XLIII
CILAMCE
21-25, November, 2022
FOZ DO IGUAÇU - PR - BRAZIL

Settlement analysis of an oil storage tank considering inclined subsoil layers

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Abstract. Oil storage tanks are usually designed and built in coastal regions where the subsoil is characterized by stratigraphic intercalations of fine sands, silts, soft clays and marine sediments. The loading applied by thank is generally of small magnitude, but the occurrence of differential settlements, due to compression of the soil, may seriously damage the main tank components, including pipes and connections for oil supply. The main objective of this study is a numerical evaluation of a tank foundation with respect to slightly inclined subsoil layers, comparing the results with measured data from field hydro tests. The consideration of slope variation in the subsoil layers has a direct influence on the settlement, especially with respect to the clay layers. This study also highlights the importance of several factors that affect the foundation behavior and may be helpful for engineers to make appropriate decisions from a technical and economical point of views.

Keywords: numerical modeling, storage tanks, differential settlement, inclined subsoil layers.

1 Introduction

Storage tanks are containers that hold liquids, such as oil and its derivatives, and operate under atmospheric pressure. In Brazil, it is usual to design cylindrical storage tanks with capacities ranging from 16 m³ to 112,000 m³. The larger the volume, the lower the cost of storage per barrel, making the construction of very large tanks economically advantageous. Fuel storage tanks are often built in coastal regions, due to industrial logistic strategies, where the soil is characterized by a stratified geotechnical profile, formed by recent sediments from the Quaternary period. According to Marr et al. [1], many engineers incorrectly believe that differential settlements do not represent a main design requirement for flexible storage tanks, but the fact is that differential settlements have led to the rupture of tanks or some components of storage systems, triggering the spillage of fuel and contamination of the ground (Bell and Iwakiri [2], Clarke [3], Green and Hight [4]).

The objective of this study is to numerically evaluate the performance of a storage tank foundation with respect to slightly inclined subsoil layers. The stratigraphic characterization of the soil deposit was obtained through SPT tests and data from field hydro-tests carried out in a storage tank provided the evolution of settlement according to several levels of loading. The analyses were made using the commercial software Plaxis 3D, considering different elastoplastic constitutive models for representation of the mechanical behavior of soil: (a) Mohr Coulomb model (MC) for sand and clay; (b) Mohr Coulomb model (MC) for sand and Soft Soil model (SS) for clay; (c) Hardening Soil Modeling (HSM) for sand and Soft Soil model (SS) for clay.

2 Settlement Evaluation

For economic reasons, foundations of large tanks tend to be shallow and may consequently suffer differential settlement under load. Steel cylindrical tanks for the storage of fluids, such as oil or water, have either floating or fixed roofs. Although floating roofs are sometimes used in smaller tanks to prevent the evaporation of volatile materials, their most important application is in large diameter tanks which are relatively shallow. Concerns related to settlement include distortion of the tank shell which may affect the smooth operation of the floating roof and overstressing of the shell and primary wind girder. Total settlement of the periphery is normally measured during tank construction, at hydro-tests and periodically in service. From these measurements, the following three components are derived: uniform settlement, planar tilt and differential settlement. The uniform component does not cause serious problems to the shell but may damage pipework and connections.

Differential settlement results from one or more of the following causes: nonuniform geometry or compressibility of the soil deposit, nonuniform distribution of the load applied to the foundation and nonuniform stress acting on a limited area of the soil stratum. These causes exist in varying degrees of importance in the foundation of tank structures. The engineer evaluates their importance when developing an acceptable design, with the objective to minimize differential settlement by keeping: (a) the applied load less than the foundation bearing capacity; (b) deformations due to volume and shear strains in the foundation within allowable limits.

