Application of composite foundation in marine environment

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Abstract: Under the marine environment, most of the underground projects will be eroded by the corrosive materials in varying degrees, which will lead to the deterioration of engineering materials, the reduction of structural strength, and affect the normal use and service life of the project; the rich sea water in the marine environment is often the premise of the smooth implementation of the underground projects, and the chaotic scouring of the intertidal sea water will affect the underground structure. It has great influence on the strength of concrete. Generally, the measures taken for underground structure concrete include: improving concrete grade according to environmental category, adding admixtures, reducing water cement ratio, increasing compactness, etc. to improve concrete performance, anti-seepage, anti-freezing, anti-carbonization, anti-corrosion performance, increasing concrete protective layer thickness, brushing anti-corrosion materials, etc. to extend concrete durability; the measures taken for reinforcement include: coating epoxy resin, mixing anti-rust agent, etc. They can protect the concrete of underground structure to a certain extent, and the relevant specifications have corresponding provisions on it, but only qualitative provisions, the real effectiveness and validity period are unknown, the durability of the structure leaves long-term hidden danger, and also leads to the increase of construction cost. In marine environment, the foundation treatment under complex geological conditions can provide reliable working face for the construction of underground structure, eliminate the adverse impact of marine environment on the concrete of underground structure, and provide guarantee for improving the durability of concrete.

1. Construction examples and analysis

1.1. Construction profile
A construction project is located along the coast and is intended to build an integrated project for the port, energy storage, and power generation. The berth is constructed by clearing the seabed and introducing precast box culverts. The foundation site adopts plastic drainage boards to carry out the consolidation drainage method of vacuum surcharge preloading to form a thousand-ton coal storage yard. The land and sea reclamation projects are combined to build a power generation project. The north side is a mountain, the east side is a village, and the south side is the sea. The integrated project for the port, energy storage, and power generation will be arranged in sequence from the east. The design overview is that the northeast side is set as a flood detention basin, which is later planned to be a wetland park. An anti-seepage wall is set along the junction of the flood detention basin, the southern sea area, and the power storage area (the lower part is foundation treatment, the upper part is concrete structure). The length is about 1km on the north, 2km on the east, 2km on the south, and 2.8km on the west. The original soil layer was found to be moderately corrosive after exploration.
### Table 1: The basic soil conditions

| Layer   | Soil Type            | Description                                                                                     |
|---------|----------------------|-----------------------------------------------------------------------------------------------|
| Layer 1 | Plain fill           | Newly backfilled and formed by land reclaiming in the factory area. Mountain rocks: this layer is formed by backfilling stones on the hills. They generally vary in diameter from 30 to 80 cm. Uncompacted, poor grain composition, large voids and strong water permeability. The average thickness of this layer is 5.50m. The south side is deeper with a thickness of about 8.6 meters and above. |
| Layer 2 | Silt                 | Dark gray, saturated, fluid plastic, rancid, pure in quality, partly contains a small amount of shells. There is a thin layer of fine sand sandwiched by the silt layer in a part layer. The silt in a part area is transformed into silty soil. This layer of soil is a highly compressible under-consolidated soft soil, not an organic soil. PH=6.8, weak acidity, moderate corrosion. The average thickness of the layer is 9.50m. |
| Layer 3 | Clay                 | Reddish-brown, yellowish-brown, plastic, wet, partly hard plastic and soft plastic, partly transformed into silty clay, not pure in quality, mixed with a small amount of gravel. It exists in the form of a lens with an average thickness of 3.1m. |
| Layer 4 | Silty clay mixed with gravel | Purple-gray, gray-yellow, brown-yellow, wet, plastic, partly hard plastic, uneven soil, gravel content accounting for 3.4-39.3%. This layer has an interlayer of clay, silty clay and silty soil in the form of a lens. The average thickness of the layer is 20.70m. |

### 1.2. Construction complexity

1.2.1. Complicated surcharge preloading
The coal storage yard is arranged on the west side, which adopts plastic drainage boards to carry out the consolidation drainage method of vacuum surcharge preloading (hereinafter referred to as zone 1, with better pretreatment effect).

