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Improvement of Ultra-Soft Soil Using Prefabricated Vertical Drain with Vacuum Preloading System: Laboratory Model Study

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ABSTRACT This study describes the use of Prefabricated Vertical Drains (PVDs) with vacuum preloading method to improve ultra-soft soil in a laboratory scale. A laboratory model was conducted in a vacuum chamber with dimensions of 1 m x 1 m x 1 m, with one PVD in the center connected to a vacuum pump. During the vacuum preloading test, three settlement markers, installed at varying distances from the PVD, were monitored for 60 days. In addition, two samples were taken (@15 and 45 cm from the PVD) before and after the treatment for laboratory testing.,. The settlement results show that the soil in the vicinity of PVD settles less than the soil located farther away from the PVD. The laboratory tests results show that the soil nearer to the PVD experienced larger changes compared to the soil located farther away from the PVD. The unit weight (γ) of sample taken 15 cm from the PVD increased by 16.47%, while the one taken 45 cm from PVD increased by 9.59%. Meanwhile, the water content (w) decreases by 92.81% and 34.47%, respectively. The results of the permeability test show a decrease of 97.05% and 85.77%, respectively. From the results, it can be concluded that the soil nearer to the PVD is denser than those located farther. This maybe counterintuitive considering the lower settlement observed nearer to the PVD. However, this can be explained by soil particles migrating towards the PVD during the slurry state, resulting in denser state nearer to the PVD.

KEYWORDS Vacuum Chamber; Prefabricated Vertical Drain; Ultra-Soft Soil; Vacuum Preloading; Soil Improvement

1 INTRODUCTION

Ultra-soft soil is a term used to describe soil with very low strength, usually in the form of mud or slurry. Unlike soft soils found on continental ground, dredged mud soils usually have very low strength, high water content and can flow easily, which can sometimes behave differently when compared to traditional category of soft soils. These special soils are referred to as "ultra-soft soils" (Bo, 2002; Chu et al., 2006; Sahdi et al., 2014). It has been stated that the settlement process of ultra-soft soil is different from that of soft clay. Settlement of ultra-soft soil occurs in two stages, i.e., sedimentation, which includes flocculation and settling stages, and then follow by consolidation stages. During the sedimentation process, it is postulated that there is zero effective stress in the slurry and the slurry behaves as a fluid (Xu et al., 2012). When soil particles come into contact with each other, soil structure is developed, and the slurry can be considered a soil and the effective stress becomes non-zero. On natural condition, self-weight consolidation takes place at the bottom of the settling Layer after the sedimentation process.

Tests involving use of vacuum preloading with PVD in laboratory scale have also been conducted in the past by several researchers using large diameter consolidation tank or Triaxial equipment (Chu et al., 2004; Ngo et al., 2020; 2021). To accelerate the transition of ultra-soft soils from the slurry phase to soil, PVD with vacuum preloading is applied, as demonstrated in the works of Liu et al. (2010), Tang et al. (2015), and Sun (2010). These studies show that vacuum preloading could change properties of slurry material into material with better mechanical properties. Some researchers also commented that the process of soil improvement of ultra-soft soil is more difficult and challenging than those traditional soft soils due to ultra-soft soil extremely low strength and bearing capacity (Bo, 2008; Chu et al., 2006; Bo et al., 1997, 1999, 2011). Despite all the challenges faced when using ultra-soft soils, there have been successful implementation of ultra-soft soils in reclamation projects, such as Kitakyushu Airport in 2003 and Changi East Reclamation in 2005.

Vacuum consolidation method has been widely used worldwide, including Indonesia. However, improving ultra-soft soils using this method is still uncommon, especially in Indonesia. This paper aims to study the properties of ultra-soft soil obtained from Jakarta Bay, before and after improvement by vacuum preloading. The test is conducted in laboratory scale to simulate the improvement of ultra-soft soil using prefabricated vertical drains with vacuum preloading.

