Technology for Rapid Consolidation of Shallow Ultra-soft Soil

LIU Tianyun*

Tianjin Port Engineering Institute Company LTD. Of CCCC, CCCC First Harbour Engineering Company Ltd., Key Laboratory of Port Geotechnical Engineering of Ministry of Communications, Key Laboratory of Port Geotechnical Engineering of Tianjin, Tianjin 300222, China.

*Corresponding author’s e-mail: 386461238@qq.com

Abstract. The shallow ultra-soft soil needs to be consolidated quickly to form the early working layer in more and more land reclamation. Through the innovation and improvement of the conventional vacuum preloading method, the technology for rapid consolidation of the shallow ultra-soft soil is created, which adopts auxiliary measures such as erection of foam floating bridges, construction of water retaining dams, and laying of geotextiles on the mud to realize the manual construction of plastic drain plates, and innovatively applies of the recyclable tri-planer geonet instead of the sand cushion. The technology has been successfully applied to the practical reinforcement engineering of the shallow ultra-soft soil and achieved good effect, which has a good prospect of popularization and application.

1. Introduction

In the process of reclamation, due to the hydraulic separation, the flowing mud or floating mud layer often generates on the shallow surface of reclamation [1]. Compared with the conventional soft soil, its water content is higher and its strength is lower, so it is called ultra-soft soil. Ground treatment of the ultra-soft soil by conventional vacuum preloading method needs longer drying time, and pouring of the mud often occurs when plastic drain plates are driven. More and more land reclamation projects encounter the problem of shallow ground reinforcement affected by the ultra-soft soil [2] - [4].

Based on the vacuum preloading reinforcement method of soft soil, the technology for rapid consolidation of the shallow ultra-soft soil is developed, which can reinforce the shallow ultra-soft soil and form the hard shell layer which can not only be used as the working cushion of the second deep reinforcement to save the drying time of the hydraulic fill and the materials of the working cushion, but also eliminate the problem of mud pouring when plastic drain plates are driven during the deep reinforcement.

2. Technology for rapid consolidation of the shallow ultra-soft soil

For the deep soft soil ground, the comparatively practical reinforcement method is the vacuum preloading method. Due to the method can apply all the preloading loads instantaneously without soil instability, it has obvious time and economic benefits [5] - [8].

The technology for rapid consolidation of the shallow ultra-soft soil introduced in this paper is the improvement of conventional vacuum preloading, and the construction technology and alternative materials for the shallow ultra-soft soil are proposed. The schematic diagram of reinforcement technology is shown in Fig. 1.
Compared with the conventional vacuum preloading method, the technology for rapid consolidation of the shallow ultra-soft soil has the following main characteristics.

The plastic drain plates with shallow depth are manually driven on the ultra-soft ground. The bearing capacity of the ultra-soft ground is very low, so the conventional machine cannot enter the site for operation. After laying the woven fabric and non-woven fabric on the ultra-soft ground, the plastic drain plates can be manually driven, and the driving depth can only pass through the ultra-soft soil layer.

The plastic drain plates are directly connected with the filter pipes. The sand cushion is cancelled, and the filter pipes are arranged between each two rows of plastic drain plates. The plastic drain plates are directly connected with the filter pipes to improve the vacuum degree in the plastic drain plates, and ensure the reinforcement effect.

The sand cushion can be replaced by the recyclable tri-planer geonet. The tri-planer geonet is laid on the plastic drain plates and filter pipes to replace the sand cushion as the horizontal drainage cushion, so as to promote the vertical drainage of the surface soil. The tri-planer geonet can be recycled and reused after reinforcement, saving the expensive sand.

3. Engineering application

3.1. Project overview

The total area of the reinforcement area is about 84000 m². The distance between plastic drain plates is 0.7m, and the depth of setting is 4.0m. The physical property indexes of the shallow ultra-soft soil are shown in table 1. The technology for rapid consolidation of the shallow ultra-soft soil is adopted, and the indexes of the ground after reinforcement meet the requirements of the design.
Table 1. Physical property indexes of the shallow ultra-soft soils before improvement.

