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Ground Improvement via Vacuum Consolidation Method in Vietnam

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ABSTRACT: In recent years, vacuum consolidation method has been extensively used in Vietnam on various types of infrastructural projects. The main reason for adopting this method is that the construction cost is relatively close to the conventional prefabricated vertical drain method with less surcharge fill and shorter construction time. Hauling or transporting large amount of fill has been a major problem in most infrastructure projects. With the stringent settlement requirements specified by the Vietnamese Government, ground improvement via vacuum consolidation has become very popular hence attracting various International vacuum consolidation specialists to participate in Vietnamese projects. This paper describes the vacuum consolidation design and the construction practice in Vietnam along with some examples on the performance of vacuum consolidation works for highway projects.

KEYWORDS: Vacuum consolidation, Vertical drain, Surcharge, Highway.

1. INTRODUCTION

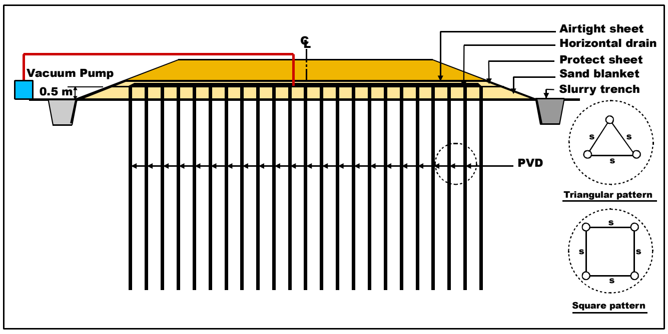
In the past decade, ground improvement methods have been widely used to minimize the residual settlements of earth-filling for large scale industrial facilities, power plants, highways, port terminals in Vietnam. In 1990s, the prefabricated vertical drain (PVD) method was first introduced to Vietnam for the use on major highway projects (for example National Highway No. 10 etc.). By early 2000s, the Vietnamese Government through the Ministry of Transport had introduced stringent residual settlement criteria for highway design, leading to extensive use of ground improvement for controlling the residual settlements. In mid 2000s, the conventional PVD method was extended to include the vacuum application instead of applying surcharge fill only.

The vacuum consolidation method (VCM) was first introduced to some Southeast Asian countries, including Thailand and Malaysia, back in early 2000s. The largest vacuum consolidation application in Southeast Asia during that period was carried out at the Bangkok Suvarnabhumi International Airport (Seah, 2006) with a total treatment area of over 240,000 m^2. The success of the vacuum application in Thailand had led to the introduction of this method in Southern Vietnam with similar soft ground conditions. For past few years, the VCM has become one of the most popular ground improvement methods in Vietnam with project scale far greater than other countries second only to China.

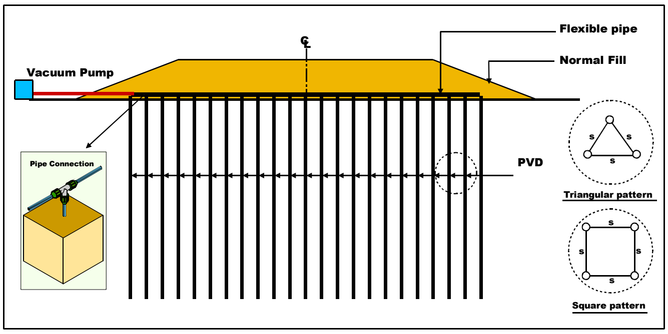
The main advantage of the VCM method is that it accelerates the consolidation of the soils with installed vertical drains in a relatively stable manner. In conventional PVD method, stage loading is required to control the stability through strength gain via consolidation, but the vacuum consolidation method increases the effective stress with very small change in the shear stress, creating a gain in effective stress with better stability. Typically, a minimum of 6 ton/m^2 or 60 kPa of vacuum can be achieved in the depressurized improved zone with installed vertical drains as illustrated in Figure 1, and this vacuum pressure is equivalent to the load of around 3 m of surcharge fill.

The effectiveness of the method depends greatly on the sealing or isolation of vacuum within the depressurized zone and the distribution of vacuum in the drains. Therefore, the PVDs used have to be designed to withstand the vacuum pressure; any collapse of flow channel within the drains will result in catastrophic consequences, such as embankment failure or unacceptable degree of consolidation. As a result, this type of work is normally executed by ground improvement specialists. Each specialist firm will adopt his own vacuum application system ranging from the type of drains to connections and vacuum pumps etc.

Apart from applying the vacuum pressure, it is also common to place additional surcharge fill on top of the depressurized zone to increase the total stress of the soil, resulting in greater acceleration of consolidation and reduction in the consolidation time. But it should be noted that there is also a limit in placing the surcharge due to stability as in PVD preloading method. Therefore for high surcharge load, it may require to place the fill in stages or to fill at slow rate, and it is also possible to introduce counterweight berms for improving stability during consolidation if there is sufficient right of way for construction. The vacuum consolidation method can be considered as a subset of the vertical drain method with additional loading by the vacuum instead of the fill surcharge. This method has been incorporated in European Standard EN 15237:2007 entitled "Execution of special geotechnical works: Vertical drainage".



(a) Vacuum Consolidation with Sheet Isolation



(b) Vacuum Consolidation with Direct Tubing

Figure 1 Types of Vacuum Consolidation Systems

2. DESIGN CRITERIA

Unlike most countries, the design criteria for highways have been specified in the Vietnamese Highway Design Standards (22 TCN211-06) issued by the Vietnamese Ministry of Transport. When designing a highway over soft ground in Vietnam, the designer should be aware of the following criteria specified in the standards:

a. Settlement criteria. According to the Vietnamese Standards (22 TCN 211-06), the settlement criteria for various sections of the embankment shall be as follows:
   - Near Abutment: Post Construction Settlement ≤ 10 cm in 15 years
   - Culvert zone: Post Construction Settlement ≤ 20 cm in 15 years
   - Fill Embankment: Post Construction Settlement ≤ 30 cm in 15 years

b. Factor of safety. The adopted factor of safety against instability during construction shall be maintained above 1.2. The long term stability of the roadway shall be controlled with factor of safety of no less than 1.4.

