Hindawi
Advances in Civil Engineering
Volume 2022, Article ID 6442750, 10 pages
https://doi.org/10.1155/2022/6442750

Research Article

Comparison and Cost Analysis of Soft Soil Foundation Treatment Schemes in Port Construction

Qiang Ren

Department of Engineering Management, Sichuan College of Architectural Technology, Deyang 618000, China

Correspondence should be addressed to Qiang Ren; renqiang@scac.edu.cn

Received 14 June 2022; Revised 6 September 2022; Accepted 13 September 2022; Published 12 October 2022

Academic Editor: Mohammed Jameel

Due to the characteristics of soft soil foundations in port engineering construction, there is a problem of insufficient bearing capacity, which needs to be treated. This paper analyzes the construction process and key points of the dynamic compaction method, vacuum preloading method, and vibroflotation method, and expounds on the advantages and disadvantages. The cost of different methods is compared. It can be seen that compared with other methods, the vibration impact method has a simple construction process and low cost.

1. Introduction

In recent years, with the rapid economic development of coastal cities, many port projects, cofferdams, and coastal new areas have begun to build, and land resources have become a key factor restricting their sustainable development. Therefore, the most important project for the development and utilization of tidal flat resources and the development of the marine economy is to reclaim land from the coastal tidal flat to alleviate the contradiction between rapid economic development and the relative shortage of land resources [1]. Port projects and other near-shore projects have undergone nearly 20 years of large-scale construction; the natural excellent port sites have been basically developed and constructed. To this end, people gradually began to shift their vision back to the original view that is not suitable for the construction of port sites, through a variety of man-made means to improve their natural conditions, so that they also have the corresponding construction conditions [2]. Soft soil foundation is one of the most common problems in offshore engineering.

Soft soil foundation is widely distributed throughout the world, in which marine facies and lacustrine facies are the main characteristics: high water content, easy compression, low strength, a small permeability coefficient, and easy thixotropy. In our coastal areas, the Bohai Bay, the East Sea coast, the Taiwan Strait, the Pearl River estuary, and nearby waters are widely distributed. There are some problems, such as insufficient bearing capacity in port engineering construction on soft soil foundations. Improper treatment will directly affect not only the quality and cost of the project but also may cause engineering accidents [3]. In order to improve the soft soil foundation and make it meet the requirements of shear, compression, and dynamic characteristics of the project, as well as to ensure the safety and normal use of port engineering [4, 5]. Aiming at the soft soil foundation, foundation treatment, as a commonly used technique, can effectively improve the bearing capacity of the foundation or reduce the settlement of the foundation or other special requirements.

At present, there are several kinds of treatment methods in port engineering. Replacement method: The main idea of this method is to excavate all or part of the weak soil and then use better materials to replace it. This kind of method can effectively improve the bearing capacity and obviously reduce foundations settlement. Some scholars use the dynamic compaction replacement method in the treatment of soft soil foundation of expressways, using the lifting equipment to lift the heavy hammer to a certain height to make it fall down freely, and using the impact energy to repeatedly tamp the crushed and gravel cushion laid on the soft soil surface, squeeze it into the soft soil layer, occupy the soft soil position, and play the role of replacement, so as to improve the bearing capacity of the foundation within a certain range, reduce its compressibility, and improve the bearing performance of the foundation. This method has strong applicability and remarkable reinforcement effect, and can effectively reinforce the soft soil subgrade of expressways [6, 7]. Drainage consolidation method: Drainage consolidation is a method to drain the soil, promote the dissipation of excess pore water pressure, reduce the pore ratio of soil, improve the shear strength of the soil, so as to improve the bearing capacity of the foundation, and reduce the settlement of the foundation after construction. Some scholars have used the dynamic drainage consolidation method of multidrop and multitamping combined with depth and shallowness during the reclamation of coastal tidal flats. This method combines precipitation and dynamic consolidation through the dynamic characteristics and dynamic consolidation mechanism of saturated soft clay to achieve foundation treatment. Dynamic compaction is used to change the structure of soil mass, resulting in excess pore water pressure, and then dynamic drainage is used to accelerate the dissipation of excess pore water pressure, strengthen the soil mass, shorten the consolidation time of the soil mass, improve the strength of the soil mass, and reduce the compressibility of the soil mass, which has a good application effect [8, 9]. The surcharge preloading method, vacuum preloading method, and vacuum combined surcharge preloading method are mainly used in port engineering. Low-energy dynamic compaction can reduce the compaction energy and improve the bearing capacity of the foundation. The cost of treatment is low, and the operation is very simple, reducing the impact on the surrounding environment. Some scholars have adopted the construction technology of the low-energy dynamic compaction method and CFG pile to jointly treat the foundation, which not only solves the load requirements of the engineering ground and foundation but also meets the extremely strict settlement design value. It has the advantages of a short construction period, low cost, low pollution, and high safety. However, due to the large vibration during the dynamic compaction construction, it is necessary to consider whether the surrounding environment of the proposed building is allowed before construction [10]. Vibroflotation is a method of compacting the soil by vibration or compaction in order to improve the bearing capacity of the foundation and reduce settlement.

