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Numerical Investigation of Embankment Settlement Improved by Method of Preloading by Vertical Drains

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***Abstract*—**Time dependent settlement due to loading on soft saturated soils produces many problems such as high consolidation settlements and low consolidation rates. Also, long term consolidation settlement of soft soil underlying the embankment leads to unpredicted settlements and cracks on soil surface. Preloading method is an effective improvement method to solve this problem. Using vertical drains in preloading method is an effective method for improving soft soils. Applying deep soil mixing method on soft soils is another effective method for improving soft soils. There are little studies on using two methods of preloading and deep soil mixing simultaneously. In this paper, the concurrent effect of preloading with deep soil mixing by vertical drains is investigated through a finite element code, Plaxis2D. The influence of parameters such as deep soil mixing columns spacing, existence of vertical drains and distance between them, on settlement and stability factor of safety of embankment embedded on soft soil is investigated in this research.

***Keywords*—**Preloading, soft soil, vertical drains, deep soil mixing, consolidation settlement.

I. Introduction

Construction of geotechnical structures like embankments on soft soils leads to so many problems. These soils have a low shear strength and low permeability and settle a lot under loading. On the other hand, the rate of consolidation and strength increase due to the increase in effective stress is low [1]. Long-term consolidation on the road embankments leads to unwanted settlement and cracking in the base. Soil improvement in soft soils increases strength properties and make the construction of engineering structures possible. Preloading is a common method for the improvement of soft soils [2]. In this method, loading is applied on the substrate soil to allow for initial settlement to happen. After the removal of loading and construction of the main structure, the settlement is less than what is expected due to the pre-consolidation of substrate soil. Preloading of the substrate soil is usually done by construction of an embankment or vacuuming [3], [4]. In both approaches, initial settlement of soil occurs that leads to the increase of effective stress and pre-consolidation of soil, therefore it is expected that little settlement happens under the main loading. Use of vertical drains increases preloading efficiency in both embankment construction and vacuuming. Vertical drains reduce the drainage path and increase consolidation rate, therefore increase of strength of soft soils happens faster and less time is needed for application of preloading on the soft substrate [5].

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In this paper, the effect of preloading on the improvement of the behaviour of soft soil substrates is examined numerically. The effect of preloading and the height of vertical drains on the settlement of substrate in a given time period is investigated. Also, the simultaneous use of preloading with vertical drains, and deep mixing columns are inspected. Utilization of deep mixing columns is one of the common methods of soft soil improvement. To this end, the finite element method and the Plaxis software are used. First verification and validation of the models based on a real project is presented.

II. Verification and Validation

For verification and validation of numerical models, the presented results of Larsen et al. are used [6]. They compared monitoring data of a test embankment on the soft soil with results of finite element model. Deep mixing columns were used for the improvement of the soft substrate. Two embankments with different heights are used to examine the effect of preloading with deep mixing columns. A view of the constructed embankment is shown in Fig. 1.

Fig. 1 Constructed embankment

Fig. 2 depicts the cross-section of the embankment in Plaxis software. The water table is 2 m below the earth surface and at the level of the clay layer. Deep mixing columns have a square arrangement with a center to center distance of 1 meter and penetrate 7 meters in the clay layer. The higher embankment is 1 m taller than the lower one. This difference in the height is considered as preloading. For soft clay layer and also deep mixing columns, Soft Soil creep model is used. For the other strata, Mohr-Coulomb constitutive model is used [7]. The material properties are given in Table I.

The simulation results plus the results presented by Larsen et al. are shown in Fig. 3. It is observed that the created numerical model could simulate embankment settlement well. Moreover, preloading results in more settlement to happen compared to the typical embankment in a given time.