It should be noted that the above criteria have also been adopted for other types of earthworks including ports, power plants and other infrastructural projects as well. Therefore, such requirements may lead to higher construction cost in ground development.

3. VACUUM CONSOLIDATION METHOD

To minimize the surcharge height in the PVD preloading method, it is possible to apply a vacuum pressure directly to the vertical drains creating a greater hydraulic gradient for accelerating the flow or consolidation of the soft soils. The applied vacuum pressure is somewhat similar to the placement of a surcharge over the soft ground but with better stress transfer to the tips of PVDs. In conventional PVD preloading, the increase in stress for a narrow surface loading, such as highway embankment, will decrease gradually with depth based on Boussinesq equation. In other words, the stress transfer to the tip of the PVD will be less than the stress near the surface whereas in the vacuum application, full vacuum pressure may reach the tips of the PVDs if the head loss in the PVDs is not significant. As long as the PVDs have sufficient discharge capacity, this head loss will be relatively small. Figure 2 illustrates the stress distributions in PVD preloading and vacuum consolidation systems, showing greater stress distribution in the vacuum system.

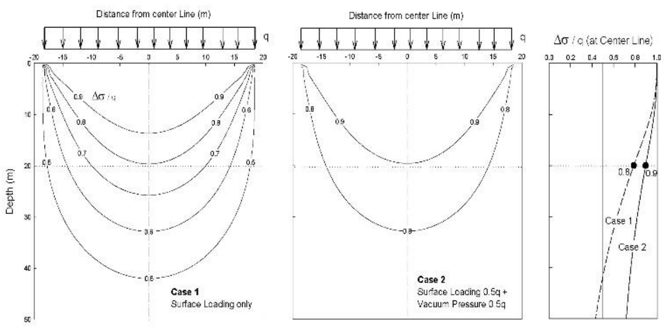


Figure 2 Stress Distributions in Conventional PVD and Vacuum Consolidation Methods

There are several methods (tabulated in Table 1) of improving the properties of soft clay to reduce the post-construction settlement. The main merits of the vacuum consolidation include less fill and sand required as well as shorter construction time etc. Once vacuum is applied through the PVDs, the loading effect is immediate compared with filling which requires certain time for the earth filling. As mentioned before, with the applied load from the vacuum rather than from the fill, counterweight berms for stability reason can be minimized with less lateral movement when compared with the PVD method.

Two (2) methods of vacuum consolidation are available in Vietnam, namely the airtight sheet method and the direct tubing method.

Table 1 Available Ground Improvement Method

	Method	Prefabricated Vertical Drain (PVD) with preloading	Vacuum Consolidation with preloading	Soil Cement column + Cement Stabilized Mat
Technical Issues	***Initial Settlement***	Low if factor of safety is high	Low because of low plastic flow to the side	Very low due to load transferred to lower stiffer layer
	Consolidation Settlement	High	High	Very Low
	Residual Settlement	Can be controlled through proper application of surcharge	Can be controlled through proper application of surcharge	Very low due to load transferred to lower stiffer layer
	Stability	Increase in Factor of Safety due to increase in soil strength during consolidation	Very stable for vacuum alone, but lower factor of safety when surcharge is placed.	High Factor of Safety initially, but may reduce with time
Financial Issues	***Maintenance Cost***	Low	Low	Low
	Construction Cost	Moderate	High	High for high embankment
Other Related Issues	***Construction Period***	Longest - depend on surcharge time	Moderate – need 5-8 months per vacuum section	Short to Moderate – Depend on equipment used
	Long Term Performance	Small differential settlement	Small differential settlement	Small differential settlement
	Right of Way	Require significant area for counterweight berm	Require some ROW	No ROW problem
	Local Experience in Construction	Very good – less operator dependent	Low – Introduce recently to Vietnam	Moderate – Highly operator dependent
	Use in Vietnamese Road project before	Yes	Yes, but limited	Yes, but limited
	Market Supply	No problem, except sand mat supply	Some import of material and equipment required	Relatively new to Vietnam
	Likelihood of Usage	Attractive method but requiring long construction period	Most suitable if construction time and right of way are limited	More expensive with short construction period

The airtight sheet method illustrated in Figure 1 consists of an airtight sheet over a drainage layer where the PVD tops are located. The sheet isolates the drainage layer and the PVDs so that the vacuum can be directly applied to the PVDs by the vacuum pump located next to the embankment.

To reduce any hydraulic head loss in the drainage layer, additional prefabricated drains (circular perforated pipes or prefabricated horizontal drains) are normally used. This system is most commonly used in Vietnam.

The direct tubing method is presented in Figure 1, having a direct connection of the PVD through the flexible tube to the vacuum pump. The direct tubing method has the advantage of lesser vacuum loss since the vacuum is applied directly to individual PVDs. Leakage check on the connections can be done after placing the surcharge. This method also eliminates the use of the drainage layer (clean sand) and the slurry trench for better isolation of the vacuum in the airtight sheet system.

Similar to PVD preloading method, it is necessary to estimate the consolidation settlement during preloading and after operation in the vacuum consolidation system. The most important design soil parameters in the settlement analysis are the consolidation properties, such as compression ratios, stress history of the soils and the coefficients of consolidation which govern the rate of settlement and the preloading period. The settlement analysis will involve estimating the fill required to raise the level to required elevation, the surcharge and vacuum required for accelerating the settlement in reaching a certain degree of settlement and the settlement caused by filling and depressurization. Apart from settlement estimation, the stability of the embankment will need to check at different stages of loading with consideration of strength gain due to consolidation, the methods of estimating the settlement and strength gain are described in latter section.

Ideally, the soft soils under treatment should be consolidated to the normally consolidated range, then unloaded to stress below the final stress so that the treated soils will be in the overconsolidated state to minimize the residual settlement as illustrated in Figure 3.