The southeast corner is a temporary cross-sea passage. A storage yard for flat materials and equipment (hereinafter referred to as zone 2 below) consisting of blasting stones with discrete particle sizes is set nearby as a temporary passage for entering the port and a storage yard for mechanical equipment. One unlayered landfill is formed, and the particle size of the landfill varies. The upper part is rolled by heavy vehicles without treatment. The soft soil layer is more than 7-8 meters thick, with flow-plastic silt inlaid with stones of different sizes. The soft soil layer has been severely disturbed, and the physical and mechanical indicators are discrete. The flood detention basin reserved on the east side and the whole south side is affected by the tide and is covered by undrained, untreated silt and silty soil. The height and thickness of one side are squeezed by the mountain stones, causing the original soft soil layer to be disturbed. In this way, the generated earth pressure destroys the stability of the original soft soil layer (hereinafter referred to as zone 3).

1.2.2. Hydrological data reveals that the water head difference is about 6 meters during the tide. The reciprocating water head in the intertidal zone is large, and the high water head causes serious loss of cement paste, which has a large impact on the strength of cement-based materials.

1.2.3. Moderate corrosion
Geological investigation data reveals that the soft soil layer is weakly acidic, which is mainly caused by the combined action of silty soil and seawater with moderate corrosion. What's worse, it causes serious damage to the pile foundation engineering, underground concrete structures, and underground pipe networks of power generation projects.
2. Analysis and foundation treatment

2.1. Foundation treatment

The purpose of foundation treatment is to accelerate the consolidation of the soft soil layer, improve the bearing capacity of the foundation, and ensure the stability of the site. For this construction project, the first and second layers of soft soil with a thickness of about 15 meters are mainly processed. According to the nature of different areas such as normal treatment area, complete disturbance area, and local disturbance area, vibro compaction and high-pressure grouting are combined to a different extent. When encountering boulders, the grouting pressure and grouting spacing should be adjusted flexibly and appropriately.

For zone 1, vibro compaction is mainly used, and filter material is added as an auxiliary. During compaction, the saturated silt soil undergoes liquefaction within a certain range of the vibroflot. The soil is recombined under the action of vibration force, its own weight, backfilled rocks, and the pressure of the overlying soil. In this way, the soil becomes dense due to the reduction of the pore volume. Additionally, due to the filter material with a large permeability coefficient, clear drainage channels, and faster settlement, vibro compaction can reduce the final settlement and improve the bearing capacity of the foundation.

For zone 2, the muck becomes thicker due to the squeezing of the mountain rocks from one side. Because the soft soil layer is not treated, the permeability of the soft soil is weak. The excess pore pressure generated under the action of vibration is difficult to dissipate, resulting in a poor compaction effect. Owing to disordered backfilling and the weight difference between the upper load and the loading equipment, the filter material is mainly added here. This is equivalent to a deep replacement, forming a large diameter sand pile in the soft soil and a composite foundation accompanied by the surrounding soil. The orifice is supplemented with medium-coarse sand to restore a working condition between the gravel pile and the compaction pile, and form a better vertical and radial drainage channel. After the orifice bears the load, it will produce radial deformation and cause the passive resistance produced by the surrounding consolidation and the reinforced soil. Stability can be guaranteed under the lateral constraints of the surrounding soil. When the vibration load occurs, the pore water pressure can dissipate faster. Due to the artificial liquefaction in advance, the ability of the original soil to resist earthquake liquefaction is improved. At the same time, the pore water pressure generated during the earthquake can be quickly dissipated. The consolidation time is significantly shortened, the final settlement is reduced, and the bearing capacity of the foundation is enhanced.

For zone 3, during the low tide period, geotextile-wrapped sandbags are loaded. After it molds, the work plane is grouted and then backfilled in layers.

