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Review

Recent Developments in the Vacuum Preloading Technique in China

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Abstract: A series of studies have confirmed that vacuum preloading can effectively accelerate the consolidation process of soft soil. In recent years, further improvement in the efficiency of this method is still the continuing goal of scholars. This paper reviews the recent improvements in the vacuum preloading techniques as well as their practical applications in China. The advantages and disadvantages of each method are discussed. It is found that replacing or eliminating one or more components of the vacuum preloading system, such as sand-free, membrane-free, horizontal drain, multiple-step, and air booster vacuum preloading methods, achieved similar soil improvement effects to those of the traditional vacuum preloading method. Vacuum preloading combined with other soil improvement methods could improve the soil with the lower average water content and the higher average shear strength.

Keywords: soil improvement; vacuum preloading; soft soil; consolidation

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1. Introduction

The land requirement for the construction of housing, industry and airports and some other infrastructures in coastal areas of the world is being rapidly increased in recent years. Marine clay dredged from the seabed using a cutter suction dredger has been widely used as a filling material for land reclamation in China [1,2]. The vacuum preloading method is often adopted to improve the engineering properties of the newly pumped marine clay slurry due to its advantage of being more environmentally friendly and having lower energy consumption [3–6]. The conventional vacuum preloading method uses atmospheric pressure as a temporary surcharge and prefabricated vertical drains (PVDs) to shorten the drainage path to accelerate the consolidation process. Compared with the surcharge preloading method using the equivalent loads, the vacuum preloading method is cheaper and faster [7].

The vacuum preloading system consists of vertical drains, horizontal vacuum pipes embedded in a layer of the sand blanket, membranes, and vacuum pumps as shown in Figure 1. The mechanism of the vacuum preloading method, the change process of pore water pressure and the effective stress are clearly illustrated by Chu and Yan [4], as shown in Figure 2. The applied vacuum load instantly transfers to the pore water pressure and gradually increases the soil skeleton to gain effective stress. The amount of effective stress increment equals the amount of pore water pressure dissipation which does not change the total stress. The effective stress is equal to $\sigma_0{}' + u_0(z) - u_t(z)$, where $\sigma_0{}'$ is the initial effective overburden stress, $u_0(z)$ is the hydrostatic pore water pressure, and $u_t(z)$ is the pore water pressure.

The sand blanket acts as a drainage layer and distributes the vacuum pressure from the horizontal pipes to vertical drains [8]. Clean sand is required for the sand blanket and it may not be available in some construction sites. The vertical drains mainly include pipe drains, sand drains, and prefabricated vertical drains (PVDs) which are the most popular type of drains used in the vacuum preloading method. As the vertical drain is one of the key factors that enables the technique to be cost-effective, the development of vertical drains is never stopped. The membranes are used to seal the whole site to create airtight conditions. As only a limited size of membranes can be placed at one time, site subsections are therefore required for a large land reclamation project [9]. When applying the vacuum preloading technology for dewatering and consolidation of clay with a high water content, such as newly dredged slurry, sewage slug, and mining ponds mud, one more limitation is the fine particles may move inward to the PVDs' surface, clog the drainage path, decrease drainage efficiency and form a soil column [10].

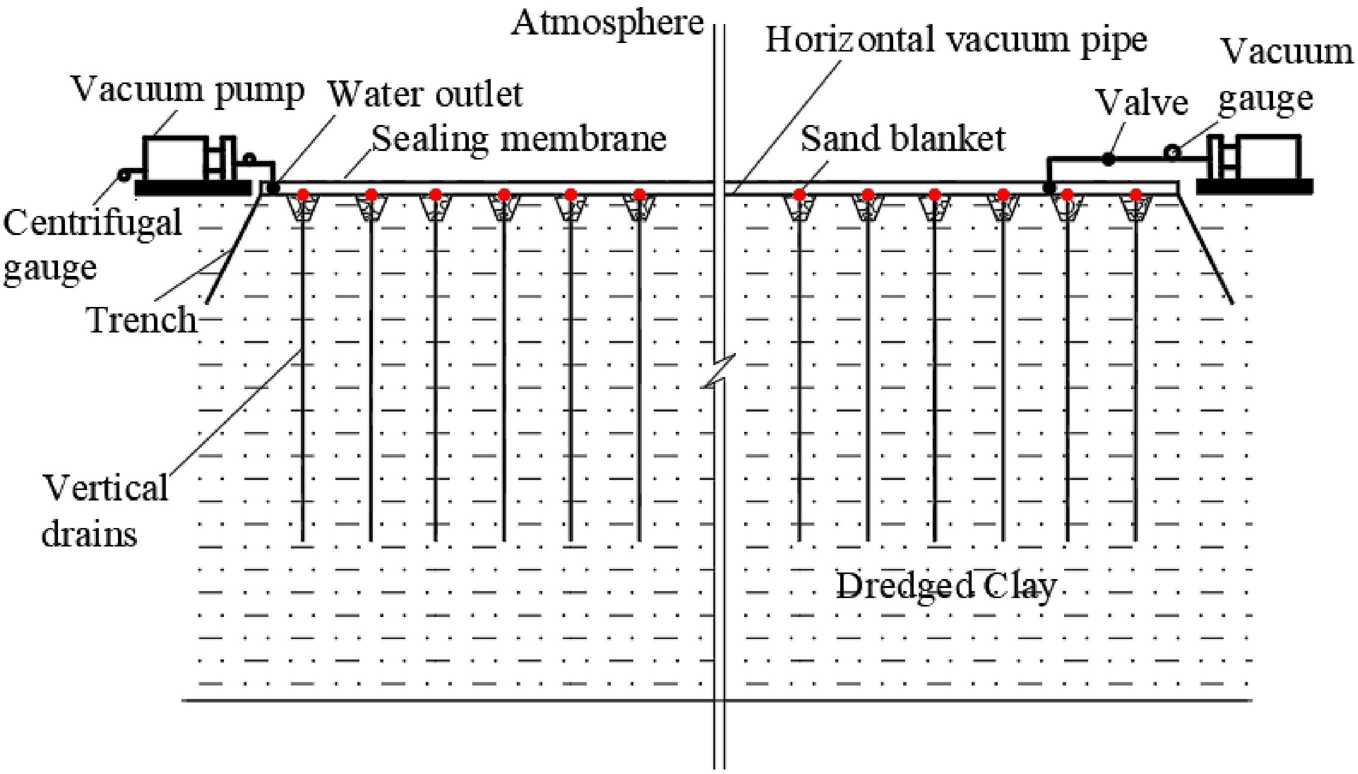


Figure 1. Vacuum preloading system (Modified after Chu et al. [7]).

To solve above-mentioned limitations, several new vacuum preloading techniques or vacuum preloading combined with other soil improvement techniques have been successfully developed recent years in China. The major categories and applications of the vacuum preloading technique including the methods of replacing or eliminating one or more components of the vacuum preloading system, i.e., sand-free, membrane-free, horizontal drain, multiple-step, and air booster vacuum preloading methods, and combining with other soil improvement methods, i.e., vacuum preloading combined with dynamic compaction, electro-osmosis, thermal treatment and airbag methods. This paper reviews these techniques as well as their practical applications. The advantages and applications of each method are also discussed.