3 Constitutive Soil Models

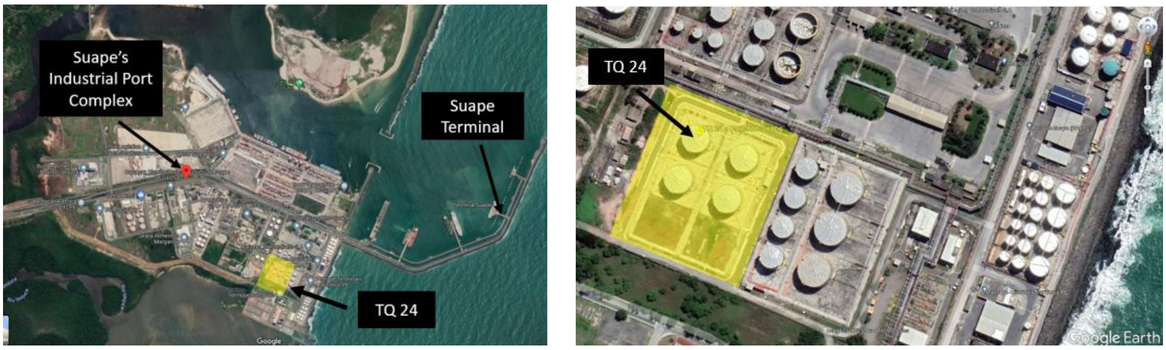
The Mohr-Coulomb model (MC) is a well-known elastic perfectly plastic model which can be used as a first approximation of soil behavior. The calculation of the linear elastic strains is based on Hooke's law and the plastic strain increments are estimated from the Mohr-Coulomb model formulated within a non-associate plasticity framework.

The Hardening Soil Modeling (HSM), proposed by Schanz et al. [5], is a reformulation of the hyperbolic model (hypoelastic model) in light of the plasticity theory, using three different stiffness parameters: the triaxial deformation modulus E_{50}, corresponding to 50% of the yield stress, the unloading / reloading triaxial deformation modulus E_{ur} and the edometric (or constrained) soil modulus E_{edo}. The HSM model includes dilatancy for heavily consolidated soils and simulates the occurrence of plastic deformations under shear and compression hardening. As the very name of the model suggests, there is no simulation of soil softening. The hydromechanical behavior of soft soils (normally or lightly consolidated clays, silty clays and peats) is characterized by their high deformability [6] and a linear dependence of the stiffness on the stress state. Generally, the HSM model may be applied for all types of soil, but specifically for very soft soils the recommendation is to use the Soft-Soil model (SS) which may better represent their mechanical behavior under compression.

4 Case Study

The metallic storage tanks under investigation are located in the Suape's Industrial Port Complex, one of the biggest development projects in Brazil (Figure 1a) situated in the metropolitan region of Recife, PE.

As a preliminary study, the results of four hydro-tests carried out in four cylindrical steel storage tanks, relatively close to each other (Fig. 1.b) were investigated, and the tank denominated TQ24 was selected for this case study since it presented the best quality of data and the most coherent results. This tank has a height of 15 m, diameter of 30 m and a reinforced concrete ring foundation with a height of 1.4 m and thickness of 0.3 m.



(a) (b)

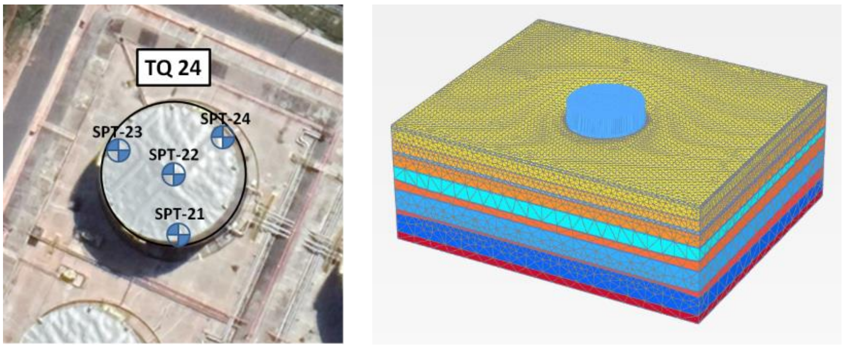
Figure 1 – (a) Location of the TQ24 tank in Suape, PE; (b) Position of tank TQ24 with respect to neighboring tanks with same geometry

4.1 Soil Stratigraphy

In order to know the geotechnical parameters of the subsoil, four SPT penetration tests (SPT21, SPT22, SPT23, SPT24), indicated in Figure 2a, were carried out to a depth of 44 m in the area delimited for the construction of the TQ24 storage tank. Based on the recovered soil samples and measured blow count, or N_{SPT}-values, the stratigraphy suggested the existence of slightly inclined soil layers, which required a 3D discretization of the problem geometry, as shown in Figure 2b, consisted of 120,865 tetrahedral finite elements (20 nodes).

