Consideration of Multiple Factors for Quality Control of Improved Clay from Vacuum Consolidation Method

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ABSTRACT: The degree of consolidation of clay under improvement by the Vacuum Consolidation method is typically used as a deciding factor of whether the improvement is fair enough for its use in Engineering purposes. It is a determining factor whether to stop the consolidation of clay by shutting down the vacuum pump or continue for additional improvement in soil. The ASAOKA method is a widely accepted technique for the calculation of the degree of consolidation for this purpose. However, the results from this method can only be reliable when the load is constant. It is particularly challenging to keep the loading constant. This may be due to the addition of extra load due to rain or sudden reduction of vacuum pressure, due to accidents such as power cuts. Vacuum leakage has also been observed on site due to the presence of cracks on stiff clay or the presence of sand layers. It is, hence, beneficial to include several other factors to decide to stop vacuum preload. This paper deals with the use of multiple factors in the decision for the vacuum pump to shut down. Research is conducted in two sites in Bangkok, each divided into multiple zones. The over-consolidation ratio and soil strength parameters before and after improvement from various in-situ and laboratory tests, the field settlement rate, the amount of post-vacuum settlement are some of the methods incorporated as deciding factors for quality control of improved clay, and finally, the decision to stop vacuum preloading. Furthermore, the final field settlement in each zone is compared with the value of theoretical settlement obtained by Terzaghi's consolidation approach as well as results from other recent research. Consideration of such multiple factors together not only ensures a better quality of work in soil improvement but also reduces the chances of under-looking certain crucial aspects and prevents failure from those disciplines instead of relying solely on the ASAOKA method.

KEYWORDS: Vacuum Consolidation Method, Pump Shut down, Quality control, Settlement rate, and ASAOKA.

1. INTRODUCTION

The vacuum consolidation method of soil improvement has become one of the most popular methods and is suitable when the site consists of soft clay over the course of the year. Due to several advantages and conveniences provided by this method such as the non-obligatory use of other forms of preloading other than vacuum, accelerated consolidation method, and an environment-friendly approach, it has become the first choice for improvement of soft clay deposit for Geotechnical Engineers. Various applications of the use of the vacuum consolidation method have been performed and studied (Bergado, Chai et al. 1998, Bergado, Balasubramaniam et al. 2002, Indraratna, Rujikiatkamjorn et al. 2005, Mesri and Khan 2011, Mesri and Khan 2012).

(Asaoka 1978) developed a statistical method to calculate the degree of consolidation (DOC) of clay at any time under improvement by vacuum consolidation method using field settlement data. Due to its simplicity, it is a highly prevalent method to calculate the DOC, and the very data is used as the basis for the decision of whether to stop or continue the further consolidation. However, several problems arise while using this method. Firstly, it is only a statistical method, which depends on the value of field settlement, indicating that the value of DOC changes accordingly when field settlement is changed. Furthermore, the ASAOKA method can only be used when the load is constant, which is not the case in the field. There exist uncertainties on the site such as unexpected disruption in the electricity supply, vacuum leakage, and rain effect. The leakage of vacuum pressure from the area also reduces the efficiency of soil improvement by VCM. The vacuum leakage occurs due to some unavoidable site conditions such as the presence of sand layer, garbage, or cracks in stiff clay in the area that has to be improved by VCM. The abrupt power cut reduces the vacuum pressure to nil for that particular time period. The rain adds extra load which also acts as preload, the duration and magnitude of which is not predictable and it is next to impossible to avoid the preload increase due to rain. The use of the ASAOKA method in such a scenario adds error in the result making it unreliable, and decisions taken according to this could be fatal. Hence, quality control in such projects demands the decision to be taken based on several criteria. This will minimize the possibility of taking a biased and possibly incorrect decision based on a single criterion and possible danger and legal issues in future.

This paper deals with the use of multiple criteria for quality control of the soil improved by vacuum consolidation. In this paper, Vacuum preload is used to consolidate the soil in two different sites in Bangkok City. Each site is divided into multiple zones. The field data of settlement, settlement rate, pore water pressure, and vacuum pressure are recorded every day. These data are used to monitor ongoing soil improvement and soil behaviour in real-time and possibly predict the additional time required to complete the consolidation process. The field settlement of each zone in real time is continuously compared with the theoretical value of the final settlement obtained at 90% consolidation i.e., at U = 90% from Terzaghi approach (Terzaghi, Peck et al. 1996) and (Phakdimek 2019). (Phakdimek 2019) indicates that the final settlement at 90% consolidation of backfilled clay is 6.5% of the backfill depth. The study was based on the cases of backfilled clay in several sites of Bangkok, Thailand. The soil exploration tests such as the Field vane shear test, Cone penetration test, SPT, and Spectral Analysis of Surface Waves (SASW), are performed before and after improvement by vacuum. The laboratory tests such as Unconfined compression (UC) tests, and oedometer tests are also performed before and after the soil improvement. The strength and over-consolidation ratio of soil samples before and after improvement are compared. The post-vacuum settlement after 3 years' time period is calculated, which is also considered a crucial factor to decide whether the pump shut down.

