Time-Dependent Response of Soft Soil Under Tilted Storage Tanks

Suhit Chakraborty and Amit Kumar Das

1 Introduction

Cylindrical storage tanks are often considered as one of the most important structures for continuing the proper functioning of the industries. Most of these storage tanks are cylindrical in shape. Storage tanks are often built in coastal regions, where, in general, soft marine clay soils are found. Many times, it was noticed that there was a differential settlement, distortion of the tank, and tilting of the structure occurred due to the poor soil condition. So, the design and construction of storage tanks are not only limited to superstructure but also need proper soil investigation. Moreover, since such kind of structure is operational for a long period so even after the construction of such structure, proper monitoring is required.

Many researchers have studied the behavior of a circular raft foundation considering the steel storage tanks. Brown and Paterson [1] investigated the failure history of oil storage tanks founded on sensitive marine clay to determine the suitable bearing capacity. D'Orazio and Duncan [2] studied the settlement of the steel tank and made an effort to determine the tolerable limit of differential settlement. Also, they defined three different settlement profiles of the steel tank. Berardi and Lancellotta [3] conducted a study on oil tank settlement due to the yielding of soil. For this they considered the Critical State concept and plasticity model to incorporate soil behavior. Zanjani et al. [4] performed numerical analysis and compared the settlement of the steel tanks with available codes by keeping the ratio of tank diameter to height of order four and by varying slenderness ratio. Mistrikova and Jendzelovsky [5] performed the analysis of the circular symmetric tanks resting on elastic subsoil. The authors considered concrete storage tanks and simulated foundation soil with different constitutive models to observe the effect on the deformation of soil. Ramdane et al. [6]

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performed the case study of the settlement of oil storage tanks located in the marine terminal of Bejaia. Hotala and Ignatowicz [7] studied the settlement under steel tanks with different foundation arrangements. Deb and Das [8] and Das and Deb [9, 10] also addressed soft soil engineering related to concrete rafts and storage tanks.

Most of this research work was performed considering the steel storage tanks. Also, a study was conducted to check for the differential settlement of steel tanks on the untreated ground. But alongside differential settlement, it is also required to study the tilting phenomenon of the tanks. Moreover, it is also very important to find the reason behind the tilting as well as to analyze the changes in the response of soft soil with time. Thus, the present study investigates the time-dependent behavior of soft foundation soil under tilted cylindrical storage tanks considering the foundation of the storage tank as a circular raft.

2 Modeling

In the present work, a hypothetical soil profile is considered for the numerical analysis to study the tilting and differential settlement of storage tanks. Numerical analysis is performed using finite element software package Plaxis 3D. Details of the soil layers and soil properties of each layer considered for the numerical model are shown in Table 1.

The diameter of the circular raft is assumed as 20 m and it is made of concrete with unit weight, $\gamma = 25$ kN/m^3 and Young's Modulus, $E = 31 \times 10^6$ kN/m^2. The Height of the tank is assumed as 6 m. The overall surcharge acting on the raft due to stored material is considered as 60 kN/m^2. Ultimate bearing capacity of footing resting on stratified soil layer is determined for the case considering top soil is dense sand and bottom soil layer is saturated soft clay [11]. It is found to be safe. There may be different reasons for tilting of structures of which one of the main reasons is expected to be variable soil layer thickness beneath the structure. In the case of large structures like storage tanks, there is a high possibility of change in soil layer thickness beneath the structures. If this soil layer of variable thickness is weak and

Table 1 Soil profile and properties used in the present study

Layers	Soil	Parameters
First	Sand	$c = 0$ kN/m^2, $\phi = 30^\circ$, $E = 30{,}000$ kN/m^2, $\gamma = 16$ kN/m^3, $e = 0.7$, $\mu = 0.3$, $k = 8.64$ m/day, $S = 0$
Second	Soft clay	$c_u = 10$ kN/m^2, $\phi = 0^\circ$, $E = 300c_u$ kN/m^2, $\gamma = 17$ kN/m^3, $e = 1.2$, $\mu = 0.4$, $k = 0.000864$ m/day, $S = 1$
Third	Rock	$c = 20$ kN/m^2, $\phi = 45^\circ$, $E = 150{,}000$ kN/m^2, $\gamma = 21$ kN/m^3, $e = 0.15$, $\mu = 0.15$, Non-Porous

c = cohesion of soil, ϕ = friction angle, E = modulus of elasticity, μ = Poisson's ratio, e = void ratio, γ = unit weight of soil, k = permeability, S = saturation of soil

