Analysis of Monitoring in settlement For Vacuum Combined Stack Preloading about Soft foundation Sluice

Yao Yong-xin¹,², Ji Fanng-yi³

¹Zhejiang Institute of Hydraulics & Estuary, Hangzhou, 310020, China
²Zhejiang Guangchuan Engineering Consulting Co., Ltd., Hangzhou, 310020, China
³Wenzhou Oufei Economic Development Investment Co., Ltd., Wenzhou, 325000, China

Corresponding author’s e-mail: yaoyx237@163.com

ABSTRACT: Vacuum combined surcharge preloading is a kind of drainage consolidation method, having many advantages, such as low reinforcement cost, short construction period and good reinforcement effect, and suitable used in foundation treatment in soft foundation. Based on vacuum combined surcharge preloading reinforcement project of one Sluice soft soil foundation in the east coast of Zhejiang Province, this paper introduced the in situ monitoring situation in the vacuum preloading process, mainly summarized the monitoring result of vacuum degree and surface subsidence, and found out the changes and connections of indicators in the preloading process. At the same time, the development process of vacuum combined with preloading and settlement is simulated by finite element method.

1. Foreword

Vacuum preloading is an important method of drainage consolidation for soft soil foundations. It was first proposed in 1952 by Professor W. Kjellman of the Royal Swedish Institute of Geology at the Soft Soil Reinforcement Conference held in Massachusetts Institute of Technology. The method has the advantages of short reinforcement time, low cost, simple process and no pollution. After decades of continuous research and exploration at home and abroad, the method has also been greatly improved. However, the defect of vacuum preloading is that the maximum load can be applied less than 100kPa. For the sluice project, the reinforcement effect needs to be further improved. Generally, the method and the stack preloading are combined to form a vacuum combined with stack preloading method. The vacuum combined stack preloading method can combine the advantages of both vacuum and preloading, and greatly enhance the reinforcement effect. Therefore, it has been widely used in soft soil reinforcement engineering in recent years.

2. Project Overview

The vacuum combined preloading reinforcement project of the sluice soft soil foundation supported by this paper is located in the Oujiang Estuary of Wenzhou City and is an important part of a cofferdam project. The sluice is located at the axis of the dam, which is the drainage channel between the inner and outer seas. To ensure construction in dry land, the project utilizes earth and stone cofferdams. The sluice is responsible for flood control and drainage. The scale of the sluice is 7 holes×6m, and the designed drainage flow is 498m³/s. The chamber adopts a box-and-span structure with a chest wall,
and the elevation at the bottom of the sluice is -2.0m. The gate of sluice is a flat concrete gate with a screw type. The hoist, the outer sea side and the surrounding side inspection gates adopt flat steel gates. The layout is shown in Figure 1.

The sluice foundation is deep marine soft soil. This soil is flow plastic state with poor physical and mechanical properties mostly, having some characteristics such as high water content (about 60%), high compressibility, low water permeability, low carrying capacity\(^4\). However, through designer calculated, the required bearing capacity of the foundation needs to be 70kPa through calculated, so basic treatment measures are needed to meet the bearing capacity requirements\(^5\). The project is to use vacuum combined with preloading method to reinforce the foundation.

At the same time, the soft foundation treatment of sluice is not only the bearing capacity, but also coordination and transition problems of settlement deformation considering comprehensive\(^6\). The settlement of natural soft soil foundation is large, so it often occurs the phenomenon that soft soil take off the sluice floor. Therefore on the basis of bearing capacity requirements, measures are taken to increase the preloading height and increase the depth of the drainage board for the both sides part and the wing wall which sink largely.

The total area of the soft soil foundation treatment in this project is about 15410 m\(^2\). Considering the comparison of vacuum and low-load preloading treatment, vacuum and high-load preloading treatment and non-load preloading treatment on the foundation reinforcement effect and physical and mechanical properties. The sluice foundation treatment area is divided into block A, block B, and block C.

Block A: vacuum + low-load preloading zone, the drainage board is set to a depth of 15m, the piled material is gravel, the stacking height is 1.5m, and the total area is 6691.04 m\(^2\).

Block B: no-treatment area, one piece of the vacuum combined with the preloading area is not treated. The length and width of the untreated area are 15m, and the total area is 225 m\(^2\), which is
located at the left wing wall of the surrounding area.

