Settlement Prediction under a Combined Vacuum and Surcharge Preloading in New Reclaimed Land

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Abstract
Rapid settlement assessment in new reclaimed land is important to follow-up engineering construction. Vacuum-surcharge preloading combined with prefabricated vertical drains (PVDs) is a high-efficient and widely used reclaimed soil-reinforced method. This work focuses on micro-macro mechanism of vacuum and surcharge preloading, and the settlement characteristics of subsoil subjected to vacuum-surcharge pressure are discussed. The surcharge preloading is applied to soil particles directly by vertical stress, and the effective stress increases directly by direct contact among particles. However, vacuum pressure increases the effective stress and decreases the pore pressure at the same time. In new reclaimed land, the proposed method is working on the assumption that the new reclaimed land full of water with particles arranging in a loose state of simple cube (SC) way before treatment, while a dense state of terse tetrahedron (TH) way, a stable structure of soil, after treatment. An approach for calculating the final settlement of new reclamation land is derived in two-dimensional (2D) and three-dimensional (3D) perspective, respectively. Meanwhile, this method has been preliminarily applied to two case histories reported in the literature. Results show that 2D estimation method might be more useful for the preliminary assessment of settlement under a combined vacuum and surcharge preloading in new reclaimed land.

1. Introduction

With the development of society and economy, land reclamation projects have been developing rapidly in low-lying marshy areas in southeastern coastal cities in China, which are usually located in the coastal plain or in the alluvial plain deposited by large rivers from highland regions [1]. Soft clayey soils including dredged clay slurry or marine clays are extensively employed to form reclaimed lands utilizing the hydraulic fill technique, while the fillings could cause geo-technical problems for construction structure above them because of their high water content, large void ratio, high compressibility, low strength, low permeability, and low bearing capacity [2]. Hence, it is necessary to stabilize the new reclaimed land before any construction can be conducted in order to prevent the differential settlements. The ground improvement can be used to increase the bearing capacity of subsoils and allow the site to experience consolidation settlement before construction in order to minimize further settlement or differential settlement for infrastructure [1].

Preloading is one of the most successful and widely used ground improvement techniques, which involves loading of the ground surface to accelerate the consolidation process for soft subsoils. It can help to induce a greater part of the ultimate settlement that the ground is expected to experience after construction [3–5]. There are several types of preloading methods available so far, such as vacuum preloading [6], surcharge loading [7–10], electroosmotic treatment [11], or any combination of above approaches.

The vacuum preloading method has been developing for over 70 years since it was originally introduced in Sweden by Kjellman [12] for cardboard wick drains, and it has been well developed thanks to intensive laboratory research and field
trials [6, 13–19]. In vacuum preloading, the cost becomes substantial when a high load is required to achieve the desired undrained shear strength, and then, the combined vacuum and surcharge preloading method has been the optimum solution [2]. Surcharge embankment with a multi-stage exercise could well control the development of excess pore pressure [20]. The combined vacuum and surcharge preloading technique has been proved the most effective approach in terms of increasing the effective stress of subsoils, reducing the consolidation time, and reducing the lateral displacements in subsoils based on the field experience in Japan [21]. In general, a lengthy time period is required to achieve the desired degree of primary consolidation; however, it may not be feasible with busy construction schedules and short deadlines in practice [2]. The arise of prefabricated vertical drains (PVDs) provides a much shorter drainage path length in the radial direction and distributes vacuum pressure to a deep subsoil layer, thereby increasing the consolidation rate of reclaimed land and reducing the preloading period significantly [1, 17, 22, 23]. At present, vacuum-surcharge pressure combined with prefabricated vertical drains (PVDs) as a well-established soft ground improvement method has been widely used for preloading a soft clayey deposit [24], owning to its enormous advantages, especially in new reclaimed soil with high compressibility and high water content [25]. Reclaimed land is seriously affected by ground settlement episodes, which are primarily caused by unconsolidated soils, and could result in severe damage to buildings and public infrastructures [26]. Rapid assessment of foundation ultimate settlement is of great importance to subsequent vacuum-surcharge consolidation treatment and follow-up building construction.

