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Research Article

The Settlement Models of Deep Vacuum Dewatering Method

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The deep vacuum dewatering method is effective for groundwater control in projects. By now, although the vacuum consolidation in soft soil foundation treatment has been analyzed much, the settlement of deep vacuum dewatering has not been researched sufficiently. Because of the extra vacuum pressure, the settlement should be analyzed further. In this paper, the settlement models are derived and analyzed based on the 2 vacuum pressure distribution models (plane seepage model and Johnson's model), Imai and Chai's vacuum consolidation models, and elastic model of traditional soil mechanics. And then a project case is provided to verify the theoretical models. The results show that the proposed model is suitable to predict the settlement and provide new references for vacuum dewatering engineering.

1. Introduction

Vacuum consolidation has been extensively applied [1–6] and proved very effective in improving soft ground [7, 8]. Vacuum consolidation usually applies a vacuum pressure into soil and a sealing membrane at the surface of the ground. It is very different from Terzaghi's consolidation theory for the isotropic additional stress caused by vacuum pressure. Therefore, the settlement of soft soil foundation caused by vacuum pressure has been researched in theoretical, numerical, laboratorial, and practical ways. Chai et al. [9] proposed a method of determining the vacuum-drain consolidation based on unit cell finite element analysis results and proved the method at Tokyo Bay in Japan. Chai et al. [10] also developed a method for the consolidation of dredged mud or clayey soil deposits containing prefabricated horizontal drains (PHDs). Chen and Xiang [11] carried out a theoretical analysis of the settlement of the piles caused by vacuum treatment of the submerged layer, which indicated that the settlement caused by dewatering increased the negative frictional resistance of the pile and increased the settlement. Robinson et al. [12] studied the influence of lateral displacement of soil volumetric strain under vacuum preloading. Then, the lateral displacements of soil under different stress states were analyzed, and the prediction model of volume strain and lateral displacement was proposed, which was validated by 2 projects in China.

Rujikiatkamjorn et al. [13] presented numerical analysis of a combined vacuum and surcharge preloading project in China. The simulation analyzed the settlement of the soil by modified Cam-clay model. Indraratna et al. [14] carried out the simulation of vacuum consolidation using finite element. Subsequently, the vertical displacements were predicted by the 2D and 3D numerical multidrain model. Ji et al. [15] analyzed the surface settlement of vacuum preloading of reclamation sludge foundation by using the finite difference method.

Saowapakpiboon et al. [16] conducted large-scale consolidation experiments on soil samples with and without vacuum pressure, and then the geotechnical parameters of the soil were analyzed. Kianfar et al. [17] investigated the influences of the duration of application and removal of vacuum pressures on radial consolidation by using excess pore-water pressure, axial strain, and over consolidation ratio. Long et al. [18] conducted trial sections to investigate the soft ground improvement performance using different vacuum consolidation methods. Sun et al. [19] analyzed a

site trial of vacuum preloading and vacuum preloading in combination with electro-osmotic. The physical mechanical properties and bearing capacity of soil after treatment were tested, which revealed the consolidation law of vacuum preloading and the combination method.

Many results have been obtained and some of them were used in practice. However, the thickness of soil needs to be considered in deep well dewatering project since it is usually larger than in foundation treatment project because the dewatering wells are deep in tunnel excavation. Thus, there is a need to investigate the suitable consolidation model to predict the surface settlement of deep vacuum dewatering method. Because of the capillary force in silty and clay soil, there is still much water that cannot be drained out by the nonvacuum dewatering method. As a result, the deep vacuum dewatering wells are usually applied in tunnel and deep foundation pit excavation. However, there is no specific consolidation model by now to calculate the settlement in the deep vacuum dewatering method. In this paper, 3 methods are proposed based on Imai's model, Chai's model, and elastic model. Then, a project case is provided to verify the theoretical models.

2. Vacuum Pressure and Water Level Distribution in Vacuum Dewatering

It is needful to use the vacuum pressure distribution laws in deriving the theoretical settlement model. Therefore, 2 models of air pressure distribution in soil are proposed. One is the plane seepage model [20] and the other one is Johnson's model [21], which are shown as equations (1) and (2), respectively:

$$p = \frac{p_e - p_w}{\ln(r_e/r_w)} \ln \frac{r}{r_e} + p_e, \tag{1}$$

$$p = p_w \left[1 + \frac{\left(1 - (p_a/p_w)^2\right) \ln(r/r_w)}{\ln(r_w/r_I)} \right]^{1/2}, \tag{2}$$

where r = distance from the well, p = air pressure at distance of r, p_e = measured air pressure at the known distance of r_e, r_w = the radius of the well, p_w = air pressure of the well, p_a = absolute ambient pressure, and r_I = largest influence distance of vacuum pressure.

