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NUMERICAL ANALYSIS OF PREFABRICATED VERTICAL DRAINS IMPROVED SOFT SOIL BENEATH AN EMBANKMENT DURING STAGED CONSTRUCTION

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Abstract: This study is concerned with investigating the advantages of using prefabricated vertical drains (PVD) to improve the foundation soft soil under an embankment. PVD combined with staged construction of embankment is considered as a common technique to reduce both the time for full consolidation and the excess pore water pressure. Rocscience Settle 3D software was used to analyze the embankment and the underlying soft soil which is chosen to be at Basra region. The numerical analysis showed that the PVD is very effective in accelerating the consolidation process and increasing the long term stability of the embankment. It is interesting to note that installing the PVD with spacing (1 m) leads to a rapid dissipation of most of the excess pore water pressure at the end of each stage. The length of PVD sheets can significantly accelerate the consolidation more than the spacing.

Keywords: *Soft soil; Prefabricated vertical drains, Embankment; Staged construction*

التحليل العددي للمبازل الشاقولية المسبقة الصنع لتحسين التربة الضعيفة أسفل التعلية الترابية المنفذة على مراحل

الخلاصة: تعنى هذه الدراسة بالتحقيق في مزايا استخدام المبازل الشاقولية مسبقة الصنع (PVD) لتحسين تربة الأساس الضعيفة تحت التعلية الترابية. يعتبرإستخدام PVD جنبا إلى جنب مع البناء على مراحل للتعلية الترابية أسلوبا" شائعا" لتقليل الوقت لكل من الإنضمام وضغط المياه المسامي الزائد. تم استخدام برنامج (Rocscience Settle 3D) لتحليل التعلية والتربة الضعيفة الأساسية والتي تم اختيارها لتكون في منطقة البصرة. أظهر التحليل العددي أن PVD فعال جدا في تسريع عملية الإنضمام وزيادة الاستقرار طويل الأمد للتعلية الترابية. ومن المثير للاهتمام أن نلاحظ أن تثبيت PVD مع تباعد (1 م) يؤدي إلى التبديد السريع لمعظم ضغط المياه المسامي الزائد في نهاية كل مرحلة. طول شرائح PVD يمكن أن يسرع بشكل كبير من اللاإنضمام أكثر من التباعد فيما بينها.

1. Introduction

In the past few decades embankments on soft soil are widely used for railways, roads, and buildings due to the rapid development in construction and the urgent demand to simplify the movement all over the countries. Soft soil posses a low coefficient of permeability, high compressibility, and low bearing capacity which cause large geotechnical problems to the foundations. Therefore, the need for accelerating the soil consolidation becomes of major concern.

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Several techniques were adopted to minimize the risk of embankments failure and increasing their stability. Rising up the embankment with a slow rate multi-staged construction is one of these techniques [1] and [2]. Although this technique succeeded in controlling the failure risks, but it was more effective for thin soft clay layers where a short drainage path are provided. In case of thick soft clay layers, this method needs a long time to complete the consolidation process which leads to combine it with the installation of PVD to accelerate the consolidation under the embankment surcharge.

The prefabricated vertical wick drain consist of perforated plastic core is made of high quality flexible polypropylene which exhibits a large water flow capacity in the longitudinal direction of the core. The dimensions of most PVD are in the order of 100 mm width and 4 mm thickness. Such type of drains speed up the soil consolidation by shortening the horizontal drainage path for water flow to reach the nearest drain strip [3], [4] and [5]. The utilization of PVD exhibits a good reputation due to the ease and speed installation using simple equipment in many ground improvement projects.

The present study considers the effects of both PVD and the staged construction simultaneously and investigates the combined benefits resulting from the partial consolidation of soil due to PVD and the staged construction. To achieve these targets, the Rocscience program *Settle 3D* [7] was used as a first attempt to verify a case study of full scale embankment on soft clay with PVD at the new Bangkok International Airport in Thailand [8]. At the second attempt, the *Settle 3D* program is used to investigate the effect of using PVD in the soft soil improvement of Al-Basra site south of Iraq in case of such an embankment is to be constructed for engineering purposes.

2. Literature Review

The system of vertical drain is one of the most popular methods of increasing the shear strength of soil, and of reducing its post construction settlement by shortening the drainage path. The theoretical solution for vertical drain consolidation was first proposed for the unit cell condition (i.e., a single drain surrounded by a soil cylinder) by Barron [9].

There has been considerable research examining the behavior of embankments over soft clay treated with PVDs in terms of field behavior [8], [10], [11], [12], [13], [14] and [15],in terms of theoretical behavior as predicted using finite element methods[16], [17], and [18], and as observed in laboratory model tests[19], [20], [21], and [22].

