Analysis on deformation characteristics of Hengli Island soft strata by vacuum preloading

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Abstract: The deformation monitoring value of Hengli Island soft strata by vacuum preloading was analyzed. The results show that the vertical settlement and lateral displacement of strata mainly occur in the first 20 days. The negative pressure attenuation at different positions is quite different, and the average negative pressure attenuation rate with depth is about 3.2kPa/m. The difference of additional stress by the overlying water leads to the average settlement of the central area of the preloading area is greater than that of the marginal area. The settlement calculation results of Layered Summation Method are basically consistent with the measured values. According to the lateral displacement law of different projects, it is concluded that the lateral displacement has a progressive relationship with the vacuum preloading area half width, the prefabricated vertical drains (PVDs) length and the vertical settlement ratio of about 10 times, and the calculated value of lateral displacement agrees well with the measured value.

1. Introduction
Vacuum preloading is widely used in soft strata treatment. The negative pressure generated by vacuum reduces the pore water pressure and increases the effective stress, thus accelerating the consolidation of soils [1]. Negative pressure gradually decays with depth, and the law of negative pressure attenuation varies slightly in different projects [2-6].

The deformation by vacuum preloading can be divided into vertical settlement and lateral displacement. The lateral displacement is shown as shrinkage deformation [7]. Negative pressure can be equivalent to additional stress for deformation calculation [8]. For vertical deformation, the Layered Summation Method is recommended in the specification [9]. Wu J.H [7] compared the settlement calculation results of elastic theory, Layered Summation Method and one-dimensional consolidation method, and concluded that the Layered Summation Method was close to the elastic theory, while the one-dimensional consolidation theory had a large error. The vertical settlement of vacuum preloading is accompanied by lateral displacement, which will lead to cracks on the surface [10-12]. Yan H [13], based on the elastic theory, concluded that the surface lateral displacement was the largest and decreased with the increase of depth. Qiao X.L [14] obtained the lateral displacement based on the elastic theory through analysis, and the deformation modulus was calculated according to the Duncan-Chang model. Zhang P [15] explained through laboratory test of vacuum combined surcharge that when the surcharge is small, the lateral shrinkage deformation occurs. When the surcharge is large, the lateral expansion deformation
occurs. J.C.Chai[10] found that lateral displacement would cause cracks on the surface of the vacuum preloading area through field and laboratory tests, and gave the calculation formula of crack depth and lateral displacement.

Due to the vast territory of China, different projects have quite different situation, and the deformation characteristics are quite different. Aiming at the Hengli Island Project in Nansha District of Guangzhou, combined with the monitoring results of the completed vacuum preloading area, the deformation characteristics of vacuum preloading are calculated to provide reference for the background design and construction of similar projects in Nansha District in the future.

2. Project situation

2.1. Vacuum preloading area

Located in Nansha District, Guangzhou City, Hengli Island is surrounded by water on three sides and covers an area of 7.2km². The strata are mainly alluvial and diluvial silty soft strata, and there are many fish ponds, river gushing and farmland on the surface. 1# vacuum preloading area is located in the planned Dayuan Road K1+800 ~ K2+120 miles, length of 320m, width of 82m.

The drainage way of vacuum preloading is prefabricated vertical drains (PVDs), the spacing is 1.2m, the layout is equilateral triangle, and the average depth of drainage board is 18.5m. The 1.2m high earth bag cofferdam is set around the vacuum preloading, and the groundwater extracted by the vacuum pump is discharged to the vacuum membrane, and the final overlaying water depth is 1m. The water on the membrane not only acts as additional load, but also protects the vacuum membrane from weathering.
2.2. Geology and Hydrology

The physical and mechanical indexes of the strata is shown in Table 1. e-P curve is shown in Figure 3.

Table 1. Physical and mechanical parameters of soils

| Strata       | \( h_i \) (m) | \( \gamma \) (kN/m\(^3\)) | \( E_s \) (MPa) |
|--------------|--------------|-----------------|--------------|
| ① Fill       | 0.5          | 18.7            | 4            |
| ② Silty sand | 4.4          | 16.2            | 2.36         |
| ② Silty clay1| 6.1          | 17.6            | 3.9          |
| ② Silty clay2| 3.6          | 17.9            | 3.16         |
| ③ Sandy clay | 2.2          | 16.5            | 2.63         |
| ③ Silty sand | 1.7          | 19.5            | 4.1          |

where \( h_i \) is average thickness; \( \gamma \) is density; \( E_s \) is Young modulus in 0.1-0.2MPa.

