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Sensitivity Analysis of Soil Treatment Systems including Surcharge and Vacuum and PVDs

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ABSTRACT

In Finite element modelling (FEM) of the soil treatment systems that includes prefabricated vertical drains (PVDs), either for preliminary designation, or in the evaluation period, one the main challenges of geotechnical engineers are the correct estimation of the parameters used in the model. The main objective of these kind of soil treatment is the acceleration of the consolidation process to reinforce the weak soft clay stratum underneath. In the consolidation process the initial soil parameters changes, such as void ratio, hydraulic conductivity, swelling and compression index and so on and that is why the modelling of such reclamation process is so challenging. In previous published literature, there was no paper, especially concentrate on the sensitivity analysis. In this literature first, a case history is presented and verified, and then base on the verified model, the following parameters as: void ratio, vacuum pressure, phi and over consolidation ratio, rate of loading of the surcharge embankment, mesh size, Lambada (λ) and Kappa (κ), Hydraulic conductivity ratio and Mesh type were parametrically investigated. It was shown that, even a minute change in the quantity of some parameters can adversely affect the precision of the prediction of the model. The results of this study can be used by both field and design engineers, involved in the construction of embankments on soft ground for soil treatment systems in weak and rate-sensitive clays.

Keywords:

Sensitivity analysis, clay, PVD, surcharge, vacuum preloading, FEM.

1. Introduction

In recent years, the urgent need for construction of various infrastructure over unsuitable soft soil deposits has advanced soil improvement techniques. Preloading prior to construction is considered to be one of the most practical methods of avoiding excessive settlement of highly compressible soil after construction; preloading being the application of surface or vacuum loading, or groundwater lowering to attain the expected consolidation settlement under permanent load. However, for thick soil deposits with low permeability, the required consolidation time by preloading alone can be too long and, bearing failure, may take place during rapid embankment construction. Therefore, a system of vertical drains with preloading is frequently introduced to accelerate the consolidation process by shortening the drainage path from vertical to horizontal [1]. The utilization of geosynthetic PVDs has become an economical and viable option because of their rapid installation with simple field equipment [2]. Due to the scarcity of suitable surcharge material and the relatively low cost of electrical power in certain areas, vacuum-assisted preloading with the vertical drain system has been used to achieve rapid consolidation and reduce the height of surcharge fill [3]. The increase in the effective stress in soil mass for the vacuum preloading method is attributed to the vacuum application in companion of conventional surcharge. The cost of soil improvement by vacuum preloading is approximately 30% less than that by conventional surcharge alone[4]. The characteristics of vacuum preloading compared with conventional preloading are as follows [5]: 1)The effective stress related to suction pressure increases equiaxially, and the corresponding lateral movement is compressive. Consequently, the risk of shear failure can be minimized even at a higher rate of embankment construction. 2) The vacuum head can be distributed to a greater depth of the subsoil using the PVD system. 3) The extent of surcharge fill can be decreased to achieve the same degree of consolidation, depending on the efficiency of the vacuum system in the field (i.e., air leaks). 4) Because the surcharge height can be reduced, the maximum excess pore pressure generated by vacuum preloading is less than by the conventional surcharge method. 5) With vacuum pressure, the inevitable unsaturated condition at the soil– drain interface may be improved, resulting in an increased rate of consolidation. [6] state that in In soft soil deformation analysis, stiffness and consolidation parameters are deemed key inputs. The main parameters required for the PVD induced consolidation process are the discharge capacity of PVD (q_w), the smear zone diameter (ds) around the PVD and the ratio of horizontal permeability of the undisturbed zone (k_h) to the soil smear zone (k_s), i.e. k_h/k_s [7, 8]. These parameters were widely investigated by different authors [9-12]. although the FEM modeling procedure and the soil model parameters used in the analysis themselves, can change the predictions even in the case of best choice of the mentioned parameters. This literature unlike other articles would focus on FEM modeling procedure and Modified Cam-Clay (MCC) that has been used in the model, to investigate the sensitivity of these parameters. Settlement curve is chosen as the criterion for comparison of the different cases.

