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Observations from Ground Improvement Using Vacuum Consolidation Method

Nishkarsha Koirala[1], Suttisak Soralump[2,*], Sartsin Phakdimek[3]

[1]Graduate Researcher, Department of Civil Engineering, Faculty of Engineering, Kasetsart University, Bangkok, Thailand
[2]Associate Professor, Department of Civil Engineering, Faculty of Engineering, Kasetsart University, Bangkok, Thailand
[3]Graduate School of Environmental Studies, Tohoku University, Japan

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Abstract In the modern world of Civil Engineering, challenges arise during the various phases of construction, starting from the project development phase to the completion of the project. One of the main factors to be considered before commencing any infrastructure project is the foundation of where it is to be built. Without a strong foundation, it's not possible to proceed further to subsequent stages and in some cases, significant improvements may be required before starting the construction process. Although there are several different available methods for soil improvement in Civil Engineering, preloading using vacuum pressure with prefabricated vertical drains (Vacuum Consolidation Method) is one of the commonly applied techniques. Nowadays, it is widely used in countries having soft soil settlement problems. This paper presents the observations made from a soil improvement project using VCM including the site conditions and methodologies adopted during the process. The field data related to parameters such as pore pressure, settlement and shear strength improvement in natural soft clay have been presented and discussed. The degree of consolidation in the field has been back-calculated from settlement data and compared with values obtained from the 1-D consolidation equation. Field investigation tests, such as borehole tests and field vane shear tests, were performed before and after the soil improvement and it was found that the soft soil properties can be enhanced using vacuum consolidation without the use of any surcharge loading as well.

Keywords Soft Soil, Vacuum Consolidation Method (VCM), Prefabricated Vertical Drains (PVD), Vacuum Pressure, Pore Pressure, Settlement, Shear Strength

1. Introduction

In foundation engineering, the consolidation settlement in soft clay gives rise to numerous problems [1]. Especially, in the coastal regions of Southeast Asia, soft clays are a big obstacle as they extend to deeper depths varying from 10-25m. Their low shear strength and high compressibility have posed a huge challenge for engineers to tackle problems related to settlement and stability during construction [2]. So, before developing any civil engineering infrastructure, soil improvement becomes an essential procedure. One of the common soil improvement techniques which have been widely opted for is preloading with the combination of prefabricated vertical drains (PVD).

Conventional preloading methods involve the use of fill surcharge, which creates excess pore-water pressure in soils that is drained out by the vertical drains. PVD's increase the rate of consolidation by shortening the drainage path in soils, thus reducing the time required for soils to undergo required consolidation [3-5]. However, surcharge increases the total stress in soils and its use might not always be feasible due to stability issues in soft soils. An alternative to this is the use of PVD combined with vacuum pressure, also known as the VCM method. Initially proposed by Kjellman [6], the application of vacuum generates negative pore pressure, increases the effective stress in soils without increasing the total stress as well as accelerates the consolidation process [7]. Due to the increase in effective stress, the soil becomes able to bear a higher load without undergoing a considerable amount of settlement, reducing the issues related to settlement during and after construction. The main concept of this method is to get the soil to an over-consolidated state, beyond a certain stress state, so that on future loadings it is safe from settlement and bearing failures. A typical schematic diagram showing the arrangement of the vacuum-PVD method has been presented in Fig. 1.

In the present context, VCM has gained huge popularity because of its advantages over conventional preloading methods i.e. environment-friendly nature, faster application, and higher cost efficiency [8]. Initial cases on the successful application of vacuum was reported for the case of Suvarnabhumi International Airport(SBIA) where the undrained shear strength of soil was improved 1.5-2 times, a higher consolidation rate was achieved and there was a reduction in preloading time [9]. Following the recent advances in the techniques of vacuum application and development of advanced methods, many case studies related to improvement and utilization of reclaimed lands as well as natural soft soils have since then been reported [10-18].

The present case involves Bangkok, a rapidly growing city where the increased population has created a higher demand for housing projects. Especially inside the urban areas, since there is a lack of available lands, it is essential to utilize the existing unoccupied lands to build infrastructures [19]. This paper presents a case study of soft soil improvement using the vacuum preloading method for a housing project in Samut Prakan, Thailand. It aims to report the field monitoring results from one of the preloaded sections. The initial site conditions, the soil properties, methodologies of preloading are presented, the influence of vacuum on the dissipation of pore pressure in soils, and settlement during and after the termination of vacuum pressure are explained. The variation in the groundwater table around the VCM Zone is studied and the improvement in shear strength of soils with depth is reported. Overall, the paper shows the successful application of vacuum pre-loading as a soil improvement method in Civil Engineering.