Block C: vacuum + high load preloading zone, the drainage board is set to a depth of 25m. It is divided into C1 area on the north side and C2 area on the south side. C1 area is the remaining part as B area is deducted, and the pile material is gravel. The stacking height is 4.0m and the total area is 8492.2 m². The specific partitioning situation is shown in Figure 2.

![Figure 2 Sluice foundation treatment Plane layout](image)

3. Site construction

3.1 Construction process

The soft soil foundation to be reinforced is a rectangular area with an average length of about 139m in the north and south and an average width of about 118m in the east and west. The main processes of vacuum combined surcharge preloading construction are:

1. Vacuum preloading stage: cleaning the site → measuring stakeout → inserting equipment, material entering the field → surface treatment → laying a layer of spinning geotextile → laying drainage board → laying sand cushion → laying filter tube → paving with spinning One layer of geotextile → laying two layers of sealing film → installing monitoring equipment → pumping to vacuum.

2. Combined surcharge stage: After the vacuum is reached, a layer of woven geotextile is laid on the vacuum membrane to prevent the gravel from damaging the vacuum membrane, a 0.5m thick clay is laid → the first stage is piled up (1.5m gravel) → Second stage stacking (2.5m gravel, only area C).

3. Unloading stage: According to the monitoring data and the monitoring report, it is unloaded after the data reached design standard.

The vacuum combined surcharge preloading system includes vertical drainage system, horizontal drainage system, sealing system, vacuum system, stacking system and monitoring system.

3.2 Design requirements

After vacuum combined surcharge preloading treatment, the pile foundation treatment is carried out to form a composite foundation, which serves as the holding foundation of the sluice. The vacuum combined surcharge preloading stability and unloading technical standards are as follows: (1) The
effective vacuum preloading time is not less than 120 days, the full load preloading is not less than 70 days; (2) The average daily settlement is less than 2 mm for 5 consecutive days. At the same time, the bearing capacity of the shallow foundation after the treatment is required to be not less than 70kPa.

4. Monitoring arrangement

The project monitoring items include: vacuum degree, surface settlement, pore water pressure, stratified settlement, horizontal displacement, water level and so on. The monitoring workload is shown in Table 1, and the monitoring project layout is shown in Figure 3.

| Monitoring items     | Quantity | Requirements                                                                 | Monitoring frequency                                      |
|----------------------|----------|------------------------------------------------------------------------------|----------------------------------------------------------|
| vacuum degree        | 9        | Three vacuum monitoring points are arranged in the pre-pressing zone, distributed in the A, C1 and C2 zones. | Usually read twice a day, once in the afternoon           |
| surface settlement   | 6        | There are 1 distribution in areas A, B and C1, 2 in C2 area, and 1 on cofferdam. | 1 time/day in the first month, then 1 time/3 days         |
| pore water pressure  | 3        | A pore water pressure monitoring hole is arranged in the middle area of the A, B and C2 areas. |                                                          |
| stratified settlement| 4        | There are 1 in the area A and 1 on cofferdam, and 2 in the C2 area.           | 1 time/day                                               |
| horizontal displacement| 3    | Use inclined tube to bury depth 30m                                          | 1 time/day in the first month, then 1 time/5 days        |
| water level          | 3        | Hole depth 10m                                                               | Initial 1~2 days/time, adjusted to 3~5 days/time in the middle and late period |
5. Monitoring data analysis

5.1 Vacuum under the membrane
Vacuum monitoring is the most important and direct means to understand the vacuum preloading situation, control the construction process and judge the preload abnormality in real time. The effect of preloading can be estimated according to the vacuum level in a period of time. The average vacuum degree under the film is shown in Figure 4.
membrane leaked seriously, and the vacuum was maintained at a low level (20~40kPa). The membrane was sealed on the 26th day of vacuuming. The sealing effect is improved, and the vacuum rises to about 70kPa; however, due to the presence of silt layer and silt mixed mud in the soil, the structure of the layer is loose, and it is prone to leak gas. The pump is stopped for the 35th day of vacuuming and the sealing system is re-reinforced. The cement mixing pile was constructed from the vacuum for 37 days. The vacuum was restarted on the 39th day of preloading, and the vacuum degree under the membrane rose to about 75kPa. The geotextile was laid on the 72nd day of vacuuming, the vacuum increased with the number of pumps. The degree gradually recovered and remained at around 75kPa until unloading.