Because of its high compressibility, a large amount of deformation, long duration, and low shear strength, soft soil may cause such engineering disasters as pavement cracking, bridgehead jumping, serious embankment deformation, and even instability, which is a major hidden danger for road safety and stability [11–13]. Therefore, in order to solve the problem of settlement or differential settlement brought by soft soil foundations in a coastal area, this paper studies different foundation treatment schemes and their cost comparison. The research flow of the article is shown in Figure 1.

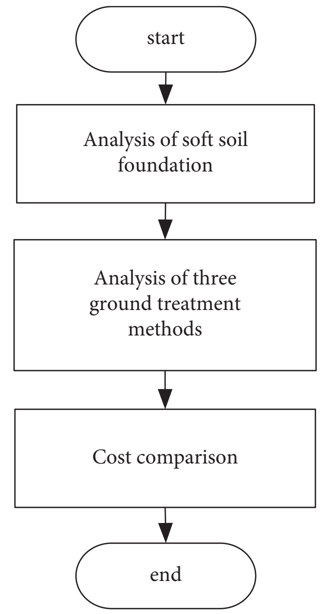

Figure 1: Flow chart.

2. Characteristics of Soft Soil and Common Treatment Methods of Soft Soil Foundation

Because of its easy deformation, soft soil foundation is easy to appear unstable. In its natural state, it can maintain stability, but when the soft soil is disturbed, its structure is easy to destroy and begin to flow. Therefore, the main engineering problems in the treatment of soft ground are attributed to the promotion of settlement and the maintenance of stability. Soft soil is divided into many kinds according to its different forms. But they all have the following common engineering characteristics, as shown in Figure 2.

(1) The natural water content is high, generally higher than the liquid limit, generally higher than 30% or even higher than 200%, and the relative water content is higher than 1.0. (2) The natural void ratio is large, and e is generally greater than 1.0. (3) The permeability coefficient is small, with a range of 10–6 to 10–8 cm/s, and the natural settlement consolidation speed is slow and the time is long. (4) High clay content and large plasticity index. (5) The strength index is small and has a high consolidation quick shear strength index, and the shear strength is less than 0.02 MPa.

Foundation treatment generally refers to the engineering measures taken to change the bearing capacity of the foundation or improve the deformation or permeability. Through the foundation treatment, we generally want to achieve the following purposes:

(1) To improve the bearing capacity of the foundation, the concrete manifestation of the shear failure of the foundation is that the bearing capacity of the foundation is insufficient and the shear strength is insufficient. Therefore, in order to prevent shear failure, we must take certain foundation treatment measures to improve the shear strength of foundation soil.

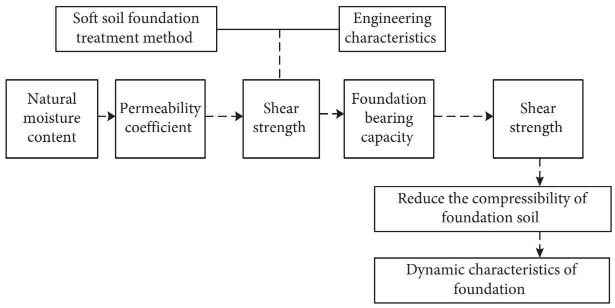

Figure 2: Flow chart of the land-based processing method.

(2) Reduce the compressibility of the foundation soil. The compressibility of the foundation mainly lies in the settlement and differential settlement of the foundation. Therefore, the foundation treatment method is adopted to improve the compression modulus of the soil so as to make the post-construction settlement and settlement difference meet the use requirements.

(3) Improving the seepage and dynamic characteristics of the foundation. Due to the poor permeability of the soft soil foundation, some of the soft soil will liquefy under dynamic load. The purpose of foundation treatment is to improve the dynamic characteristics of the foundation.

Commonly used methods of soft soil foundation treatment include chemical reinforcement, load reduction, filling, drainage consolidation, composite foundations, and other methods. Methods for comparative analysis are given as follows.

3. Comparison of Construction Schemes for Soft Foundation Treatment in Different Ports

After nearly 10 years of development, port engineering has achieved fruitful results, especially the progress of soft foundation treatment technology. At present, the methods of soft foundation treatment commonly used in port engineering include the vacuum preloading method, pile-up preloading method, vacuum combined surcharge preloading method, dynamic compaction method, and vibroflotation replacement method [14]. The cost analysis at the design stage is mainly based on the Provisions on the Budget Preparation of Coastal Port Construction Projects and the supporting quotas (hereinafter referred to as the “current quotas”) [15]. However, there is a contradiction between the development of soft foundation treatment technology and the relative lag of the current quota, which makes it particularly important to master the construction methods and techniques, properly use the quota, and obtain the price index for correctly compiling the cost documents of soft foundation treatment [16]. In this paper, three classical methods of soft soil foundation treatment are selected, namely dynamic compaction, vacuum preloading, and vibroflotation replacement. The characteristics and construction process are summarized.