2. Material and methods

The Bangkok Airport is situated in a wet area where there is about 10 m of soft clay under a 2 m surficial over-consolidated crust[13]. Stiff clay extending to a depth of 20 to 24 m underlies the soft clay. For analysis purposes the subsoil is divided into three layers as shown in Figure 1 and the lower stiff clay is ignored [14]. The PVD drains were installed to a depth of 12 m. The embankments were constructed to a height of 4.2 m with 3H: 1V side slopes. The base areas were approximately 40 x 40 m. There were actually 1 m high berms around the base extending out 5 m but this detail is not included in the illustrative analysis presented here. A one-meter thick sand blanket was placed on the site as a construction working pad. The drains were installed from on top of the sand pad. The sand blanket was presumably also included to ensure that there would be no build-up of excess pore-pressures at the base of the embankment and to drain away water being squeezed out of the clay. The position of the drains in the two-dimensional analysis is shown in Figure 2. The horizontal spacing is 1.5 m except at the embankment toe where the spacing is 2 m (this was done purely for modeling convenience so that there is a drain at the embankment toe). Figure 1 shows the layering used to simulate the sequential fill placement. The sand blanket is not included in the model as a separate material. The effect of the sand can be modeled by specifying a zero-pressure boundary condition along the ground surface. The physical implication is that there will be no build-up of positive pore-pressures at the ground surface. Any water arriving at the ground surface will have the opportunity to disappear through the sand somehow. The boundary condition simulates this effect. This is much simpler than trying to include the sand blanket in the model but achieves the same objective. The Modified Cam-Clay constitutive relationship is used here for the soft clay. The clay is essentially normally to slightly over-consolidated. It appears that the degree of over-consolidation varies somewhat with depth. For the illustrative analysis here the clay is treated as having an OCR of 1.5. Also, the Lambda and Kappa values were taken to be the same for the very soft and the lower soft clay. This gives settlements closer to what was measured. The weathered surficial clay is over-consolidated and consequently it is acceptable to treat this layer as behaving in a linear-elastic manner. Using a linear-elastic constitutive relationship also helps with maintaining numerical convergence near the ground surface where the stresses approach zero. The sand fill is also treated as a soft linear-elastic material and the soil parameters are viewed as being total-stress parameters. This avoids having to deal with pore-pressures in the fill. These simplifying assumptions are acceptable because we are primarily interested in using the fill as a means to apply the load [13].

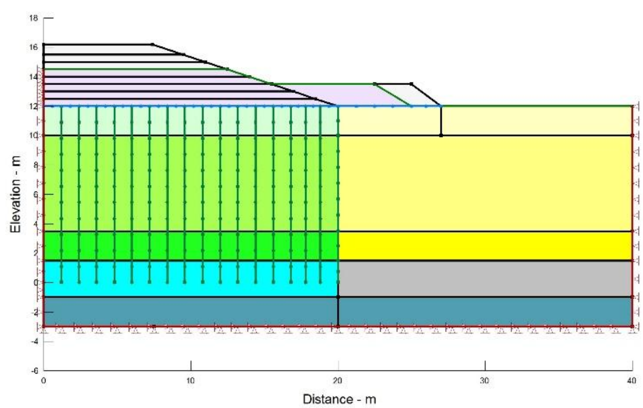

Figure 1. A schematic view of the sequential embankment construction in FEM and its boundary condition.

Mohr-Coulomb (MC) and Modified Cam-Clay (MCC) are the most popular elastoplastic soil models. They are widely used to model the behavior of soils because of their simplicity and having the capability to describe strain softening, yielding conditions, and failure mechanisms. Particularly, MCC is used to simulate the behavior of clay soils [15]. MCC used successfully in many simulations for different case histories, including surcharge and vacuum and PVDs, around the world [16-18].

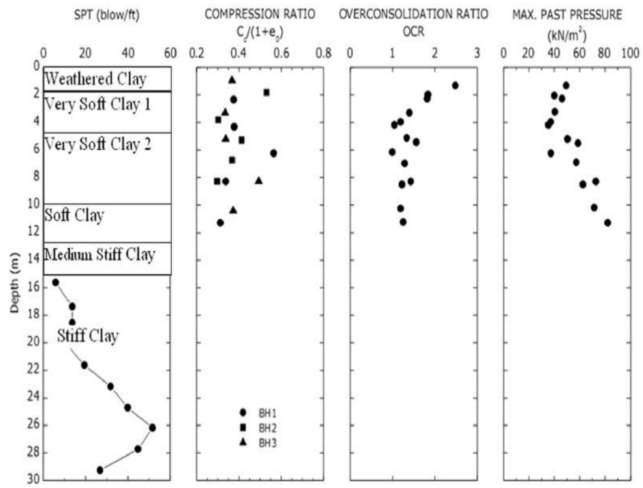

Figure 2. soil parameters in Bangkok airport [19].