| Depth /m | Moisture content (%) | Wet density (g/cm$^3$) | Plasticity index | Clay content (%) |
|----------|----------------------|------------------------|------------------|------------------|
|          | Max value | Min value | Ave value | Max value | Min value | Ave value | Max value | Min value | Ave value |
| 0.5      | 133.0     | 70.7      | 103.8    | 1.59      | 1.37      | 1.47      | 22.4      | 15.9      | 18.5      | 66.1      | 52.9      | 59.6      |
| 1.5      | 117.0     | 61.0      | 87.3     | 1.63      | 1.41      | 1.52      | 20.5      | 16.4      | 18.0      | 67.4      | 58.3      | 61.9      |
| 2.5      | 107.0     | 56.9      | 75.3     | 1.68      | 1.44      | 1.59      | 19.9      | 12.3      | 15.3      | 63.5      | 48.3      | 57.8      |
| 3.5      | 42.2      | 33.3      | 38.4     | 1.90      | 1.80      | 1.85      | 19.3      | 10.5      | 15.5      | 62.5      | 41.8      | 51.0      |

3.2. Main technical characteristics

3.2.1. Erection of floating bridges
As the bearing capacity of the surface layer on the shallow ultra-soft is very low, and it is very difficult for equipment and personnel to enter the construction site, it is necessary to adopt the method of erection of floating bridges to solve the construction access problems of material transportation and personnel walking. A specially designed high-density flat foam with round holes at four corners is directly laid on the surface of water or mud, fixed by bamboos deeply inserted in the soil through the round holes at four corners to form a floating bridge, as shown in Fig. 2. This type of floating bridge has the advantages of convenient construction, smooth walking, easy dismantling and reverse transportation. The foam material of the floating bridge has the advantages of high strength and not easy to be damaged, which can be repeatedly recycled and is very suitable for construction in large area.

3.2.2. Construction of cofferdams
The construction site is a new reclamation area, and a large amount of accumulated water remains on the surface after settling. During the construction, combined with the floating bridges, the partition cofferdams are built to draw out the accumulated water in the reinforcement area for the convenience of subsequent construction. The cofferdams are close to the floating bridges, supported by bamboos deeply inserted in soil, and with coloured steel plates directly inserted into the soil layer. The coloured steel plates are covered by plastic clothes which bottom is pressed below the mud surface. The construction of the cofferdam is shown in Fig. 3.

3.2.3. Laying of geotextiles
Another necessary auxiliary measure adopted in this technology is to lay woven and non-woven fabrics directly on the mud surface after the water is pumped out, so as to ensure that the construction personnel can stand on the mud surface and driving plastic drain plates. In addition, it avoids the direct contact between the tri-planer geonet and the mud surface, which can improve the permeability and
recovery rate of the tri-planer geonet. The width of the non-woven fabrics and woven fabrics produced by the factory is generally 2m. They must be sewn as a whole on site and then laid. The woven fabrics and non-woven fabrics must have sufficient strength. Generally, the woven fabrics of 150g/m² and the non-woven fabrics of 350g/m² are used. Different specifications can also be adopted according to the actual geological conditions of different areas, or only one layer of the geotextiles can be laid to save construction costs.

3.2.4. Installation of plastic drain plates
Before the installation, it is necessary to carry out the test of installation of the plastic drain plates in the area to determine the setting depth. The plastic drain plate is cut into a short board to meet the size requirement according to the setting depth. Wrap, bend and bind the end of the plastic drain plate, so as to prevent the soil particles from sucking into the plate core from the end to block the drain plate during the vacuum preloading process. The steel pipe with flattened end is used to manually install the plastic drain plate. The flattened end of the steel pipe is placed in the bending section of the plastic drain plate to press it into the design depth. When the installation of plastic drain plates completed, the filter pipes shall be laid immediately. The filter pipes shall be laid between each two rows of plastic drain plates and directly connect with the plastic drain plates, so as to improve the vacuum degree in the plastic drain plates and ensure the reinforcement effect.

![Figure 4. Ground covered by geo-textiles.](image1)

![Figure 5. The plastic drain plates directly connected with the filter pipes.](image2)

