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RELATION BETWEEN THE PLASTICITY INDEX AND KEY CONSOLIDATION PARAMETERS OF SOFT GROUND STABILIZED BY VACUUM PRELOADING TOGETHER WITH VERTICAL DRAINS

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ABSTRACT: This study addressed the relationship between the plasticity index (PI) and the key parameters of the vacuum consolidation process including the consolidation time (t), the degree of consolidation (U), and the thickness of the treated soft soil layer (H) when improving soft ground by vacuum preloading together with vertical drains. For this purpose, the coupled analysis technique which combines SEEP/W and SIGMA/W modules in Geostudio commercial software is applied for the simulation. Three different foundations corresponding to different soft soils in Dinh Vu- Hai Phong, Duyen Hai – Tra Vinh, Nhon Trach – Dong Nai were considered. The suitability of the predicted numerical models was calibrated using experimental results of laboratory and field tests. The results show that it is possible to link the consolidation time of the foundation and PI by a linear relationship. Higher values of PI results in a longer consolidation time. This relationship is clearer when it comes to the foundation with a higher thickness of the treated soft ground. The results of this study, therefore, help technical workers to quickly give suitable predictions about the process of consolidation when applying the vacuum preloading method in soft soil treatment.

Keywords: Vacuum consolidation, Plastic index, Degree of consolidation, Soft soil, Coupled analysis

1. INTRODUCTION

As a developing country, the demand for infrastructure development on soft and compressible clayey soil in Vietnam increases significantly, especially in urban areas. Such critical geotechnical condition causes many challenges to the constructions of infrastructures. Preloading coupled with vertical drains has been a widely used method for soft ground improvement in engineering practice. The combination of vacuum preloading and vertical loading has been proved to be an efficient solution for the treatment of soft soil foundation [1]. The technique was originally suggested by Kjellman (1952) [2] in order to improve the soft foundation of the Philadelphia International airport. Since then it has become well known and broadly accepted for improving very soft soil deposits [3].

The effectiveness of the prefabricated vertical drains (PVD) combined with vacuum preloading has been discussed by many researchers. Compared to other ground improvement approaches for a large area, vacuum preloading is one of the most cost-effective methods in foundation engineering practice [4, 5]. According to Indraratna et al. (2005) [4], the behavior of soft clay foundations stabilized by vertical drains is now able to give results with satisfactory accuracy due to considerable progress that has been made in the past decade through numerical analysis. However, in order to increase the effectiveness of the method, it is important to note that more studies are required.

Plasticity index (PI) is a very basic parameter of soil which can be defined by simple laboratory tests. The value of PI plays a vital role in controlling the consolidation characteristics [6]. Therefore, in literature, several studies have been conducted to find the relationship between the index properties of soil and the consolidation process. In the study of Solanki and Desai (2008) [7], the coefficient of consolidation is well correlated with the liquid limit and plasticity index of soil. Sridharan and Nagaraj (2004) [6] established the relationship between the index properties and the coefficient of consolidation of the remolded soils. Ng et al. (2018) [8] used laboratory tests to find a clear relationship between consolidation characteristics and soil index properties.

Alptekin and Taga (2019) [9] also used results from laboratory tests to establish links between the compression and swelling index parameters and index test at Mersin District, Turkey.

In this study, the relationship between the plasticity index and the key parameters of the vacuum consolidation process including the consolidation time (t), degree of consolidation (U), and thickness of the soft soil foundation (H) when improving soft ground by vacuum consolidation method were addressed. For this purpose, the coupled analysis technique which combining SEEP/W [10] and SIGMA/W [11] modules in Geostudio software was utilized. The suitability of these numerical models was calibrated using experimental results of laboratory and field tests.

2. SITES FOR THE INVESTIGATION

In this study, three different types of soft soils in different project sites around Vietnam namely: Dinh Vu in Hai Phong City; Duyen Hai thermal power plant in Tra Vinh Province, and Nhon Trach thermal power plant in Dong Nai Province were considered. The soil in those sites is classified following the unified soil classification system (USCS). All the necessary parameters of the soft soils required for the consolidation modeling of the selected sites are determined by laboratory tests using ASTM. Their average values are presented in Tables from Table. 1 to Table. 3.