2. METHODOLOGY

2.1 Test Site and General Description

The test site consists of two sites in Bangkok, named the Noble Wisdom site and the Grandio site. The Noble Wisdom site was located in Khwaeng Lat Phrao, Khet Lat Phrao, Bangkok, whereas the Grandio site was situated in Bang Kaeo, Bang Phli District, Samut

Prakan Province. Each of the sites has six or more zones. Table 1 shows the details of the test sites for this research.

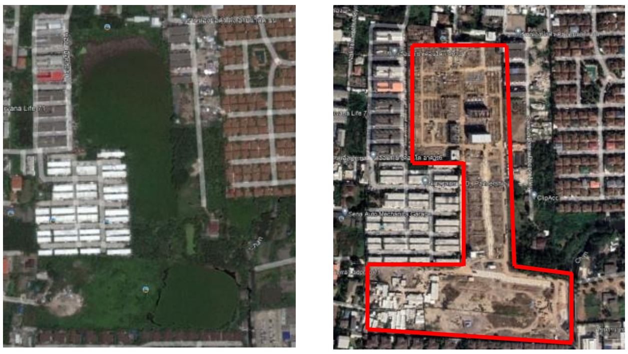
Table 1 Test sites for the research

Site name	Total number of zones	Location
Noble Wisdom	5	Khwaeng Lat Phrao, Khet Lat Phrao, Bangkok Province
Grandio	6	Bang Kaeo, Bang Phli District, Samut Prakan Province

The Grandio site, as shown in Figure 1 was initially an abandoned pond, which was backfilled with soft clay. The maximum depth of reclamation was 17m, whereas the maximum depth of PVD was 19.5m, since the height of the embankment from the ground level was 2m and PVD was inserted 0.5 m deeper from the base of the pond, since there was a layer of soft clay naturally below the base. The target vacuum pressure was 80 kPa. The site would be used for housing construction after the soil improvement. The Noble Wisdom site was also an abandoned pond, which was backfilled with soft clay. The area had to be improved for the housing project, for which the maximum depth of PVD was 14.7m. The target vacuum pressure was 80 kPa. Figure 2 shows the Noble Wisdom site before and after improvement by VCM.

2019 (before) 2023 (now)

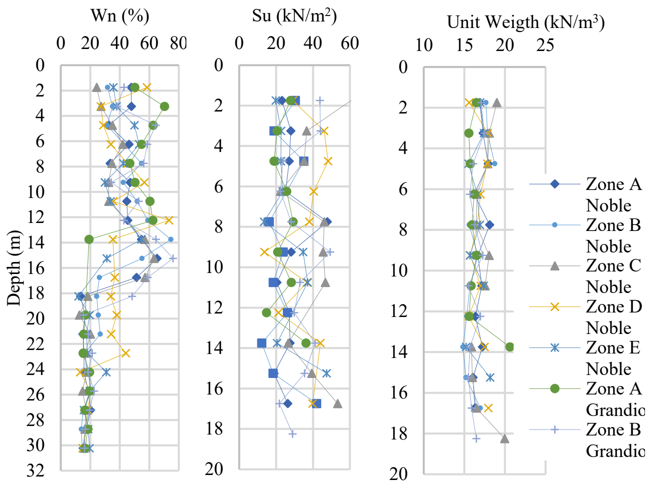
Figure 1 Location of Grandio site before backfill in 2019 and after VCM improvement in 2023



2016 (before) 2023 (now)

Figure 2 Location of Noble Wisdom Site in its natural form 2016 and after the completion of improvement by VCM in 2023

The soil investigation at test sites shows that the backfilled soil was primarily soft-to medium-stiff with an undrained shear strength of approximately 20kN/m2 to 40kN/m2. Figure 3 shows the profile of moisture content, undrained shear strength of the test sites from the unconfined compression (UC) test, and unit weight before improvement by vacuum consolidation.



(a) (b) (c)

Figure 3 Soil properties of backfilled soil at test site

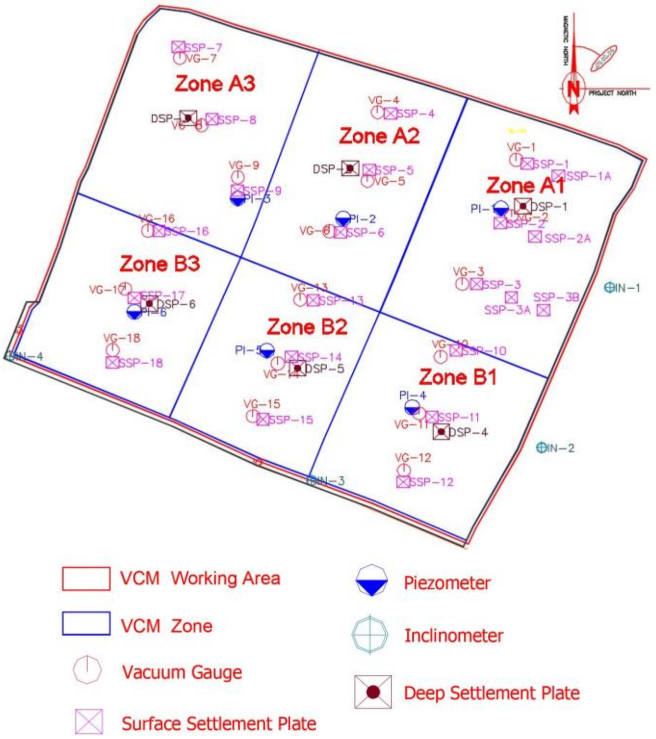
The settlement at different zones of each site at 90% consolidation i.e., at U = 90% was predicted from (Terzaghi, Peck et al. 1996) and (Phakdimek 2019) method, the details of which is given in Table 2. (Phakdimek 2019) indicates the final settlement at 90% consolidation of backfilled site is 6.5% of the depth backfilled.

