A Pilot Test of Dehydration of Tiver dredged Mud using Vacuum Consolidation with Different Vertical Drains

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ABSTRACT

The combination of vacuum preloading and vertical drains provides an effective approach to the usage of dredged slurry for reclamation. However, the efficacy of this approach in improving soil quality is often impeded by clogging, a prevalent issue that frequently arises in the vicinity of Prefabricated Vertical Drains (PVD) during vacuum preloading. In addition to numerous efforts aimed at improving the performance of vacuum systems, this study conducts a pilot test to explore innovations in vertical drain types, including PVD, Filter Pipes (FP), and Sand Drains (SD). The monitoring data indicate that the use of SD is advantageous in mitigating the effects of clogging and enhancing the performance of vacuum consolidation techniques. Specifically, after 160 days of vacuum operation, the volumetric strains of dredged mud reached approximately 30.2%, 27.1%, and 23.1% for SD, FP, and PVD, respectively. The treated dredged mud exhibited disparate enhancements in physical properties and strength, reflecting the differential impacts of clogging phenomena among the cases of vertical drains.

Keywords-vacuum consolidation; land reclamation; dredged slurry; vertical drain; clogging effect

I. INTRODUCTION

In conjunction with the accelerated expansion of urban centers and population growth, the necessity for land is intensifying in Vietnam, particularly in coastal regions. Marine reclamation, which offers the benefits of low cost and high speed, has emerged as the most promising method for expanding the available space for living and development. The conventional material used for marine reclamation is dredged fill derived from the maintenance activities of harbor basins or sea channels. However, these dredged soils exhibit a high-water content, high compressibility, and low shear strength, which classifies them as ultra-soft soil. In the recycling process, it is essential to treat these dredged soils with stabilizing agents, such as cement, to achieve substantial strength. However, this often results in financial and environmental challenges [1, 2]. A substantial number of studies have been conducted to examine the potential of using sustainable materials derived from industrial processes as a means of reducing the reliance on cement as a construction material [3-6]. Over the past decade, the combination of vacuum preloading with vertical drains has been successfully employed as an effective and environmentally friendly technique for improving soft clay. This approach has been particularly effective in treating newly reclaimed mud [7–10]. However, the application of vacuum preloading to dredged fill foundations has been hindered by the occurrence of clogging, which has reduced the effectiveness of this conventional method. The occurrence of clogging results in a deterioration of the quality of the treatment and a near-total absence of soil consolidation outside the zone. A number of studies were carried out with the aim of improving the efficiency of the vacuum preloading method [7, 11–13]. Authors in [14] provided evidence that the multi-stage method is an effective approach for strengthening dredged fill foundations. Authors in [8] developed a novel approach to vacuum preloading with booster PVDs, with the objective of improving deep marine clay strata. Nevertheless, the practical implementation of these recently developed methods may be hindered by economic considerations. Similarly, authors in [15] examined the efficacy of various vertical drains, including PVD, FP, and SD, using a laboratory-scale model. Their findings revealed that the clogging effects of these drains differed, leading to varying degrees of improvement. Accordingly, this paper presents the procedure of dewatering by vacuum consolidation preloading method using a pilot test, with the objective of investigating the treatment effectiveness as well as the clogging effects of the aforementioned vertical drains in detail. A comprehensive monitoring program was implemented to assess the surface and layered settlement, as well as pore-water pressure, in order to evaluate the performance of the work. Furthermore, the soil properties were examined both before and after the vacuum loading to ascertain the efficacy of the treatment, in accordance with the preceding discussion to elucidate the observed clogging phenomena.

II. MATERIALS AND METHODOLOGY

A. Materials

1) Dredged Mud

The dredged mud used in this research was obtained directly from maintenance activities conducted on a canal in Vietnam. Eight samples were collected from various locations within the maintenance area and stored in containers for a period of two weeks, during which time they were permitted to settle naturally. Following the removal of surface water, the samples were subjected to an investigation of their basic properties. As shown in Figure 1, the clay content (particle size less than 0.005mm) was found to be approximately 18% to 20%, which was relatively lower in comparison to the sedimentary mud. As presented in Table I, the properties of the collected samples exhibited a relatively uniform distribution, with an average water content and wet density of approximately 209% and 1.18 g/cm³, respectively. The mean organic content was approximately 6.6%.

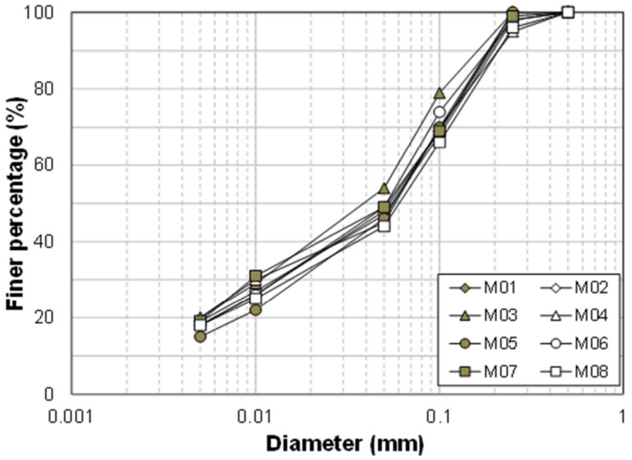

Fig. 1. Particle size distribution (PSD) of the collected samples.

