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ABSTRACT

An oil storage tank at the North suburb La Goulette (Tunisia) was founded on reinforced soft soil by floating sand columns of 6 m in length and 11% of improvement area ratio within a thick compressible clayey soil. Serious contamination of tank due to very significant differential settlement forces the decision to terminate its operations. Reinforcement by inclined rigid inclusions was suggested to neutralize the evolution of consolidation settlement in sub compressible clay layers. Numerical predictions were implemented for the study of the post behavior of tank on reinforced soil by rigid inclusions. Effectiveness of solution using inclined rigid inclusions is illustrated and, then, discussed. Modeling of the contact between the rigid inclusions, by means of element of interfaces, and soft clay has been seen of great importance when predicting the evolution of long term settlement.

INTRODUCTION

A 33-m cylindrical oil storage tank was built in the early nineties in the storage area of the Tunisian National Society of Petroleum located in Rades in the suburbs of Tunis City. Available geotechnical data, from the neighboring construction projects, showed that the subsoil is mainly composed by a high compressible clay layer of about 10 m in thickness overlaid by 1 m of fill material. The underneath layers are mostly compressible silty to sandy clays. In order to reduce and to significantly accelerate consolidation settlement, the tank foundation was improved by sand piles, 6 m in length and 0.6 m in diameter, installed in an unspecified pattern with an improvement area ratio of about 11%. The reinforced layer was overlaid by a blanket layer made up of 1.6m thick compacted sand in order to avoid differential settlements. Although the tank was used in normal conditions, a tilting was observed after only five years of service and continues to occur thereafter. After thirteen years of service, the tank was declared as a source of a serious contamination and, for safety reasons, a decision to stop its use was undertaken.
The present paper presents a numerical analysis using the finite element software package Plaxis to validate the solution of inclined rigid inclusion for the purpose of tank stabilization.

ANALYSIS OF THE PRIMARY FOUNDATION DESIGN OF TANK

Bouassida et al. (2011) have addressed the primary foundation solution to be adopted to solve the stability of the oil tank. Their major recommendations consisted on using micro piles and rigid inclusions. Since micro piles execution requires the tank disassembly which will result in a considerable economic loss (the tank offers US$30,000 as monthly net benefit), the rigid inclusions alternative seems to be more suitable since it does not require the stoppage of the tank operations, and their installation are cheaper than that of micro piles.
Therefore, it was suggested to retain the rigid inclusions solution.

Prediction of short term and consolidation settlements

Before addressing the numerical analysis, an estimation of the settlement was carried out using odometer test results and an elastic approach incorporated in software Columns 1.0, Bouassida and Hazzar (2011). Tables 1 and 2 show the corresponding results. According to Table 1, one can clearly remark that short term settlement occurs in the first sandy layer (about 30% of the total settlement). If it is assumed that this settlement is completed by the end of the tank construction, the residual long-term settlement (due to the consolidation process) is 35 cm. This can lead easily to dramatic damages affecting the structure of the tank. Therefore, eliminating the consolidation process is the primal criterion for any proposed solution in this case.

Layers	Thickness (m)	C_u (kPa)	E(kPa)	ν	φ(°)	γ (kN/m^3)	Settlement (cm)
Compressible sand	6	10	2500	0.3	21	17,5	23.9
Sandy clay 1	3	15	2000	0.3	0	17	47.8
Sandy clay 2	6	30	7000	0.4	10	19	3.8
Sandy clay 3	3	0	15000	0.2	37	18,5	1.4
Clay	5	0	4000	0.3	35	19	5.3
Sand	5	1	7000	0.3	17	20	3
Total settlement (cm)							85.2

Table 1- Linear elastic prediction of settlement

In order to confirm such an assessment, Table 2 presents the different results of predicted long-term settlement based on recorded data from odometer test.

Layers	Thickness (m)	C_c	e_0	σ'_0(kPa)	Δσ (kPa)	Settlement (cm)
Compressible sand	6	0.725	2.35	22.5	99.4	95.1
Sandy clay 1	3	0.6	1	55.5	89.4	37.5
Sandy clay 2	6	0.572	1.88	93	77	31.2
Sandy clay 3	3	0.365	1.33	132.75	61	7.7
Clay	5	0.145	0.67	168	19.3	2
Sand	5	0.145	0.7	215.5	16	1.3
Total Settlement (cm)						175

Table 2- Settlement estimation based on oedometer test data

The solution of floating sand columns, with an improvement area ratio of 11%, reduced eight times the settlement that was predicted to occur within the first layer. However, this settlement only represents 30% of the total one with 50% of the total settlement predicted to occur in the second compressible layer (located at a depth between 6 and 18 meters). Hence, the alternative of sand columns is clearly inconsistent in terms of the reduction of total settlement.

Indeed, the observed settlement during the first 13 years (estimated through a system of measurement) varied between 15 and 20 centimeters. This is obviously pertained to the second compressible layer which degree of consolidation has attained 46%. However, the settlement of the first layer had entirely occurred during the construction phase.
In order to prevent the evolution of the contamination of oil storage tank it has been thought to proceed for a lateral reinforcement within compressible layers overlaid by the reinforced layer by sand piles, by means of inclined rigid inclusions.

Numerical Analysis

The numerical modeling was carried out using the finite element software Plaxis V8.6. The implemented soil characteristics were already presented in Table 2, while the properties of other elements, such as sand columns, inclusions, and the footing supporting the tank load are shown in Table 3.

Element	Length (m)	Thickness (m)	Stiffness (MPa)
Plate	16.5	0.2	20
Inclusions	25	0.1	272
Columns	6	0.2	40

Table 3- Properties of elements used in the model

It is to be noted here that the thicknesses shown in Table 3 are those introduced to run the numerical analysis. Indeed, they are the result of conversions of real geometric dimensions to those introduced for the model. This is due to the fact that an axisymmetric analysis was used to run the numerical model.

