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THE HYDROLYSIS CHARACTERISTICS AND COMPRESSIBILITY OF SOFT CLAY SOIL IMPROVED USING VCM

*Ratna Dewi[1], Anis Saggaff[2], Hanafiah[2], and Wiwik Rahayu[3]

[1]Ph.D Student, Civil Engineering Department, Faculty of Engineering, Universitas Sriwijaya, Indonesia;
[2]Civil Engineering Department, Faculty of Engineering, Universitas Sriwijaya, Indonesia;
[3]Civil Engineering Department, Faculty of Engineering, Universitas Indonesia, Depok, Indonesia

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ABSTRACT: Soft clay is identified to have some unfavorable characteristics when used as the foundation for construction work. This is due to the low bearing capacity and high compressibility which often leads to prolonged consolidation settlement. Therefore, soil improvement is necessary, and this can be achieved through the Vacuum Consolidation Method (VCM). This research focused on conducting laboratory-scale model tests to determine the characteristics of clay soil improved by vacuum consolidation in terms of its physical properties, hydrolysis, and compressibility. The results showed that the water content decreased as soil approached the Prefabricated Vertical Drain (PVD). A similar trend was also observed for the compression index value; this is because local density occurs in the soil near the PVD as a result of the movement of fine particles towards the PVD, which fills the empty pore space. Moreover, soil permeability in both vertical and horizontal directions reduced, and the soil became anisotropic after VCM improvement. The results of this research can be a consideration in the use of the VCM method for soft soil improvement, especially the problem of clogging zones that occur due to the suction pressure of the vacuum pump, which can reduce the performance of the VCM.

Keywords: Vacuum consolidation, Soft clay, Permeability, Compressibility

1. INTRODUCTION

The characteristics of soft clay are observed to be undesirable for construction. This can be associated with the low bearing capacity, high water content, and high compressibility. Therefore, there is a need for improvement before its application, specifically to avoid significant and prolonged settlement issues when constructing on top of soft clay soil.

The issue of settlement, in this case, consolidation, can be addressed by applying preloading to achieve minimal or no further settlement during construction. Therefore, it is necessary to implement efforts to improve soft clay soil. Several studies on soft clay soil improvement include utilizing timber as raft-pile foundation material [1], the use of the surcharge preloading method [2], and prefabricated vertical drain (PVD) to accelerate the consolidation of road embankment in the Mekong [3].

In addition to the above methods, one of the alternatives to improve soft clay soil is the Vacuum Consolidation Method (VCM), which was first introduced by Kjellman in 1952 [4]. The process focuses on distributing negative pore pressure (suction) along water channels and placing an impermeable air-tight sheet on the soil surface to accelerate consolidation, reduce lateral displacement, and increase effective stress [5, 6].

Previous studies were observed to have been widely conducted individually to determine the effectiveness of combining VCM with PVD [6 -11], as well as through the application of analytical and numerical approaches [12 - 16]. The focus is mostly on marine clay soil to achieve coastal reclamation. According to [17], the results of the numerical analysis showed that the behavior of soft clay soils improved by vacuum consolidation on circular embankments was able to give satisfactory results in the last decade. Therefore, there is a need for further research to determine the effectiveness of this method.

Based on research [18] using sand drain as vertical drain media by comparing soft soil properties after treatment with vacuum and preloaded surcharge showed consolidation properties are not much different and the shear strength of the soil after vacuum is higher than that of preloaded surcharge. Soil samples using vacuum generally show flocculated microstructure but with sample surcharge preloaded show dispersed structure.

Pham Quang Dong [19] discussed the relationship between the plasticity index and consolidation parameters from the vacuum process such as the total degree of consolidation of soil (Ut), time of consolidation (t), and thickness of the treated soft soil layer (H). The results showed that there is a linear relationship between consolidation time and plasticity index, the higher the IP the longer the soil to undergo the consolidation process.