TABLE I. PHYSICAL PROPERTIES OF DREDGED MUD

Sample	Wet density, γ_n (g/cm^3)	Water content, w_n (%)	Liquid limit, w_L (%)	Plastic limit, w_P (%)	Organic content (%)
M01	1.22	202.3	76.0	40.9	6.2
M02	1.17	217.0	67.4	47.2	6.6
M03	1.12	222.8	63.8	42.9	7.6
M04	1.20	200.8	70.9	40.0	6.4
M05	1.11	214.5	63.5	48.5	7.1
M06	1.14	217.8	65.1	45.9	4.6
M07	1.22	199.5	69.1	40.4	6.9
M08	1.23	195.9	69.4	41.9	7.5
Average	1.18	208.8	68.2	43.5	6.6

2) Vertical Drains

In accordance with the research findings presented by authors in [15], this investigation incorporates three distinct categories of vertical drains: PVD, FP, and SD, as shown in Figure 2. The PVD used in this study had a width of 95 mm and a thickness of 4 mm, with an equivalent diameter of 63 mm. The FP was composed of a flexible perforated PE pile encased in a layer of filter geotextile, while the base of the FP was covered with non-woven geotextile to prevent the ingress of mud. The diameter of the outer surface was approximately 63 mm. The SD, composed of medium sand, was introduced into the mud using a PVC casing with an outer diameter of approximately 63 mm. Table II presents a summary of the principal parameters of the vertical drains.

PVD FP Casing for installation of SD

Fig. 2. The vertical drains for the test.

TABLE II. PARAMETERS OF USING VERTICAL DRAINS

Item		Parameter	Unit	Value
SD	Medium sand	Outer diameter	mm	63
		Particle finer than 0.14 mm	%	≤ 10
	Casing	Particle greater than 0.5 mm	%	≥ 50
		Permeability	m/s	≥ 1×10^{-4}
FP	Pipe	Outer diameter	mm	63
		Inner diameter	mm	50
		Perforated diameter	mm	3.0
	Filter	Effective aperture size	mm	0.075
		Permeability	m/s	2.5×10^{-4}
PVD	Composite	Width	mm	95
		Thickness	mm	4
		Equivalent diameter	mm	63
		Tensile strength	kN	2.0
		Longitudinal flow conductivity at pressure of 350 kPa	10^{-6} m^3/s	60
	Filter	Tear strength	N	100
		Effective aperture size	mm	0.075
		Permeability	m/s	1.5×10^{-4}

B. Performance of Consolidation Test

1) Preparation of Dredged Mud Pond

A pond with dimensions of 6 meters in width, 21 meters in length, and 5 meters in depth (h_0) was excavated on natural ground in close proximity to the dredging area, as shown in Figure 3. To prevent the mud from overflowing outside the pond, a small embankment was constructed surrounding it. It is noteworthy that the natural soil stratum situated beneath and in the vicinity of the pond was identified as a clay layer, which could be regarded as a low-permeability layer. Prior to its deposition in the pond, the mud was subjected to filtration through a mesh with a diameter of 3 cm, with the objective of removing any sharp objects and ensuring uniformity. Following a period of approximately one month in storage within the pond, the remaining free water on the surface of the mud was extracted. It was determined that the dredged mud retained a liquefied state. A comparison of the condition of the mud with that of the original sample, as detailed in Table I, revealed only minor variations.

Fig. 3. Preparation of mud pond.

2) *Installation of Vertical and Horizontal Drains, and Monitoring Instruments*

The pond was subdivided into three distinct sub-zones, each equipped with a unique vertical drain. Prior to the installation of the vertical drains, the thickness of the dredged mud (subsequent to the removal of free water) was established at approximately 5.0 meters. The vertical drains were then installed into the dredged mud at a spacing of 0.9 m in a square pattern, as shown in Figure 4. The PVD was then inserted into the mud layer by means of attachment to a rigid rod, which served as a proxy for the mandrel used in the large-scale construction machine. The FP was inserted directly into the mud layer. Meanwhile, the SD was constructed by driving the casing pipe down to the full depth of the mud layer. Thereafter, the medium sand was filled in layers into the pipe, and the pipe was gently tapped while being withdrawn to ensure that the sand remained entirely within the mud. It is noteworthy that prior to insertion, the end of the casing pipe was sealed with a cap that could be readily opened once the casing pipe was extracted. Once the vertical drains were installed, they were connected to the horizontal drainage system, which consisted of perforated pipes wrapped in non-woven geotextile. Subsequently, a layer of geotextile was installed above the horizontal drainage system to provide protection for the geomembrane. A single layer of geomembrane was applied to the top surface and sealed within the mud layer to maintain an airtight condition, while the horizontal drainage system was connected to a vacuum pump with a power output of 7.5 kW, which was capable of generating a maximum vacuum pressure of 95 kPa. Figure 4 shows the configuration of monitoring instruments in the mud pond. Seven Vacuum Gauges (VG) were installed at various points at a depth of 0.2 meters to monitor the vacuum pressure at the surface during vacuum loading. Additionally, three other VG were placed at a depth of 4.5 meters to assess the vacuum pressure at that level. To quantify the surface settlement during the vacuum loading process, nine Surface Settlement Plates (SS) were installed at various locations. A single group of Piezometers (PZ) and Extensometers (EX) was installed at the center of each sub-zone. Pore-water pressure and layered settlement were measured at depths of 1 m and 4.5 m.