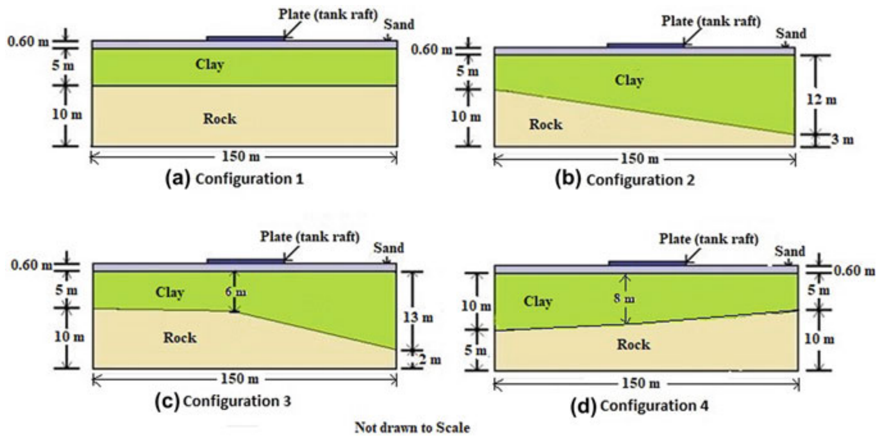

Fig. 1 Cross-sectional view of four different soil profiles

compressible, then differential settlement and tilting are expected to occur. Four different cases of soil profiles with or without variation in thickness are configured, as shown in Fig. 1, for numerical analysis to evaluate the tilting of the structure.

Initially, convergence study is performed using coarse, medium, and fine meshing and medium meshing is found satisfactory enough. The medium meshing technique is adopted for the analysis with 133,630 elements and 208,254 nodes. Ten-noded tetrahedral elements for the 3D soil model and 6-noded triangular elements for raft simulated by plate are used in the numerical model. Soil layers in the numerical models are simulated using Mohr–Coulomb constitutive model. In all the numerical models, side boundaries are partially fixed, while the bottom is fully fixed and the top surface is free. The numerical modeling in Plaxis 3D is performed in five steps: gravity loading, placing of sand layer, construction of tank raft, loading, and consolidation. All the steps, excluding gravity loading, are kept under the consolidation stage considering consolidation of soil a continuous process starting from the construction of tank to loading with surcharge. Among the four configurations mentioned in Fig. 1, configuration 3 is selected for the study of the time-dependent behavior of the tilted structure. The model prepared in Plaxis 3D for time-dependent study with configuration 3 is shown in Fig. 2.

3 Validation of Numerical Model

In order to validate the numerical model developed in Plaxis 3D, a case study is selected from Ramdane et al. [6] and the results obtained are compared. Ramdane et al. [6] presented a case of the settlement of hydrocarbon liquids storage tanks located in the marine terminal of Bejaia. After 25 years of construction of tanks, a differential settlement, ovalization, and tilting occurred in few tanks. Figure 3 shows

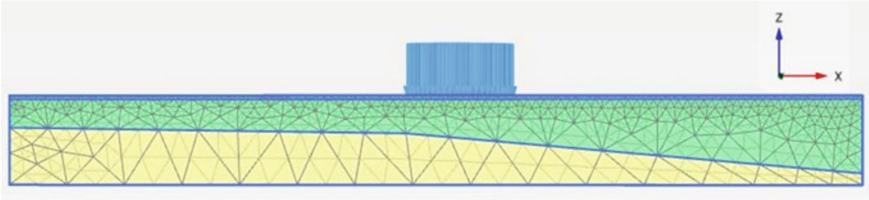

Fig. 2 Numerical model developed in Plaxis 3D with configuration 3 soil profile for time-dependent analysis