TABLE I
MATERIAL PROPERTIES

Material	Embankment	Existing fill	Clay dry crust	Columns	Clay	Silt	Moraine	Sand
e_{init}	0.5	0.5	0.5	0.8	1.0	1.7	0.5	0.5
γ_{unsat}	20.0	18.0	19.3	-	-	-	-	-
γ_{sat}	22.0	21.0	20.0	17.9	17.9	19.0	21.0	20.0
E'	50	70	-	-	-	40	60	60
ϑ'	0.25	0.3	0.2	0.2	0.3	0.3	0.3	0.3
C_u	-	-	-	-	20	-	-	-
C'_{ref}	0.2	0.21	20	60	2.0	0.1	0.1	0.21
$\emptyset'$	42	34	30	32	30	35	40	40
ψ	12	4	-	2	-	5	10	10
λ^*	-	-	-	0.08	0.08	-	-	-
K^*	-	-	-	0.015	0.029	-	-	-
μ^*	-	-	-	24e-5	4e-3	-	-	-
OCR	-	-	-	3.0	1.1	-	-	-
K_0	0.33	0.44	0.80	1.6	0.67	0.43	0.35	0.35
K_v	864	864	1	35e-4	3.50E-05	0.008	0.086	86.4
K_h	864	864	1	0.01	1.36E-04	0.0008	0.086	86.4

$\gamma\left(\frac{kN}{m^3}\right), E\ (MPa), C\ (kPa), \emptyset\ (\text{deg}), \psi\ (\text{deg}), K_v\left(\frac{m}{s}\right), K_h\left(\frac{m}{s}\right)$

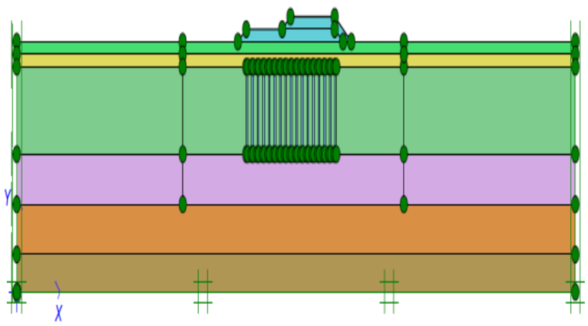

Fig. 2 Modeled embankment cross section

III. PARAMETRIC STUDY

A. The Effect of Unloading-Reloading

After a while, the fill preloading is removed, and loading of the main structure is applied. Therefore, after 100-day initial consolidation, fill embankment load is removed and the main embankment load is applied in models. In Fig. 4, the settlement of the embankment crown after application of the main embankment load is shown for two cases of with and without deep mixing columns. It is seen that the settlement after reloading is much less than the settlement after initial loading. When deep mixing columns are present, the settlement decreases from around 4.1 cm for preloading to 2.6 cm for reloading. If the effect of deep mixing columns is neglected, the settlement is equal to 5.5 cm for preloading and 2.6 cm for reloading. It is observed that when two methods are utilized, the settlement difference between preloading and reloading is 68%, while the use of preloading without deep mixing columns reduces the difference to 52%. Deep mixing columns in both cases lead to less settlement of the structure due to their higher stiffness.

B. Vertical Drains Effect

In order to investigate the effect of the presence of vertical drains on preloading, analyzes with the assumption of square arrangement with 2 meters distance and 2 meters depth for drains are carried out. For drains, the drain element is used in Plaxis software. Since plane strain condition is considered for the embankment, the drain element is considered as a continuous element perpendicular to the cross section of the model while in reality drains are discontinuities. Consolidation happens faster in the numerical model due to the continuity assumption, and the strength increase of soil becomes unreal. Heard et al. proposed the following relation which is used to compensate for the soil permeability between vertical drains in plane strain conditions [8]:

$$\frac{K_{pl}}{K_{ax}} = \frac{2}{3\left[Ln\left(\frac{R}{r_s}\right) + \left(\frac{K_{ax}}{K_s}\right)Ln\left(\frac{r_s}{r_w}\right) - \left(\frac{3}{4}\right)\right]} \quad (1)$$

where r_w is the radius of the drain (strip drains have an effective radius of 30 mm), r_s is the radius of shear zone that is considered to be equal to r_w regardless of contamination of materials, and R is the radius of equivalent of each drain where the horizontal permeability is corrected in the clay layer according to the equation. K_{ax} is the actual permeability of the rock, and K_{pl} is the corrected permeability. Considering this modification, analyzes are performed in two cases of with and without deep mixing columns.