Table 1. Stratigraphy from SPT tests

Soil	SPT21	SPT22	SPT23	SPT24
Sand 1	0 m - 1 m	0 m - 1 m	0 m - 1 m	0 m - 1 m
Sand 2	1 m - 6 m	1 m - 6 m	1 m - 5 m	1 m - 5 m
Sand 3	6 m - 10 m	6 m - 10 m	5 m - 10 m	5 m - 10 m
Clay 1	10 m - 11 m	10 m - 11 m	10 m - 11 m	10 m - 11 m
Sand 4	11 m - 16 m	11 m - 16 m	11 m - 16 m	11 m - 16 m
Clay 2	16 m - 21 m	16 m - 21 m	16 m - 20 m	16 m - 20 m
Sand 5	21 m - 25 m	21 m - 25 m	20 m - 25 m	20 m - 25 m
Clay 3	26 m - 33 m	26 m - 33 m	26 m - 33 m	26 m - 32 m
Sand 6	33 m - 34 m	33 m - 37 m	33 m - 37 m	32 m - 37 m
Clay 4	34 m - 42 m	37 m - 42 m	37 m - 42 m	37 m - 42 m
Sand 7	42 m - 44 m	42 m - 44 m	42 m - 44 m	42 m - 44 m



(a) (b)

Figure 2 – (a) Localization of four SPT tests; (b) stratigraphy with slightly inclined subsoil layers

4.2 Geotechnical Parameters

Laboratory tests are quite important to characterize the mechanical behavior of soils, but when not available an alternative is to use correlations with corrected N_{SPT} proposed in the literature for estimation of geotechnical parameters. Such was the approach for the sandy soil layers, while for the clayey layers the necessary information could be obtained from Freire [7] and Coutinho and Bello [**8**]. Table 2 shows the main geotechnical parameters for the three constitutive soil models considered in this research.

Table 2. Geotechnical Parameters

				MC			**HSM**				**SS**		
Layer	$\mathbf{N_{SPT\,1\,(60)}}$	$\boldsymbol{\Upsilon_{sat}}$ **[kN/m³]**	**e** **–**	**c** **[kPa]**	**φ** **[degrees]**	**E** **[kPa]**	E_{50}^{ref} **[kPa]**	E_{oed}^{ref} **[kPa]**	E_{ur}^{ref} **[kPa]**	**OCR** **–**	$\mathbf{C_C}$ **–**	$\mathbf{C_S}$ **–**	$\mathbf{C_V}$ **[m²/s]**
Sand 1	15,30	17	1,00	0	39	35594,85	35595	23729,89	106784,52	1,00	–	–	–
Sand 2	8,00	17	1,23	0	36	25730,43	25169	16779,57	75508,08	1,00	–	–	–
Sand 3	26,83	17	1,14	0	37	47108,24	44847	29898,13	134541,60	1,00	–	–	–
Clay 1	6,91	14	3,98	15	–	3878,00				1,62	2,03	0,22	$13{,}6 \times 10^{-8}$
Sand 4	29,38	17	1,20	0	36	49309,56	47562	31708,05	142686,21	1,00	–	–	–
Clay 2	3,27	14	2,82	15	–	2757,00				1,60	1,62	0,2	$7{,}3 \times 10^{-8}$
Sand 5	11,69	17	1,34	0	34	31108,48	31108	20738,98	93325,41	1,00	–	–	–
Clay 3	3,50	14	2,82	15	–	2811,00				1,60	1,87	0,1	$8{,}9 \times 10^{-8}$
Sand 6	13,03	17	1,36	0	33	32849,27	32849	21899,51	98547,81	1,00	–	–	–
Clay 4	3,15	14	2,82	15	–	2736,00				1,60	1,88	0,2	$9{,}0 \times 10^{-8}$
Sand 7	26,34	17	1,32	0	34	46703,02	46703	31135,35	140109,06	1,00	–	–	–

where $N_{SPT\,1\,(60)}$ is the corrected SPT value; Υ_{sat} the saturated unit weight; e represents the void ratio; c is the cohesion; φ the friction angle; E denotes the Young's modulus; E_{50}^{ref}: is the secant stiffness in conventional drained triaxial test; E_{oed}^{ref} is the tangent stiffness for primary oedometer loading; E_{ur}^{ref} is the unloading/reloading stiffness; OCR means de isotropic over consolidation ratio; C_C is the compression index; C_S represents the swelling index or reloading index and C_V is the consolidation coefficient.

5 Results

The settlement results predicted by numerical simulations carried out with the finite element software Plaxis 3D were compared with those measured in the hydro tests of the storage tank TQ24. Experimental data were measured with the tank loaded with 50% of water, 100% full of water and 100% full plus one day. The phase of unloading lasted for another 19 days. The filling and emptying sequences of the hydro tests were taken into account in the finite element analysis.

