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Vertical Drain Depth Optimization in Vacuum and Surcharge Preloading Using Finite Element Method

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ABSTRACT

One of the most challenging parts of every project including prefabricated vertical drains (PVDs) combined with vacuum and surcharge preloading for ground improvement is the determination of the PVDs depth of installation and its configuration. In this paper Finite element was used for modeling and verification of a full-scale test embankment (TV2) which was constructed to study the effectiveness of PVDs combined with vacuum preloading for accelerating the consolidation along with surcharge at Bangkok airport. Different depths and scenarios were modeled and the results were compared and analyzed. Since the ultimate goal of soft clay soils treatment is attaining pre-determined settlement, the settlement curve under soil embankment was used for investigation of the results. A new Finite Element Modeling (FEM) based procedure as "One and Between Configuration" has been introduced. Based on the results, it was shown that; 1) the inward forces of vacuum preloading in proposed configuration is greater than the conventional method and lateral displacement reduced by 15 percent; 2) As a result of the lesser penetration of the mid PVD, the disturbance of the soil and accordingly, the smear zone becomes lesser; 3) Because of the "one and between" installation, in a case that a percentage of the every PVDs become clogged in any possible length, which may vary from PVD to PVD, the overall performance of the PVD itself, and in relation to adjacent PVDs don’t diminish as much as common constant penetration method.

Keywords: partial penetration, vacuum, soil treatment, finite element, optimization

1. INTRODUCTION

Most of the world’s essential infrastructure is built along congested coastal belts that are composed of highly compressible and weak soils up to significant depths. Soft alluvial and marine clay deposits have very low bearing capacity and excessive settlement characteristics, with obvious design and maintenance implications on tall structures and large commercial buildings, as well as port and transport infrastructure. Stabilizing these soft soils before commencing construction is essential for both long term and short term stability. Pre-construction consolidation of soft soils through the application of a surcharge load alone often takes too long, apart from which, the load required to achieve more than 90% consolidation of these mostly low lying, permeable, and very thick clay deposits can be excessively high over a prolonged period. A system of vertical drains combined with vacuum pressure and surcharge preloading has become an attractive ground improvement alternative in terms of both cost and effectiveness. This technique accelerates consolidation by promoting rapid radial flow, which decreases the excess pore pressure while increasing the effective stress. Apart from the method of drainage and PVDs combined with surcharge preloading, vacuum pressure has been used to enhance the efficiency of PVD when a desired degree of consolidation is required over a relatively short time period. Negative pore pressures (suction) distributed along the drains and on the surface of the ground accelerate consolidation, reduce lateral displacement, and increase the effective stress. This allows the height of the surcharge embankment to be reduced to prevent any instability and lateral movement in the soil. Today, PVDs combined with vacuum preloading are used more and more in practical ground improvement all over the world [1]. Vacuum pressure creates an inward force into the subsoil. As a result, there is a slight chance of sliding failure. So, the influence of vacuum pressure on adjacent structures is low [2-4]. The vacuum suction decreases the atmospheric and pore water pressure, thereby creating a pressure difference between vertical drains and pore water in soils. The pressure difference causes the pore water to flow towards the vertical drain, resulting in soil consolidation. Vacuum suction keeps taking out water and air and accelerates the process of soil consolidation. Vacuum pumps generate a vacuum suction that spreads into the soil along the drainage system.

From its introduction by kjellman in 1942, vacuum preloading has been used widely for soft ground treatment, for example at the Philadelphia International Airport, USA; Tianjin port, China; North South Expressway, Malaysia; Reclamation world in Singapore and Hong Kong, China; Suvarnabhumi Second Bangkok International Airport, Thailand; Balina Bypass New South Wales and the Port of Brisbane, Queensland in Australia and among many other projects [5-12]. [13] showed that when a vacuum is applied in the field through PVDs, the suction head along the length of the drain may decrease with depth, thereby reducing its efficiency. Laboratory measurements taken at a few points along PVDs installed in a large-scale consolidometer at the University of Wollongong clearly indicated that the vacuum propagates immediately, but a gradual reduction in suction may occur along the length of the drain. The rate at which the suction develops in a PVD depends mainly on the length and type of PVD (core and filter properties). However, some field studies suggest that the suction may develop rapidly even if the PVDs are up to 30 m long [14, 15].

If the PVDs install with a mandrel, the mandrel would change the characteristic of subsoil, especially in its very near vicinity. This disturbed annulus that is called the smear zone has a reduced lateral permeability and increased compressibility. In varved clays, the finer and more impervious layers are dragged down and smeared over the more pervious layers, which in turn decrease the permeability of the soil near the periphery of the drain [1]. [16] suggested the concept of reduced permeability by arbitrarily lowering the apparent value of the coefficient of consolidation.[17] included a further explicit smear zone with a reduced permeability near the drain, surrounded by an outer undisturbed zone.[18] introduced a three zone hypothesis defined by (a) a plastic smear zone close to the drain where the soil is highly remoulded during installation, (b) a plastic zone where the permeability is reduced moderately, and (c) an outer undisturbed zone where the soil is unaffected by installation. For practical purposes, a two-zone approach is generally sufficient. The effect of the smear zone should be taken into account in any model and design by proper parameters.

