Journal of Science and Technology in Civil Engineering NUCE 2018. 12 (5): 63–72

INFLUENCE OF VERTICAL DRAINS ON IMPROVING DREDGED MUD BY VACUUM CONSOLIDATION METHOD

Phan Huy Dong[a,*]

[a]*Falcuty of Bridge and Highway Engineering, National University of Civil Engineering, 55 Giai Phong road, Hai Ba Trung district, Hanoi, Vietnam*

Article history:
Received 30 July 2018, Revised 27 August 2018, Accepted 30 August 2018

Abstract

Vacuum consolidation preloading method (VCM) has been widely adopted as an effective solution for soft soil improvement over the world. Recently, VCM has been successfully applied for improving the geotechnical properties of dredged mud, which is normally dumped at reclamation area by hydraulic pumping. However, it has been also reported that application of VCM for treatment of the dredged mud has been failed in some particular cases. The failures are mainly caused by clogging problem in vertical drains due to fine-grained soils that reduces the drainage efficiency of drainage system. To address this issue, a series of model tests have been conducted to investigate the performances of vertical drains among prefabricated vertical drain, sand drain and filter pipe. As the goal, the performances of types of the vertical drain solutions are analyzed based on the monitoring data of settlement, influencing zone surrounding the vertical drains. The test results reveal that sand drain shows the best performance among the others. In addition, the clogging problem is clearly shown in case of PVD.

Keywords: dredging slurry; vacuum consolidation method; model test; PVD; filter pipe; sand drain.

https://doi.org/10.31814/stce.nuce2018-12(5)-07 © 2018 National University of Civil Engineering

1. Introduction

Along with rapid development of infrastructures, Vietnam has high demand for construction of mega projects along the coastal line area, where number of dredging projects has been increasing significantly. The mud generated from dredging work has been mainly dumped at the disposal sites by hydraulic pumping method, only small amount has been utilized for reclamation. The dredged mud is normally in fluid state and it has very low engineering properties, almost no bearing capacity. After hydraulic reclamation, hundreds of hectares landfill area has been formed. Since the dredged mud needs a long period to be settled down and solidified, the disposal sites cause serious environmental and ecological issues at its surrounding area. On the other hand, construction activities at the coastal area normally needs huge amount of sand filling material, whereas a shortage of sand materials raises it prices rapidly, especially when regulations on preservation of natural sand resource from Vietnam national law has become more strictly. Consequently, treatment of dumping disposal sites to create landfill reclamation has been strongly demanded.

Vacuum consolidation method (VCM) was initially proposed by [1]. Currently, the VCM has been widely applied in wide areas of infrastructure development in many countries, such as China, Thailand, Japan and Vietnam. Literature and engineering projects both indicate that the vacuum preloading

*Corresponding author. *E-mail address:* dongph@nuce.edu.vn (Dong, P. H.)

method is an effective technique for the treatment of soft soil deposits [2–4]. In recent years, VCM has been successfully applied to treat the newly reclaimed mud. However, big challenges has been remained due to the extremely high water content and nearly zero bearing capacity condition of the dredged mud. Besides success applications of VCM for treatment of dredged muds [5–7], several failures have been also observed. For an example, the failure of VCM for improving newly hydraulic reclaimed site at Tianjin province, China as reported by Bao et al. [8], where the effective depth is extended to very shallow depth. Shear strength of soil obtained by Vane shear test ranges from 4.0 kPa to 9.0 kPa after 30 days of vacuum loading. In addition, many engineering practices have also proved that after a short period time of improvement, vertical drains have larger bending and very serious clogging problem, resulting in the poor drainage performance of vertical drains as well as low effective improvement.

In this study, a series of model tests have been conducted to investigate the performance of vertical drainage among prefabricated vertical drain, sanddrain and filter pipes. As the goal, performances of types of drainage solution are analyzed based on the monitoring data of settlement, influencing zone surrounding the vertical drains.

2. Methodology of Vacuum consolidation method

The methodology of vacuum consolidation method is applying a vacuum pressure into an isolated soil mass to reduce the atmosphere pressure and pore water pressure in the soil, resulting soil consolidation and effective stress enhance. Therefore, instead of increasing the effective stress in the soil mass by increasing the total stress by means of conventional surcharge filling, the vacuum preloads the soil by reducing the pore water pressure while maintaining a constant total stress.