2 METHODS

2.1 Laboratory Model Sample Preparation

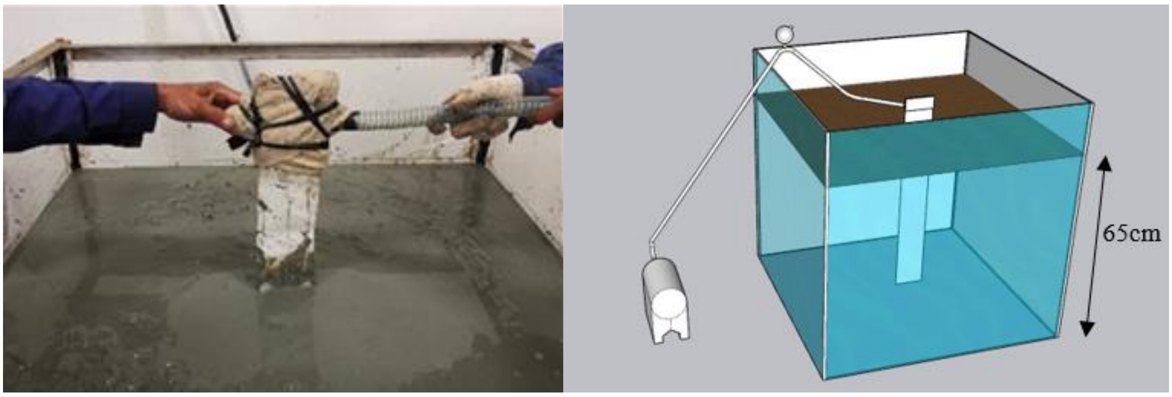
The sample used in this research was taken from Jakarta Bay, Indonesia. The sample was dredged from seabed using the hydraulic fill method. As a result of this reclamation technique, the sample was heavily disturbed. The slurry material was manually scooped and placed in a barrel for transportation (see Figure 1a). In the testing facility, a 1 x 1 x 1 m vacuum box made of acrylic glass panels was prepared beforehand. The glass panels were connected using plates and sealants to ensure an airtight seal. A prefabricated vertical drain (PVD), roughly 1 m in length, was hanged with a frame in the middle of the vacuum box (Figure 1b). The slurry was moved from the barrel to the vacuum box using a bucket. The process was continued until a 0.65 m thick slurry was formed in the vacuum box (Figure 1c).

(a) (b) (c)

Figure 1. Sample of ultra-soft soil: (a) container for transportation; (b) vacuum chamber with PVD hanged in the center; (c) Sample after being placed inside the vacuum chamber

The PVD was connected to a vacuum hose (Figure 2a). The other end of the vacuum hose was connected to a water pump (model GP-129-JPX) with a capacity of 35 liters/minute and a suction pressure limit of 70 kPa. The pump would later be used for the vacuum consolidation process. Figure 2b shows the schematic diagram of the test setup.

The PVD used had specification that conforms to the Indonesian Standard SNI 8460:2017. The detailed properties are shown in Table 1.



(a) (b)

Figure 2. Test preparation and setup: (a) connecting vacuum hose to the PVD; (b) schematic diagram of the test setup

Table 1. PVD specification

Parameter	Method ASTM	Unit	Value
Filter Tensile Strength	D 4595	kN/m	≥ 4
Filter Tensile Strength at 10% elongation	D 4595	kN/m	≥ 3
Apparent Opening Size	D 4751	µm	≤ 75
Permeability	D 4491	mm/s	≥ 0.005
Thickness	D 5199	mm	4±0.5
Width	D 5199	mm	100±2
Composite Tensile Strength at 10% elongation	D 4595	kN	≥ 1.5
Discharge Capacity	D 4716	cm3/s	≥ 70

2.2 Soil Laboratory Testing

In order to investigate the effectiveness of vacuum preloading in treating the dredged soil, a total of four samples were taken and tested, two samples before and two samples after the vacuum process. The samples were taken with Shelby tube at 15 and 45 cm away from the PVD. Figure 3 shows the insertion and extraction of the Shelby tube, while Figure 4 shows the position of the sample relative to the PVD position. One interesting observation during sampling was that the slurry was so weak that the Shelby tube would sink under its own weight.

The slurry was tested for its unit weight, water content and permeability. A summary of the tests conducted, and the referenced ASTM is given in Table 2. It should be noted that the soil/slurry sample is considered disturbed, considering the disturbance that the soil was subjected to during dredging, transporting, placement in model box, and sampling method.