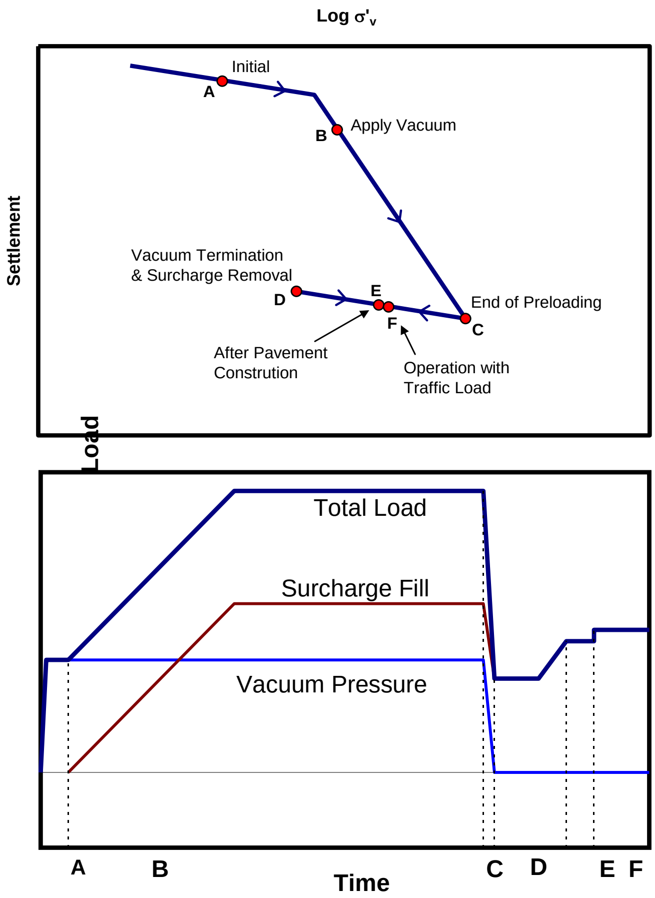


Figure 3 Overstressing Concept of Treated Soil

Therefore, it is essential to estimate the magnitude of surcharging (both vacuum pressure and thickness of fill) required to produce the overconsolidated state in the treated soils at the final stress condition. In most Vietnamese PVD projects, around 10% of consolidation settlement remains in the preloading under the final stress state, that is, 10% of consolidation settlement is expected during operation with state of stress in the normally consolidated range, resulting in greater secondary compression or creep during operation. If it is required to minimize the residual settlement, then overstressing concept should be applied as illustrated in Figure 3.

The duration of preloading in vacuum consolidation is usually kept to a minimum, which is around three (3) to eight (8) months due to high cost in depressurization or vacuuming. Hence greater surcharge load is needed in reducing the degree of consolidation for surcharge termination with value from 65% to 85%. In conventional PVD method, the specified degree of consolidation for surcharge termination is usually around 85 to 90%. In this respect, the vacuum consolidation method will require higher surcharge load (fill and vacuum) than the PVD method to reduce the running cost of vacuum pumps during preloading.

As for stability, the vacuum consolidation method reduces the fill thickness, hence it improves the stability. Furthermore, in the air-tight sheet vacuum system with a layer of sand blanket beneath the air-tight sheet, the vacuum will also increase the effective stress of the sand layer by the same magnitude as the applied vacuum pressure, creating an additional shearing resistance against instability as illustrated in Figure 4. In some projects, the vacuum consolidation specialist utilizes this concept by providing a very thick sand layer beneath the air-tight sheet in improving the stability of the embankment, but it is crucial to maintain a constant vacuum pressure during preloading if high surcharge fill is used. Any malfunction in the vacuum system without immediate remedy may lead to catastrophe failure in this case.

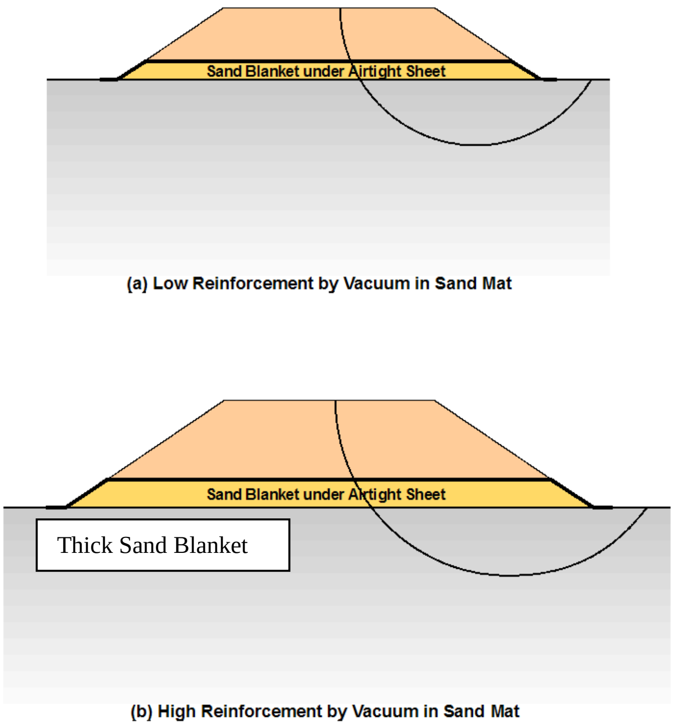


Figure 4 Stability Improvement on Vacuum Consolidation Embankment

In Southern Vietnam, hydraulic fill is commonly used via pumping the sand from the barges to the construction site. When the hydraulic fill is placed over the PVD area, the hydraulic gradient for water to flow out of the PVD is reduced due to the water from the fill, hence the rate of settlement will be reduced until the buildup water is released through gravity flow. But in the airtight sheet vacuum system, the sheet acts as a barrier in disconnecting the water from hydraulic fill to the PVDs, then the water from the hydraulic fill provides additional surcharge load to the system.