Table 1. Properties of soft soil in Dinh Vu – Hai Phong

Soil parameters	Unit	Soil layer
Unit weight	kN/m^3	17.000
Permeability	m/s	2.9×10^{-8}
Poisson’s ratio	-	0.260
Elastic modulus	kPa	0.310
Plasticity index	%	24.640
Soil type	-	SC-CH

Table 2. Properties of soft soil in Duyen Hai – Tra Vinh

Soil parameters	Unit	Soil layer
Unit weight	kN/m^3	16.40
Permeability	m/s	2.9×10^{-8}
Poisson’s ratio	-	0.27
Elastic modulus	kPa	3380.0
Plasticity index	%	18.40
Soil type	-	CH

3. BOUNDARY CONDITIONS

The study utilized the coupled analysis technique combining SEEP/W and SIGMA/W in Geostudio v2019 commercial program to model the vacuum preloading combined with vertical drains in soft ground treatment.

To establish relationships between key parameters of the vacuum consolidation process, boundary conditions that reflect the in situ were applied. To assess the influence of the treated soil depth, numerical models with five different scenarios for the soft soil thickness including 10 m; 15 m; 20 m; 25 m; and 30 m were considered for the simulation and analysis. The common vertical drain with a cross-section of 100 mm × 4 mm, a length equal to the depth of the soft soil layer (varying from 10 to 30 m as indicated) were installed in a triangular pattern at an effective spacing of 1.0 m.

The loading process was divided into two separate stages. In the first stage, a 0.5 m sand blanket (γ_{sand} = 16 kN/m^3) was placed on the ground surface to create the platform for installing the horizontal perforated pipes. At the same time, an average vacuum pressure of – 55.0 kPa was applied and kept constant for a period of 10 days. In the second stage (after 10 days), the surcharge represented by the sand layer was increased to 1.5 m and the vacuum pressure was also rose to 89 kPa.

Table 3. Properties of soft soil in Nhon Trach – Dong Nai

Soil parameters	Unit	Soil layer
Unit weight	kN/m	14.17
Permeability	m/s	2.94×10^{-8}
Poisson’s ratio	-	0.27
Elastic modulus	kPa	230
Plasticity index	%	33.8
Soil type	-	MH

4. RESULTS AND ANALYSIS

4.1 Relationship Between The Degree Of Consolidation, The Thickness Of The Soft Soil Layer And The Consolidation Time

The simulated degree of consolidation (U) of selected soft soil foundations corresponded to different thickness of the treated soft soil was presented in Table 4. As can be seen, for all types of studied soils, higher values of the soft soil thickness result in a longer time to reach a specific degree of consolidation. In addition, to reach the same degree of consolidation, soft soils with larger values of the plasticity index require more time. The corresponding relationship between the degree of consolidation and the time corresponding to various scenarios of the thickness of the foundation are illustrated in Figures 1-5.

Table 4. Degree of consolidation of selected soft soils

Site	PI (%)	Soft layer thickness (m)	Time to get % degree of consolidation (day)			
			80%	85%	90%	95%
Duyen Hai Tra Vinh	18,40	10	13,78	19,11	26,76	37,07
		15	18,40	25,86	35,52	47,29
		20	20,13	30,12	44,25	60,89
		25	23,33	36,20	52,78	77,72
		30	25,55	39,01	59,62	90,70
Dinh Vu Hai Phong	24,64	10	18,61	25,99	35,46	46,82
		15	23,69	32,71	44,38	58,46
		20	27,25	40,65	58,29	81,45
		25	28,14	43,75	65,59	93,73
		30	31,82	50,10	75,28	109,17
Nhon Trach Dong Nai	33,80	10	28,33	39,00	51,01	62,69
		15	36,06	47,35	60,77	77,99
		20	40,16	55,43	78,11	106,27
		25	46,18	65,25	90,39	128,32
		30	48,72	72,10	103,85	151,06