Various types such as ZCQ75, ZCQ100, ZCQ132, ZCQ180A, and ICEV230 are adopted for the port foundation treatment project, and the matching model is selected through the vibration test of the test section. As shown in Table 1.

3.1. Dynamic Compaction. Dynamic compaction is often used in foundation treatment. This method is a new technology of soft soil reinforcement that has been developed and studied for more than 10 years. There is a marked difference between the construction method and the dynamic compaction method [17]. According to the basic principle of dynamic compaction, the structure of the soil must be destroyed first and then consolidated again. However, dynamic compaction can only be used in the case of clay with a certain water content. The low-energy dynamic compaction method can be used to tamp the soil under the condition that the structure of the soil does not change or significant damage does not occur.

3.1.1. Mechanism Analysis of Consolidation by Dynamic Compaction. According to the previous research results, the mechanism of dynamic compaction is as follows: the shock wave produced by compaction breaks the connection between soil particles, and with the increase of compaction energy, the pore and a particle shape of the pit subsoil develop from a pore shrinkage stage to a particle deformation stage to a particle inlay stage, thus changing the distribution state of all kinds of pores in the soil and their relative content [10]. That is to say, compaction destroys the original loose structure of the soil, changes the connecting mode between the skeleton particles, and makes the soil particles rearrange into a dense structure. With the recovery of soil thixotropy, the cohesive, colloidal, and crystalline salts in a more compact state can play a better role in cementation and improve the shear strength and deformation resistance of the soil. The dynamic consolidation of filler is shown in Figure 3.

According to Mena’s equation, the relationship between the depth of reinforcement and the main influencing factors is established.

$$H = \beta\sqrt{\frac{Qh}{10}}. \quad (1)$$

In (1), β is the coefficient related to the properties of foundation soil. Q is the hammer weight, kg. h is the height, m. H for design reinforcement depth, m.

Key indexes of the dynamic compaction method: The indexes affecting the effect of dynamic compaction mainly include compaction energy (weight of the hammer and falling distance), times of compaction, compaction distance, and safety distance. As shown in Figure 4.

(1) Tamping energy: Tamping energy is the most significant factor that affects the effective depth of dynamic consolidation and is also the decisive factor in cost of the treatment project. The choice of

Table 1: Main technical parameters of vibroflotation device.

Project	ZCQ75D	ZCQ75D	ZCQ132A	ZCQ180A	ICE V230
Motor power	75	100	132	180	230
Speed	1460	1480	1480	1480	3000
Rated current (A)	150	197	246	336	—
Exciting force (kN)	160	190	220	300	388
Overall dimension	420 ∗ 3210	402 ∗ 3215	402 ∗ 4003	402 ∗ 4470	—
Weight (kg)	1800	1900	2500	3000	3260

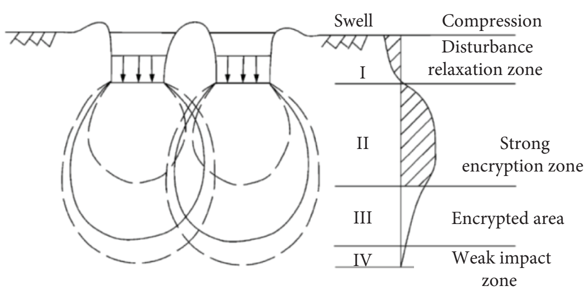

Figure 3: Dynamic consolidation of filler.

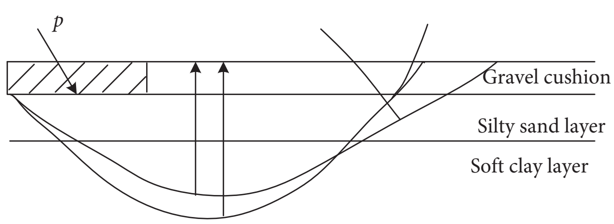

Figure 4: Schematic diagram of the depth of the foundation holding layer.

ramming energy is mainly based on the depth of reinforcement and the extrusion of the abutment. According to the predicted depth of treatment, the maximum tamping energy should not be less than 40 tm.

(2) Determination of hammer weight and fall distance: In order to maximize the performance of dynamic ramming machinery, generally, the greater the rammer weight is, the better (the weight shall be more than 10 t). After the rammer weight is determined, the fall distance can be determined according to the ramming energy.

(3) Tamping times: The engineering data show that the dynamic stress at the same position increases with the increase of tamping times; the dynamic stress of soil tends to be stable after 3–5 hits, and the tamping settlement of soil tends to be stable after 5–10 hits, which indicates that the soil is compacted. According to the ramming energy, the criterion for judging the end of ramming is that the difference between the adjacent two ramming sinks is less than 3–5 cm.

