J. Eng. Technol. Sci., Vol. 54, No. 5, 2022, 220501

Evaluation of Asaoka and Hyperbolic Methods for Settlement Prediction of Vacuum Preloading Combined with Prefabricated Vertical Drains in Soft Ground Treatment

Quang Dong Pham[1], Van-Linh Ngo[2], The Viet Tran[2,*] & Minh Thu Trinh[2]

[1]Quang Nam Irrigation Department, 117 Hung Vuong, Tam Ky, Quang Nam, Vietnam
[2]Faculty of Civil Engineering, Thuyloi University, 175 Tay Son, Dong Da, Hanoi, Vietnam
*E-mail: trantheviet@tlu.edu.vn

Highlights:

- Important properties of the soil were tested to evaluate the effectiveness of the treatment method.
- The measured settlement was used in the Asaoka and the hyperbolic method to predict the potential ultimate settlement. The results showed the superiority of the vacuum consolidation approach in improving the fundamental engineering properties of soft soil.
- The ultimate settlement predicted by both the Asaoka method and the hyperbolic method showed a good agreement with the measured value, proving that these methods are suitable for estimation of the ultimate settlement of soft soil treated with vacuum consolidation

Abstract. This study evaluated the use of the Asaoka and hyperbolic methods to estimate the ultimate settlement of soft ground treated by vacuum preloading combined with prefabricated vertical drains. For this aim, a large-scale physical laboratory model was constructed. The model was a reinforced-tempered glass box containing a soil mass with dimensions of 2.0 × 1.0 × 1.2 m (length × width × depth). Physical models of this scale for the same purpose are rare in the literature. The soil was taken from a typical coastal region in Dinh Vu Hai Phong, Vietnam. The surface settlement near and between the two drains was measured right after the vacuum preloading started. Important properties of the soil were tested to evaluate the effectiveness of the treatment method. The measured settlement was used in the Asaoka and hyperbolic methods to predict the potential ultimate settlement. The results showed the superiority of the vacuum consolidation approach in improving fundamental engineering properties of soft soil. Furthermore, the ultimate settlement predicted by both methods showed a good agreement with the measured value, proving that the Asaoka and hyperbolic methods are suitable for the estimation of the ultimate settlement of soft soil treated with vacuum consolidation.

Keywords: *Asaoka method; ground treatment; hyperbolic method; soft soil; ultimate settlement; vacuum consolidation.*

Received July 29th, 2021, 1st Revision 19 October 2021, 2nd Revision March 17th, 2022, Accepted for publication April 19th, 2022.

DOI: 10.5614/j.eng.technol.sci.2022.54.5.1

1 Introduction

The vacuum preloading approach for soft ground improvement has been implemented as a practical, cost-effective, and environmentally sustainable technique [1-5] since the time it was first introduced [6]. The method is now considered one of the most effective techniques for soft ground improvement projects worldwide, considering both the time of treatment and soil parameters [1-3,7-11]. The vacuum preloading technique can increase the strength of the treated soft soil at a rapid rate and reduces its post-construction consolidation settlement [5,12]. The method often requires a quick assessment of the potential effectiveness of the treatment, but up to now finding a settlement prediction model with acceptable results is still a challenge.

Reliable settlement estimation is vital for monitoring field settlement as construction progresses [13-15]. Terzaghi's one-dimensional consolidation theory has been broadly accepted to estimate the potential ultimate settlement [13]. However, this theory is not always practical due to the use of numerous simplified assumptions regarding the uncertainties of the foundation as well as the magnitude and distribution of surcharge loads. Furthermore, using laboratory-determined parameters, Terzaghi's theory substantially overestimates the settlement [13], since it is hard for parameters defined in the laboratory to well represent in-situ conditions. At present, numerous approaches have been developed for the estimation of settlement based on observation data, such as the hyperbolic method [16], the Asaoka method [17], and in-situ testing [18].

The hyperbolic method, which is able to show the effect of secondary consolidation of the soil to a certain extent, can successfully predict the ultimate settlement [19]. For this method, the surcharge is assumed to be constant, so the settlement before the end of loading cannot be predicted [20]. In-situ measurements often give valuable data required to evaluate the foundation conditions, especially in estimating the ultimate settlement. However, field testing is often time-consuming and expensive. On the other hand, the Asaoka method has been widely accepted due to its simplicity and high accuracy in settlement prediction [21]. The Asaoka method is based on 'observational procedure', where future settlement is estimated using past measurements [17,21]. Through settlement observation data analysis, it is possible to investigate current trends and predict the final settlement.