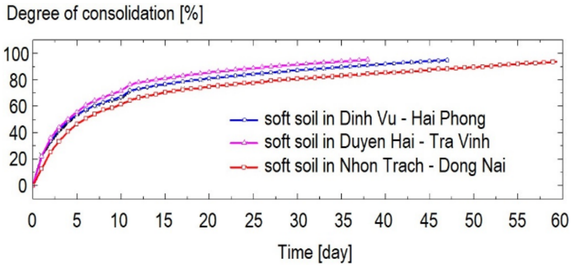

Fig. 1. Relationship between U and time when the soft soil layer is 10 m

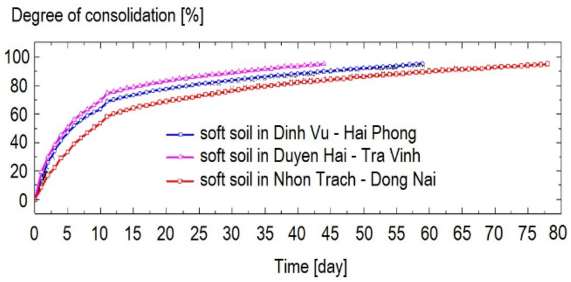

Fig. 2. Relationship between U and time when the soft soil layer is 15 m

4.2 Establish The Relationship Between The Plasticity Index And The Key Parameters Of The Vacuum Consolidation Process

The speed of the consolidation of the foundation depends considerably on its permeability and the thickness of the drainage path [12, 13, 14].

However, it is often more complicated to define the relationship between the degree and time of consolidation using traditional methods [15].

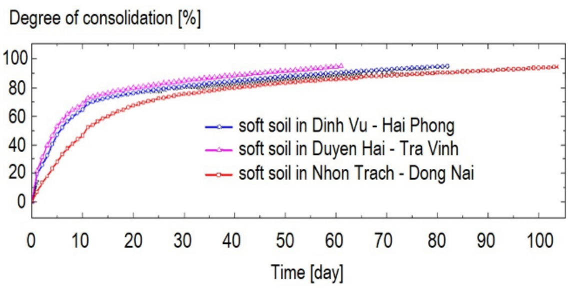

Fig. 3. Relationship between U and time when the soft soil layer is 20 m

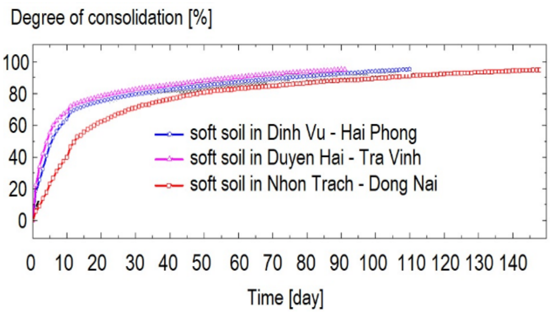

Fig. 4. Relationship between U and time when the soft soil layer is 25 m

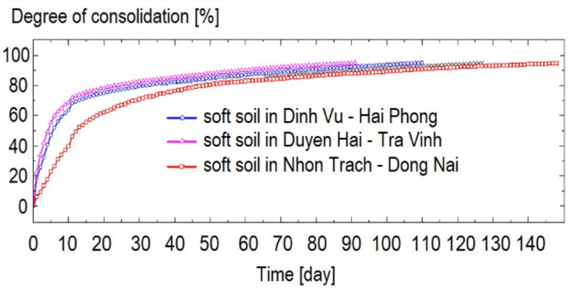

Fig. 5. Relationship between U and time when the soft soil layer is 30 m

Therefore, this study used the plasticity index, a common soil parameter that is simply defined using simple and cheap laboratory tests. To make it easy in making predictions of the change of parameters of the consolidation process when applying vacuum preloading method for soft soil treatment, the following cases were considered:

+ Case 1: To establish the above relationship when the thickness of the soft ground is defined to be from 10 m to 30 m. It is possible to consider the consolidation time (t) as a function of the plasticity index (PI), the degree of consolidation (U%) and the thickness of the treated soft foundation (H) which is a constant.