(4) Tamping point layout and spacing: Tamping point layout generally uses plum blossom or square network arrangements with a tamping point spacing of 3 to 5 m. Considering the actual situation of the project, it is suggested that the first ramming point should be arranged as a regular triangle with a spacing of 3 m, and the second ramming point should be located at the center of the first ramming point.

(5) Safety distance: Reducing the impact of ramming on bridge structures and ensuring the stability of embankments is the key to limiting the applicable scope of this method. In design, in order to ensure ramming quality and avoid quality accidents such as abutment cracking and embankment instability, the distance from the ramming point edge to the abutment (embankment edge) shall be determined before ramming, that is, the safety distance. According to the contour map of dynamic compaction hole pressure distribution, when the radial distance is more than 2 m, the impact degree of compaction is obviously reduced, so the safety distance can be determined as 2 m.

3.2. Vacuum Preloading. The vacuum preloading method is one of the most commonly used technologies for soft soil foundations. Its weak drainage effect and siltation of the drainage plate seriously restrict the consolidation effect [2]. This method is generally applied to soft clay and ultra-soft clay and is suitable for storage yards and warehouses. It is characteristic that the foundation does not increase the total stress, the soil is in lateral compression, it does not need to carry out heaping, and it can save the relevant information. The construction example is shown in Figure 5.

3.2.1. Mechanism Analysis of Strengthening by Vacuum Preloading. When using a vacuum load to reinforce a soft soil foundation, the vacuum load is applied to a sand cushion by a vacuum pump. The vacuum load is transferred to the deep part of the soil through the plastic drainage plate; thus, the pore water pressure of the soil is gradually reduced, and the effective stress of the soil is correspondingly increased. This is the basic principle of vacuum preloading [18]. In the vacuum preloading method, a vertical drainage channel is set up in the soft soil foundation and a layer of sand cushion is laid on the ground as a horizontal drainage channel. A vacuum under the membrane forms a pressure difference. This pressure difference is what we usually call a “vacuum.” The vacuum formed in the sand cushion is transferred to the deep soil through the vertical drainage passage, and the pore water pressure of the soil is reduced so that the water of the soil is seeped up to the sand cushion along the vertical

Figure 5: Construction example.

drainage passage, and finally, the water is drawn out of the reinforcement area to achieve the effect of drainage consolidation.

The vacuum preloading method uses the vacuum pump to reduce the pressure under the sealing membrane to P_n', and the pressure outside the sealing membrane to P_0, thus forming a certain degree of vacuum $\Delta P = P_0 - P_n'$.

The empty load is transferred to the deep soil through the plastic drainage slab, which makes the pore water pressure in the plastic drainage slab decrease rapidly. But because the permeability coefficient of soil is small and the transfer speed of vacuum in the soil is slow, the atmospheric pressure P_n of soil is in the state before vacuuming, so the pore water pressure difference between soil and the plastic drainage plate is formed. Under the action of the pressure difference, the pore water in the soil is drained up through the plastic drainage plate, the pore water pressure in the soil is reduced gradually, and the soil is consolidated.

The degree of consolidation can be drawn as a hyperbola according to the settlement plate of each reinforcement area, and settlement calculation can be carried out according to the load change. The equation is as follows:

$$S_t = S_o + \frac{t}{\delta + \eta t}. \quad (2)$$

After deduction, the following may be obtained:

$$\frac{t}{S_t - S_o} = \delta + \eta t, \qquad S_\infty = S + \frac{1}{\eta}. \quad (3)$$

In the equation: t is the time from the full load. S_o is the foundation settlement under full load; S_∞ is the final settlement of the foundation δ, β is the constant related to foundation and load; It can be determined according to the linear expression of (2) α, β. The measured settlement value is determined by (2), and the linear regression is analyzed. In the equation: t is the time starting from the full load. S_o is the settlement of the foundation at full load. S_∞ is the final settlement of the foundation. δ and η is the constant relating to the foundation and load. δ and η value can be determined according to the linear expression (2), and the measured settlement value can be determined by the expression (2), and linear regression analysis is conducted.

3.3. Impulse Displacement Method. In port engineering, this kind of method can be divided into two kinds: the vibration and impact replacement method and the vibration and impact compaction method. The method of vibration and impact compaction, in which the displacement material is not filled into the vibration and impact hole but only the effect of vibration and impact is used. Filling the vibration punching hole with broken stone or coarse sand to form a replacement pile is called the vibration punching replacement method [19]. Such methods are applicable to sandy soil, silty soil (silty clay), and unsaturated soil (mixed soil). The final characteristic is that the composite foundation can be formed, the speed of reinforcement is faster, the equipment is simpler, and the construction process is more convenient.