Phan Huy Dong [20] also applied the model-scale tests to simulate the performance of soil preloading and vacuum consolidation on newly deposited dredged mud. The results showed that VCM combined with PVD experienced blockage problems in vertical drains on soils with high fine grain content. This can lead to a decrease in the efficiency of the drainage system and weaken the vacuum pressure in the soil.

In addition, Sun [21-22] used particle size distribution and changes in soil sample moisture content with Particle Image Velocimetry (PIV) technology to determine the thickness of the blockage zone against a single PVD model test. The formation of the blockage zone is the result of the accumulation of soil particles near the PVD with the gradual transfer of vacuum pressure from near the PVD to the farthest place during consolidation so that the influence of the location of one PVD with another on the displacement of soil particles will subsequently have an impact on the formation of the blockage zone.

Cai [11] used 2 PVDs to look at the behavior of the soil within the clogging zone; the results stated the transmitted vacuum pressures of the two PVDs offset each other in the horizontal direction, resulting in a thinner clogging zone, thus improving the pore water pressure dissipation efficiency. The study proved that PVD, individually and together with others, gives slightly different results.

Meanwhile, this study focused on modeling the application of vacuum consolidation on the Sumatra toll road on a laboratory scale. This study presents the effect of vacuum consolidation on clay soil improvement with an emphasis on physical properties, hydrolysis, and soil compressibility.

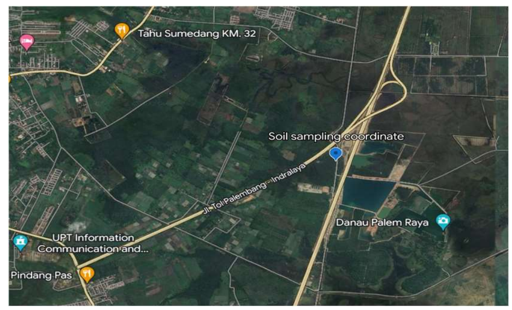
2. RESEARCH SIGNIFICANCE

After using vacuum consolidation with PVD to improve the condition of soft soil, in practice, problems often occur, especially the formation of blockage zones near the PVD

The method that has been used to resolve the problems that occur is using dredged slurry clay or Marine clay for coastal reclamation. Meanwhile, the soil characteristics in the toll road area in South Sumatra are soft clay. Based on the above, this research discusses the performance of vacuum consolidation after toll road construction. The vacuum consolidation performance studied is based on the parameters of soil physical properties, permeability in the vertical direction and horizontal direction of the soil, and consolidation parameters before and after the soil is treated so that the vacuum performance can be more accurately applied to soft clay.

3. MATERIALS AND METHOD

The samples of clay soil tested in both undisturbed and disturbed conditions were obtained from the vicinity of the Palembang-Indralaya Toll Road shoulder lane, KM18, Ogan Ilir Regency, South Sumatra, as presented in Fig. 1. Fig 1 (a) shows the coordinates of sampling in the field (latitude: -3.2089744, longitude: 104.6943809) and Fig. 1 (b) shows the sampling site condition in the field. The focus was on soil properties, permeability, and consolidation.



(a)

(b)

Fig. 1. Coordinates of Sampling in the Field (a), Undisturbed Sampling Site Condition (b)

Then the samples from the field were placed in a test vacuum consolidation modeling tank made of concrete with dimensions of 6 m x 1 M x 1 m and a PVD width of 2 cm. PVD was installed in a rectangular pattern with a spacing of 20 cm and integrated to a depth of 90 cm, as indicated in the model presented in Fig. 2. The geomembrane applied was produced using tarpaulin material with a 1 mm thickness.