Figure 2 illustrates the soil parameters of the Bangkok airport. Geostudio 2018 coupled analysis with sequential embankment loading was used for modelling. The MCC soil parameters that has been used are shown in Table 1.

Table 1. soil parameters used in FEM [20].

Depth (m)	λ	κ	M	ν	K_v 10^{-4} (m/day)	K_h 10^{-4} (m/day)	e_{cs}
0-2	0.34	0.07	1.2	0.25	25.9	25.9	2.80
2-7	0.90	0.18	0.9	0.30	5.9	10.1	5.90
7-12	0.50	0.10	1.0	0.25	2.6	5.2	4.00
12-15	0.34	0.07	1.2	0.25	1.0	2.1	3.00
15-22	0.10	0.02	1.2	0.20	0.3	0.5	1.30

Three trial embankments were built as TS1 with 1.5 m PVD spacing, TS2 with 1.2 m PVD spacing and TS3 with 1 m PVD spacing to examine the performance of the system in various situations. TS1 was chosen for sensitivity analysis in this study. Since the authors preformed the FEM modelling before, the detailed specification and Complementary data on FEM modelling procedure can be found in [16]. The verification of TS2 embankment is shown fig 3. As it can be seen in figure 4, the FEM results are slightly overestimated the pass but the final settlement was predicted according to field instrumentations. This might be the result of delayed consolidation of natural clays due to the degradation and reconstitution of the structure as pointed out by [21, 22].

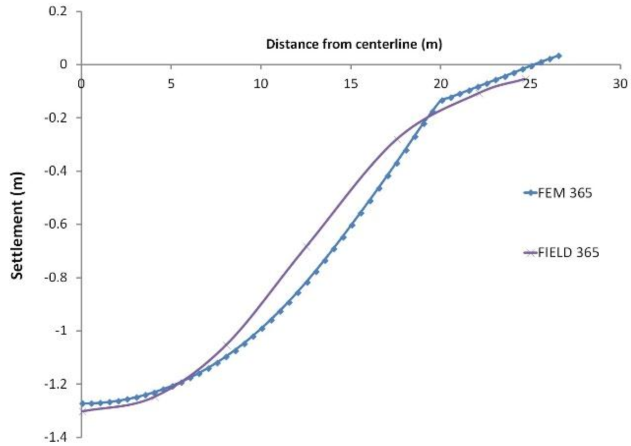

Figure 3. The FEM results for verification of TS1 settlement after 365 days, at the centerline of the embankment vs measured data's , field measured data's from [19].

3. Discussion and results

Base on the verified model, the following parameters as: void ratio, vacuum pressure, phi and over consolidation ratio, rate of loading of the surcharge embankment, mesh size, Lambada ($\boldsymbol{\lambda}$) and Kappa ($\boldsymbol{\kappa}$), Hydraulic conductivity ratio and Mesh type were changed and the resultant settlement curve is drawn to investigate their effect on the modelling process.

3.1. Void ratio

Fig 4 illustrate the sensitivity analysis for void ratio. As it can be seen the unrealistic estimation of void ratio, can have a significant effect on the estimation of final settlement. The settlement for the verified model has overestimated from 1.27 m to 1.85 m for 0.5x void ratio and underestimated to 0.85 m for 2.0x void ratio. It should be noted that during the consolidation process, the effect of increase in void ratio is accounted in calculations by defining the hydraulic modifier function, otherwise all the results of FEM would be unrealistic as stated by [23].