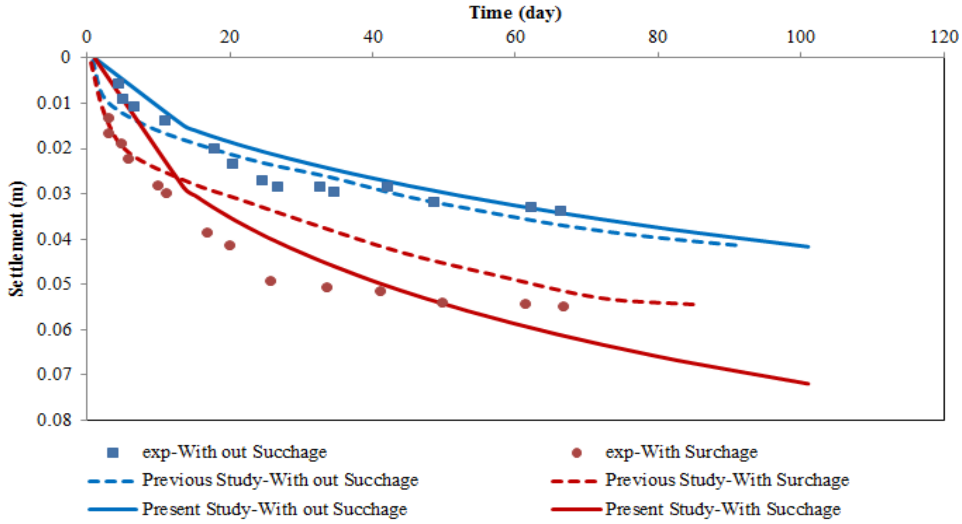

Fig. 3 Comparison of settlements recorded in monitoring, results presented in Larson et al. and the current study

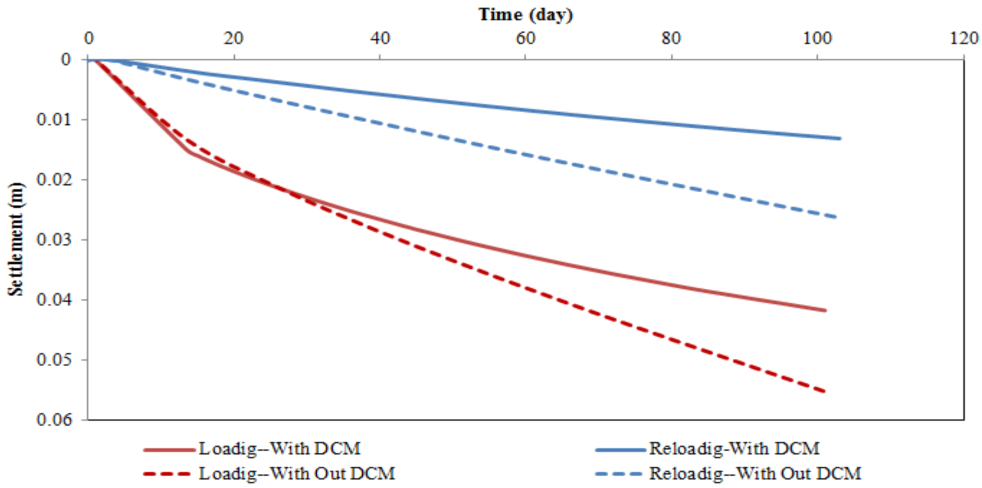

Fig. 4 Settlement in two cases of with and without deep mixing columns in preloading and reloading