Due to the effect of vacuum on removal of moisture from the treated soils, tension cracks are expected along the outer boundary of treated area. The presence of tension cracks will lead to vacuum leakage in the sealed system. In addition, the use of shallow trench filled with water or some other liquid is to prevent vacuum pressure leakage between the sand drainage blanket and the external atmosphere at the perimeter of the treatment area. This is necessary to maintain a complete air-tight condition below the membrane. A deep slurry cut-off wall is necessary to prevent vacuum pressure leakage when permeable soil layer is encountered at greater depth beyond the depth of the shallow trench. Therefore, slurry trench and cutoff wall are often used to prevent such leakage of vacuum.

4. METHOD OF ESTIMATING SETTLEMENT

In the design of vacuum consolidation, the procedure is relatively simple. From the design load (σ_d), one could estimate the corresponding settlement (ρ_d) at the end of primary consolidation. For a given vacuum period (t), the degree of consolidation (U_t) can be obtained from the established graph of U versus time for a particular drain arrangement, giving the total surcharge load ($\sigma_s= \sigma_d/U_t$). Since the soil is a non-linear material and the criterion of acceptance in loading is often based on measured settlement, therefore the degree of settlement has to be adopted instead. For a given stage in the consolidation process, the ratio of the settlement at σ_d to the total settlement at σ_s is defined as the degree of settlement (S), which is used as the criterion of acceptance in the ground improvement work. The total settlement (ρ_s) at σ_s can be estimated from the Asaoka method; hence if the measured settlement reaches a value equal to S x ρ_s, then the criterion is satisfied. The total consolidation settlement is estimated based on one-dimensional consolidation equation.

The methods of estimating the settlement due to surface loading differ according to the soil types. For clayey soil, the rate of settlement will depend on dissipation of the excess pore water pressure, which governs by the coefficient of consolidation.

To estimate the magnitude of consolidation settlement in preloading, the finished grade of the embankment along with the expected live load will have to be applied in the computation. The settled fill during preloading should also be considered as part of the loading in the settlement estimation.

The total settlement due to consolidation can be expressed as:
Total settlement of clay,

$$\rho_{clay}=H\left[RR\,\log\frac{\sigma'_p}{\sigma'_{vo}}+CR\,\log\frac{\sigma'_{vf}}{\sigma'_p}\right] \tag{1}$$

Where H is the thickness of clayey soil;

RR is the recompression ratio;

CR is the compression ratio,

σ'_{vo} is the effective overburden stress;

σ'_p is the preconsolidation pressure; and

σ'_{vf} is the final vertical stress.

The settlement due to the embankment fill and vacuum can easily be estimated from the settlement equation given in Equation 1.

5. RATE OF SETTLEMENT IN VACUUM CONSOLIDATION SYSTEM

The rate of settlement can be estimated based on a given vertical drain spacing under radial flow condition. For radial flow as in vertical drains, Barron (1948) proposed a solution for consolidation by radial drainage as follows:

Degree of consolidation,

$$U_h=1-e^{\left[-8T_h/F\right]} \text{ where } T_h=\frac{c_h t}{d_e^2} \tag{2}$$

c_h = horizontal coefficient of consolidation

d_e = diameter of equivalent soil cylinder

Hansbo (1979) suggested that the factor, F, consisted of the following components with consideration of the effect of smear zone and well resistance:

$$F=F(n)+F_s+F_r \tag{3}$$

where $$F(n)=\ln\frac{d_e}{d_w}-0.75 \tag{4}$$

= 2.10 for PVD or Band Drain, d_w = 0.067 m, d_e = 1.13 m

(d_w = equivalent diameter of the drain)

$$F_s=\left[\frac{k_h}{k_s}-1\right]\ln\frac{d_s}{d_w} \tag{5}$$

($\frac{k_h}{k_s}\approx 1.4$ (assumed), and $\frac{d_s}{d_w}=2$ based on recommendation by Hansbo, 1979)

$$F_r=\pi z(L-z)\frac{k_h}{q_w}=0.001 \tag{6}$$

(*Assumed* k_h = 0.014 m/year, q_w = 1,000 m^3/year)

Giving, F = 2.10 + 0.28 + 0.001 = 2.38 for Band Drain

It is assumed that the coefficient of permeability of the disturbed clay is similar to the vertical coefficient of permeability, giving rise to low Fs value. For the third component, since the discharge capacity of the PVD is over 1,000 m^3/year at hydraulic gradient of 1, the Fr value is therefore negligible. In summary, the F value is dominated by the first component; the other two components have small contribution to the degree of consolidation, hence the effect of smear zone is not of major concern. Based on the above equations, the relationship between the degree of consolidation and time can be estimated.

In Vietnam, there is no direct measurement made on the horizontal coefficient of consolidation (c_h), the adopted value is usually considered to be 1.4 to 2 times of the measured vertical coefficient of consolidation (c_v). The constant rate of strain consolidometer with radial flow (Seah and Juirnarongrit, 2003) had recently been introduced to Vietnam, more measured data will be available in near future.

6. METHOD OF ESTIMATING GAIN IN SHEAR STRENGTH DURING PRELOADING

The rate of settlement can be estimated based on a given vertical drain spacing under radial flow condition. For radial flow as in staged construction over soft ground, it is important to estimate the gain in undrained shear strength of the soft soils due to consolidation for stability analysis. Though Vietnamese standards have suggested certain method in estimating the strength gain, the SHANSEP method proposed by Ladd and Foott (1974) offers a more rational approach with the following expression:

Normalized strength ratio, $\frac{c_u}{\sigma'_{vo}} = S\,(OCR)^m$ (7)

or $\frac{c_u}{\sigma'_{vc}} = S\,(OCR)^m$

Where σ'_{vo} = Effective overburden stress,

OCR = Overconsolidation ratio

S = the normalized strength ratio at OCR=1. For treated soil below the embankment, triaxial compression (TC) mode can be assumed and the normalized strength ratio can be obtained from Figure 5 as a function of plasticity index; and

m = 0.8 (assumed)

It should be noted that when the vertical effective stress is greater than its preconsolidation pressure, that is, the soil is in the normally consolidated state, and then the relationship becomes:

$\frac{c_u}{\sigma'_{vc}} = S$ or $c_u = S\,\sigma'_{vc}$ (8)

To obtain better SHANSEP parameters, special triaxial tests could be performed, but this type of test is not common in Vietnam. Therefore, assumed parameters based on data from Figure 5 are used in the design. The field vane test results with plasticity correction are often used to verify the assumed strength parameters.