This study evaluated the effectiveness of soft soil treatment using vacuum preloading combined with prefabricated vertical drains in Hai Phong, Vietnam, and the use of the Asaoka and hyperbolic methods to estimate the ultimate settlement. For these purposes, a large-scale physical laboratory model was constructed. The soft soil was taken from a typical coastal region in Dinh Vu

Industrial Zone, Hai Phong, Vietnam. Important properties of the soft soil before and after loading were tested. The surface settlement near and between the two drains was measured right after the vacuum preloading started, using settlement gauges. The measured settlement from the physical model was used in the Asaoka and hyperbolic methods to predict the potential ultimate settlement.

2 Use of the Asaoka and Hyperbolic Methods in the Prediction of Ultimate Settlement

2.1 Asaoka Method

For the application of the Asaoka method, the following steps are required: (1) observation of the settlement of the foundation, S_i, corresponding to equal periods Δt; (2) construction of a graph showing the relationship between S_i and S_{i-1}; (3) determination of the trend of the S_i and S_{i-1} line; and (4) determination of the intersection between the S_i and the S_{i-1} line, which gives the ultimate settlement value (S_{ult}), where S_i and S_{i+1} are equal. An equation represents the linear trend between S_i and S_{i-1} in Asaoka's plot, as shown in Figure 1. The settlement at time *i* can be written as in Eq. (1):

$$S_i = \beta_o + \beta\, S_{i-1} \tag{1}$$

where β_o and β are unknown parameters that can be defined using Figure 1. The ultimate settlement, S_{ult}, can be defined, where S_i and S_{i-1} are equal, by using Eq. (2) [22]:

$$S_{ult} = \frac{\beta_o}{1-\beta} \tag{2}$$

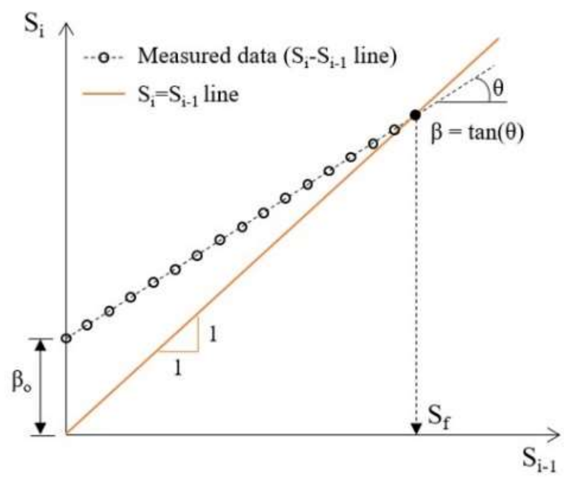

Figure 1 Plot of field settlement for the Asaoka method.

2.2 Hyperbolic Method

In 1981, Sridharan and Rao [23] introduced a rectangular hyperbola fitting method to predict ground settlement according to Terzaghi's consolidation theory. After that, Tan, *et al.* [16] suggested a hyperbolic curve for plotting T_v/U (the time factor/degree of consolidation) versus T_v, as shown in Figure 2(a). The settlement–time relationship between 60% and 90% degree of consolidation (i.e., U_{60} and U_{90}), which can be expressed in terms of the degree of consolidation (U) and time factor (T_V), is considered linear. This can be illustrated in Eq. (3):

$$T_v / U = \alpha T_v + \beta \tag{3}$$

where α and β are the slope and the intercept of the hyperbolic plot, respectively. A similar trend was also obtained for cases with coupling vertical and radiational drains. Tan [24] applied the method and plotted time (t) over settlement (S) versus time (t/S vs t), as shown in Figure 2(b).

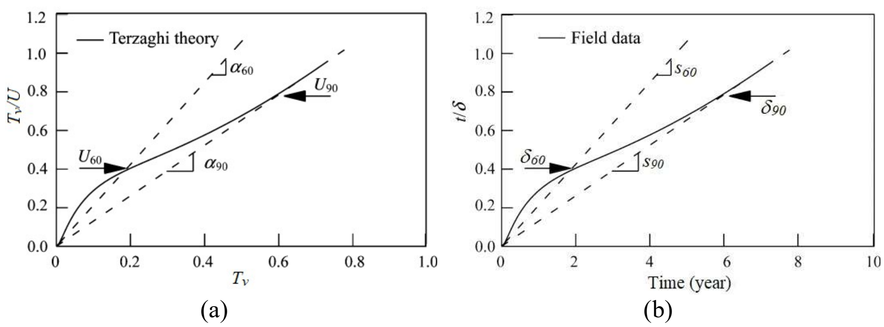

Figure 2 Plot of field settlement for the hyperbolic method in (a) Tv and (b) time series [24,25].