According to the principle of effective stress, the ultimate effect of vacuum and surcharge is the increase of effective stress to consolidate strata. The vacuum negative pressure can be equivalent to additional stress\(^1\), and the overlaying water is equivalent to the additional load. According to relevant studies\(^{13,17}\), strata deformation is three-dimensional isotropic shrinkage by vacuum preloading, and the additional stress \( \Delta \sigma_{vac} \) on soil elements is shown in Figure 4(a). The additional stress \( \Delta \sigma_v \) of soil by overlying water is shown in Figure 4(b). The formation at the Hengli Island is subjected to the above two kinds of loading simultaneously.

Under additional stress by overlying water, the vertical additional stress at the center point is about \( \Delta \sigma_v=10\) kPa, and the vertical additional stress at the edge is about \( \Delta \sigma_v=5\) kPa.

According to Technical Code for Building Foundation Treatment, the strata settlement can be calculated according to Equation (2).
\[ S_v = \xi \sum_{i=1}^{n} \frac{\Delta e}{1 + e_{0i}} h_i \]  

(1)

Where, \( S_v \) is vertical settlement; \( \xi \) is empirical coefficient, between 1.1~1.4; \( e_{0i} \) is initial void ratio of soil; \( \Delta e \) is change of void ratio; \( h_i \) is soil thickness.

3. Analysis of measured soil deformation data

Displacement curves of each side pile are shown in Figure 5. Once the vacuum preloading starts, the side pile moves towards the preloading zone. The displacement rate of the side pile in the first 20 days is obviously greater than that of the later days, mainly because the strata in the 1# vacuum zone contains sand silt with high permeability. In addition, a new type of water-gas separation vacuum pump is used in Zone 1#, instead of conventional jet vacuum pump. The new type vacuum pump has high power and high efficiency. Except for the deviation of side piles of section DS20, the displacement trends of other side piles are relatively similar, and the final average displacement of side piles is 238mm.

The surface settlement is shown in Figure 6, and the settlement curve has a high similarity to the lateral displacement curve in Figure 5, showing that the displacement rate of first 20d is significantly higher than that of later days.

The edge average settlement is smaller than the center average settlement, the former final settlement is 840.6mm, the latter is 974mm. It accords with the characteristic that the additional stress of the overlying water in the middle is greater than the edge.

![Figure 5. Displacement of side pile](image-url)

![Figure 6. Average surface settlement](image-url)

Negative pressure at different depths is shown in Figure 7, Which under the film is -90kPa. The negative pressure at the three points decreases with the increase of depth in different curves. It can be seen from the average curve that the attenuation rate within 9m is greater than the attenuation rate below 9m. According to the test results in Literature [3], the attenuation rate in vacuum in PVDs is about 2kPa/m, and that in silt is about 6kPa/m, with a difference of 3 times. The difference in negative pressure attenuation of DK1-3 may be caused by the difference in the distance between the pore pressure measuring point and the PVDs, as shown in Figure 8.

After linear fitting of the average data, the relationship between negative pressure \( \Delta \sigma_{vac} \) and depth \( h \) is roughly as follows:

\[ \Delta \sigma_{vac} = 3.2h - 87 \]  

(2)

The average decay rate with depth is about 3.2kPa/m.
4. Vertical displacement calculation

According to the negative pressure attenuation law, the average equivalent additional stress of different strata (i.e., the median negative pressure value of strata) can be obtained, and the change of void ratio of different strata can be obtained through the combination of additional stress and e-P curve. The soil deformation of each layer can be calculated by substituting it into Equation (2). As shown in Table 2.

According to the calculation results in Table 2, the average settlement at the center is greater than that at the edge. The calculated value of the center is less than the measured value, and the calculated value of the edge is greater than the measured value. According to the recommended method in the specification, the average calculated value is 926.54mm, and the average measured value is 907.3mm, they are in good agreement.

Table 2. Calculated vertical deformation according to e-P curve

| Soils | $\Delta \sigma_{vap}$/kPa | $\varepsilon_0$ | $\varepsilon_1$ | $\varepsilon_2$ | $\varepsilon_3$ | $S_v$/mm | $S_v + S_{w1}$/mm | $S_v + S_{w2}$/mm |
|-------|--------------------------|----------------|----------------|----------------|----------------|--------|----------------|----------------|
| ①    | -86.2                    | 0.945          | 0.909          | 0.905          | 0.907          | 9.38   | 10.41          | 9.89           |
| ②_1  | -78.36                   | 1.572          | 1.444          | 1.430          | 1.437          | 219.44 | 243.73         | 231.58         |
| ②_2  | -58.36                   | 1.238          | 1.116          | 1.103          | 1.109          | 331.77 | 368.84         | 350.30         |
| ②_3  | -38.04                   | 1.382          | 1.293          | 1.295          | 1.291          | 134.02 | 131.37         | 137.72         |
| ②_4  | -28.28                   | 1.347          | 1.195          | 1.184          | 1.189          | 142.39 | 153.08         | 147.74         |
| ③    | -19.96                   | 0.889          | 0.855          | 0.850          | 0.852          | 30.83  | 35.33          | 33.08          |
| Total |                          |                |                |                |                | 867.83 | 942.76         | 910.32         |

Where, $S_v$, $S_{w1}$ and $S_{w2}$ are vertical deformation caused by vacuum preloading, additional stress at the midpoint and additional stress at the edge respectively.