Table 2 Settlement prediction at 90% consolidation by (Terzaghi, Peck et al. 1996) and (Phakdimek 2019)

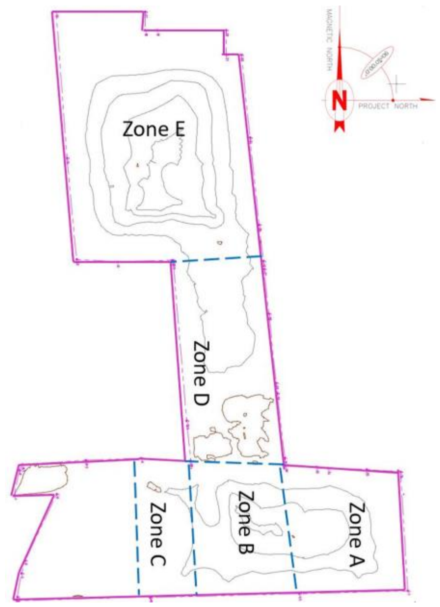
Site name	Zone	PVD length (m)	Settlement at U=90% from Terzaghi approach (m)	Settlement at U=90% from empirical approach (m)
Grandio	A1	17	0.965	1.1
	A2	17	1.245	1.1
	A3	17	0.709	1.1
	B1	17	0.97	1.1
	B2	17	0.894	1.1
	B3	17	0.71	1.1
Nobel Wisdom	A	14.7	0.97	0.94
	B	14.7	1.21	0.94
	C	14.7	1.05	0.94
	D	14.7	1.01	0.94
	E	14.7	1.2	0.94

2.2 Instrumentation

The vacuum preloading for the Grandio site was applied for the whole area, which was divided minutely into six zones, namely; A1, A2, A3, B1, B2, and B3. The preload was vacuum pressure of 80 kPa and sand embankment of 2m height. The Noble Wisdom site; however, was divided into 5 zones, namely; A, B, C, D, and E. Both areas were covered with an air-tight geomembrane sheet to prevent vacuum leakage. The prefabricated vertical drains (PVD) were arranged in a rectangular layout with a 1m distance between each PVD. Figure 4 (a) shows the plan view for monitoring the Grandio site separated into various zones with monitoring instruments. There are 19 surface settlement gauges, 6 deep settlement gauges, 4 inclinometers, 18 vacuum gauges, and 8 piezometers. Table 3 shows the details of the number of instruments in each zone in both sites. Figure 4 (b) shows the Noble site separated into 5 zones, instrumentation layout in each of the sections in the site is shown in Figure 4 (c).



(a)



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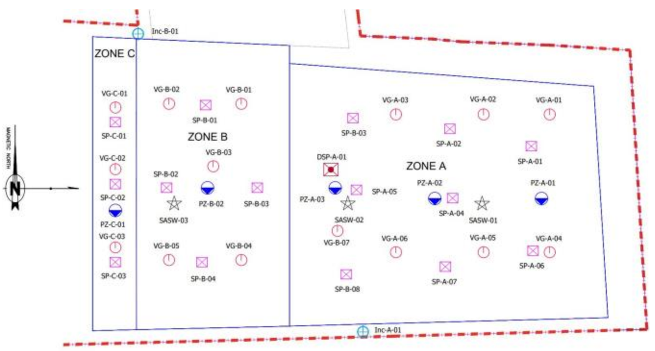
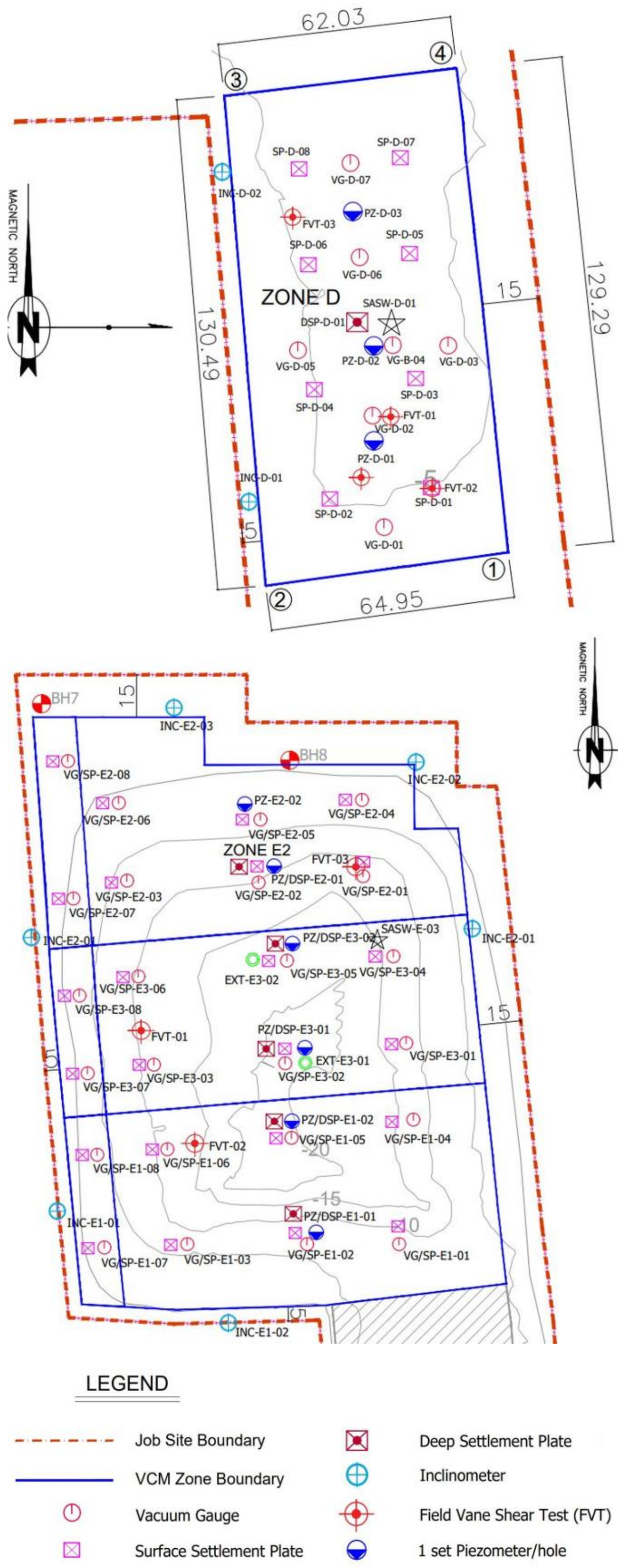