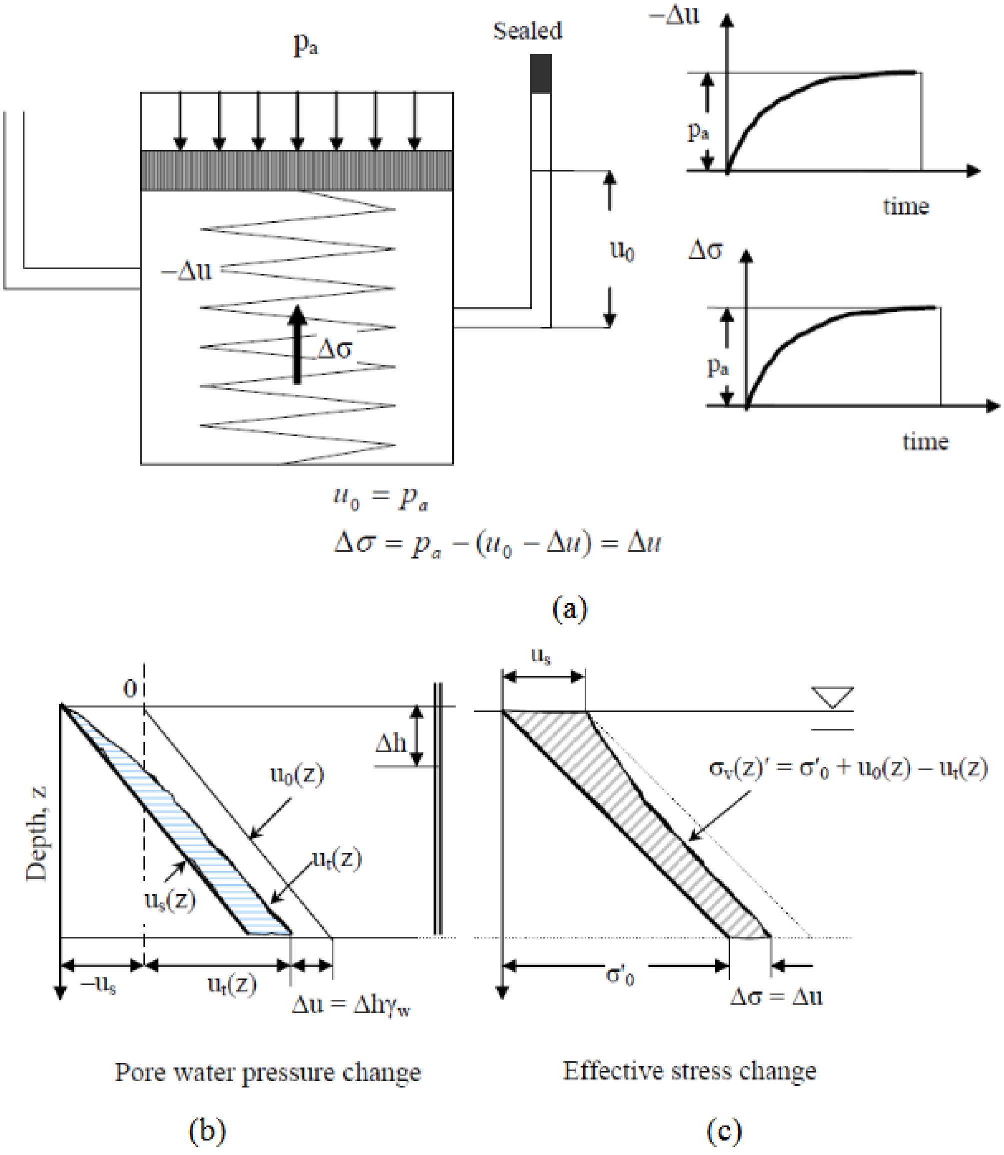


Figure 2. (**a**) Spring analog of the consolidation process, (**b**) pore water pressure, and (**c**) effective stress changes of vacuum preloading method (Chu et al. [5]).

2. Improvement of Vacuum Preloading System

2.1. Improvement of PVDs

The method of vacuum preloading combined with short PVDs is used to form a working platform for future soil improvement work at a land reclamation site in Tianjin, China [11]. Short PVDs were installed in square grids with spacings of 0.4 m and 0.6 m, and short PVDs connected using embedded vacuum pipes installed at 0.4 m spacing present a better effect in forming a working platform on the surface of the dredged slurry. The degree of consolidation (DOC) after 60 d of vacuum preloading combined with short PVDs at 0.4 m and 0.6m spacing are 96.2% and 85.1%, respectively.

To improve the newly dredged marine clay layer together with the bottom sediment clay, the sand-free vacuum preloading method can combine with short and long PVDs as schematically shown in Figure 3a. Pilot tests were conducted at a construction site in Tianjin port, China, to investigate the performance of this method [12]. The long PVDs are installed into the sediment soil layers in a square pattern with a grid of 0.8 × 0.8 m. The short PVDs are installed in the dredged clay layer with their positions in-between the long PVDs as shown in Figure 3b. The vane shear strength profile of the soil improved by the vacuum preloading combined with short and long PVDs was more uniform than those improved by that combined with only long PVDs to improve top dredged clay together with the bottom sediment clay. The maximum undrained shear strength in the depth of 0–10 m from the soil surface can reach 40 kPa. The average DOCs on the 30, 60, and 110 d were estimated as 52.3%, 83.7%, and 90.1% based on pore water pressure data, respectively. A similar layout of short and long PVDs was adopted by Liu et al. [13] to improve the newly dredged fills, and two lengths of PVDs can be simultaneously processed. The improved synchronous and alternate method increases the water discharge by 27.9% compared with the traditional vacuum preloading. The average vane shear strength of 49 kPa with the newly improved method is achieved at the surface. In addition, the better effect of consolidation achieved by the newly improved method is also presented from MIP data.