The behavior of geosynthetic-reinforced embankments constructed over soft cohesive soils installed with prefabricated vertical drains (PVD) was investigated numerically examining an embankment constructed over different foundation soils [16].They showed that the construction rate and spacing of PVD can significantly affect the degree of consolidation at the end of construction and the stability of the embankment. Comparing the embankment heights for spacing (S) of 1, 2, and 3 m, the improvement in stability due to a change in spacing from 2 m to 1 m was much greater than that observed where the spacing was changed from 3 m to 2 m.

A numerical study of the behavior of geosynthetic-reinforced embankments constructed on soft rate-sensitive soil with and without prefabricated vertical drains (PVDs) is described [17]. The time-dependent stress–strain-strength characteristic of rate-sensitive soil is taken into account using an elasto-viscoplastic constitutive model. The presence of PVD considerably reduced the differential settlement of the foundation soil. Moreover, the excess pore water pressure rapidly decreased following the end of construction and reinforcement with lesser stiffness could be employed with faster rate of construction while maintaining similar performance.

Belén and Schmidt [18] presented a numerical 3D comparison between real PVD and equivalent permeability during consolidation: one simulating soil with a real PVD installed, and the other one simulating soil with equivalent permeability (k_{ve}). Both the unit cell with real PVD and the unit cell with k_{ve} gave similar final settlement results, but the consolidation rate and predicted excess pore pressure were somewhat different. The unit cell with a real PVD simulation resulted in a faster consolidation rate and lower predicted excess pore pressure.

Hansbo [19] summarized the results of several researches and mentioned that the discharge capacity is greatly influenced by confining pressure. The reason is that the filter sleeves are squeezed further into the channel system at higher confining pressures, which entails a reduction in the channel areas, or the channels themselves are squeezed together under higher pressures. Another systematic laboratory test program was carried out to identify the important factors influencing the discharge capacity [20].These results indicated that the confinement conditions and the test duration are two key factors affecting the discharge capacity of a PVD.

Large-scale laboratory model tests were carried out to assess the suitability of the selected PVD and the effectiveness of the PVD in the consolidation of the ultra-soft soil [21]. The model tests indicate that the discharge capacity of the drain can decrease substantially after the drain has experienced large deformations. The model tests indicate that there was an 84% reduction in the discharge capacity after the PVD had experienced a vertical strain of 46%.Therefore, it is effective to use PVD to accelerate the consolidation process of ultra-soft soil.

Bergado et al. [22] used a large diameter consolidometer to study the effect of using PVD combined with surcharge, surcharge and vacuum pressure, surcharge and heat up to 90^{o} C . The horizontal coefficients of consolidation for these cases were 1.93, 2.23, 4.17, and 4.38 m^2/year respectively.

3. Subsurface Conditions and Soil Properties

The soil profile and properties for the two mentioned sites adopted in this research are described below.

- Bangkok soil [8]: The soil profile consists of a 2 m thick weathered crust overlying very soft to soft clay approximately 10 m thick. Underlying the soft clay is a medium stiff clay layer about 4 m thick followed by a stiff clay layer extending down to 24 m depth which is in turn underlain by a layer of dense sand (standard penetration test (SPT) *N* values of 30–50). The natural water contents are reasonably uniform across the site and lie close to the liquid limit between depths of 2 and 16 m. Most of the Atterberg limit values lie above the A line in the plasticity chart, confirming the high plasticity of the Bangkok clay. The groundwater table varies between 0.5 and 1.0 m below the ground surface.

- Basra soil [23]: Basra soil usually characterized by non pronounced stratification and sometimes organic matter, shell and well-preserved recent fossils (bivalves and gastropods) are present in this deposits. The soil profile consists of (2.5-4.0) m thick medium stiff to stiff clay overlying soft clay approximately (10-14) m thick. Below this depth, and down to a depth of 30m, the soil becomes stiffer with the presence of cohesionless layer of silty sand. The underground water table in Basra was encountered at depths varied from (0.55 to 3.0)m below the natural ground level. Some Physical properties and consolidation parameters of Basrah soil are listed in Table (1).

Table 1 Physical properties and consolidation parameters of Basra soil [23]

	w_c%	γ_t	L.L	P.L	e_o	C_c	C_s
Max. value	40.8	23.06	46	28	1.187	0.43	0.057
Min. value	26.4	17.71	34	22	0.659	0.18	0.012

4. Staged Construction of the Tested Embankment

The test embankment is 40 m × 40 m in plan dimensions with 3*H*:1*V*side slopes and has a final height of 4.2 m (Fig. 1). Clayey sand was used to raise the embankment to 4.2 m (i.e., 75 kPa of surcharge) in stages. As shown in Figure (2) the loading for stage 1 was up to 18 kPa, for stage 2 up to 45 kPa, stage 3 up to 54 kPa, and stage 4 up to 75 kPa (4.2 m fill height).

After the test embankment was preloaded to a certain height in the stage loading, a waiting period is needed in order for the underlying soft clay foundation to gain additional shear strength. The waiting period was 30 days with a 45 kPa surcharge, which was subsequently increased to 54 kPa. The design waiting period was 105 days for the embankment when the surcharge increased from 54 to 75 kPa.