(c)

Figure 4 Plan view test sites with monitoring equipment at (a) Grandio Site (b) Noble Wisdom site (c) Nobel wisdom site separated into different zones

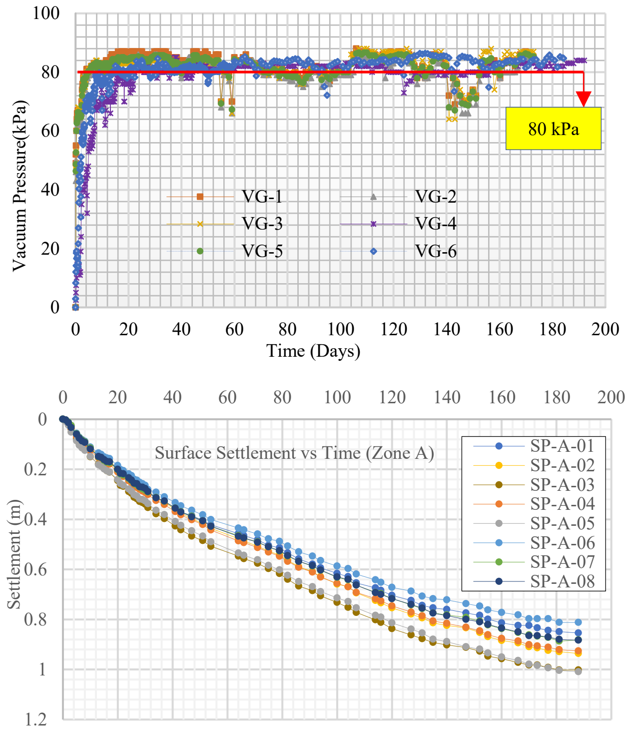
Table 3 Instrumentation detail

Site name	Zone	Surface settlement plate	Deep settlement plate	Vacuum gauge	Piezometer	Inclinometer
Grandio	A1	3	1	3	1	1
	A2	3	1	3	1	-
	A3	3	1	5	1	1
	B1	3	1	3	1	1
	B2	3	1	3	1	1
	B3	4	1	3	2	-
Nobel wisdom	A	8	4	7	3	-
	B	4	-	5	2	-
	C	3	-	3	1	-
	D	8	1	7	3	-
	E	24	5	24	6	-

3. RESULTS

3.1. Vacuum pressure and settlement

The area for improvement was preloaded with a vacuum of 80 kPa in both sites. Figure 5 shows the vacuum pressure under the sheet and corresponding settlement values at the same time for zone A, B, and C of the Noble Wisdom site. The settlement values are plotted in cumulative form and were measured in the field by surface settlement plate. The settlement values concerning time show high settlement during the starting time of the application of the vacuum. This value, however, becomes less with time, and towards approximately 170 days of application of vacuum, further settlement is almost nil. Similarly, the pressure under the sheet in most zones is slightly below 80 kPa. This is caused due to many unavoidable circumstances such vacuum leakage, and disruption in power supply. There are some points where the vacuum pressure is higher than 80kPa which is due to the rain effect. The rain increases the total weight of the unsaturated soil above the geomembrane, which is acting as preload. This increases the total stress applied to the soil under improvement, and hence, affects the settlement rate. These cases are almost inevitable to prevent totally; however, minimized to the extent possible. These reasons prevent the load being constant, which makes the using of only ASAOKA method for shutting down the pump unreliable, and hence demands other methods for taking the crucial decision to stop vacuum preloading.