Basically, vacuum consolidation system consists of drainage system, isolation system and vacuum pumps (Figs. 1 and 2). Once generated in vacuum pumps, vacuum suction rapidly spreads into soils along horizontal and vertical drainages system, reducing atmosphere and pore water pressure and forming pressure difference between vertical drains and pore water in soils. This pressure difference causes the pore water flows toward vertical drain, which means soil consolidation happens. Vacuum suction keeps taking out water and air, accelerating soil consolidation. Drainage system is a connected network of the vertical drains, horizontal filter pipes and sand layer, forming a complete path for

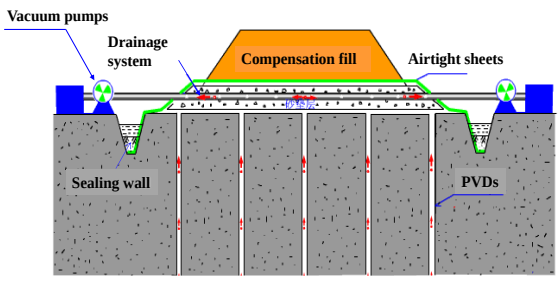


Figure 1. Schematic chart of vacuum consolidation system



Figure 2. An application of VCM for an industrial project in Vietnam

spreading of vacuum suction and water flow. The conventional VCM normally combined with PVD, which comprised a plastic core wrapped by a geotextile layer for filter function.

So far, numerous books, papers, reports and documents about mechanism, methodology and practice of vacuum consolidation method have been published over the world. A lot of experimental or monitoring data has been presented among these literals [3, 4, 9]. All these efforts or achievements provide a better understanding on quality control of this technique.

3. Case history for application of VCM for improving dredged mud

It has been demonstrated that key challenges of VCM for improving the dredged mud are: (1) How to create of a construction platform on the top surface of disposal site; (2) How to enhance effectiveness vertical drainage against the clogging and bending problems due to large settlement. In order to provide a reference, the application of VCM for improving the dredged mud at Dalian Zhuanghe port industry and logistic estate project in China [5] is subsequently summarized. The project site covers an area of about 170 hectares and is divided into several blocks with every 30 to 40 hectares. Each block was filled by dredging slurry with thickness from 7 to 8 m. The dredging slurry is completely clayey silt or silty with extremely high initial water content, nearly zero bearing capacity, very soft and flowable to soft plastic.



(a) Dike construction (b) Dredged mud filling (c) Construction platform (d) Sand blanket filling

(e) PVD installation (f) Horizontal pipes (g) Air-tight sheet (h) Vacuum operation

(i) Dredging mud before and after improvement

Figure 3. Application of VCM for improving the newly hydraulic reclaimation mud at Dalian Zhuanghe port, China [4]

As illustrated in Fig. 3, the construction work at the project was conducted into following steps:

- Surround dike construction: Dikes were built along the boundary or interface of the blocks by filling of compacted mountain soil.

- Dredged mud filling: the dredged mud was filled by hydraulic pumping method. It is noted in the dredged mud that its silty content (particle size varies from 0.005 to 0.05 mm) is about 18%, and its clay content (particle size less than 0.005 mm is round 12%).

- Setting up a construction platform: A combination of woven geotextile, bamboo grid and 0.4 m hydraulic sand filling was developed to build working platform.

- Installation of vertical and horizontal drains: Conventional PVDs were installed using lightweight installation machine. Horizontal perforated pipes wrapped by non-woven geotextile were buried into the sand blanket layer.

- Installation of airtight sheets: Two airtight sheets protected by two non-woven geotextile layers were covered on the surface.

- Operation of vacuum system: vacuum pumps system was executed and kept running until the average consolidation degree reach 90%. After vacuum loading was removed, the compensation fill by means of sand was conducted.

During vacuum loading, a vacuum pressure of over 90 kPa was observed. The consolidation settlement measured at surface ranges in a relatively wide scatter and average settlement reaches 0.65 m, the equivalent volumetric strain is about 9.3%. Based on monitoring data (vacuum pressure, surface settlement, sub-layer settlement) and in-situ tests (VST, CPT, SPT), following specifications were archived: (1) surface bearing capacity is greater than 100 kPa by plate loading test; (2) shear strength at any point along 13 m depth is not less then 50 kPa; (3) long term settlement under 50 kPa working load is less than 30 cm.