The settlement at time t is in a hyperbolic function of the initial settlement (S_o), and time (t) as in Eq. (4) [12,26]:

$$S_t = S_o + \frac{t}{\alpha + \beta t} \tag{4}$$

where α and β are the parameters defined as the intersection and slope of the fitting line for the data when plotting $t/(S_t-S_o))$ versus t. Finally, the ultimate settlement can be estimated as in Eq. (5):

$$S_{ult} = S_o + 1/\beta \tag{5}$$

3 Selected Soft Soil, Physical Model, and Testing Equipment

3.1 Selected Soft Soil

The Dinh Vu Industrial Zone is located in Hai Phong city in northern Vietnam. The project's total improved area is 9.2 hectares, with the average thickness of the soft soil layer varying from 22 to 32 m [27]. The soil samples were taken at a depth of 4.0 to 5.0 m below the ground surface at the research site, where a soft to very soft layer composed of alluvial and marine clay deposits is found. According to the Unified Soil Classification System (USCS), this soil is classified as CL (clay with low plasticity) [28]. The basic properties of the soft soil samples are presented in Table 1. The typical grain size properties of the soil are shown in Figure 3.

Table 1 Index properties of the studied soil in Dinh Vu, Hai Phong, Vietnam.

Parameters	*Symbol*	Unit	Value range
Specific gravity	G_s	-	2.67 - 2.71
Liquid limit	LL	%	33.04 - 35.6
Plastic limit	PL	%	21.95 - 23.5
Plasticity index	PI	%	11.09 - 12.5

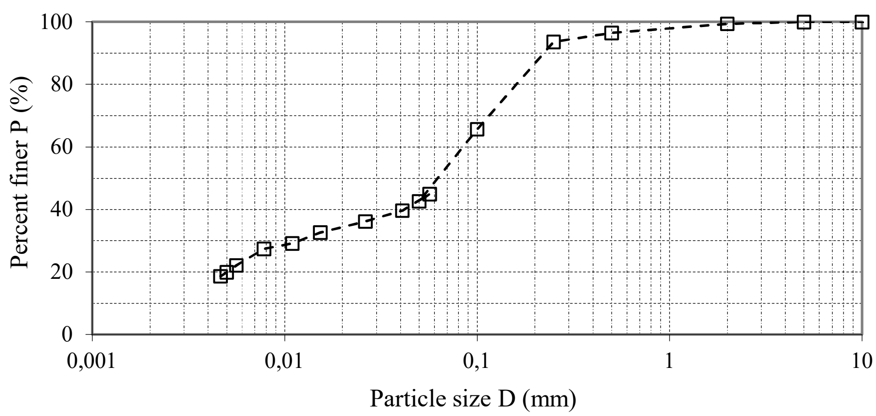

Figure 3 Typical grain size distribution of the soft soil in Vu, Hai Phong.

3.2 Preparation of the Physical Laboratory Model

A large-scale model was constructed following the Airtight Sheet Approach. The whole system was constructed in a test box supported by an iron frame and with a tempered glass surface of 1.0 cm thickness. The dimensions of the box were 100 cm × 200 cm × 120 cm in length, width, and height with a volume of 2.4 m^3. The whole test system (as presented in Figure 4) included: 1: vacuum pumping system, 2) gauges for the measurement of pore water pressure and surface settlement, 3) supporting frame, 4) water collecting system, 5) membrane to create vacuum pressure.

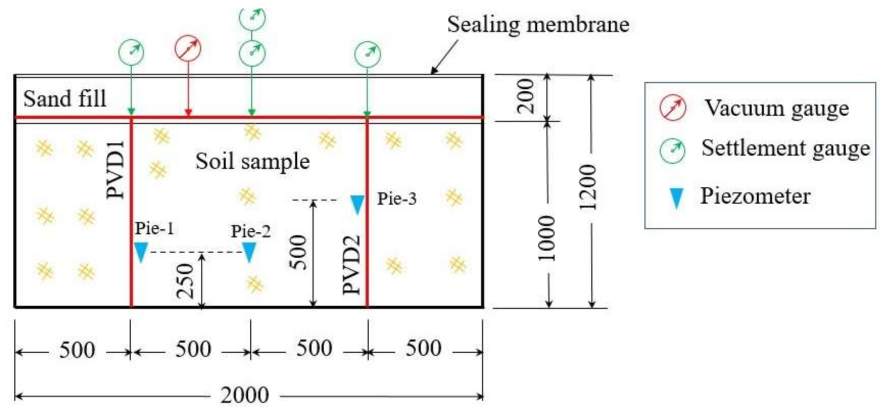

Figure 4 Equipment used for model testing (dimensions in mm).