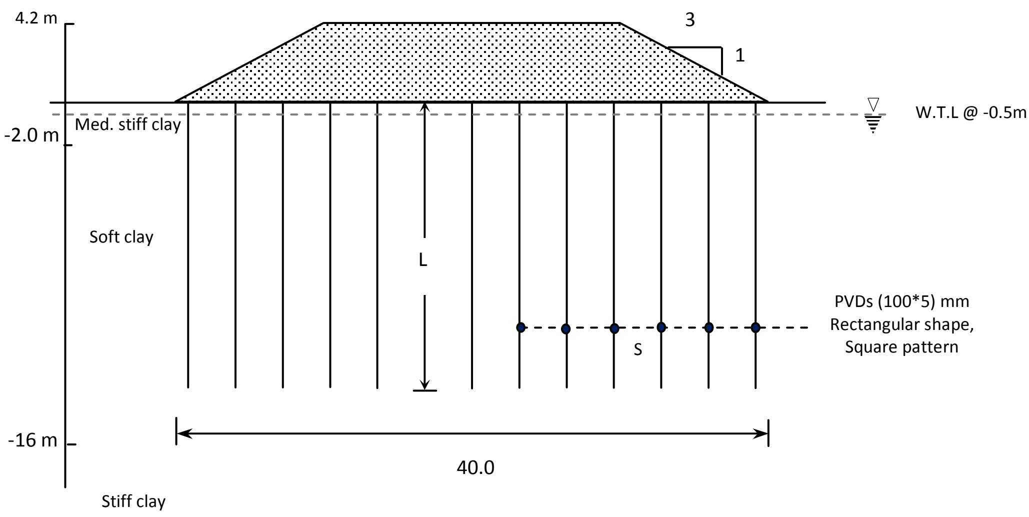

Figure (1) Test embankment on soft clay with PVD and soil profile

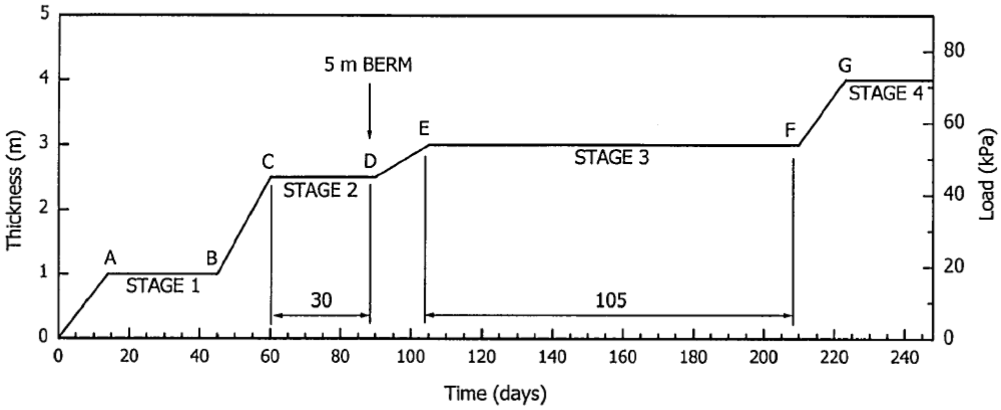

Figure (2) Staged construction of embankment with time

4.1. *Verification of a Case Study in Bangkok*

The embankment shown in Figure (1) was analyzed first with staged construction on PVD improved Bangkok soft soil to verify the Settle 3D software. Figure (3) shows the relation of settlement with time of construction which reflects a good agreement with the results of Bergadoet et al. [8].

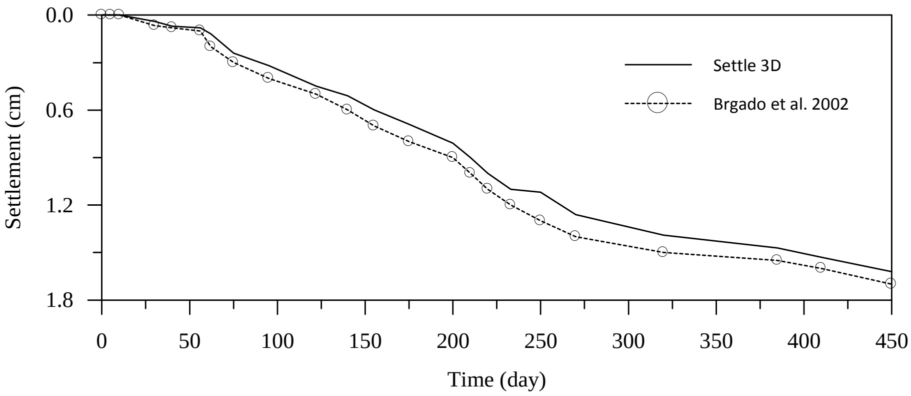

Figure (3) Staged construction of embankment with time

4.2. *Some Consideration of the Present Study*

For most natural deposits the hydraulic conductivity in the horizontal direction is higher than that in the vertical direction. The value of k_h/k_v can be estimated as [1]

$$k_h/k_v = (1 \text{ to } 15) \qquad (1)$$

where K_h is the hydraulic conductivity in the horizontal direction, and K_v is the hydraulic conductivity in the vertical direction.