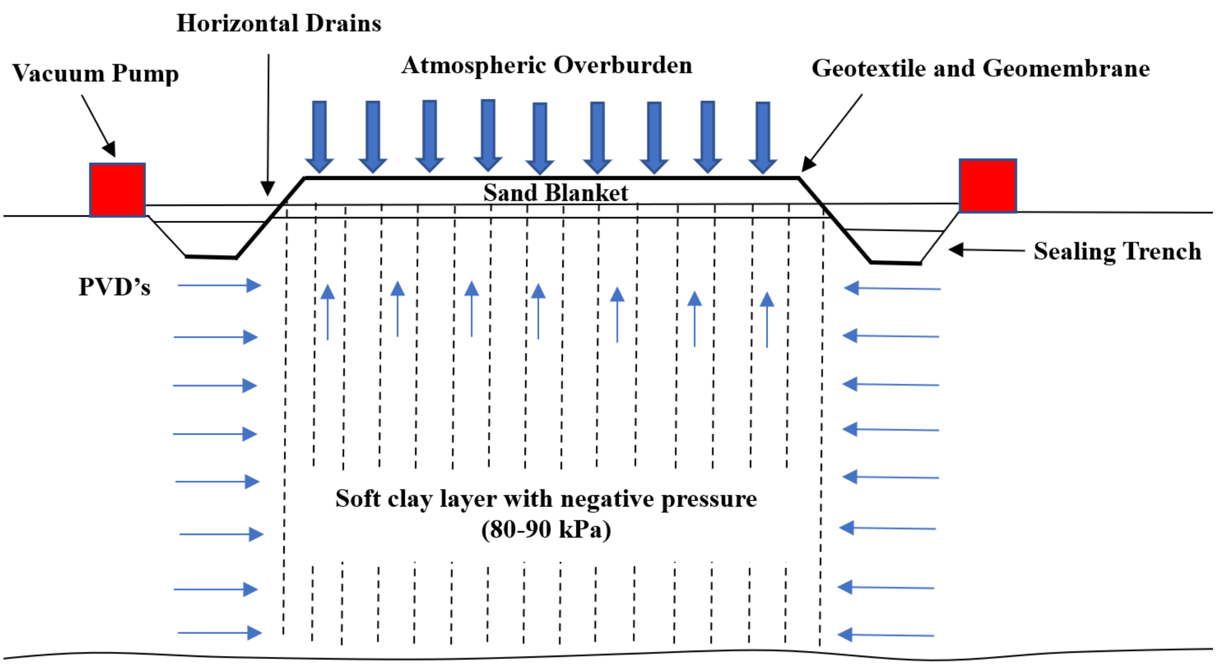

Figure 1. Schematic diagram of VCM using airtight sheet method

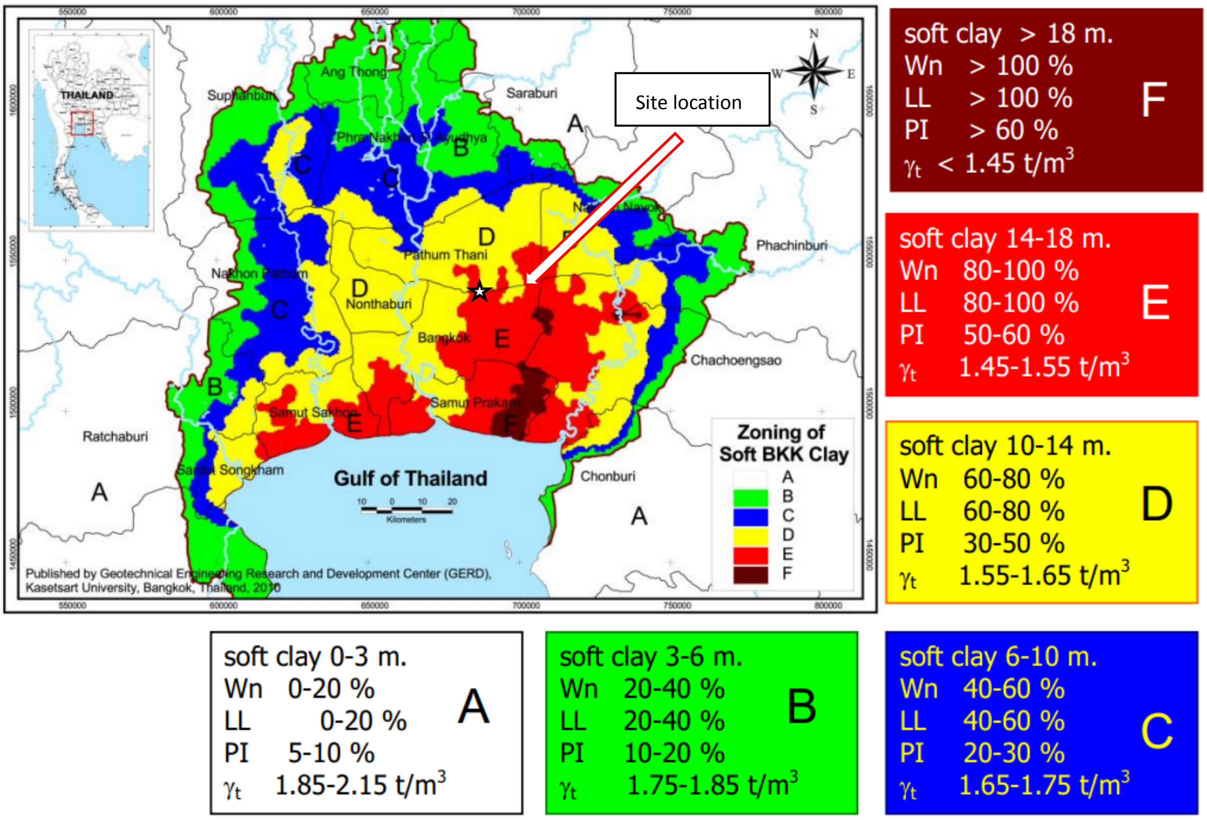

Figure 2. Bangkok soft soil zoning map

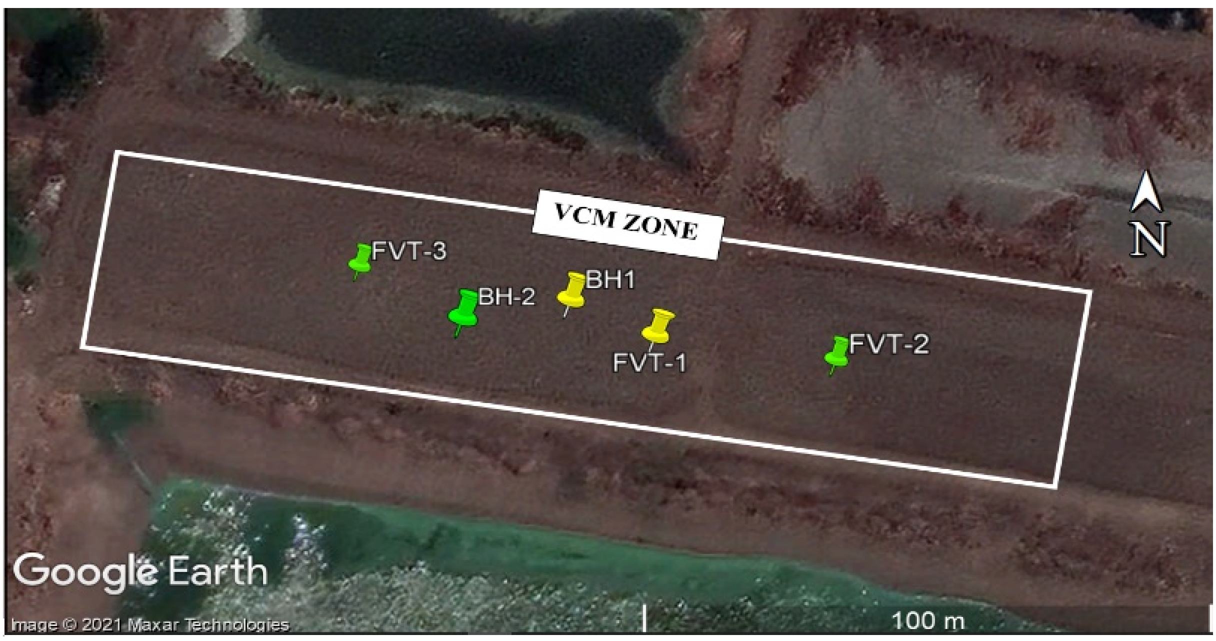

Figure 3. Location of boreholes in Zone 2-2 (May 2020)

2. Site Description and Instrumentation

2.1 Site and Field Testing Locations

The area of study is on the southern outskirts of Bangkok, Samut Prakan district, Thailand. This region is located adjacent to the Gulf of Thailand where the presence of soft soil is very deep (up to 18 m) with very high water content as shown in Fig. 2. There were 8 different blocks for VCM and one of the weaker sections was taken for study.

The study area partially had a pond of 1.5-2m depth, which was filled in by soft clay before the starting of the preloading works. The improved area had an area of 2927m^2 with an approximate width of 19 m and a length of 155 m approximately. The location of soil investigation tests carried out has been shown in Fig. 3. BH-1 and FVT-1 indicate the location of boreholes and field vane shear test carried out before VCM, whereas BH-2 and FVT-2, FVT-3 are the tests carried out after completion of VCM. Different locations for FVT were chosen to check the improvement of soil at various places within a single zone. However, the distance was maintained within 30-50 m to avoid drastic variation in soil properties.

2.3. Borehole and Soil Properties

The detailed index properties have been tabulated in Table 1. The soil investigation carried out before improvement showed the presence of very soft soil of high plasticity from the depth of 0-12 m. The groundwater table was located at 1.3m below the ground level. The in-situ water contents over the entire soft soil depth were high except in the fill material which had relatively low water content. The average water content in the top 7.5m below the fill was approximately 107.54% and reduced with the increase in depth from ground level. Furthermore, the average undrained shear strength obtained from the Unconfined Compression test of undisturbed soil samples showed the presence of very soft soil in the depth 1.5-7.5 m, followed by soft soil up to 12 m which was underlaid by medium stiff clay. Based on these results, the soil improvement was applied only in the very soft and soft soil layer.