+ Case 2: To establish the above relationship when the degree of consolidation is defined. In this case, the consolidation time (t) is considered as a function of the plasticity index (PI), the thickness of the treated soft soil layer (H), and the degree of consolidation (U%) which is a constant in this case.

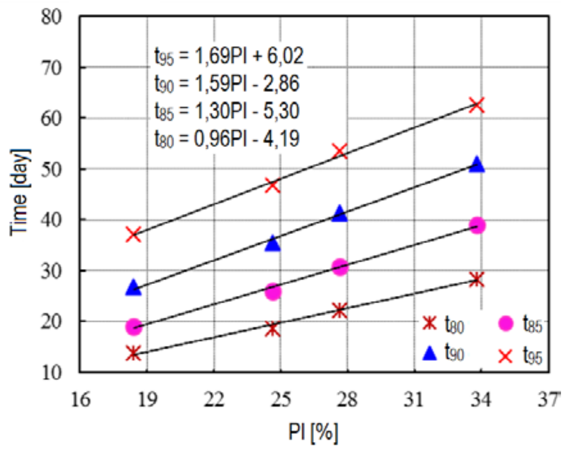

Fig. 6. Relationship between the consolidation time, PI, and U when the thickness of the soft ground foundation is 10 m.

For the first situation, using the plasticity index given in Table 1 combining with numerical predictions, the results in establishing relationships between parameters of the vacuum consolidation in soft ground treatment correspond to various ground thickness (H = 10 m to 30 m) are presented in Figures from Fig. 6 to Fig. 10.

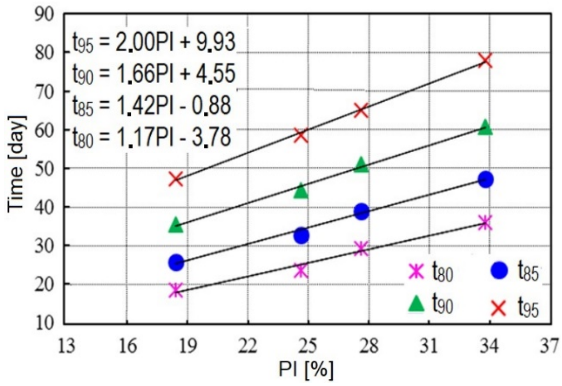

Fig. 7. Relationship between the consolidation time, PI, and U when the thickness of the soft ground foundation is 15 m.

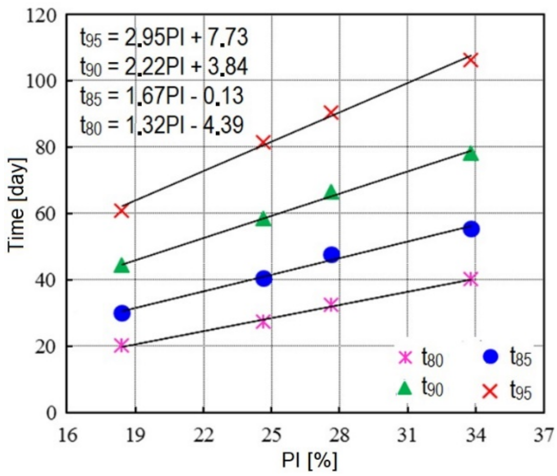

Fig. 8. Relationship between the consolidation time, PI, and U when the thickness of the soft ground foundation is 20 m.