To prepare the model, the soft soil was mixed uniformly with water to reach the liquid limit. It was then poured freely into the box layer by layer until reaching a thickness of 1.0 m; each layer was about 10 cm thick. One layer of geomembrane was added on top and sealed to maintain an airtight condition. A vacuum gauge was set up right under the geomembrane to monitor the vacuum pressure during the test. Horizontal perforated pipes were wrapped with filter geotextile to connect all vertical drains. The following procedure was used to prepare the soil sample:

1. The soil mixture was added to the testing flume layer by layer until the thickness reached the designed value. During this procedure, a weight of 3.0 kg was used to preliminary compress the soil.
2. For convenience, all measuring gauges were installed simultaneously during the construction of the testing model. Two piezometers were installed at a depth of 750 cm (PIE 2-1 and PIE 2-2) and another one at a depth of 500 cm (PIE 2-3), as presented in Figure 5'
3. The sample was soaked under water for seven days before conducting the test to ensure it was completely saturated.
4. A vacuum pressure of 43 kPa was maintained during the test. This was reduced to below the practical value for clay, approximately 90 kPa [8], to be stable during the test. This pressure was removed until the settlement rate had reduced and reached a stable value.
5. A 20-cm thick sand layer was added on top as a surcharge (Figure 5), which also had the role of collecting and draining the seepage water.

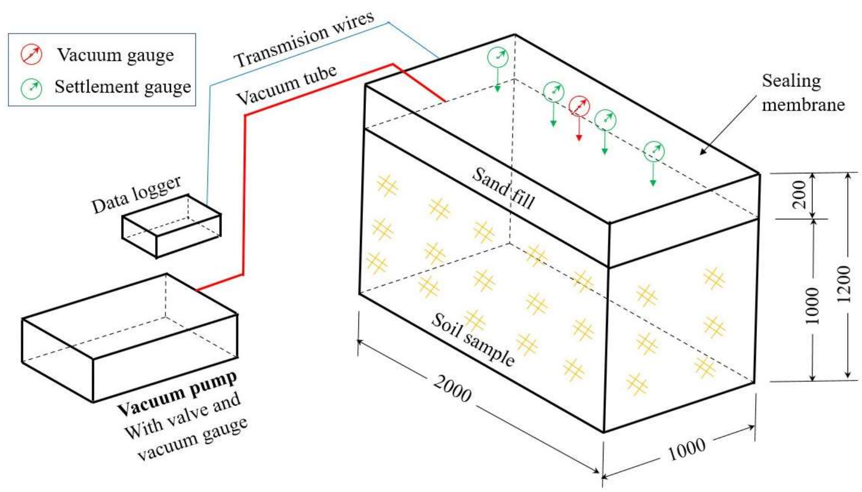

Figure 5 Diagram showing the arrangement of the pore-water pressure and deformation gauges (dimensions in mm).

PVDs are often installed in soft soils to improve their overall drainage properties and ultimately their strength and stiffness in order to accelerate the soft soil consolidation under the imposed loading [1]. PVDs serve a dual purpose during vacuum consolidation. They aid in achieving a balanced distribution of vacuum pressure over the soil treatment depth while also discharging extracted pore water up to the permeable soil cushion at the ground surface level [7]. The used PVD, which is widely used in practical engineering, had dimensions of 100 × 4 mm. The distance between the installed drains was 1.0 m, and the length of the drains was 1.0 m, i.e., equal to the soil sample's thickness. The drains' caps were connected to the pipe system and directly linked to the vacuum pump for vacuum loading. Before starting the experiment, the test box was stabilized to maintain an airtight condition. A thin layer of plastic paper covered all of the box's inside surfaces to observe the settlement and compare it with the results from the measuring gauges. A thin pipe with a diameter of 7.0 cm was used to take soil samples for laboratory tests to determine the soil's engineering properties before the test.