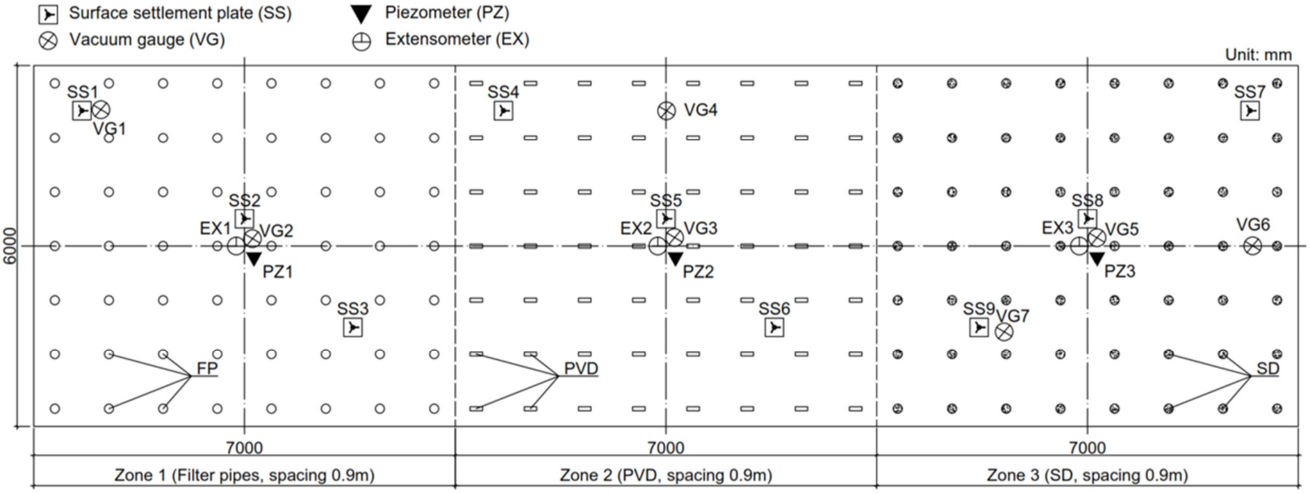

Fig. 4. Layout of vertical drains and monitoring instruments.

III. TEST RESULTS AND ANALYSIS

A. *Vacuum Pressure*

Following a 10-day vacuum loading period, the vacuum pressure at a depth of 0.2 m reached a stable value of over 60 kPa in all cases. Figure 5 presents the average vacuum pressure development at a depth of 0.2 m. The increase rate of the vacuum pressure was also similarly recorded across these samples, indicating that the vacuum pressure was evenly distributed across the entire pond area. However, the data indicated that the vacuum pressure at a depth of 4.5 meters exhibited a slower rate of increase than that observed at the surface. On the final day of vacuum operation, the vacuum pressure measured by VG at a depth of 4.5 meters was still less than that at a depth of 0.2 meters. As observed by authors in [15] the accumulation of silt around vertical drains impeded the further development of vacuum pressure. Additionally, the rate of increase in vacuum pressure at a depth of 4.5m differed depending on the type of vertical drain in question. The greatest increase in vacuum pressure was observed with the use of SD, while the least increase was observed with the use of PVD. Figure 5 also shows that for the SD and PVD cases, the vacuum pressure readings at 4.5 m tend to approach those at the 0.2 m depth. In contrast, the vacuum pressure measured at 4.5 m for the PVD case remained relatively stable at approximately 50 kPa. These findings indicate that SD exhibited superior vacuum transmission characteristics compared to FP and PVD. Therefore, it can be concluded that SD may offer the most optimal improvement outcomes among the three types of vertical drains.

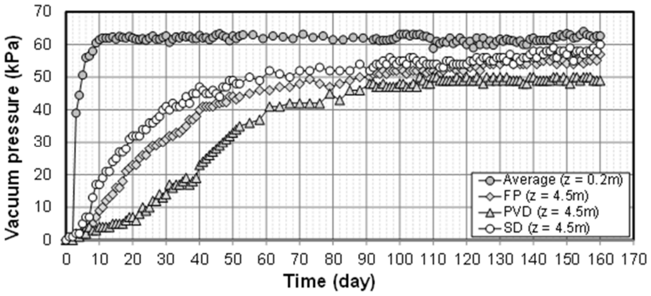

Fig. 5. Vacuum pressure during the test

Figure 6 shows the decline in pore-water pressure during the vacuum preloading process. During the initial five days of vacuum preloading, the reduction rate in pore-water pressure exhibited minimal variation regardless of the depth of PZ. However, it was observed that the reduction in pore-water pressure decreased with increasing depth for longer periods of vacuum preloading. At a depth of 1.0 m, the reduction rate of pore-water pressure exhibited minimal variation among the cases of vertical drains. The pore-water pressure was observed to decrease rapidly during the initial 20 days of vacuum preloading. Following a 40-day vacuum preloading period, the pore-water pressure was observed to be almost stable and maintained until the completion of the test for all cases of vertical drains. With regard to the depth of the PZs, a reduction in the rate of pore-water pressure was more evident at 4.5 m than at 1.0 m. While the pore-water pressure at a depth of 1.0 m reached a stable value by the 20th day, the pore-water pressure at a depth of 4.5 m required a longer period of time to do so. In the cases of FP and SD, the measured pore-water pressure exhibited a continued decrease at the conclusion of the test, although the rate of decrease was relatively modest. In the case of PVD, the measured pore-water pressure reached a stable value after approximately 90 days of vacuum preloading. As presented in Figure 6, the reduction in pore-water pressure at a depth of 1.0 m is less pronounced than that at a depth of 4.5 m, particularly in the case of PVD. This suggests that the vacuum pressure was unable to be fully transmitted to the bottom of the mud due to clogging, as previously discussed. Figure 6 also shows that the reductions in pore-water pressure were not uniform across the various vertical drains. Although there was some variation, the reductions in pore-water pressure in cases of FP and SD were comparable. At a depth of 1.0 m, the pore-water pressure generated by FP and SD reached a stable value by the 40th day, equaling the vacuum pressure of 60 kPa by the end of the test. In the case of PVD, a smaller reduction in excess pore-water pressure was obtained. At the conclusion of the testing period, the measured pore-water pressure generated by the PVD was approximately -41 kPa.