Chai et al. [27] proposed a semiempirical method to calculate the settlement at the end of consolidation of deposit induced by vacuum pressure based on the laboratory test results and theoretical analysis. Sun et al. [28] put forward a settlement calculation method for PVDs installation period based on the analysis about the loading characteristics, and the results are in accordance with the field data. Xia et al. [29] researched the settlement of dredger fill consolidation with vacuum preloading, and the investigation results indicate that the settlement has the best modified exponential model. Chai et al. [30] proposed the calculation of corresponding settlement according to the different degrees of consolidation and effective stress increment, and comparing the calculated results with the measured field values indicates that the methods can be a useful tool for designing vacuum consolidation project. Xiong et al. [25] studied the sedimentation characteristics of the reclaimed area in Wenzhou, a coastal city in China, by settlement column experiments, the investigation results indicate that the sedimentation of the hydraulic-dredged mud is large deformation, and the settlement curve could be divided into self-weighting sedimentation stage, self-weighting consolidation stage, and balance stage. The first and second stages occupy almost 100% of total settlement only considering its own gravity. With the development of computer technology, artificial intelligence method has also been used for predicting of displacement in engineering geology filed [31–33] and it made a great success. A series of prediction method has been studied; however, they are not easy to be used in the field. Rapid prediction method of foundation settlement for new reclaimed land during the period of backfill was few yet.

The aim of this study is to effectively analyze the phenomenon of the final steady state induced by the combined vacuum and surcharge consolidation method from micro-mechanism perspective. The mechanism of vacuum and surcharge is analyzed based on effective stress principle. Meanwhile, a simple and rapid prediction approach of ultimate settlement for new reclaimed land is derived according to microstructure variety of layer particles, and then, two cases published in the literature are analyzed by preliminarily utilizing the method proposed in this study. The prediction results were compared with field-measured data to conduct engineering design application in the future.

2. Microscopic Mechanism of Combined Vacuum and Surcharge Preloading

2.1. Dynamic Equilibrium State Analysis. A vacuum pressure up to 80 kPa, about a fill with 4.5 m in height, can be achieved in practice using the vacuum equipment [6]. And in general, it cannot satisfy the requirement of the foundation bearing capacity and usually cause inward lateral displacement under the vacuum pressure. Hence, surcharge preloading was always combined to minimize the lateral deformation, and PVDs installed in the transverse and longitudinal direction after installing the sand blanket could distribute the surface suction uniformly and then accelerate the consolidation rate of subsoils. Subsequently, these PVDs could be connected to the edge of a peripheral trench, which is normally sealed by an impervious membrane called membrane system [2]. The vacuum pumps generating the suction are connected to the horizontal PVDs (i.e., prefabricated discharge system), and then, the excess pore water pressure in the subsoil toward the PVDs and the surface is accelerated out via PVDs. The diagram of the combined vacuum and surcharge preloading method in two-dimension (2D) is shown in Figure 1.

In practice, sealing is incomplete strictly and cannot block the connection thoroughly between stabilized zone and unstabilized zone. When the vacuum pressure reaches a steady state, the reinforced section is connected with the outside atmosphere through the unreinforced zone. Finally, recharge amount of pore air (Q_a) and pore water (Q_w) from outside unstabilized zone area equals to discharge amount of pore air (Q_a') and pore water (Q_w') from inside stabilized area, as shown in the following equation.

\[ Q_a + Q_w = Q_a' + Q_w' \]  

2.2. Microscopic Mechanism Analysis

2.2.1. Surcharge Preloading Analysis. For the surcharge pressure applied to the reclaimed land, total stress (σ) of foundation consists of two parts according to the principle of
effective stress: one is the value of \( u \) of pore water pressure, and the other is the effective stress \( (\sigma') \) of soil particles, as follows:

\[
\sigma = \sigma' + u.
\]  

(2)

Consolidation could be regarded as a process of orderly rearrangement of particles. At the beginning of surcharge consolidation, which is a method of undrained consolidation, soil consolidates in a way of top-down, and then terse tetrahedron (TH), an ideal steady state, will achieve finally in theory. That is, the particles of upper layer arrange orderly first, then the lower. Surcharge pressure improves the effective stress of soil by applying vertical stress to soil particles, causing total stress increase directly. The 2D microstructure of soil and micromechanics analysis of surcharge pressure in the final ideal state are shown in Figure 2.