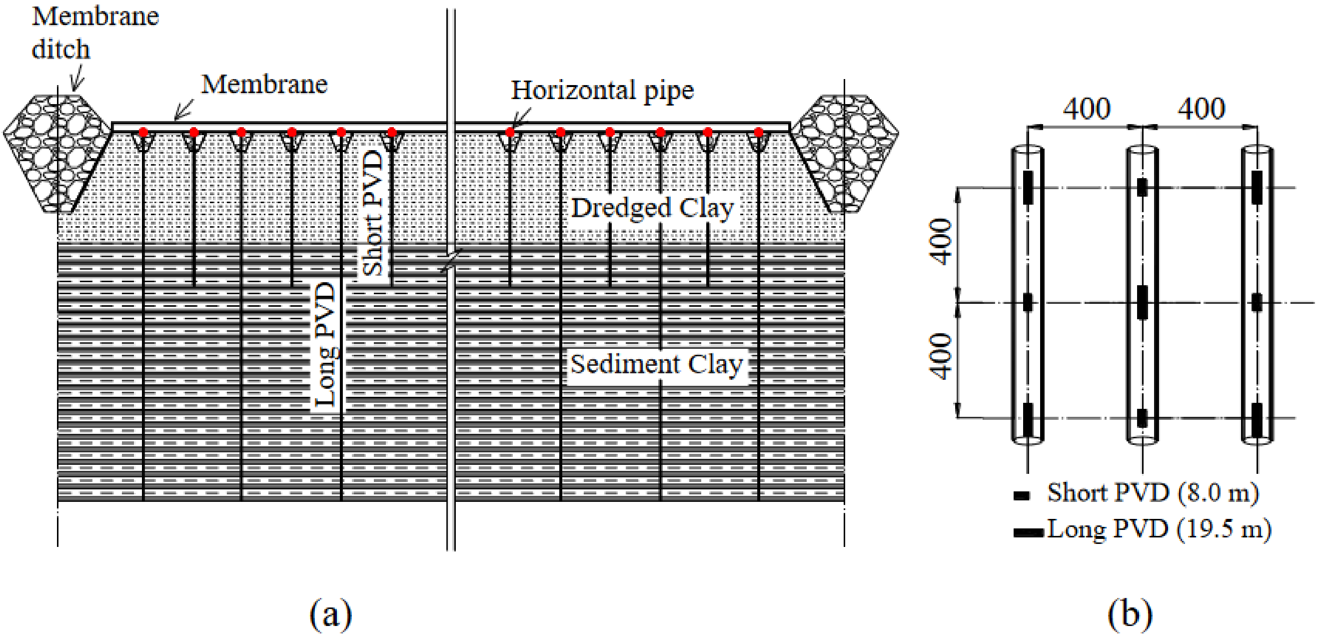


Figure 3. (**a**) Schematic configuration, and (**b**) PVDs installation pattern (unit: mm) for sand-free vacuum preloading method combined with short and long PVDs (Sun et al. [12]).

Considering environmental impacts, a method of using wheat straw as degradable vertical drains and blankets has been proposed in China. The feasibility of this method has been verified by the model tests conducted by Xu et al. [14], and the field test by Liu et al. [15]. Photos of using wheat straw for the sand-free vacuum preloading method are shown in Figure 4. The wheat straw drain was fabricated using short straws with their length ranging from 5 to 20 cm and covered by a layer of geotextile as shown in Figure 4a. The permeability coefficient of this wheat straw drain ranges from 10^{-2} to 10^{-5} mm/s [14]. The fabricated wheat straw drain with a density of 0.121 g/cm^3, a diameter of 12 cm, and a length of 3 m were installed in a square pattern with a grid of 0.6 × 0.6 m. The blanket was layered by the wheat straw mat with dimensions of 20 m in length and 3 cm in thickness. It is suggested to weave the wheat straw mat using the wheat straw with a length of more than 50 cm. Four layers of wheat straw blankets were placed across vertically with a total thickness of 12 cm as shown in Figure 4c. Two layers of membranes with a thickness of 0.25 mm were covered to provide airtight condition. The field test results showed that the vacuum pressure in the wheat straw blanket can be maintained at 80 kPa after 12 h of vacuum pumping.

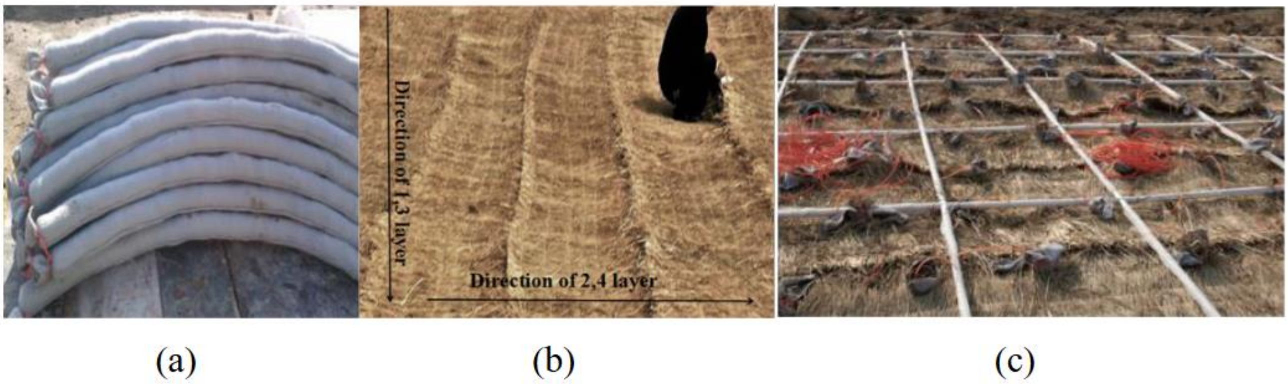


Figure 4. Photos of using wheat straw for sand-free vacuum preloading method. (**a**) Geotextile covered wheat straw drainage, (**b**) using wheat straw as drainage blanket, and (**c**) after installation (Liu et al. [15]).

2.2. Sand-Free Vacuum Preloading

The surface drainage system of the vacuum preloading method connects the top of the vertical drains to the vacuum pump. It consists of a sand blanket layer and horizontal vacuum pipes. To save the cost of the sand blanket layer in the conventional vacuum preloading method, a sand-free vacuum preloading method has been proposed by Sun et al. [12]. The schematic configuration of the proposed method is shown in Figure 5. The horizontal vacuum pipes are connected to the end of PVDs by using plastic cable ties and embedded in the excavated trenches with a depth between 30 to 50 cm as shown in Figure 5b. The PVDs are installed into the soft clay in a square pattern with a grid of 0.8 × 0.8 m. The edges of the airtight membrane are embedded below the soft clay surface of not less than 1.0 m in the excavated trench and backfilled with in situ clay. The results showed that the sand-free vacuum preloading method of using an airtight tubing system to connect PVDs and horizontal vacuum pipes was effective for improving the 20 m-thick soft clay. The DOCs of 86.4% and 90.1% can be achieved based on settlement and pore water pressure data, respectively. A similar method of using this system was adopted by Zhu et al. [16] to improve the dredged marine clay slurry at a reclamation site at Leqing port zone, China. Field tests show that the average water contents of clay were approximately 50.1 % and 54.4 % in the depth of 0–1.5 m and more than 1.5 m from the soil surface, respectively. The average DOC was more than 88% based on the settlement data. Wang et al. [17] proposed a membrane–connector vacuum preloading method where airtight membranes over the surface of the dredged slurry are used to maintain the vacuum pressure and PVDs are connected to a horizontal non-porous vacuum pipe by a sealed connector, as shown in Figure 6. In the model tests, the membrane–connector method with spacings of 0.8 m and the traditional PVD-hose method with spacings of 0.7 m has a similar effect. About 13% cost can be reduced by the decrease in the number of PVDs.