Table 1. Soil Properties

BH-1							
Depth(m)	**Soil Type**	**Avg.S_u (kPa)**	**Avg.W_n (%)**	**LL**	**PL**	**R.R**	**C.R**
0.0-1.50	Fill Soil	9.12	114.45%			0.052	0.301
1.50-7.50	CH (Very Soft)	9.30	107.54	151.43	44.3	0.041	0.338
7.50-12.0	CH(Soft)	17.3	73.7	116.28	34.71	0.06	0.272
12.0-15.0	CH (Medium Stiff)	21.13	57.3				

Note: LL and PL are from samples at depths of 3m and 9m depth. LL: Liquid Limit; PL: Plastic Limit; S_u: Undrained Shear Strength W_n: Water Content; R.R: Recompression Ratio; C.R: Compression Ratio

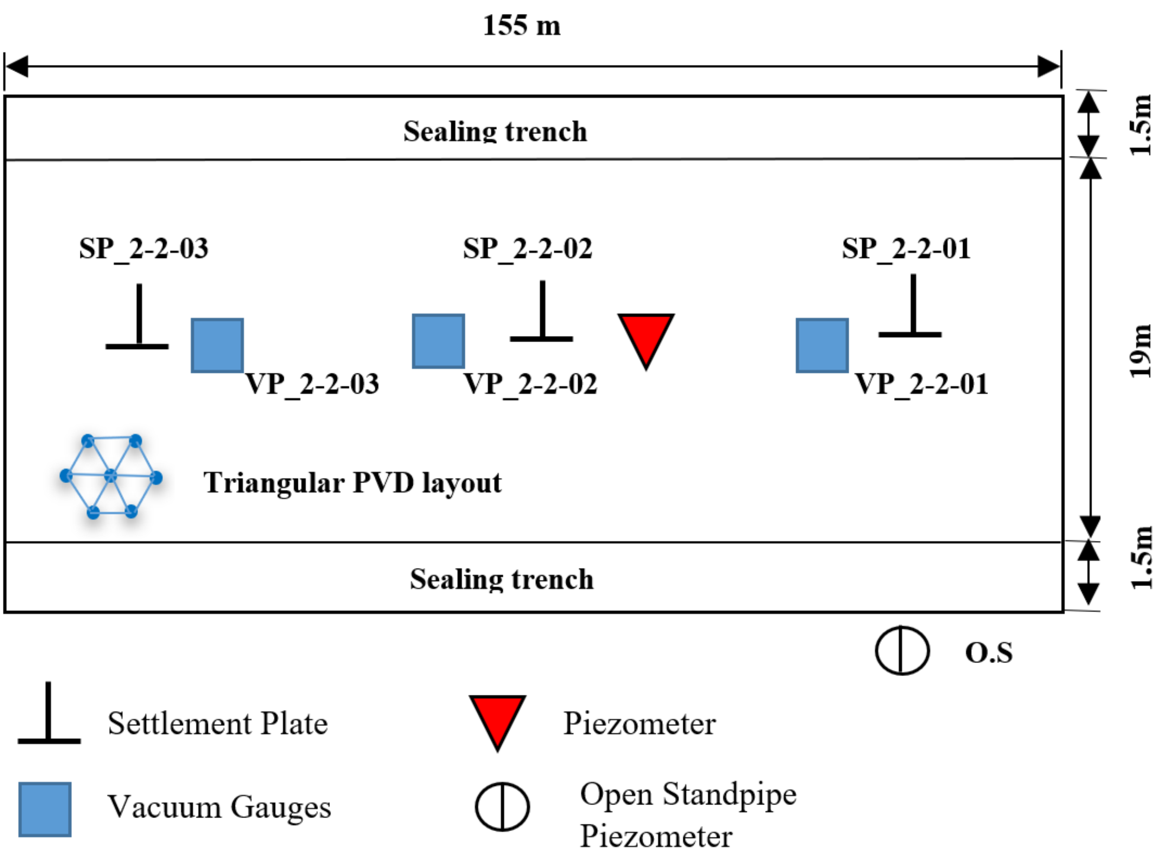

Figure 4. Plan View of Instruments

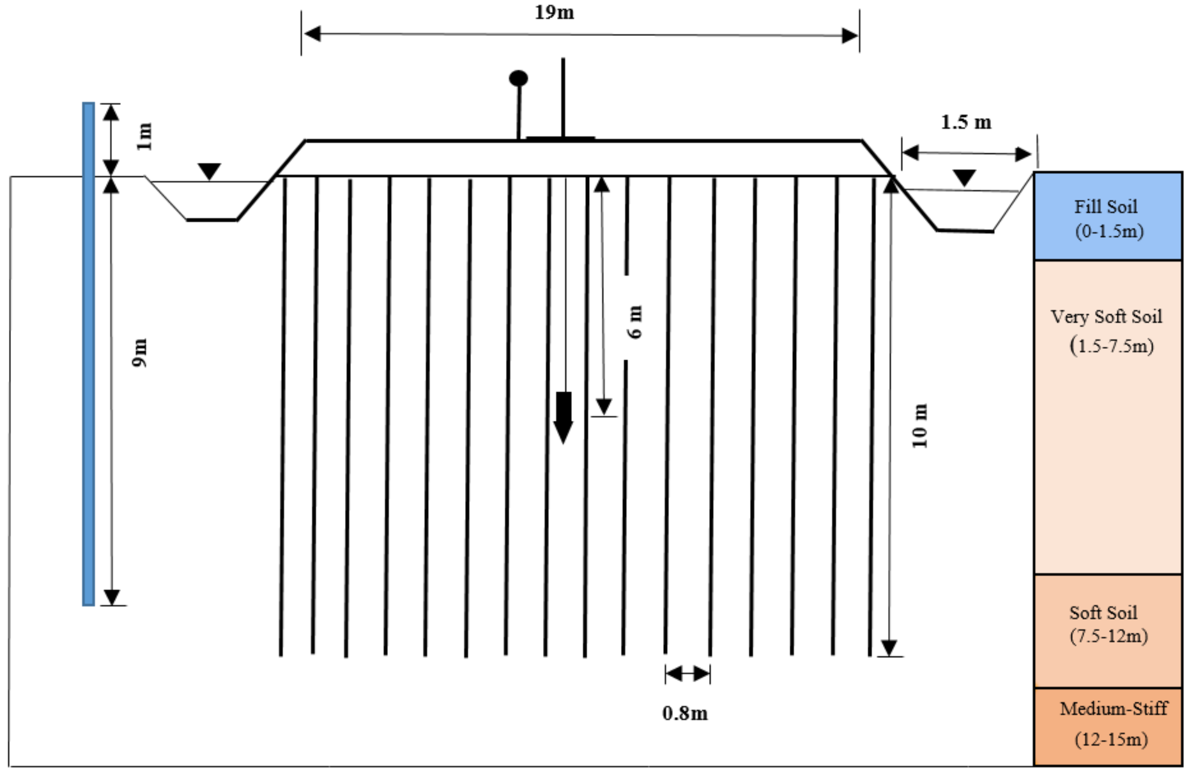

Figure 5. Elevation view of instruments and section

2.4. Instrumentation Outline

Instruments were set up to record the surface settlements, pore pressure, and groundwater level in the field during and after the soil improvement. Three surface settlement plates, namely SP_2-2-01, SP_2-2-02, and SP_2-2-03 were arranged in a longitudinal direction along the centreline of the embankment to record the surface settlements. One standpipe piezometer (10m deep) was installed 3.5m away from the consolidated area to measure the groundwater table and for monitoring the porewater dissipation inside the consolidated area, a piezometer was installed at a depth of 6m below the ground level. Three vacuum pumps were used to facilitate the consolidation process and connected to subsequent gauges i.e. VP-2-2-01, VP-2-2-02, and VP-2-2-03 to measure the available vacuum pressure below the airtight sheet. A sealing trench of 1.5m width was dug on either side to isolate the area using geotextiles and geomembranes. The plan of instruments along with the section has been presented in Fig. 4 and 5, respectively.