(a) (b)

Figure 3. Photographs of soil sampling for laboratory tests: (a) insertion; (b) extraction

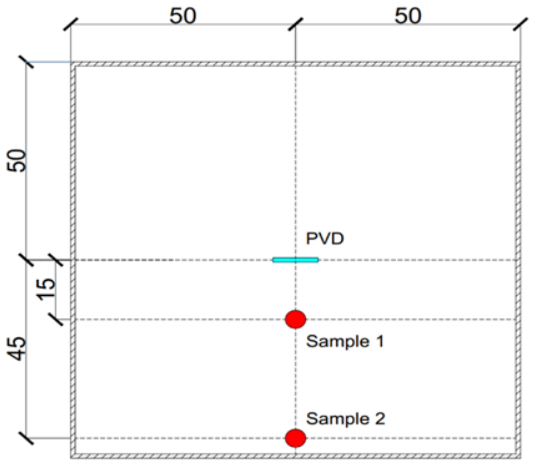


Figure 4. Plan view of soil sample location (dimensions are in cm)

Table 2. Summary of laboratory tests

Parameter test	Method ASTM
Unit Weight	D 7263
Water Content	D 2216
Permeability	D 2434

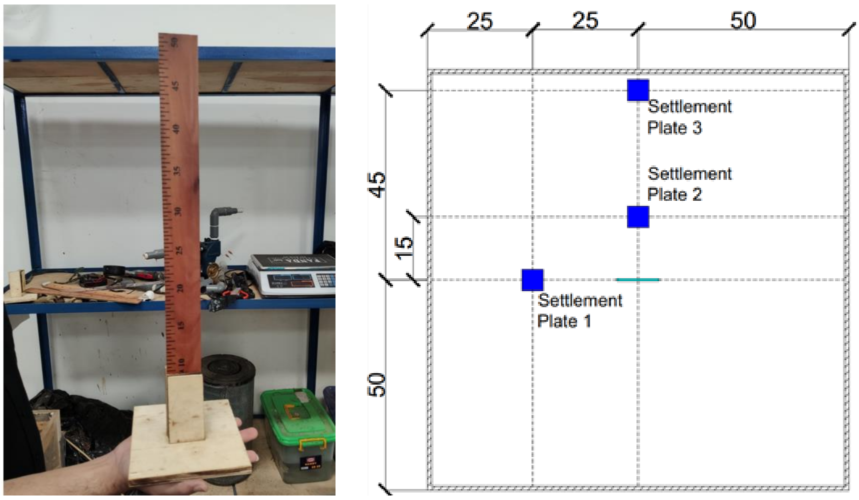
2.3 Sealing of Vacuum Chamber, Instrumentation and Test Procedures

After the test preparation and soil sampling were completed, the vacuum chamber was sealed, and instrumentation was installed. The beginning of sealing process started with placement of a layer of nonwoven geotextile with density of 200 gr/m² above the slurry. The protruding PVD above the slurry was folded and placed on the slurry, below the geotextile. Only the vacuum hose was allowed to pass through the geotextile (Figure 5a). Then a layer of geomembrane (elongation > 200%) was placed above the geotextile. Similar to the geotextile, the vacuum hose was allowed to pierce through the geomembrane (Figure 5b). The edge of geotextile and first layer of geomembrane was embedded inside the slurry for about 20 cm. Another layer of geomembrane is installed above the first layer and sealed along the glass panels with tape.

After the second layer of geomembrane had been placed on the slurry, three settlement markers, placed at a distance of 15 cm, 25 cm, and 45 cm from the PVD points, were installed. Figure 5a shows the photograph of the settlement markers. Each settlement marker was made of wooden ruler fixed to 10 x 10 cm wide board. Figure 6b shows the plan view of where the settlement markers were installed above geomembrane layer.

(a) (b) (c)

Figure 5. Sealing process of vacuum chamber: (a) placement of geotextile; (b) after first layer of geomembrane was installed; (c) final setup



(a) (b)

Figure 6. Settlement marker: (a) photograph of the instrument; (b) installed locations (dimension in cm)

Once the vacuum chamber is properly sealed, the vacuum process was initiated by turning on the water pump. The pump was continuously turned on for a duration of 60 days. During the vacuum process, in addition to the daily monitoring of settlement markers, the water pumped out from the water pump was also measured daily. The purpose of the water measurement was to calculate the overall settlement that occurred in the slurry. When the vacuum process had been completed, the geomembrane layers and geotextile layer were removed. Then, another 2 samples, at the same locations as before (Figure 4), were taken for laboratory testing.

3 RESULTS

Table 3 shows the summary of laboratory testing before and after improvement. The results indicates that the unit weight of slurry increases, while the water content and permeability of slurry decreases after improvement.

The results show that the soil improvement impact is more significant in the area around the PVD. The changes in soil properties are more pronounced in sample 1, located 15 cm from the PVD, compared to sample 2, located 45 cm away. The summary of property changes can be seen in Table 3.