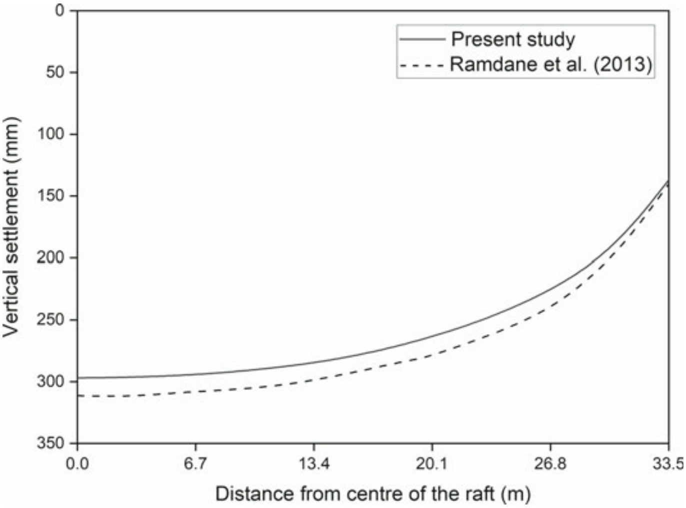

Fig. 3 Comparison of vertical settlement between results obtained from the present study and Ramdane et al. [6]

the vertical settlements reported by Ramdane et al. [6] and the same obtained from the numerical model developed in Plaxis 3D. The results show good agreement.

4 Results and Discussion

Figure 4 shows the vertical settlement profile of raft for different soil profile configurations (as shown in Fig. 1) just after the application of surcharge load. Further settlement takes place with the consolidation of soil. The tilting behavior of storage tanks under different configurations is observed, excluding configuration 1, even at this stage, when major consolidation is yet to occur. In the case of configuration 1, where each layer has a uniform thickness, only differential settlement is observed. This differential settlement is measured as the difference in the vertical settlement

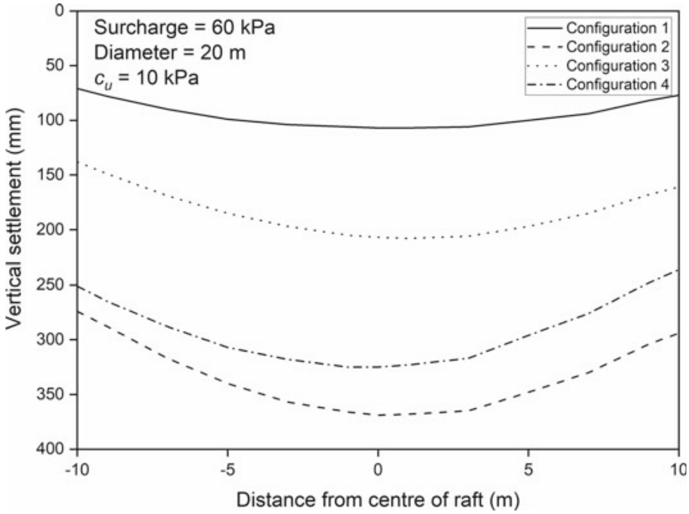

Fig. 4 Vertical settlement profile of raft for different soil profile configuration

between the edge and center of the raft, which is expected if the raft is flexible. At this stage, in configuration 2–4, the amount of tilting (difference in the vertical settlement between two opposite edges) is 20 mm towards the right side, 23 mm towards the right side, and 15 mm towards the left side, respectively. It may be noted that the tilting is higher in the case of configuration 3 despite the settlement is lower than configurations 2 and 4.

Figure 5 shows vertical settlement for configuration 3 soil profile at different times after application of the surcharge load. The results of the time-dependent analysis show that the raft is tilted by 23 mm up to the loading step of the analysis. The analysis is then continued for further consolidation. Consolidation steps are further subdivided into different steps in order to monitor the settlement behavior of the raft. Finally, settlement up to 90% consolidation data is noted. It is observed that there is an increase in tilting of the tank with further consolidation and after 90% consolidation tilting of the raft is 105 mm. Therefore, ultimate tilting is almost 4.5 times the initial tilting observed just after the application of the surcharge.