3.3.1. Mechanism Analysis of Vibration and Impulse Replacement Reinforcement. The vibration and impact displacement method also uses the water impact force and the horizontal vibration force to form the hole, and it vibrates the backfill material in the hole with the vibrator. A series of piles are made in the foundation soil to replace part of the soft clay in the foundation soil to form a composite foundation [20]. The gravel pile is composed of vibrating stone piles and soft clay on the original foundation. The gravel pile not only has the bearing capacity of a pile foundation but also can play a certain drainage role to accelerate the drainage and consolidation of foundation soil. In the process of vibrating and punching piles, the horizontal vibrating force produced by the vibrating and punching machine will squeeze the backfill material out of the hole and push it into the soft soil layer around the hole wall, so that the diameter of the pile body is further enlarged. When the external force produced by vibrating and punching with the constraint force of the soil body, the diameter of the pile body is fixed [21]. It should be noted that if the strength of the original soil in the foundation is low, the binding force of the backfill to resist the squeezing of the backfill under the external force will be relatively small, and the backfill will become coarser if it is further diffused around the hole. If the original soil strength in the foundation is too low to balance with the forcing force produced by vibroflotation, the backfill will spread around the hole unlimitedly, the pile body cannot be generated, and the vibroflotation replacement method cannot be used to strengthen the soft foundation. The scene shock picture is shown in Figure 6.

Vibroflotation foundation reinforcement requires a certain amount of gravel, coarse sand, gravel, or slag for backfilling, and its effects are mainly in two aspects: the vibrator impacts to form a hole, and the vibrating body may be left on the foundation soil after it is lifted upwards. Holes: the backfill is used to backfill this part of the holes, which is the first function of the backfill. The horizontal excitation force generated by the vibrator during operation will vibrate and compact the backfill, and the backfill continuously filled in the hole will act as a force transmission medium and further compact the foundation soil by squeezing. Body: this is the second function of backfilling. The suitable degree of backfill gradation in the course of vibration impact construction can be judged by index, and the suitable number is calculated by the following equation :

$$S_n = 1.7\sqrt{\frac{3}{D_{50}^2} + \frac{1}{D_{20}^2} + \frac{1}{D_{10}^2}}. \quad (4)$$

In the equation, D_{50}, $D_{20,}$ and D_{10} are corresponding to the particle diameter (mm) of 50%, 20%, and 10%, respectively.

In vibroflotation construction, if broken stone is used as backfilling material, weathered stone or semi-weathered stone should not be used as much as possible. In the course of vibroflotation construction, the strength and permeability of piles formed by vibroflotation become lower and worse because of broken weathered stone and semi-weathered stone caused by vibroflotation [22, 23]. Equation (5) can be used to estimate the amount of backfill to be filled in per unit volume of sand foundation:

$$V = \frac{(1 + e_w)(e_0 - e_1)}{(1 + e_0)(1 + e_1)}. \quad (5)$$

In equation (5), V is the amount of filler needed to be based on a unit volume. e_0 is the original void ratio of sand layer before vibration and scour. e_w is the void ratio of the pile. e_1 is the required void ratio after vibration impact.

Gravel, broken brick, crushed stone, slag, pebble, and so on can be used as pile materials in the vibroflotation replacement construction process, so it is an economical choice to take materials on the spot. However, no matter which material is used as backfill, there should not be more than 10% clay content. Generally, the gradation of backfill is not required, but the maximum particle size of backfill is more than 50 mm, which may cause the hole problem and will wear out the shell of the vibrator, so do not choose it easily.

Figure 6: On-site vibroflotation.

Based on the above methods, the advantages and disadvantages of different methods are compared and analyzed. The results are shown in Table 2.

4. Cost Analysis

4.1. Cost of Dynamic Compaction Method [24]. The current quota contains dynamic tamping items with tamping energies of 1000 kN/m, 2000 kN/m, and 3000 kN/m and is divided into many cases according to the number of tamping points for every 100 m^2, including a tamping pit material backfilling a quota. The number of ramming points per 100 m^2 in the dynamic compaction quota is determined by multiplying the reciprocal of the shortest square distance between the ramming points in the layout of the final ramming points by 100 m^2, excluding the ordinary ramming points. The quota of dynamic compaction, including the number of tamping, the number of tamping times, and the number of knocking times of dynamic compaction should be adjusted according to the design. During the construction of dynamic compaction, the drainage machinery of the compaction pit has been calculated into other ship and machinery fees, and the use of the quota does not need to be increased. When the underground water level is unfavorable to construction, the sandstone cushion that needs to be bedded may be calculated according to the relevant quota of the bedding layer. Leveling includes leveling before ramming, after ramming, and in the ramming room. No additional calculation is required. For example, when ramming a strip foundation, the manpower in the ratio is multiplied by the coefficient of the ship. The backfill type of rammed pit material should be adjusted according to the design, such as soil, sandstone, or mountain soil.

Table 2: Comparison of advantages and disadvantages of different treatment methods.