At a depth of 4.5 m, the variations in the reduction of pore-water pressure were more evident among the cases of vertical drain. The most rapid reduction rate was observed in the SD case, while the smallest reduction rate was generated by the PVD case. In the cases of FP and SD, the pore-water pressure reached values of -11 kPa and -8 kPa, respectively, after approximately 130 days of vacuum preloading. It then continued to decrease until the end of the test, though the decrease rate was quite small. In the case of PVD, the pore-water pressure reached a stable value of -4 kPa after 90 days of vacuum preloading. The reduction of pore-water pressure observed during the test indicates that, in the case of very high-water content mud, the use of SD as a vertical drain appears to be the most effective method for transmitting vacuum pressure. This phenomenon may be attributed to the differing degrees of clogging observed for each type of vertical drain.

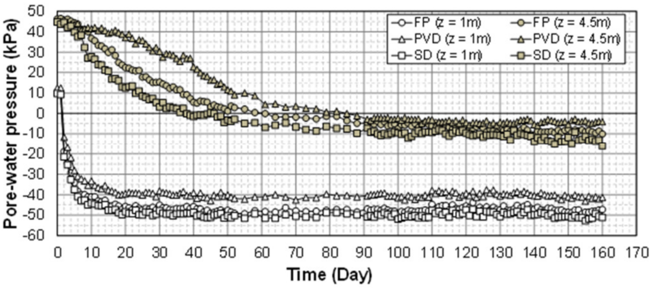

Fig. 6. Excess pore-water pressure during vacuum preloading.

B. Settlement and Consolidation Degree

Figure 7 presents the surface settlements observed during the vacuum loading process, as recorded by the installed SS. It is evident that, despite the consistent application of vacuum pressure across all vertical drain types, the use of PVD as the vertical drain resulted in the smallest settlement values, while the use of SD as the vertical drain resulted in the largest settlement values. In the case of PVD, following a period of 155 days of vacuum preloading, the settlement rate reached a stable equilibrium at a rate of less than 2 mm per day. The mean settlement after 160 days of vacuum loading using PVD was 904 mm. However, on the final day of testing, the average settlements in cases of FD and SD were approximately 1,092 mm and 1,240 mm, respectively. In both instances where FP and SD were utilized, the average settlement rate recorded over the final five-day period was approximately 2.5 mm per day. This indicates that the settlement process in instances where PVD was employed was nearly complete, whereas the settlement process in instances where FP and SD were used may continue for several more days. Furthermore, it was determined that the rate of settlement remained consistent regardless of the type of vertical drain installed during the initial 20-day period. Subsequently, significant discrepancies in the settlement rate were apparent among the PVD, FP, and SD cases. In comparison to the settlement rate observed in the SD case, the development rate in the PVD and FP cases exhibited a decline from the 20th and 35th days, respectively. In the cases of PVD and FP, the settlement rate declined to less than 5 mm per day from approximately the 105th day and the 112th day, respectively. In the case of SD, the settlement development rate was less than 5mm per day from the 125th day onwards. This finding was consistent with the development of vacuum pressure and reductions in pore-water pressure with depth, as shown in Figures 5 and 6. This result further substantiates the superiority of SD over PVD and FP.

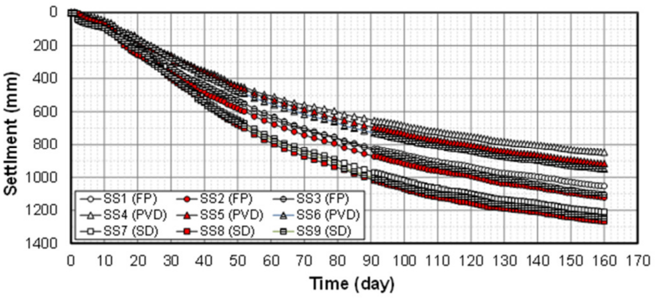

Fig. 7. Settlement of dredged slurry during vacuum preloading.

Figure 8 shows the layered settlement observed during the course of the test. The formation of layered settlement occurred in a manner that was consistent with the development of surface settlement, vacuum pressure, and a reduction in pore-water pressure. The development of layered settlement also reflected the advantages of using SD compared to FP and PVD, with the use of SD resulting in the greatest layered settlement. At a depth of 4.5 meters, the settlement exhibited a notable increase in the SD case. As previously observed and explained by authors in [15], the distribution of vacuum pressure and settlement among cases of vertical drains is influenced by the phenomenon of clogging. The influence of vacuum pressure resulted in the formation of a layer of fine particles on the surface of PVD, which impeded the transmission of vacuum pressure. However, in cases involving FP and SD, the layers of fine particles were observed to be of a greater thickness than that observed in the case of PVD. Therefore, the transmission of vacuum pressure in these cases is prolonged, resulting in elevated vacuum pressure and enhanced consolidation.