Table 3. Slurry properties changes from before iand after improvement

Sample	Properties	Before	After	Change
1 (15 cm)	γ_{wet} (t/m3)	1.24	1.45	▲16.4%
	w (%)	194.4	101.6	▼47.7%
	k (cm/s)	4.78E-06	1.41E-07	▼97.0%
2 (45 cm)	γ_{wet} (t/m3)	1.23	1.34	▲9.5%
	w (%)	212.4	139.2	▼34.4%
	k (cm/s)	2.48E-06	3.53E-07	▼85.7%

During the vacuum preloading process, three settlement markers were placed above the geomembrane to monitor settlement of the slurry. The location of these markers can be seen in Figure 5, and the settlement at SP1, SP2, and SP3 varies between 17 cm to 25 cm.

In addition to daily recordings of settlement, water from the pump was also collected and weighed daily. Since the slurry material was fully saturated (S_r = 1) and the testing box was a controlled environment with no materials, fluids, or air capable of entering the system, the water volume coming out of the system should be equal to the total soil deformation. By dividing the water volume with the area of the box, the average settlement was determined.

During the first 7 days, the water discharge went from 33 l/day to 7 l/day. After that, the water discharge was relatively stable and slowly decreased from 5 l/day to 2 l/day. Figure 6 shows the water discharge during the vacuum preloading period.

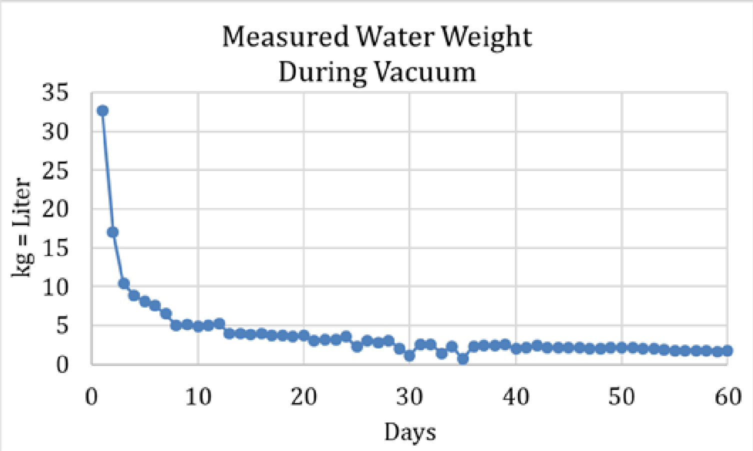


Figure 2. Measured water discharge during vacuum preloading

Figure 7 shows the vacuum pressure gauge during the vacuum preloading process and settlement marker monitoring. The red line indicates the average settlement of the slurry obtained from water weight calculation. The large difference in settlement between SP1, SP2, and SP3 is related to the final slurry contour shown in the next section. From the graph below, it can be seen that SP2, which is closest to the PVD, experiences less settlement than SP1 and SP3. The average settlement observed during the vacuum chamber test is 23.6 cm. The initial height of the sample before the vacuum process was 65 cm, thus indicating a slurry compression of 36.4% during the 60-day vacuum period. This observation will be explained in a latter section.