Parametric studies are performed to observe the effect of different important factors on the tilting of the structure. In parametric studies, other parameters are kept unchanged, while tilting is studied for variation of any one parameter. Figure 6 shows the effect of undrained cohesion (c_u) of soft clay on time-dependent change in tilting of the structure. The change in undrained cohesion, also indicates a change in stiffness of soil, since the value of modulus of elasticity (E) for clay soil also changes with undrained cohesion considering $E = 300c_u$. It is observed that with the increase in undrained cohesion of soft soil, as well as an increase in stiffness of the soil, tilting of the structure reduces. It is also observed that the tilting of the structure may become insignificant in stiffer soil.

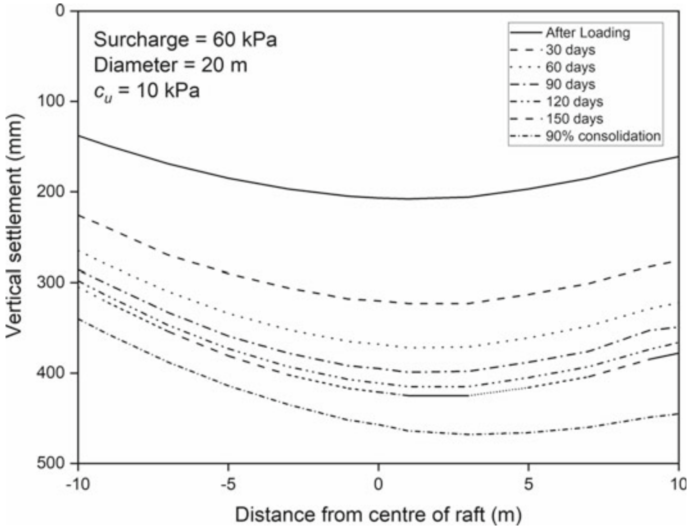

Fig. 5 Vertical settlement profile of the raft at different times after application of surcharge for configuration 3 soil profile

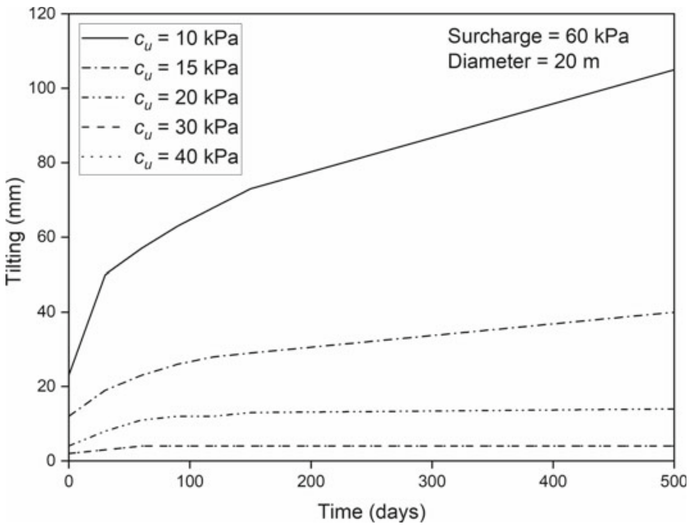

Fig. 6 Tilting of the raft for different undrained cohesion (c_u) of soft soil

The effect of the intensity of surcharge on time-dependent change in tilting of structure is presented in Fig. 7. In this study, undrained cohesion of soft clay (c_u) is considered as 15 kPa to ensure safety against bearing failure. It is observed that the increase in the intensity of surcharge causes an increase in tilting of structure. Tilting