Finite element analysis (FEA) is a powerful method that can be used to model very demanding cases such as complex geometries, loadings and material properties, even for the simulation of a large-scale radial drainage consolidometer [13], where analytical solutions are hard to obtain. Many literatures have attributed the difference between the numerical predictions, and measured field data taken at site to various factors such as soil disturbance, smear zones, time-dependent load, well resistance, and partial penetration of drains and permeability. [19] predicted the field behavior of a full-scale test embankment using the modified Cam-Clay model. [20] introduced a numerical analysis model using an elasto-plastic finite element program (FEM) incorporating the SYS Cam-clay for soil, and water coupled problems. In order to investigate the effect of a combined vacuum, and surcharge load on lateral displacement a simplified plane strain (2-D) finite element analysis could be used [2]. [21] developed a new plane strain lateral consolidation equation, which can be applied to the exponential and linear correlation between the hydraulic gradient and flow velocity, while neglecting the well resistance of vertical drains. Finite element analysis can predict the ground deformations induced by a vacuum pressure and/or the combination of a vacuum pressure and a surcharge load. However, the accuracy of these predictions depends on the constitutive models used to represent the stress–strain behavior of the soils in question. In many practical cases, there is often not enough information to reliably define the parameter values of sophisticated soil models. Two practical easy to use methods have been proposed for calculating the settlement, and lateral displacement of a soil deposit induced by vacuum pressure [22, 23]. Imai's method is based on elasticity theory, and the method proposed by [22] considers the elasto-plastic deformation behavior of a deposit, and as such is considered more relevant for clay soils. However, deformation induced by a vacuum pressure is different from that induced by a surcharge load [24]. A vacuum pressure will induce settlement, and at the same time has a tendency to induce inward lateral displacement of the ground. Consequently, for vacuum consolidation, if inward lateral displacement occurs, the settlement induced by a vacuum pressure will normally be less than that induced by a surcharge load of the same magnitude [25].

[2] had numerically analyzed the effects of partially penetrating vertical drains and vacuum pressure on the corresponding settlement and lateral displacement. The models showed that if the PVDs fully penetrate towards the bottom of the soft clay layer and reach the underlying pervious sand layer, then the resulting settlement at any given time would become smaller due to the loss of vacuum.[26] stated that under a vacuum pressure PVDs have to be partially penetrated into the soft clayey deposit to prevent the vacuum pressure losing from the bottom drainage boundary. [27] proposed a method to determine the appropriate arrangement of PVDs based upon multiple objectives, such as cost, safety, and design robustness using Monte-Carlo simulation based on the statistics of uncertain soil parameters. [28] have considered the drain's end as a permeable region, while most of the current construction techniques use an anchor plate element at the end of a PVD, which prevents water flowing from beneath untreated soil, and obtaining acceptable results.

Based on the previous studies, the 2D plane strain condition would be used for finite element modeling of soil treatments including PVDs, and surcharge and vacuum preloading. The effect of the smear zone on soil conductivity, and compressibility should be accounted for in the model. As far different literatures had investigated partial penetration refer to underlying pervious layer or insufficient install depth but none had investigated different pattern of installation lesser than designed installation depth (base on empirical or analytical methods) for a percent of PVDs, which can reduce the final cost and related obstacles of the system for soil remediation. As the depth of PVDs increases, maintaining the vacuum pressure head would become harder as [29] reported in Bangkok airport test embankments. Shortening 50 percent of PVDs length besides lowering the material and installation cost, would decrease the possibility of clogging issues. After verification of a case, the proposed method would be applied in FEM and results would be analyzed to investigate the efficiency of the method.

2. MATERIALS AND METHODS

2.1. Test embankments TV2 stabilized with PVDs along with vacuum preloading and surcharge, Bangkok, Thailand

The Second Bangkok International Airport or Suvarnabhumi Airport is situated about 30 km from the city of Bangkok. In the past, the site was occupied by rice fields for agricultural purposes. The area is often flooded during the rainy season and the soil generally has very high moisture content. Therefore, soft marine clays often present considerable construction problems, which require ground improvement techniques to prevent excessive settlement, and lateral movement [29]. Test embankment TV2 were built for investigating the efficiency of vacuum, and surcharge preloading. Fig 1 illustrates the subsoil cross section of International Airport, Thailand [30]. In each embankment, a vacuum pressure up to 70kPa could be achieved using the available vacuum equipment. This pressure is equivalent to a fill height of 4m. After 45 days of vacuum application, the surcharge load was applied in 4 stages up to 2.5m high [29]. Figure 2 shows the Multi stage surcharge loading for embankment TV2 [31] which is exactly modeled by staged construction. Figure 3 shows the Time dependent vacuum pressure [31].