In the field, PVDs are installed by using a mandrel, which is pushed into the subsoil with a PVD inside it. The mandrel is subsequently withdrawn leaving the PVD in the subsoil. This process creates a completely disturbed zone around the PVD, called the smear zone, with an effective radius of r_s (diameter d_s). The value of *ds* can usually be estimated as[1]

$$d_s = (2 \text{ to } 3)\, d_m \qquad (2)$$

where d_m= the equivalent diameter of the cross-sectional area of a mandrel. In design, if there are no test data available for evaluating the smear zone size, the value of $d_s = 3d_m$ is suggested [24].

No information appears in Bergado et al. [8] about these two parameters adopted in the research. Therefore, $k_h/k_v= 2$, and $d_s= 3d_m$were used in the analysis of this study.

5. Results and Discussion

The embankment shown in Figure (1) would be analyzed using the staged construction detailed in Figure (2) assuming the properties of Basra soil outlined in Table (1).

Figure (4-a) shows the settlement of untreated soil, i.e. without PVD, during staged construction under midpoint of embankment. Although the soil stratum extends below to about (17 m) N.G.L, but the settlement disappeared after (6 m) depth under a point of embankment centerline. Figure (4-b) shows the effect of using PVD in duplicating the settlement of the untreated soil. The existence of the PVD offer a short drainage path for water which increase the settlement to more than twice its initial value with an approximate rate of (0.45 cm/day). Moreover, a deeper stratum can be covered by the existence of PVD.

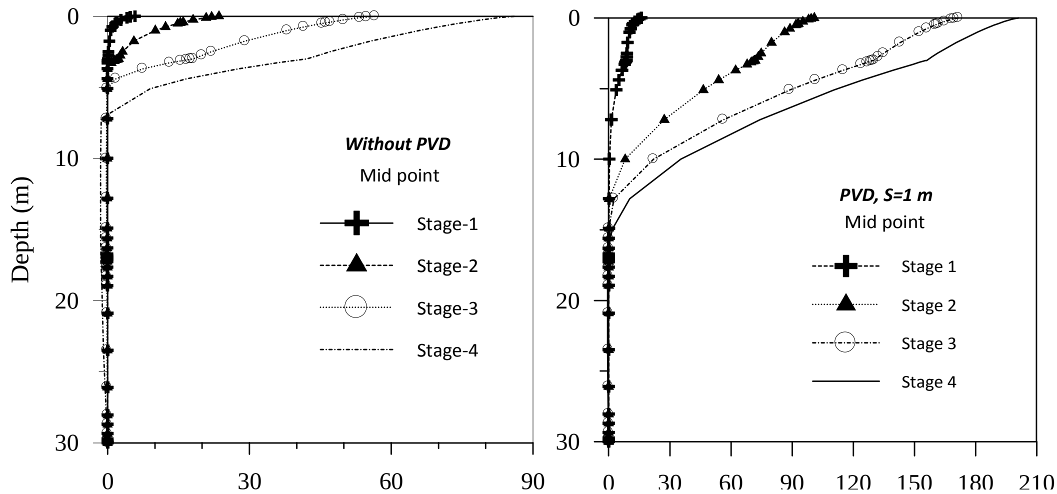

Figure 4: Variation of ground settlement with depth under the midpoint of embankment for treated and untreated soil.

The positive effect of PVD is also clear at the edge point of embankment which reveals the considerable amount of settlement at each stage of loading as shown in Figure (5).