2.2. Anti-seepage treatment of the site

When the site consolidation degree reaches 90%, the construction of the anti-seepage wall should be organized. The construction project in this article uses high-pressure rotary jet grouting to prevent seepage. When the nozzle rotates 360 degrees and sinks, the high-pressure water sprayed is used to cut and disturb the soil. Under the same circumstance, the high-pressure fluid sprayed is then used to cut the soil. Afterward, The injected fluid is mixed up with the soil, and a new approximately cylindrical consolidation is solidified, which is cement soil. The soft soil layer is processed into mortar or concrete column occlusive piles or composite foundation. The composite soil layer after drainage consolidation (compacting or replacing the soft soil after consolidation) is a coarse aggregate of mortar or concrete, among which the cement is the main component that provides strength after solidification. Compared with undisturbed soil, cement soil has higher compressive performance and favorable impermeability. The anti-seepage body formed by cement soil can cut off or reduce the seepage flow in the foundation under the marine environment, so the seepage stability in the foundation can be guaranteed.
2.3. Brittleness of the anti-seepage body in marine corrosive environment and exploration of processing materials

According to the research results of Han Pengju et al. [1-5], Fatahi B [6], Wongprachum W [8], etc., by incorporating fiber materials including recycled carpets, polypropylene, and steel, the fiber matrix obtained plays a significant role in the process of changing cement soil from brittleness to ductility, effectively improving the performance of cement soil. By solving the problem of high compressibility, it helps improve the brittleness of cement soil, thereby increasing its ductility. The cement soil made by cement alone as the curing agent has poor corrosion resistance. As long as a certain amount of external admixtures including slag, fly ash, etc. are infiltrated to replace part of the cement, its compression resistance strength will greatly be elevated, and the durability of cement soil can also be improved. The corrosion-resistant formula for the cement soil required for site construction is given, that is, the mass of fly ash and slag accounts for 40%-60% of the curing agent. The results show that in the marine environment, fly ash has a good effect on restraining the expansion and destruction of the cement soil, and obviously improves the mechanical properties of its structure in the later stage.

2.4. Reducing the impact of tides

Adding admixtures, including accelerators, sodium silicate, early strength agents, superplasticizers, etc. can shorten the initial setting time, reduce the water-cement ratio, and elevate the fluidity of the mortar. Based on the tidal law, quickly increasing the early strength of cement soil is conducive to resisting the water head erosion of the intertidal zone and lower the loss of cement slurry, to relieve the impact of the water head in the intertidal zone. Since the admixture has a greater influence on the strength of cement-based materials, the amount of admixture must be determined through experiments. The water-cement ratio of the construction project in this article is controlled within 1:1-1.2, and the initial setting time is 45-55 min.

2.5. Impermeability and process parameter control

After testing in the laboratory, this project should be combined with the fiber content of structural impermeable concrete. Based on the ash content, polypropylene fiber should be blended with a dosage of 4kg/t. In addition, it is mixed with 40% fly ash, and the mixing amount is 40% of the solidified material. The pozzolan cement 42.5R is selected, which helps increase the strength by about 25%. In actual engineering, the effect of foundation treatment is mainly controlled by speed increase and pressure. Impermeability is closely related to the process parameters of high-pressure rotary jet grouting piles, especially the following three indicators include water-cement ratio, grouting pressure, and speed increase of the rotary jet grouting axis.

Based on relevant specifications and standards, this project is executed according to the following parameters:

Water and gas supply: The high pressure (slurry) water pressure is not less than 20MPa, and the gas pressure is controlled at 0.7~0.8MPa. The shotcrete pump capacity is 80L/min. The pump discharge of shotcrete is 80L/min.

Water-cement ratio: 1:1-1.2, the proportion of mortar is about 1.5, and the shotcrete lifting speed is 0.15-0.2m/min.

The shotcrete volume per meter of the pile is =1m/0.15m/min×0.08m3/min=0.533 m3.

The actual ash consumption per meter of the pile is 0.403 tons×1.2-1.4=0.483 tons-0.564 tons.