In a first step, the reinforced soil supporting the load of the tank was introduced. This process is executed to model two phenomena: plastic behavior and the consolidation process for a duration of 13 years. Once these two phases are modeled separately, it is feasible to introduce the inclusions in a second step and then to evaluate its effect on the stress and strain distributions. This has allowed to go one step further and to assess the contribution of the inclusions in reducing the consolidation process. Details of the numerical analysis pertained to both plastic analysis and consolidation process are introduced in the next section.

PLASTIC ANALYSIS

First Phase: Soil behavior before introducing the inclusions

Figure 1 shows the developed axisymmetric model. Since the observed settlement of the reinforced soil was considerably large, interfaces to model the frictional contact between sand columns and the first layer of the subsoil were not used.

This is due to the fact that interfaces are only useful in computational analysis on a context of small strain contact problems (Sheng, *et al* , 2007).

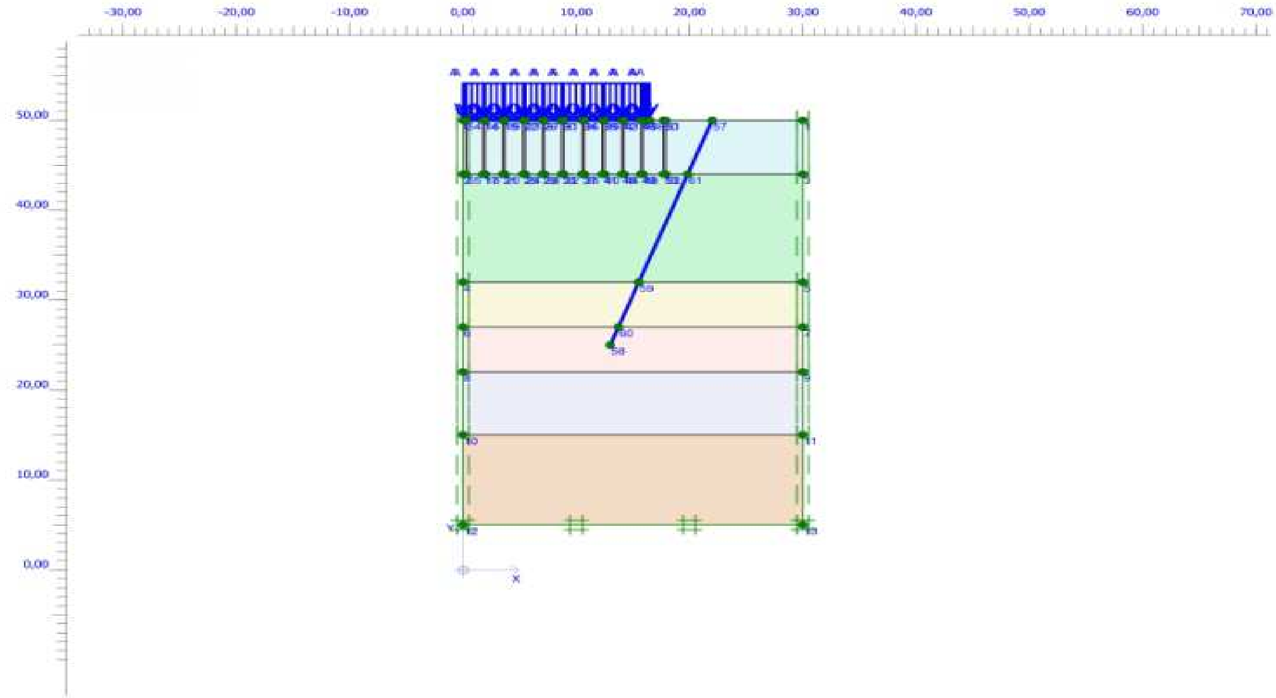

Figure 1 – Numerical model of the soil supporting the tank

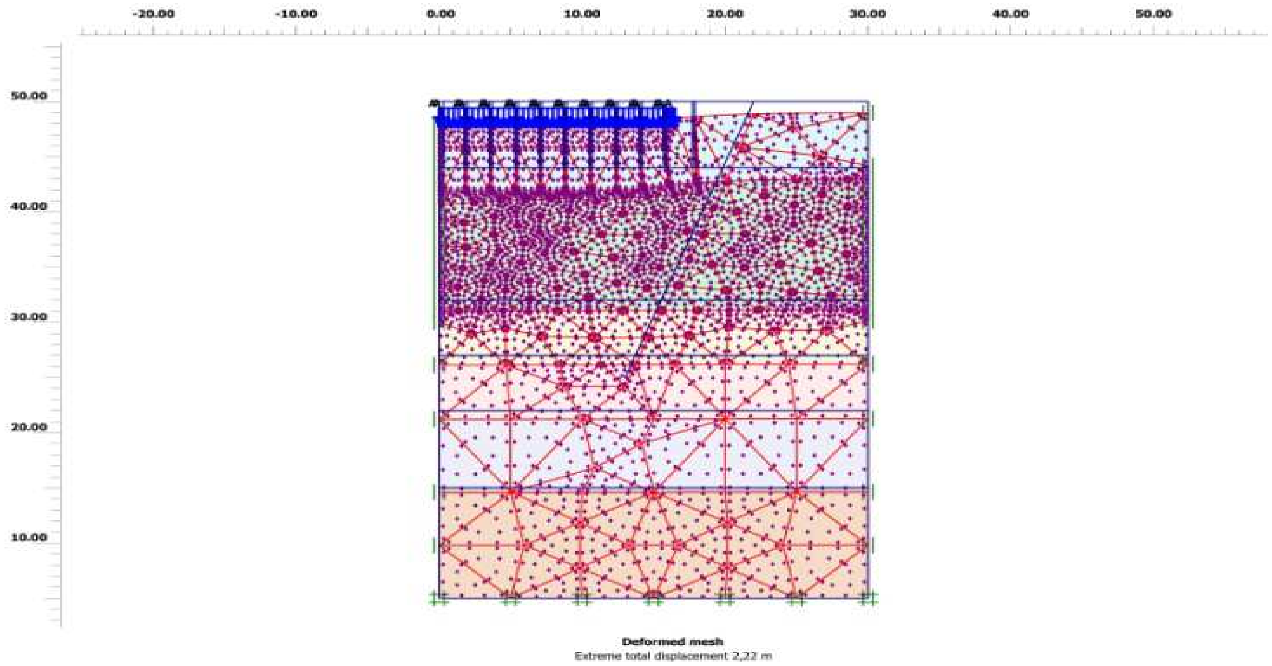

Figure 2 – Deformed mesh due to the applied load of tank

It is important to notice that plastic analysis had been executed in order to highlight that the major part of large settlements of the reinforced soil is pertained to the second compressible layer. Indeed, the behavior of the major points belonging to this layer is plastic. This can explain the inconsistency of the reinforcement executed within the first layer and which the target was to limit the settlement on the domain located beneath sand columns.

Figure 2 shows the deformed mesh under the loaded tank, while Figure 3 presents the distribution of plastic points within the soil. The total calculated vertical displacement before

