A new method to improve the effectiveness of vacuum preloading on the consolidation of dredged fill in Wenzhou

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ABSTRACT

A new method is developed to improve the effectiveness of vacuum preloading on the consolidation of dredged fill in Wenzhou, China. This is achieved by adding some flocculants (floc) to the dredged fills while maintaining a certain level of vacuum pressure through prefabricated vertical drains (PVDs). The floc agent adopted in this study is a mixture of polyacrylamide (PAM) and calcium hydroxide (Ca(OH)₂), which would dehydrate soil particles through changing the bound water into free water. The water states transformation occurs inside the soil particles, which would significantly mitigate the risk of clogging around PVDs and enhance the soil permeability, thereby improving the efficiency of consolidation. A number of laboratory tests are conducted to testify this method. Comparison between conventional vacuum preloading method and the proposed method demonstrates that, the new method achieves better improvement of dredged fill in a shorter period of time.

Keywords: dredged fills, vertical vacuum preloading, flocculant agent, PAM and Ca(OH)₂, consolidation

1. INTRODUCTION

Recently, with the fast development of economy and booming population in Eastern regions of China, land crisis has been the urgent issue for both Central, State and Local Governments. One typical city in Eastern China is Wenzhou, which is the representative of strong business based on private sectors. It is also a coastal city surrounded by mountains, thus, land only can be reclamed in tideland along the coast. The biggest tideland reclamation program in China-Wenzhou Oufei Project, was approved in 2004 by the state government. Wenzhou Oufei project is going to reclaim tideland along the eastern sea belt up to 448 km².

Clay slurry dredged from the nearby seabed has been served as the fill materials for land reclamatation, it is also named as dredged fill. After years’ deposition, the dredged marine slurry settle in the pre-treatment area. It is typically characterized by high water content, high compressibility, low undrained shear strength, low coefficient of consolidation, low penetrability and so on (Chu et al. 2000 ; Yan et al. 2010). Thus, the main challenge for geotechnical engineers in tideland reclamation projects is: (1) how to save the consolidation time, and (2) how to improve the consolidation effectiveness with a reasonable cost. Considering the extremely low strength of dredged fill, pretreatment needs to be carried out before conducting any soil improvement work through heavy machines. Thus, lower level preloading is usually adopted to achieve the pretreatment. The most common and effective approach in tideland reclamation projects is the vacuum preloading method (Kjellman 1952). In this approach, a vacuum pressure of up to 90 kPa (normally above 80 kPa) can be applied and maintained as long as it is required. This approach has been successfully used in numerous soil improvement projects across the world (Bergado et al. 2002 ; Chu et al. 2004 ; Chu and Yan 2005 ; Chu et al. 2000 ; Holtan 1965 ; Seah 2006). The mechanism of vacuum preloading have been discussed extensively by many investigators, i.e., Kjellman (1952), Holtz and Wager (1975), Qian et al. (1992) and Chu and Yan (2005).

However, the performance of the vacuum preloading method is not always satisfactory in most coastal cities of China, e.g., clogging in PVDs, insufficient consolidation in deep soil layer, and excessive settlement after construction. Thus, the vacuum preloading method needs to be improved. This...
paper presents a new method to improve the effectiveness of vacuum preloading on the consolidation of dredged fill in Wenzhou, China. This is achieved by adding some flocculants (or floc, hereafter called floc) to the dredged fills while maintaining a certain level of vacuum pressure through prefabricated vertical drains (PVDs). The floc adopted in this study is a mixture of polyacrylamide (PAM) and calcium hydroxide (Ca(OH)$_2$), which would dehydrate soil particles through changing the bound water into free water. Thus, this approach mitigate the risk of clogging around PVDs and enhance the soil permeability, thereby improving the efficiency of consolidation. A number of laboratory tests are conducted to testify this method.

2 THE NEW VACUUM PRELOADING METHOD

In this new approach, some floc is added into the fresh dredged fill and then the conventional vacuum preloading method is applied to dewater the mixture of marine clay and floc. The mechanism of floc in sludge dewatering industry has been investigated extensively in some literature (Bache and Papavasilopoulos 2003; Chih Chao et al. 1997; Lee and Liu 2000; Zhao 2003). The floc agent adopted in this study is a mixture of polyacrylamide (PAM) and calcium hydroxide (Ca(OH)$_2$), aiming to dehydrate soil particles through changing the bound water into free water. As known, the form of water in sludge plays an influential role in determining the characteristics of dewatering process and its effects (Turchiuli and Fargues 2004; Zhao 2003). The free water would be dewatered quickly with the help of some extra pressure, and meantime the soil permeability also would be enhanced when the structure of sludge is changed. Thus, after adding floc the water states transformation occurs inside the soil particles, which would significantly mitigate the risk of clogging around PVDs and enhance the soil permeability, thereby improving the efficiency of consolidation.

3 EXPERIMENTAL PROCESS

The new vacuum preloading method is shown in Fig. 1. It consists of a testing bin and a vacuum preloading system. The testing bin (1.5 cm thick) with inner dimension of 60 cm in diameter and 90 cm in height, was employed in this study. The vacuum preloading system consists of a vacuum pump, vacuum pipes, water-air separation bottles, PVDs, geotextile and geo-membranes. The water content of the testing dredged fill is around 84.3%, with nearly no shear strength, details of the soil properties is summarized in Table 1.