Soil saturation was conducted after clay soil was introduced into the tank. The process continued with the assessment of the properties, hydrolysis characteristics, and compressibility of soil within the tank before the vacuum process was initiated. Soil permeability was assessed using the falling head test in vertical and horizontal directions, as indicated in Fig. 3

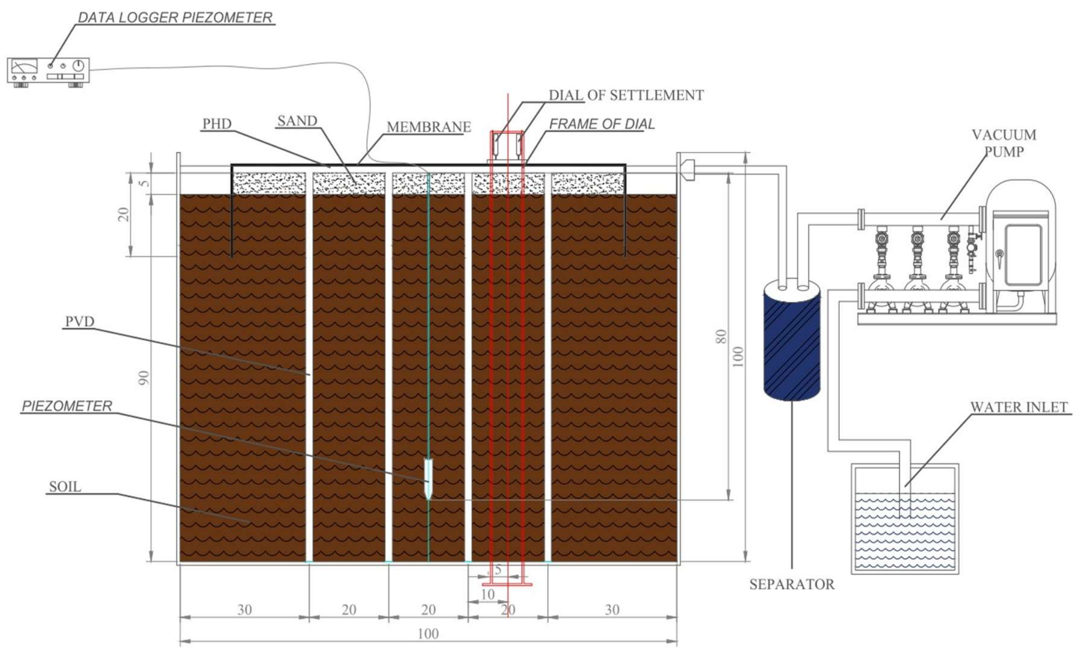


Fig. 2. VCM Modeling Illustration

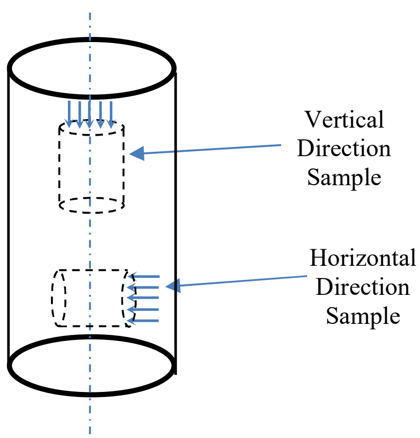


Fig. 3. Permeability Test for Soil Samples

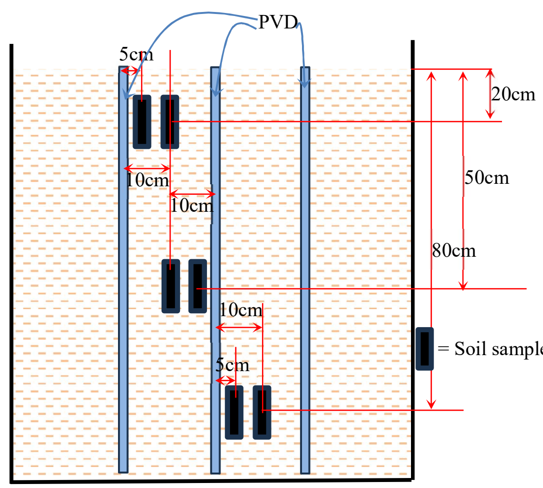


Fig 4. Illustration of Soil Sampling

The equipment used for monitoring includes piezometers installed at a depth of 80 cm, a piezometer data logger, a vacuum gauge, and a surface settlement dial gauge. The VCM was implemented up to the period a constant value was recorded for the piezometer/water pore readings and settlement.