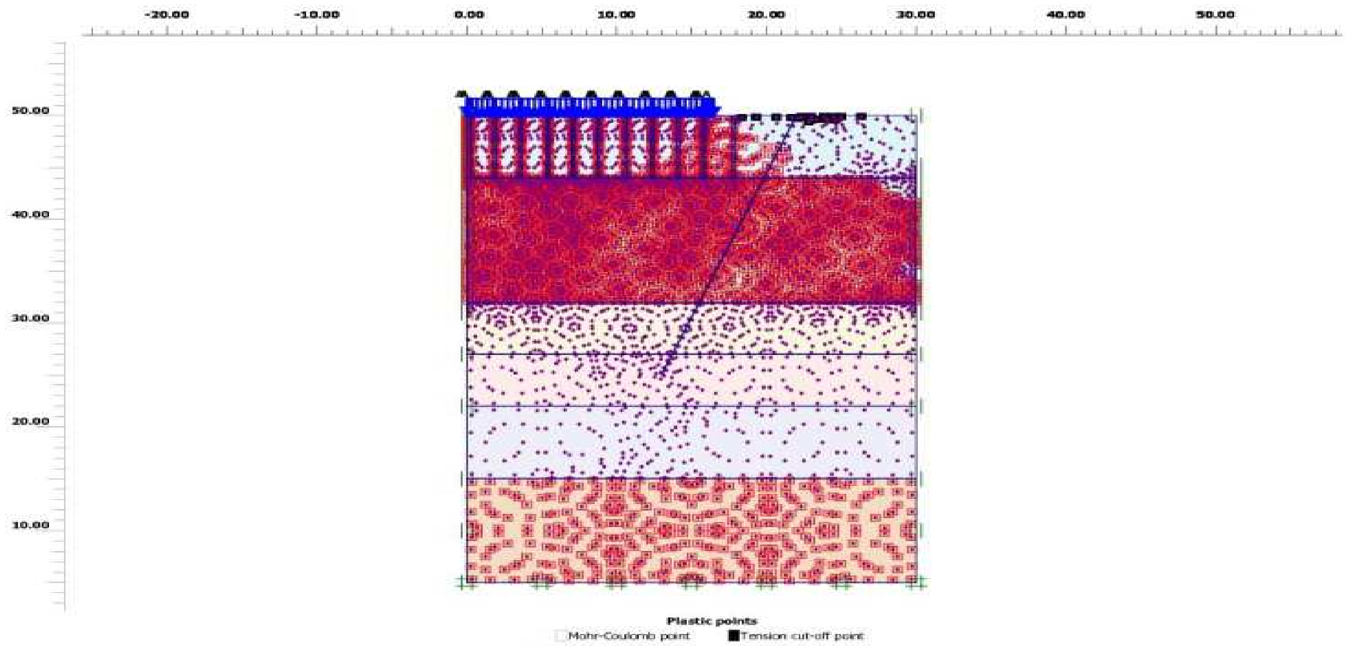

Figure 3-Distribution of plastic points

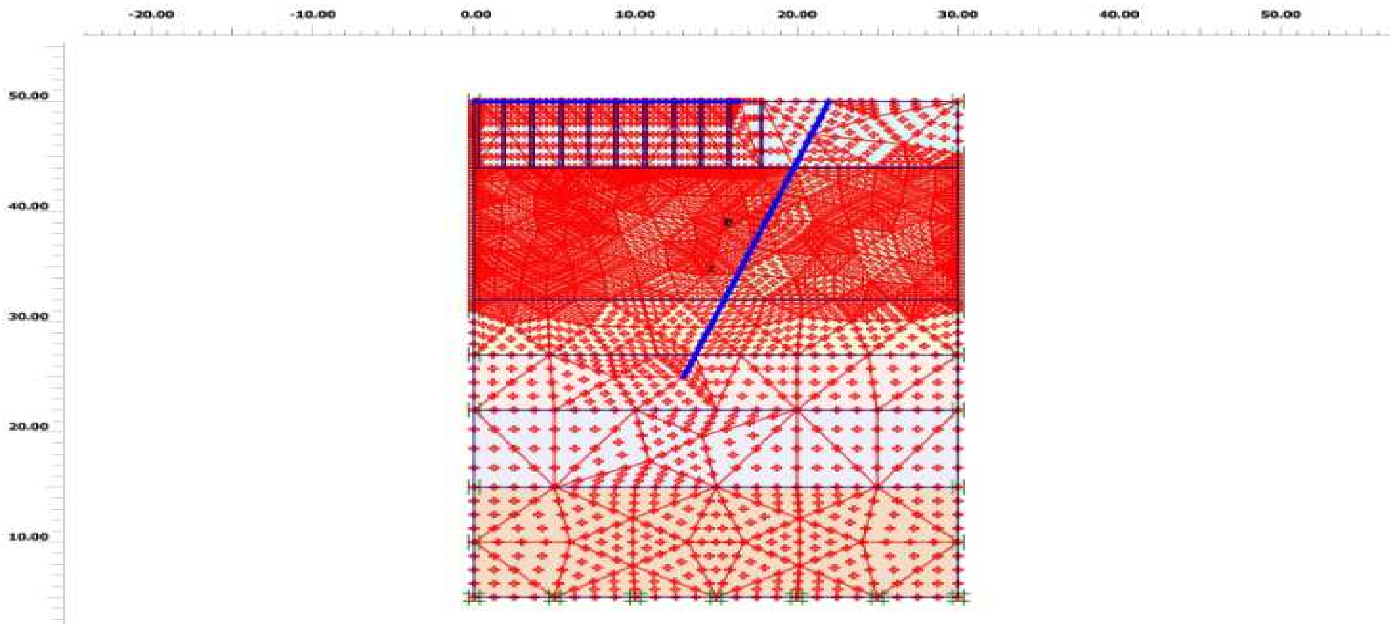

Figure4- Locations of points A and B

activating the inclusion is 2.22 meters that is too much significant because of very pronounced compressibility of soil layers.

Second Phase: Effect of inclusions on soil behavior

In order to test the effect of the inclusions on the distribution of vertical displacements, two points A and B belonging to the compressible layer (the second one) were selected to compare their calculated vertical displacements without the inclusions and with the inclusions. Figure 4 shows the locations of points A and B while Figure 5 presents the results of the carried out analysis.