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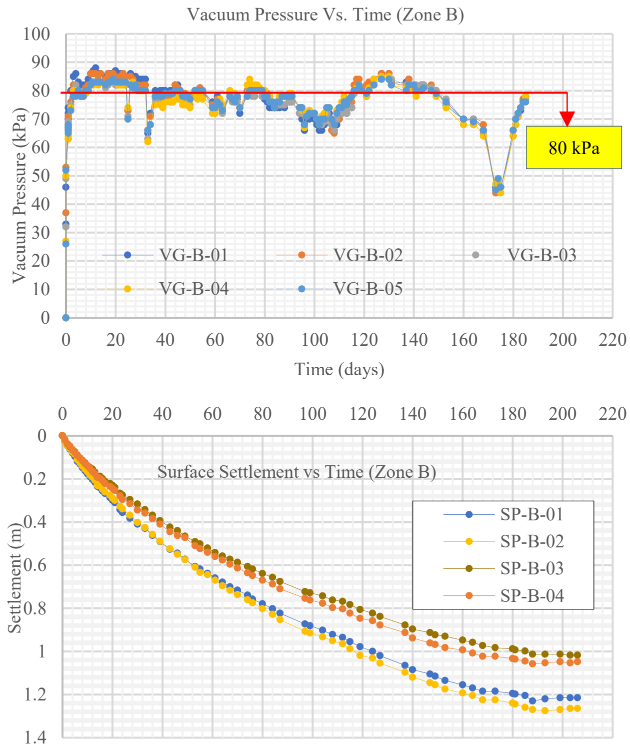

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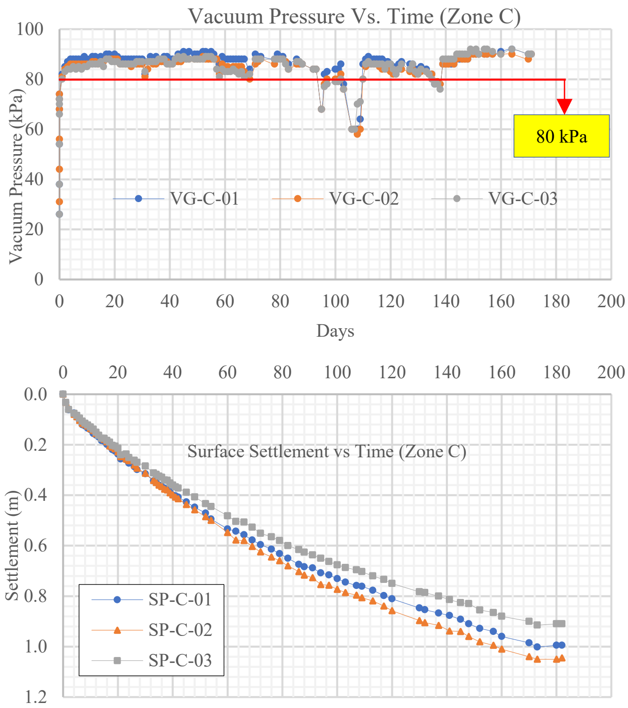


(c)

Figure 5 Vacuum pressure under sheet for different zones and test sites

Each vacuum pressure graphs in Figure 5 shows a straight horizontal line representing 80 kPa pressure. The number of days that that had the vacuum pressure equal to or more than 80kPa was counted for all zones on both test sites. The data from all vacuum gauges of each zone were taken and averaged. Table 4 illustrates the number of days each zone was under the vacuum pressure of 80kPa or more. It should be noted that this value of number of days is the actual day the soil was consolidated for. Hence, it must be nearly equal to or greater than the designated time allocated for improvement of soil.

Table 4 Number of days vacuum pressure was equal to or more than 80kPa in test area

Site name	Zone	Number of days
Grandio	A1	169
	A2	167
	A3	166
	B1	176
	B2	173
	B3	178
Nobel Wisdom	A	183
	B	151
	C	161
	D	170
	E	172

The consolidation by vacuum preload increases the porewater pressure on the test areas. The porewater pressure was measured by piezometers. Although the rate is slow, there was definite dissipation of the pore water pressure due to the application of vacuum, which indicates the increase in consolidation of the soil in the VCM area.

The settlement rate is calculated to study the rate of change of settlement. This is taken as one of the methods for monitoring the area with VCM. Figure 6 shows the 7-day average settlement rate of various zones of the Noble Wisdom site. The settlement time graph of several zones of both sites shows a high settlement rate at the beginning, whereas, it gradually decreases in the long run. Theoretically, the settlement rate should increase during the initial phase of the application of vacuum preloading. This is because the soil will undergo consolidation due to the preload. The consolidation process slows down with time even with the same amount of preload. In that situation, the settlement rate also must slow down accordingly. In practice, when the settlement rate decreases to 0.002m/day or lesser, it is usually considered the correct time to shut down the pump i.e., stop the vacuum preloading operation and perform post-vacuum site investigation to check the quality of improved soil. These settlement values were monitored from the surface settlement plate on the site. Towards the end of the improvement by VCM, the value of the settlement rate was as low as 0.002m/d, before the vacuum preload was discontinued.