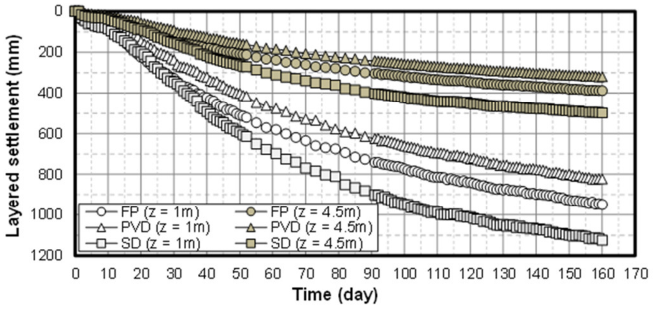

Fig. 8. Layer settlement during vacuum preloading.

TABLE III. ESTIMATION OF FINAL SETTLEMENTS AND DEGREE OF CONSOLIDATION (DOC) BY ASAOKA'S METHOD

Surface settlement plate	**Final consolidation settlement, S_∞ (mm)**	**Last measured settlement, S_t (mm)**	**DOC (%)**	**Final volumetric strain, S_∞ / h_0 (%)**
FP				
SS1	1,248	1,052	84.3	25.0
SS2	1,376	1,122	81.5	27.5
SS3	1,446	1,103	76.3	28.9
Average	1,356.7	1,092.3	80.7	27.1
PVD				
SS4	1,066	846	79.4	21.3
SS5	1,187	916	77.1	23.7
SS6	1,209	949	78.5	24.2
Average	1,154.0	903.7	78.3	23.1
SD				
SS7	1,465	1,209	82.5	29.3
SS8	1,531	1,265	82.6	30.6
SS9	1,533	1,246	81.3	30.7
Average	1,509.7	1,240.0	82.1	30.2

The volume reduction of the liquid mud was examined, based on the settlement data and according to the previous methodology. Figure 9 shows the estimated volumetric strain of the mud during vacuum loading. Upon completion of the vacuum loading process, the average volumetric strain was observed to be 18.1%, 21.9%, and 24.8% for PVD, FP, and SD, respectively. These values were found to exceed those reported by authors in [15]. This phenomenon may be caused by the clogging of the system due to the organic content and Particle Size Distribution (PSD) of the dredged mud. As documented by authors in [15], the mud was dredged from urban lakes with an organic content of approximately 20%. In contrast, the mud collected from the canal in the present study exhibited an average organic content of 6.6%. The PSD of the mud used in this study was also slightly larger and more uniform than that reported in [15]. To assess the efficacy of the treatment across different vertical drains, the consolidation degree of the mud following vacuum preloading was evaluated. In this study, the common approach developed by Asaoka [16] was employed to estimate final consolidation settlement. The vacuum pressure at a depth of 0.2 m reached a stable state on the 10th day in all cases of vertical drain. Accordingly, the settlement data used in the Asaoka analysis were extracted from the 10th day until the point of vacuum unloading. Given that the monitoring was conducted on a 24-hour basis, the time interval of one day was deemed appropriate for the Asaoka analysis. Table III provides a summary of the final consolidation settlements and the degree of consolidation (DOC) as determined from the monitoring data across all zones. Further details regarding the analysis are presented in Figures 10–12.

Asaoka's analysis revealed that at the time of vacuum unloading, the average estimated DOC was comparable across cases involving vertical drain. However, the discrepancies in measured settlement and estimated final settlement among cases were considerable. Furthermore, the ultimate volumetric strain in the PVD case was the smallest, while in the SD case, it was the largest. This indicated that the effectiveness of the vertical drain type should be evaluated in terms of volumetric strain. As previously stated, the volumetric strain of the mud was proportional to the settlement. Therefore, the effectiveness of the vertical drain types was examined based on the normalized consolidation degree, which was identified as the ratio between the measured settlement and the estimated final settlement of the SD case.

Figure 13 presents a comparison of the mean normalized consolidation degree for the various vertical drains. The results demonstrate that the vertical drain of SD exhibited the most effective treatment outcomes. Following vacuum unloading, the normalized consolidation degree for the SD was approximately 82.1%. In the cases of FP and PVD, the normalized consolidation degree was found to be approximately 72.4% and 59.9%, respectively, in comparison to the use of SD. Given that the tests were conducted under identical conditions, it can be posited that the discrepancy in treatment effects can be attributed to the varying degrees of clogging observed in each type of vertical drain.

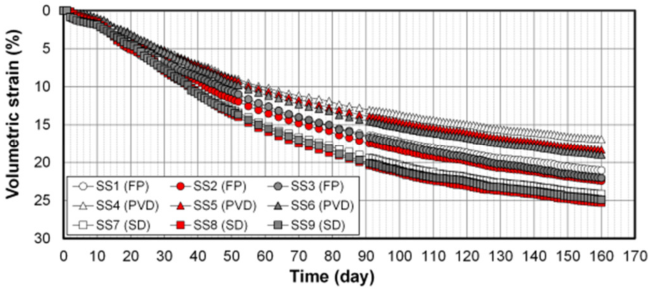

Fig. 9. Volumetric strain during vacuum preloading.