The water level, h_{vac} (equation (3)), in flow boundary condition has been established by the author [20]:

$$h_{vac} = h_{phreatic} \times \left(\left(1 + \left(p_w \left[1 + \left(1 - (p_0/p_w)^2\right) \left(\ln(r/r_w)/\ln(r_w/r_I)\right) \right]^{-1/2} \left(1 - (p_0/p_w)^2\right) \sqrt{h_w^2 + \left(H_0^2 - h_w^2\right)\left(\ln(r/r_w)/\ln(R/r_w)\right)} \cdot \ln(R/r_w) \right) / \left(9806\left(H_0^2 - h_w^2\right)\ln(r_w/r_I)\right) \right) \right)^{-1}, \tag{3}$$

where $h_{phreatic}$ = water head, R = influence radius of dewatering, p_0 = atmosphere pressure, and H_0 = thickness of aquifer.

The water level distribution law under the vacuum pressure derived by the authors was used to calculate the final draw down of the groundwater in this paper. Then, the water level distribution models were combined to three existing consolidation models to analyze the vacuum settlement.

3. Modified Imai's Method

Imai [22] proposed a method of calculating the final settlement and lateral displacement in vacuum consolidation. It is assumed that the vacuum pressure p_{vac} keeps stable in soil and affects the active earth pressure. The increase of effective stress, $\Delta\sigma_{vac}$, is equal to vacuum pressure in both vertical and horizontal directions. At this time, the effective stress in horizontal direction will be reduced to $K_a\sigma'_{v0}$ (K_a is active earth pressure coefficient) from $K_0\sigma'_{v0}$ ($K_0 = \nu'/(1-\nu')$, ν = poisson's ratio). The effective stresses in vacuum condition are shown as follows:

$$\sigma'_v = \sigma'_{v0} + p_{vac}, \tag{4}$$

$$\sigma'_h = K_a\sigma'_{v0} + p_{vac}, \tag{5}$$

where σ'_{v0} = vertical effective stress without vacuum pressure, σ'_v = vertical effective stress in vacuum field, and σ'_h = horizontal effective stress in vacuum field.

Equations (6) and (7) present the changes of effective stress:

$$\Delta\sigma'_v = p_{vac}, \tag{6}$$

$$\Delta\sigma'_h = p_{vac} - (K_0 - K_a)\sigma'_{v0}. \tag{7}$$

I is defined as the ratio of the change of effective stress in horizontal and vertical direction in the following equation:

$$I = \frac{\Delta\sigma'_h}{\Delta\sigma'_v} = 1 - \frac{(K_0 - K_a)\sigma'_{v0}}{p_{vac}}. \tag{8}$$

The vertical and horizontal strains in consolidation area are shown in the following equations:

$$\varepsilon_v = -a_v m_v p_{vac}, \tag{9}$$

$$\varepsilon_h = -a_h m_v p_{vac}, \tag{10}$$

where, a_v, a_h, and m_v are presented in the following equations:

$$a_v = \frac{(1+K_0) - 2K_0 I}{(1+2K_0)(1-K_0)}, \tag{11}$$

$$a_h = \frac{I - K_0}{(1+2K_0)(1-K_0)}, \tag{12}$$

$$m_v = \frac{(1-2\nu')(1+\nu')}{(1-\nu')}\frac{1}{E'}, \tag{13}$$

where E = elastic modulus.

It is also proposed that the lateral displacement will not happen when $I = K_0$. Equation (14) can be obtained at the depth where there is no lateral displacement:

$$\frac{\sigma'_{v0}}{|p_{vac}|} = \frac{1-K_0}{K_0 - K_a}. \tag{14}$$

If the depth calculated from equation (14) is larger than the well's depth, I can be changed into the following equation:

$$I = 1 - (1-K_0)\frac{z}{H}, \tag{15}$$

where z = distance from ground surface and H = consolidation depth of vacuum well.