4 Results and Analyses

4.1 Effectiveness of Vacuum Preloading Combined with Prefabricated Vertical Drains

Soil samples were taken at various depths to determine the physical properties before and after the loading process (before VP and after VP, respectively, see

Figure 5. The basic properties along with the shear strength and compressibility of these samples were determined, as shown in Table 2. As can be seen, in the initial condition, the soil was very soft and had a high water content (44.19%) and a high void ratio (*e* of 1.21). However, after vacuum loading, the mechanical and physical characteristics had considerably improved. Notably, the density and shear strength parameters obtained by direct shear or triaxial tests had all increased. Simultaneously, the compression indexes (i.e., C_c and C_r) and coefficient of compressibility (a) had considerably decreased. Besides that, the degree of consolidation (C_v) and hydraulic conductivity (K) had been reduced by about three and ten times, respectively, indicating the improvement method's effectiveness.

Table 2 Parameters of the soil before and after applying vacuum consolidation.

Parameters	Symbol	Unit	Value TT	
			Before VP	**After VP**
Natural moisture content	w	%	44.19	35.94
Natural unit weight	γ_w	kN/m^3	17.48	18.34
Dry unit weight	γ_k	kN/m^3	11.97	13.50
Void ratio	e	-	1.21	0.98
Degree of saturation	S	%	97.75	98.01
Liquid index	LI	-	2.01	1.26
Direct shear test	φ	degree	4°27'	10°50'
	c	kN/m^2	8.10	12.60
Consolidated undrained triaxial test (CU)	φ	degree	25°05'	28°27'
	c	kN/m^2	9.9	18.37
Degree of consolidation	C_v	cm^2/s	17.46×10^{-4}	6.06×10^{-4}
Compression index	C_c	-	0.33	0.216
Swelling index	C_s	-	0.06	0.055
Hydraulic conductivity	K	cm/s	4.725×10^{-6}	5.97×10^{-7}
Coefficient of compressibility	a	m^2/kN	11.48×10^{-4}	9.33×10^{-4}

4.2 Observation of Settlement Results

The relationship between the average ground surface settlement over time is illustrated in Figure 6. As can be seen, the trend of settlement over time was consistent with previous studies in the literature. During the first four days, large increments in the surface settlement were observed at both points (i.e., TEN 2-1 (near the PVD) and TEN 2-2 (between the two drains)) due to the increase in the applied vacuum pressure. After that, the magnitude of reduction gradually decreased with a stable vacuum pressure at around -40 kPa. The ground settlement reached a stable value of about 9.0 cm after about 26 days of loading. Moreover, there was a difference between the measured surface settlement at the drain and between the two drains. The value of surface settlement at the drain was more significant than the value between the two drains because, in radiational consolidation, the consolidation speed reduces at points with a more considerable distance to a vertical PVD. However, this difference was not significant; it was almost stable after the first 4 days. This means that the differential settlement caused by the increase in vacuum pressure at the beginning of the loading process was reduced. The whole model's settlement was stably increased when the vacuum pressure was kept constant during the test.

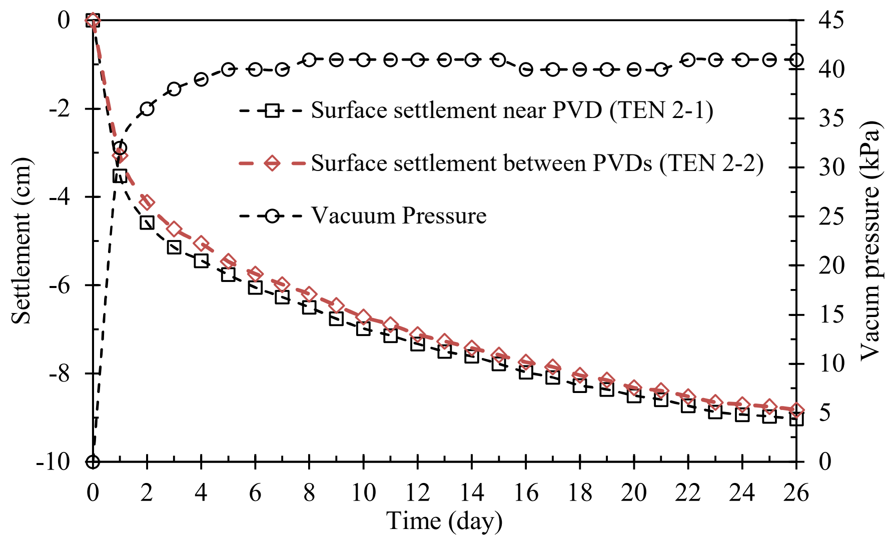

Figure 6 Settlement over time at studied locations.