Method	Advantage	Shortcoming
Dynamic compaction	(1) The dynamic compaction method is applicable to the treatment of gravel soil, silty soil, and cohesive soil with low saturation of sandy soil, collapsible loess plain fill, and miscellaneous fill. Especially for the treatment of collapsible loess, the practice has proved to be effective and reliable. (2) It exerts great impact energy on the foundation, and the general energy is 1000 kN m~8 000 kN. *m*. The shock wave and dynamic stress generated in the foundation can improve the strength of the foundation, reduce the compressibility of the soil, and eliminate the collapsibility of the collapsible loess. (3) Relative excavation and replacement can reduce the area of arable land occupied by spoil; reduce the amount of sand and gravel; compared with other soft soil subgrade treatment methods, the cost is low, the reinforcement effect is obvious, the construction period is short, and the cost is low.	(1) The reinforcement depth should not exceed 7 m. It has certain limitations. (2) The magnitude and dissipation speed of pore water pressure depends on the level of groundwater level and the permeability of the soil, which limit the construction period. (3) The noise and vibration are large, and it is not suitable for use in densely populated cities and residential areas.
Vacuum preloading method	(1) In addition to vertical compression, the soil will also be accompanied by lateral contraction during the reinforcement process, which will not cause lateral extrusion, making it especially suitable for the reinforcement of super-soft soil foundations. (2) Generally, the vacuum degree under the membrane can reach 600 mmhg, and the equivalent load is 80 kPa, which is about equivalent to a 4.5 m soil load; the vacuum preloading load can be overlapped with the surcharge preloading. When a preloading reinforcement load greater than 80 kPa is required, it can be used simultaneously with the surcharge preloading method. The preloading load exceeding 80 kPa is supplemented by the surcharge preloading. (3) Vacuum preloading load will not cause foundation instability, so it is not necessary to control the loading rate during construction. The load can be applied quickly at one time, with fast reinforcement speed and a short construction period. (4) Construction machines and equipment are simple and easy to operate; convenient for construction, high operation efficiency, low reinforcement cost, suitable for large-scale foundation reinforcement, easy to promote, and apply. (5) It does not need to load materials vigorously, which can avoid the transportation tension, turnover difficulties and construction interference caused by the transportation of materials; no noise, vibration, and environmental pollution during construction. (6) Suitable for foundation reinforcement in narrow sections and near slopes.	(1) Sufficient and continuous power supply is required: the reinforcement time should not be too long, otherwise, the reinforcement cost may be higher than the surcharge preloading of the same load. (2) In the process of vacuum preloading reinforcement, horizontal deformation will occur around the reinforcement area to the inside of the reinforcement area, and cracks often occur around 10 m away from the edge of the reinforcement area. Therefore, during construction near buildings, attention should be paid to the impact of foundation horizontal deformation on the original buildings during vacuum pumping.

Table 2: Continued.

Method	Advantage	Shortcoming
Vibroflotation method	(1) Reduce the settlement, form a composite foundation through the replacement principle of gravel pile, and greatly improve the bearing capacity and integrity of the foundation. (2) Eliminate liquefaction, and eliminate the liquefiable sand layer through the vibration compaction principle. (3) To improve the strength of foundation soil, the gravel pile is used as the vertical drainage channel of the foundation to squeeze and discharge the water in the saturated soft clay void, so that the foundation will gradually undergo consolidation deformation under the gradual action of the upper load, and finally improve the strength of foundation soil.	Gravel, electricity, water, and other materials are used in large amounts, and it is difficult to discharge sewage, especially in the process of vibroflotation.

In practical applications, it is found that the unit price of dynamic compaction quotas is expensive, and dynamic compaction with larger compaction energy is often used in construction. When the compaction energy is more than 3000 kN/m, there is no quota, and the engineering cost needs to be calculated by using the related cost indexes in the near future. In the northern port engineering area, the unit price of 3 times of the ramming technology (the first 2 times of point ramming, ramming capability of 5000 kN/m, ramming interval of 8 m, 10 strikes per ramming point, 3 times of normal ramming, ramming capability of 1000 kN/m) is generally about 50 yuan/m^2, and the actual bid price in construction is lower. In the southern port area, the unit price of 3 times ramming technology is generally about 25 yuan/m^2, and the actual construction price is lower.

4.2. Cost of Vacuum Preloading Method. The current quota mainly includes a vacuum preloading quota suitable for silt soil, and also includes leveling, sand cushion cleaning, fabrication and installation, etc. If the geotextile reinforcement is increased, the impervious layer quota of the laid plastic sheet can be adopted and the plastic sheet can be changed into geotextile. However, the artificial sand cushion can remove the loader and the bulldozer, and when the sand layer is blown to fill a large area, there is no relevant quota, and the real cost table of the project site is used, or the price is obtained through relevant exchanges with the owner. Compared with the general straight-row vacuum preloading, the supercharging system uses the drainage plate late supercharging; the supercharging system increases 4 yuan/m^2, and the other parts of the joint increase costs. But compared with the straight type, it needs more than 4 months to vacuum according to the treatment experience of dredger fill in Wenzhou, and the technology can achieve the expected effect in 3 months and can save about 10 yuan per m^2. The cost of pressurized vacuum preloading is basically the same as that of conventional direct vacuum preloading.

