Improvement of Fine Soils by Controlled Water Test of Aboveground Oil Storage Tank

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Abstract

A system of preloading by water in aboveground oil storage tanks is an effective method to reduce whole construction time and expenses to improve soil layers under these tanks. This study presents 3 main steps of preloading with water procedure design. These steps which are discussed include initial design to predict settlement of tanks, 3D FEM model of tank with ABAQUS and analyzed data which are gained from monitoring of tank in site during water test.

Keywords: *fine soils; controlled water test; aboveground oil storage tank; ABAQUS; model; monitoring.*

1 Introduction

There are various approaches to control consolidation settlement in saturated fine soils, one of the routine ways to accelerate the consolidation process is the use embankments and vertical drains to preload the area in which the tanks will be built. Soil embankments require a large amount of soil to be transported so they are time consuming and costly. Preloading by water is a way to reduce whole construction time and eliminate cost of earthworks. In this approach, the tank is gradually filled with water and kept full for a while. Water test is a routine work in the construction of steel tanks and used to control any construction defeat. Therefore soil improvement by water test do not imposed considerable additional cost to the project. Soil consolidation is being done during the process of controlled water test. It should be mentioned that during the consolidation period, all deformation in tank should be monitored to prevent any damages to the tanks. To predict the tank behavior during a controlled water test, the shell and base of a tank were modeled using a 3 dimensional finite element program (ABAQUS). The analysis was performed for a number of projects to be constructed in the south of Iran. To conclude, criteria were established and recommendations are made for this soil improving method.

1.1 Background

There are a few case histories which water is used as the surcharge. One of these cases which could be referred was done at a tank farm site in central Java, Indonesia. In this project, first soil was improved by embankments and vertical drain then water test had been done for 90 to 150 days, the maximum settlement recorded from water test was 90 mm. This amount of settlement is not considerable to assume that soil improved by water test. Although, water test should be done to control any construction defeats, but preloading with water is not routine method for soil improvement .Because, the process in use of preloading with water and vertical drain has high risk and requires that all monitoring should be done carefully because of large and unpredictable settlement amounts during construction.

1.2 Possible and Allowable Settlement in Above Ground Storage Tank

Since various forms of settlements could take place, it is crucial to define all required variables at the beginning of this chapter as depicted in figure1.

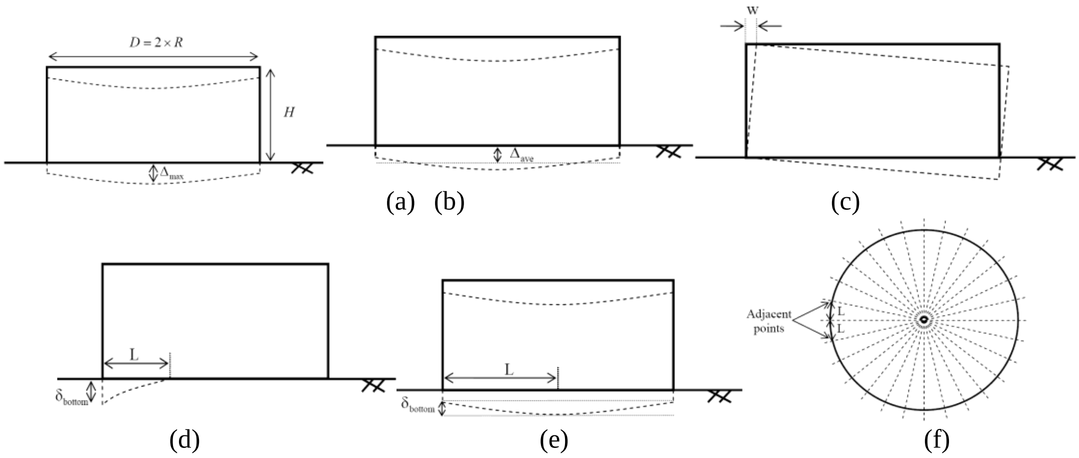


Figure 1. Possible settlements in steel storage tanks: (a) Total Maximum Settlement of Steel Tank(bowled-shaped), (b) Average Settlement of a Steel Tank, (c) Tilt of a Steel Tank, (d) Bottom-Edge Differential Settlement of a Steel Tank, (e) Bottom-Center Differential settlement of a Steel Tank and (f) Shell Differential Settlement of Steel Tank.

Table1 presents a comparison of allowable settlements of steel storage tanks from different references; table 2 presents allowable settlement for the tanks in Mahshahr Oil Product.

Table 1. Comparison of allowable settlements from different references.

