Study on settlement characteristics of deep soft strata by vacuum preloading

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Abstract: In order to study the vacuum preloading settlement characteristics of Hengli Island soft strata, the monitoring data of the vacuum preloading area are analyzed, and the hyperbolic method and the three-points method are used to predict the final settlement. The results show that the variation trend of settlement, vacuum degree and water level has a high consistency. The larger the calculated data span, the larger the calculated result. The three-points method is closer to the measured value than the hyperbolic method, the ratio of the three-points method to the measured value was 94%~110%, and the latter 110%~120%. However, the three-points method is sensitive to settlement saltation, and the calculation result error will be large if the calculated data span the saltation region, while the hyperbolic method is not sensitive to settlement saltation. According to the settlement rate and predicted settlement, the unloading time is earlier than the actual unloading time, which provides a reference for the reasonable evaluation of the unloading time and the reduction of the low-efficiency preloading time.

1. Introduction

As the center of the Guangdong-Hong Kong-Macao Greater Bay Area, Hengli Island in Nansha, Guangzhou, is under large-scale construction and development. The strata at the Hengli Island are mainly composed of silt and silty soils, and vacuum preloading is one of the main methods of foundation treatment. This construction method has been widely used in soft strata treatment of coastal engineering. Wang C.F[1] analyzed the monitoring data of vacuum preloading in Shanghai area, obtained the distribution law of settlement and pore water pressure, and compared it with the numerical simulation results. Zhang M[2] et al. applied three methods for predicting the unloading time of vacuum preloading to the vacuum preloading project in Shenzhen, and compared the applicability of the three methods. Sun L.Q[3] et al. and Cheng Q[6] et al. respectively studied the settlement of soft strata in Tianjin area and Lianyungang area during vacuum preloading and reached different conclusions. He T[5] et al. believed that compared with the three-points method, the hyperbolic method was more suitable for the settlement law of Zhuhai Hengqin vacuum preloading project. Kong G.Q[6] et al. and Cao J[7] et al. respectively found through the monitoring data of vacuum preloading...
engineering that the layered settlement and lateral displacement of vacuum preloading increased with the passage of time and decreased with the increase of depth, and the total settlement rate decreased gradually. Wang G.X[8] et al. introduced the construction and effect of vacuum preloading in Weihai Port Project.

It is found that there is a great difference in the shape of the monitoring curve of vacuum preloading soft strata treatment in different areas, indicating that the feedback of preloading effect in different areas has a great difference. The above studies are mainly on soft strata treatment engineering in the Yangtze River and the north region. For the soft strata in Nansha area of Guangzhou, only the research on Nansha Port Engineering[8-11] has been done so far. Nansha Port area is soft strata of dredging sand, which is different from the naturally formed soft silty strata at Hengli Island. This paper studies the settlement characteristics of Hengli Island in vacuum preloading engineering.

2. Project situation

2.1. Vacuum preloading area
Hengli Island covers an area of about 7.0 square kilometers. The foundation treatment of Hengli Island was carried out in sections and batches. The vacuum preloading area is located on the planned Dayuan Road at Hengli Island, with length of 320m, width of 82m.

The main processes of vacuum preloading include sealing ditch, sand cushion, prefabricated vertical drains (PVDs), sealing film, pump body installation, etc. According to the distribution of soft strata, the average depth of the PVDs was 18.2m. The vacuum pump adopts the new type of water-gas separation vacuum pump, as shown in Figure 1. There are 6 vacuum pumps in the research area. The 1m high soil bag cofferdam is set around the vacuum preloading area, and the extracted groundwater is directly discharged to the vacuum film, which can not only increase the preloading load, but also protect the vacuum film.

This paper does not consider the settlement in the construction process such as the plugboard before the formal vacuum extraction.

![Figure 1. On-site water vapor separation vacuum pump](image)

2.2. Monitoring point layout
The distribution of monitoring points such as groundwater level (SW), surface settlement (DD) and vacuum degree (Z) is shown in Figure 2. The monitoring time was 131 days from August 14, 2019 to December 23, 2019.
2.3. Geology and Hydrology
Before the development of Hengli Island, it was mainly farmland, ponds, vegetable fields, river chills, etc. The geology in the range of vacuum preloading is mainly $Q_{4}^{ml}$ filling soil, $Q_{4}^{mc}$ silt and silty soil, $Q_{4}^{sl}$ sandy clay, weathered rock, etc.