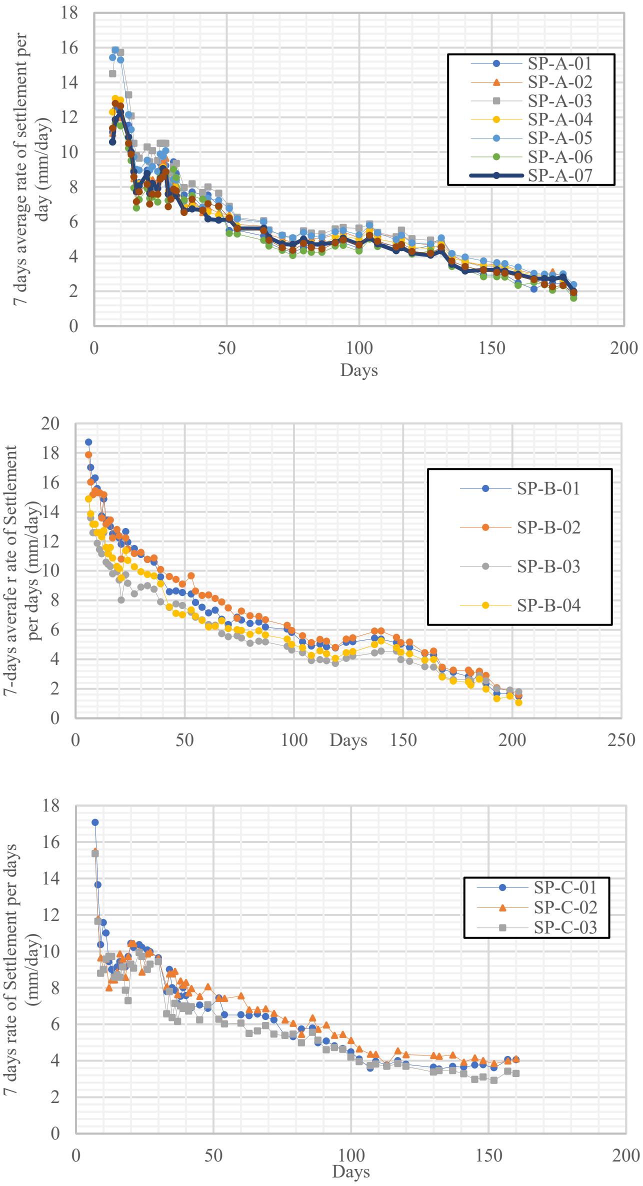


Figure 6 Settlement rate of Zone A, B, C of Noble wisdom site

ASAOKA method of predicting the degree of consolidation (DOC) is another factor used to consider the time to stop the vacuum preloading operation. Asaoka method proposed by (Asaoka 1978), is a statistical method to determine the current degree of consolidation from the settlement values obtained from the field. It consists of Sn and Sn-1 as consequent surface settlement, taken in a fixed time interval analysed about time interval (Δt). Eq (1) and (2) are used to predict the current DOC of the improved area.

$$S_n = \beta_0 + \beta_1 (S_{n-1}) \quad (1)$$

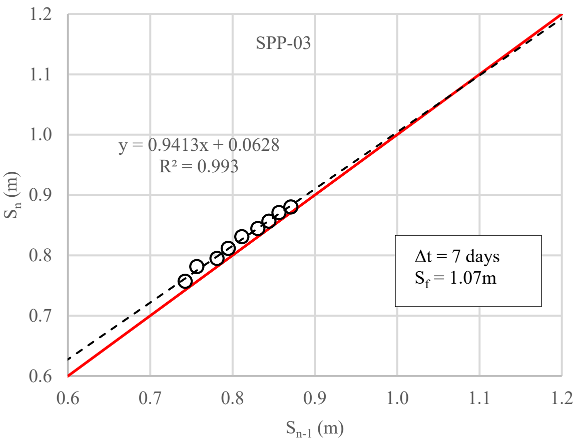
where Sn is settlement at time $t = t_n$ and S_{n-1} is settlement at time $t = t_{n-\Delta t}$ and Δt is time interval.

From Eq. (1), the values of β_0 and β_1 can be obtained as the intercept and the slope of the best fitted straight line of (S_n and S_{n-1}) plot. S_f is the intersection between the S_n-S_{n-1} graph and 45 degree-line. The final primary settlement can be calculated by the following:

$$S_f = \beta_0 / (1-\beta_1) \quad (2)$$

Where S_f is the final settlement at U=100% calculated from ASAOKA method.

The ASAOKA method is used to calculate the DOC for every zone of both test sites. A sample calculation of zone A1 of the Grandio site is shown in Figure 7. The final DOC obtained for different zones in the test sites by using data from surface settlement plate is listed in detail in Table 5. The coefficient of determination (R^2) is high because authors have taken data in a very short interval of time where the loading was constant. However, extrapolation based on this short time interval may not give reliable results.