2.3. Membrane-Free Vacuum Preloading

The airtightness of the vacuum preloading system strongly influences the applied vacuum pressure and thus the efficiency of the soil treatment [18]. The conventional vacuum preloading method uses 2–3 layers of airtight PVC membranes to cover the treatment site and imbed their edges in the peripheral trench excavated at least 0.5 m-deep below the ground surface. To save the membrane and avoid the dike constructions in each subsection of the site for a large land reclamation project, the membrane-free vacuum preloading technique using mud to cover the site surface to form the airtight system was proposed by Sun et al. [9], as schematically illustrated in Figure 6. Because of the low permeability of the covered clay at a land reclamation site in Tianjin, China, a vacuum pressure above 80 kPa can be maintained for a long time under the mud-covering. At the end of the pilot test, the average DOCs of 85.1% and 83.5% can be achieved based on settlement and pore water pressure data, respectively. Field vane shear tests show that the average undrained shear strength of the soil in the very soft marine clay layer and the soft clay layer increased from 5.6 kPa and 14 kPa, to 20 kPa and 30 kPa, respectively. However, there are several disadvantages to these approaches. Firstly, it may be difficult to ensure that each drain is operating at the same vacuum pressure. Secondly, vacuum can only be transported to the soil by vertical drainage [19]. Thirdly, the absence of membranes and deformation of the sealing slurry layer are the main reasons that low pressure was maintained [20].

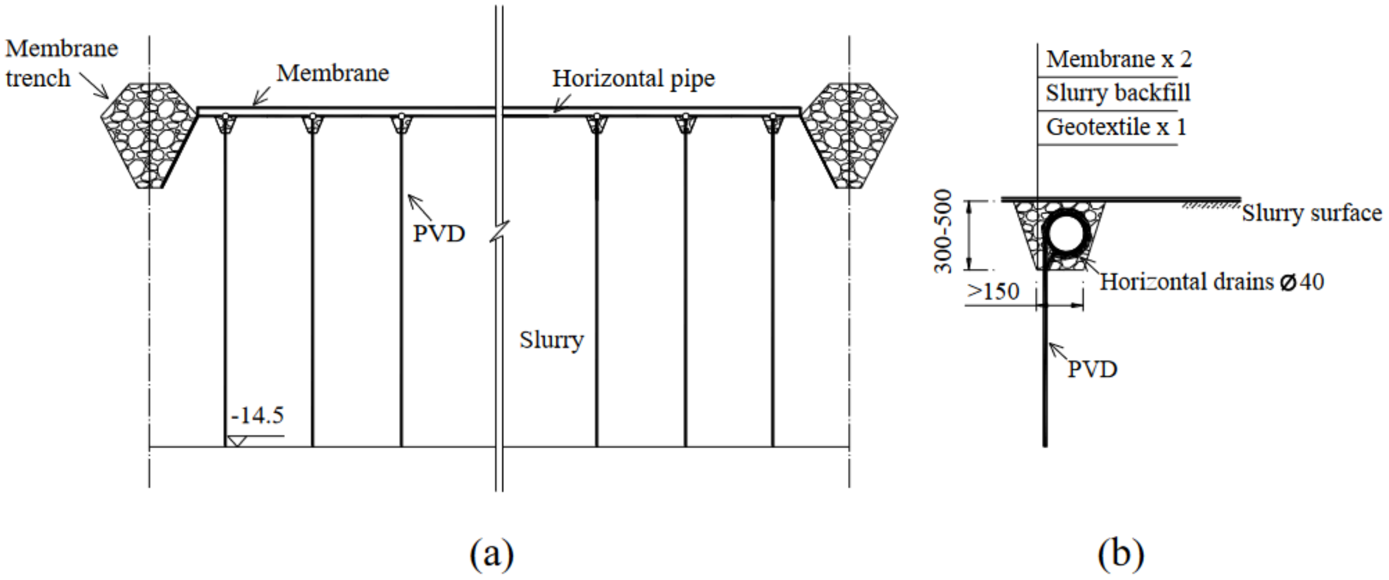


Figure 5. (**a**) Schematic configuration, and (**b**) installation pattern of PVDs (unit: mm) for sand-free vacuum preloading method (Sun et al. [12]).

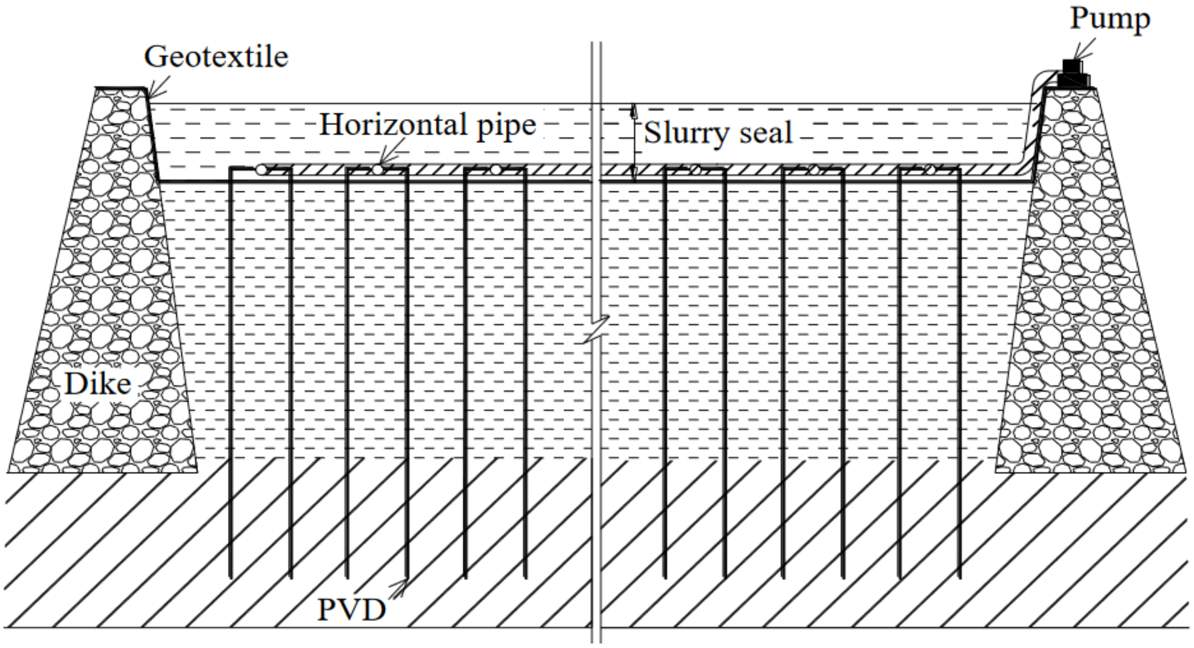


Figure 6. Membrane-free vacuum preloading method (Sun et al. [9]).

The sand blanket is an alternative method of forming the drainage system in the membrane-free vacuum preloading system. The PVDs can be connected to the horizontal vacuum pipes directly to enable each vertical drain to work independently and thus in turn eliminate the requirement of a sand blanket [19]. There are several ways to connect PVDs to horizontal vacuum pipes. One method is to wrap PVDs around horizontal vacuum pipes directly as shown in Figure 7a. Although vacuum pressure can be transferred from horizontal vacuum pipes to PVDs, this is not a direct connection system. Alternatively, the PVDs can connect to the horizontal vacuum pipes through a specially designed connector to form the airtight tubing system as shown in Figure 7b. However, the larger requirements of the connectors greatly increase the connection time and construction cost. The fish-bone shape connecter to connect the drainage pipes and PVDs was proposed by Sun et al. [11].