2.5. Methodology

The method of VCM adopted was the air-tight sheet method (Fig. 1) and no embankment surcharge was used in this case. The construction sequence can be summarized as follows:

- Site clearance and filling of the pond with soft clay lumps without pumping the water out.
- Leveling of the site and building a 0.5m thick sand blanket platform using clean sand.
- Installation of PVD’s (triangular pattern) at a spacing of 0. 8 m using installation rig (Fig. 6).
- Installation of perforated horizontal drains (HDPE) and connecting them to vertical PVD’s for drainage (Fig. 7).
- Spreading of geotextiles over the sand cushion (to prevent geomembrane from being damaged) followed by geomembranes (air-tight sheet) and sealing the area using a 1.5 m wide sealing trench (Fig. 8).
- Operation of vacuum pumps at -75 to -85 kPa until the required degree of consolidation is achieved (Fig. 9).

Figure 6. Installation of PVD using installation rig

Figure 7. Installation of perforated horizontal drains

Figure 8. Spreading of geotextiles and sealing trench excavation

Figure 9. Site during operation of pumps

Criteria for soil improvement: Required Degree Of Consolidation (DOC) = 80%
Required Shear Strength: 2 t/m^2
Design preloading Period: 120 days

3. Results and Discussion

3.1. Vacuum Pressure and Settlement:

The surface settlement data were recorded during and after the preloading period. The vacuum pumps were operated for a total of 112 days whereas the settlement data were recorded till 128 days from the start. The vacuum pressures from all the vacuum pumps were recorded throughout the preloading period. The vacuum pressures(negative) were well maintained in between 75-85 kPa except during some duration where there was a shortage of electricity. Fig. 10 shows the surface settlement against the elapsed time corresponding to the available vacuum pressure at that time.

During the normal operation of vacuum pumps, the settlement followed a constant trend. Fig. 10 also shows that when the vacuum pressures dropped from an average of -76 kPa to -26 kPa (in between the 56th -60th days), there was a sudden reduction in the rate of settlement. To illustrate the changes in settlement behavior starting from the initial stages of vacuum preloading to the post vacuum stage, the rates of settlement with elapsed time have been plotted in Fig. 11. Two of the settlement plates, SP_2-2-01 and SP_2-2-02 amongst the three available have been used for plotting the graphs as the second and third settlement plates have similar values.