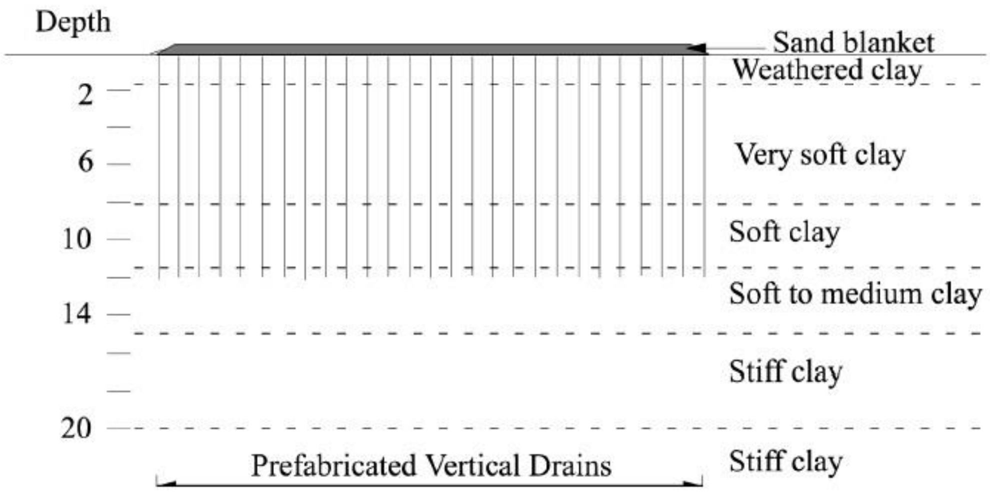

Figure 1. Cross section of an embankment with the subsoil profile, Second Bangkok International Airport, Thailand [30].

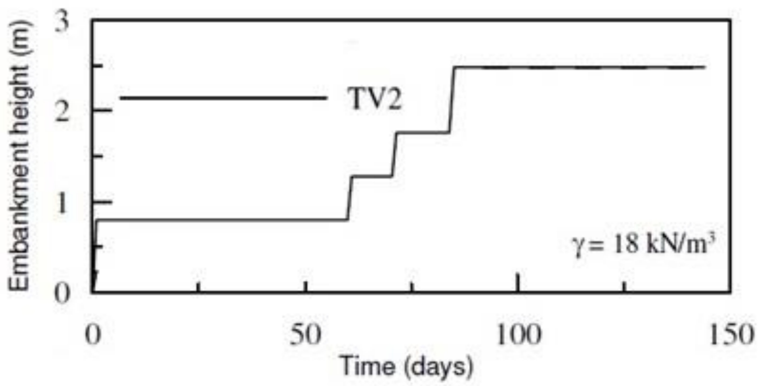

Figure 2. Multi-stage loading for embankments TV2 [31]

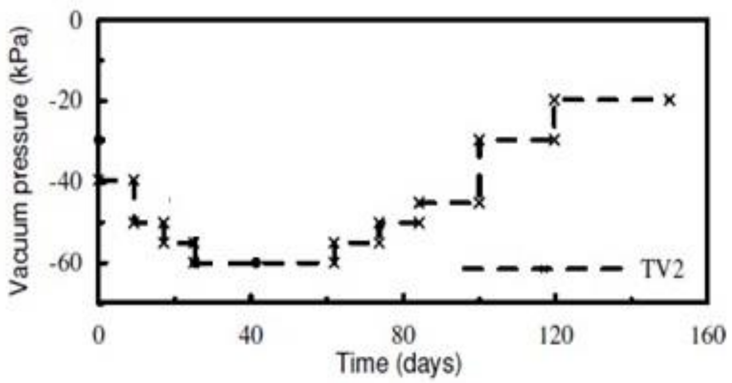

Figure 3. Time dependent vacuum pressure TV2 [31]

2.2. Equivalent plane strain consolidation model

As [32] states FEM simulations produced better results than the analytical analyses, when the preloading was not constant and the vacuum was not steady which is the case in TV2. Most finite element analyses on embankments are carried out based on the 2D plane strain assumption [33, 34]. However, the consolidation around vertical drains is mainly axisymmetric. Therefore, to employ a realistic 2D finite element analysis for vertical drains, the equivalence between the plane strain analysis and axisymmetric analysis needs to be established especially for hydraulic conductivity [29]. Because of the clay deposition process, the horizontal conductivity is higher than the vertical direction and the flow is horizontal to the drains. The procedure proposed by [35] and [30] used to convert an axisymmetric to plane-strain conductivity. Table 1 shows the hydraulic conductivities used in the model including the smear effect zone.