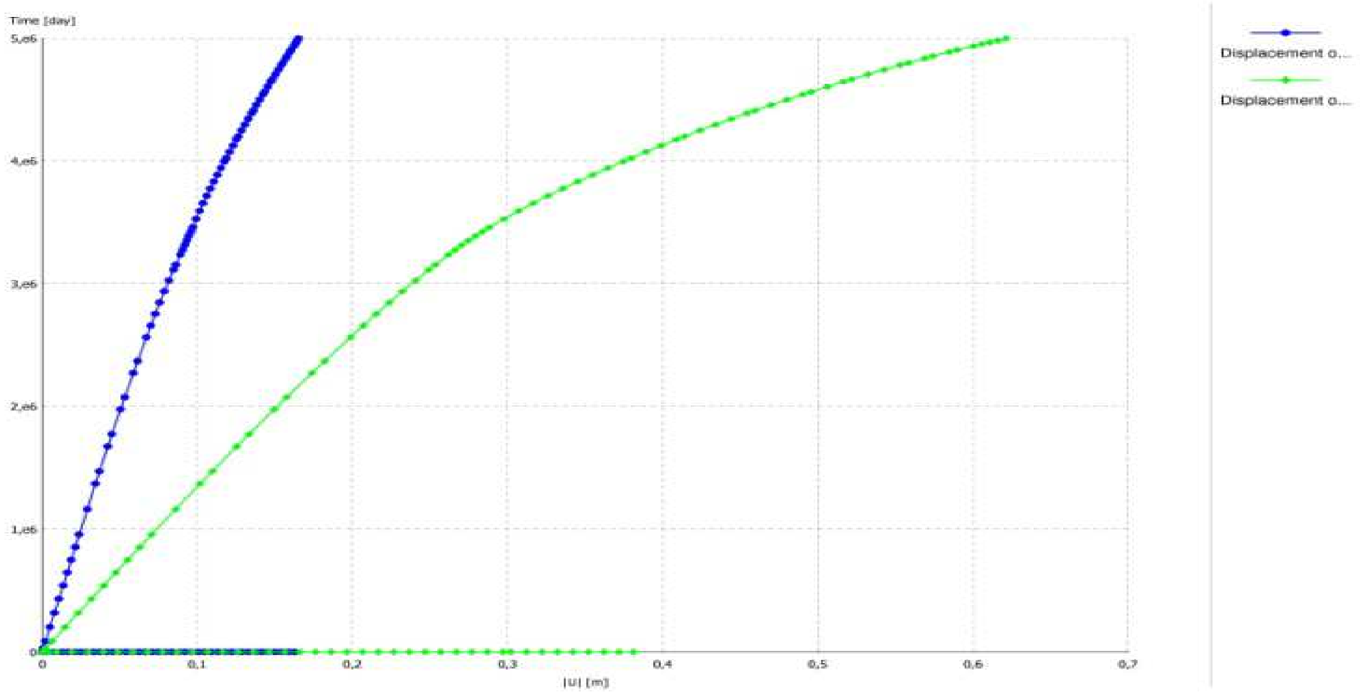

Figure 5- Behavior of points A & B before and after activating the inclusion

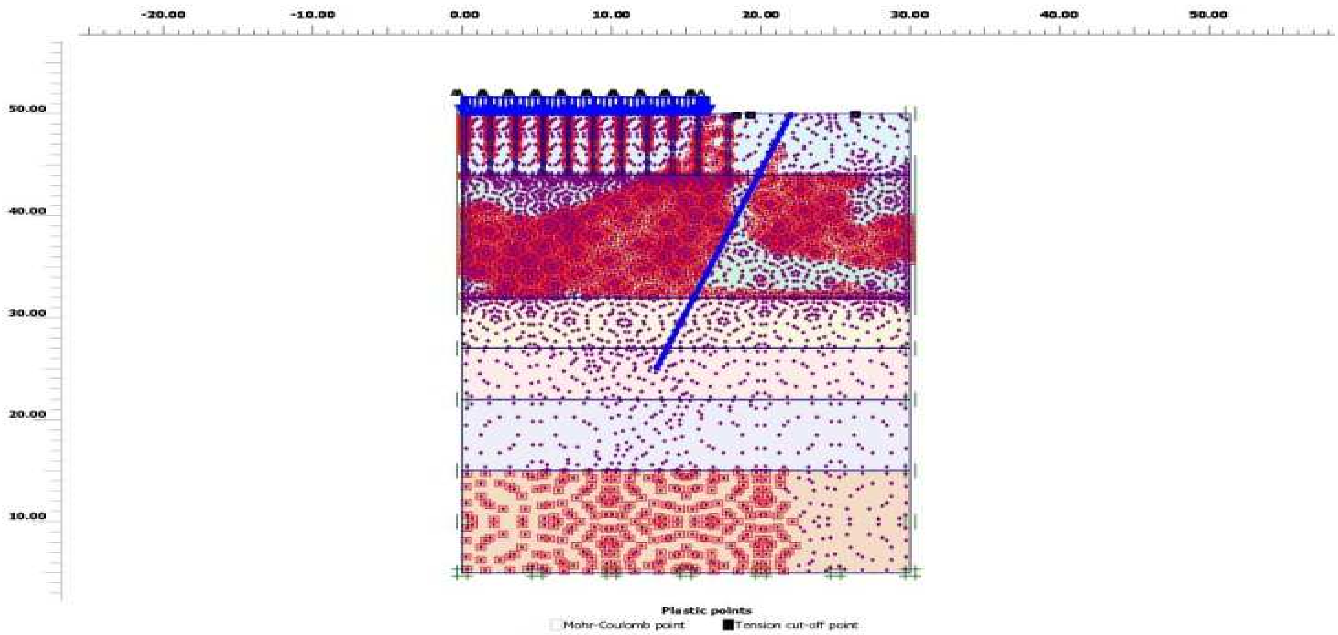

Figure 6- Distribution of plastic points after activating the inclusion

According to the predicted results, one can clearly remark that the vertical displacement of the two points decreases due to the presence of the inclusions. More precisely, when the inclusions are active, the evolution of the displacement of the two points vanishes after a short duration. Such comment can be viewed through the horizontal segments describing the displacement evolution of points A and B as a function of time when the inclusions are active. However, the process of this evolution continues with large displacement values when inclusions are inactive. This can be confirmed by the distribution of the plastic points when activating these elements. Figure 6 shows the corresponding distribution of plastic points.

Compared to Figure 3, Figure 6 indicates that the amount of plastic points within the second compressible layer decreases when inclusions are activated. Therefore, the introduction of these elements has a considerable effect on the reduction of settlement to be occurring within the second layer. This can lead to progress on these analyses and to test the behavior of these inclusions in the long run. Such case can be similarly modeled in terms of consolidation analysis. Part 2 treats the effect of introducing the inclusions with respect to the consolidation process. This will allows to model the real behavior of the oil storage tank and then to validate the consistency of the suggested solution.

Consolidation analysis

The first phase of this numerical modeling is pertained to the consolidation process of the oil tank. As it was indicated, the duration of such process is equal to 15 years. Figure 7 exposes the vertical strain distribution during this phase. This can lead one to test the effect of introducing the inclusions and their ability to eliminate the consolidation process.

When activating the inclusions, the strain distribution remains the same and the total extreme value of vertical strain slightly decreases. Therefore, one can conclude the efficiency of these elements on decreasing the residual settlements. Figure 8 shows the distribution of vertical strains when the inclusions are active.

It is crucial to point out that the activation of inclusions had been tested on the second phase during 20 years. Hence, the contribution of these elements can be judged as efficient since it decreases all the major part of the residual settlement that can occur during the next 20 years.

Figures 9 and 10 show the difference between the extreme total displacements without activating the inclusions and with the contribution of these elements when activated, respectively.