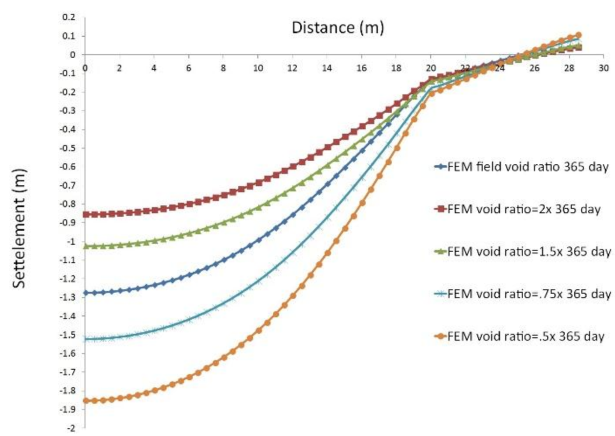

Figure 4. The comparison of FEM settlement curve of TS1 verified model vs FEM results for void ratios for 2x, 1.5x, 0.75x and 0.5x

3.2. Vacuum pressure

Four different vacuum pressures as 20,40,60 and 80 kpa were applied to models to investigate the efficiency of application of vacuum preloading in an ideal situation that the pressures were maintained unchanged for 365 days. By applying the vacuum pressure the efficiency of the system has risen considerably as it can be seen clearly in fig 6. The parametric study of the application of different pressure has been investigated before by different authors [16, 24]. The 80 kpa vacuum pressure is the maximum applicable pressure in field, because in higher pressures, as result of cavitation higher pressure are not applicable [25]. By applying the vacuum pressure of 20,40,60 and 80 kpa, the settlement has increased from 1.27 to 1.46,1.64,1.84 and 2.01 m respectively. One of the obstacles in construction of embankments on soft clay soil, is the heave on the toe of the embankment and also in the vicinity of the embankment [26]. By application of vacuum preloading, the heave on the toe of the embankment has decreased as it can be seen in fig 5. As the vacuum pressure increase, the heave decrease as well. This phenomenon is one the main advantages of applying vacuum preloading, especially in area, where sensitive structures or equipment do exist.

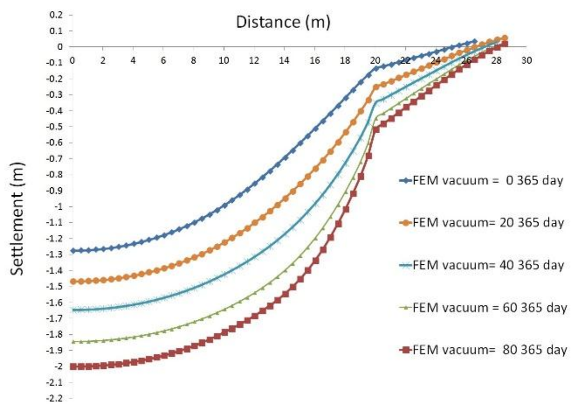

Figure 5. The comparison of FEM settlement curve of TS1 verified model vs FEM results for vacuum application of 20, 40, 60 and 80 kpa.

3.3. Internal friction angle and over consolidation ratio

As two basic soil parameters, internal friction angle (ϕ) and over consolidation ratio (OCR), has a great effect in correct in estimation of settlement in such ground improvements techniques as it can be seen in fig 6 and 7. This profound effect, necessitate the precise preliminary field and lab tests, otherwise, the resultant predictions would be either highly overestimated or underestimated.

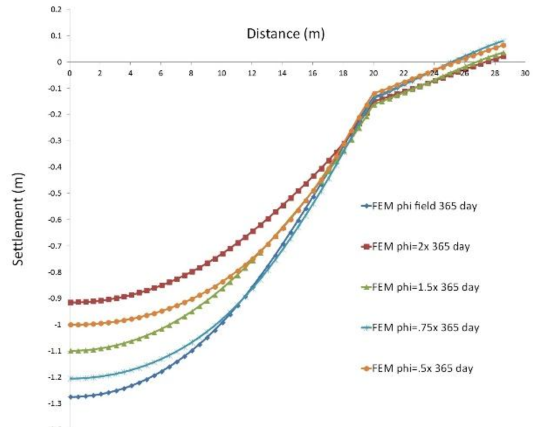

Figure 6. The comparison of FEM settlement curve of TS1 verified model vs FEM results for phi for 2x, 1.5x, 0.75x and 0.5x.