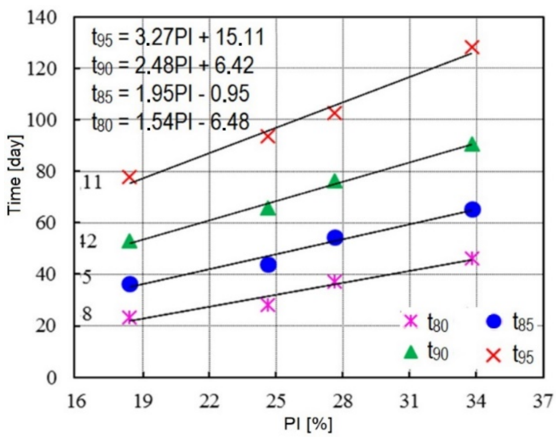

Fig. 9. Relationship between the consolidation time, PI, and U when the thickness of the soft ground foundation is 25 m.

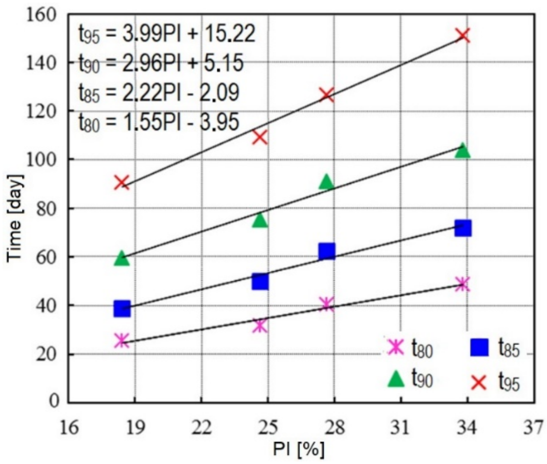

Fig. 10. Relationship between the consolidation time, PI, and U when the thickness of the soft ground foundation is 30 m.

For case 2, using the plasticity index presented in Table 1 combining with the predicted results by numerical models, it is possible to establish the relationships between key parameters of the vacuum consolidation in soft ground treatment correspond to various degree of consolidation values of U = 80%, 85%, 90%, 95%. The results are shown in Figures from Fig. 11 to Fig. 14.

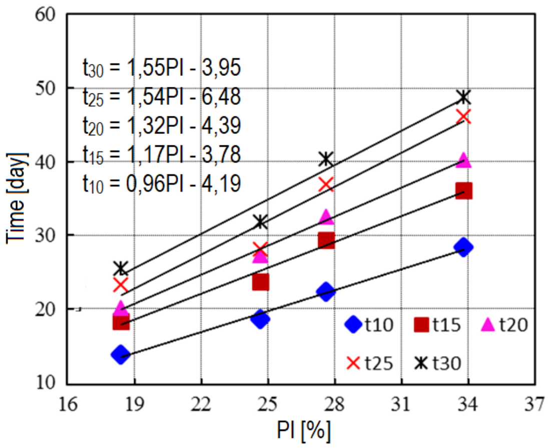

Fig. 11. Relationship between the consolidation time, PI and the thickness of the soft soil layer when U = 80%

Figures from Fig. 6 to Fig. 14 show the relationship between the time of consolidation, the plasticity index, the thickness of the treated soft soil layer, and the degree of consolidation of the three types of soft soils when improving by vacuum preloading method. These relationships are represented by equations denoting as t_{80}, t_{85}, t_{90}, and t_{95}. It should be noted that t_{80}, t_{85}, t_{90}, and t_{95} are the time (t) to get the corresponding degree of consolidation of 80%, 85%, 90%, 95%. On the other hand, t_{10}, t_{15}, t_{20}, t_{25}, and t_{30} are the consolidation time when the thickness of the soft ground varies from 10 m to 30 m. It can be seen that, for all cases, it is possible to link the consolidation time and the plasticity index by a linear relationship. Higher values of plasticity index result in a longer time of consolidation and the larger the thickness of the treated soft foundation, the clearer the above relationship.