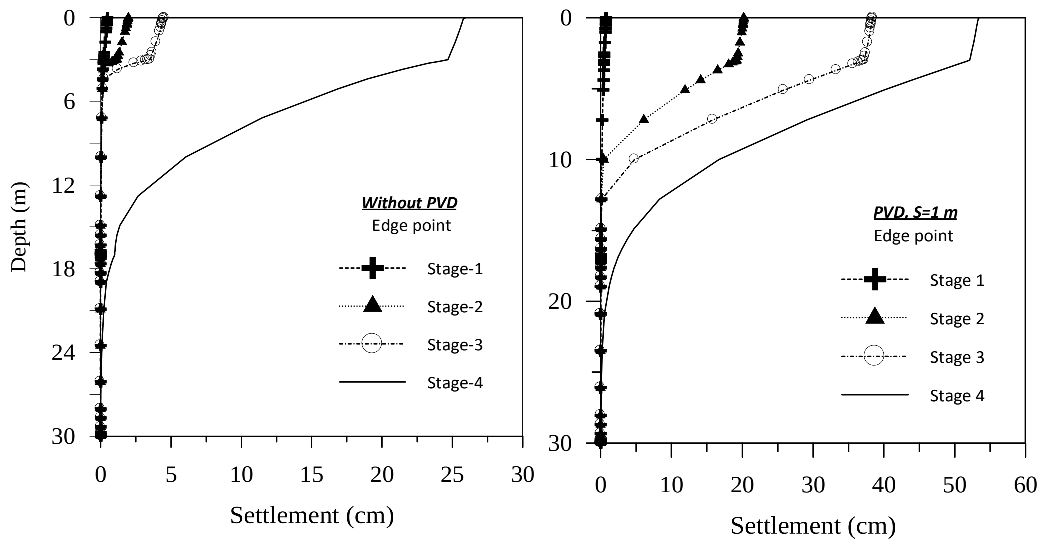

Figure 5: Variation of ground surface settlement under the embankment for treated and untreated soil.

Form Figure (6-a) it could be seen that the maximum degree of consolidation (U%) is (30%) at the end of construction (450 days) which means that an additional time is needed to finish the consolidation. On the other side, the PVD increases (U%) to (67%) at the end of construction which reflects the good drainage condition provided as shown in Figure (6-b).

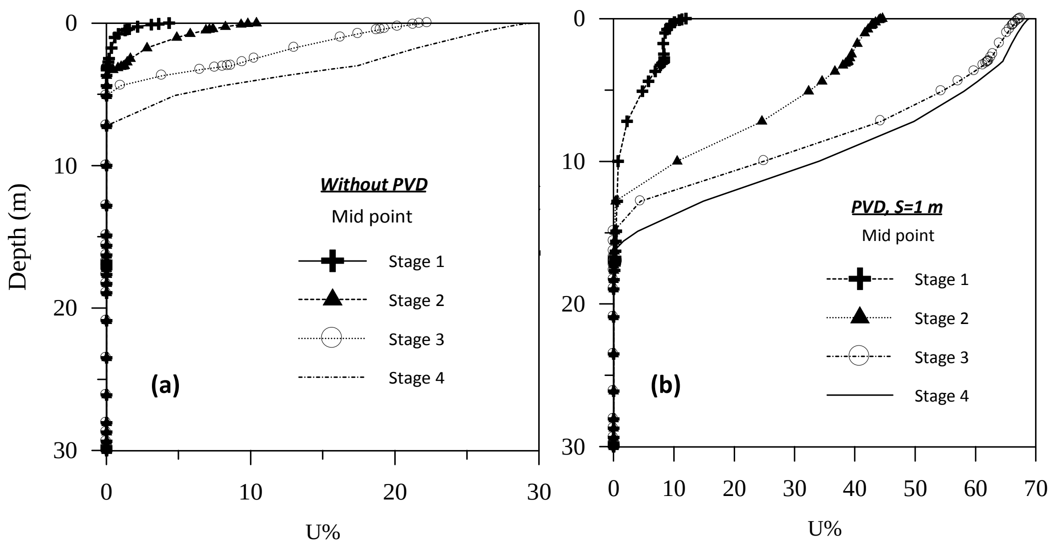

Figure 6: Variation of degree of consolidation with depth under the midpoint of embankment for treated and untreated soil.

The subsequent loading on the clay layers leads to generation of excess pore water pressure, PWP, due to low permeability of clay. This criterion is appeared in Figure (7) where the gradual increase in the excess PWP is a result of the stage construction. Installing the PVD leads to 40% reduction in the excess PWP especially within the range of PVD length.

The presence of PVD in soft clay retards or reduces the build-up of PWP along its length and a rapid increase is shown at deeper soil layers.

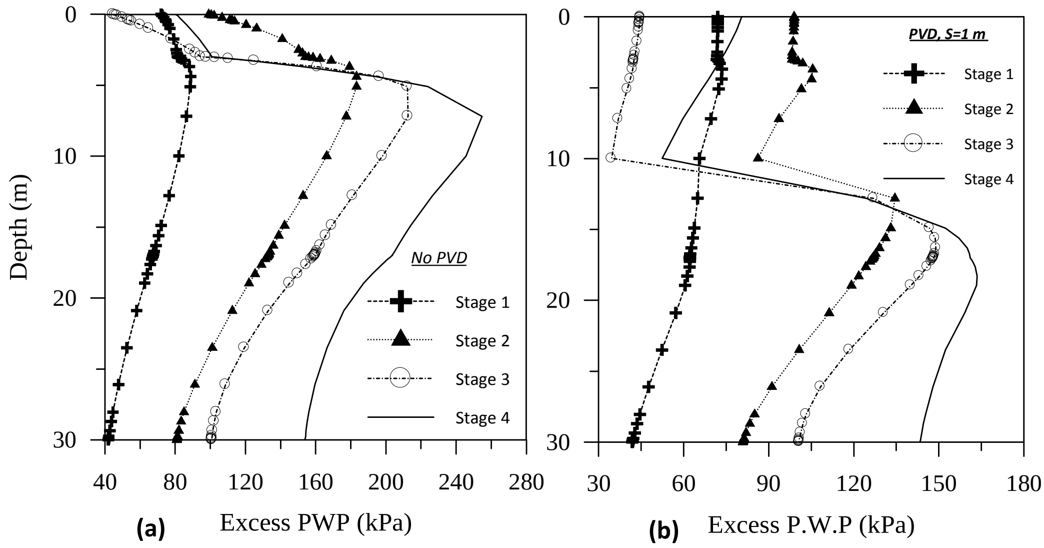

Figure 7: Variation of excess PWP with depth under the midpoint of embankment for treated and untreated soil.