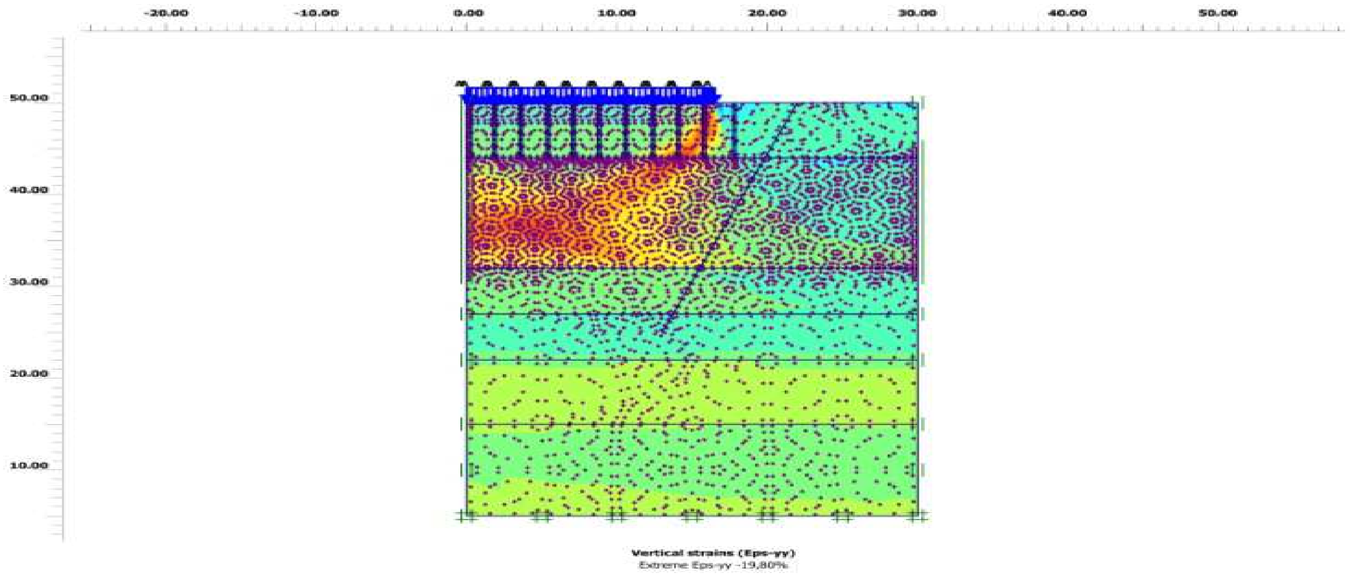

Figure 7- Distribution of vertical strain during the first phase

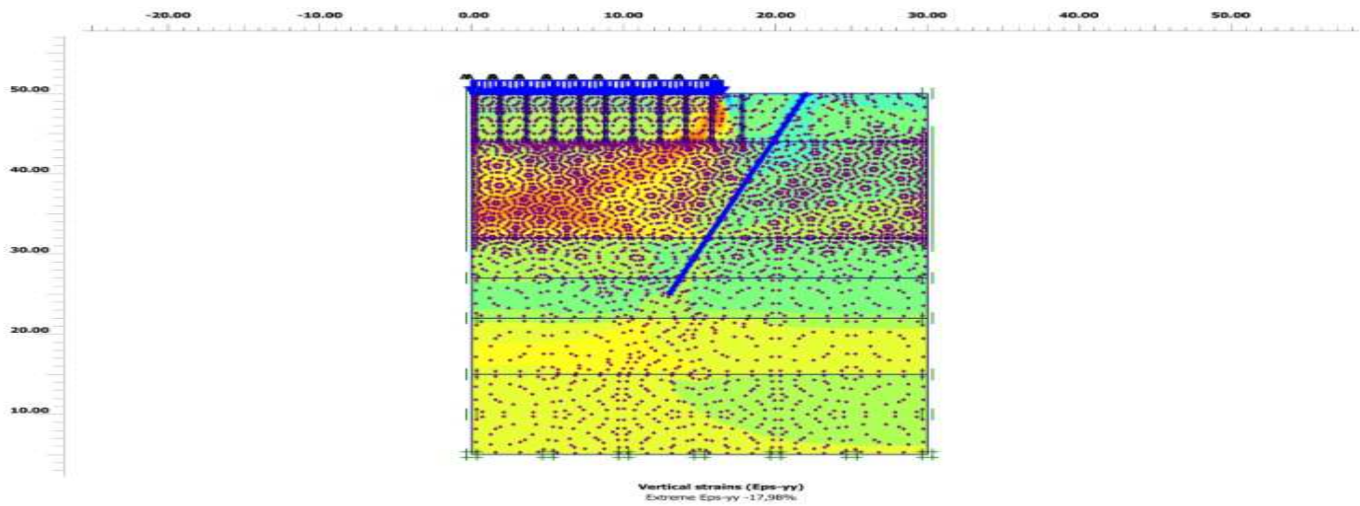

Figure 8- Distribution of vertical strain during the second phase

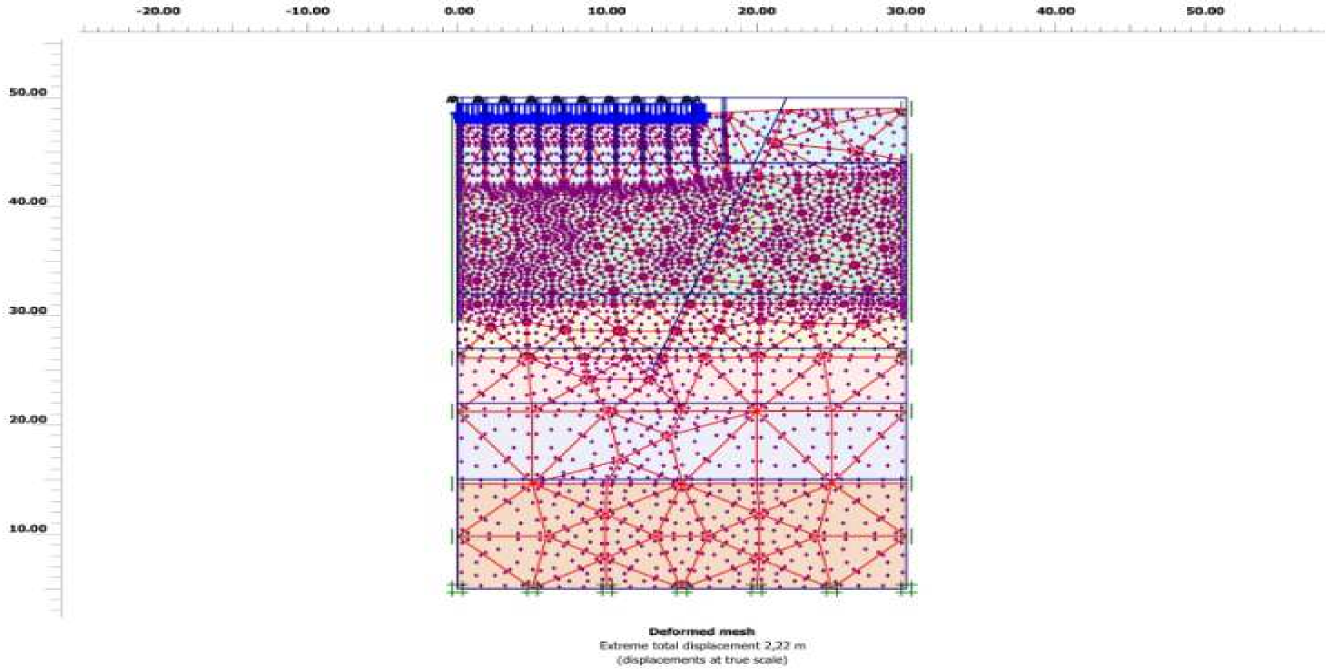

Figure 9- Distribution of vertical displacement without inclusions

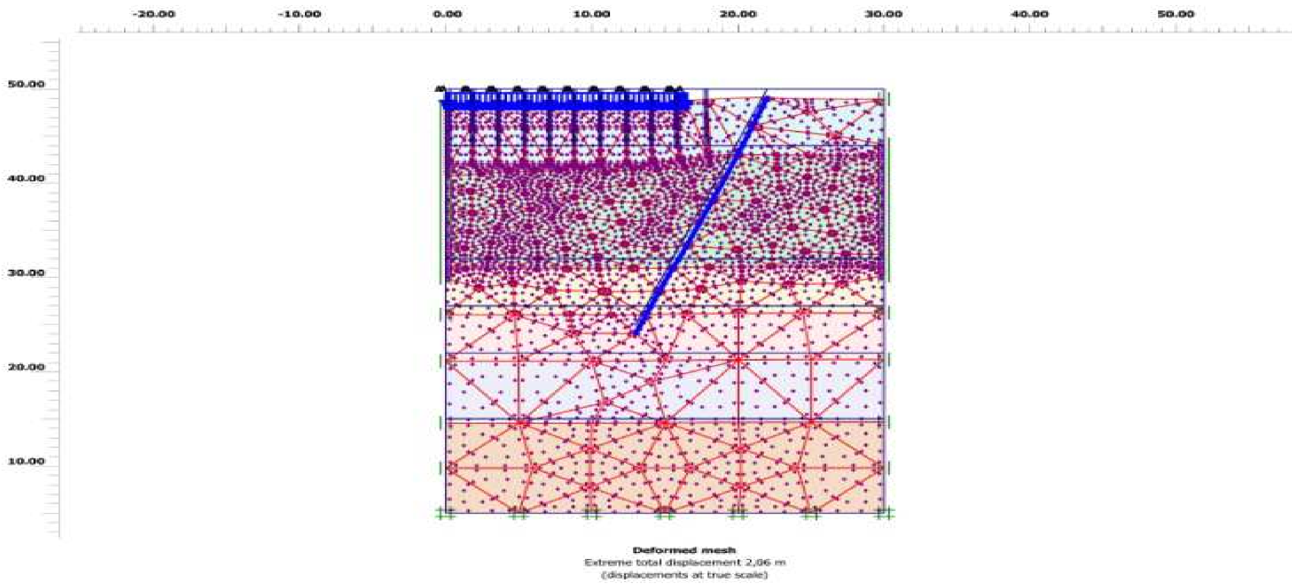

Figure 10- Distribution of vertical displacement with the contribution of inclusions

In order to confirm such finding, two different points were selected in several locations of the compressible clayey layer with the objective to evaluate the vertical displacement of each point during the two phases for two separate cases: the first one deals with the ordinary case (no inclusions introduced) and the second one describes the contribution of the inclusion after the consolidation phase for the duration of 15 years.

Figure 11 exposes the location of the correspondent points while Figures 12 and 13 show the vertical displacements of points A (5, 8) and E (7, 10). Note that the first number of the point coordinates refers to the radius at which the point is located with respect to the axis of the tank while the second number represents its depth. Both numbers are expressed in meters.

According to the two curves, on can easily remark that the consolidation process is reduced during the phase when inclusions are activated. This can be viewed through the difference between the red curves which are related to the ordinary case (inclusions are not active) and the blue ones describing the consolidation process in the presence of the inclusions.