Figure 4 presents the settlement evolution along time (Fig. 3a on the left column) and according to loading / unloading sequences (Fig. 3b on the right column) for eight points situated around the tank perimeter. Besides the experimental results measured in the hydro test (curve HT), each graph in Fig. 3 shows the settlement calculated using a combination of soil models: MC+MC (Mohr Coulomb model for sand and clay), MC+SS (Mohr Coulomb model for sand and Soft Soil model for clay) and HSM+SS (Hardening Soil model for sand and Soft Soil model for clay).

It can be observed that the better representation of the hydro test results was obtained considering the HSM model for the sandy layers and the SS model for the clayey layers. Although there still are some differences between measured and predicted settlements, a refinement may be possible if a more precise parameter estimation could be obtained through laboratory tests of the different materials that form the soil stratigraphy of tank TQ24.

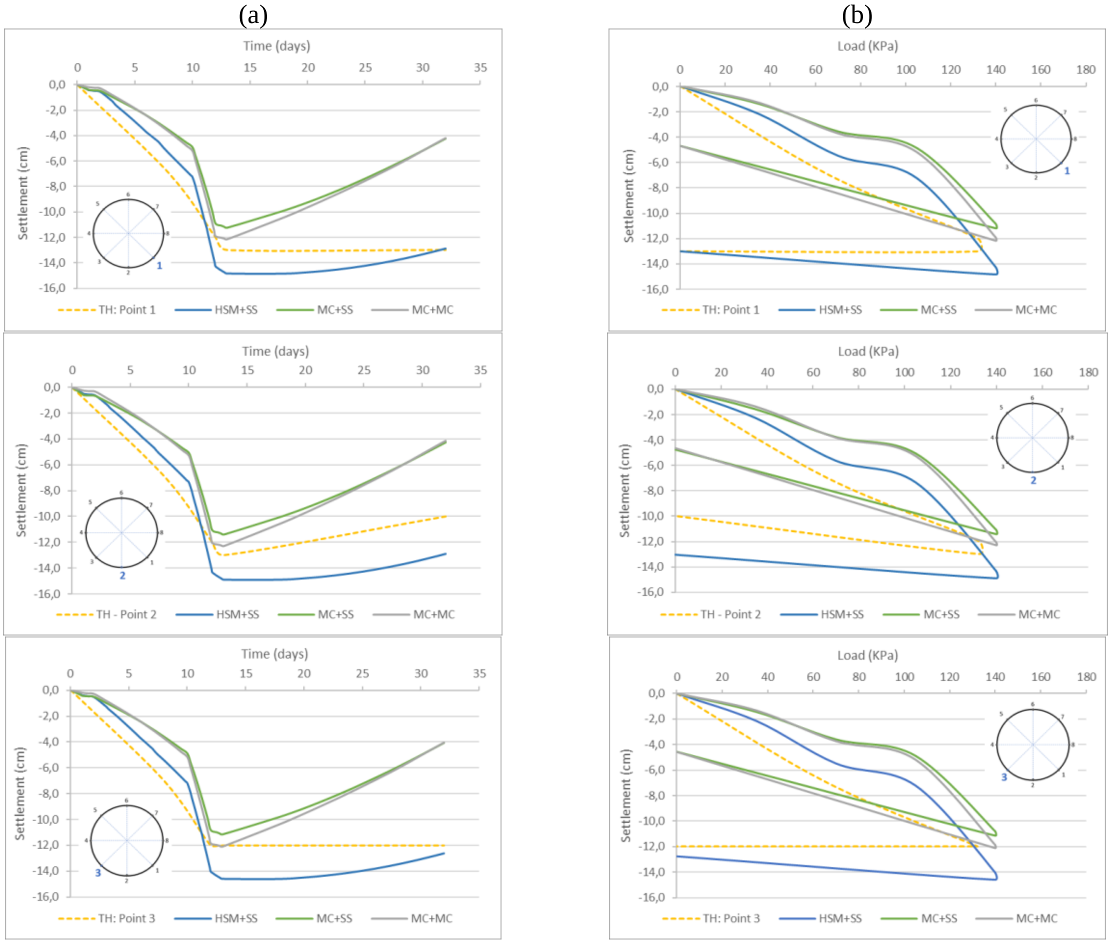


Figure 3 – (a) time vs. settlement; (b) load vs. settlement