2.2.2. Vacuum Preloading Analysis. Vacuum preloading, a drainage consolidation method, tends to apply a relative isotropic consolidation pressure to a point in the reinforced area [34]. Vacuum consolidation consists of two effects: one is air pressure difference \( (P_{\text{vac}}) \) which is the same role as surcharge preloading, applying vertical stress and increased effective stress directly; the other is drainage of pore water and pore air brought about by isotropic pressure which caused pore water pressure decrease directly and effective stress increase indirectly. An ideal terse tetrahedron (TH) state will be reached finally in the assumption.

\[
P_{\text{vac}} = P_0 - P,
\]

(3)

where \( P \) is air pressure in the reinforced area and \( P_0 \) is normal atmosphere. A diagram is shown in Figure 3.

2.3. Comparison between Surcharge and Vacuum Preloading. Shortly, both surcharge preloading and vacuum consolidation conform to the principle of effective stress, but the difference is also obvious. When the total stress is constant, surcharge loading increases the effective stress directly by applying vertical stress to soil particles, whereas vacuum pressure decreases pore pressure directly by draining water and air, and forms a vertical load \( (P_{\text{vac}}) \) to improve effective stress rapidly. In theory, the real condition of vacuum-surcharge consolidation consists of two parts: a vertical equivalent surcharge load \( (P_{\text{sur}} + P_{\text{vac}}) \) and an isotropic vacuum pressure \( (P_{\text{vac}}) \). It can be seen vacuum pressure is better than surcharge load with the same amount due to the vertical load and isotropic pressure at the same time. Meanwhile, it shows the reason why vacuum consolidation as an effective soft soil improved method developed rapidly and widely.
3. The Calculation Method of Ultimate Settlement in New Reclaimed Land

Hydraulic fill is composed of soil particles with a small difference in size especially in the new coastal reclamation land. For soft soils in reclaimed land, the water content is very large and there could be lots of macro pores in the soil. The simple cube (SC) way is the relative loose state in nature under the force of gravity after reclamation. The soil particle is surrounded by water, and it could move by water disturbance, which is similar to the characteristics of simple cube (SC) state. Consolidation is a process of orderly rearrangement of soil particles under vacuum-surcharge pressure. After treatment, the soil particles will be rearranged in the way of terse tetrahedron (TH) when there is no deformation in rigid soil particles under pressure. In new reclamation land, the soil particles are in a loose state and assumed in a dense state of terse tetrahedron (TH) arrangement before treatment, whereas the soil particles are in a dense state and assumed in a terse tetrahedron (TH) arrangement after treatment in this study. For this study, the settlement is a result of orderly rearrangement of soil particles in two-dimension, as shown in Figure 4. The ultimate settlement of consolidation in two-dimensional (2D) perspective and three-dimensional (3D) perspective is calculated in Tables 1 and 2, respectively.

The 2D and 3D calculation method for \( n \) layer soil particles between SC and TH arrangement state is as follows:

\[
\Delta h_{2D} = (n - 1)(2 - \sqrt{3})r, \quad (4)
\]

\[
\Delta h_{3D} = 2(n - 1) \left(1 - \frac{\sqrt{2}}{3}\right)r, \quad (5)
\]

where \( r \) is the radius of soil particle and \( n \) is soil particle layers. The utilization of PVDs distributes vacuum pressure to a deep subsoil layer, thereby increasing the consolidation rate of reclaimed land and reducing the preloading period significantly. The influence depth is the length of PVDs (\( H_0 \)) in theory, and the reinforcement effect will be enhanced with time. The soil particle layers (\( n \)) within the influence depth could be obtained by the following expression, i.e.,

\[
n = \frac{H_0}{2r}. \quad (6)
\]