Table 1. hydraulic conductivities used in the model for TV2 with 1 meter PVD spacing

layers	$K_{horizontal}$ (m/day)	$K_{plane\text{-}strain}$ (m/day)	K_{SMEAR} (m/day)	$K_{blended}$ (m/day)
Weathered clay	4.52e-3	1.35e-3	1.02e-4	**1.67e-4**
Very soft clay	1.04e-3	3.1e-3	2.33e-5	**3.83e-5**
Soft clay	4.54e-4	1.35e-4	1.03e-5	**1.7e-5**
Soft to medium clay	4.54e-4	1.35e-4	1.03e-5	**1.7e-5**
Hard clay	4.54e-4	1.35e-4	1.03e-5	**1.7e-5**

A component of Geostudio 2018 suite of software, Sigma/W, was used to simulate the test embankments in coupled state. The effect of vacuum pressure was simulated by assigning the negative water head along the drain boundaries. Since the top weathered clay was over consolidated, for obtaining a better convergence, it was modeled as linear elastic. The mesh used in the model was quad and triangle which gives acceptable results for coupled analysis including consolidation. Vacuum preloading was modeled by boundary conditions with respect to Fig 4 along the PVDs. The upper air bound layer along with sand fill was modeled by a zero pressure boundary condition to account for water and air discharge true PVDs because of vacuum preloading. Fig 4 shows the geometry, and the mesh of finite elements used for TV2 modeling. The FEM of soil treatment including vacuum, surcharge and PVD is very complex and more details regarding the detailed FEM procedure that was done by the authors can be accessed from [34, 36].

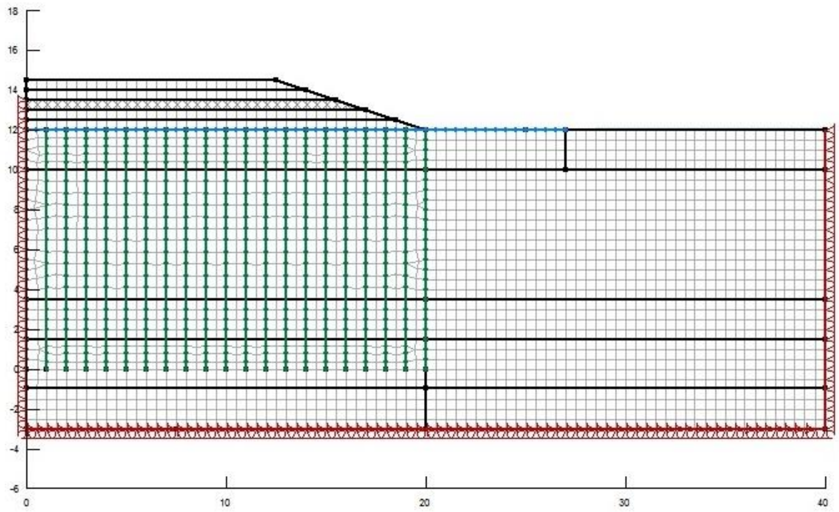

Figure 4. geometry and the mesh of finite element of TV2

2.3. Different scenarios and model verification of TV2 test embankment

2.3.1. Model verification and different scenarios

[29] and [30] despite incorporating the smear effect, had neglected the well resistance and in modeling of PVDs interface used a constant 12 meter pore pressure. In this study in addition to the smear effect, the well resistance, and the effect of clogging is also considered. As can be seen from the fig 3 in the process of applying vacuum preloading the pressure was fluctuating constantly, and in none of the time laps a constant pressure couldn't be

maintained which nearly happens in most of the project using vacuum preloading. One of the main issues responsible for this is the clogging in PVDs, which reduces, and sometimes diminishes the effect of vacuum preloading. Different techniques were developed such as ultrasonic waves or Electrokinetic Geosynthetics to overcome this obstacle like reported by [37] and [38]. For investigation of the effect of well resistance and clogging the following 3 models were numerically examined (centerline) and compared with measured field data as:

(a) FEM model with no well resistance, and no clogging
(b) FEM model with well resistance, and no clogging
(c) FEM model with both well resistance, and clogging

The well resistance was modeled by a decrease of 2 meter of PVD head in applied time dependent vacuum pressure, and the clogging was modeled by a decrease of 1-meter pressure head after the day 75 based on fig 3 which shows a critical loss of pressure head in the project. As it can be seen in fig 5, the model which neglects both the well resistance and clogging has overestimated total settlement in every step in comparison to field measured data while the model, which incorporates both the well resistance and clogging matched best. The model with well resistance, and no clogging, till the day 40, predicts the settlement as it was, but as stated in previous section, when the clogging of soils in vicinity of PVDs begans to occur, it overestimates the predictions. Based on the results obtained so far, the model, which includes both well resistance and clogging and matches well with the field measured data, that would be used for the rest of FEM modeling.