The properties, permeability, and consolidation of clay soil were tested after the process using samples obtained from sites located 5 cm and 10 cm from PVD at different depths of 20 cm, 50 cm, and 80 cm. (Fig. 4).

4. RESULTS AND DISCUSSION

The characteristics of clay soil before it was improved through vacuum consolidation are described as follows.

3.1 Clay Soil Properties

Soil samples were tested to determine the physical characteristics before the vacuum process with a focus on the moisture content (ω), bulk density (γ), and specific gravity (GS). The Atterberg limit including the liquid, plastic limit, and plasticity index was also evaluated. Moreover, hydrometer and sieve analyses were conducted and the results are presented in the following Table 1.

The liquid limit value was observed to be higher than the moisture content. This led to the classification of soil as soft with the MH type (high plasticity silt clay).

Table 1. Clay Soil Properties

No.	Soil Properties	Value
1.	Specific Gravity (Gs)	2,512
2.	Water Content (ω)	58,644 %
3.	Unit Weight (γ)	1,707 gr/cm^3
4.	Plastic Limit (PL)	38,97 %
5.	Liquid Limit (LL)	61,10 %
6.	Plasticity Index (PI)	22,13 %
7.	Soil passing No. 40 sieve	96,115 %
8.	Soil passing No. 200 sieve	91,434%
9.	USCS Soil Classification	MH

3.2 Hydrolysis and Compressibility Properties of Soil

Permeability was tested in the vertical and horizontal directions using a falling head tool. The results presented in Table 2 showed that the value for the vertical direction (kv) was 3.857 x 10^{-6} cm/s while the horizontal direction (kh) had 3.730 x 10^{-6} cm/s. These values indicated a low permeability and isotopic nature of soil before vacuuming are isotropic. The trend was further confirmed by the soil permeability ratio (kh/kv) which was recorded to be 0.97 or close to 1.

Table 2. Hydraulic parameters and compressibility of soil before the vacuum process

No.	Parameter	Value
1.	Vertical Permeability (kv)	3.857 x 10^{-6} cm/sec
2.	Horizontal Permeability (kh)	3.730 x 10^{-6} cm/sec
3.	Compressibility index (Cc)	0.303
4.	Consolidation coefficient (Cv)	0.023 m^2/year
5.	Initial pore number (e_0)	1.245
6.	Pre-consolidation pressure (Pc)	0.057 kg/cm^2

Soil consolidation parameter was also assessed in the test basin before vacuuming. The compression index (Cc) was found in the e-logp graph to be 0.303, the coefficient of consolidation from the time root graph using the Taylor method was 0.023 m^2/year, and the initial void ratio was 1.245.

3.3 Monitoring Results during the Vacuum Test

The settlement was evaluated during the vacuum process based on the average watch reading as shown in Fig. 5.

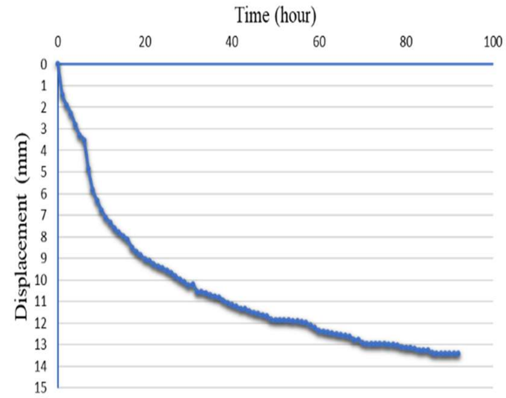


Fig. 5. Relationship graph of displacement or settlement (mm) with time (hours)

The value was observed to be close to constant at 13.41 mm. The final settlement was later determined using the Asaoka method [6] by evaluating the relationship between Sn and Sn-1 through a graph as indicated in Fig. 6.