where \( H_0 \) is the penetrating depth of PVDs in soil layer. Therefore, once reaching steady state under vacuum combined with surcharge consolidation, the approximate calculation methods for ultimate settlement in reclaimed land are obtained from equations (4)–(6), i.e.,

\[
\Delta h_{2D} = \left(1 - \frac{\sqrt{3}}{2}\right)H_0 - (2 - \sqrt{3})r, \quad (7)
\]

\[
\Delta h_{3D} = \left(1 - \frac{\sqrt{2}}{3}\right)H_0 - 2 \left(1 - \frac{\sqrt{2}}{3}\right)r.
\]
4. Analysis of Two Case Histories

4.1. Xingang Port, Tianjin, China. Xingang Port, the major port handling international trade in north China, is located in Tianjing, China. This case history was reported by Shang et al. [6]. The subsoil of site consisted of more than 20 m of thick soft clayey soil, including a very soft newly reclaimed surface layer 4 m in thickness. Soil improvement was necessary prior to the construction of the structures, and it was divided into six sections by Roman numerals I-VI for the purpose of ground improvement, as shown in Figure 5. In addition, the design criteria of soil improvement are summarized in Table 3.

To achieve the design pressure requirement in divisions III-VI, the total preloading pressure of 97 kPa was designed, including a vacuum pressure of 80 kPa and a surcharge of 17 kPa, 1.11–1.21 times greater than the design pressures. Prefabricated vertical drains (PVDs) were then installed in a square pattern at spacing of 1.3 m to a depth ranged between 16 m and 20 m, and the embedded depth was extended to 25 m in some areas where the thick soft soil layer was encountered. Shang et al. [6] reported that the surface settlement for each of the subdivisions was measured using settlement pins installed approximately 3m from the anchor trenches and the ground settled about 0.6 to 1.2 m induced by the fill materials (0.3 m hill cuts and 0.4 m medium sand) during the pretreated stage. The vacuum pressure was considered to have reached 80 kPa within 15 days, and treatment was terminated when the settlement rate was less than 1 mm/day over a period of 10 days based on past experience [6].

The ultimate settlement of the soil ranged from 1.6 to 2.3 m and consisted of those induced by pretreatment surcharge and by vacuum preloading treatment, as plotted in Figure 5. Generally, a larger settlement was observed in divisions III-VI, 2.2 m, induced by combined effects of surcharge load and vacuum pressure in Figure 5. PVDs penetrate the peat or organic clay deposit, impermeable soil, and one-way drainage condition was formed. There was no information about the accurate penetration depth in divisions III-VI, and an average value, 18 m, was adopted in the approximate method. Comparison between the field data and the simple method for settlement calculation is shown in Table 4. The contour map is showing total settlement due to the combined effects of surface settlement and vacuum preloading (after [6]).

Partial self-weight consolidation occurs before pretreated, and the measured data are absent. Meanwhile, the accurate final settlement value and penetration depth are unknown. Therefore, soil particles arranged orderly in self-weight consolidation stage and the calculation data are bigger than the measured data. The relative error of 2D estimation result is 9.55%, which is much smaller than 3D estimation result (332.27%). It indicates that the influence induced by vacuum-surchage pressure of 97 kPa is close to 2D model. If the pressure could increase further, it will develop toward 3D model. Therefore, according to the research specific to analysis of vacuum-surchage preloading in this study, 2D model is more suitable for the final settlement prediction induced by vacuum-surchage preloading method.

### Table 2: Derivation of settlement in SC and TH arrangement in three-dimensional (3D) perspective.

| N   | SC ($h_1$) | TH ($h_2$) | $\Delta h_{3D} = h_1 - h_2$ |
|-----|------------|------------|-----------------------------|
| 1   | 2r         | 2r         | 0                           |
| 2   | 4r         | $(2 + 2\sqrt{2}/3)r$ | $2(1 - \sqrt{2}/3)r$       |
| 3   | 6r         | $(2 + 4\sqrt{2}/3)r$ | $4(1 - \sqrt{2}/3)r$       |
| 4   | 8r         | $(2 + 6\sqrt{2}/3)r$ | $6(1 - \sqrt{2}/3)r$       |
| ... | ...        | ...        | ...                         |
| $n$ | $(2n)r$    | $[2 + 2(n - 1)\sqrt{2}/3]r$ | $2(n - 1)(1 - \sqrt{2}/3)r$ |