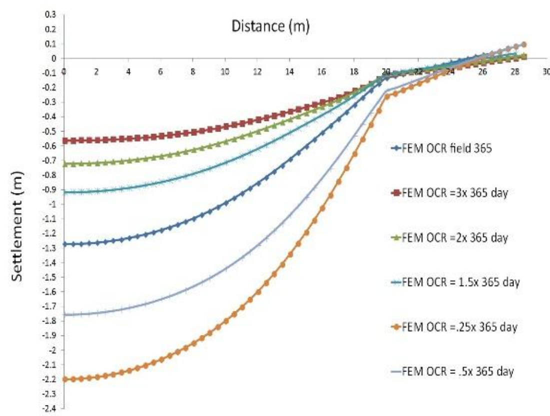

Figure 7. The comparison of FEM settlement curve of TS1 verified model vs FEM results for OCR for 3x, 2x, 1.5x,0.5x and 0.25x

3.4. Rate of loading of the surcharge embankment

The installation of PVDs has the potential to minimize the effect of the delayed build-up in excess pore pressures and improve the short-term stability of embankment as illustrated by [27]. [28] pointed out that the critical period with respect to the stability of reinforced embankments on rate-sensitive soils occurs after the end of construction as a result of a build-up in excess pore water pressure due to soil creep. Meanwhile in fast rate of loading of embankment can cause catastrophic failures, as stated by many researches [29, 30]. As it was shown in fig 8, by the increase of rate of loading, the final settlement has increased too as well. The settlement has increased from 1.27 m in case history to 1.47 m in 2.5 times faster rate after 365 days. Although the settlement has increased, but in real field practise, one of the main challenges both for design and field engineers, is the organization of the embankment loading process, in such a way that tensile failures be avoided.

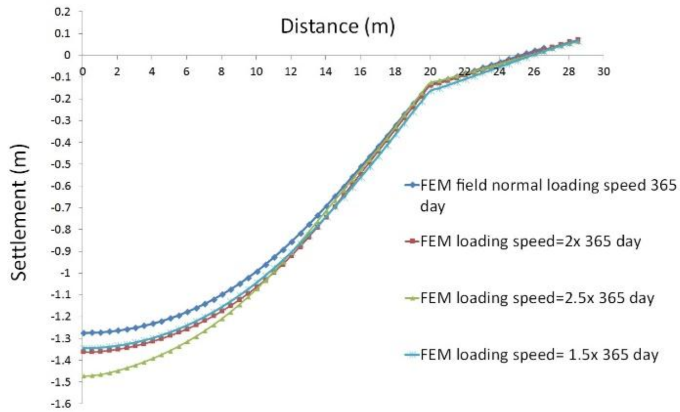

Figure 8. The comparison of FEM settlement curve of TS1 verified model vs FEM results for loading speed for 2x, 2.5x and 1.5x.

3.5. Mesh size

Figure 9 illustrates the effect of the mesh size on settlement calculations. the mesh that has been used in verification model had 0.5 m size. It can be seen that mesh with smaller quantities as 0.1 m gives almost the same results. For higher values as 1 m, there is still no change in the precision of the predictions but for the mesh size with 2 m, the results become highly overestimated. The acceptable range for mesh size in this analysis is between 0.1 to 1 m.

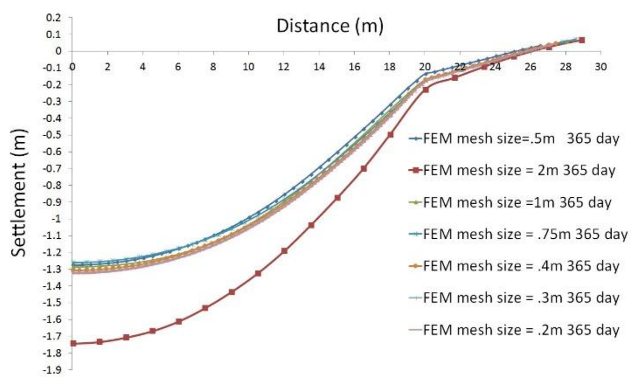

Figure 9. The comparison of FEM settlement curve of TS1 verified model vs FEM results for FEM mesh size for 2,1,0.75,0.4,0.3 and 0.2 m.