The site is low-lying and flat, with many reservoirs and streams distributed, and sufficient groundwater recharge sources. The buried depth of the stable groundwater level is 0.1~1m.

Physical and mechanical indexes of strata are shown in Table 1.

| Stratum     | Thickness (m) | Density (kN/m$^3$) | Initial void ratio | Permeability coefficient ($10^{-7}$ cm/s) | Young modulus (MPa) |
|-------------|---------------|---------------------|--------------------|------------------------------------------|---------------------|
| Fill        | 0.5~2         | 18.7                | 0.89               | 2.1                                      | 4                   |
| Silt        | 14.8~17       | 16.2                | 1.52               | 0.6                                      | 2.36                |
| Silty sand  |               | 17.6                | 1.12               | 1.17                                     | 3.9                 |
| Silty clay 1| Total         | 17.9                | 1.1                | 0.62                                     | 3.16                |
| Silty clay 2|               | 16.5                | 1.45               | 0.8                                      | 2.63                |
| Sandy clay  | 0~2           | 19.5                | 0.88               | 2.25                                     | 4.1                 |

3. Analysis of monitoring results

3.1. Vacuum change
As can be seen from Figure 3, after vacuum preloading starts, the vacuum degree under the membrane rises rapidly from 0 to 87.6kPa, which lasts about 15 days. After that, the vacuum degree fluctuates within the range required by the design, and the average vacuum degree is 90kPa.

3.2. Variation of water level
According to the field water level monitoring results, the water level dropped rapidly before 23d, with an average rate of 280mm/d, and then rapidly attenuated to 8.75mm/d. After 100d, the water level rose briefly and then dropped to a stable level.

The water level drops mainly because the negative pressure is transmitted downward, and the groundwater is discharged along the PVDs. Finally, it reaches a balance about 6.5m below the surface, i.e., the gradual balance between groundwater discharge and surrounding groundwater infiltration, forming the current water level.
3.3. Settlement

The settlement of each measuring point is shown in Figure 5. By vacuum preloading, the settlement rate is fast in the first 20 days, with an average settlement rate of 40mm/d. 20 days later, the settlement rate decreases rapidly, and it settles at a low rate in 20d−78d. The overall settlement curve is approximately L-shaped.

The final settlement of different measuring points has great difference, the minimum settlement is 755.6mm (DD21-5), the maximum settlement is 1037.4mm (DD20-6), the difference between the two is 281.8mm. The reason for this difference may be the stratigraphic difference in different regions.

3.4. The relationship between vacuum degree, water level and settlement

The average vacuum degree, average settlement and average water level are normalized, and the results are shown in Figure 6. The trends of vacuum degree, water level and settlement are highly consistent, showing a rapid increase in the early stage and a rapid flattening after reaching the inflection point.

Figure 6 shows that the strata at Hengli Island is sensitive to vacuum negative pressure, and the settlement and water level change closely follow the change of vacuum degree. After the vacuum degree reaches the design value, the range of settlement and water level change also decreases rapidly. This characteristic is different from other projects [4,7,9].
4. Comparison of settlement prediction
Reasonable prediction of final settlement is beneficial to elevation control and unloading time prediction. Hyperbolic method and three-points method are used to predict the final settlement.

4.1. Hyperbolic method
Its principle is to assume that the settlement curve conforms to the hyperbolic distribution, and the expression is:

\[ s_t - s_i = \frac{t - t_i}{\alpha + \beta (t - t_i)} \]  

(1)

Where, \( s_t (\text{mm}) \) is the settlement at time \( t \); \( s_i (\text{mm}) \) is the settlement at the time of \( t_i \); \( \alpha \) and \( \beta \) are the undetermined coefficients of the hyperbola.