Three spacing among the PVD sheets (S=1, 1.5, and 2 m) are chosen in this study to investigate their effect on the embankment stability. Figure (8) shows the lateral distribution of the excess PWP at a depth of (7 m) for the second and fourth stage of loading during which large effects in soil behavior are shown. The results represent half of the embankment since the considered problem is symmetric. Comparing the untreated with treated soft soil beneath the embankment, using PVD with a spacing (1 m) can lower the excess PWP to the half with lesser effects for the other spacing (1.5 and 2 m). It is evident that that the excess PWP can sufficiently be reduced as long as a shorter drainage path is provided. For (stage- 4), i.e. at the end of construction, the difference among spacing is almost diminished since there is enough time for the PWP dissipation.

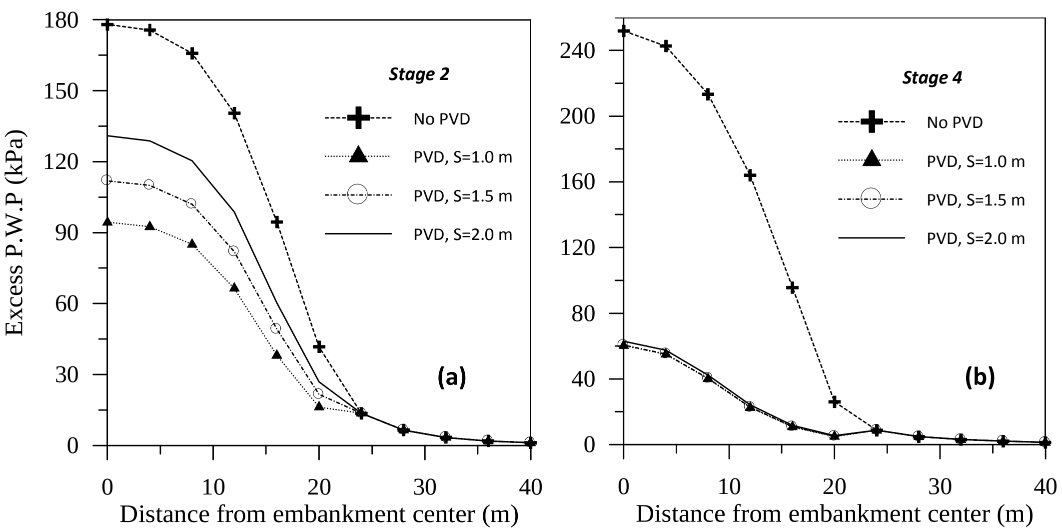

Figure 8: Lateral distribution of excess PWP along ground surface at a depth of 7.0 m under the embankment for treated soil.

Figure (9) shows the PWP behavior during the time of construction. It seems that 95% of the PWP can be reduced at the end of each stage with PVD spacing S=1 m irrespective of the construction time. Doubling the spacing to 2 m leads to minimize its efficiency with a nonuniform reduction in the PWP at each stage.