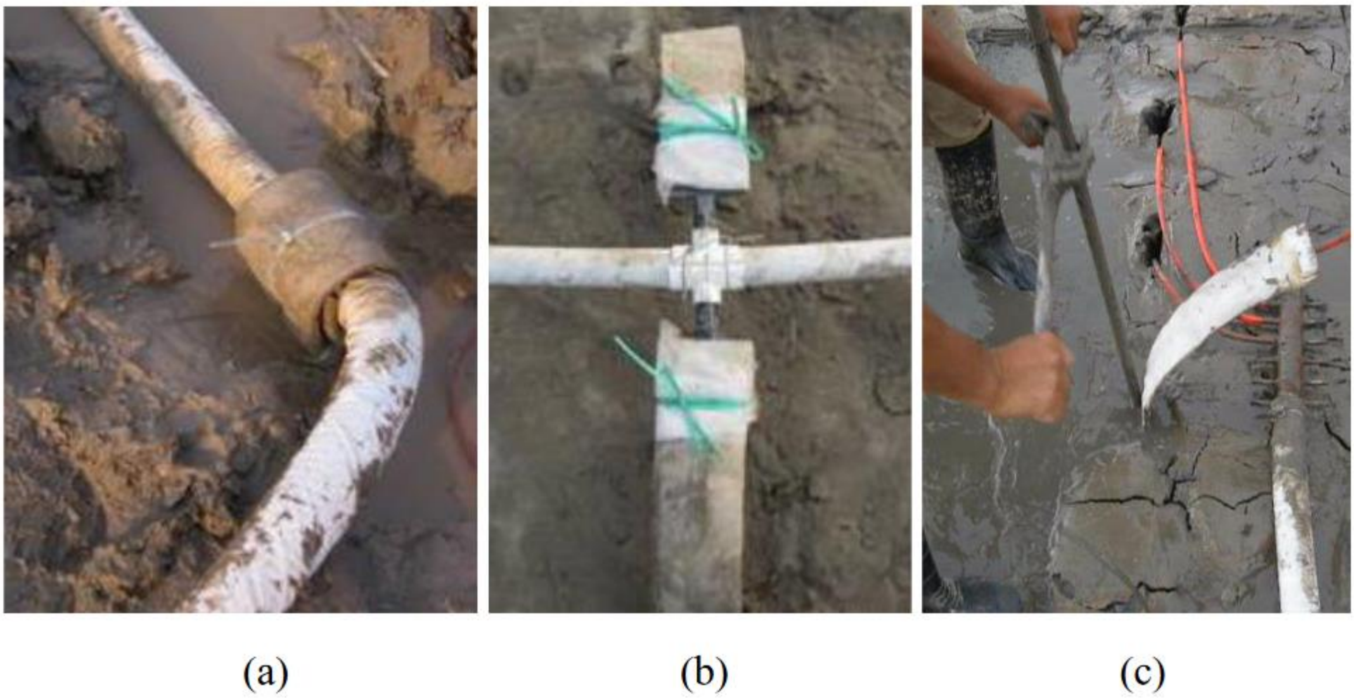


Figure 7. Methods to connect PVDs and vacuum horizontal drains. (**a**) Wrap PVDs directly, (**b**) connect using connectors and (**c**) connect using fish-bone connectors (Sun et al. [11]).

2.4. Horizontal Drain Vacuum Preloading

A horizontal drain method presented by Park et al. [21] and Kim and Shin [22], which installs plastic drains in the reclaimed ground in the horizontal direction, combined vacuum or gravity preloading to improve the bearing capacity of dredged clay. To reinforce and consolidate the soft soil, a new method of sewing prefabricated vertical drains onto a layer of geotextile sheet, or so-called geotextiles with horizontal drains (GHD), was proposed by the third author to improve the reclaimed ground in the horizontal direction as shown in Figure 8. Using GHDs, the installation of vertical drains is no longer required. The GHDs can be placed in the fill materials, layer by layer, during the fill placement process. Once a layer of GHDs is placed, vacuum pressure can be applied immediately through GHDs for soil consolidation. This is a huge advantage compared to the use of vertical drains where the vacuum or surcharge load can only be applied after all the fill materials have been placed. Furthermore, the fill materials placed on top of the layer of GHDs can now contribute to the surcharge preloading. A 1D consolidation solution was proposed by Zhou et al. [23] considering the vacuum boundary and critical flow gradient.

Another prefabricated radiant drain (PRDs) was proposed by Lei et al. [24] to improve the consolidation effect of the dredged clay. As shown in Figure 9, the PRDs were fabricated by horizontally attaching several short PVDs, so-called PHDs, onto a vertically installed PVD. The PRDs were arranged according to the design requirements before filling, or PRDs were rooted into the dredged clay which was in the fluid–plastic state by using manual installation method. The heads of PVDs are directly connected to the horizontal vacuum pipes through a specially designed connector to form the airtight tubing system as shown in Figure 9b. It is found by Lei et al. [24] that the effect of vacuum preloading combined with PRD is better than that combined only with PVDs. The PRDs fabricated with horizontal drainage spacing of 0.5 m and installed into the soft clay in a square pattern with the grid of 0.8 × 0.8 m provide the best consolidation effect. Compared with conventional vacuum preloading, the maximum settlement of vacuum preloading with PRD was increased by 88.9 %. However, this method also has the following several disadvantages. For example, it may be difficult to ensure each PHD to be horizontal after installation especially in relative hard soil. Although vacuum pressure can be transferred from PHDs to PVD, this is not a direct connection system that reduces the water flow efficiency.

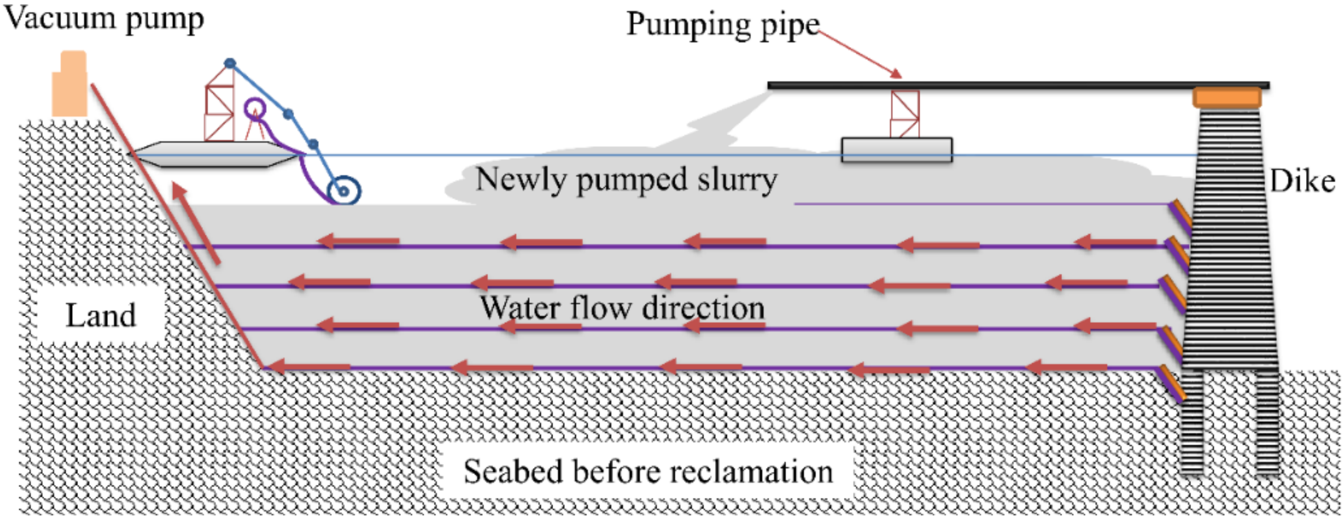


Figure 8. Construction process of the horizontal drain vacuum preloading.