Equation (1) can be written as:

\[ \frac{(t - t_i)}{s_t - s_i} = \alpha + \beta (t - t_i) \]  

(2)

When \( t \to \infty \), the final calculated settlement \( s_f \) is:

\[ s_f = s_0 + \frac{1}{\beta} \]  

(3)

4.2. Three points method
On the settlement curve, three points of \( s_1 \), \( s_2 \) and \( s_3 \) in the dead load period are used, and set \( \Delta t = t_3 - t_2 = t_2 - t_1 \), the final settlement formula can be obtained as follows:

\[ s_f = \frac{s_3(s_2 - s_1) - s_2(s_3 - s_2)}{(s_2 - s_1) - (s_3 - s_2)} \]  

(4)

4.3. Comparison of calculation results between the two methods
In this paper, 8 sets of data were analyzed. The calculated results are shown in Table 2, and the calculated results and measured values are shown in Table 3. The calculated settlement at different measuring points in different time spans gradually increase. For the same measuring point in the same time span, the settlement calculated by the three-points method is generally less than that by the hyperbolic method. No matter when it is calculated, the final settlement calculated by hyperbolic method is generally larger than the measured one, and the calculated value is 110%~120% of the measured one. In the first 2 months of dead load (stable vacuum), the settlement calculated by the three-points method is slightly lower than the measured value, while in the second month, the settlement calculated by the three-points method is slightly greater than the measured value, with the proportion mostly between 94% and 110%.

It is worth noting that, among the values calculated by the three-points method, there is a large deviation between the calculated values of DD19-4 in dead load for 3 months and the measured values, with the ratio of the two reaching 230%. The reason for this error is shown in Figure 7. The settlement curve of the measuring point appears a saltation around 78 days, so the difference between \( s_3 \) and \( s_2 \) increases sharply. Let \( \Delta s_1 = s_2 - s_1 \) and \( \Delta s_2 = s_3 - s_2 \) in Formula (4), then Formula (4) can be written as:

\[ s_f = s_2 + \frac{\Delta s_1}{\Delta s_2} \]  

(5)

Other factors remain unchanged, \( \Delta s_2 \) increases sharply, causing the calculated settlement to be too large. It can be seen that when the settlement curve fluctuates greatly, the error of the calculation results of the three-points method is large.

Since hyperbolic method is a fitting curve, it automatically neutralizes the influence of settlement saltation in the fitting process, so the hyperbolic method is less sensitive to curve saltation than three-points method.
The values of $s_1$, $s_2$ and $s_3$ across the saltation region should be avoided as far as possible when using the three-points method. The results of the three-points method are more accurate than that of the hyperbolic method when there is no abrupt change in the value range.

Table 2. Calculated settlement of different measuring points with different time span

| Monitoring points | Computing method | Settlement calculation values for different time spans | Measured value /mm |
|-------------------|------------------|-------------------------------------------------------|--------------------|
|                   |                  | 1 month  | 2 months | 3 months | 4 months |                      |
| DD18-1            | Hyperbolic       | -902.45 | -915.27 | -940.91 | -948.60 | -796.4                |
|                   | Three points     | -749.97 | -783.93 | -814.01 | -811.74 |                      |
| DD18-2            | Hyperbolic       | -841.50 | -856.44 | -902.79 | -913.91 | -800.9                |
|                   | Three points     | -751.29 | -807.01 | -1006.84 | -883.10 |                      |
| DD18-3            | Hyperbolic       | -835.41 | -855.88 | -867.16 | -867.16 | -758                 |
|                   | Three points     | -731.52 | -755.77 | -758.60 | -761.62 |                      |
| DD18-4            | Hyperbolic       | -869.66 | -885.53 | -902.24 | -903.79 | -762.5                |
|                   | Three points     | -731.49 | -758.29 | -767.58 | -766.54 |                      |
| DD18-5            | Hyperbolic       | -889.73 | -903.53 | -957.57 | -967.02 | -808.6                |
|                   | Three points     | -755.50 | -781.23 | -891.16 | -854.01 |                      |
| DD19-4            | Hyperbolic       | -993.70 | -1006.06 | -1060.37 | -1066.11 | -951.8              |
|                   | Three points     | -896.27 | -943.22 | -2184.43 | -1123.87 |                      |
| DD20-3            | Hyperbolic       | -1112.94 | -1119.32 | -1154.89 | -1164.77 | -996.2              |
|                   | Three points     | -938.69 | -971.05 | -1016.22 | -1021.70 |                      |
| DD21-3            | Hyperbolic       | -951.48 | -955.40 | 977.62 | -993.50 | -809.1              |
|                   | Three points     | -756.63 | -780.05 | -823.32 | -827.08 |                      |