4. Model tests for evaluating performance of vertical drains

4.1. Sample preparation

The model tests were conducted using a dredged soil, which was taken from West Lake, Hanoi. Since Hanoi City plans to launch a dredging work for West Lake, in order to deal with environmental pollution, making the West Lake area becomes a future tourist area of the city for sustainable development. The dredging work is proposed to be conducted by cutter suction dredger, the mud is then collected at a designate area within the lake, it subsequently will be transported outside the lake by trucks. The project will generate approximate 1.3 million cubic meters of dredged mud. An area of about 30 hectares would be required for dumping such huge amount of dredging mud, while the land fund of Hanoi city for disposal site has been very limited. In addition, the disposal of that huge dredged mud has many consequences impacts for the ecological environment. Therefore, possibility to treat the disposal site by VCM will be a good reference for the manager units in order to select a proper method for dredged mud treatment.

Several physical properties of mud sample were carried out in laboratory (Fig. 4). Table 1 summaries physical properties of 03 typical mud samples. Notably, the mud has been generated from decay of aquatic plants and animals for many years, so the soil is very soft with high water content, high void ratio, fine particles and high organic content. Detail discussion on the project as well as geotechnical engineering of the dredged mud can be referred to Dong P. H. [10].

4.2. Equipment development

The test equipment mainly consists of several components as numbered as shown in Figs. 5 and 6. In Fig. 6, (1) indicates the vacuum system includes a vacuum pump with a power output of 7.5



Figure 4. Mud samples and laboratory test for evaluating physical properties

Table 1. Physical properties of the mud samples

Sample	Unit weight (kN/m^3)	Water content (%)	Specific gravity, Δ	Void ratio, e	Organic content (%)	Silt content, % (d = 0.005 - 0.05 mm)	Clay content, % (d < 0.005 mm)	PH
1	1.24	210.9	2.52	5.3	18.6	22.4	19.4	7.19
2	1.27	202.5	2.50	5.0	22.1	23.6	18.6	7.18
3	1.31	216.3	2.53	5.1	11.4	25.7	17.7	6.96

kW which can generate a vacuum pressure of 95 kPa; (2) is the model test box with inner dimensions of 200 cm × 150 cm × 150 cm in length, width and height. The dredged mud was then freely poured in the box with thickness of 1 m; (3) One layer of geomembrane was covered on the top and sealing in the mud to keep airtight condition; (4) A vacuum gauge is set up right under the geomembrane to monitor the vacuum pressure during loading; (5) A set of 02 vacuum gauges was also set up at different depths of 0.2 m and 0.8 m from the surface in order to observe the transmission of vacuum pressure along the depth. Location of the vacuum gauges is presented in Fig. 5; (6) The horizontal perforated pipes wrapped by filter geotextile to connect all the vertical drains. (7) and (8) shows the vertical drains.

To evaluate the effectiveness of different types of vertical drains, this study performed three sets of model tests using either prefabricated vertical drain (PVD), Sanddrain (SD) or filter pipes (FP). Detail arrangement of the vertical drains is shown in Fig. 5, where the PVD is conventionally comprised a plastic core wrapped by geotextile filter. Permeability coefficient of the filter is 0.014 cm/s. The size of PVD is 100 mm × 3 mm. The SDs with diameter of 5 cm using medium sand were placed in the mud by using a PVC pipe casing, the casing was then carefully removed from the soil. The FP is comprised by a slotted PVC pipe with diameter of 5 cm and wrapped by a geotextile layer for filter. The FPs were also inserted at the same positions with those of PVD and SD. In addition, network of