2.5. Multiple-Step Vacuum Preloading

When using the conventional vacuum preloading technique to consolidate the newly pumped dredged clay, there is often a reduction in drainage capacity due to the clogging of the filter sleeves of PVDs. A multiple-step vacuum applied method has been investigated in recent years through laboratory model tests [25–27] and field cases [28,29]. The vacuum pressure could be applied in two-step of 40 and 80 kPa, in three-step of 20, 40, and 80 kPa, and even in five-step of 10, 20, 40, 60, and 80 kPa [29]. The DOC was 88.2% and 94.7% for the one-step and two-step vacuum preloading method based on final settlement data [25], and the average DOC reached 97.8% for the three-step method based on settlement data [27].

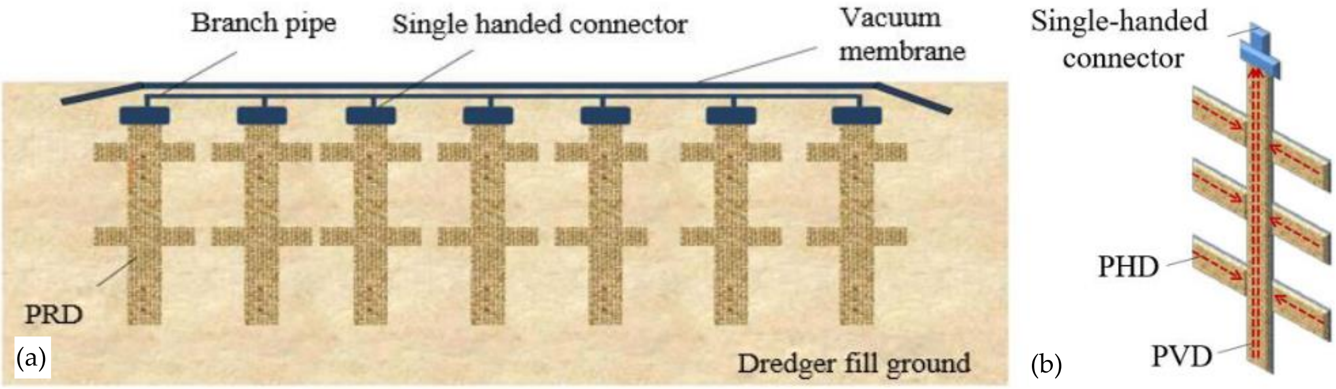


Figure 9. Prefabricated radiant drain vacuum preloading. (**a**) Layout of in field, and (**b**) details of the PRDs (Lei et al. [30]).

Compared with the traditional vacuum preloading method that applies the vacuum pressure in one go, the multiple-step vacuum preloading method could effectively improve the soil strength, delay the formation of clogging by reducing the non-uniform settlement and the radial movement of soil particles [30]. SEM images show that a large number of fine particles accumulate on the surface and inside of filter sleeves resulting in severe clogging in the conventional vacuum preloading method, however, the number of flow channels in filter sleeves increases significantly with the increase in vacuum steps. Moreover, particle analysis tests show that more vacuum steps are beneficial to reduce the movement of fine particles to PVDs under negative pressure [27]. The permeability tests show that multiple-step vacuum preloading can delay the decrease in the permeability coefficient of filter sleeves, thus reducing the aggregation of fine particles around PVDs [27]. However, more vacuum steps require more consolidation time which has to be fully considered in the design stage.

2.6. Air Booster Vacuum Preloading

The air booster vacuum preloading technique was proposed to solve the shortcoming of the conventional vacuum preloading technique in that the PVDs' drainage capacities were often reduced due to the clogging of the filter sleeves. The effectiveness of this method was verified by the field practices [31,32] and laboratory model tests [33–35]. The principle of the air booster vacuum preloading technique is schematically shown in Figure 10. This method includes vacuum and air-booster systems, both of which are sealed by the membrane. The vacuum preloading system has to connect the PVDs directly to the vacuum pipes using the airtight connectors. The air booster system consists of a high-pressure air pump and injection PVC pipe. The high-pressure air applied through the injection PVC pipe washes the fine particles accumulated on the PVD surface, increases the hydraulic gradient, and creates the rapid free water flow into the PVD. The high air pressure may generate fractures in soil which significantly increase the coefficient of permeability and thus speed up the consolidation process. After the high-pressure air pump was activated, the DOC increased from 80% to 85.7%. For adapting the conventional vacuum preloading method, the DOC only increased from 69.3% to 70.1% [32]. However, the disadvantage of this method is that the injected air may reduce the vacuum pressure. The excess pore water pressure in soil reported in the literature is mostly limited to 60 kPa and variable once the high-pressure air is injected into the soil. The booster activation time critically affects the vacuum preloading process with the optimum time to start the air booster system at the soil DOC of 60% [36].