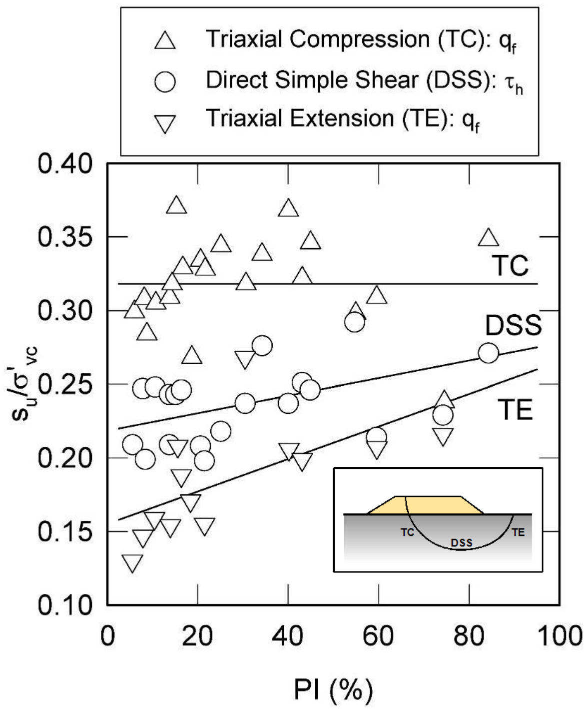


Figure 5 Undrained Strength Ratio used on Embankments over Soft Ground

7. ESTIMATION OF RESIDUAL OR POST CONSTRUCTION SETTLEMENT

As mentioned in earlier section regarding the stringent post-construction settlement stated in Vietnamese standards, it is required to estimate the residual settlement after operation.

The vacuum consolidation will reduce the future consolidation settlement to a minimum with over-stressing concept as presented in Figure 3, then the residual settlement or post-construction settlement will consist of secondary or creep settlement of the treated soft soils along with the consolidation settlement of any lower untreated clay.

The secondary compression ($C\alpha\varepsilon$) can be estimated from established correlation as follows (Ladd and DeGroot, 2003):

$C_{\alpha\varepsilon} = \frac{\Delta\varepsilon}{Log\,t_1 - \log t_0}$ = Change in strain over change in logarithmic time (9)

$\frac{C_{\alpha\varepsilon}}{CR} = 0.04 \pm 0.01$ for inorganic clays and

$\frac{C_{\alpha\varepsilon}}{CR} = 0.05 \pm 0.01$ for organic clays and silts

For most soft soils encountered in the vacuum consolidation projects, the clay contains some organics, hence the following relationship can be assumed:

$\frac{C_{\alpha\varepsilon}}{CR} = 0.045 \pm 0.01$ or

$$\frac{C_{\alpha\varepsilon}}{CR}(NC\,clay) = \frac{C_{\alpha\varepsilon}}{RR}(OC\,clay) = 0.045 \pm 0.01 \quad (10)$$

To reduce the secondary compression or creep following upon the primary consolidation, the soft soil can be overloaded to create lightly overconsolidated soil, then the $C_{\alpha\varepsilon}$ value would be:

$C_{\alpha\varepsilon} = 0.045$ RR

There is no documentation on creep settlement in the Vietnamese standards, but this factor should be taken into account in the residual settlement estimation.

8. CRITERIA FOR ACCEPTANCE

During preloading, there is a need to predict the total settlement in advance so that the degree of consolidation at that stage could be determined. Since the criteria for acceptance (that is, completion of preloading) is primarily based on settlement, the method of estimating the final settlement has to be defined. Frequently, Asaoka method is adopted, which is briefly described below.

Asaoka method (1978) is commonly used to estimate the magnitude of final settlement as well as the horizontal coefficient of consolidation from the measured settlement data. This method adopts a curve fitting procedure based on the consolidation theory, and some essence of the method is explained below.

The solution of the consolidation equation under radial drainage condition takes the following form:

Settlement, $\rho(t) = \rho_f - \rho_f \exp\left[-\frac{8c_h}{d_e^2 F}t\right]$ or

$$\rho(t) = \rho_f\left[1 - \exp(\lambda t)\right] \quad (11)$$

where $\lambda = -\frac{8}{d_e^2 F}c_h$

By expressing the above equation in the form of an ordinary differential equation, and dividing the time evenly into Δt interval, the constants, β_0 and β_1, are obtained:

$$\beta_1 = \frac{1}{1-\lambda\,\Delta t} \text{ and } \beta_0 = \frac{\Delta t}{1-\lambda\,\Delta t} \qquad (12), (13)$$

The constants (β_0 and β_1) are the intercept and the slope of the fitted straight line in ρ_{i-1}-ρ_i axes, which can be obtained graphically. The final settlement and the horizontal coefficient of consolidation can also be obtained from the following expressions:

$$\rho_f = \frac{\beta_0}{1-\beta_1} \text{ (based on } \rho_i = \rho_{i-1} = \rho_f \text{ as time approaches infinity)} \qquad (14)$$

$$\text{and } c_h = \frac{(1-\beta_1)\, d_e^2\, F}{8\,\beta_1\,\Delta t} \qquad (15)$$

It should be emphasized that some experience in data interpretation and analysis would be needed; otherwise the results might be misleading. From the above equations, the horizontal coefficient of consolidation and the final settlement can be determined from this method. At the same time, it should be kept in mind that if low degree of consolidation were achieved, then the error in estimation of final settlement would be more significant. If the degree of consolidation is beyond 80-85%, that is, the settlement has reached 80-85% of the final settlement, and then the error would be negligible.

9. MONITORING INSTRUMENTS

A series of monitoring instruments, such as settlement plates, inclinometers, piezometers and observation wells, are often used in verifying the performance of vacuum consolidation with typical arrangement shown in Figure 6. Measurements are normally made periodically and the monitoring data are analysed and evaluated to verify the degree of settlement and stability of the embankment.