5.2 Surface settlement

In this project, six subsidence marks are arranged in the whole ground, one in zone B (without treatment), one in zone A (loaded at 1.5m), three in zone C (loaded at 4.0m), and one on cofferdam. Grand total settlement = settlement during plugging period + vacuum preloading settlement + vacuum combined with preloading settlement, the settlement of plugging period is estimated based on ground elevation before and after construction of drainage board, and this article takes 600mm.

The settlement observation data of each area in the preloading process is shown in Table 2. The settlement curve with time is shown in Figure 5. The sedimentation rate with time is shown in Figure 4-3.

| Areas | Serial number | Settlement during plugging period (mm) | Vacuum preloading settlement (mm) | Vacuum combined with preloading settlement (mm) | Sedimentation rate before unloading (mm/d) |
|-------|---------------|----------------------------------------|----------------------------------|-----------------------------------------------|------------------------------------------|
| A     | ET2           | 600                                    | 618                              | 766                                           | 0.6                                      |
| B     | ET6           | 600                                    | /                                | 219                                           | 0.3                                      |
| C     | ET1           | 600                                    | 543                              | 1031                                          | 1.3                                      |
|       | ET3           | 600                                    | 622                              | 1253                                          | 2.0                                      |
|       | ET4           | 600                                    | 546                              | 1034                                          | 1.7                                      |

As can be seen from Table 2 and Figure 5:

(1) The original foundation soil becomes unfixed soil after precipitation in the cofferdam. From the monitoring results of Block B, the settlement of the foundation under self-weight can reach 200mm, and the settlement is completed at 60 days.

(2) If the natural settlement of the foundation is deducted, during the vacuum preloading period: the settlement in Zone A is 618 mm, and the average settlement in Zone C is 570 mm; during the combined surcharge period: the settlement in Zone A (1.5 m in stack) is 766 mm, the average
settlement in Zone C (4.0m in stack) was 1106mm. Judging from the settlement of each area, the effect of preloading reinforcement is very obvious.

(3) In the whole area along the north-south direction, the A area is in the middle of the preloading area, and the C area is on both sides of the preloading area. Before the pile-up construction, the settlement in the A area is significantly larger than the C area, indicating that only during the vacuum preloading period. The surface settlement shows a concave shape of the bottom, and the settlement in the middle of the preloading area is larger than that of the edge area.

(4) If the settlement increases by H under the action of external load P, then the ratio of H/P can be used to evaluate the settlement effect of the soil under the load. Due to poor sealing, the actual vacuum load is about 70kPa, the 1.5 m stack load is about 30kPa, and the 4.0 m stack load is about 80kPa. After calculation, the H/P of the vacuum load is: 6.1 mm/kPa (A, C average); the H/P of the load is: 6.75 mm/kPa (C zone), 4.33 mm/kPa (zone A). Since the high-pressure stacking in Zone C will cause surface rebound in Zone A, the H/P in Zone A cannot be used as a reference. From the calculation results and the sequence of settlement occurrence, the effect of stacking preloading on the settlement deformation is better than vacuum preloading.

(5) When the vacuum preloading is carried out for about 80 days, the pile-up construction begins, and the settlement of each area increases rapidly. Among them, the area A is 1.5m and the C area is 4.0m, and the high-pressure stacking in the C area will cause a surface rebound trend in Zone A. It can be seen from the settlement curve that the settlement of the C area develops rapidly and the settlement of A is slow.

(6) It should be pointed out that the B area (untreated block) is located between the C1 blocks. Although it is isolated, the construction of the C area will have an impact on the B area. The surface rebound of Zone B during construction for 90 days is caused by the piled up construction in Zone C1.

![Figure 6 Sedimentation rate-time curve](image)

It can be seen from the sedimentation rate-time curve:

1. At the initial stage of preloading, with the increase of vacuum degree, the pore water is discharged under the action of vacuum load, the soil is consolidated, the surface is quickly settled, and the sedimentation rate is large.