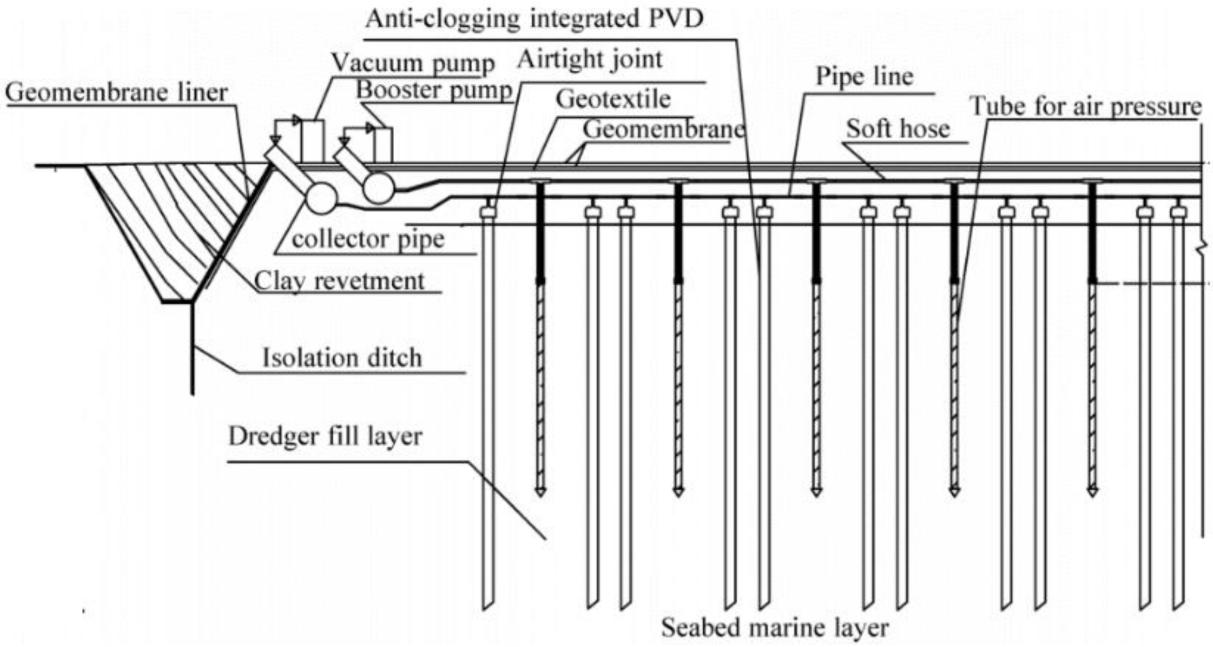


Figure 10. Schematic of the air booster vacuum preloading method (modified after Wang et al. [32]) (Reprinted with permission from Ref. [32]. 2022, Shuli Chen).

3. Vacuum Preloading Combined with Other Methods

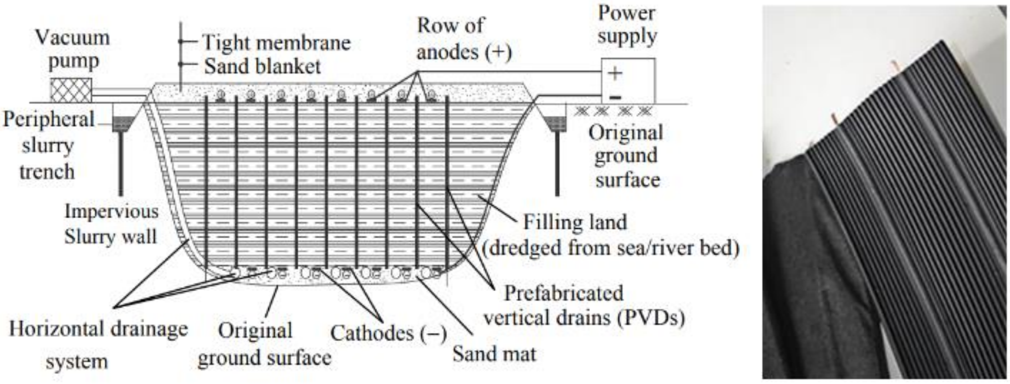
3.1. Vacuum Preloading Combined with Dynamic Compaction Method

As the vacuum preloading method is time-consuming during the consolidation stage, a method to overcome this problem is to combine vacuum preloading with dynamic compaction. The basic idea is to use dynamic compaction with low impact energy to generate excess pore pressure which can be then dissipated quickly under the vacuum action [37]. The dynamic compaction can even create micro-cracks in the soil and thus form new drainage channels to accelerate the vacuum preloading process. The quick dissipation of pore pressure in turn improves the efficiency of dynamic compaction. Another advantage of this method is that the dynamic compaction-induced lateral expansion of the soil foundation could somehow balance the lateral shrink induced by vacuum preloading. This method has been used successfully in several soil improvement projects in China. However, the time interval between the tamping rounds significantly influenced the effects of soil improvement. The laboratory investigations approved that the tamping interval time controlled by pore water pressure dissipation of 80% could improve the soil with the lowest average water content and the highest average shear strength [37]. However, the quantitative control of the method still lacks investigation which makes it difficult to apply in the field.

3.2. Vacuum Preloading Combined with Electro-Osmosis (EO) Method

The electro-osmosis method applies direct current to the soft soil through electrodes to drag the hydrated water molecules towards the cathode and thus create a flow of water and negative pore water pressure in the soil. The EO technique works effectively in soft soil improvement as it has the potential to enhance the hydraulic flow in fine-grained, low-permeability materials such as sludge and clays. However, the high cost efficiency and the erosion of the cathode restrict the applications of this method. The vacuum preloading combined electro-osmosis method overcomes the shortcomings of the pure electro-osmosis method. Considerable results have been achieved with the combined application of vacuum preloading and the electro-osmosis method [38,39]. The distributions of the excess pore water pressure in soil depend on the electrical potential distribution and boundary conditions [40]. The maximum magnitude of the excess pore water pressure is determined by the electrical potential between the cathode and anode. One key limitation of the method is that the metal electrodes undergo electrochemical reactions and become prone to corrosion, which in return consumes a large amount of electric energy. New methods have been proposed to reduce the energy consumption and improve the consolidation efficiency, such as vacuum preloading combined with stepped voltage electro-osmosis [41], with intermittent electro-osmosis [42], or with variable spacing electro-osmosis [43], or applying vacuum preloading pressure at the bottom [39].

A new type of corrosion-resistant electrode material, named EKG, has been proposed by Hu et al. [43] and applied as vacuum transferring and drainage shown in Figure 11a. The photo of the EKG is shown in Figure 11b. The EKG consists of a drainage tray, copper wires, and a conductive geomembrane [44]. The copper wires were protected by the electric polymer plastics and transmission electric energy during the test. The EKG can make the coupling between the electric seepage field and the hydraulic seepage field more effective. This new material can shorten the relative consolidation time and avoid the electrolytic reaction of metal electrodes [39]. However, the EKG method may change the mineral content and chemical component of the soil after treatment. Further improvement of the EKG product is still required to eliminate this pollution to the environment.

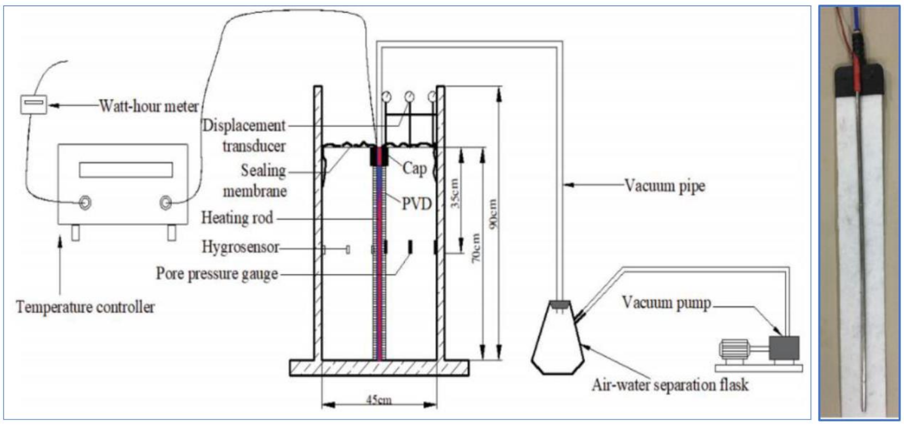


(a) (b)

Figure 11. (**a**) Schematic of the vacuum preloading combined EO method (Wang and Vu [44]) and (**b**) photos of EKG drain (Shen et al. [43]) (Reprinted with permission from Refs. [43,44]. 2022, You Zhou).