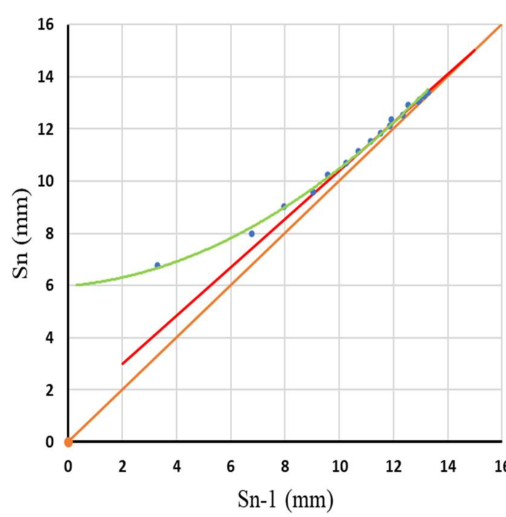


Fig. 6. Graph to determine the degree of consolidation using the Asaoka method

The Asaoka observation method is the most popular because apart from being able to predict the final settlement it can also enable consolidation parameters to be obtained. The steps taken are as follows:

1. From the time to decrease curve, select the decrease points S_1, S_2, ..., Sn, such that Sn is the magnitude of the settlement at time t_n and the time

interval is constant $\Delta t = t_n - t_{n-1}$;
2. plot the points (Sn, Sn-1);
3. These points will form a straight line.
4. The final decline is expressed by the intersection of the line with the diagonal line on the graph.
The graph shows that the estimated final settlement was 15 mm and this led to a total degree of consolidation, U, of 89%. The degree of consolidation is similar to the degree of consolidation that occurs in road embankment soil improvement in the Mekong Delta[3].

3.4 Soil Characteristics After Improvement

The characteristics of clay soil were measured after it had been improved to assess the effectiveness of the VCM.

3.4.1 Physical properties of soil

After the vacuum consolidation, variations in moisture content concerning distance from PVD and depth were observed. Soil samples were taken at different depths and distances. The variation of moisture content and percentage distribution of escapes along the depth at different distances from PVD (5 cm and 10 cm) and depth from the surface (z = 20 cm, z = 50 cm, and z = 80 cm) are presented in Table 3 below.

The moisture content value of clay soil was observed to have reduced from 58.644% to an average of 49.314% at a distance of 5 cm and 51.819% at 10 cm from PVD after vacuum consolidation. This reduction was because the water was drawn out from the soil due to the vacuum process. The phenomenon also increased the tendency of the moisture content in samples closer to PVD to decrease more significantly than those farther away. This phenomenon is also seen in the results of research [23] which states that the water content increases with increasing depth and radius distance from the vertical drains.

Table 3. Moisture content and pass percentage distribution of clay soil after treatment

Depth of sample (cm)	Distance of 5 cm from PVD (r = 5 cm)		
	Moisture Content (%)	Pass percentage No.40	Pass percentage No.200
Before	58.644	96.115	91.434
20 cm	48.624	97.320	93.090
50 cm	49.299	98.261	94.473
80 cm	50.020	98.531	94.966
	Distance of 10 cm from PVD (r = 10 cm)		
20 cm	51.279	96.264	89.340
50 cm	51.198	96.706	90.003
80 cm	52.981	95.809	90.308

The movement of fine soil particles towards PVD was evident in the increasing pass percentage on the No. 200 sieve at a distance of 5 cm and decreasing value at 10 cm after the vacuum process. The pass percentage on the No. 40 sieve also showed a slight increase at 5 cm and remained relatively consistent at 10 cm, as shown in Fig. 7.