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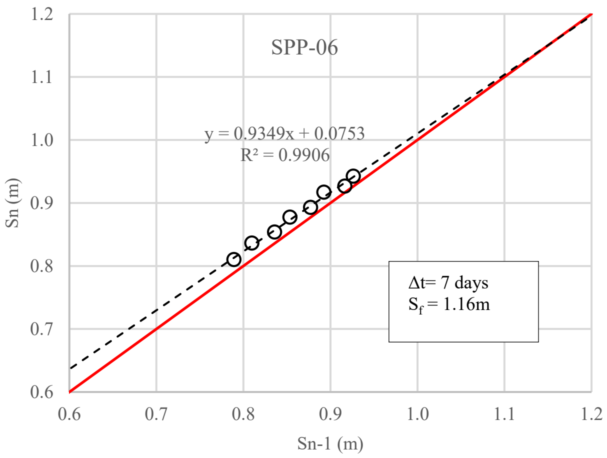

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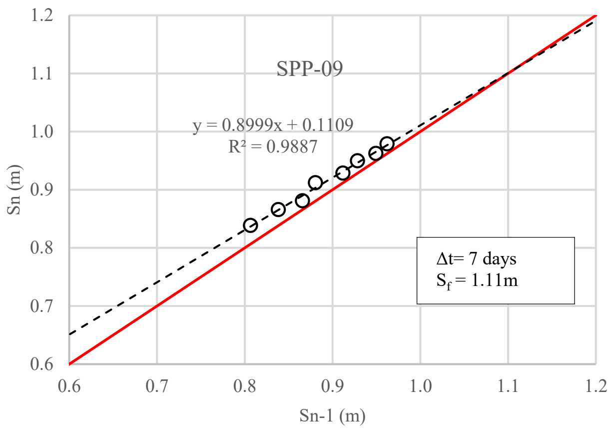

(c)

Figure 7 ASAOKA method to determine the degree of consolidation (DOC) for A Grandio site for Zone (a) A1, (b) A2 (c) A3

Table 5 Degree of consolidation (DOC) obtained from ASAOKA method

Zone	Settlement plate	Length of PVD	S_f (m)	Field settlement (m)	Current DOC by ASAOKA (%)
A1	SPP 01	5	0.76	0.679	88.8
A1	SPP 02	17	1.11	0.908	81.6
A1	SPP 03	17	1.07	0.898	83.9
A2	SPP 04	10	1.06	0.828	88.3
A2	SPP 05	17	1.15	1.009	87.5
A2	SPP 06	17	1.17	0.937	80.1
A3	SPP 07	5	0.73	0.51	80
A3	SPP 08	10	0.89	0.762	86
A3	SPP 09	17	1.06	0.973	92
B1	SPP 10	17	1.20	1.057	86.8
B1	SPP 11	17	1.48	1.341	89.8
B1	SPP 12	5	0.66	0.652	95.7
B2	SPP 13	17	1.18	0.965	80.4
B2	SPP 14	17	1.39	1.357	96.6
B2	SPP 15	10	1.11	1.081	96.4
B3	SPP 16	17	1.61	1.099	87.4
B3	SPP 17	17	1.54	1.255	80
B3	SPP 18	17	1.02	0.969	93.7
B3	SPP 16A	15	1.23	1.194	95

3.2. Undrained shear strength, moisture content, OCR and consolidation parameters

Consolidation by vacuum increases the undrained shear strength, the over-consolidation ratio (OCR), and the pre-consolidation pressure whereas decreases the natural moisture content. This result has been shown in Figure 8. Many borehole and consolidation tests were taken through the test area before and after the soil improvement by VCM. The values shown in the plot are the average values taken from those multiple tests in a particular site. The undrained shear strength (S_u) of improved soil was determined by the unconfined compression test (ASTM D 2166). Figure 8 (a) shows the profile of undrained shear strength before and after the improvement by vacuum preload. It shows the overall strength has increased. In addition to an increase in the undrained shear strength, the water content is also decreased. The moisture content after the improvement by vacuum preload is much lower than that before the improvement in all depths, which is shown in Figure 8 (b). Additionally, there exists a significant increase in the over-consolidation ratio (OCR) and pre-consolidation pressure of clay after the improvement by VCM, which is illustrated in Figure 8 (c) and 8 (d) respectively. While sampling the soil for post vacuum treatment, for laboratory tests, and specially triaxial tests, it must be made sure that the vacuum pressure is stopped. Else, while the sample is taken out, the vacuum pressure is suddenly released, which causes swelling of the sample eventually lowering its strength.