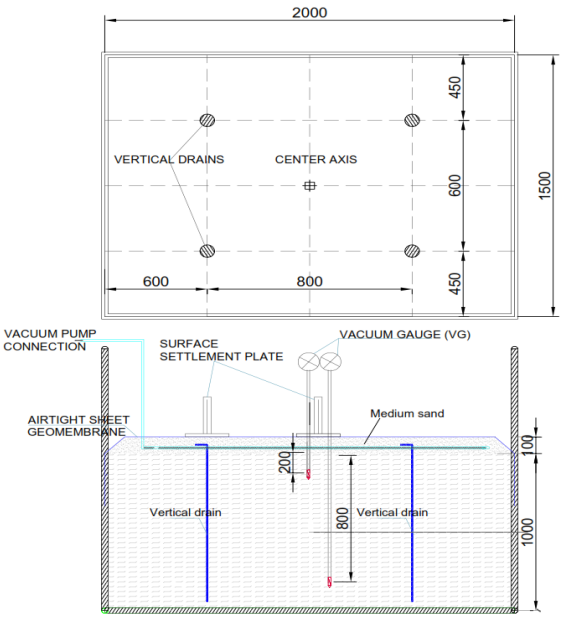


Figure 5. Schematic chart of the model test

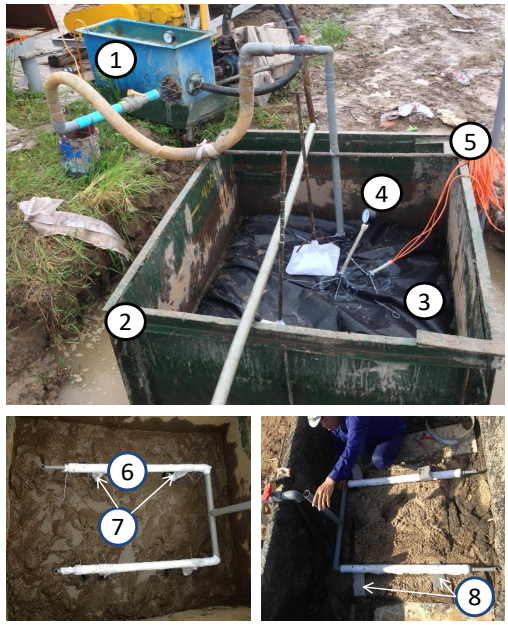


Figure 6. Equipment of the model tests

the vertical drains and horizontal pipes was placed into a 0.20 m sandmat layer.

4.3. Monitoring work

Along with 02 vacuum gauges located at 0.2 m and 0.8 m from the surface to observe the transmission of vacuum pressure, the surface settlement was also observed at positions near the vertical drain and between the vertical drains. Detail locations of monitoring equipment are shown in Fig. 5.

5. Results and discussions

5.1. Settlement and rate of volume reduction

The vacuum loading in case of PVD was removal after 15 days, until the settlement rates has reduced and get stable value under 2 mm/day in 5 consecutive days. For a comparison purpose, the vacuum loading time in other cases of the vertical drains was also performed at same duration. The surface settlement measured at vertical drain's position and that between the vertical drains was plotted in Fig. 7. Since the test box has very high stiffness, the horizontal deformation is ignored. Therefore, vertical strain is equivalent to volumetric strain or rate of volume reduction as shown in Fig. 8. At the end of vacuum loading time, the maximum settlement in case of PVD is only 62 mm with equivalent volumetric strain is 6%. This amount seems be lower than the value reported by Liu and Marcello [5], as it was 9.3%. However, advantages of SD and FP are revealed again with corresponding maximum settlement of 119 mm and 92.5 mm. The equivalent volumetric strain in case of SD and FP is 11.5% and 9.1%, respectively. It is here noted that the volumetric strain or volume reduction rate is a significant parameter for the mentioned project, because the mud is dredged and collected at the lake before transporting to dumping landfill, so the transportation cost can reduce with higher volume reduction. In addition, the average settlement rate at last 05 days in case of PVD, FP and SD is 1.17, 2.23 and 3.75 mm/day, alternatively. This means that consolidation process as well as workability of FP and SD has still significantly undergone until end of vacuum loading.