3.2.5. Laying the tri-planer geonets
During the construction of vacuum preloading method, horizontal sand cushion with thickness of 40cm is necessary. This kind of high-quality medium coarse sand is not only deficient, but also expensive. In addition, for the shallow ultra-soft soil, it is difficult to lay sand cushion because of its low strength. In view of the above shortcomings, the technology for rapid consolidation of the shallow ultra-soft soil proposes to replace the sand cushion with the recyclable tri-planer geonet as the horizontal drain layer. The raw material of the tri-planer geonet is high-density polyethylene, which is extruded three ribs through processing machinery, and arranged into a three-dimensional spatial structure with drain channel according to a certain angle and spacing, with the geotextiles of 200g/m² stuck top and bottom, as shown in Fig. 6. After the filter pipes are connected with the plastic drain plates, the tri-planer geonets can be laid manually, with the lap length not less than 5cm, as shown in Fig. 7.
On the one hand, the tri-planer geonets can make the surface vacuum transfer more evenly and ensure that the surface soil can get better reinforcement effect; on the other hand, the tri-planer geonets possess continuity and certain strength, which can be used as the working layer of the personnel when the sealing film is laid and the vacuum equipment is installed. The inspection shows that a hard shell layer of about 30cm is formed on the surface after reinforcement, and the strength of the field vane test of the hard shell layer is about 20kPa, which shows that the tri-planer geonets play a good role in vacuum transmission and horizontal drain, and can completely replace the sand cushion. After unloading, due to the laying of geotextiles on the mud surface, the tri-planer geonets are easy to roll up and recover, and the recycling rate is higher.

4. Inspection of reinforcement effect

The effective loading time was about 82 days. In order to detect the transmission and attenuation of the negative pressure in the tri-planer geonets, three high-precision pore water pressure probes were set up at different positions between the two rows of filter pipes in the test area, the buried position of which shown in Fig. 8. The monitoring results of the pore pressure under the membrane are shown in Fig. 9, and the number of the probe is 1, 2 and 3 in the figure. According to the test results in Fig. 9, in the range of filter pipes spacing, the negative pressure does not appear obvious attenuation along the direction of vertical filter pipes, and the pore pressure under the membrane has been maintained at about minus 80kPa, which illustrates that the tri-planer geonets can effectively transfer the vacuum negative pressure, and can completely replace the sand cushion. The obvious abrupt rise in Fig. 9 is due to the temporary pump shut down for maintenance.

The average total settlement during vacuum preloading in the reinforced area is 946mm, and the final degree of consolidation calculated from the settlement curve is 82.5%. The settlement process during vacuum preloading is shown in Fig. 10.
The change of the water content during reinforcement is shown in Fig. 11. It can be seen from the figure that the change of water content index at the initial stage of reinforcement is faster than that at the later stage. This is due to the large water content of ultra-soft soil, which is mostly free water, and the water content in the soil mass is discharged quickly. Generally speaking, during the consolidation period, the moisture content of the soil decreased, the wet density increased, the soil property indexes changed significantly, and the consolidation effect was significant. The comparison of main physical and mechanical indexes before and after reinforcement can be seen from the table 2.

5. Conclusion
Based on the conventional vacuum preloading method, the technology for rapid consolidation of the shallow ultra-soft soil is put forward in this paper. The technology is characterized by the construction of floating bridges with foams, the use of coloured steel plates to make water retaining dams, the laying of geotextiles on the mud, the manual installation of plastic drain plates, the connection directly between filter pipes and plastic drain plates and replacing sand cushion with the recycled tri-planer geonets as horizontal drainage cushion. The technology has been successfully applied to the reinforcement of shallow ultra-soft soil in practical projects, which provides a new method and a new idea for the reinforcement of the similar projects.

References
[1] JTS 133-2013, Code for Geotechnical Investigation on Port and Waterway Engineering [S].
[2] ZHU Yao-ting, ZHENG Ai-rong, LI Wei. Laboratory tests for the consolidation property of dredger fill in the Shenzhen area[J]. Journal of Hunan University (Nature Sciences), 2008, 35(11): 120-123.
[3] Yao-gang. Analysis consolidation super on governing factors of seepage and soft soil[J]. Journal of Chongqing Architecture University, 2000, 22(9): 9-14.
[4] HUANG Song-tao. Common problems about corresponding consolidation of ultra-soft soil ground and countermeasures[J]. Port and Waterway Engineering, 2008(10): 176-182.
[5] CHEN Huan. Reviews of mechanism of vacuum preloading method[J]. China Harbour Engineering, 1991(4): 17-26.
[6] GAO Zhi-yi. Analysis on mechanics of vacuum preloading method[J]. Chinese Journal of Geotechnical Engineering, 1989, 11(4): 45-56.

[7] BO M W, CHO A V. Reclamation and soil improvement on ultra-soft soil[J], Ground Improvement, 2005, 9(1): 23-31.

[8] BO M W, CHO A V, Wong K S. Compression test on slurry with small scale consolidation. Canadian Geotechnical[J]. 2002, 39: 388–398.