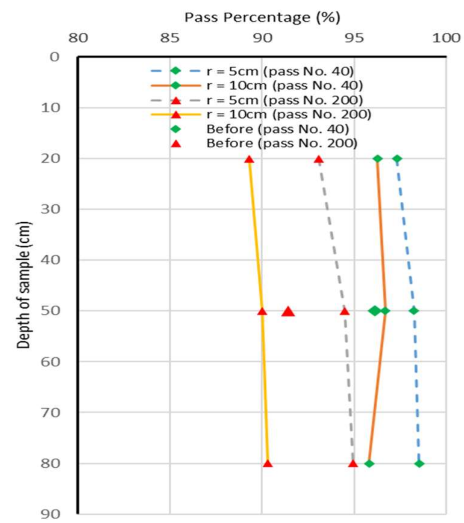


Fig. 7. Pass percentage on the No. 40 and 200 sieves for clay soil after the vacuum process.

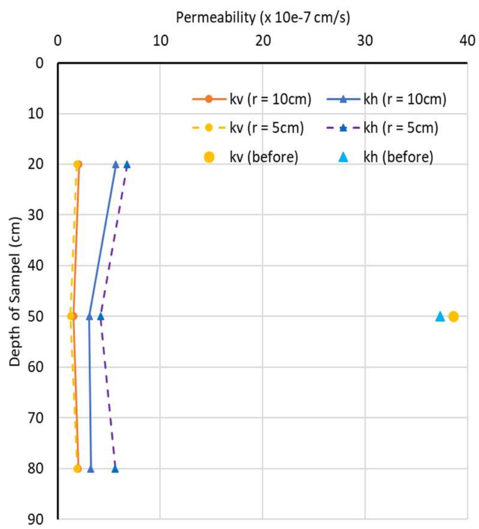
This indicated a post-vacuum change pattern of mode A where fine particles migrated through empty pores and accumulated near PVD as articulated by Bin-Hua Xu [23]. The phenomenon led to local density near PVD and a reduction in the moisture content as PVD proximity increased, resulting in the formation of a clogging zone. The thickness of the clogging zone can be determined by physical properties of soil, PVD parameters, and vacuum preloading test conditions [21].

3.4.2 Soil Permeability

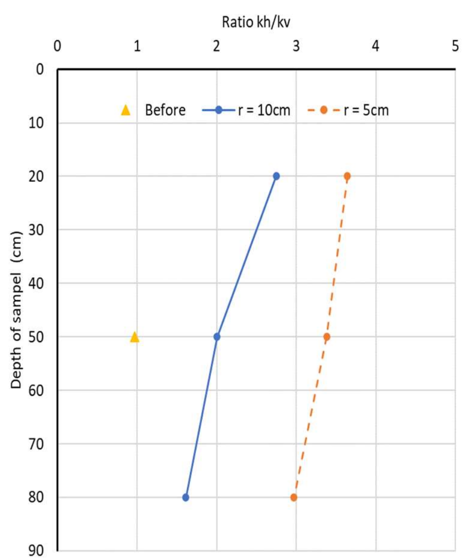
The permeability coefficient values of clay soil after the vacuum process are presented in Fig. 8. It was discovered that both vertical and horizontal permeability values reduced compared to soil conditions before the vacuum process, as indicated in Fig. 8(a).

The horizontal permeability value tended to be higher as soil samples became closer to PVD but the opposite trend was recorded for the vertical aspect. This was closely related to the changes in the particle size distribution with the pass percentage on the No. 200 sieve observed to be increasing as the samples approached PVD. Moreover, the depth of soil affected the horizontal permeability with the value discovered to be reduced as the depth from the surface increased.

Soil particles tended to migrate in the horizontal direction, and the reorientation of clay particles reduced the vertical permeability coefficient more than the horizontal. This also leads to soil permeability anisotropy or a kh/kv ratio of more than 1 in the clogging zone, as presented in Fig. 8(b).