For clarity, $r$ plays a small role and can be neglected, and then, this prediction method is suitable for both single and multiple layers. The following expression for $\Delta h$ is obtained, i.e.,

$$\Delta h_{2D} = \left(1 - \frac{\sqrt{3}}{2}\right) H_0,$$

$$\Delta h_{3D} = \left(1 - \frac{\sqrt{2}}{3}\right) H_0.$$
Japan. The site was divided into two sections: Section A (about 3600 m²) and Section B (about 3750 m²) on a square pattern, as shown in Figure 6 [35, 36]. The site was reclaimed land, and the soil profile included two layers that required improvement. The first layer, about 12 m, was clayey silt layer, and the second layer below the first, about 29 m, was a clayey deposit which in turn underlain a sand layer. The majority of the reclamation was carried out between 2003 and 2005 with a rate of about 3.5 m/year. A technique of applying vacuum pressure to soft clayey subsoil has been developed, in which vacuum pressure is combined with a special PVD, consisting of a PVD and a drainage hose, named cap-prefabricated vertical drains (CPVDs) [37]. A surface or subsurface soil layer was used as a sealing layer, and there is no need to worry about air leakage caused by damage to the sheet.

CPVDs used at this site had a cross section of 150 mm × 3 mm. CPVDs had a spacing of 2.0 m for Section A and 1.8 m for Section B with a square pattern. CPVDs were installed to 30 m depth from the ground surface for both sections including the sealing surface layer thickness of about 1.0 m. Therefore, the actual penetrated depth is 29 m. CPVDs did not penetrate through the thick clayey deposit of about 20 m. Therefore, the drainage boundary is one-way drainage condition. The partial self-weight consolidation periods before vacuum pressure application were about 165 days and 135 days for Section A and Section B, respectively. Vacuum pressure of 80–90 kPa at the vacuum pump location was applied for 204 days.

Based on the field-measured data reported by Miyakoshi et al. [35], the final settlement is about 3.60 m and 3.88 m for Section A and Section B, respectively. Comparison between the field data and the simple method for settlement calculation is depicted in Table 5.

To sum up, for vacuum-surcharge consolidation project, although there are some uncertain factors, the 2D calculation method has reasonable prediction results for ultimate

| Table 3: Criteria of soil improvement (after [6]). |
|-----------------------------------------------|
| Design load $P_d$ (kPa) | Method of treatment | $C_u$ (up to 10 m depth) (kPa) | Residual settlement under design load (cm) |
|-------------------------|---------------------|-------------------------------|------------------------------------------|
| 50                      | Vacuum              | ≥15                           | ≤20                                      |
| 50                      | Vacuum              | ≥15                           | ≤20                                      |
| 87                      | Vacuum + preloading | ≥20                           | ≤30                                      |
| 83                      | Vacuum + preloading | ≥20                           | ≤15                                      |
| 80                      | Vacuum + preloading | ≥20                           | ≤15                                      |
| 80                      | Vacuum + preloading | ≥20                           | ≤15                                      |
| 80                      | Vacuum + preloading | ≥20                           | ≤15                                      |

| Table 4: Comparison between the field data and the approximate method. |
|-------------------------|----------------------|----------------------|----------------------|----------------------|
| Drainage boundary | Depth of PVDs (m) | Method of treatment | Settlement of field (m) | $\Delta h_{2D}$ (Error) | $\Delta h_{3D}$ (Error) |
|-------------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| Xingang, Tianjin | One-way | 18 | Vacuum + preloading | 2.20 | 2.41 (9.55%) | 9.51 (332.27%) |

Figure 5: Field test conditions and contour map showing total settlement due to the combined effects of surface settlement and vacuum preloading (after [6]).
settlement than the 3D one. During the period of land reclamation, it is easy to predict the final settlement after consolidation treatment and feed back the thickness of fill. The 2D estimation method specific to this study could be used to predict the final settlement well under condition of vacuum-surcharge pressure. Even so, the 3D model is still a promising method for ultimate settlement of granular soil formation. The 3D model is the ideal state for rigid particles if the preloading is sufficient.