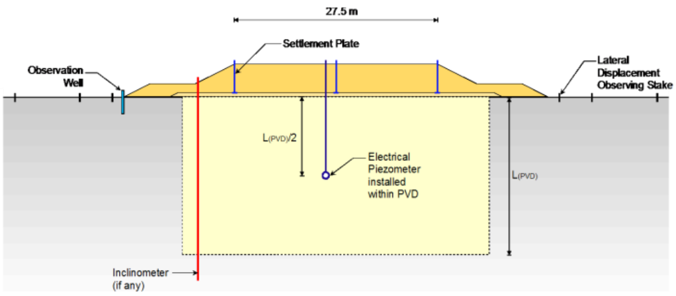


Figure 6 Example on Monitoring Instruments

The settlement plates are mainly used for checking the vertical settlement during preloading, and they would eventually be used for determining the end of the preloading period based on the specified settlement criteria. The inclinometers can be used for checking the horizontal movements of the embankment; they are usually placed at locations where the maximum horizontal movements are expected, that is, between the main embankment and the counterweight berm. The inclinometers can be installed in critical areas adjacent to any existing structure if any. The piezometers should be installed at mid-length of PVD within the PVD to monitor the vacuum pressure during depressurization. As for the observation wells installed beyond the embankments and counterweight berms, they can be used as groundwater level reference for computing the net vacuum pressure of the piezometer within the PVD.

Any malfunction of the vacuum system will hamper the rate of consolidation, and it will also reduce the stability of the embankment. Therefore, it is highly recommended that the performance of the embankment based on the measurements of the instruments should be evaluated periodically, so that preventive measures could be made. Any damage to the settlement plate or the piezometer will affect the decision on termination of preloading, therefore it is important to replace the damaged instruments immediately, otherwise it will be very difficult to evaluate the performance of the preloading.

10. COMPARISON OF VARIOUS VACUUM CONSOLIDATION SPECIALISTS IN VIETNAM

Since 2005, there have been a number of vacuum consolidation specialists operating in Vietnam. The vacuum consolidation system provided by each specialist differed to certain extent in terms of horizontal drain arrangement, airtight sheets, protective layers, types of vacuum pumps etc. A comparison on the various components of the system is tabulated in Table 2.

Table 2 Comparison of Various Vacuum Systems used by Different Companies

Technical Issue		Company A	Company B	Company C
PVD	Type	B	B	B
	Width (mm)	100	100	100
	Thickness (mm)	3.5, 7	3.5	3.5
Horizontal Drain	Type	B	P	P
	Size	300 mm width Thickness 7 mm	Diameter 32 mm	Diameter 50 mm
	Interval (m)	1	1	1
Longitudinal Drain	Diameter (mm)	65	76	63
	Spacing (m)	1	1	1
Connection between PVD and Horizontal Pipe		Connect by stable	Wind PVD around horizontal drain and tie by string	Wind PVD around horizontal drain
Airtight Sheet (membrane)	membrane	PP	HDPE	Geo membrane
	Thickness (mm)	0.5	1.5	0.15
	Layer	1	1	2
	Connect by	heating welding	heating welding	glue welding
Cutoff Wall System		cutoff	steel sheet	slurry wall
Vacuum Pump system		2 Types of pumps: External and Internal	External pump	Use of Submersible Pump for Vacuum
Vacuum Pump Size (kW)		25	25	7.5
Treatment Area (m^2)		3,000 - 3,500	2,500	800 - 1,000

Two (2) systems were used in Vietnam, air-tight sheet and direct tubing as shown in Figure 1. A total of four (4) specialists adopted the air-tight sheet system, that is, the vacuum is applied to the upper horizontal drainage system (consisting of sand and horizontal drains) which is enclosed by an air-tight sheet (plastic). Geotextile is placed above and/or below the air-tight sheet to protect the air-tight sheet from any possible puncturing by sharp objects. There were a number of good features provided by each company. For example, Company A had adopted two (2) pumps, such as external vacuum pump and internal water pump as shown in Figure 7, for maintaining the maximum vacuum pressure after ground settlement. The internal water pump controls the water level in the horizontal drainage layer, and the external pump maintains the same vacuum pressure within this horizontal drainage layer. Without the internal pump, the effectiveness of the vacuum will reduce when the ground settles since the water head is maintained at the external pump level. For the system provided by Company C with two (2) layers of very thin air-tight sheets, the full sheets can be manufactured directly from the factory without any welding or jointing at the site. Because of the possible puncturing, second sheet is added, and two (2) layers of

geotextiles are placed below and above the air-tight sheets for protection purpose. This method can shorten the installation by over three (3) times when compared with other heavy air-tight sheet requiring welding. Company C has also adopted submersible pump placed in a water bath to produce vacuum pressure by means of Venturi effect. For this pump, known as aspirator, the water flows through a narrow tube at high speed and vacuum is produced in an outlet at that narrow point. The main advantage of this system is that the pump is constantly cooled by the water in the bath. Because of its ligl
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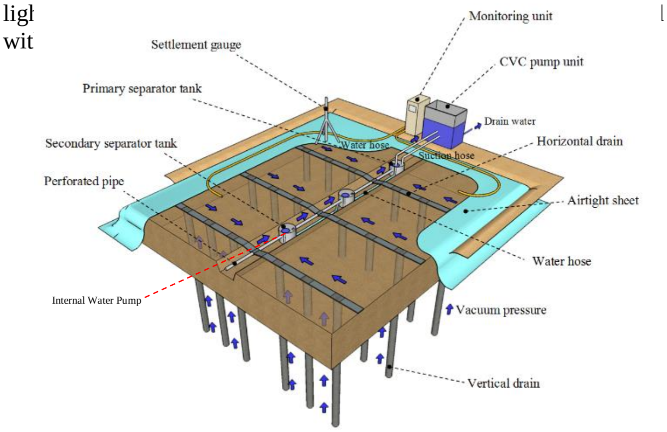

Figure 7 Vacuum System with Double Pumps

As for the direct tubing system as shown in Figure 8, the PVD with tube at the upper end has to be installed individually during installation. The exposed tubes are then connected to another set of horizontal tubes by special connectors leading to the manifold and the vacuum pump. The main advantage of this system is that the vacuum can be applied directly to the PVDs.