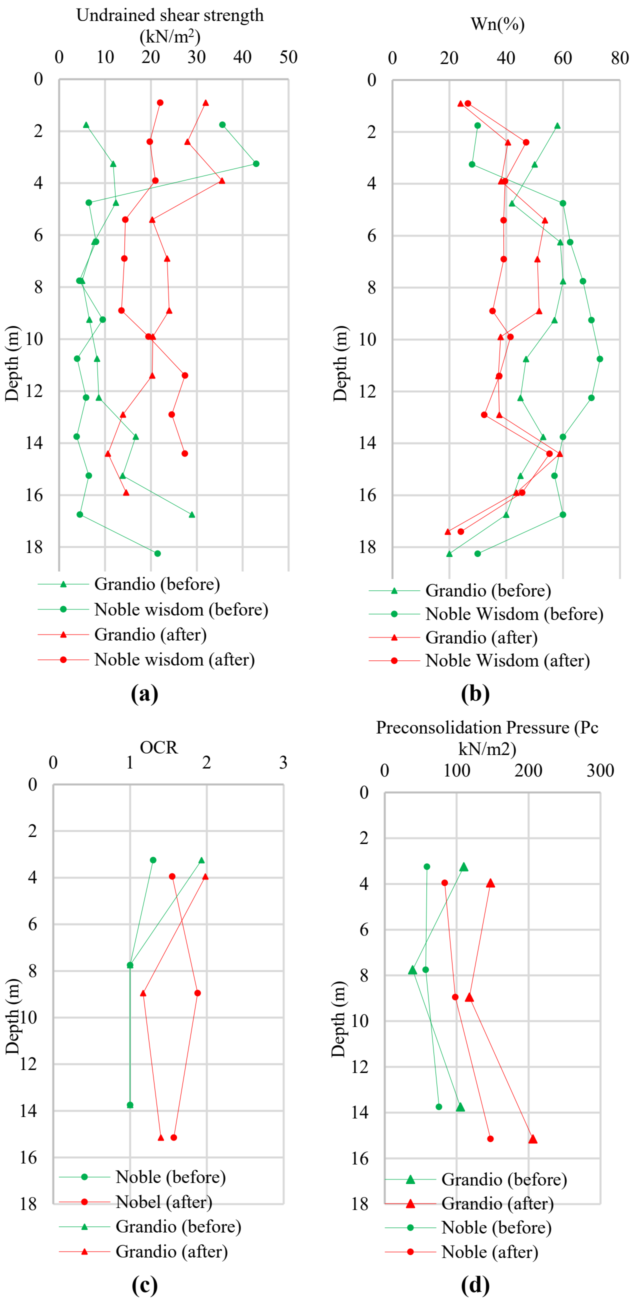

Figure 8 The profiles of (a) undrained shear strength by UC test (b) natural moisture content and (c) OCR (d) pre-consolidation pressure before and after the improvement by VCM

3.3. Undrained shear strength from other field tests

In addition to the tests already mentioned, other in-situ tests were also conducted. The field vane shear test (FVT) and Cone penetration test (CPT), SASW were conducted before and after the improvement of the test site area. Results of field tests showed a significant increase in strength parameters of soil after the improvement by vacuum preloading.

3.4. Long-term settlement

To avoid further settlement in the long run after the soil improvement by VCM is completed, the settlement value must be calculated considering secondary settlement. In Engineering practice, settlement of less than or equal to 10cm in 3 years is generally considered a safe long-term settlement. The settlement after 3 years is calculated for various zones of both test areas using (Terzaghi, Peck et al. 1996) and none of them exceed 10cm. The calculated total settlement in 3 years (S) is the sum of the secondary settlement (S_s) and recompression settlement (S_r), which are calculated by Eq. (1) and Eq. (2) respectively. The detailed values are tabulated in Table 6.

$$S_s = \frac{H_0}{1+e_0} . C_a . \log\left(\frac{t}{t_p}\right) \tag{1}$$

$$S_r = \frac{H_0}{1+e_0} . C_s . \log\left(\frac{\Delta\sigma_z + \sigma'_{zo}}{\sigma'_{zo}}\right) \tag{2}$$

Table 6 Long-term settlement after 3 years in the test site

Site name	Zone	Secondary settlement (S_s) (cm)	Recompression settlement (S_r) (cm)	Calculated settlement after 3 years (S) (cm)
Grandio	A1	4.15	2.15	6.3
	A2	4.28	2.21	6.49
	A3	2.87	1.83	4.70
	B1	12.04	1.99	6.05
	B2	6.08	3.64	9.72
	B3	4.57	2.38	6.95
Nobel Wisdom	A	4.91	3.81	8.72
	B	5.04	3.62	8.66
	C	5.03	2.98	8.01
	D	4.34	1.9	6.24
	E	7.31	2.8	7.31

3. CONCLUSIONS

The improvement of backfilled clay by vacuum consolidation method with prefabricated vertical drains on sites in Bangkok has been dealt with in this paper. It further discusses multiple ways to decide the ideal time to stop the vacuum preload considering many factors. Concisely, the following conclusion can be derived:

- ASAOKA method of predicting DOC can only be applied when the load is constant, which is not the case most of the time in the field due to some unavoidable circumstances such as rain effect or abrupt power cut. So other methods must be used for checking the quality of the improved soil and time for stopping the vacuum preload
- The final settlement obtained by field must be compared with the settlement obtained at 90% consolidation from Terzaghi's approach and other available empirical methods for the area
- Since soil improvement by VCM is performed in a large area in the field, it is practically challenging to maintain a constant vacuum pressure on the site. In such a scenario, it is important to count the number of days the site has been subjected to the vacuum pressure equal to or more than the designated pressure (generally 80kPa). This number of days must not be less than the time required for the soil to have 90% consolidation.
- The settlement rate should be decreased to 0.002m/d or less to consider enough consolidation has occurred

- The long-term post-vacuum settlement should be calculated and should not exceed a particular value in desired years
- The over-consolidation ratio and other consolidation parameters must show significant change before and after the soil improvement by vacuum preload
- The soil investigation must be done before and after the improvement by vacuum. These are primarily the SPT with borehole test accompanied by laboratory consolidation tests. In addition, other in-situ tests such as FVT, SASW, CPT can be performed

4. ACKNOWLEDGMENTS

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