4.3 Use of the Asaoka and Hyperbolic Methods in Ultimate Settlement Estimation of Marine Clay Deposit Foundation Treated by Vacuum Preloading Combined with Prefabricated Vertical Drains

In the projection process of the Asaoka method, the value of discrete time, Δt, has a direct impact on the final prediction results [21]. A small Δt value will cause greater volatility in the fitting point and as a result, the fitted line's correlation coefficient will be small. On the other hand, if Δt is too large, the S_i point is more minor, and a significant deviation is obtained. In this study, an interval time of two days was chosen. In addition, Huat, *et al.* [29] have suggested that plotting settlement versus time data for use in the Asaoka method works best if we first determine an estimate of t_{50} (the time when half of the estimated settlement has occurred) and start plotting and estimating the time to completion of consolidation and the amount of total consolidation settlement at time t_{50}. In this study, the settlement on the fourth day, which was about 5.006 cm and 4.64 cm at locations near and between the two drains, was about 50 percent of the final settlements measured on the 26th day. The first values for plotting the Asaoka method were chosen on the fourth day for two reasons: (1) the suggestion of Huat, *et al.* [29], and (2) the stable differential settlement between the two aforementioned measured points. It was possible to construct regression lines using data from the 11 simulated points as presented in Figure 7 with high regression values (i.e., R^2 of 0.991 and 0.988 for locations near and between the two drains, respectively).

The β_o value was estimated to be 1.409, and 1.330 and the β parameter was 0.859 and 0.868 for the measured points located near and between the two drains. An ultimate settlement of about 10 cm was estimated for the two measured locations using Eq. (2). Huat's condition agreed with the initial settlements on the fourth day (i.e., 5.006 cm and 4.64 cm for the two locations), which were more than 40% of the estimated final settlements for both locations [29]. Therefore, the ultimate settlement following the Asaoka method was 10.0 cm. Thus, we can see that the measured results and those predicted by the Asaoka method had good agreement, which proves that the Asaoka method is suitable in the case of soft soil for near coach areas treated by vacuum preloading combined with prefabricated vertical drains.

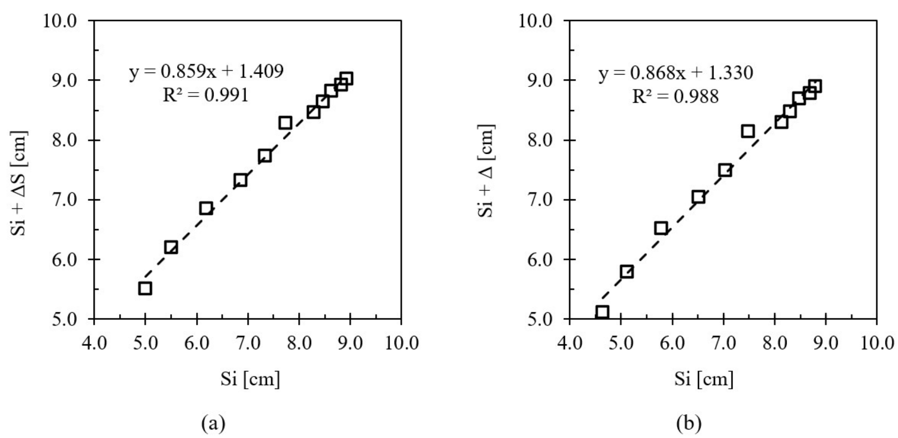

Figure 7 Regression line showing the settlement trend for the Asaoka method: a) near the drains and b) between the drains.

Figure 8 shows the settlement trend for the hyperbolic method, where $t/(S_t\text{-}S_o)$ is plotted versus time (t). S_o could be measured after the first day of loading, which was 3.52 cm and 3.06 cm for the location near and between the two drains. The interval time of 2 days was chosen following the Asaoka method. High regression values were obtained, and the β parameter was 0.114 and 0.111 respectively for the two points. The ultimate settlements were then estimated to be about 12.33 cm and 12.05 cm from the S_o and β values ($S_{ult} = S_o+1/\beta$), indicating higher settlement than previously found with the Asaoka method. This result agreed with the reports of Tan [24] and Tan and Chew [14], where the hyperbolic method overestimated the total primary settlement of the ground.