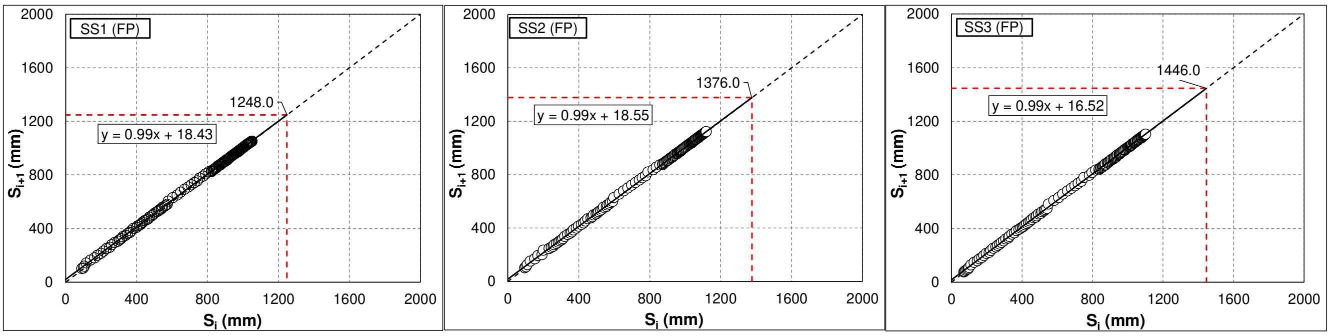

Fig. 10. Asaoka's analysis of test results in cases of FP.

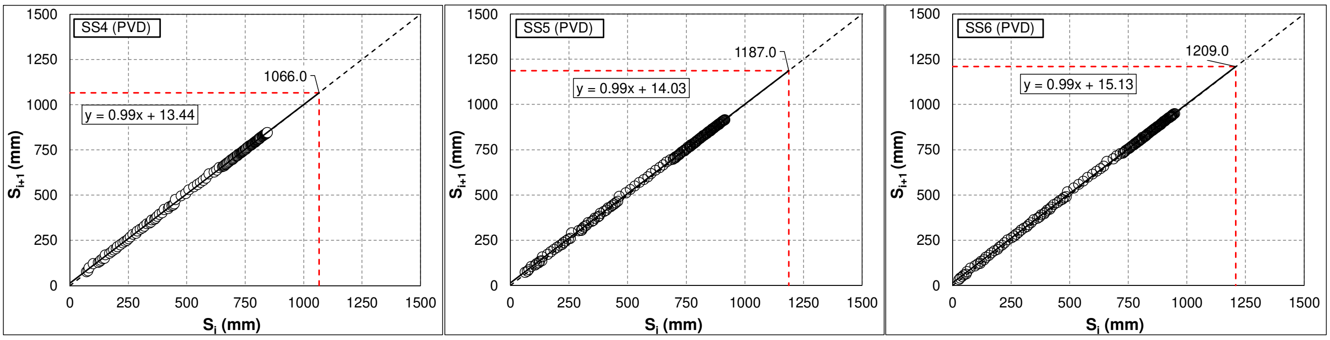

Fig. 11. Asaoka's analysis of test results in cases of PVD.

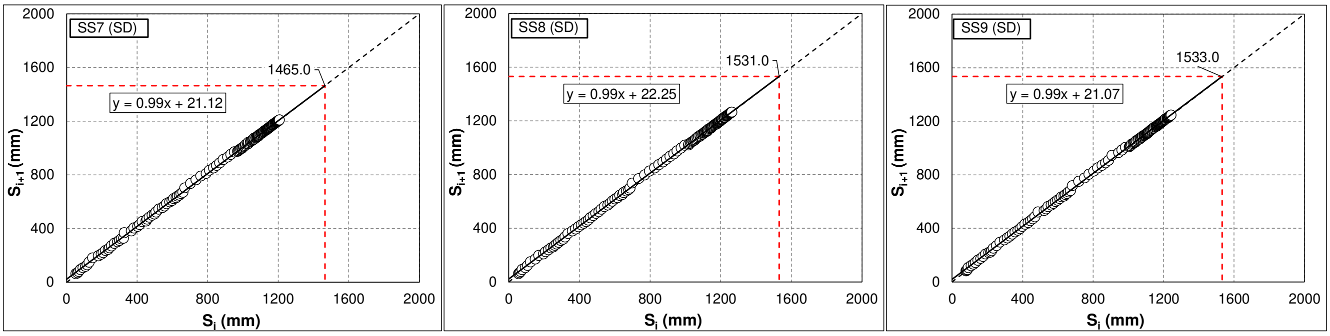

Fig. 12. Asaoka's analysis of test results in cases of SD.

Although the depths of mud differed between the two studies, the vertical drains were installed to a depth approaching the maximum vertical extent of the mud in both cases. Therefore, it can be posited that for dredged mud with a high-water content and the same configuration of vertical drains, the maximum volumetric strain under vacuum loading could be achieved through the usage of SD. In practical applications of the vacuum preloading method, the distance between PVDs is typically within the range of 0.9 m to 1.2 m. It can thus be posited that the application of the vacuum preloading method to the treatment of dredged mud with a high-water content may result in an ultimate volumetric strain of approximately 30%. Nevertheless, additional research is required to substantiate this finding.