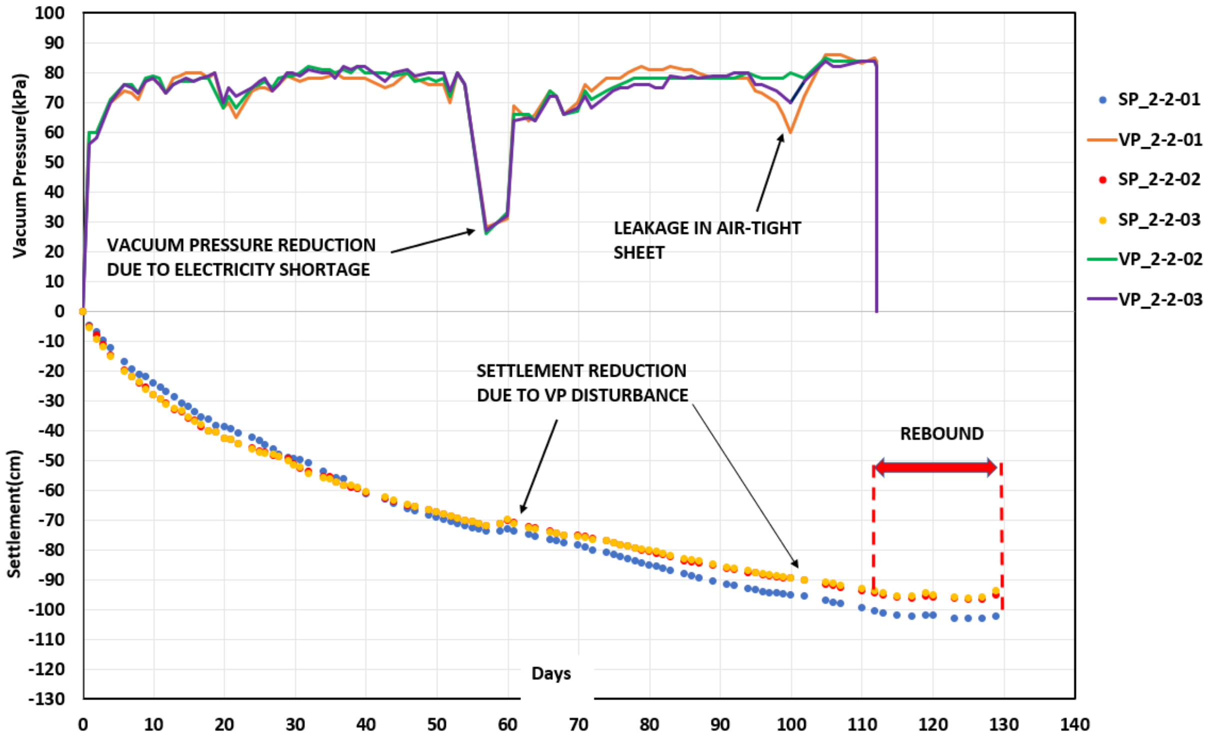

Figure 10. Settlement behavior with vacuum pressure

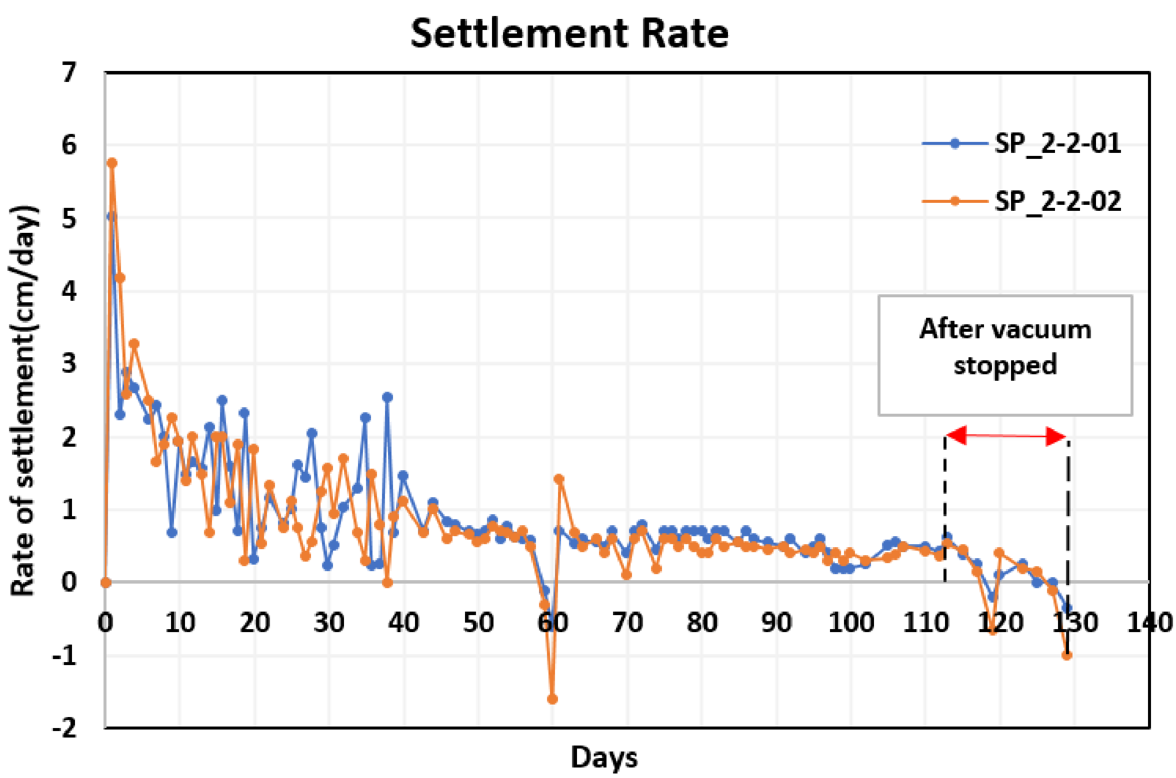

Figure 11. Surface settlement rates during and after vacuum application

Fig. 11 depicts that during the initial stages of vacuum application the surface settlement had a high rate; 5.5cm/day and 5.7cm/day as recorded from the first and second settlement plates respectively. This can be explained by the fact that in the early stages of VCM the soil still had a low degree of consolidation and thus experienced larger settlement. However, with the increasing time, the consolidation degree in soil increased and in the later stages, the rate of settlement was almost constant, which corresponded to the end of consolidation. Furthermore, after stopping the vacuum pumps, the settlement rates from SP_2-2-01 and SP_2-2-02 were -0.35ccm/day and -0.65 cm/day. This is due to the rebound phenomena, indicating that soil underwent swelling due to a rise in pore pressure in the absence of vacuum. Throughout the preloading period, the rate of settlement from SP_2-2-01 was slightly higher than that recorded from SP_2-2-02 until the 60^{th} day after which they had relatively similar values.

3.2. DOC and Final Settlement Estimation

In vacuum preloading, the final settlement needs to be predicted to calculate the DOC in the field at that time. Furthermore, the DOC requirement needs to be met before stopping the ground improvement procedures, so it is one of the important parameters. The prediction of the final settlement, in this case, has been made based on two different methods, and a comparison of the final DOC has been done. The first method involves the use of a 1-D consolidation equation to predict the final primary consolidation settlement which can be given as:

$$S_c = H[R.Rlog\left(\frac{\sigma'_p}{\sigma'_{vo}}\right) + C.R\left(\frac{\sigma'_{vf}}{\sigma'_p}\right) \quad (1)$$

where;

S_c= Final settlement under primary consolidation; R.R = Recompression Ratio; C.R = Compression Ratio; σ'_{vo}= Initial overburden; σ'_p= Maximum Past Pressure; σ'_{vf}== Final Effective Stress; H= Height of Soil Layer

The final settlement calculated based on Eq.1 has been presented in Table 2.

The second method is based on the use of an observational procedure proposed by Asaoka [20], in which the field settlement data is used to calculate the final settlement and DOC.

In this method, he expressed the settlements at a certain time interval (7 days) as a first-order approximation:

$$S_j = \beta_o + \beta_1 S_{j-1} \quad (2)$$

where S_j is the settlement at time j, S_{j-1} is the settlement at time j-1. β_o and β_1 are the intercepts and slope of the straight line, respectively.

First, the plot of S_j on the y-axis and S_{j-1} on the x-axis is made and the equation of trendline is obtained in the form as expressed in Equation 2. Another straight line (45°) with equation x=y is plotted and the final primary settlement is the intersection between these two lines, i.e., S_j=S_{j-1}. If S_f is the final settlement, it can be expressed as:

$$S_f = \frac{\beta_o}{1-\beta_1} \quad (3)$$

For calculation of final settlement and DOC, settlement data recorded from SP_2-2-01 and SP_2-2-02 were used. Fig. 12 shows the plot of the final settlement based on this method.

The DOC at time j can be calculated as the ratio of settlement at that time and the final settlement under primary consolidation obtained from Fig. 12. The values have been presented in Table 2.

The final values for settlement and DOC obtained from both the applied methods were in a very good agreement and indicated that the final DOC after preloading had met the required criteria within the stipulated design period.

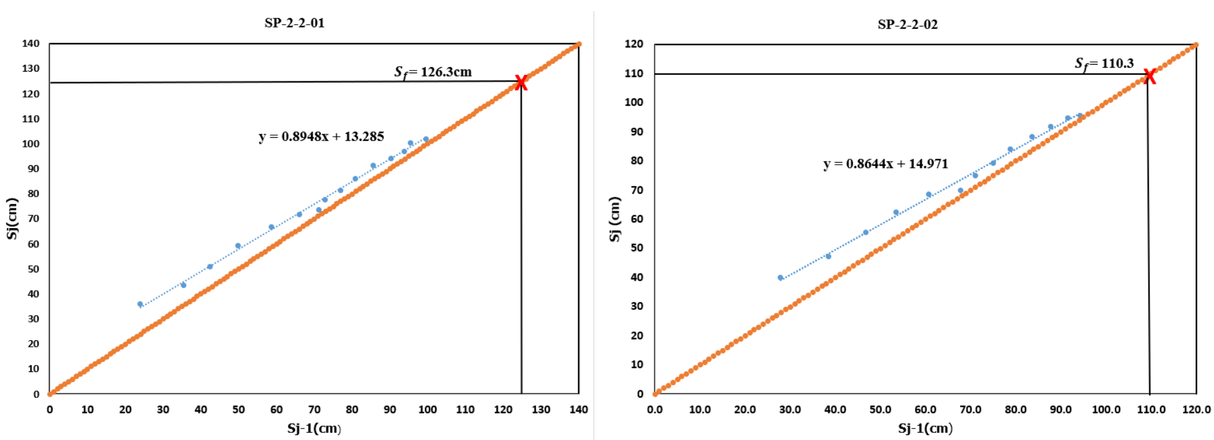

Figure 12. Final settlement prediction using Asaoka Method

Table 2. Final settlement and DOC calculation

Settlement Plate	Settlement (Sj) cm	Final Settlement(S_f) cm		DOC(%)	
		Asaoka	1-D Consolidation	Asaoka	1-D Consolidation
SP_2-2-01	101.8	126.28	121.3	80.61	83.2
SP_2-2-02	95.9	110.41	121.3	86.8	80