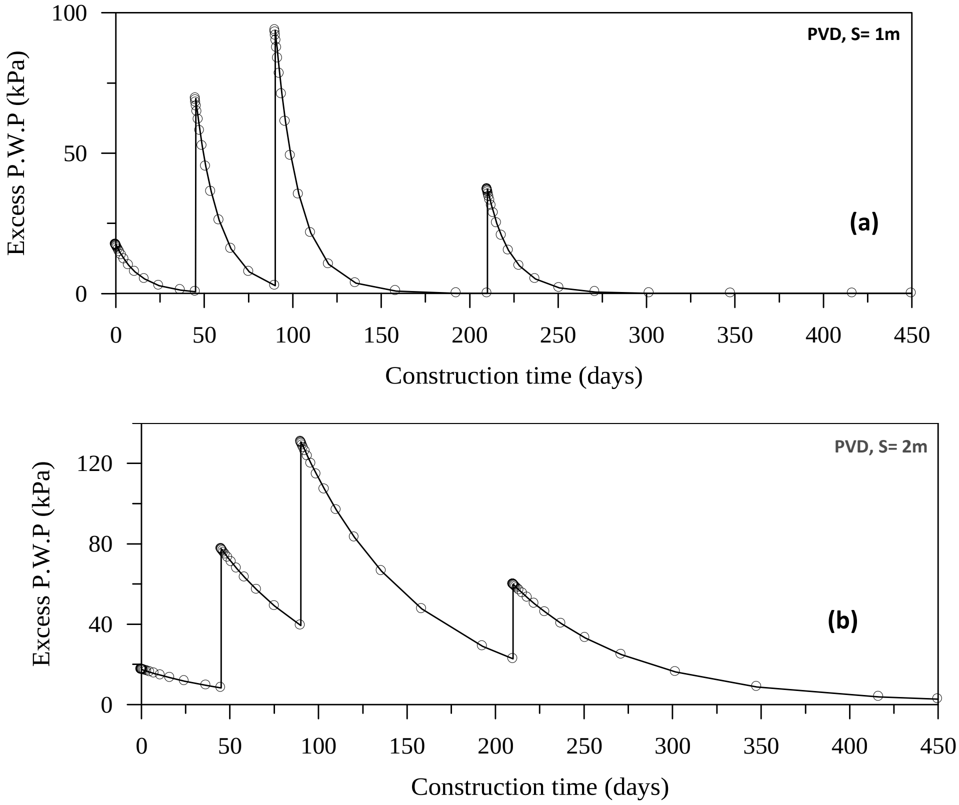

Figure 9: Variation of excess PWP with time under the midpoint of embankment

Holtz et al. [3] refers to that the advantage of PVD is accelerating the consolidation process which leads to increase the effective stress, the shear strength, and thus improve the stability of embankment. This is obvious in Figure (10) which reveals that the smaller PVD spacing can gradually increase the strength gained by the soft soil at the end of each stage. This can also be supported by Figure (11) which shows the role of PVD spacing on the excess PWP within the soft clay region.

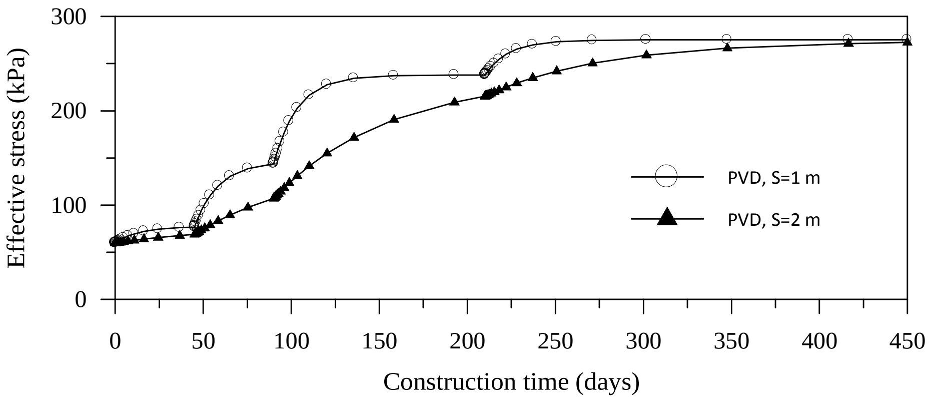

Figure 10: Variation of effective stress with time under the midpoint of embankment.

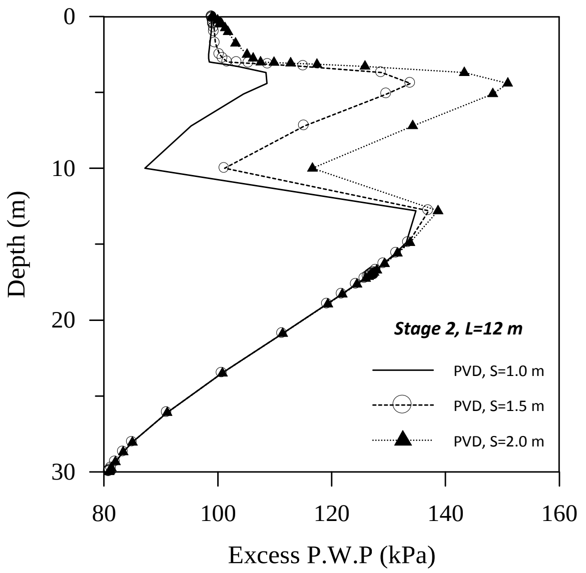

Figure 11: Effect of PVD spacing on the excess PWP under the midpoint of embankment

Figure (12) shows the distribution of PWP under midpoint of embankment on soft clay with different length of PVD. Increasing the PVD length from (8 m) to (16 m), at which the soft layer is extended, succeeded in lowering the excess PWP by approximately 60%. At the end of (stage- 4), a considerable amount of undissipated PWP is noticed for L= 8 and 12 m which means that an additional time is required to finish the consolidation.