Reference	Tank type	Total Settlement (mm) Δ_{max} (Figure11a) Center	Total Settlement (mm) Δ_{max} (Figure11a) Edge	Total Settlement (mm) (Figure 1b) Δ_{ave}	Differential Settlement δ_{bottom} Center (Figure 1 e)	Differential Settlement δ_{bottom} Edge (Figure 1d)	Differential Settlement δ_{shell} Outline (Figure 1f)	Tilt w (Figure 1c) Visible	Tilt w (Figure 1c) Ultimate
API 653 -1995	Large-Small	-	-	-	0.031(R)	-	$0.0055(L^2)/H$	-	-
Klepikov -1989	Large	-	-	180	0.004(D)	-	0.01(L)	0.004(H)	0.007(H)
	Small	-	-	110	0.008(D)	-	0.008(L)		
USACE (1990)	Large-Small	-	-	-	0.008(R)	-	-	-	-
D'Orazio and Duncan -1987	Large-Small	-	-	-	0.025(D)	-	-	-	-

Table 2. Proposed allowable settlements for the steel tank in Mahshahr Oil Product Terminal.

Type of Tank	D(m)	H(m)	Total Settlement (mm)	Differential settlement (mm)	Tilt (mm)
Large	60	14.15	500	375	56
Small	9	8	100	75	32

1.3 Case Study

The above ground storage tank which is analyzed in the study has been constructed in Mahshahr Oil product Terminal in the south of Iran. The ratio between diameter (D) and the height (H) of the tank is of order 4 and slenderness ratio (radius to the thickness of shell) of the tank is order of 1000 (first course of shell) to 3750 (last course of shell).Tank height and diameter are respectively 14.15 and 60 m. The tank was redesigned to tolerate the settlement caused by water test, so the top angle was improved and three more angle were erected at the height of 0, 1.7 and 2.53 meter from the base. At this time, the tank construction has been completed and all monitoring for the water test have been done.

2 Design of preloading with controlled water test in Mahshar Oil Product Terminal.

2.1 Settlement Analysis before Soil Improvement

Regarding the soil investigation which have been done up to the depth of 50 meters, it has been concluded that the most parts of the site consist of low plasticity sandy silts (ML) and sandy clays (CL). Though, in calculation it has been assumed that subsoil layers are ML/CL. Furthermore, the investigations indicate that water table is almost at the ground level. Therefore, subsoil layers are saturated or nearly saturated. The lateral displacement of the soil masses beneath the tank center, where the maximum consolidation happens, is negligible also the sub layers are very soft, so immediate settlement can be ignored. Additionally, because few peaty soil layers have been found on the site, creep consolidation is negligible. Therefore, calculations of the consolidation settlement are necessary; on the other hand, immediate and creep settlement can be ignored.

For settlement calculation it is necessary to estimate the pressure increase in the soil mass. In this study Newmark method is used, Eq. 1 presents the mentioned formula (from Bowels, 1996).

$$\Delta q_v = \frac{1}{4\pi}\left[\frac{2MN\sqrt{V}}{V+V'} \times \frac{V+1}{V} + \tan^{-1}\left(\frac{2MN\sqrt{V}}{V-V'}\right)\right] \times q_0$$

$$\text{Where: } \begin{cases} M, N = \frac{B}{z}, \frac{L}{z} \\ V = M^2 + N^2 + 1 \\ V' = (MN)^2 \end{cases} \qquad (1)$$

As mentioned, the principle parts of subsoil settlement in this study are consolidation settlement. The Eq.2 is used to calculate settlement which is based on Terzaghi’s one dimensional theory.

$$\Delta H = \frac{1}{1+e_0} C_c \log\left(\frac{\sigma_1'}{\sigma_0'}\right) = \frac{1}{1+e_0} C_c \log\left(\frac{\Delta\sigma'}{\sigma_0'}\right) \qquad (2)$$

Because of several reasons in many cases the values of settlement derived from theoretical one dimensional consolidation settlement are more than actual values (Tomlinson, 2001). To modify the calculated consolidation settlement Eq.3 is used in which μ is the settlement reduction dimensional (3D) factor, ΔH_{cal} is the theoretical one dimensional settlement and ΔH is the real settlement which is expected in the field.

$$\Delta H = \mu \times \Delta H_{cal} \qquad (3)$$

Skempton and bjerrum (1957) related the values of the μ to the value of “A” coefficient (pore pressure coefficient of pressure coefficient of cohesive soils). Based on the transcribed values and engineering judgment some values has been chosen for the μ coefficient of different sub layers. Table 3.

Table 3. The selected values for the 3D dimensional correction factor of different layers.