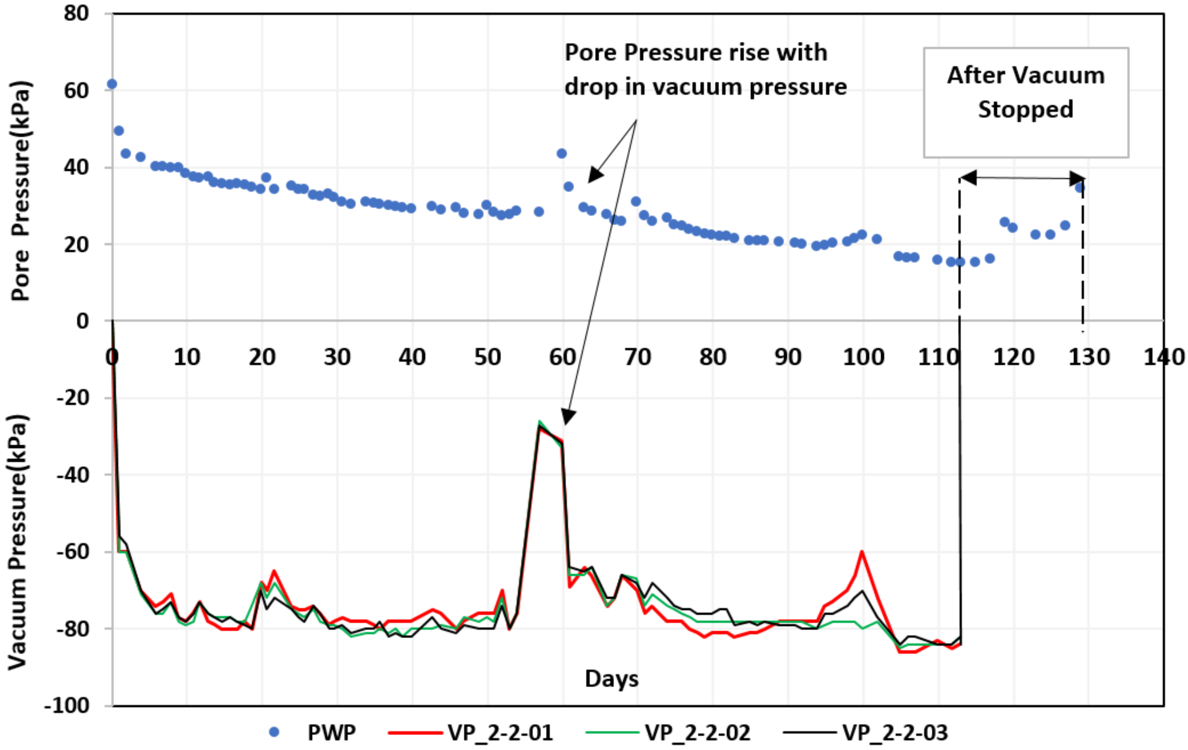

Figure 13. Pore pressure dissipation with time

3.3. Vacuum Pressure and Pore Pressure

Vibrating Wire Piezometer was installed at a single depth of 6 m below the ground level to monitor the pore water pressure. The dissipation of pore pressure in the soils with elapsed time has been plotted in Fig. 13, the measured pore pressure values correspond to the available vacuum pressure at that time under the air-tight sheet. After the application of vacuum pressure, the pore pressure started to drop down as the water started draining out of the soil particles towards the PVD's and in turn to the drainage layer at the surface.

The initial pore pressure measured at t=0, or day 0 before the pump operation was 61 kPa, which shows that there was excess pore pressure of about 11 kPa at 6m depth. Considering the groundwater level was at 1.3 m below the surface, this could be because of 2 reasons; due to the filling works or due to excess pore pressure generation during the installation of the piezometer. With the increase in time, the pore pressure constantly dissipated, except in between days 56-60, when the vacuum pressure dropped down and the pore pressure significantly rose from 28 kPa to 43 kPa in 3 days. Furthermore, approximately 95 days later there was another power outage and a 3 kPa rise in pore pressure. Finally, on the release of vacuum pressure on the 112th day, the increase in pore pressure was 19 kPa in 16 days. It is to be noted that all these incidents indicate that a drop in vacuum pressure showed a significant effect on the pore pressure dissipation of the consolidated area. In the consolidation of clay layers, as the increase in effective stress is directly related to the reduction in pore pressure, thus it is essential to maintain a constant vacuum pressure for a better strength gain.

3.4. Local Groundwater Table Variation during Vacuum Preloading

Groundwater table can be an important factor to be considered when there are structures such as buildings, or critical slopes nearby the improved area, and fluctuations in the water table can create problems. To monitor the behavior of the groundwater table outside the VCM area, an open standpipe piezometer was installed 3.5m away from the VCM Zone. The top face of the piezometer was 1m above the ground level and the remaining 9m was below the ground level as shown in Fig. 14. Since the piezometer was located adjacent to VG_2-2-01; pressure recordings from the same gauge have been used for comparison with the fluctuations in the water table. The initial readings were taken on August 8, two days before the start of vacuum pumps which showed that the groundwater table was located 1.38 m below the ground surface. Hereinafter, the piezometer was monitored at an interval of every 7-10 days, the final readings were taken until 12 days after the termination of the pump.