Based on the groundwater distribution in flow boundary condition, the thickness of the consolidation (H_{Imai}) after draw down will be

$$H_{Imai} = H_0 - h_{vac} = H_0 - (h_{phreatic}) \times \left(1 + \left(p_w\left[1 + \left(1 - (p_0/p_w)^2\right)(\ln(r/r_w)/\ln(r_w/r_I))\right]^{-1/2} \cdot \left(1 - (p_0/p_w)^2\right)\sqrt{h_w^2 + \left(H_0^2 - h_w^2\right)(\ln(r/r_w)/\ln(R/r_w))}\ \ln(R/r_w)\right) / \left(9806\left(H_0^2 - h_w^2\right)\ln(r_w/r_I)\right)\right)^{-1}. \tag{16}$$

Thus, the vertical displacement of the soil above the water surface in vacuum dewatering method can be derived based on Imai's method. Imai's solution is proposed in equations (17) and (18) based on plane seepage model and Johnson's model, respectively:

$$\Delta h_v = -a_v m_v p_{vac-plane} H_{Imai}, \tag{17}$$

$$\Delta h_v = -a_v m_v p_{vac-Johnson} H_{Imai}, \tag{18}$$

where $p_{vac-plane}$ = vacuum pressure of plane seepage model and $p_{vac-Johnson}$ = vacuum pressure of Johnson's model.

4. Modified Chai's Method

Chai and Carter [22] believed that when the vacuum pressure is larger than the stress needed to keep K_0 status, the lateral displacement will happen and the vertical displacement will be less than that without vacuum. Otherwise, there is no lateral displacement and the settlement will not be affected. The vertical strain of vacuum consolidation model is shown as follows:

$$\varepsilon_v = \alpha \frac{\lambda}{1+e} \ln\left(1 + \frac{\Delta\sigma_{vac}}{\sigma'_{v0}}\right), \tag{19}$$

where λ = compression index, e = porosity ratio, and p = consolidation stress. $\alpha = \alpha_{min}$ at the ground surface and $\alpha = 1$ when $z \geq z_1$ (z_1 is the depth where there is no lateral displacement) or $\Delta\sigma_{vac} \leq (k_0\sigma'_{v0} - \sigma'_{av})/(1-k_0)$. However, if

$$\Delta\sigma_{vac} \geq \frac{(k_0\sigma'_{v0} - \sigma'_{av})}{(1-k_0)},$$
$$\alpha = \alpha_{min} + \frac{1-\alpha_{min}}{|\Delta\sigma_{vac}|}\left(\frac{k_0\sigma'_{v0} - \sigma'_{av}}{1-K_0}\right), \tag{20}$$

where $k_0 = (1-\sin\phi)(\mathrm{OCR})^{\sin\phi}$, ϕ = effective friction angle, OCR = over consolidation ratio, and $\alpha_{min} = \alpha_{min-T}$ or $\alpha_{min} = \alpha_{min-P}$ in triaxial stress condition and plane strain condition. $\alpha_{min-T} = 0.8$ and $\alpha_{min-P} = (1 + \alpha_{min-T})/2$ proposed by experimental results.

5. Elastic Method

Soil is assumed elastic in the elastic method. When the air extraction is performed in the dewatering well, the air pressure in the pores of the soil will be reduced. At this time, the pressure difference between the atmospheric pressure at the ground surface and the pressure in the soil leads to a compression, resulting in settlement. The soil above the original phreatic water surface can be considered as a sealing layer. Boussinesq [23] used the elastic theory to derive the analytical solution of the stress at any point M (shown in Figure 1) when the vertical concentrated force (P) acts on the surface of the semi-infinite space elastomer.

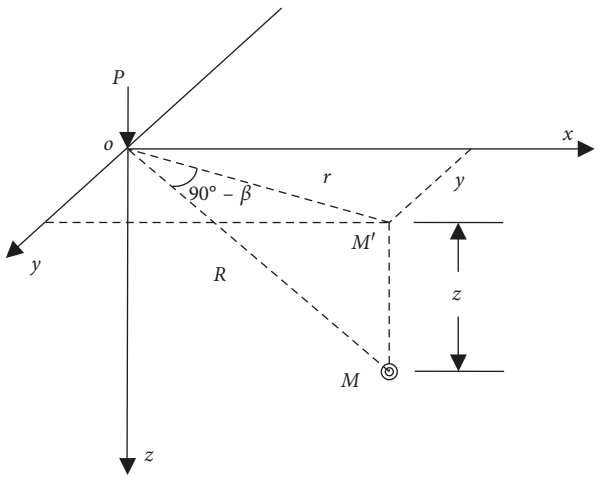

Figure 1: Diagram of Boussinesq's model.