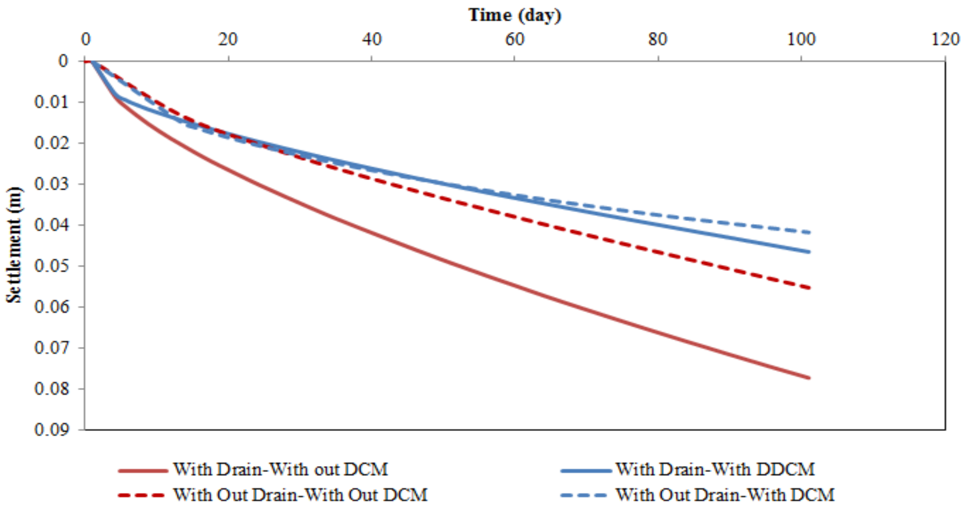

Fig. 5 Initial settlement in two cases of with and without vertical drains and with and without deep mixing columns

It observed that without deep mixing columns, use of vertical drains increases initial settlement by 40%. This increase shows that by use of vertical drains, a higher degree of consolidation is achievable at a given time. It is essential in projects that have a limited construction time. On the other hand, use of vertical drains with deep mixing columns does not have a significant effect on preloading consolidation that might be due to the higher permeability of deep mixing columns compared to clay layer that partly facilitates the drainage.

C. The Effect of Depth of Vertical Drains

In the previous section, the results of the settlement of embankment when the vertical drains have a square pattern with the distance of 2 meters are presented. In this section, the effect of depth of vertical drains is investigated. Since the vertical drains are most effective when deep mixing columns are not constructed, the results are presented for the case of without deep mixing columns. In Fig. 6, the ultimate settlement of preloading is presented for different drain depths. It is seen that increase of drain depths results in the growth of initial settlement or in the other words, the growth of soil pre-consolidation due to the main loading, but the increase of the depth more than 4 meters has not any effect on the settlement. Therefore, it can be stated that the increase of depth of vertical drains to some extent leads to increase of efficiency of preloading and growth of soil pre-consolidation and more depth increase has no effect on the effectiveness of the method. In the performed analyzes, this ratio is equal to the 57 % of the depth of soft soil.

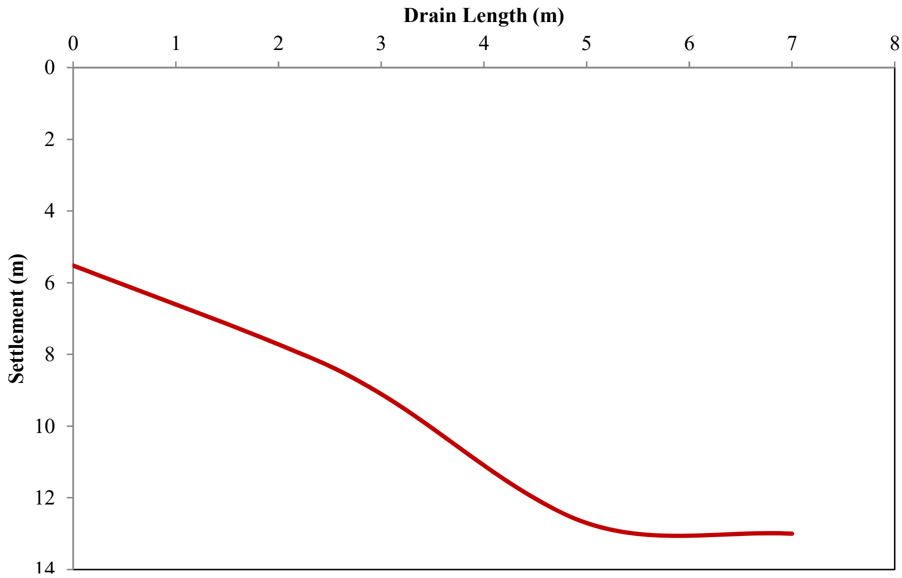

Fig. 6 Change of initial settlement by changing of the depth of vertical drains

IV. Conclusions

In this study, preloading of saturated soft soils is investigated numerically. First, the numerical model is verified by the use of results of a real project, then the effect of parameters like the simultaneous use of preloading and deep mixing columns, vertical drains, and their depth are assessed. It is observed that preloading could reduce settlement of the main structure considerably around 50 %. Use of vertical drains also increases initial settlement (around 40 % more than the case of without drains) and pre-consolidation of soil. The increase of drains depth by around 57 % of layer depth leads to an increase of efficiency of drains and after it, no significant change is observed in the performance.

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