5. Conclusions

This paper discusses the mechanism of vacuum consolidation and surcharge consolidation based on the principle of effective stress. Furthermore, a simple approximate method for estimating the ultimate settlement has been proposed and two case histories were analyzed. The following conclusions specific to the analysis in this study can be drawn:

1. Sealing is incomplete strictly and cannot block the connection between reinforced section and unreinforced area. The recharge amount of pore air and pore water from outside the unreinforced area equals to discharge amount from inside the reinforced area, and then, a dynamic equilibrium state reached at last.

2. Surcharge consolidation reinforces soft soil by increasing the effective stress directly based on the principle of effective stress, whereas vacuum pressure can not only increase effective stress but decrease pore water pressure. Compared to the surcharge preloading, vacuum consolidation is a more efficient method with the same amount due to its surcharge effect and drainage effect.

3. Consolidation is a process of rearrangement of soil particles. A rapid settlement prediction method even by oral was proposed, and the proposed method has been applied to two case histories reported in the literature. It is shown that the 2D calculation method works better than the 3D one under the vacuum-surcharge pressure of about 100 kPa, suggesting that the 2D method might be useful for the primary estimating of the final settlement and fill thickness in land reclamation projects, and some measures could be adopted in advance.

4. The 3D model is an ideal method for ultimate settlement of granular soil formation in theory, which is hard to be achieved in practice. The proposed method could be a promising method although it is simple in style. Further research work about the

| Sections | Drainage boundary | Spacing of CPVDs (m) | Depth of PVDs (m) | Method of treatment | Settlement of field (m) | $\Delta h_{2D}$ (Error) | $\Delta h_{3D}$ (Error) |
|----------|-------------------|---------------------|------------------|--------------------|------------------------|------------------------|------------------------|
| Section A | One-way           | 2.0                 | 29               | Vacuum             | 3.60                   | 3.89 (8.06%)           | 15.33 (325.83%)        |
| Section B | One-way           | 1.8                 | 29               | Vacuum             | 3.88                   | 3.89 (0.26%)           | 15.33 (295.1%)         |
influence factors including time, PVD spacing, and scale effect will be considered as the further research work in the future.

Data Availability

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

Disclosure

No potential conflicts of interest were reported by the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] P. Ni, K. Xu, G. Mei, and Y. Zhao, “Effect of vacuum removal on consolidation settlement under a combined vacuum and surcharge preloading,” Geotextiles and Geomembranes, vol. 47, no. 1, pp. 12–22, 2019.

[2] B. Indraratna, X. Geng, and C. Rujikiatkamjorn, “Review of methods of analysis for the use of vacuum preloading and vertical drains for soft clay improvement,” Geomechanics and Geoengineering, vol. 5, no. 4, pp. 223–236, 2010a.

[3] B. Indraratna and I. W. Redana, “Numerical modeling of vertical drains with smear and well resistance installed in soft clay,” Canadian Geotechnical Journal, vol. 37, no. 1, pp. 132–145, 2000.

[4] B. Indraratna, C. Rujikiatkamjorn, and I. Sathansanathan, “Analytical and numerical solutions for a single vertical drain including the effects of vacuum preloading,” Canadian Geotechnical Journal, vol. 42, no. 4, pp. 994–1014, 2005a.

[5] B. Indraratna, C. Rujikiatkamjorn, R. Kelly, and H. Buys, “Sustainable soil improvement via vacuum preloading,” Proceedings of the Institution of Civil Engineers - Ground Improvement, vol. 163, no. 1, pp. 31–42, 2010b.

[6] J. Q. Shang, M. Tang, and Z. Miao, “Vacuum preloading consolidation of reclaimed land: a case study,” Canadian Geotechnical Journal, vol. 35, no. 5, pp. 740–749, 1998.