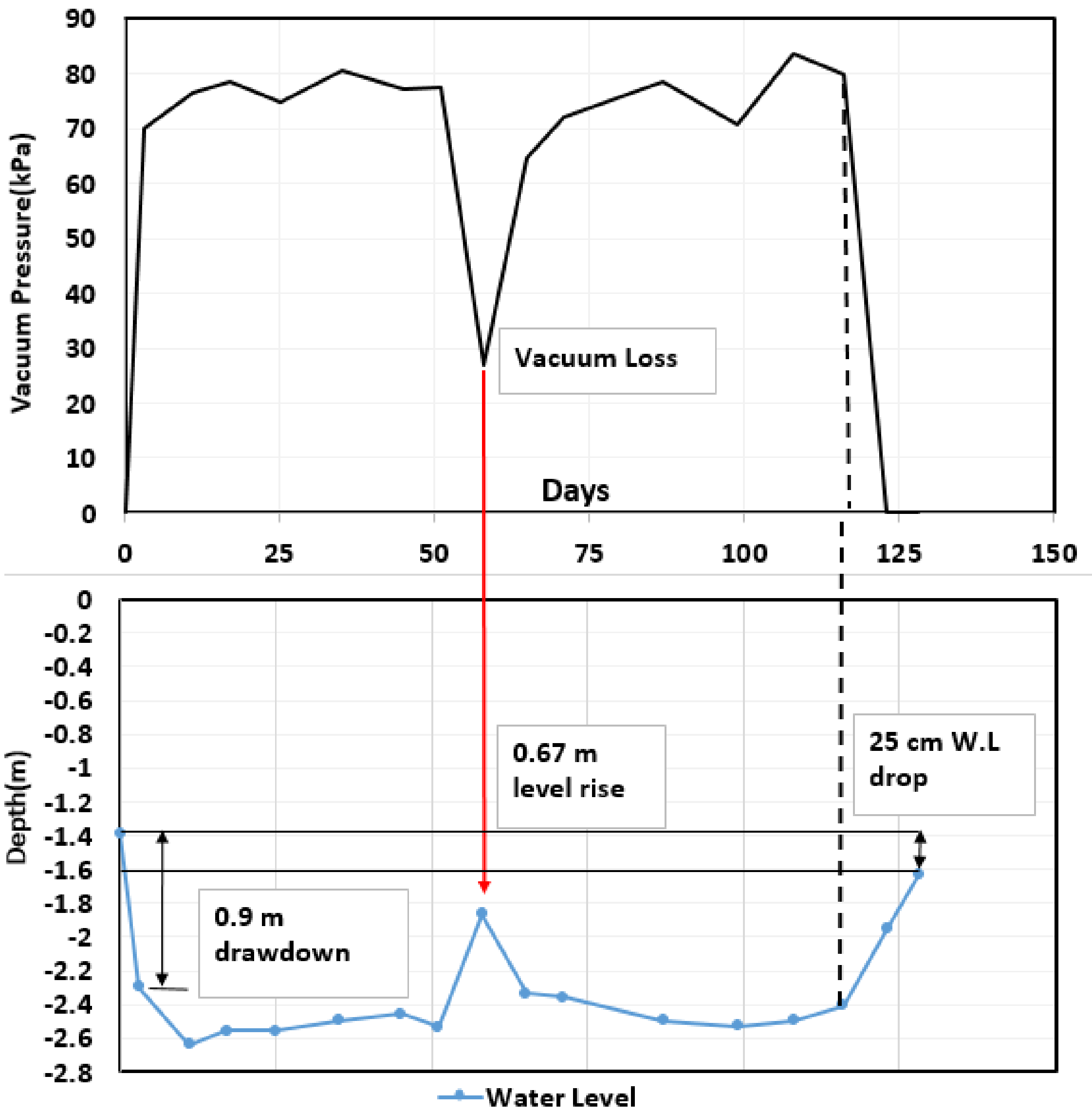

Figure 14. Groundwater table variation outside VCM Zone

Initially, when the pumps were turned on, there was a water level drawdown of 0.9 m in 3 days and with the rise in pump pressure it increased to 1.2 m. Fig. 13 shows that after a sudden drop initially, the water level remained constant thereafter, and rose by 0.67 m when there was a disturbance in the pump pressure in between. The sudden drawdown in the water level may have been caused by the suction effect in the VCM zone and in the absence of a deep cutoff adjacent to the improved area, the water level in the surrounding area lowered. After the termination of vacuum pumps, the water level rose again and the final elevation was 1.6 m below the ground surface. The final groundwater table inside the VCM zone was measured after the completion of the works, and it was found to be 0.4 m below the ground surface. Considering the settlement of approximately 1 m in the VCM zone, the final water level is nearly the same as the initial stage. Outside the VCM Zone, the local groundwater table lowered by around 25 cm. The pre and post-investigation results showed that during the pump operation the groundwater table outside the VCM area lowered and remained stable throughout but the local groundwater level pre and post improvement do not vary significantly.