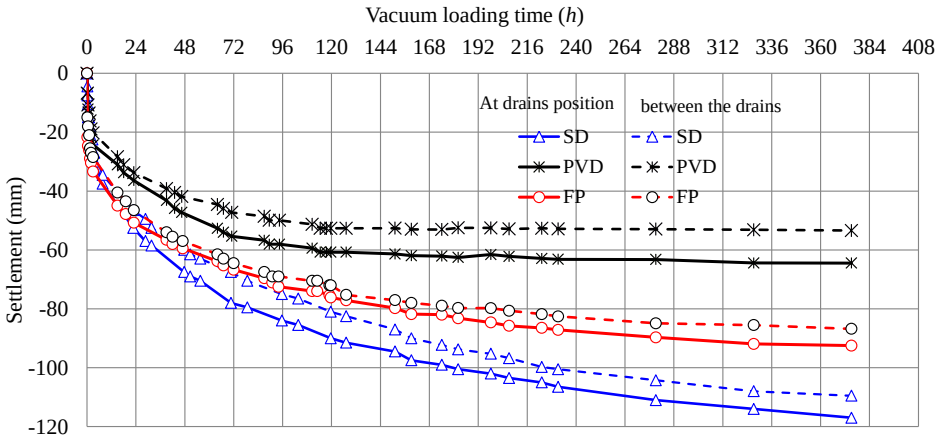


Figure 7. Settlement versus loading time

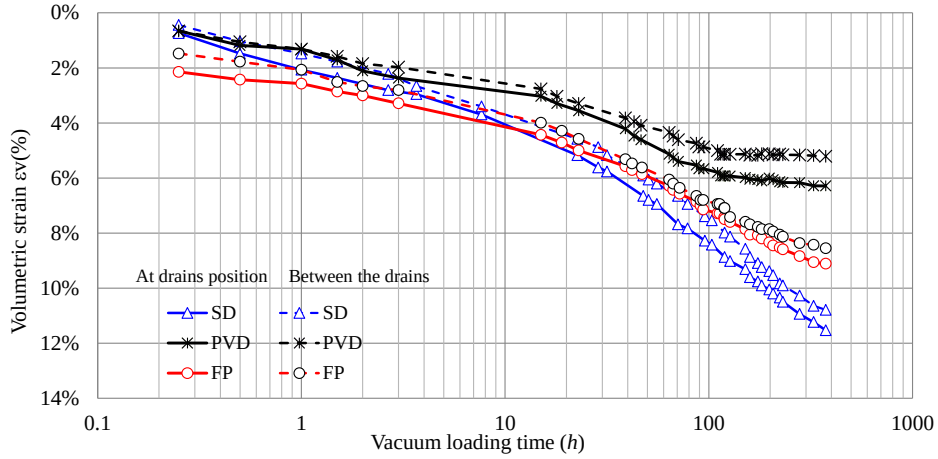


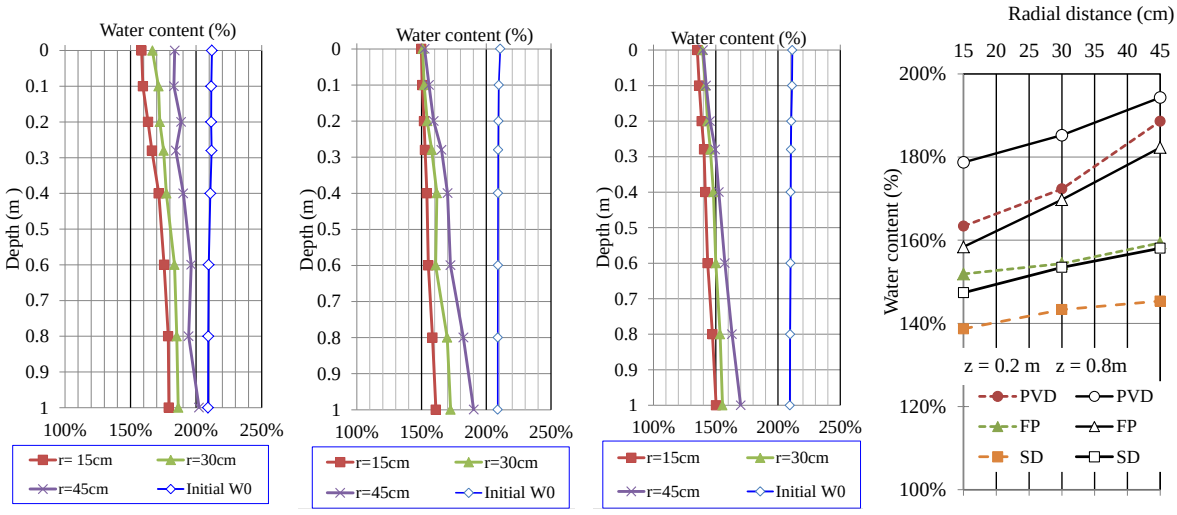
Figure 8. Volumetric strain versus loading time

5.2. Influenced zone and clogging phenomenon

The influenced zone, which clearly shows transmission area of vacuum pressure, can be observed based on the soil core appeared surround the vertical drains. For more detail, it could be analyzed from the variation of water content along the depth and radius range. Again, it is in this project noted that rate of water content reduction will evaluate possibility whether the mud can be treated by premixing with cement for filling material.