5. Calculation of surface horizontal deformation

According to the literature [18], the microscopic clay lamellae are arranged vertically along the maximum pressure, and the directional and anisotropic properties of structural units increase, that is, the flocculating structure changes to the dispersed structure. It can be inferred that the difference of principal stress causes the change of soil microstructure, which is the fundamental reason for the difference of vertical and horizontal strain.

According to the relevant literature data [19-20], the relationship between the lateral displacement of vacuum preloading and other indicators is obtained, as shown in Table 3. It can be seen that the lateral displacement has a certain proportional relationship with the half width of the reinforcement zone B, the depth of the PVDs, and the vertical deformation $S_v$. The ratios are of orders of magnitude $10^{-3}$, $10^{-2}$, and $10^{-1}$, which are roughly 10 times more progressive. It can be used to estimate the displacement around the vacuum preloaded foundation treatment.
Literature [10] proposed that \( \varepsilon_h = (\varepsilon_{vol} - \varepsilon_{vv}) \), where \( \varepsilon_h \), \( \varepsilon_{vol} \) and \( \varepsilon_{vv} \) are horizontal strain, volumetric strain and vertical strain respectively, and the expression is as follows:

\[
\varepsilon_{vol} = \frac{\lambda}{1+e} \ln \left( 1 + \frac{\Delta \sigma_{vac}}{\sigma_{vo}} \right) 
\]

\[
\varepsilon_{vv} = \alpha \frac{\lambda}{1+e} \ln \left( 1 + \frac{\Delta \sigma_{vac}}{\sigma_{vo}} \right) 
\]

Where, \( \lambda \) is the compression index, \( \sigma_{vo} \) is the initial effective stress, \( \alpha \) is the coefficient obtained from the test, and 0.85 is taken according to literature [10].

Using the measured data of this project, there are:

\[ \varepsilon_h = 0.15 \varepsilon_{vol} = 0.00675 \]

So we have a lateral displacement:

\[ S_h = B \varepsilon_h = 276.75 \text{mm} \]

B is the half width of the reinforcement area, which is 41m in this project.

Compared with the lateral displacement of this project of 238mm, the calculated value is close to the actual value. It can be used to evaluate the lateral displacement around the vacuum preloading area.

| Projects         | B(m) | L(m) | \( S_v \) (mm) | \( S_h \) (mm) | \( S_h / B \) | \( S_h / L \) | \( S_h / S_v \) |
|------------------|------|------|----------------|----------------|--------------|--------------|----------------|
| Airport\[19\]   | 20   | 12   | 326            | 110            | 5.5e-3       | 0.027        | 0.34          |
|                  | 115  | 20   | 856            | 310            | 2.7e-3       | 0.016        | 0.36          |
| Oil storage\[20\]| 115  | 20   | 856            | 483            | 4.2e-3       | 0.024        | 0.56          |
|                  | 65   | 20   | 925            | 317            | 4.9e-3       | 0.016        | 0.34          |
| This project     | 41   | 18.5 | 907            | 238            | 5.8e-3       | 0.013        | 0.26          |

Where L is depth of PVDs.

6. Conclusion and Suggestion

(1) The strata deformation is caused by the combined action of the additional stress of overlying water and the equivalent additional stress of vacuum preloading, and the difference of the additional stress of overlying water causes the edge average settlement to be less than the center average settlement.

(2) The lateral displacement is shrinkage deformation. The lateral displacement curve and the settlement curve are similar in shape, and the change is synchronous. Both of them show a rapid change in the first 20 days, followed by a rapid decline in the rate. The final mean lateral displacement is 238mm.

(3) The negative pressure decreases with the increase of depth, and the average attenuation rule is roughly \( \Delta \sigma_{vac} (kPa) = 3.2h - 87 \).

(4) The settlement is calculated according to the recommended method of the code, and the calculated results agree well with the measured values.

(5) There are great differences between vertical and lateral displacements. The relationship between lateral displacement of partial vacuum preloading project and other indicators is counted, and the ratios of lateral displacement to half width B of reinforcement zone, depth L of PVDs and vertical deformation \( S_v \) are \( 10^{-3} \), \( 10^{-2} \) and \( 10^{-1} \), respectively, showing a progressive relationship of about 10 times. The calculated value of lateral displacement of 276.75mm is agree well with the actual value of 238mm.

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