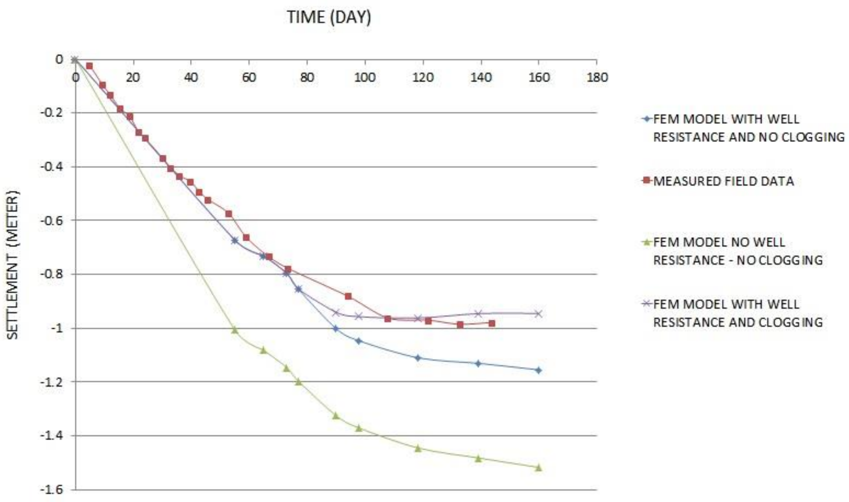

Figure 5. Settlement curve of (centerline) (a) FEM model with no well resistance, and no clogging (b) FEM model with well resistance, and no clogging (c) FEM model with both well resistance and clogging vs. Field measured data

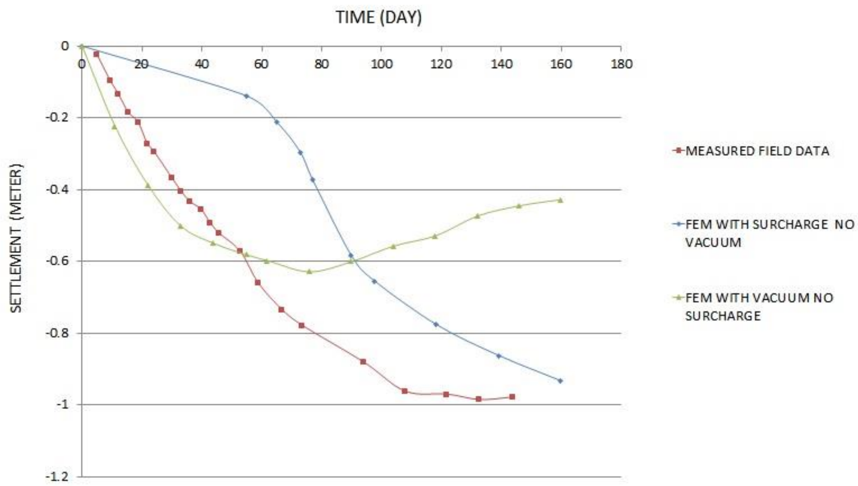

Figure 6. Settlement curves of (centerline) (a) FEM modeling in the case of PVDs without any surcharge preloading and (b) FEM modeling in the case of PVDs without any vacuum preloading vs. Field measured data

Fig 6 shows the results of two cases of TV2 as (a) FEM modeling in the case of PVDs without any surcharge preloading and (b) FEM modeling in the case of PVDs without any vacuum preloading. A system that consists of only vacuum and PVDs would fail to reach the required degree of consolidation (90 percent), while in the model without vacuum preloading only the settlement is delayed. In surcharge, and PVD systems significant heaves occur in embankment toes because of outward forces beneath the embankment. In vacuum and PVD systems major cracks occur in the toe and beneath the embankment because of inward forces, beneath the premier of reclaimed land [3, 4, 39]. A vacuum application combined with a PVD system, and surcharge can accelerate the consolidation process significantly while minimizing the unexpected soil movements in the project because of the counter-effect of forces.

2.4. FEM modeling of different depths

The TV2 embankment was analyzed with different percentages of penetrations, and the results of settlements vs. time were obtained. Fig 7 shows FEM modeling of TV2 test embankments for 90,80,70,50,33,16 and 10 percent full penetration corresponding to 10.8,9.5.8.3,6,4,2,1.2 meters. It can be seen, as the depth of penetration decreases the resulting settlement decreases as well. As it can be seen from the fig 9 if the depth of PVDs wouldn't be sufficient to mobilize the vacuum preloading, and dissipate the resulted excess pore pressure from surcharge preloading, the efficiency of the system decrease dramatically, and the required percentage of degree of consolidation would not be achievable. In penetration depth of 10.8, 9.5 and 8.3 meters despite the reduction of penetration the settlement curve remained constant and the system had an identical efficiency.