3.6. Lambda (λ) and Kappa (κ)

λ, is one the main factors of MCC parameters, is the slope of the isotropic compression line in a ν-ln p´ plot, where, ν is the specific volume, p´ is the isotropic compression pressure, in MCC model. The soil compressibility normally consolidated state, λ, would be obtained from the odometer test results using the following expressions:

$$\lambda = C_c / 2.303 \quad (1)$$

Where C_c is the compression index. ***κ***, is one the main factors of MCC parameters, is the slope of the unloading-reloading lines in ν-ln plot where, ν is the specific volume, p´ is the isotropic compression pressure, in MCC model. The soil compressibility in over consolidated state, κ, would be obtained from the odometer test results using the following expressions:

$$\kappa = C_r / 2.303 \quad (2)$$

Where C_r is the swelling index. Even a minute error in the estimation of C_r and C_c lead to an exaggerated estimation of the settlement curves as it is demonstrated clearly in fig 10 and 11.

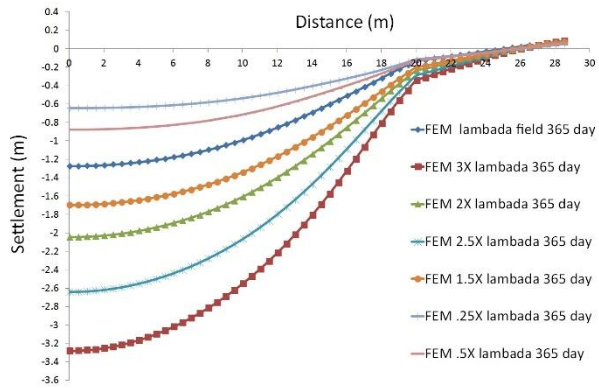

Figure 10. The comparison of FEM settlement curve of TS1 verified model vs FEM results for Lambada for 3x, 2x,2.5x, 1.5x,0.5x and 0.25x.

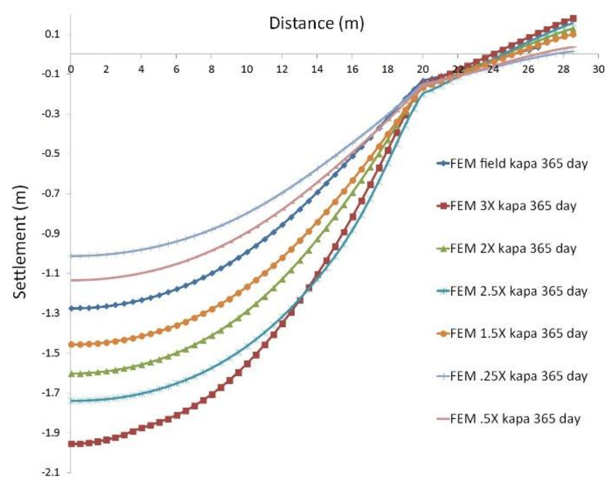

Figure 11. The comparison of FEM settlement curve of TS1 verified model vs FEM results for kappa for 3x, 2x,2.5x, 1.5x,0.5x and 0.25x.

3.7. Hydraulic conductivity ratio

The conductivity of soft soils can change significantly as the soil compresses and the void ratio decreases. Geostudio suits, used in this paper has a built in algorithm, where the hydraulic conductivity can be adjusted as the effective stress increases in response to the dissipation of the excess pore-pressure. This function is an indirect way of adjusting the conductivity resulting from decrease in void ratio and water discharge from the structure of the clays. In order to obtain reliable data's for obtaining hydraulic conductivity function, the results of an odometer test can be efficiently used and the conductivity can be recorded for each load increment in an odometer test. The inclusion of Hydraulic conductivity ratio is very essential in prediction of soil treatment systems as indicated by [23], where not inclusion of this function lead to 40 percent overestimation in results. As it can be seen in fig 12, the FEM is not very sensitive to changes in the range this function in the magnitude of 0.25x to 2x.

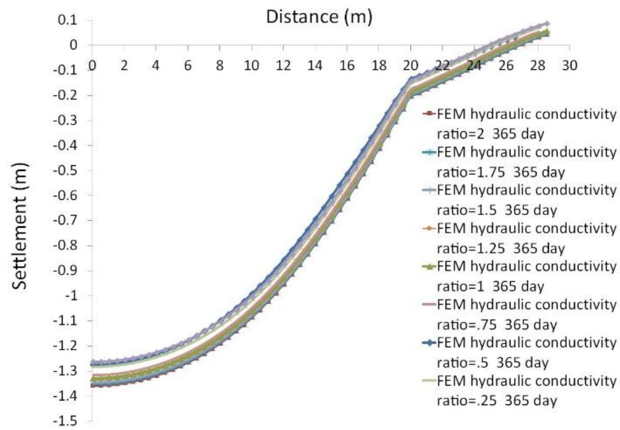

Figure 12. The comparison of FEM settlement curve of TS1 verified model vs FEM results for hydraulic conductivity ratio for 2x,1.75x,1.5x,1.25x,1x,0.75x,0.5x and 0.25x