After the vacuum loading, mud samples were collected at different depths and distances from the vertical drains for checking water content. The variation of water content along the depth at different range from the vertical drains (r = 15 cm, r = 30 cm and r = 45 cm) is presented in Fig. 9. The initial water content (W_0) is also shown for referent value. It can be seen that the water content increases with the increasing depth and radius distance from the vertical drain in all three cases. However, in case of PVD, water content reduces only 20% on the top and even almost 10% at the depth of 0.8 m. In general, the distribution of water content in case of PVD (Fig. 9(a)) is relative difference from that in cases of FP (Fig. 9(b)) and SD (Fig. 9(c)), since the values of water content at different

radius distance near the surface are not close together. Although more efforts should be investigated, this manner could be explained that exceed pore water pressure was generated due to the clogging problem, after removal of vacuum loading, pore water could be rearranged and rebind to surface. In addition, the sampling work for water content test was conducted after few days from the removal of vacuum loading. Fig. 9(d) shows the variation of water content with radius distance from the vertical drains at two depths of 0.2 m and 0.8 m. It is again clearly shown that SD case gives the best transmission effect of vacuum pressure, which results in a better preloading effect.



(a) PVD case (b) FP case (c) SD case (d) Water content vs. radial range

Figure 9. Variation of water content with depth and radius

Fig. 10 shows the vertical drains after removal of the vacuum loading. In case of PVD, clogging phenomenon was visually observed. A tiny layer of fine particles appeared on surface of filter layer, whereas no soil particle is seen in plastic core. In both cases of the FP and SD vertical drains methods, a soil core is clearly created surrounding the vertical drains. Radius of soil core in case of FP is about 12 cm, and that in case of SD is approximately 25 cm. This observation is coincided with the change of water content as described in Fig. 9. Consequently, it is suggested that the SD drain case has a better treatment effect both in decreasing the moisture content and in increasing the process uniformity at different depths.

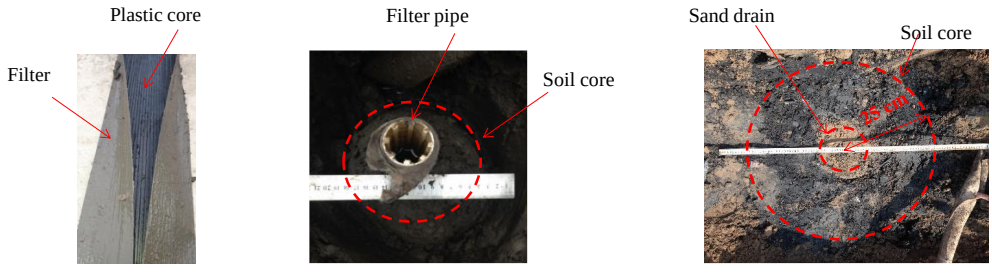


Figure 10. The vertical drains after removal of vacuum pressure

5.3. Distribution of vacuum pressure

Vacuum pressure was monitored during loading. Fig. 11 presents the vacuum pressure at depth of 0.2 m and 0.8 m for 03 cases among the vertical drains. The vacuum pressure at shallow depth was quickly reached stable value right after operation of vacuum system. It however needs a specific time to be transmitted at depth of 0.8 m. The delayed time and rising rate increase by sequence of SD, FP and PVD. It can be explained that during a short period of vacuum loading, the whole vacuum loading is focused on the formation of tiny ripples and building of some larger channels. After formation of tiny ripples and building of larger channels inside the soil, the vacuum pressure reaches to stable value because of the silt clogging around the PVDs, thus no longer development of vacuum pressure can be observed.