To facilitate on-site guidance and organization of construction and control process parameters, the anti-seepage treatment data of nearly 8km is compiled for different foundations. Under the 20-25 Mpa working conditions required by the specification, the following empirical formulas are summarized for reference: Vp =P/200*p. Where,

Vp: speed increase (m/min), P: shotcrete pressure (MPa), p: porosity (%)

Process parameters: to ensure the anti-seepage effect, reduce the settlement, and boost the bearing capacity, drawing on the principle of concrete pouring and vibrating process, the vibrating rod is required to be inserted quickly and pulled out slowly, staying and re-vibrating, staying and re-spraying. In this
way, a relatively uniform and dense cement-soil column can be formed during vibrating and shotcreting, which is beneficial to improve the ability to resist lateral water pressure, earth pressure, and vertical load.

Pile rest period: after the foundation treatment is completed, well-functioning vertical and radial drainage channels are being formed. At this time, the consolidation speeds up and the settlement increases, which requires a certain period of pile rest to avoid the settlement of the composite soil after the jet grouting, resulting in severe negative friction. What's worse, it may cause deformation of the composite foundation, affect its impermeability, lower the bearing capacity of the composite foundation, and even fail the project.

3. Treatment process and related parameters
According to the characteristics of the soil layer, the settlement under the surcharge preloading is calculated theoretically. Furthermore, it is possible to estimate the specific time point when a certain degree of consolidation is reached and the growth value of the foundation strength after the surcharge preloading. Given this, the foundation conditions are evaluated, and a practical backfilling plan and foundation treatment are proposed.

3.1. The typical soil layer is treated traditionally.
Due to the large construction area corresponding to the coal storage yard, the drainage consolidation method of vacuum surcharge preloading is adopted to deal with the soft soil foundation. The backfill materials are the mountain rocks. The rock density is taken as $r=17.0 \text{kN/m}^3$, and the average backfill height is 7.0m. The calculated layer thickness of the weak soil layer (including the silt layer and silty soft clay) is 13.0m, $C_u=10.1 \text{kPa}$ (vane shear test), and the internal friction angle of triaxially consolidated undrained shear soil is $\phi_{cu}=10.1^\circ$. According to theoretical calculations, in the case of inserting the plastic drainage board, the loading is divided into three levels. The total load height is 8.60m, the theoretical settlement is 1.48m, the corresponding consolidation time is 0.83 years, and the consolidation degree reaches 90%. The shear strength of the foundation can be increased from 10.1kPa to 29.71kPa.

3.2. The complete disturbance area corresponds to the temporary entry port.
The soft soil layer is more than 7-8 meters thick with flow-plastic silt and different sizes of rocks inlaid. The particle size of the piled load is unequal and it is only formed by one filling. The upper part is rolled by heavy vehicles. The soft soil layer has been severely disturbed, and the physical and mechanical indicators are discrete. The original soil layer has been severely disturbed and destroyed under the action of reciprocating tidal erosion. According to the Fellenius formula, the maximum level-1 load of a natural foundation is $P_1=42.83 \text{kPa}$. Under the maximum $P_1$ load, when the degree of consolidation reaches 70%, the corresponding consolidation time is 12.07 years. Moreover, the shear strength of the foundation has not increased much, only 36.7%. The thickness of the surcharge is 8.50m, and the increase in the degree of consolidation and strength of the foundation after 5 years of preloading is 18.43kPa. Besides, one surcharge causes the block stones to be wrapped in silt, resulting in disturbed soil. The actual effect is worse than the theoretical calculation and fails to meet the requirements.

3.3. The local disturbance area corresponds to the shore of the flood detention basin.
It is squeezed on one side and is subject to the combined action of lateral earth pressure and reciprocating intertidal water pressure. The original soft soil layer is squeezed and disturbed to a certain extent, and there is a certain deformation.