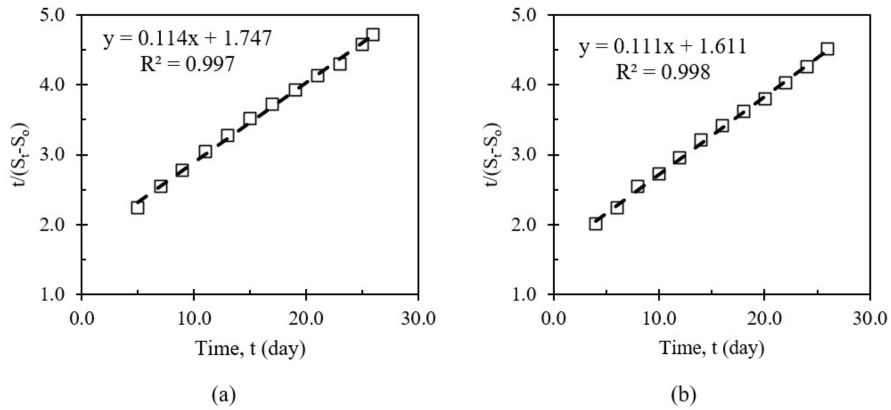

Figure 8 Regression line showing the settlement trend for hyperbolic method: a) near the drains and b) between the drains.

5 Conclusion

The performance of vacuum preloading combined with prefabricated vertical drains in soft soil treatment was investigated using a large-scale physical test. A series of laboratory model tests were conducted to define the soil's engineering properties before and after treatment. The variation of the PWP and the surface settlement of the soil were measured and analyzed. The results indicate that a system of PVDs combined with vacuum preloading is an effective method for accelerating the consolidation of soft soil, which may be challenging to treat using conventional methods. The mechanical and physical characteristics of the soil were considerably improved after vacuum preloading. The Asaoka and hyperbolic methods could successfully predict the total primary settlement of the treated soil at locations near and between the two drains. The results of the Asaoka method were slightly lower than those obtained with the hyperbolic method, which showed a good agreement with previous studies. Large-scale physical models are an excellent tool for understanding the behavior of soft soil under vacuum preloading. Future studies should be conducted to apply this study's results to increase the reliability of numerical models for sites with similar soft soil properties. Additionally, the effectively treated depth of the vacuum pressure should also be considered.

References

[1] Chai, J.C. & Carter, J.P., *Deformation Analysis in Soft Ground Improvement*, Springer Netherlands, Netherlands, 2011.

[2] Griffin, H. & O'Kelly, B., *Ground Improvement by Vacuum Consolidation – A Review*, Proceedings of the Institution of Civil Engineers Ground Improvement, **167**(4), pp. 274-290, 2014.

[3] Indraratna, B., *Recent Advances in the Application of Vertical Drains and Vacuum Preloading in Soft Soil Stabilisation*, Geomechanics Journal **45**(2), pp. 1-43, 2010.

[4] Jiang, J. & Liu, R., *Effect of Improvement and Application of Composite Prefabricated Vertical Drain Method in Marine Soft Ground: A Case Study*, Advances in Civil Engineering, 2019, 6097504. 2019.

[5] Dermawan, H., Hutapea, B.M., Susila, E. & Irsyam, M., *Finite Element Simulation of Vacuum Preloading at Palembang-Indralaya Toll Project*, Journal of Engineering & Technological Sciences, **53**(4), 210410, 2021.

[6] Kjellman, W., *Consolidation of Clay Soil by Means of Mamospheric Pressure*, Proc. Conf. on Soil Stabilization, Massachusetts Institute of Technology, Boston, USA, pp. 258-263, 1952.

[7] Chu, J. & Yan, S., *Vacuum Preloading Techniques - Recent Developments and Applications*, in: K. Reddy, M. Khire, A. Alshawabkeh (Eds.) The GeoCongress 2008: Geosustainability and Geohazard Mitigation, New Orleans, USA., 2008.

[8] Chu, J., Yan, S. & Yang, H., *Soil Improvement by the Vacuum Preloading Method for an Oil Storage Station*, Géotechnique, **50**(6), pp. 625-632, 2000.

[9] Liu, H., Cui, Y., Shen, Y. & Ding, X., *A New Method of Combination of Electroosmosis, Vacuum and Surcharge Preloading for Soft Ground Improvement*, China Ocean Eng., **28**(4), pp. 511-528, 2014.

[10] Pham, Q., Tran, T. & Trinh, M., *Relation between the Plasticity Index and Key Consolidation Parameters of Soft Ground Stabilized by Vacuum Preloading Together with Vertical Drains*, International Journal of Geomate, **118**(69), pp. 224-229, 2020.