The stress and strain of Boussinesq's method are presented in the following equations:

$$\sigma_z = \frac{3P}{2\pi} \cdot \frac{z^3}{R^5} = \frac{3P}{2\pi R^2} \cdot \cos^3 \beta, \tag{21}$$

$$\sigma_x = \frac{3P}{2\pi} \cdot \left\{ \frac{x^2 z}{R^5} + \frac{1-2\nu}{3} \left[\frac{1}{R(R+z)} - \frac{(2R+z)x^2}{(R+z)^2 R^3} - \frac{z}{R^3} \right] \right\}, \tag{22}$$

$$\sigma_y = \frac{3P}{2\pi} \cdot \left\{ \frac{y^2 z}{R^5} + \frac{1-2\nu}{3} \left[\frac{1}{R(R+z)} - \frac{(2R+z)y^2}{(R+z)^2 R^3} - \frac{z}{R^3} \right] \right\}, \tag{23}$$

$$\tau_{xy} = \frac{3P}{2\pi} \cdot \left[\frac{xyz}{R^5} - \frac{1-2\nu}{3} \cdot \frac{(2R+z)xy}{(R+z)^2 R^3} \right], \tag{24}$$

$$\tau_{zy} = \frac{3P}{2\pi} \cdot \frac{yz^2}{R^5}, \tag{25}$$

$$\tau_{zx} = \frac{3P}{2\pi} \cdot \frac{z^2 x}{R^5}, \tag{26}$$

$$\overline{u} = \frac{P}{4\pi G} \left[\frac{xz}{R^3} - (1-2\nu') \frac{x}{R(R+z)} \right], \tag{27}$$

$$\overline{v} = \frac{P}{4\pi G} \left[\frac{yz}{R^3} - (1-2\nu') \frac{y}{R(R+z)} \right], \tag{28}$$

$$\overline{w} = \frac{P}{4\pi G} \left[\frac{z^2}{R^3} - 2(1-\nu') \frac{1}{R} \right], \tag{29}$$

where σ_x, σ_y, and σ_z are the stresses and $\overline{u}$, $\overline{v}$, and $\overline{w}$ are displacements in x, y, and z directions, respectively; τ_{xy}, τ_{zy}, and τ_{zx} are shear stresses; $G = E'/(2/(1+\nu'))$; and $R = \sqrt{x^2+y^2+z^2}$.

The vacuum pressure in y direction shown in equations (30) and (31) is obtained from equations (1) and (2):

$$p_v = p_0 - \frac{p_e - p_w}{\ln(r_e/r_w)} \ln \frac{y}{r_e} - p_e, \tag{30}$$

$$p_v = p_0 - p_w \left[1 + \frac{\left(1 - (p_a/p_w)^2\right) \ln(y/r_w)}{\ln(r_w/r_I)} \right]^{1/2}. \tag{31}$$

The stress at M caused by $P_v dy$ is presented in the following equation:

$$d\sigma_z = \frac{3p_v z^3}{2\pi R^5} dy. \tag{32}$$

It is assumed that the dewatering well is located at point o. Then, the vertical stresses in the plane seepage model and Johnson's model can be expressed in equations (33) and (34), respectively:

$$\begin{aligned} \sigma_z &= \int_0^{r_1} \frac{3P_v z^3 dy}{2\pi (y^2+z^2)^{5/2}} \\ &= \int_0^{r_1} \frac{3\left((p_w - p_e/\ln(r_e/r_w))\ln(y/r_e)\right) z^3}{2\pi (y^2+z^2)^{5/2}} dy, \end{aligned} \tag{33}$$

$$\begin{aligned} \sigma_z &= \int_0^{r_1} \frac{3P_v z^3 dy}{2\pi (y^2+z^2)^{5/2}} \\ &= \int_0^{r_1} \frac{3\left(p_0 - p_w\left[1 + \left(1 - (p_a/p_w)^2\right)(\ln(y/r_w)/\ln(r_w/r_I))\right]^{1/2}\right) z^3}{2\pi (y^2+z^2)^{5/2}} dy. \end{aligned} \tag{34}$$

Then, the settlement can be calculated with the following equation:

$$S = \sum_{i=1}^{n} \frac{\sigma_{zi}}{E_{si}} \cdot H_i, \tag{35}$$

where H_i = soil layer thickness. The calculation depth is where the ratio of vacuum pressure and soil gravity stress is 0.2.

6. Case Studies

Andinglu-Beitucheng range of line 10, Beijing subway, is taken as an in situ example. According to the geological survey, the geotechnical parameters before dewatering are proposed in Table 1, the stratigraphy of the test site is shown in Figure 2, and the layout of the monitor points is shown in Figure 3.