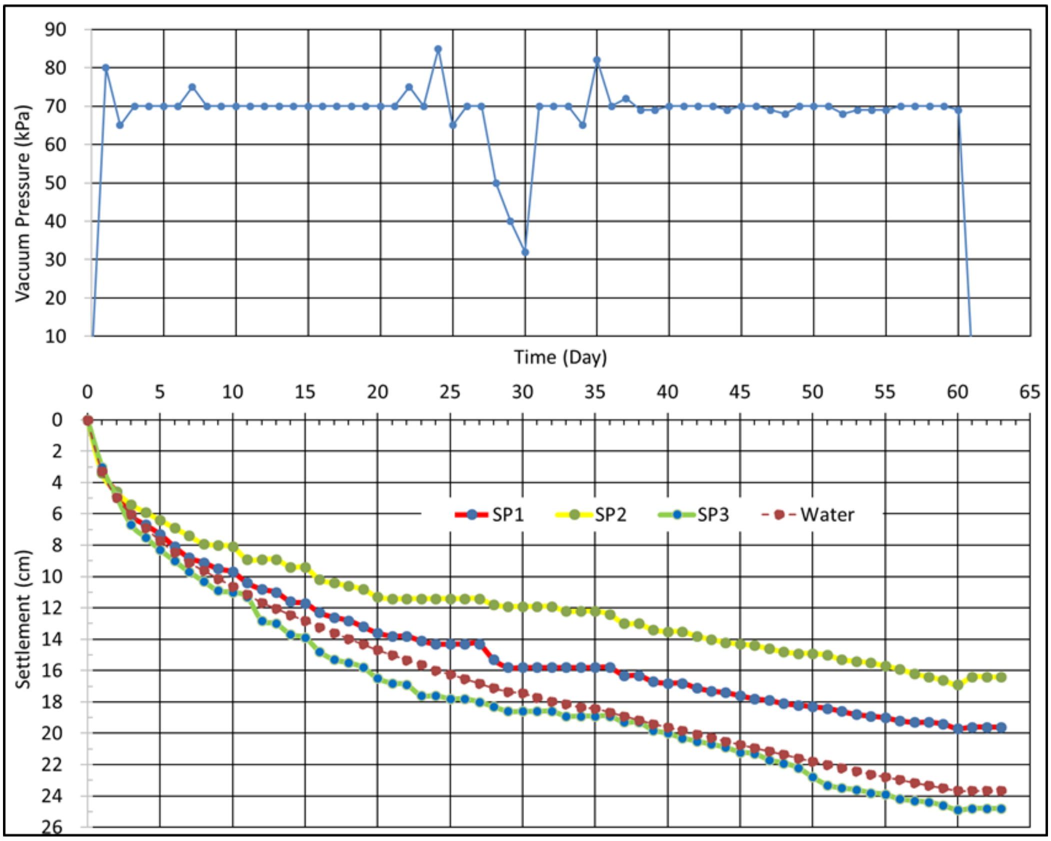


Figure 3. Monitoring data of vacuum pressure and settlement graph

Based on the average settlement rate, the degree of consolidation can be estimated using the Asaoka (1978) method. Figure 8 shows that at the end of the experiment, after 60 days of improvement, the average consolidation degree reaches ± 81%. Degree of consolidation method by Asaoka simply calculated from the rate of settlement, this method does not differentiate the slowing of settlement rate is due to elimination of pore water pressure or clogging around PVD filter due to fine slurry material.

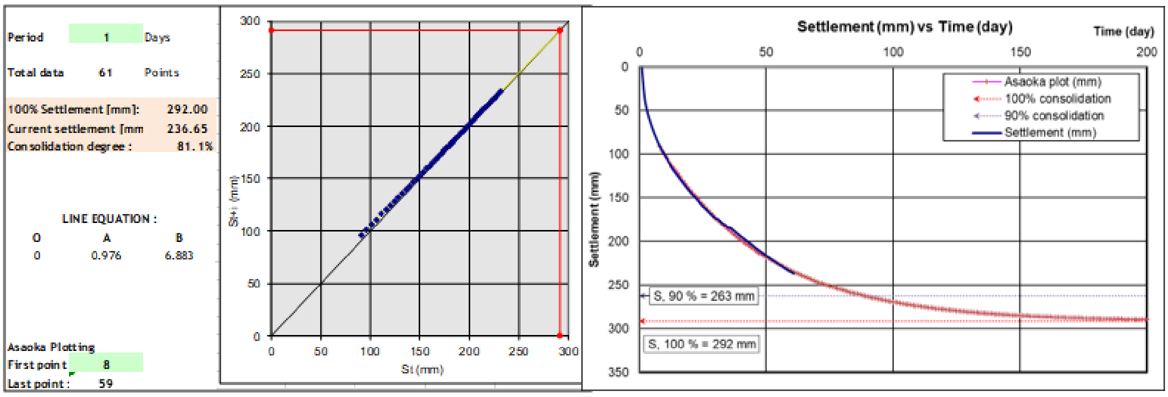


Figure 4. Estimate degree of consolidation with Asaoka method

Figure 9 illustrates the slurry contour after being subjected to vacuum conditions. To measure the slurry surface settlement, a ruler was used to record the measurements in a 10 cm x 10 cm grid from the top of the chamber. The color contour in Figure 9 represents the settlement, with blue indicating smaller settlement and red indicating larger settlement. The results suggest that the soil in the central part of the chamber (near PVD) has less settlement compared to the soil farther from the PVD. Upon physical inspection by pushing the slurry with thumb, it was found that the slurry in the central part (near PVD) was stiffer than the slurry in the farther part (away from PVD).