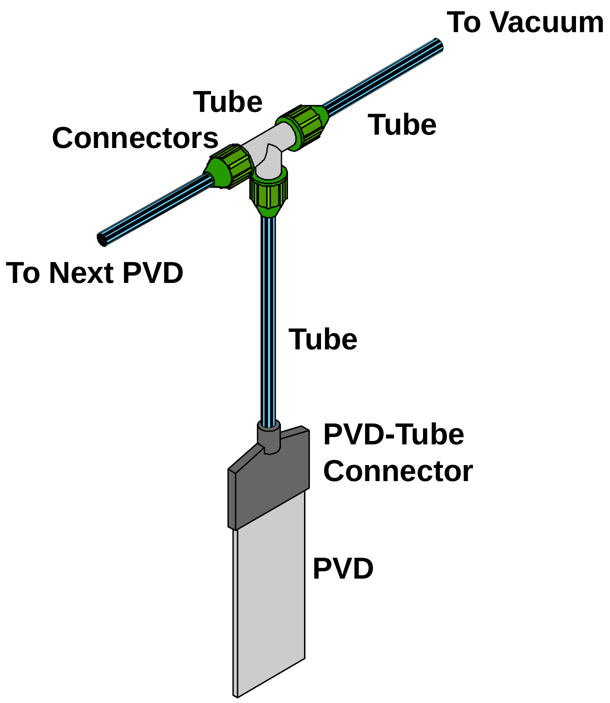

Figure 8 Components of Direct Tubing System

11. EXAMPLES OF VACUUM CONSOLIDATION WORKS

To demonstrate the effectiveness of vacuum consolidation, two (2) sections (Section A and Section B) of a highway near Ho Chi Minh City have been selected. Airtight sheet system had been applied to both sections with different PVD lengths and surcharge thickness.

For Section A, the soft clay was found from the ground level to depth of around 23 m. The soft clay was lightly overconsolidated with compression ratios of around 0.25. With PVDs installed down to depth of 23 m at 0.9 m spacing in triangular pattern, vacuum was applied with maximum fill thickness of 4 m placed in stages to ensure stability. The vacuum pressure was measured inside a PVD by a piezometer installed at depth of 11.5 m. The measured vacuum pressure with time is plotted in Figure 9. The total applied load is plotted in the same figure. Under such loading, the settlement along the centreline of the embankment was measured periodically with results shown in Figure 9. For the applied loads, the predicted settlement-time curve is presented in Figure 9. In general, the prediction matches well with the measurement.

For Section B, the maximum fill thickness was slightly higher than Section A at 5 m with vacuum pressure reaching 7 ton/m^2. The soft clay extended to depth of 17 m, and the PVDs were installed to depth of 17 m with spacing of 0.9 m in triangular pattern. The loading and settlement with time are presented in Figure 10. Again, the prediction on the settlement was made, which also agreed well with the measured data except at the initial stage of loading when the soft clay was at overconsolidated state.

To predict the total consolidation settlements of these two (2) sections, Asaoka method was adopted. The estimated total consolidation settlements presented in Figures 11 and 12 for Sections A and B by Asaoka method were 3.32 m and 3.05 m, respectively. The horizontal coefficients of consolidation for these sections were 0.82 m^2/year and 1.27 m^2/year, which are close to the values in design.