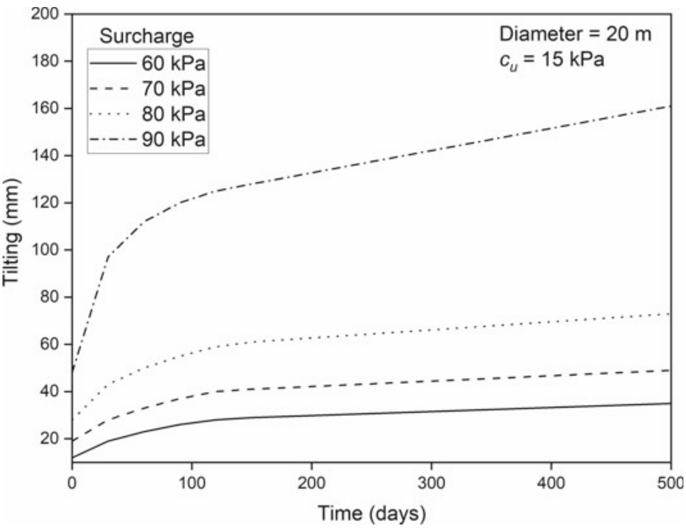

Fig. 7 Time-dependent change in tilting of the structure for different intensity of surcharge

reaches 3 times the initial tilting when the intensity of the surcharge is 60 kPa, but the same is 3.4 times the initial tilting as observed for the 90 kPa surcharge after 500 days. It is also observed that the possibility of ultimate tilting is higher when the intensity of surcharge is higher. In the present study, tilting is a function of the consolidation settlement, which increases non-linearly with surcharge intensity and time. Therefore, tilting is observed to increase disproportionately with an increase in surcharge intensity, because the rate of consolidation settlement increases with surcharge intensity, but decreases with time.

Figure 8 shows the change in tilting with time for different diameters of the raft. It shows that the smaller the raft diameter, the chances of tilting of structure reduces. The percentage decrease in tilting observed after 500 days is about 37% while the diameter of the raft changes from 20 to 15 m and the same for change in diameter from 20 to 10 m is about 80%. It is also observed that the change in tilting of the structure with time is almost linear for rafts of lower diameter, whereas the same is nonlinear when the diameter of the raft is large. Such change in tilting behavior may be attributed to the decrease in relative stiffness of the raft with an increase in diameter, while the thickness of the raft remains constant.

5 Conclusions

The present study shows that the tilting of structure should be studied as a function of time, otherwise the design of appropriate remedial measures may prove to be erroneous or ineffective. The following conclusions are drawn from the present study:

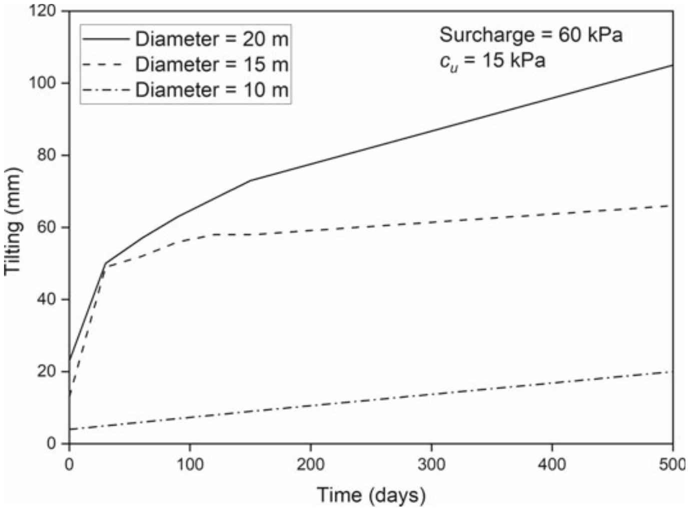

Fig. 8 Tilting of the raft with change in diameter of the raft

(1) Differential settlement may occur even in foundations resting on uniform soft soil, but tilting is governed by a change in thickness of compressible soil layer.
(2) Tilting of the structure increases with time as consolidation of the soil progress.
(3) With an increase in undrained cohesion of soft clay as well as stiffness of the soil, tilting of the structure reduces.
(4) Larger the diameter of the storage tank, the possibility of tilting is higher.

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