4.3. Cost of Pulse Displacement Method. First, the current quota situation. There is no relevant quota in the current quota. The second is the matter needing attention in the application. There is a direct relation between the unit price, diameter, spacing, and length of vibrating piles, so the cost can be calculated according to the unit price index of vibrating piles, and the cost of filling materials can be calculated separately. For example, in the Dalian area, the diameter of piles is 1.2 meters, the distance between piles is 1.8 meters, and the length of piles is 15 meters, which can be calculated by using a 130 KW vibrator. The unit price of a vibration-driven pile is related to the distance between piles, the length of pile, and the soil to be reinforced. The cost may be calculated according to the unit price index of the prolonged rice, and the cost of the supplementary packing shall be separately calculated and listed. In the northern port area, the unit price of vibrating crushed stone piles (excluding the price of gravel filling materials) with a diameter of 1.2 m, a spacing of 1.8 m between piles, and a length of 15 m adopting a 130 kW vibrator is generally about CNY15/m^2.

To sum up, the cost comparison of different methods is shown in Table 3.

5. Discussion

(1) Dynamic compaction: This method is suitable for coarse-grained soil with a particle size of more than 0.05 mm, such as sandy soil, mountain soil, and so on. It is characterized by less equipment used and a faster speed of reinforcement, but its vibration and mechanical wear are relatively large. The cost of a project needs to be calculated by using the recent relevant cost indicators for the project location, and the cost is unstable.

(2) Vacuum preloading method: The vacuum preloading method is suitable for general soft clay and super-soft clay and is suitable for storage yards, warehouses, airports, and roads. Its characteristic is that the foundation does not increase the total stress, the soil has lateral compression, the effective compaction rate is high, it does not need to pile, and it saves the investment. The cost may adopt the recent cost index of the place where the project is located, which is usually obtained through the exchange of price inquiries with the owner and the relevant construction entities.

Table 3: Cost comparison of different methods.

Method	Cost (yuan/m^2)
Dynamic compaction	25
Vacuum preloading method	40
Vibroflotation method	15

(3) Vibration-impact replacement method: It is mainly suitable for clay soil and not suitable for soft reclaimed soil; its final characteristic is that it can form a composite foundation. With a relatively fast speed of reinforcement and relatively simple machinery and equipment, the construction process is more convenient. Compared with other methods, the vibroflotation method is simpler and cheaper. So long as it is used properly, there will be more room for development in the consolidation of underwater soft soil foundations.

In the above analysis, the vacuum preloading method has the characteristics of underwater construction that cannot be obtained, and the replacement method needs a lot of excavation and replacement that is expensive. The vibration and impact method is widely used in land buildings at present, but there are few cases of underwater construction in port engineering. Compared with other methods, the vibroflotation method is simpler and cheaper. So long as it is used properly, there will be more room for development in the consolidation of underwater soft soil foundations. Therefore, the construction of some small port projects can be shifted to this method on the premise of ensuring safety and paying less cost to meet the construction requirements of the project. In the design, it is necessary to analyze the relevant regulations, but there is a certain lag in the quota standards, so it is necessary to have a clear grasp of the construction methods and techniques and the applicable quota standards to ensure that they can be better controlled at cost.

6. Conclusion

This paper discusses the characteristics of various construction schemes applicable to soft soil foundations and studies the reinforcement principle, reinforcement method, application scope, and cost of the dynamic compaction method, vacuum preloading method, and vibroflotation replacement method. By comparing the construction technology, application advantages, and limitations of different methods, the cost of different methods is analyzed. Through the comparison results, it can be seen that the vibroflotation method has lower costs and is more cost-effective.

Data Availability

The data used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The author declares that there are no conflicts of interest.

References

[1] S. Lu and X. Shi, "Selection of treatment methods for soft foundation of river in a reclamation area," *IOP Conference Series: Earth and Environmental Science*, vol. 474, Article ID 072004, 2020.

[2] W. Zhu, J. Yan, and G. Yu, "Vacuum preloading method for land reclamation using hydraulic filled slurry from the sea: a case study in coastal China," *Ocean Engineering*, vol. 152, pp. 286–299, 2018.

[3] F. Q. Chen, G. H. Yang, S. K. Sun, D. S. Guan, and S. J. Zhu, "In-situ test of soft soil in Pearl River Delta: engineering practices and effect analysis of result applications," *Journal of Yangtze River Scientific Research Institute*, vol. 36, no. 4, p. 129, 2019.

[4] F. Kassou, J. B. Bouziyane, A. Ghafiri, and A. Sabihi, "Slope stability of embankments on soft soil improved with vertical drains," *Civil Engineering Journal*, vol. 6, no. 1, pp. 164–173, 2020.