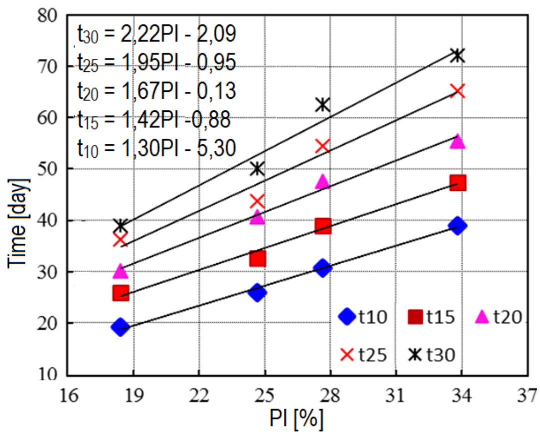

Fig. 12. Link between the consolidation time, PI and the thickness of the soft soil layer when U = 85%.

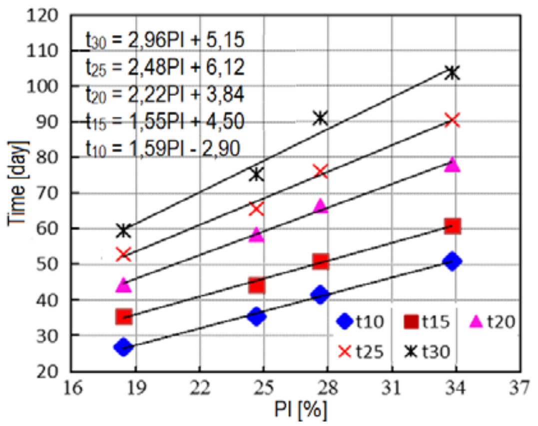

Fig. 13. Link between the consolidation time, PI and the thickness of the soft soil layer when U = 90%.

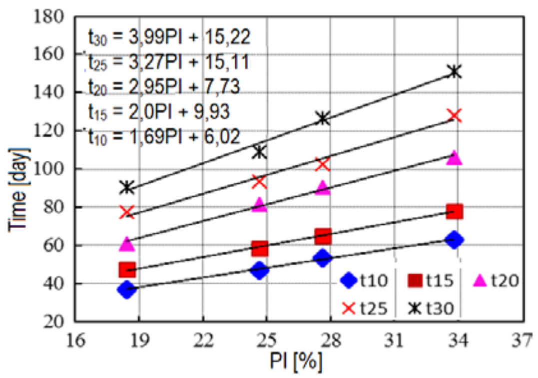

Fig. 14. Link between the consolidation time, PI and the thickness of the soft layer when U = 95%

5. CONCLUSION

From the achieved results when establishing the relationships between key parameters of the vacuum consolidation using numerical method, it can be concluded that the established equations of t_{80}, t_{85}, t_{90}, t_{95} and t_{10}, t_{15}, t_{20}, t_{25}, t_{30} show the relationship between the consolidation time, plasticity index, degree of consolidation and the thickness of the treated soft ground of different kinds of soft soils when the degree of consolidation and the thickness of the treated soft ground are defined. Based on equations defining t_{80}, t_{85}, t_{90}, t_{95} and t_{10}, t_{15}, t_{20}, t_{25}, t_{30}, it is possible to predict the consolidation time and the degree of consolidation for soft clays using the value of the plasticity index (PI) when improving the soft foundation applying vacuum consolidation method. Therefore, constructing such relationships may help engineers to have initial predictions about the consolidation processes in soft ground treatment applying vacuum consolidation.

6. RECOMMENDATIONS

This study only established relationships between mentioned parameters corresponding to various ground thickness (H = from 10 m to 30 m) and degree of consolidation U = 80% to 95%. In this case, the effective distance between drains is 1 m and the common dimensions of vertical drains are 4×100 mm. The surcharge value which has been commonly used for soft soil improvement in Vietnam was utilized. Therefore, for the future works, it is necessary to establish the relationship between the plasticity index and the key parameters of the vacuum consolidation process for more loading scenarios with a varying value of surcharge as well as the time to maintain it. Moreover, the effect of the effective distance between drains should also be considered.

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