![Testing bin and equipment](image1.png)

Fig. 1 Testing bin and equipment

| Table 1. Summary of soil properties |
|------------------------------------|
| Water content (%) | 84.3 |
| Liquid limit (%) | 51.5 |
| Plastic limit (%) | 22.1 |
| Saturation (%) | 93.8 |
| Specific gravity, Gs | 2.73 |
| Vane shear Strength (kPa) | 0 |
| pH | 8.1 |

The testing process is as follows:

(1) filling two testing bins with the same amount of fresh dredged fill (around 80 cm deep) that taken from Wenzhou Oufei project, this would secure the testing soils have the same properties, so as to make a comparison;

(2) adding one bin with around 1% floc- mixture of polyacrylamide (PAM) and calcium hydroxide (Ca(OH)$_2$), naming this test as T1, without floc being named as T2; then installing pore water pressure sensor in the middle of the bin with two different depths: 20 and 60 cm;

(3) two days later, inserting PVDs and placing one layer of geotextile and two layers of geo-membrane on the top of dredged fill, connecting PVDs with vacuum pipes and settling all connection between water-air separation bottles and the vacuum pump; installing the surface settlement plates and dial gauges: one was in the middle of the bin and the other was close to inner border the bin;

(4) sealing off the geo-membrane through keying it into the bottom of bins and placing/smeared some mud cake around the geo-membrane and bins;

(5) keeping vacuum pressure around -85 kPa for 15 days.

4 TESTING RESULTS AND DATA ANALYSIS

During the vacuum process, the both pore water pressures (20 cm and 60 cm depth) and surface settlement were measured, and after vacuum preloading, the vane shear strength and water content in different depths had been tested. The monitoring data and testing results are presented and discussed in the following.
subsections.

4.1 Surface settlement
Fig. 2 compares the average ground settlement against time in two tests. It can be seen that the surface settlements for both tests in the first 250 hours are faster than that in the later stage. At the end of this test, about 13 cm was observed at the ground surface in T1 with the help of floc, while 10 cm in T2 without floc. The surface settlement has been improved by 30% through adding around 1% floc. Considering the final settlement, it is found that settlement in T1 was accomplished in the first 250 hours, while that in T2 still continued after 350 hours. This indicates that with the help of floc, the time required to reach the final settlement could be shorter than common dredged fill without floc.

4.2 Pore water pressure changes
Figs. 3 and 4 demonstrate the variations of pore water pressures versus time at both shallow (20 cm depth) and deep layers (60 cm depth) for both tests, respectively. As can be seen in Fig. 3, the reduction in the pore water pressures T1 was higher than that in T2, with no much difference. This maybe owing to the high level of vacuum transition in shallow layers.

4.3 Water content changes
For both tests, soil samples at different depths were taken to measure the water contents after soil improvement. Fig. 5 shows the water contents against the depth in T1 and T2, respectively. It can be seen that the variation of water content in T1 was less than that in T2, indicating that the consolidation effect in T1 was more averagely than that in T2. However, there was not so much difference between the water content-time curves in two tests. The general observation within both tests are that, the water content reductions at the surface layer were much more than those measured in deep layers. This is because the vacuum pressures in shallow soil layers were higher than those in deep.
4.4 Vane shear tests

Vane shear tests were carried out after soil treatment in both tests, with testing results being shown in Figure 6. As aforementioned, the initial undrained shear strength of soil was almost zero, after vacuum preloading this value in T2 increased to 18 kPa and 8 kPa in shallow and deep soil layers, respectively; with the help of floc, this value in T1 increased to 21 kPa and 15 kPa in shallow and deep layers, respectively. This demonstrates that the mixture of floc and marine clay slurry had been improved with better quality than that in common marine clay slurry. The main trend of increments in vane shear strength of both tests are quite similar, better consolidation effect was achieved in shallow layers due to the higher vacuum pressure was maintained, and lower vane shear strength in deep soil layers owing to the vacuum loss in deep area. However, compared with T2, the variation of shear strength increment in T1 was not so large due to water state changes contributed by floc. This means that the structure of marine clay was also changed due to the water state changes, thus the overall permeability of soil was enhanced. Therefore, more free water has been drained out through vacuum preloading.

![Fig. 6. Vane shear strength measured in T1 and T2](image)

5 CONCLUSIONS

An floc-vacuum preloading method was proposed for the improvement of dredged marine clay slurry used for tideland reclamation. In this method, the vacuum system is applied throughout the whole consolidation process, and the marine lay slurry was mixed with around 1% of floc. Considering the cost and operational feasibility, the floc adopt in this study was polyacrylamide (PAM) and calcium hydroxide (Ca(OH)₂). Laboratory tests were carried out using both the new method and common vacuum preloading method. Substantial improvements in surface settlement, water content and vane shear strength had been observed. Thus, this new method is effective to consolidate dredged marine clay slurry for tideland reclamation.

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