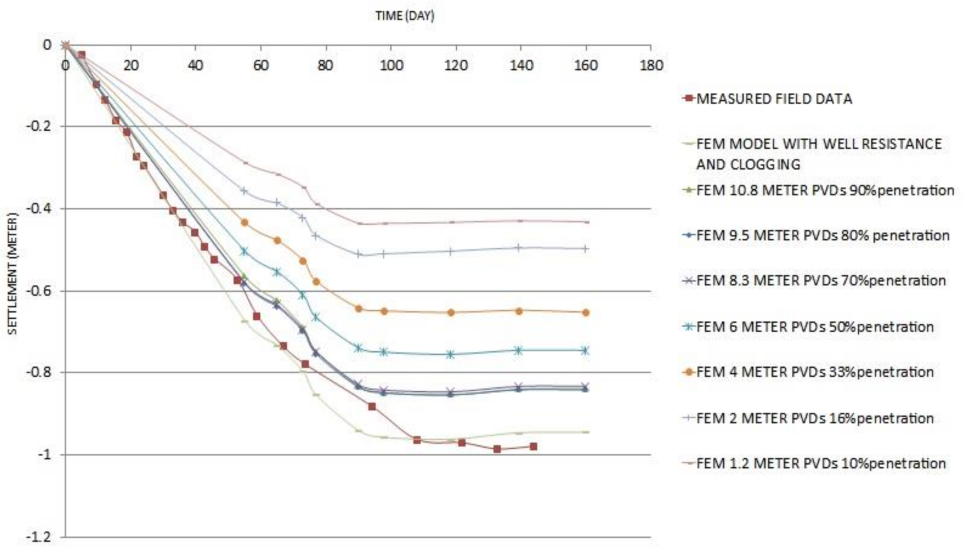

Figure 7. Settlement curves FEM modeling of TV2 test embankments (centerline) for 90,80,70,50,33,16 and 10 percent full penetration corresponding to 10.8,9.5.8.3,6,4,2,1.2 meter

Fig 8 shows the FEM modeling of TV2 test embankments for 110,120,130,140 and 150 percent full penetration corresponding to 13, 14.5, 15.6, 16.8 and 18 meters. The other test embankments, which were built at Bangkok airport was TV1 which had 15 meter PVD length, and the model with 130 percent of penetration is somehow the same as TV1. As the depth of penetration increases, the resulting settlement increases as well. In full penetration of 120 percent to 150 percent despite of an increase in penetration depth, the settlement curve is somehow identical and the system has an identical efficiency.

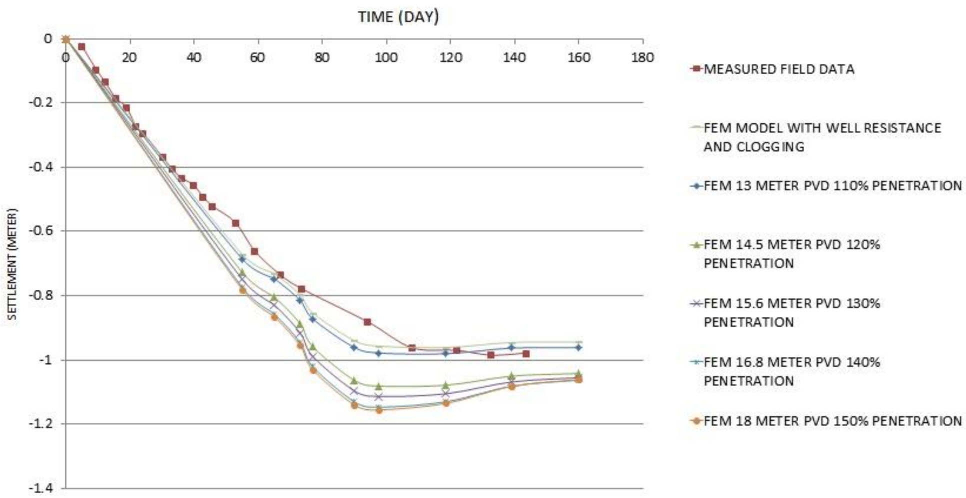

Figure 8. Settlement curves of the FEM modeling of TV2 test embankments (centerline) for 110,120,130,140 and 150 percent full penetration corresponding to 13, 14.5, 15.6, 16.8 and 18 meter

3. RESULTS AND DISCUSSION

One of the most challenging parts of every project including prefabricated vertical drains (PVDs) combined with vacuum and surcharge preloading for ground improvement is the determination of the PVDs depth of installation. Since the ultimate goal of soft clay soils treatment is obtaining pre-determined settlement to attain the required degree of consolidation, the settlement curve under soil embankment was used for investigation of the results. Two different scenarios were analyzed using FEM modeling as PVDs penetration depth increment/reduction from the original length of verified case history (12 meter).

Fig 9 shows two regions of concentration in settlement curves, which by decreasing/increasing of PVDs length, the settlement curve don't change noticeably. In the specified length range any one of them can be taken without affecting system overall efficiency. In one group there are 14.5 to 18-meter depth and in another 8.3 to 9.5. From these groups 8.5 which represents 72 percent penetration and 14.5, which represents 120 percent penetration has been used for a new "One and Between Configuration", which was proposed in this paper as a possible substitution of the common method which is now in practice. Fig 10 illustrates the schematic of the proposed method which in this case is Bangkok TV2 test embankment. Fig 11 shows the settlement curve of "One and Between Configuration" in comparison to field measured data and FEM model which has full penetration depth. Despite a minor reduction in total length of a pair from 23 to 24, the proposed configuration has even better performance in comparison to the common constant full common penetration method.

As it can be seen in fig 12 the lateral displacement curve at embankment toe of proposed "One and Between Configuration" is 15 percent lesser than the verified FEM model, and it clearly demonstrated that the inward forces of vacuum preloading in proposed configuration is greater than the conventional method. [40] reported that if the applied vacuum pressure is larger than the lateral stress required maintaining a k_o condition (no horizontal strain), there would be inward lateral displacement, and the vacuum pressure will induce less settlement. Since the nature of lateral displacement caused by embankment (outward), and vacuum preloading (inward) is different, in general the combination of them will not necessarily result in zero lateral displacement. One of the great advantages of "One and Between Configuration" is that without increasing the surcharge preloading and fill height, the overall lateral displacement has decreased.