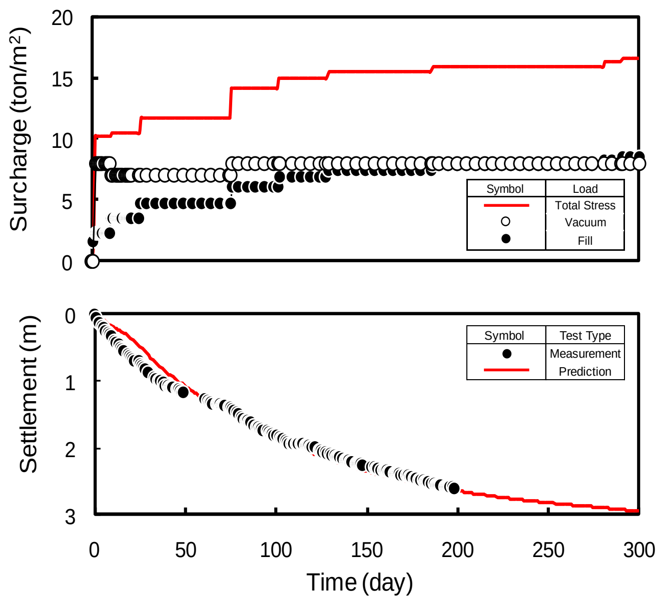

Figure 9 Performance of Section A

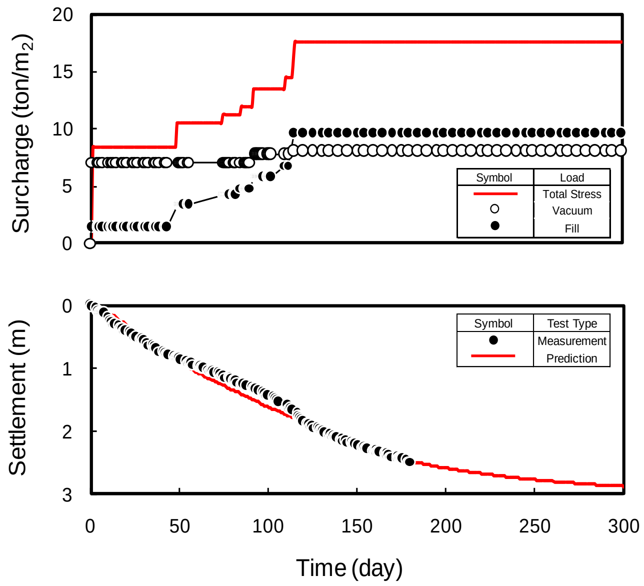

Figure 10 Performance of Section B

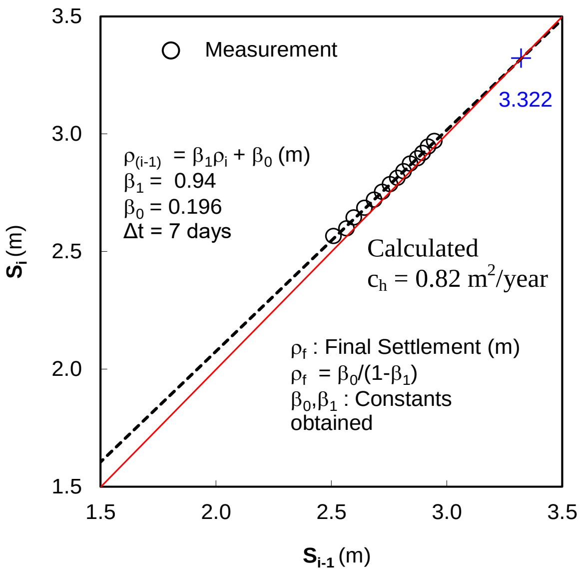

Figure 11 Asaoka Method on Section A

12. ECONOMICS OF VACUUM CONSOLIDATION METHODS

In the vacuum consolidation, significant cost lies in the operation and the maintenance of the vacuum pumps during the vacuuming or pumping period. Since part of the preloading is generated by pumping, shorter pumping period can be achieved through reducing the spacing of the PVDs, a PVD spacing of 0.9 m in triangular pattern is recommended.

From the experience, the present cost of vacuum consolidation is slightly higher than the conventional PVD method, but the vacuum consolidation can reduce the use of fill significantly which is a major issue in current construction.

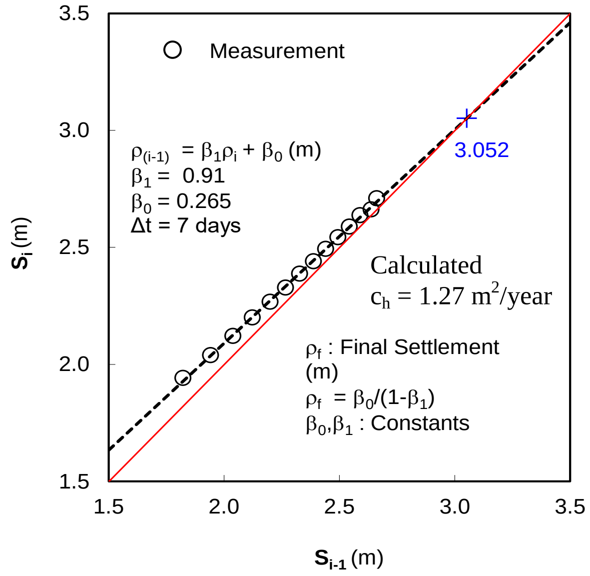

Figure 12 Asaoka Method on Section B

13. PROBLEM ENCOUNTERED IN VACUUM CONSOLIDATION

Application of vacuum to the PVD is no easy task because of possible leakage between the vacuum pump and the PVD. The most common problem encountered in the air-tight system is leakage through the air-tight sheet due to puncturing. In practice, once the air-tight sheet is placed under vacuum, close inspection has to be carried out to identify any leakage of the sheet through visual inspection and leakage noise. It is also advisable to maintain the vacuum without surcharging for a few days until the vacuum pressure is fully developed.

In one section with airtight sheet, dislocation of horizontal drains at the joint was encountered after filling. The surrounding sand fill together with the air-tight sheet was sucked into the horizontal drains, and the air-tight sheet was damaged resulting in vacuum loss. For this particular case, it was rather difficult to pinpoint the damaged area after surcharge was placed.

For direct tubing method used in Vietnam, a different problem was encountered leading to a loss in vacuum pressure. In that project, the tubes extended from the PVDs were installed over 1 m into the soft ground. When the ground settlement reached over 1.5 m, the soft soil surrounding the vertical tubes had undergone extensive consolidation causing the tubes to bend and kink as shown in Figure 13. Kinking of tubes had disconnected the drainage of the PVD and vacuum, resulting in loss of vacuum pressure which was measured at the mid-point of the PVD. Finally, additional surcharge was placed to increase the surcharge as a result.

Therefore, it should be emphasized that application of vacuum consolidation requires careful planning and execution; minor mistakes may result in unnecessary problem.

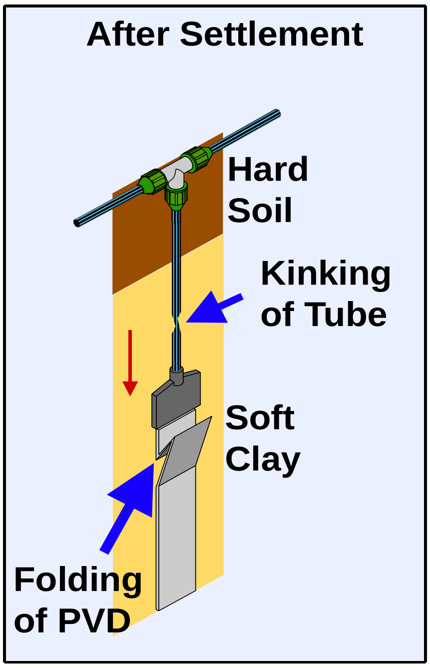

Figure 13 Kinking Problem in Direct Tubing Method

14. SUMMARY

The vacuum consolidation method has proven to be an effective technique in improving soft soils. The benefits from applying this method when compared with conventional PVD method include shorter construction time (with more flexibility in the construction time), significant reduction in the fill material, hauling and filling area etc. Considering the technical benefits along with lesser environment impact, the vacuum consolidation method will undoubtedly be very popular in Vietnam for years to come.

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