Table 3. Calculated settlement and measured settlement ratio at different measuring points with different time spans

| Monitoring points | Computing method | Proportion of settlement calculation values for different time spans | Measured value /mm |
|-------------------|------------------|-------------------------------------------------------|--------------------|
|                   |                  | 1 month  | 2 months | 3 months | 4 months |                      |
| DD18-1            | Hyperbolic       | 113     | 115     | 118     | 119      | -796.4                |
|                   | Three points     | 94      | 98      | 102     | 102      |                      |
| DD18-2            | Hyperbolic       | 105     | 107     | 113     | 114      | -800.9                |
|                   | Three points     | 94      | 101     | 126     | 110      |                      |
| DD18-3            | Hyperbolic       | 110     | 113     | 114     | 114      | -758                 |
|                   | Three points     | 97      | 100     | 100     | 100      |                      |
| DD18-4            | Hyperbolic       | 114     | 116     | 118     | 119      | -762.5                |
|                   | Three points     | 96      | 99      | 101     | 101      |                      |
| DD18-5            | Hyperbolic       | 110     | 112     | 118     | 120      | -808.6                |
|                   | Three points     | 93      | 97      | 110     | 106      |                      |
| DD19-4            | Hyperbolic       | 104     | 106     | 111     | 112      | -951.8                |
|                   | Three points     | 94      | 99      | 230     | 118      |                      |
| DD20-3            | Hyperbolic       | 112     | 112     | 116     | 117      | -996.2                |
|                   | Three points     | 94      | 97      | 102     | 103      |                      |
| DD21-3            | Hyperbolic       | 118     | 118     | 121     | 123      | -809.1                |
|                   | Three points     | 94      | 96      | 102     | 102      |                      |
According to the settlement calculated by the three-points method, the degree of consolidation of the soil during unloading can be known. Except for the second half of DD19-4 curve, the degree of consolidation of the other measured points reaches more than 90%. The degree of consolidation calculated by hyperbolic method during unloading does not meet the requirement of 90%. If the result is inferred by hyperbolic method, the loading period of 131 days still cannot meet the requirement of consolidation degree, which obviously does not conform to the actual situation of the project. The actual settlement rate is shown in Figure 8. 20d later, the settlement rate decreases sharply. After 78d, the settlement rate of each measuring point is less than 1mm/d, which has reached the unloading standard.

Technical Code for Building Foundation Treatment requires that the preloading time should not be less than 90d after the vacuum degree is stable. The three-points method of this project predicts that the degree of consolidation is greater than 90% after 3 months of deadload, and the settlement rate of each measuring point from 95d to 105d is less than 1mm/d, which has met the settlement requirements in the specification (the settlement rate is no more than 2mm/d for continuous 10d), and can be unloaded. Continuing to vacuum, both a waste of resources, and delay time. Therefore, it is suggested that in the subsequent vacuum preloading project of Hengli Island, the unloading time should be reasonably determined in combination with the calculation of settlement and actual settlement rate.

5. Conclusion and Suggestion

(1) The changes of vacuum degree, water level and settlement by the vacuum preloading all show a rapid increase in the early stage, and a rapid decrease in the rate after reaching the inflection point. The overall change curve is approximately "L" shaped.

(2) In the early period of vacuum preloading (within 20d), the settlement rate is faster, and the average settlement rate of each measuring point is as high as 40mm/d. However, the distribution of settlement rate is relatively discrete. 20 days later, the settlement rate decreases rapidly, and the average settlement rate is less than 2mm/d. Around 78d, the settlement rate experienced a brief abrupt change, and then the settlement rate further decreased until it approached 0.

(3) After the vacuum pressure is stabilized, the hyperbolic method and three-points method are used to predict the settlement. The longer the time span of the calculated point values, the greater the calculated settlement value will be. In general, the three-points method is more accurate than the hyperbolic method. However, the three-points method is sensitive to the abrupt change of settlement curve, and the error of calculation results will be large if the calculated values cross the abrupt change of settlement.

(4) In this project, according to the calculated settlement and the actual settlement rate, the unloading time is recommended to be 105d, which is earlier than the actual unloading time. It is suggested that the subsequent vacuum preloading projects at Hengli Island should reasonably evaluate
the unloading time according to the monitoring data, reduce the low-efficiency vacuum preloading time, and save resources and construction period.

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