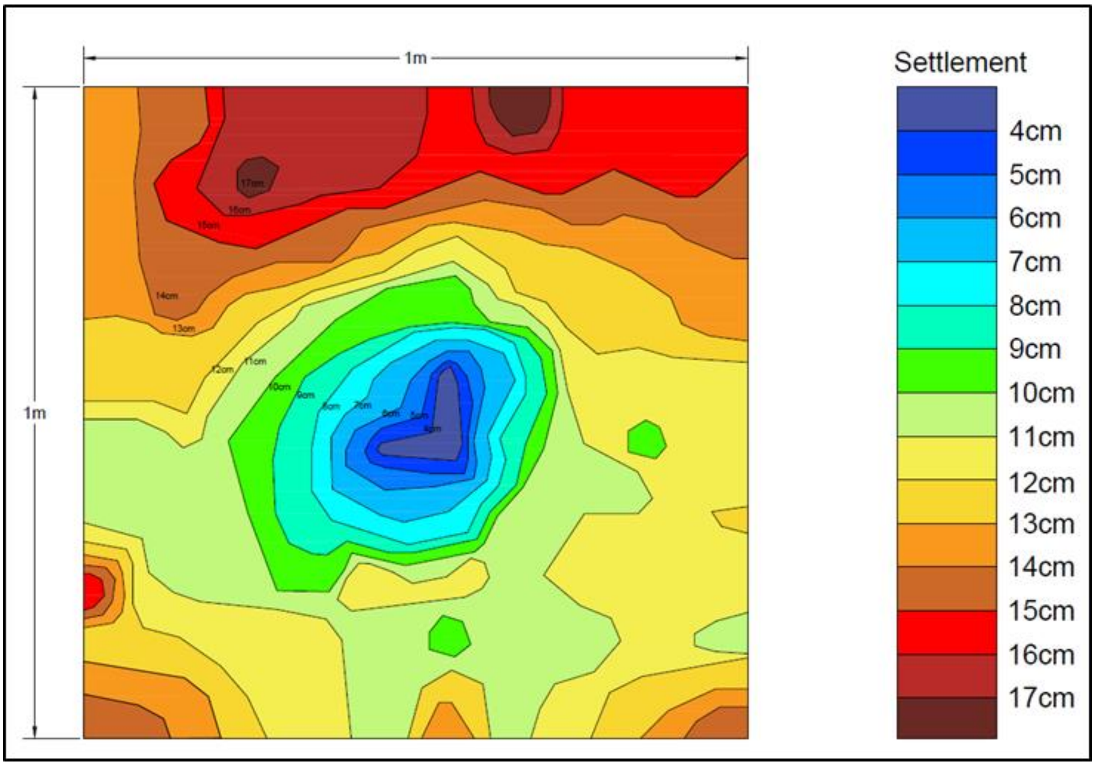


Figure 5. Settlement contour of slurry after vacuum preloading

4 DISCUSSION

The movement of soil particles from the farthest point of the PVD towards the PVD can be inferred from the observed settlement contour after the vacuum treatment. This indicates that during the slurry stage (colloid), the soil particles which are not yet in contact with each other, move closer to the PVD due to suction forces Consequently, the settlement around the PVD proximity is lower, and the soil in this region is physically stiffer compared to areas farther from the PVD. This observation is further proven by the laboratory results which show the sample taken 15 cm from the PVD is denser than the sample taken 45 cm from the PVD.

5 CONCLUSIONS

Based on laboratory studies, vacuum preloading of ultra-soft soil can alter some of the soil's properties from the slurry stage to the very soft soil stage. From finger identification test, soil still can be easily squeeze between fingers. This change in behavior occurs after two months of vacuum preloading. After the vacuum process, the overall soil unit weight increases by (9.5 - 16.4%), while the overall water content decreases by (34.4 - 47.7%). Additionally, the distance of soil from the PVD results in different values of property changes, with the soil nearest to the PVD experiencing larger changes compared to the soil farther from the PVD in terms of unit weight, water content, as well as permeability.

The final settlement contour shows that larger settlement occurs far from the PVD (15 – 17 cm), whereas smaller settlement occurs nearer to the PVD (only 4 – 6 cm). In this study, the changes in properties do not correlate with settlement, as the biggest changes in properties happened near the PVD, but the settlement near the PVD was the smallest. This behavior may be due to the slurry's behavior, where the soil particles are yet to have contact and are "floating" in water. During the vacuum process, the suction forces from the PVD not only suck the water and air but also the soil particles that are still "floating" through water. Therefore, the particles move towards the PVD area, making the soil near the PVD denser than the soil farther from the PVD.

DISCLAIMER

The authors declare no conflict of interest.

AVAILABILITY OF DATA AND MATERIALS

All data are available from the author.

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