[5] J. Yuan, D. Lei, Y. Shan, H. Tong, X. Fang, and J. Zhao, "Direct shear creep characteristics of sand treated with microbial-induced calcite precipitation," *International Journal of Civil Engineering*, vol. 20, no. 7, pp. 763–777, 2022.

[6] H. Huang, M. Huang, W. Zhang, and S. Yang, "Experimental study of predamaged columns strengthened by HPFL and BSP under combined load cases," *Structure and infrastructure engineering*, vol. 17, no. 9, pp. 1210–1227, 2021.

[7] Y. Zhai, G. Liu, F. Jin et al., "Construction of Covalent-Organic Frameworks (COFs) from amorphous covalent organic polymers via linkage replacement," *Angewandte Chemie*, vol. 131, no. 49, Article ID 17843, 2019.

[8] Y. Guo, Y. Yang, Z. Kong, J. He, and H. Wu, "Development of similar materials for liquid-solid coupling and its application in water outburst and mud outburst model test of deep tunnel," *Geofluids*, vol. 2022, pp. 1–12, 2022.

[9] L. Wang, T. Yang, B. Q. Wang et al., "RALF1-FERONIA complex affects splicing dynamics to modulate stress responses and growth in plants," *Science Advances*, vol. 6, no. 21, Article ID eaaz1622, 2020.

[10] S. Wu, Y. Wei, Y. Zhang et al., "Dynamic compaction of a thick soil-stone fill: dynamic response and strengthening mechanisms," *Soil Dynamics and Earthquake Engineering*, vol. 129, Article ID 105944, 2020.

[11] P. Barua and S. H. Rahman, "Aquatic health index of coastal aquaculture activities at South-Eastern coast of Bangladesh," *Water Conservation and Management*, vol. 4, no. 2, pp. 51–57, 2020.

[12] Z. Ding, J. Jin, and T. C. Han, "Analysis of the zoning excavation monitoring data of a narrow and deep foundation pit in a soft soil area," *Journal of Geophysics and Engineering*, vol. 15, no. 4, pp. 1231–1241, 2018.

[13] Z. Wu, J. Xu, H. Chen, L. Shao, X. Zhou, and S. Wang, "Shear strength and mesoscopic characteristics of basalt fiber–reinforced loess after dry–wet cycles," *Journal of Materials in Civil Engineering*, vol. 34, no. 6, Article ID 247530357, 2022.

[14] X. Jiang, Q. Lu, S. Chen, R. Dai, J. Gao, and P. Li, "Research progress of soft soil foundation treatment technology," in *Proceedings of the IOP Conference Series: Earth and Environmental Science*, vol. 455, Article ID 012081, Nanchang, China, January 2020.

[15] Y. Chen, Y. Wei, and L. Peng, “Ecological technology model and path of seaport reclamation construction,” *Ocean & Coastal Management*, vol. 165, pp. 244–257, 2018.
[16] X. Y. Wang, “Optimization design of subgrade strength for urban road reconstruction project,” *Computer Simulation*, vol. 35, no. 4, pp. 311–314, 2018.
[17] M. Shen, J. R. Martin, C. S. Ku, and Y. C. Lu, “A case study of the effect of dynamic compaction on liquefaction of reclaimed ground,” *Engineering Geology*, vol. 240, pp. 48–61, 2018.
[18] L. Fan and S. Chen, “Consolidation analysis and effect analysis in the treatment of soft foundation by vacuum preloading,” in *Proceedings of the IOP Conference Series: Earth and Environmental Science*, 2021, Article ID 012135.
[19] Y. W. De, C. Sheng, and C. L. Xiao, “Field test and inspection of large area hydraulic sand ground improved by vibro-compaction,” *IOP Conference Series: Earth and Environmental Science*, vol. 304, Article ID 032068, 2019.
[20] C. Ramanathan and P. Prasad, “Vibro compaction technique in liquefaction mitigation and its value addition — a case study,” in *Proceedings of the Indian Geotechnical Conference 2019*, pp. 311–319, Singapore, 2019.
[21] R. Tao, X. Hua, R. Huang, and X. Feng, “Offshore vibro-flotation with stone column by jack-up under extreme wave condition,” in *Proceedings of the The Fourteenth ISOPE Pacific/Asia Offshore Mechanics Symposium*, Dalian, China, 2020.
[22] J. H. Pogu, C. C. Okafor, and J. C. Ezeokonkwo, “Suitability of sands from different locations at Nsukka as backfill material for vibroflotation,” *Nigerian Journal of Technology*, vol. 37, no. 4, pp. 867–874, 2018.
[23] Z. Zhu, Y. Wu, and Z. Liang, “Mining-induced stress and ground pressure behavior characteristics in mining a thick coal seam with hard roofs,” *Frontiers of Earth Science*, vol. 10, Article ID 843191, 2022.
[24] J. Qian and P. Wang, “Treatment plan and cost index of soft-soil foundation,” *Building Technique Development*, vol. 48, no. 14, pp. 109-110, 2021.