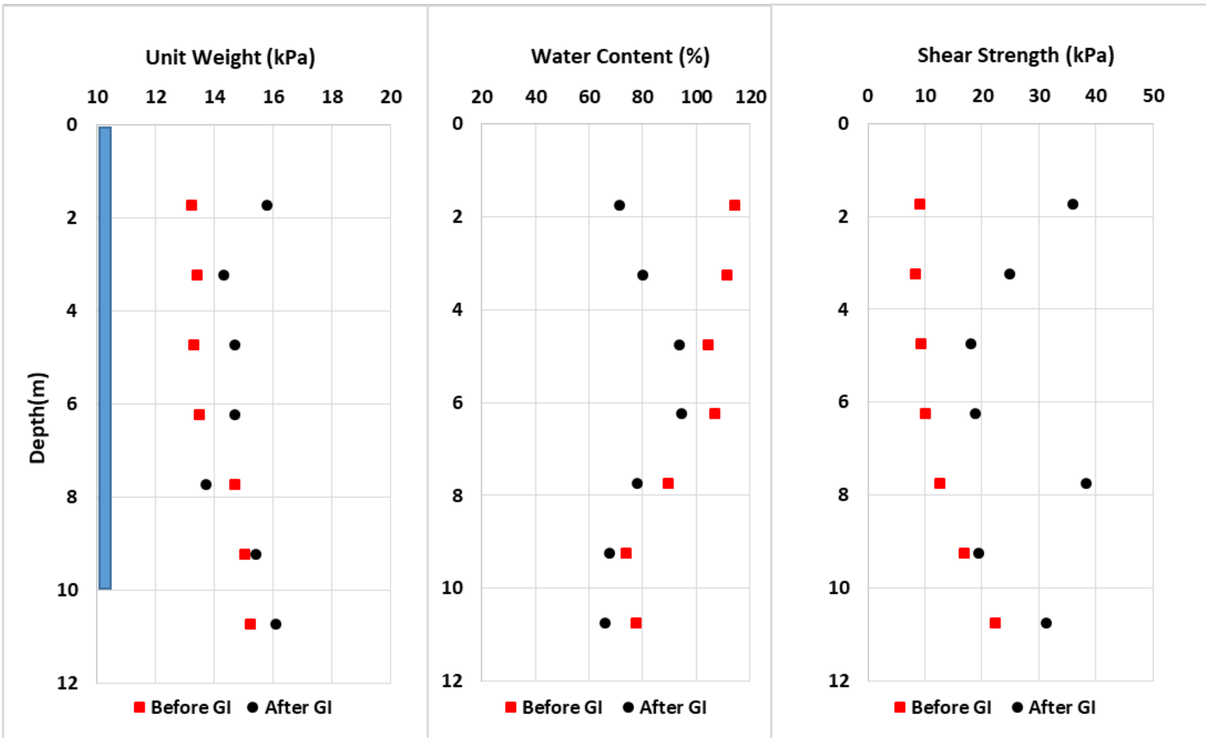

Figure 15. Comparison of soil properties

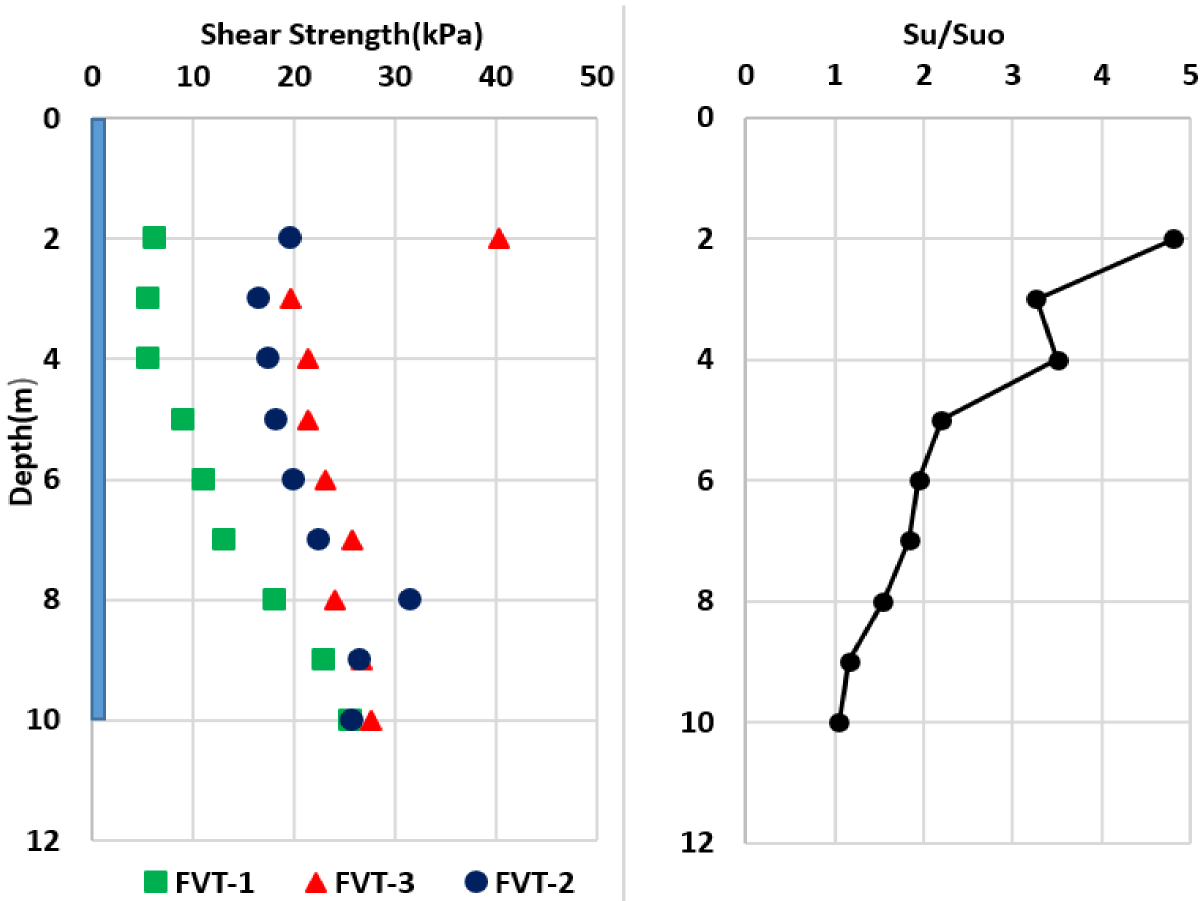

Figure 16. Shear strength improvements

3.5. Improvement in Soil Properties

After the end of soil improvement, one borehole and two field vane shear tests were done at the locations close to the previous ones carried out before the soil improvement. The initial and final groundwater tables were located 1.3m and 0.4m below the ground surface. The index properties of soil such as water content, unit weight and shear strength (UC-test) obtained before and after the soil improvement has been plotted in Fig. 15. (The blue line on the edge of the plot shows the depth of PVD i.e. 10m.) After improvement, the reduction in water content was recorded to be between 1.5-28% at different depths and the unit weight of soils increased post improvement. This is because the settlement caused the soil particles to be more compact after the improvement.

Furthermore, the shear strength measured from UC-test showed increments in the range of 15-300%. The shear strength increased by 26 kPa at the depth of 1.75 m and decreased with depth; however, at the depth of 7.75 m there is a large increment of 25 kPa which could be due to measurement errors or anomalies in soil property. Fig. 15 illustrates that the shear strengths have improved nearly two times after VCM in the depth between 3.75- 6.25 m.

Even in soil layers below the PVD depth, the shear strength measured from UC tests increased by some amount. This is because the water content is low and there is increased overburden due to consolidation in upper layers.

3.5. Shear Strength Results from FVT

Field Vane Shear Tests were carried out using Geonor Standard SGI vane borer in accordance with ASTM D 2573 in an interval of 1m. The shear strength of both disturbed, as well as undisturbed samples, were obtained, and then the values of undisturbed samples were corrected for anisotropy. Fig. 16 shows the improvements in shear strength after the completion of ground improvement.

The FVT results indicated that the shear strength increased by 1-5 times the initial undrained shear strength. At the depth of 2 m, the average shear strength increased by an average of 22 kPa, and at a depth of 4 m, it increased by an average of 19 kPa. The ratio S_u/S_{uo} in Fig. 16 is simply the number of folds by which the shear strength increased (increment ratio). It can be observed from Fig. 16 that the increment ratio is high in the upper regions and gradually decreases with the increase in depth. The results obtained from UC-tests (Fig. 15) also show a similar trend as the FVT in terms of improvement. The reason behind the better improvement in the upper regions is because of better drainage and distribution of atmospheric overburden stress which goes on decreasing with depth. This kind of behavior was also observed by Alditra [19] for ground improvement using a similar method. In addition, Mesri [21] also reported that the ratio S_u/S_{uo} decreases for normal soil profiles showing an increase in effective overburden/undrained shear strength with depth and vice versa.

4. Conclusions and Recommendations

From the field monitoring data and analysis, the following conclusions can be made:

(1) A vacuum pressure of 75-85 kPa is achievable in the field when the air-tight membrane and vacuum pump work efficiently without any disturbances and soft soil up to 10 m depth can be improved by combining vacuum pressure with PVD.

(2) The settlement and pore pressure dissipation are directly dependent on the available vacuum pressure under the airtight sheet. Since the final DOC is dependent on these two values, it is essential to maintain a constant vacuum pressure during the soil improvement.

(3) The groundwater table outside the VCM zone initially lowered, remained stable throughout the preloading period, and finally increased on the release of pump pressure. However, the initial and final groundwater levels did not vary significantly in this case.

(4) The values for final settlement and DOC from the 1-D consolidation equation and observational procedure were in good agreement and within close range. Thus, these can be used in combination for the prediction of ultimate settlement in VCM applications. Also, a DOC of 80-87% in soft soils was achieved using vacuum-PVD and the required criteria of ground improvement were met successfully.

(5) The unit weight of the soil increased, and the water content decreased by 1.5-28%. The UC and FVT test results showed shear strength improvements up to 5 folds and in the range of 1.5-300%, respectively. The results further showed that the increments in shear strength obtained from VCM are mostly high in the upper soil profile due to better drainage and distribution of overburden stress.

Post improvement, the land obtained will have primarily consolidated 80-90% under an applied load, as well as gained a substantial amount of strength as observed from the results. So, there will be fewer chances of consolidation settlement in the future and occurrence of failure as well. In the past, infrastructures such as oil storage stations, housing projects, road embankments, and warehouses have been developed on reclaimed as well as non-reclaimed lands improved by the vacuum-PVD scheme. [7, 8, 19, 22]. So, the VCM method can be recommended as a suitable method for improving foundations consisting of soft soils.

However, several challenges can be encountered during the application of VCM and one of the main challenges is maintaining airtightness in the field. Since the geomembrane is sensitive and can easily get damaged by external sources, the field needs to be continuously monitored for any leakages and damage to the sheet. In addition to this, there may be unnoticed crack layers along the boundary of the VCM area causing leakages in the field. The second challenge is maintaining the efficiency of vacuum pumps throughout the improvement duration, power outages and cuts may result in disturbances in the field which cause an immediate reduction in the settlement as presented in the paper. Besides this, due to the settlement in the field, PVD's may undergo buckling and their efficiency might decrease towards the end. The efficiency reduction over time may also be because of clogging in PVD due to fine particles. These might be some of the factors directly or indirectly impacting the degree of ground improvement from VCM and it is recommended to consider all of these while interpreting the results from VCM.

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