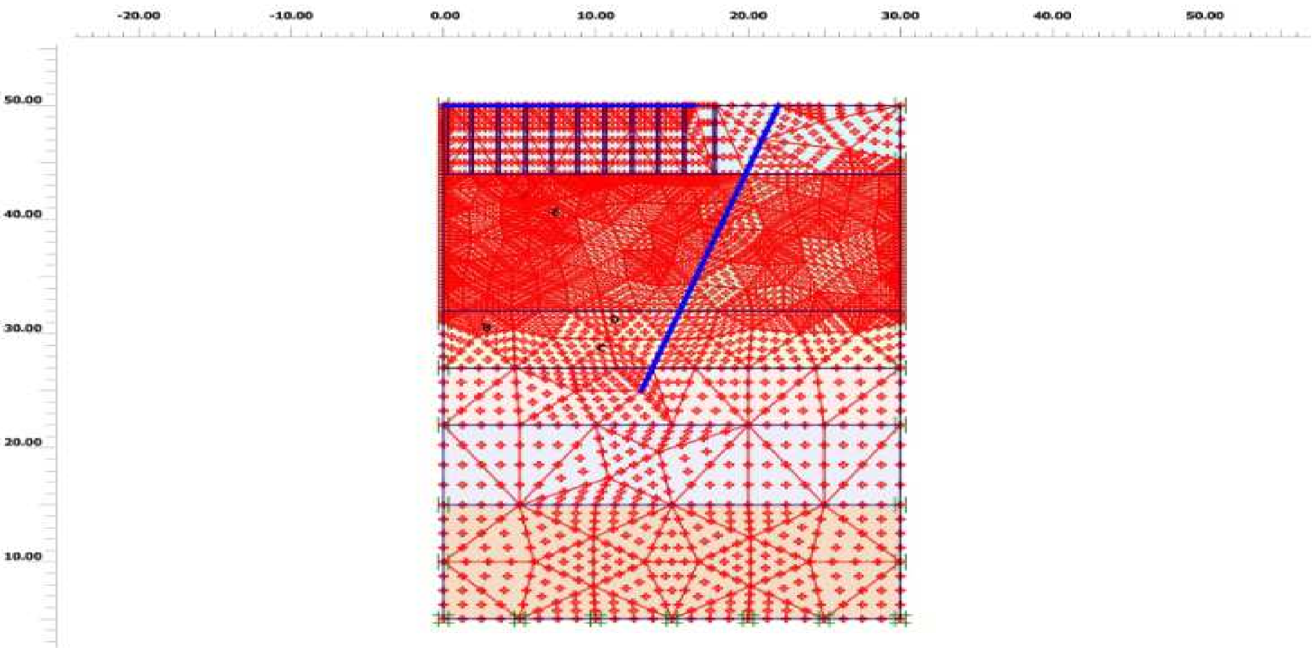

Figure 11- Locations of points A and E

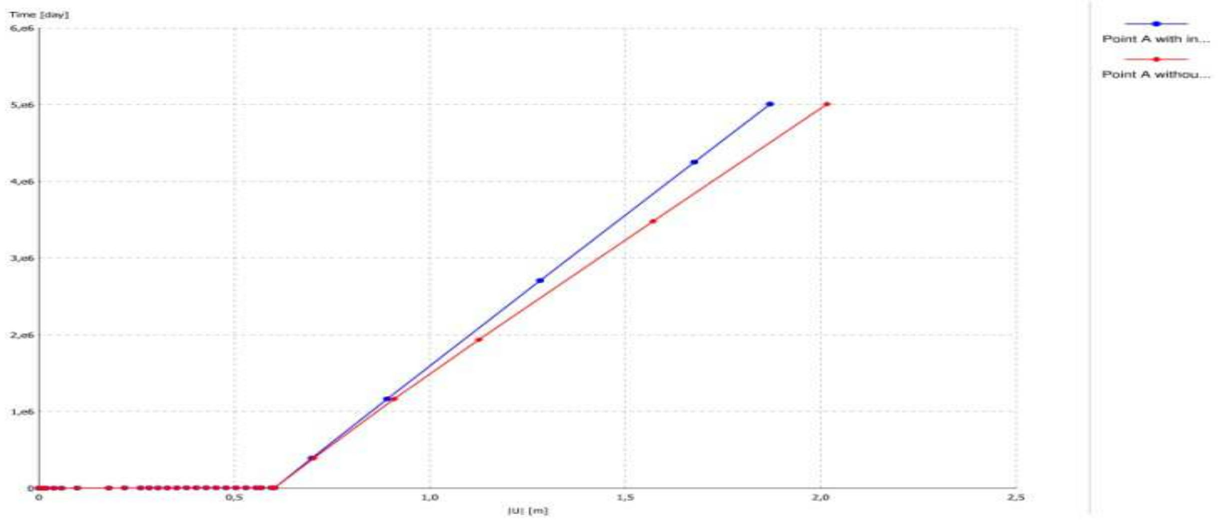

Figure 12- Evolution of settlement at point A

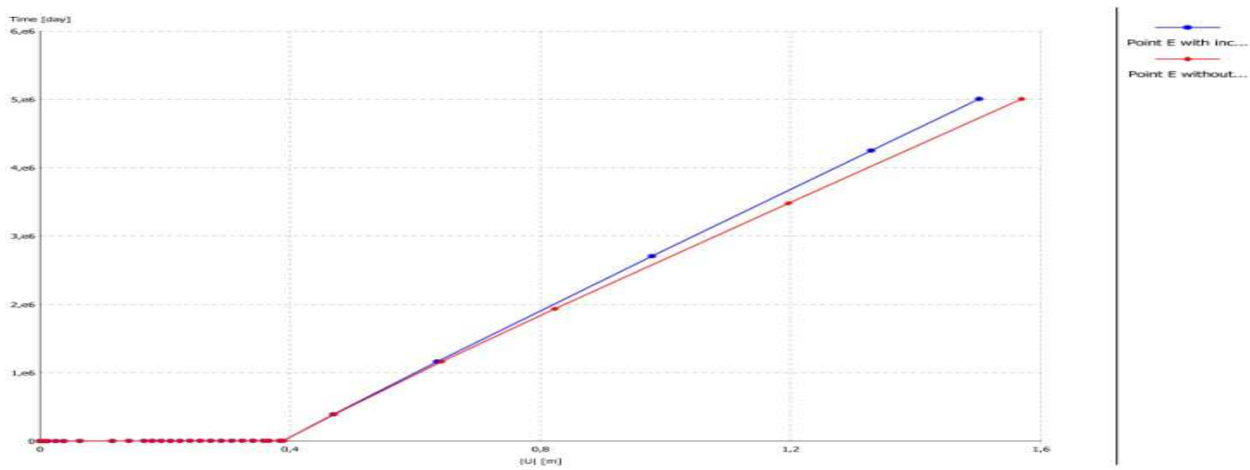

Figure 13- Evolution of settlement at point E

As it was mentioned previously, these points had been selected in different locations of the compressible clayey soil layer in order to highlight the contribution of the inclusions on the reduction of the consolidation process.

CONCLUSION

Contamination of an oil storage tank has been explained as a result of unallowable settlements which have resulted from inconsistent soil improvement using floating sand columns within thick compressible soil layers.

This contribution essentially focused on numerical investigation in order to justify the reinforcement by inclined rigid inclusions to stop the evolution of consolidation settlement in deep layers.

This work can be considered as a first contribution to confirm the consistency of rigid inclusions as solution for reinforcement of high compressible clay. Numerical study has shown the benefit of the technique of inclined rigid inclusions in the sense of neutralization of long term settlement.

A parametric study consisting of varying the incline angle of inclusions and proposing the optimal value corresponding to the vanishing of the consolidation process will certainly improve the obtained results.

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