3.3. Vacuum Preloading Combined with Thermal Treatment (TT) Method

Field tests approved that the vacuum preloading combined thermal treatment method has a positive effect on soft soil improvement. This method mainly transformed the bounding water in the soil near the PVDs by combined heating to improve the permeability coefficient and thus accelerate the consolidation procedure. A series of laboratory model tests have been conducted by Wang et al. [45] to investigate the effects of temperature on the performance of this method, as schematically shown in Figure 12a. It is found that the permeability coefficient of soil significantly increases with the increase in temperature. The pore water can even change its state from liquid to gas as the boiling point of pore water decreases under negative air pressure. The vacuum preloading was in the best performance in soil improvement with a constant thermal temperature of 75 °C. A temperature of greater than 75 °C does not significantly increase the effectiveness of vacuum preloading because the fine-grained soil particles partially obstruct the pore channels. Furthermore, a higher temperature results in more energy consumption. The thermal treatment can also be achieved by adding recirculating hot water into the soil foundation to improve its consolidation effect [46]. Compared to the heating rod treatment method, the thermal equipment for recirculating in the hot water method is easy to manage and results in the uniform heating of the foundation. The cost of thermal treatment and limitation of the equipment are two limitations to determine the application in large-scale treatment of the vacuum preloading combined with thermal treatment method.



(a) (b)

Figure 12. Schematic vacuum preloading combined with TT method, (**a**) model test setup, (**b**) PVDs with thermal rod (Wang et al. [45]) (Reprinted with permission from Ref. [45]. 2022, You Zhou).

3.4. Vacuum Preloading Combined with Airbag Method

It is proven that a good effect can be achieved in consolidating the surrounding soil by applying the air pressure using airbags, and the combined method with air pressure has also attracted more and more attention [47]. One recent development is to enhance vacuum preloading with the effect of transmitting the air pressure into the soil using an impermeable and flexible membrane airbag embedded in the dredged slurry [48]. One example of the method is at the site is shown in Figure 13. Vacuum preloading combined with air pressure is similar to the surcharge combined vacuum preloading method and the air booster vacuum preloading method, and overcomes some of their shortcomings. A large amount of equipment and surcharge materials can be saved and the vacuum loss can be avoided due to gas diffusion. A series of laboratory model tests have been conducted by Wu et al. [48] to compare the combination of air pressure and vacuum pressure with the traditional vacuum preloading. During the test, an 82 kPa vacuum degree was maintained approximately. The airbag pressure of 15, 20, and 30 kPa was applied step by step, and the time points of pressurization were 273, 484, and 918 h, respectively. A comparison of shear tests shows that the average shear strength of soil is increased by 41.5%, which greatly improves the mechanical properties of the soil. However, the method has yet to be applied in practice on a large scale. More field studies with proper instrumentations are required.

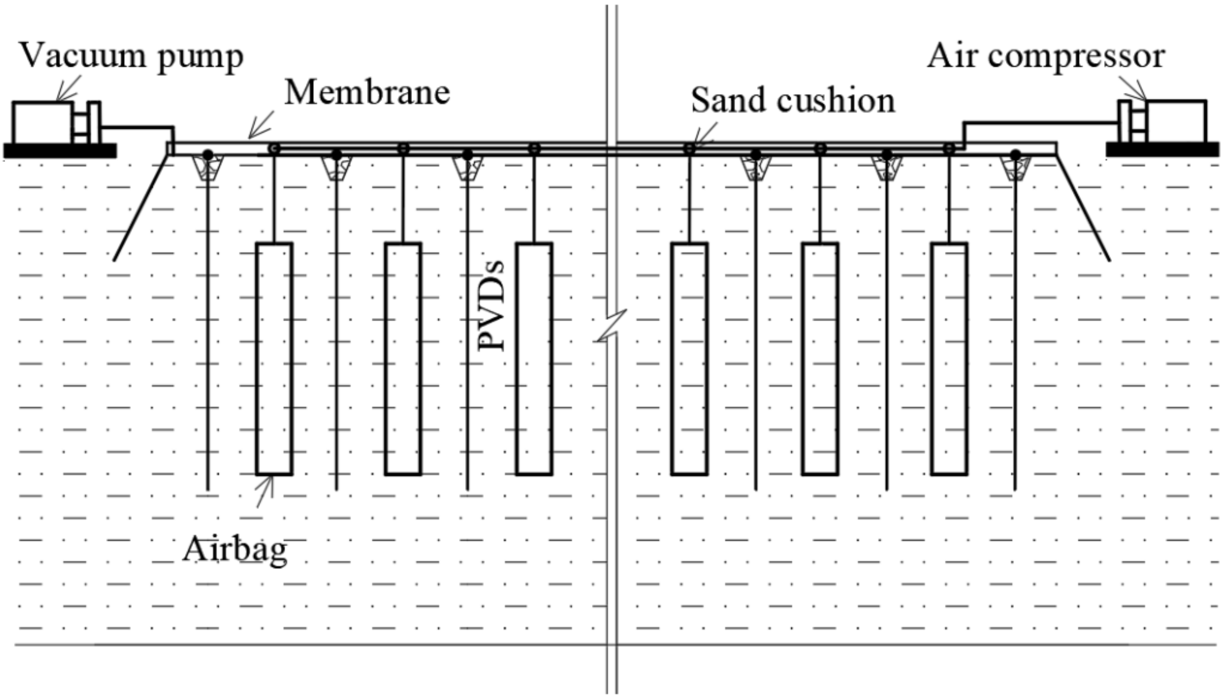


Figure 13. Schematic vacuum preloading combined with Airbag method (Modified after Wu et al. [48]).

4. Conclusions

It has been demonstrated that the vacuum preloading method can effectively improve the engineering properties of soft soil. Further improvement in the efficiency of this method is still the continuing goal of scholars. This paper reviews the recent new developments and applications of the vacuum preloading method in China. The main points discussed are summarized as follows:

(1) The vacuum preloading system mainly consists of five components, i.e., vertical drains, horizontal vacuum pipes, sand blanket, membranes, and vacuum pumps. The improvement in vacuum preloading system is to replace or eliminate one or more of these components, such as sand-free vacuum preloading, membrane-free vacuum preloading, horizontal drain vacuum preloading, multiple-step vacuum preloading,

and air booster vacuum preloading. Field tests show that the average DOCs of 86% and 85.1% were achieved using the sand-free and membrane-free vacuum methods, respectively, at a land reclamation site in Tianjin, China. Laboratory tests show that the DOC could even reach 97.8% when the vacuum pressure was applied in three steps. The air booster vacuum preloading method could improve DOC from 80% to 85.7% after the high-pressure air pump.

(2) The vacuum preloading method combined with other soil improvement methods is able to overcome the limitation of the conventional vacuum preloading method alone, including the vacuum preloading combined with dynamic compaction method, electro-osmosis method, thermal treatment methods, and air pressure method. These methods offer several advantages over either the vacuum or fill surcharge method alone. However, the environmental problems during the treatment process of some combined methods need to be eliminated.

(3) The future research works on the vacuum preloading method have to actively cross-collaborate with relevant disciplines, such as environmental engineering and chemical engineering, to achieve leaps forward in the development of this technique. Proposals for a new research area in practice have to consider their advantages and disadvantages, too.

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