The proposed method can be applied for any project which is after constructing the preliminary FEM model for the design based on special characteristic and specifications of a ground (unique in every project), different depth shall be modeled as the procedure described in this paper for a case history, and then the optimum depth for "One and Between Configuration" would be computed. The process of try and error would continue till the preferred outcome is found. FEM is a very powerful tool for design of such problems as complicated as soil treatment incorporating combined vacuum and surcharge preloading.

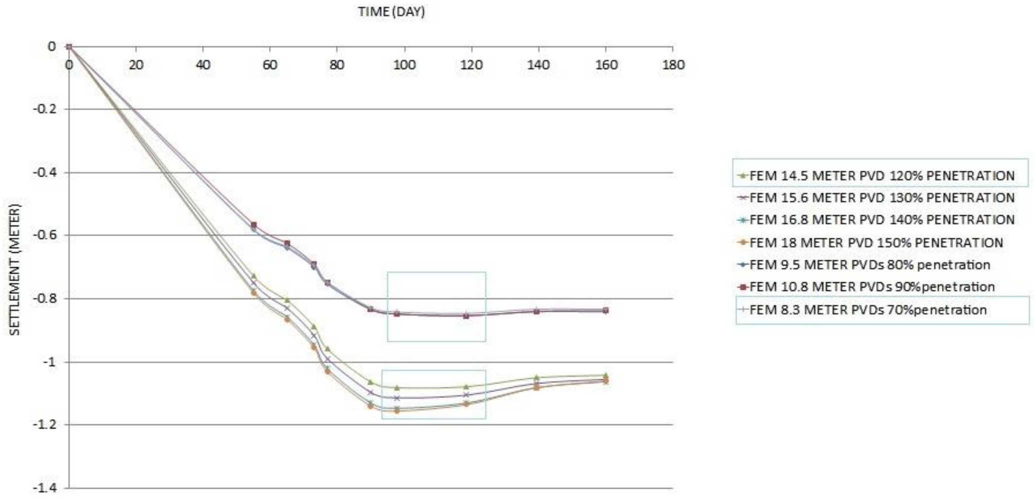

Figure 9. Two regions of concentration in settlement curves

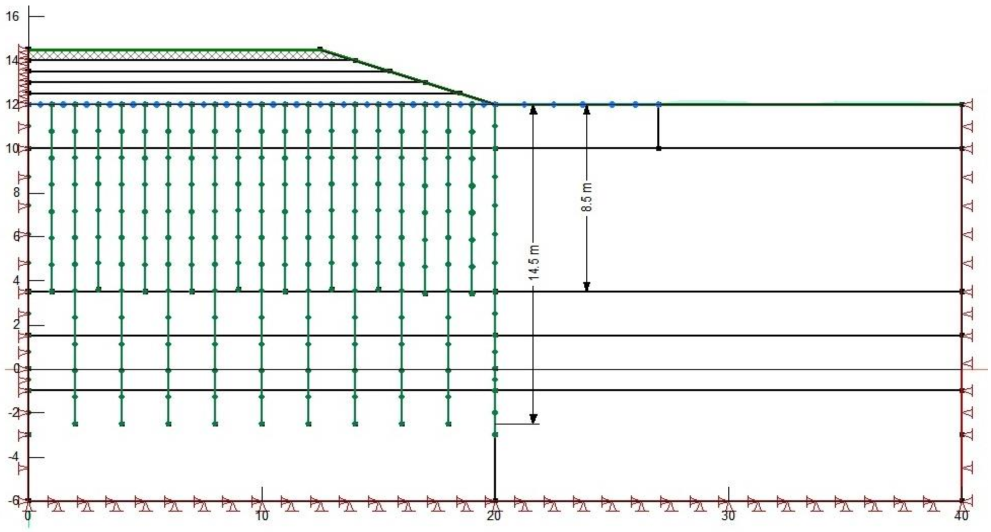

Figure 10. schematic of proposed method "One and Between Configuration"

