Shear strength, pore water pressure, discharged water volume, and water content are regarded as the indicators for the determination of LMO by the vacuum preloading method. A comparison test was also performed to verify the effectiveness of the proposed method. Briefly, the objectives of this study were as follows:

1. To develop a method for determining the optimum lime content for enhancing the dredged slurry in Wenzhou.
2. To investigate the consolidation behaviour of natural and lime-treated dredged slurry during vacuum preloading.
3. To evaluate the efficiency and feasibility of the proposed method.

2. Properties of dredged slurry

The clay slurry used for the tests was obtained from the site of the Oufei project in Wenzhou, China. The geological setting and depositional environment of the slurry are shown in Fig. 2. The sample slurry had just dredged from the seabed and had a water content of 187%. It mainly consisted of fine clay particles and had a pH of 6.8. The liquid limit (W_L) and plastic limit (W_P) were approximately 81% and 42%, respectively, while the specific gravity was determined to be 2.61.

3. Determination of LMO

The void ratio and permeability of the soil are generally increased by the lime-clay reaction (Rajasekaran and Narasimha Rao, 2002). This means that the chemical reaction generates more pore channels, which enhance water discharge from the soil during subsequent vacuum consolidation. However, as implied earlier, the pore channels do not indefinitely increase with increasing lime content, but there exists an optimum lime content that maximises the number of pore channels. Below this optimum content, only flocculation occurs, while pozzolanic reactions are also triggered above it (McCallister and Petry, 1992). To determine this optimum lime concentration, the following laboratory test was developed and conducted.

Slurry samples of equal mass (34 kg) were poured into five model buckets of height 40 cm and diameter 30 cm. Different amounts of lime representing 0%, 1%, 1.5%, 2%, and 2.5% of the dry soil by weight were respectively added to the slurry samples. Each mixture of lime and slurry was then thoroughly stirred by a slurry agitator until homogeneity was achieved, to ensure complete reaction between the lime and slurry (the first 'mixture' containing 0% lime was the natural slurry sample). PVDs with cap connections were subsequently installed horizontally in all the samples. A pore pressure sensor was placed at the bottom of each model bucket, which was filled with a sample to a height of 35 cm. A layer of geotextile and two layers of geomembranes were placed on top of the slurry in each bucket to seal the sample from the atmosphere. The cap, air–water separation flask, and vacuum pump were then successively connected by vacuum pipes. The complete test setup is shown in Fig. 3.

During the vacuum consolidation, a minimum vacuum load of 80 kPa was applied to the surface of the soil and maintained until there was no further apparent increment in the measured volume of discharged water in the air-water separation flask. Once the steady state was attained, the vacuum pump was switched off, and the vane shear strength and water content of the consolidated soil were measured.

The variations of the discharged water volume with time of all the samples are depicted in Fig. 4. It is obvious that, for all the samples, the discharged water volume increases sharply at the beginning of preloading. A stable value is attained for all the lime-treated slurry samples within 80 h, whereas the untreated sample continues to discharge water for an additional 88 h. This suggests enhanced drainage capability of the lime-treated slurries, especially that containing 2% lime, which stops draining within 48 h. Moreover, as the lime content increases from 1% to 2%, there is an increase in the volume of discharged water to the highest value among the treated samples. This can be explained by the permeability, which undoubtedly affects the draining during vacuum preloading; a higher hydraulic conductivity accelerates draining. When the lime is added to the slurry, cation exchange and flocculation immediately begin, with the permeability increased by the flocculation and resultant soil aggregation (Nalbantoglu and Tuncer, 2001; Rajasekaran and Narasimha Rao, 2002).

The increased permeability in the present tests can be expressed in terms of not only the volume of discharged water, but also the rate of drainage. However, as noted, the permeability only increases up to a maximum value afforded by an optimal lime content, the LMO, and then begins to decrease due to the formation of cementitious compounds among the soil particles (Alhassan, 2008; Milburn and Parsons, 2004; Onitsuka et al., 2001). The cementitious compounds block the flow channels, reducing the water flow (Quang and Chai, 2015) and locking part of the water within the soil. This is evident from Fig. 4, which shows that 2.5% lime content produces the lowest volume of discharged water despite the accelerated drainage. It is very noteworthy that the natural slurry produces the highest volume of

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