Combining the above situation, different foundation treatment methods should be adopted for different circumstances. The processing conditions and effects are as follows:
Table 2: Record of treatment process

| Item                                      | Area                | Zone 1 (West side) | Zone 2 (Southeast corner) | Zone 3 (East and south side) |
|-------------------------------------------|---------------------|--------------------|---------------------------|-----------------------------|
| Elevation (m)                             |                     | 0                  | 0                         | -5                          |
| Loading in three zones                    |                     |                    |                           |                             |
| How to load                               |                     | Plastic drainage board, staged vacuum surcharge preloading | No drainage, one loading (with the disorderly dynamic load above) | No drainage, one loading of geotextile-wrapped sand to 0 meter |
| The first observation elevation (m, 6 months after the loading) | -0.95 | -0.57 (located on the channel, auxiliary is added to flatten in the process, so the data here has no value in use) | -0.13                       |
| The second observation elevation (m, 9 months after the loading) | -1.42 | -0.62 | -0.25 |
| Foundation shear strength (comparison between loading before and 9 months after loading) | Cu=10.1kPa→29.71kPa | Because the boulders are wrapped in plastic silt, no valid data has been measured. | Cu=10.1kPa→12.33kPa |
| Foundation treatment                      | High pressure grouting | Vibro compaction (auxiliary added) | High pressure grouting |                             |
| Processing purpose and expected result    |                     |                    |                           |                             |
| The third observation elevation (m, pile rest period, 1 month after vibroflotation treatment, cumulative to 10 months) | -1.43 | -1.33 | -1.35 |
| The fourth observation altitude (m, after foundation treatment, cumulative to 11 months) | -1.52 | -1.43 | -1.47 |
| The fifth observation elevation (m, after the upper concrete construction, cumulative to 20 months) | -1.55 | -1.55 | -1.58 |
| The sixth observation elevation (m, 3 years after foundation treatment) | -1.58 | -1.63 | -1.62 |
4. Conclusion

4.1. This article analyzes foundation treatment measures in different foundation circumstances through engineering examples. Combined with the theoretical settlement, indicators include durability, corrosion, impermeability, and site stability are fully analyzed. According to different soil quality and different porosity at different depths at the same location, this article points out the control points of foundation treatment. Besides, Summarize the main points of the foundation treatment are summarized, including the lifting speed, pressure, and porosity formula. It provides concise and controllable guidance for the construction, thereby facilitating quality control.

4.2. During the excavation of the foundation pit of the power generation project, it was discovered that the groundwater of the foundation pit mainly came from the perched groundwater and the water in the rainy season, which proved that the tidal influence was effectively controlled. According to observations, when excavating the outlet project of the circulating water of the vertical cut-off wall, the soil texture is uniform after the foundation treatment, and the soil around the pile is dense, clear, well consolidated, and has no water seepage marks. This shows that the measures taken are appropriate, economical, and practical. On the one hand, the impact of tides is effectively controlled and construction organization is guaranteed. On the other hand, the impermeable body develops from brittleness to toughness, that is, to give full play to its strength advantages and ensure its integrity and durability with a certain seismic capacity, which is of great help to the durability of the concrete structure in the site.

4.3. The experience obtained in this article applies to many foundations including silt, silty soil, cohesive soil, silt, loess, sand, artificial backfill, and gravel soil. It has guiding significance for water conservancy projects, including flood control and seepage prevention, embankment foundation treatment, curtain grouting for seepage prevention, incomplete rock formation, and high-risk slope in the reservoir area. Moreover, reference is provided for yellow wet soil treatment. In addition, new ideas are offered for anti-seepage treatment and foundation treatment in the marine area of medium and severely corroded reclaimed land. What's more, it has a great promotion and application value for the stability of foundation pit slopes of existing and new industrial and civil buildings, such as foundation treatment, strengthening the bottom of the foundation pit, preventing leakage and piping, and retaining soil and water on the sidewalls of the deep foundation pit.

Acknowledgments:
Fujian Natural Science Foundation Project (No.: 2020J01941); University level talent introduction project (No.:FZYRCQD 201902)
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