2. The occurrence and development of subsidence is positively correlated with the degree of vacuum under the membrane. Comparing by Figure 4 with Figure 6, it can be seen that when the vacuum cannot continue to increase, the surface settlement rate decreases rapidly. When the vacuum was applied for 35 days, the sedimentation stopped and a large rebound occurred. After the sealing system is repaired, the settlement rate increases after the vacuum degree is increased.

3. During the construction of the pile, the settlement rate of the C zone is obviously increased. Under the combined vacuum negative pressure, the sedimentation rate reaches 35mm/d. Compared with the conventional preloading, 35mm/d often causes the foundation instability. However, when combined with vacuum and stacking, the negative pressure allows the ground to shrink in the same direction to offset the lateral extrusion of the pile, which can increase the stacking rate and relax the
requirements for the settlement rate of the foundation.

(4) Before unloading, the surface settlement rate of each zone reached 0.0~2.0mm/d for 5 consecutive days, which met the unloading requirements.

6. Conclusion
This paper combines the engineering examples of vacuum combined with stacking preloading and strengthening soft soil foundation near the estuary of the Oujiang River. By analyzing the on-site monitoring data, the overall preloading process is grasped, and several conclusions and experiences are obtained.

1) The level of vacuum under the membrane determines the effect of vacuum preloading. In the initial stage of vacuum preloading, the sealing problem occurred, the vacuum under the membrane was low, and the preloading effect was not satisfactory. At this time, the influencing factors should be identified in time, such as the leakage of the membrane surface and the poor compactness of the soil in the sealing groove. This problem is mainly caused by the leakage of the preload boundary for the silt soil layer. The vacuum degree rises rapidly after the implementation of the sealing wall and the cement mixing pile, but there is always a certain amplitude jump, which should be paid attention to in the follow-up project. The depth is adjusted appropriately to ensure the sealing effect.

2) Surface settlement consists of settlement during plugging stage and settlement during preloading period. The settlement during plugging period is often large, which cannot be ignored in the process. The vertical sedimentation effect is superior to the vacuum preloading, but the soil deformation characteristics are different. The vacuum load can be applied at one time, and the application process of the stack should strictly control the loading rate according to the surface sedimentation rate. When the vacuum is combined with the preloading of the stack, the sedimentation rate requirement can be relaxed.

3) The results of surface sedimentation measured at the site indicate that the settlement is gradually enlarged from the edge of the preloading zone to the center of the preloading zone, and is distributed in the bottom of the pan.

Acknowledgments
Sincere thanks to Wenzhou Oufei Economic Development Investment Co., Ltd.and all participating units for their strong support and help in monitoring! Thank you to all the scholars involved in this thesis. This article refers to the research literature of several scholars. Without the help and inspiration of the research results of each scholar, I would have difficulty completing the writing of this paper. Thanks to my classmates and friends, who gave me a lot of material during the process of writing my thesis, and also provided enthusiastic help in the process of writing and typesetting the lamp. Since my academic level is limited, the essay I write will inevitably be inadequate. I urge teachers and alumni to criticize and correct me!

Fund Project: Zhejiang Water Science and Technology Project(RB1614、RC1733).

About the Author: Yao Y.X(1990— ),Male, Master, Engineer, mainly engaged in water conservancy engineering survey, monitoring and testing services. Phone:86+13750847796

References
[1] Kjellman W. (1952) Consolidation of clay soils by means of atmospheric pressure In: Conference on soil stabilization. MIT Boston.pp.5: 32-34.
[2] Ye B.R. (1995) Development of vacuum preloading reinforcement method and engineering record. J.Ground Improvement,03: 1-10.
[3] Shang J Q, Tang M, Miao Z. (1998) Vacuum preloading consolidation of reclaimed land: a case study. J. Canadian Geotechnical Journal, 35(05): 740-749.
[4] Wu X.T. (2010) Study on Engineering Properties and Consolidation Settlement Regularity of
Soft-soil in Wenzhou Shoal. China University of Geosciences, Wuhan.

[5] Chen Z.C. (2010) Discussion on the basic treatment method of sluice. J. China Flood & Drought Management. 20(3): 59-60.

[6] Yao Q.D (2014) Talking about Soft Foundation Treatment Technology in Sluice Construction. J.1:107