(a)



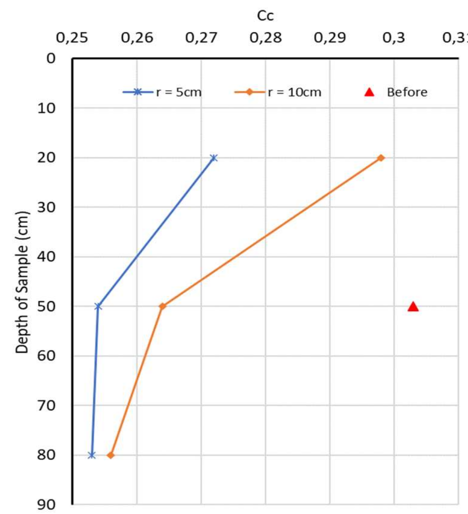
(b)

Fig. 8. Soil permeability values (a) and permeability ratio (b) after the vacuum process

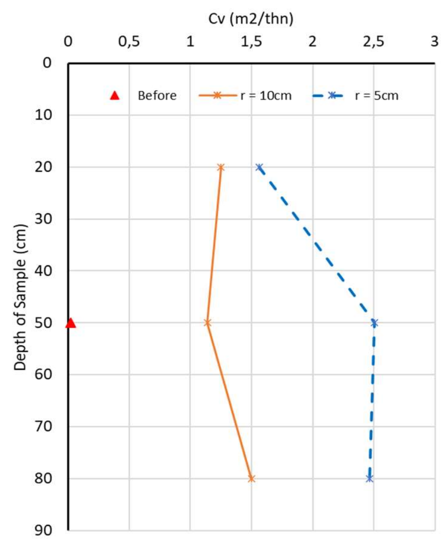
The phenomenon was similar to the results of [23] where soil was observed to have become anisotropic in the clogging zone or areas near PVD after the vacuum process. The kh/kv ratio to depth and distance of samples from PVD decreased when the samples were obtained from locations deeper from the soil surface and farther away from PVD.

3.4.3 Parameter of compressibility

Some changes were recorded in the consolidation parameter values, as shown in Fig. 9 with the compressibility index (Cc) recorded to be 0.303 before the vacuum process and the reduced further at 5 cm from PVD compared to 10 cm.



(a)



(b)

Fig. 9. (a) Cc and (b) Cv values of clay after treatment

Meanwhile, in terms of depth, the Cc tended to approach a similar value as observed in Fig. 9(a). The compressibility index was used to represent the volume change per unit load. A smaller Cc value was projected to have led to a decrease in the volume change. Consequently, it was inferred that the decreasing volume change was due to the effect of vacuum pressure, resulting in a reduction in the compressibility index.

The test conducted before the vacuum process showed that the consolidation time or coefficient of consolidation (Cv) was 0.023 m²/year but the value increased after the process as indicated in Fig. 9(b). Moreover, the value for samples at a distance of 5 cm from PVD was greater than those at 10 cm. This indicated that soil closer to PVD exhibited better water flow capabilities, leading to a faster consolidation process.

The phenomenon was also related to the horizontal soil permeability value, where soil near PVD had a higher kh value. Meanwhile, the Cv value tended to be larger as soil depth increased, this means that the consolidation time is getting longer.

5. CONCLUSION

In conclusion, the characteristics of clay soil improved through vacuum consolidation were examined in this research based on the physical, hydraulic, and compressibility properties. The results of the analyses conducted led to the following conclusions:

1. Due to the movement of fine particles towards the PVDs which fill the empty pore spaces, localized densification near the PVDs occurs.
2. Decreased soil permeability and localized densification near the PVD cause the formation of a clogging zone.
3. Soil particles tended to migrate in the horizontal direction, and the reorientation of clay particles reduced the vertical permeability coefficient more than the horizontal. This also leads to soil permeability anisotropy or a kh/kv ratio of more than 1 in the clogging zone.
4. The compressibility index value decreased as the soil became closer to PVD. This was related to the occurrence of local density near PVD due to the migration of fine particles.

6. ACKNOWLEDGMENTS

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