[11] Susila, E. & Agrensa, F., *Case Study on Soft Soil Improvement using Innovative and Cost-Effective Reinforcing Techniques*, Journal of Engineering and Technological Sciences, **47**(2), pp. 207-217, 2015.

[12] Lei, T.B., Xiong, S.D., Ling, F.J. & Zhang, J.D., *Study on Comparison of Predicting Method on Settlement and Deformation of Unballasted Track in the Button of Tunnel on High Speed Railway*, Applied Mechanics and Materials, **513-517**, pp. 2647-2650, 2014.

[13] Mosleh, A.A., *Applicability of the Rectangular Hyperbolic Method to Settlement Predictions of Sabkha Soils*, Geotechnical and Geological Engineering, **22**, pp. 563-587, 2004.

[14] Tan, S.A. & Chew, S.H., *Comparison of the Hyperbolic and Asaoka Observational Method of Monitoring Consolidation with Vertical Drains, Soils and foundation*, **36**(3), pp. 31-42, 1996.

[15] Abedian, M.A., Farrokhi, F. & Rasouli, R., *Settlement Evaluation of a Concrete Face Rock-Fill Dam (CFRD) Using a Back-Analysis Method Based on Measurement Results (A Case Study of Siah-Bisheh Dam)*, Journal of Engineering and Technological Sciences, **50**(4), pp. 516-533, 2018.

[16] Tan, T.S., Inoue, T. & Lee, S.L., *Hyperbolic Method for Consolidation Analysis*, Journal of Geotechnical Engineering, **117**(11), pp. 1723-1737, 1991.

[17] Asaoka, A., *Observational Procedure of Settlement Prediction*, Soils and foundation **18**(4), pp. 87-101, 1978.

[18] Bergado, D.T., Daria, P.M., Sampaco, C.L. & Alfaro, M.C., *Prediction of Embankment Settlements by In-situ Tests*, ASTM Geotechnical Testing Journal, **14**(4), pp.425-439, 1991.

[19] Yu, F., Li, S., Dai, Z., Li, J. & Chen, S., *Stability Control of Staged Filling Construction on Soft Subsoil Using Hyperbolic Settlement Prediction Method: A Case Study of a Tidal Flat in China*, Advances in Transportation Geotechnics, 2020, pp. 1-11, 2020.

[20] Li, C., *A Simplified Method for Prediction of Embankment Settlement in Clays*, Journal of Rock Mechanics and Geotechnical Engineering, **6**(1), pp. 61-66, 2014.

[21] Hao, J. & Dong, J., *Study on Application of Asaoka Method on Settlement Prediction of Pile Foundation for High Speed Railway Bridges*, 10th Asia Pacific Transportation Development Conference, American Society of Civil Engineers, Beijing, China, 2014.

[22] Uy, E.E.S. & Dungca, J.R., *A Comparative Settlement Prediction of Limestone Blended Materials Using Asaoka and Hyperbolic Method*, International Journal of GEOMATE, **14**(43), pp. 63-69, 2018.

[23] Sridharan, A. & Rao, A., *Rectangular Hyperbola Fitting Method for One Dimensional Consolidation*, Geotech Test J., **4**(4), pp.161-168, 1981.

[24] Tan, S.A., *Validation of Hyperbolic Method for Settlement in Clays with Vertical Drains*, Soils and Foundations, **35**(1), pp. 101-113, 1995.

[25] Li, C., *A Simplified Method for Prediction of Embankment Settlement in Clays*, Journal of Rock Mechanics and Geotechnical Engineering, **6**(1), pp. 61-66, 2014.

[26] Chung, S.G., Lee, N.K. & Kim, S.R., *Hyperbolic Method for Prediction of Prefabricated Vertical Drains Performance*, Journal of Geotechnical and Geoenvironmental Engineering, **135**(10), pp. 1519-1528, 2009.

[27] Ngoc, V.B., Dung, N.T. & Suneel, M., *Vacuum Preloading Consolidation Method: A Case Study*, Proceedings of the International Symposium of Hanoi Geo-engineering, Hanoi, Vietnam, pp. 123-130, 2010.

[28] *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System) 1*, ASTM International, West Conshohocken, PA, 2017.

[29] Huat, B.B., Hoe, N.C. & Munzir, A.H., *Observational Methods for Predicting Embankment Settlement*, Pertanika J. Sci., **12**(1), pp. 115-128, 2004.