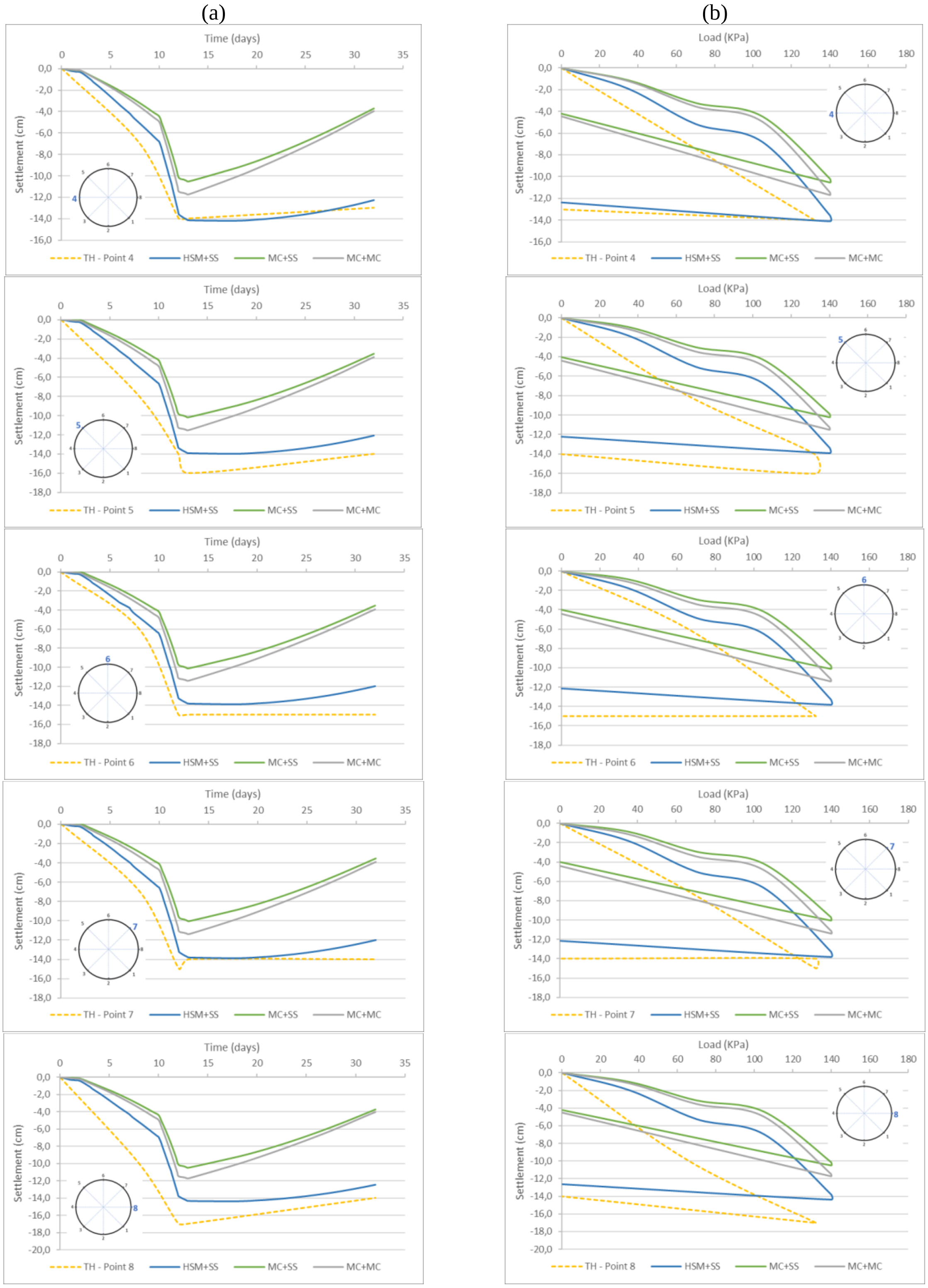


Figure 4 (continued) – (a) time vs. settlement; (b) load vs. settlement

6 Conclusions

From the results obtained in this research, it may be concluded that: (1) the constitutive soil models were approximately calibrated using N_{SPT} correlations from literature, which emphasizes the need for laboratory tests for estimation of more accurate geotechnical parameters; (2) the Mohr Coulomb model is a good model for shear strength studies but not for deformation analysis; (3) the combination of the HSM model, for sandy layers, and the SS model, for clays, yielded the best results with respect to the settlements measured during the field hydro tests; (4) the differential settlements measured in the hydro test, as well as the predicted numerical values, are within the recommendations of the Petrobras Standard N-270 [9].

Acknowledgements. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior–Brasil (CAPES)–Finance Code 001 and Conselho Nacional de Pesquisa (CNPq)–Grant 870122/1997-5.

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