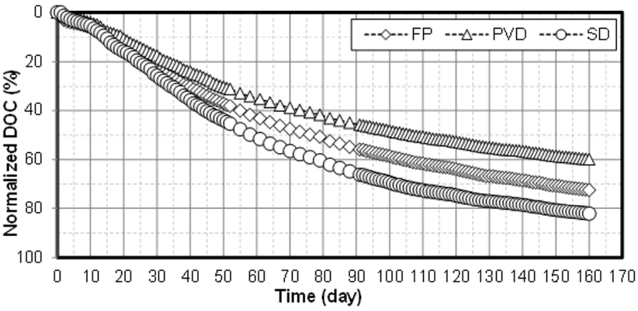

Fig. 13. Normalized consolidation degree of mud after vacuum preloading.

C. Improvement in Physical Properties and Strength

Figure 14 presents the changes in wet density, γ, and water content, w, in the mud sample before and after vacuum preloading. In addition to consolidation settlement resulting from vacuum preloading, there was an increase in γ and a decrease in w. Although there were some fluctuations, it was observed that the rise in γ and w diminished with depth, suggesting that the impact of vacuum preloading exhibited a decrease with depth as well. Furthermore, it was determined that the degree of enhancement in γ and w under different vertical drains was not uniform. In accordance with the settlement and volumetric strain, the discrepancies in depth between the improved γ and w in the SD case were minimal. Conversely, the corresponding differences in the FP case were more pronounced, with the greatest discrepancy occurring in the PVD scenario. This result corroborates the assertion that SD is more advantageous than FP and PVD.

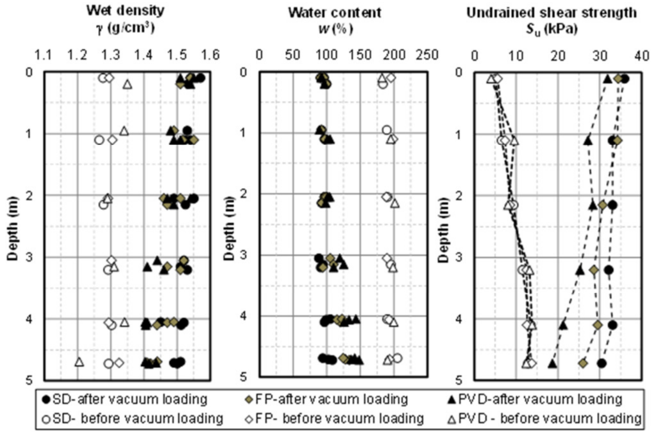

Fig. 14. Typical properties of mud before and after vacuum preloading.

Figure 14 also presents the undrained shear strength, S_u, obtained from Vane Shear Tests (VST) using a cutting blade with a diameter of 12.7 mm and a height of 19 mm, of the mud before and after improvement. The improvement in Su of the mud was observed to be consistent with the distribution of vacuum pressure and pore-water pressure observed during the test. It was noted that the improvement in Su was not the same for different vertical drains and decreased with depth. Following the implementation of the improvement, while there were some variations, the Su of the mud in the near-surface region exhibited a notable increase from 5 kPa to approximately 35 kPa, irrespective of the type of vertical drain. For the initial 1 m depth, the observed increase in Su was consistent across all vertical drain cases. However, a discernible distinction in Su enhancement was discernible with increasing depth. At the lowest point of the mud, the enhanced Su values resulting from the application of PVD, FP, and SD were 18.7 kPa, 26.0 kPa, and 30.5 kPa, respectively. These findings once again highlight the superior improvement effects of SD in comparison to FP and PVD.

D. Clogging Effects under Different Vertical Drains

The application of vacuum preloading to dredged fill soil results in the formation of clogging, a common phenomenon that predominantly manifests in the vicinity of a PVD. This phenomenon has the potential to diminish the overall improvement effects. In examining the phenomenon of clogging in the vicinity of a PVD under vacuum preloading, authors in [12] observed that due to the tenuous nature of the bond between soil particles and the high fluidity of the dredged mud, the water flow can swiftly propel soil particles under the influence of a considerable vacuum pressure gradient. As a result, the density of the clogging zone in the vicinity of the PVD increases considerably, thereby reducing its capacity to transmit the vacuum pressure exerted by the PVD. Consequently, consolidation is no longer achieved. The findings of this study indicate that the use of different vertical drains resulted in varying degrees of improvement. The occurrence of clogging indicated that the types of vertical drain also exhibited differential effects with respect to this phenomenon. To ascertain the density of the clogging area for each type of vertical drain, a series of tests on the PSD of the mud following vacuum preloading were conducted. At the center of each zone, three samples were collected at different locations. These included samples located next to the vertical drain (designated FP-1, PVD-1, and SD-1) and samples located equidistant from the surrounding vertical drains (designated FP-2, PVD-2, and SD-2), and the depth of the samples was 2.5 m.

Figure 15 shows a comparative analysis of the pre- and post-vacuum preloading PSD of the mud sample. The results demonstrated that samples FP-1, PVD-1, and SD-1 exhibited a finer consistency following vacuum preloading, in comparison to the mud sample prior to vacuum preloading. This indicated that under the vacuum pressure gradient, fine particles migrated in the direction of the vertical drains, forming a clogging zone in the vicinity of the drains. The results of the experiment demonstrated that as the sampling location was moved further away, the grain size distribution became increasingly finer. In the case of samples FP-2, PVC-2, and SD-2, the simultaneous effects of the vacuum pressure gradient transmitted from surrounding vertical drains resulted in the expulsion of a considerable quantity of fine particles. As a consequence, the PSDs of the mud in these areas were significantly coarser than the PSD of the mud prior to vacuum preloading. These observations corroborate the hypothesis that the transmission of vacuum pressure is less effective the further away from vertical drains, due to the clogging effects.