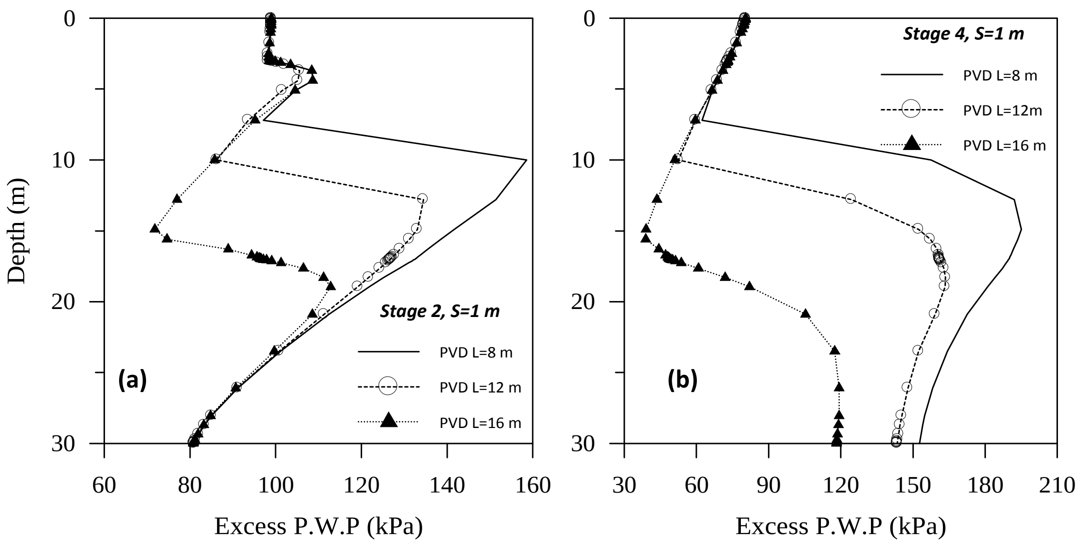

Figure 12: Effect of PVD length on the excess PWP under the midpoint of embankment

Figure (13-a) shows that the settlement is directly proportional to the PVD length. Comparing Figure (11 a and b), shows that the PVD length can significantly affects the soft soil more than the spacing.

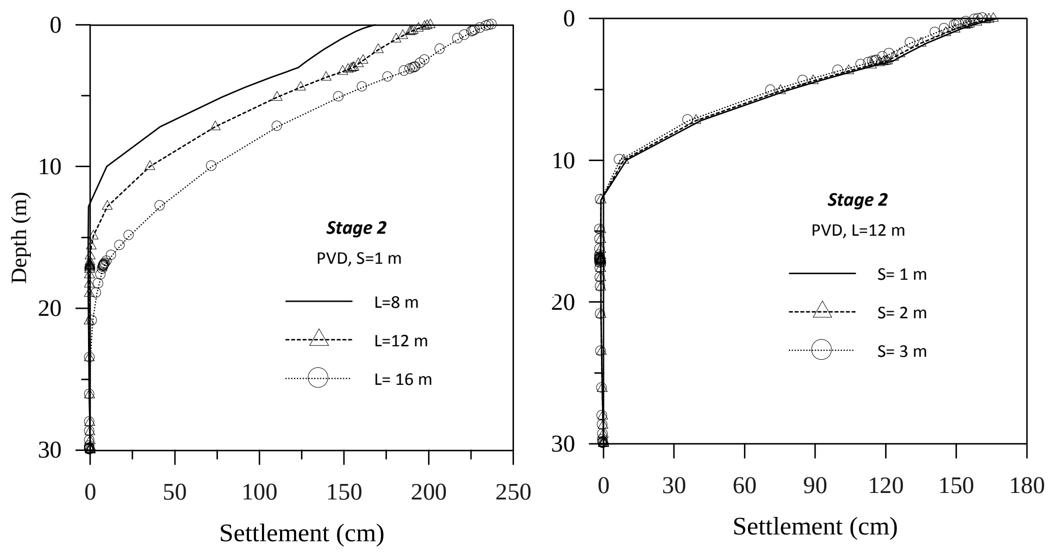

Figure 13: Variation of settlement with depth under different spacing and length of PVD

6.Conclusions

The use of PVDs in soft subsoil of Basra region has been numerically analyzed to assess its effectiveness to support an embankment constructed on such problematic soil. The effect of several parameters such as length and spacing of PVDs during staged construction of the embankment were examined. Based on the parameters adopted in this study, the following conclusions can be reported:

1- PVD leads to increase the settlement of soft soil from (87) cm to (201) cm and extend the influence to a deeper soil stratum within its length.
2- PVD accelerate the PWP dissipation which increases the degree of consolidation (U%) from 29% to 68% at the end of construction which reflects the good drainage condition provided by the PVD.
3- About 95% of the PWP can be reduced at the end of each stage with PVD spacing S=1 m irrespective of the construction time.
4- The smaller PVD spacing increases the effective stress in the soil at the end of each stage and thus the embankment becomes more stable.
5- Increasing the PVD length from (8 m) to (16 m), succeeded in lowering the excess PWP by approximately 60%.
6- The PVD length can significantly affects the soft soil more than the spacing.

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