3.8. Mesh type

Three type of mesh was applied to FEM model as quads and triangles that was used for the verification, grids and quads and only triangles. The quads and triangles elements are a mixture of squares, rectangles, trapezoids and triangles and this the most common mesh that is used in most of geotechnical modellings. The quads and triangles elements works best when the number of divisions is controlled on the shortest and intermediate sides. grids and quads pattern is ideally suited for four sided regions only as a result of compatibility problems that may occur. In only triangles case, the mesh is automatically created using Delaunay triangulation techniques. One of the great attractions of unstructured meshing is that almost any odd-shaped region can be meshed. This meshing simplicity however has some numerical and interpretation consequences in models with complicated geometry. From fig 13 it is clear that the mesh type, did not has any significant effect in the precise prediction of the settlement and all the cases gave acceptable results.

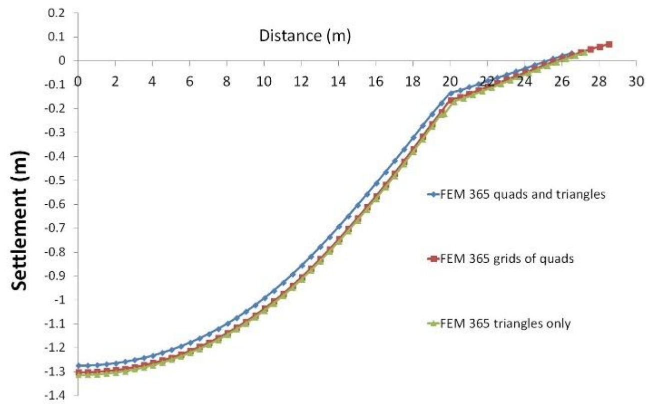

Figure 13. The comparison of FEM settlement curve of TS1 verified model vs FEM results for mesh type quads and triangles, grids of quads and only triangles

4. Conclusion

A case history was introduced and the verification was presented. Base on the verified model the following parameters were studied as: void ratio, vacuum pressure, phi and over consolidation ratio, rate of loading of the surcharge embankment, mesh size, Lambda ($\boldsymbol{\lambda}$) and Kappa ($\boldsymbol{\kappa}$), Hydraulic conductivity ratio and Mesh type. Regarding the void ratio, it was shown that the unrealistic estimation of void ratio, can have a significant effect on the estimation of final settlement. By applying the vacuum pressure of 20,40,60 and 80 kpa, the settlement has increased from 1.27 to 1.46,1.64,1.84 and 2.01 m respectively that shows the efficiency of applying vacuum pressure in weak soil treatment systems. For the basic soil parameters, phi ($\boldsymbol{\phi}$) and over consolidation ratio (OCR), it was shown that they have a great effect in correct in estimation of settlement in such ground improvements techniques that necessitate the precise preliminary field and lab tests otherwise, the resultant predictions would be either highly overestimated or underestimated. Regarding the rate of the embankment loading speed, the settlement has increased from 1.27 m in case history to 1.47 m in 2.5 times faster rate after 365 days. Although the settlement has increased, but in real field practise, one of the main challenges both for design and field engineers, is the organization of the embankment loading process, in such a way that tensile failures would be avoided. For mesh size, the quantity between 0.1 to 1 m gave reasonable results, although for quantity greater than 1 m the accuracy of the results starts to vanish and the results become overestimated. For MCC parameters lambda ($\boldsymbol{\lambda}$) and Kappa ($\boldsymbol{\kappa}$), it was demonstrated that Even a minute error in the estimation of C_r and C_c lead to an exaggerated estimation of the settlement curves. For hydraulic conductivity function, the FEM is not very sensitive to changes in the range this function although the inclusion of Hydraulic conductivity ratio is very essential in prediction of soil treatment systems. Regarding the mesh type it was shown that the mesh type, did not has any significant effect in the precise prediction of the settlement and all the cases gave acceptable results.

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