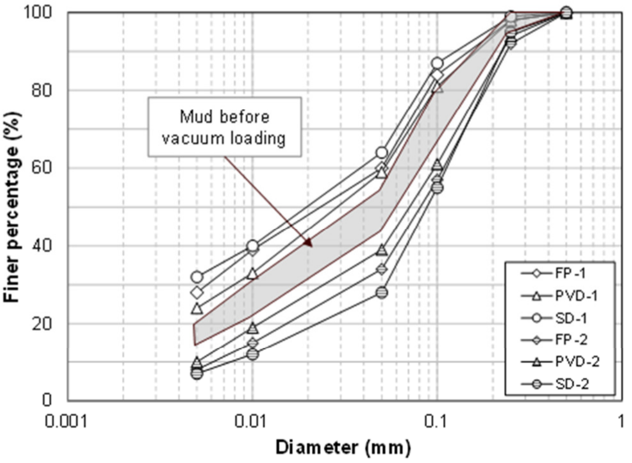

Fig. 15. Comparison in PSD of mud before and after vacuum preloading.

Additionally, it was determined that the mud samples from all sampling locations exhibited the finest consistency in the SD cases, followed by the samples from the FP and PVD cases, respectively. These results demonstrated that the greatest improvement effects were generated by the use of SD, followed by FP and PVD, respectively. The three types of vertical drain used in this study possess equivalent diameters, thereby suggesting that the theoretical improving zone surrounding the vertical drain should be identical. Therefore, the discrepancies in observed treatment efficiencies suggest that the configuration and morphology of the vertical drain may influence the development of the clogging zone. As presented in Table II, despite having an identical aperture size of 0.075 mm, the FP filter exhibited superior permeability compared to the PVD filter, resulting in enhanced vacuum pressure transmission. Moreover, as shown in Figure 16, the total drainage channel area of PVD was less than that of PVD at a given cross-section. The total cross-sectional areas of the drainage channels for PVD and FP were approximately 380 mm² and 570 mm², respectively. In addition to the higher permeability of the filter, FP generated a greater vacuum pressure gradient than PVD, resulting in enhanced treatment efficiencies. A comparable phenomenon was observed in the case of SD. Given its high void ratio, the SD drainage channel was constructed using interconnected pore matrices. Consequently, the cross-sectional area of the drainage channel in the SD case was significantly larger than that in the FP and PVD cases. Moreover, in contrast to the cases of FP and PVD, the movement of soil particles in the case of SD was not constrained by a layer of filter geotextile. The soil particles in the dredged mud and sand of SD were observed to move towards the center of the SD under the influence of the vacuum pressure gradient. Due to its high void ratio, the soil particles in the dredged mud required a considerable amount of time to fill the voids. As a result, the treatment effects of using SD were sustained for a longer period of time than those of FP.

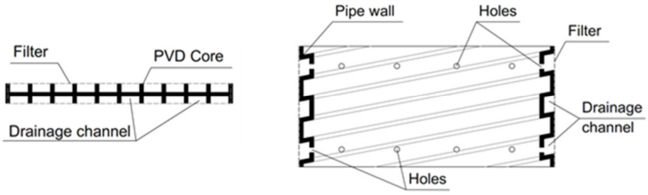

Fig. 16. Schematic of structure of cross-section of PVD (left), and vertical section of FP (right).

IV. CONCLUSIONS

This research aimed to extend the findings of previous studies by examining the impact of clogging on the dehydration improvement effects of dredged mud using vertical drains with vacuum preloading. In addition to the use of Prefabricated Vertical Drains (PVD) as in prior studies, this research also investigated two other types of vertical drains: Filter Pipes (FP) and Sand Drains (SD). In conclusion, the results obtained led to the following:

- Despite differences in the properties of the mud and the spacing of the PVDs between this study and previous research, a similar trend was observed. As a consequence of the formation of obstructions, the vacuum pressure was unable to be fully transmitted to the base of the mud pond, resulting in a longer period of time for the vacuum pressure to stabilize at greater depths. Consequently, the efficacy of the treatment diminished with depth, resulting in a reduction in the improvement of the physical properties and strength of the deeper mud. These findings were consistent with those of previous studies.
- A comparable trend in improvement effects was observed in cases where SD and FP were used as vertical drains. These results further substantiate the consistency of this research with previous studies.
- Additionally, the study revealed that, with the identical square configuration of 0.9 m × 0.9 m, the SD with vacuum preloading exhibited superior performance compared to the FP and PVD. The maximum volumetric strain of the dredged mud with SD was approximately 30%, in comparison to 27% with FP and 23% with PVD. Therefore, the most favorable improvement effects were observed in the case of using SD.
- It was determined that clogging effects varied with the shape and structure of each vertical drain. With interconnected pore matrices and the absence of a filter geotextile, SD vertical drains were capable of minimizing the effects of clogging. Consequently, the use of SD as a vertical drain resulted in superior treatment effects compared to FP and PVD.

- SD is an effective solution for vertical drains due to its ability to facilitate good drainage and prevent clogging. Furthermore, the incorporation of sand within the mud enhances the overall stiffness and bearing capacity of the reclamation area. Nevertheless, a detailed investigation of both the financial implications and the practical feasibility of the construction process is essential for the practical application of this solution.

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