The pore pressure is kept stable after a long period of dewatering according to the monitoring work, which means the moisture content is in dynamic equilibrium status. At the same time, it is rarely possible to keep a stable water head boundary condition in a limited area. Therefore, the flow boundary condition is considered in this case. In order to analyze the settlement, the vacuum dewatering is operated for more than 5 months. The settlement measured was 5.8 mm. The vacuum pressure measured in dewatering well was 13.5 kPa. The water depth is 10.75 m and 18.13 m, respectively. The thickness, H_0, of the 1st phreatic aquifer was 4.25 m while the 2nd was 4.37 m.

Table 1: Geotechnical parameters of the soil.

Layer	Depth (m)	ρ (g/cm^3)	w (%)	e_0	$\lambda(0.183e_0 - 0.0021{e_0}^2)$ [24]
Silt	3.0	1.83	21.3	0.776	0.141
Silt	4.5	1.86	23.7	0.748	0.135
Clay	7.5	1.89	24.8	0.706	0.128
Clay	10.5	1.93	20.0	0.615	0.112
Silt	12.0	1.86	17.5	0.652	0.118
Clay	15.0	1.86	18.3	0.613	0.111
Clay	16.5	1.85	20.2	0.722	0.131
Silt	18.0	1.87	18.1	0.727	0.132

Layer	Depth (m)	E_s (MPa)	φ (°)	c (kPa)
Silt	3.0	16.95	22.60	45.7
Silt	4.5	6.22	24.35	11.2
Clay	7.5	5.22	15.93	13.1
Clay	10.5	8.16	29.50	47.8
Silt	12.0	11.46	27.36	35.1
Clay	15.0	9.14	29.86	36.2
Clay	16.5	13.74	31.05	23.8
Silt	18.0	8.22	30.50	30.8

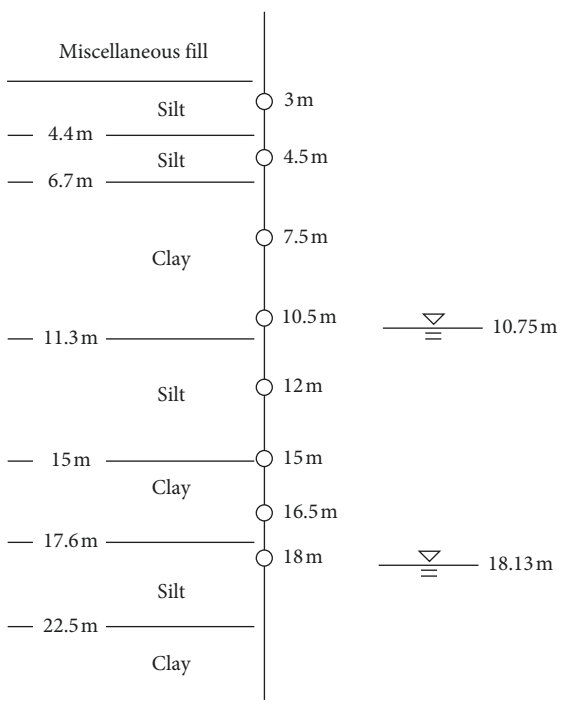

Figure 2: Stratigraphy of the test site.

In the field tests, the sensors were put into the drilled hole and buried. And then the gauges were connected to the sensors' wires. The settlement measuring instrument was fixed on the ground, and the settlements were recorded by electronic total station (ETS). A fixed point was marked firstly and then the changes in distance between the fixed point and the measuring point were measured over time.

The settlement versus time is shown in Figure 4.

The measured and calculated settlement results are shown in Tables 2–6 and Figure 5.

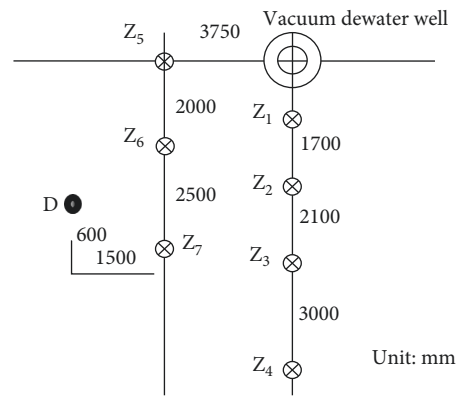

Figure 3: Layout of monitor points. z_1–z_7: vacuum pressure monitor points; D: settlement monitor point.