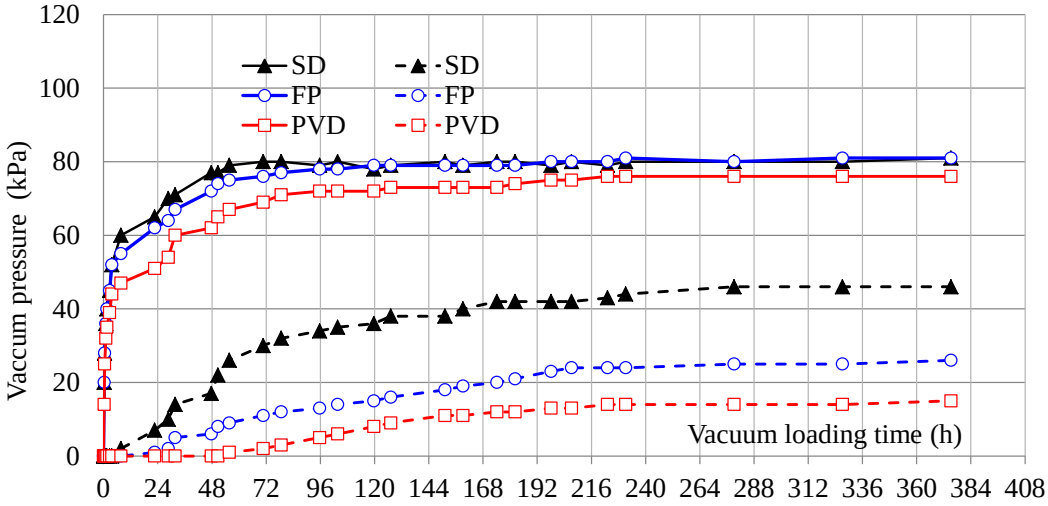


Figure 11. Vacuum pressure during vacuum loading

6. Conclusions

In most cases, dredged mud has been believed to be unsuitable material for reclamation. The advanced VCM creates more possibility to utilize dredging slurry for reclamation, which shall bring benefit in overall cost and environment protection. Although more detail study on both technical and economic aspects shall be conducted, following conclusions can be withdrawn from this study:

- The performance of VCM for treatment of dredged mud is strongly governed by workability of vertical drains. The conventional VCM combined with PVD may encounter serious clogging problem in vertical drains of high content fine-grained soils. It commonly reduces the drainage efficiency of drainage system, weaken vacuum pressure in soils, and then weaken the soil improvement effect.

- This study recommends SD as a proper countermeasure for vertical drains, since SD shows suitable stiffness, good drainage and anti-clogging phenomenon. In addition, the sand volume inserted in the mud also increase overall stiffness and bearing capacity of the reclamation area. For practical use, a consideration on both cost and construction feasibility should be detail investigated.

- Success of the combination of woven geotextile, bamboo grid and hydraulic sand filling for working platform and horizontal drainage in case history presented in this paper is a good reference for solving difficulty of establishment of working platform.

References

[1] Kjellman, W. (1952). Consolidation of clay soil by means of atmospheric pressure. In *Proceedings of Conference on Soil Stabilization, MIT*, 258–263.

[2] Dong, P. H. (2017). Design and construction experiences on soil improvement work by vacuum consolidation method. *Vietnam Journal of Construction*, 8:239–242.

[3] Indraratna, B. (2010). Recent advances in the application of vertical drains and vacuum preloading in soft clay stabilization. *Australian Geomechanics Journal*, 45(2):1–43.

[4] Loan, T. K., Sandanbata, I., Kimura, M. (2006). *Vacuum consolidation method - Worldwide practice and the latest improvement in Japan*. Hazama Research Annual Report.

[5] Liu, Y., Marcello, D. (2015). *A vacuum consolidation method application case for improving dredging slurry*.

[6] Shang, J. Q., Tang, M., Miao, Z. (1998). Vacuum preloading consolidation of reclaimed land: a case study. *Canadian Geotechnical Journal*, 35(5):740–749.

[7] Wang, J., Cai, Y., Ma, J., Chu, J., Fu, H., Wang, P., Jin, Y. (2016). Improved vacuum preloading method for consolidation of dredged clay-slurry fill. *Journal of Geotechnical and Geoenvironmental Engineering*, 142(11):286–299.

[8] Bao, S., Dong, Z., Chen, P. (2013). Causal analysis and countermeasures of vacuum consolidation failure to newly hydraulic reclamation mud. *Electronic Journal of Geotechnical Engineering*, 18:5573–5579.

[9] Long, P. V., Nguyen, L. V., Bergado, D. T., Balasubramaniam, A. S. (2015). Performance of PVD improved soft ground using vacuum consolidation methods with and without airtight membrane. *Geotextiles and Geomembranes*, 43(6):473–483.

[10] Dong, P. H. (2017). Study on physical and chemical characteristics of dredging muds in Hanoi city and proposal for recycling as land reclamation filling material. *Vietnam Journal of Construction*, 8:263–266.