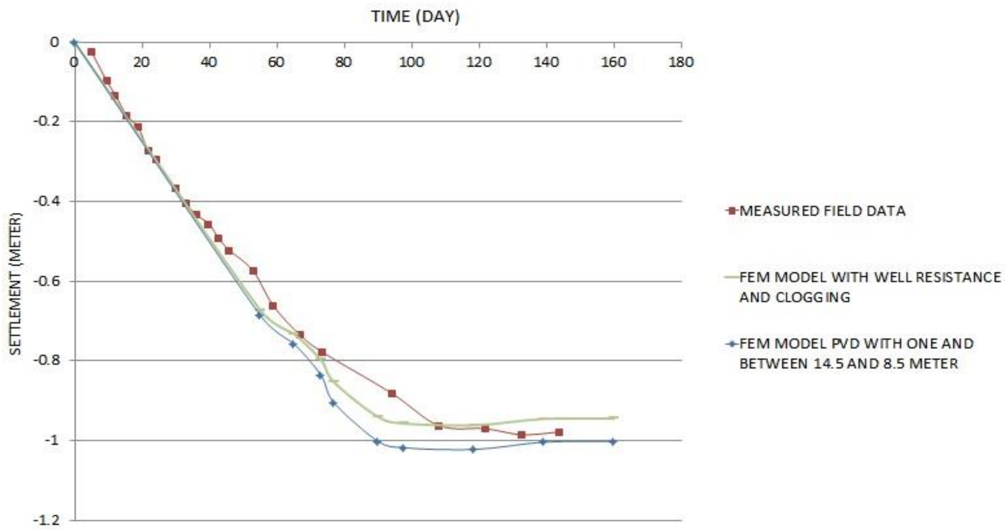

Figure 11. The settlement curve (centerline) of "One and Between Configuration" in compare to field measured data and verified FEM model

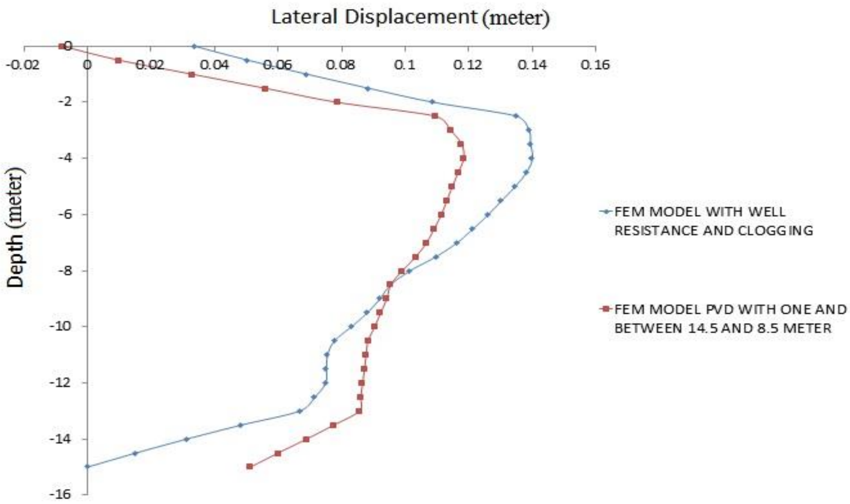

Figure 12. Lateral displacement curve (embankment toe) of "One and Between Configuration" in compare to Verified FEM model

One of the obstacles of PVD installation in real the field is partial penetration of a percentage of PVDs because of mechanical malfunction of equipment or mandrel inability to fully penetrate because of various varved clay stratification of the ground. Because of that some geotechnical designers tend to overdesign the length of PVD penetration if it is possible. If a noticeable percentage of the PVDs length in various locations become clogged during the process of vacuum preloading, or the equipment or the circuit of the vacuum pump or drainage system wrecked for an unknown time which are normal in such projects, another problem arises that is uneven settlement. One way to overcome the stated problems is instead of installing the PVDs in full length all over the project, installing them with "one and between" configuration. By this way of installation:

(1) Because of the "one and between installation", in a case that a percentage of the every PVDs become clogged in any possible length, which may vary from PVD to PVD, the overall performance of the PVD itself and in relation to adjacent PVDs don't diminish as much as common constant penetration.

(2) As a result of the lesser penetration of the mid PVD, the disturbance of the soil and accordingly, the smear zone becomes lesser, especially for the PVDs with iron plates cap underneath.

(3) In the case of the "one and between", since its configuration lessens the soil disturbance, the possibility of the uneven settlement decreases.

(4) Because of 50 percent less deep PVD installation, the cost of equipment and human resources would be decreased.

Since until now, this proposed way of installation, "One and Between Configuration" has not been executed anywhere. More detailed investigation, especially full scale tests are required to verify the performance and efficiency of this method of installation. Although it should be mentioned that like any geotechnical big scale project because of distinct soil characteristic of clay soils, and layers properties of any project and also the complexities of such soil treatment methods, complete investigation of full-scale test embankments and modeling is needed, prior to finalizing the ultimate design by competence geotechnical consultants.

4. CONCLUSION

TV2 test embankment at Bangkok was modeled as a case history and the model was verified. Different penetration lengths were analyzed ranging from 110 to 150 percent increment and 90 to 10 percent reductions from TV2 field penetration depth. A new FEM based approach as "One and Between Configuration" was introduced. Based on the analysis results 14.5 and 8.5 meters were chosen as PVDs length in the proposed model. The settlement (centerline), and displacement (embankment toe) curves of the proposed model, despite having lesser total length as a pair, has better efficiency than the case with full penetration length. It was shown that the inward forces of vacuum preloading in proposed configuration is greater than the conventional method and lateral displacement reduced by 15 percent. By following the procedure stated in this paper, the process of optimization of depth and configuration can be done for any similar project.

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AUTHORS CONTRIBUTION

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CONFLICT OF INTEREST

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