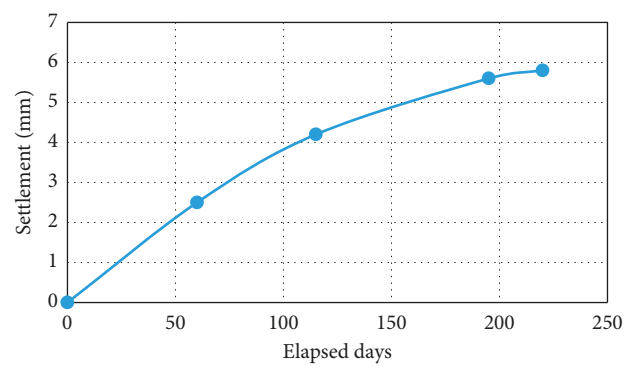

Figure 4: Surface settlement versus time.

Table 2: Settlement of modified Imai's model (mm).

Measurement	Plane seepage model	Johnson's model
5.80	8.20	8.40

Table 3: Settlement of modified Chai's model (mm).

Measurement	Plane seepage model	Johnson's model
5.80	3.70	3.68

Table 4: Settlement of the elastic model (mm).

Measurement	Plane seepage model	Johnson's model
5.80	5.322	5.321

Table 5: Settlement of the plane seepage model (mm).

Measurement	Imai's model	Chai's model	Elastic model
5.80	8.20	3.70	5.322

Table 6: Settlement of Johnson's model (mm).

Measurement	Imai's model	Chai's model	Elastic model
5.80	8.40	3.68	5.321

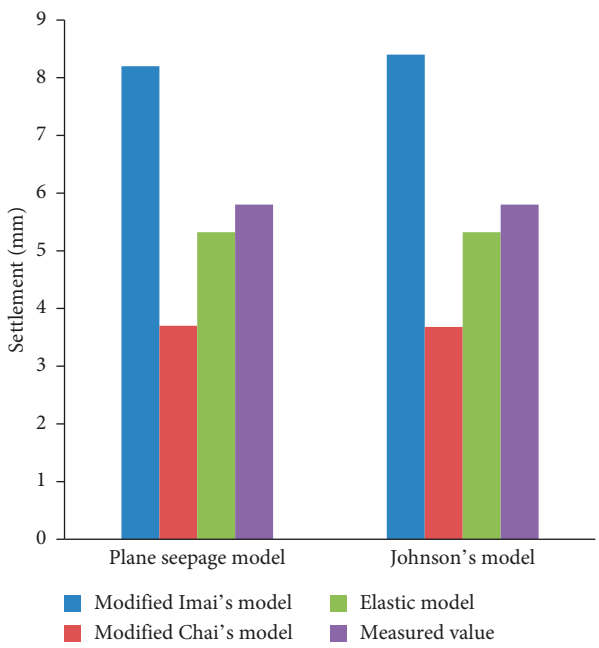

Figure 5: Results of theoretical analysis.

It can be seen from Table 2 that the results of Imai's model are larger than the measured value. It is believed that it is safe for the real project because the theoretical results are larger than the measured one, which shows that the modified Imai's model is suitable to predict the settlement of vacuum dewatering. In Chai's model, the theoretical results are smaller than the measured ones because the model considers the lateral displacement which restricts the vertical displacement. The results of elastic model in Table 4 show that the difference between theoretical and measured values is much smaller than the other two methods, which illustrates that the soil can be assumed as elastic medium in calculating settlement. The settlements caused by vacuum pressure from equations (33) and (34) are 0.112 mm and 0.111 mm, respectively. It can be seen from the results that the extra displacement by vacuum pressure is small enough to be neglected in real projects according to the elastic model. Thus, the main settlement of the soil is caused by the final drawing down of the water. However, the result of theoretical method is a little smaller than the measured value, so it is safe for the real project to modify the theoretical result with a coefficient larger than 1 according to experience.

7. Conclusion

This paper proposed 3 methods to predict the settlement of vacuum dewatering, which provide optional references for engineering.

Modified Imai's model is suggested to predict the settlement of vacuum dewatering project because of the adequate safety reserve. Modified Chai's model is suitable for the soft soil consolidation because the soft soil is sensitive to the vacuum pressure in horizontal direction, which will restrict the vertical consolidation ratio. When the soil is assumed to elastic, the elastic model is suggested. The elastic model provided the best prediction at this site but the other models may perform better in different ground conditions, which will require checking with further analysis.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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