[7] W. Guo, J. Chu, and W. Nie, “An observational method for consolidation analysis of the PVD-improved subsoil,” Geotextiles and Geomembranes, vol. 46, no. 5, pp. 625–633, 2018.

[8] P. Ni, G. Mei, and Y. Zhao, “Surcharge preloading consolidation of reclaimed land with distributed sand caps,” Marine Georesources & Geotechnology, vol. 37, no. 6, pp. 671–682, 2018b.

[9] J. Wang, Z. Fang, Y. Cai, J. Chai, P. Wang, and X. Geng, “Preloading using fill surcharge and prefabricated vertical drains for an airport,” Geotextiles and Geomembranes, vol. 46, no. 5, pp. 575–585, 2018.

[10] R. Yao, P. Ni, G. Mei, and Y. Zhao, “Numerical analysis of surcharge preloading consolidation of layered soils via distributed sand blankets,” Marine Georesources & Geotechnology, vol. 37, no. 8, pp. 902–914, 2018.

[11] H.-L. Liu, Y.-L. Cui, Y. Shen, and X.-m. Ding, “A new method of combination of electroosmosis, vacuum and surcharge preloading for soft ground improvement,” China Ocean Engineering, vol. 28, no. 4, pp. 511–528, 2014.

[12] W. Kjellman, “Accelerating consolidation of fine grain soils by means of cardboard wicks,” Proceedings of the 2nd ICSMFE, vol. 2, pp. 302–305, 1948.

[13] W. Kjellman, “Consolidation of clayey soils by atmospheric pressure,” in Proceedings of the a Conference on Soil Stabilization, pp. 258–263, Massachusetts Institute of Technology, Boston, MA, USA, 1952.

[14] H. Chen and X. C. Bao, “Analysis of soil consolidation stress under the actions of negative pressure,” Proc. 8th European Conf. on Soil Mech. found Eng., Helsinki, vol. 2, pp. 591–596, 1983.

[15] V. Choa, “Soil improvement works at tianjin east pier project,” Proc.10th Southeast Asian Geot. Conf., Taipei, vol. 1, pp. 47–52, 1990.

[16] Tpei, Vacuum Preloading Method to Improve Soft Soils and Case Studies, Tianjin Port Engineering Institute, China, 1995.

[17] J. Chu, S. W. Yan, and H. Yang, “Soil improvement by the vacuum preloading method for an oil storage station,” Géotechnique, vol. 50, no. 6, pp. 625–632, 2000.

[18] J.-C. Chai, K. Matsunaga, A. Sakai, and S. Hayashi, “Comparison of vacuum consolidation with surcharge load induced consolidation of a two-layer system,” Géotechnique, vol. 59, no. 7, pp. 637–641, 2009.

[19] V.-t. Vu, L.-h. Yao, and Y.-j. Wei, “Laboratory investigation of axisymmetric single vacuum well point,” Journal of Central South University, vol. 23, no. 3, pp. 750–756, 2016.

[20] M. Jamilolkowski, R. Lancellotta, and W. Wolski, “Pre-compression and speeding up consolidation,” in Proceedings of the 8th ECSMFE, pp. 1201–1206, 1983.

[21] J.-C. Chai, J. P. Carter, and S. Hayashi, “Vacuum consolidation and its combination with embankment loading,” Canadian Geotechnical Journal, vol. 43, no. 10, pp. 985–996, 2006.

[22] B. Indraratna, I. Sathansanathan, C. Rujikiatkamjorn, and A. S. Balasubramaniam, “Analytical and numerical modeling of soft soil stabilized by prefabricated vertical drains incorporating vacuum preloading,” International Journal of Geomechanics, vol. 5, no. 2, pp. 114–124, 2005.

[23] B. R. Rankine, B. Indraratna, N. Sivakugan, V. Wijeyakulasuriya, and C. Rujikiatkamjorn, “Foundation behaviour below an embankment on soft soils,” Proceedings of the Institution of Civil Engineers - Geotechnical Engineering, vol. 161, no. 5, pp. 259–267, 2008.

[24] J. Chu, C. Y. Ong, J. P. Carter, and D. T. Bergado, “Lateral displacement under combined vacuum pressure and embankment loading,” Géotechnique, vol. 63, no. 10, pp. 842–856, 2013.

[25] X. Xiong, J. Peng, K. Zhang, and Y. Hu, “Study on sedimentation characteristics of hydraulic-dredged mud in Wenzhou,” Journal of Water Resources and Architectural Engineering, vol. 10, no. 6, pp. 78–82, 2012.

[26] Q. Zhao, A. Pepe, W. Gao et al., “A DinSAR investigation of the ground settlement time evolution of ocean-reclaimed lands in Shanghai,” Ieee Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 8, no. 4, pp. 1763–1781, 2015.
[27] J. C. Chai, J. P. Carter, and S. Hayashi, “Ground deformation induced by vacuum consolidation,” *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 131, no. 12, pp. 1552–1561, 2005.

[28] L. Q. Sun, S. W. Yan, H. J. He, and W. Li, “Calculation of vacuum preloading settlement for soft soil foundation during PVDs installation,” *Journal of Hydraulic Engineering*, vol. 41, no. 5, pp. 588–594, 2010, (in Chinese).

[29] Y. B. Xia, Y. J. Wang, J. Song, Q. Wang, W. F. Sang, and X. L. Peng, “Research on settlement of dredger fill consolidation with vacuum preloading test,” *Journal of Engineering Geology*, vol. 18, pp. 306–310, 2010, (in Chinese).

[30] J. Chai, Z. Hong, and S. Shen, “Vacuum-drain consolidation induced pressure distribution and ground deformation,” *Geotextiles and Geomembranes*, vol. 28, no. 6, pp. 525–535, 2010.

[31] J. Ma, X. Niu, H. Tang, Y. Wang, T. Wen, and J. Zhang, “Displacement prediction of a complex landslide in the three gorges reservoir area (China) using a hybrid computational intelligence approach,” *Complexity*, vol. 2020, pp. 1–15, Article ID 2624547, 2020.

[32] Y. K. Wang, H. M. Tang, J. S. Huang, T. Wen, J. W. Ma, and J. R. Zhang, “A comparative study of different machine learning methods for reservoir landslide displacement prediction,” *Engineering Geology*, vol. 298, Article ID 106544, 2022.

[33] J. W. Ma, Y. K. Wang, X. X. Niu, S. Jiang, and Z. Y. Liu, “A comparative study of mutual information-based input variable selection strategies for the displacement prediction of seepage-driven landslides using optimized support vector regression,” *Stochastic Environmental Research and Risk Assessment*, 2022.

[34] J. C. Chai, S. Hayashi, and J. P. Carter, “Characteristics of vacuum consolidation,” in *Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering*, pp. 1167–1170, Mill Press, Osaka, Japan, September 2005.

[35] K. Miyakoshi, H. Shinsha, and D. Nakagawa, “Vacuum consolidation field test for volume reduction scheme of soft clayey ground (part-2) – ground characteristic and measured results,” in *Proceedings of the 42nd Annual Meeting Japanese Geotechnical Society*, (in Japanese), , pp. 919-920, 2007.

[36] K. Miyakoshi, K. Takeya, Y. Otsuki et al., “The application of the vacuum compaction drain method to prolong the life of an offshore disposal field,” *Nippon Koei Technical Forum*, vol. 16, pp. 9–19, 2007, (in Japanese).

[37] A. Fujii, H. Tanaka, H. Tsuruya, and H. Shinsha, “Field test on vacuum consolidation method by expecting upper clay layer as sealing up material,” in *Proceedings of the Symposium on Recent Development about Clayey Deposit—From Microstructure to Soft Ground Improvement* Japanese Geotechnical Society, (in Japanese), , pp. 269–274, 2002.

[38] B. Indraratna, C. Rujikiatkamjorn, and I. Sathananthan, “Radial consolidation of clay using compressibility indices and varying horizontal permeability,” *Canadian Geotechnical Journal*, vol. 42, no. 5, pp. 1330–1341, 2005c.