Layer	Depth (m)	Thickness (m)	Description	μ
1	0~2	2	Very Soft	1.0
2	2~12	10	Soft	0.9
3	12~23	11	Medium	0.85
4	23~38	15	Stiff	0.75
5	38~48	10	Very Stiff to Hard	0.6
6	48~100	52	Hard	0.5
7	100~200	100	Hard	0.4

For calculation of the tank settlement, because the proposed formula in literature Eq.1 is for rectangular loading area, the circular loading area transformed to the equivalent square and calculations are done for the later area. Eq.4 shows the relationship between tank diameter (D) and equivalent square (B).

$$B = \frac{\sqrt{\pi}}{2} D = 0.89D \qquad (4)$$

Because of the axial symmetry of the problem, the subsoil layers are modeled two dimensionally. Because of the importance the study, it has been tried to use very small element (compared to the geometry of the problem) in calculations. The computational mesh consists of elements with 0.5 m width and 0.2 m height. The computational mesh extends 4 times of equivalent width beneath the loading area and 2 times of equivalent width over the edge of loading area in horizontal direction (figure2).

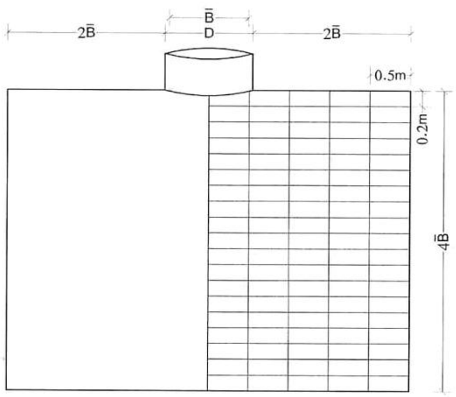


Figure 2. the used computational mesh to calculate the settlement beneath the tanks.

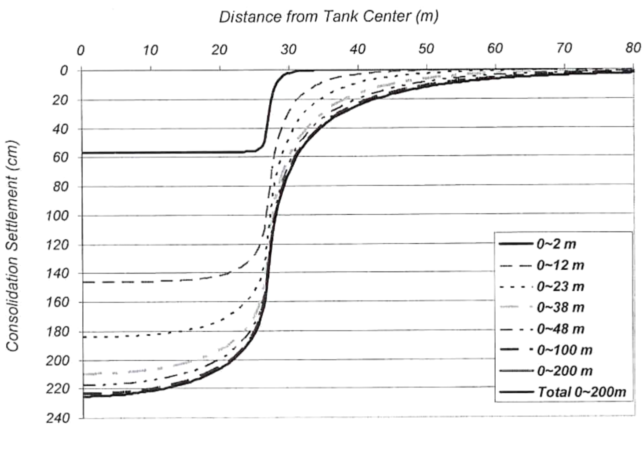


Figure 3. Cumulative consolidation settlement of different layers beneath the 60.0 m diameter tanks(Without considering 3D effects).

The calculated settlement beneath the tanks in tank farm area for different layer and also total settlement without considering coefficient of correction is presented in figure 3. Figure 4 shows settlement graphs in cumulative form with considering 3D effects.

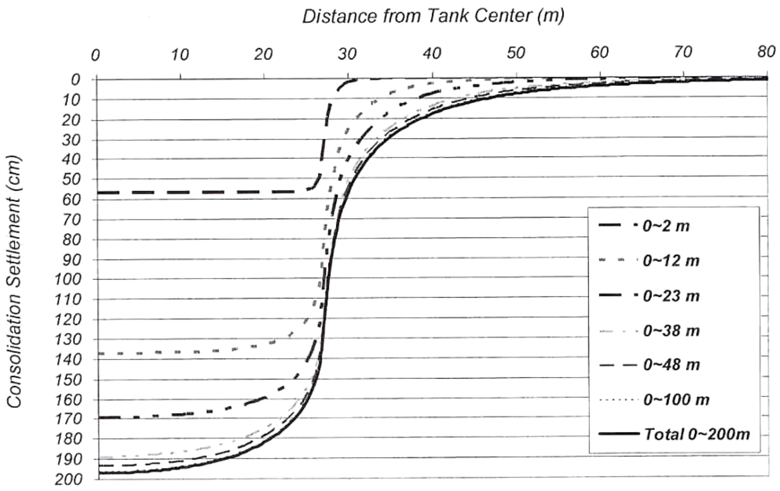


Figure 4. Cumulative consolidation settlement of different layers beneath the 60.0 m diameter tanks (Considering 3D effects).

2.2 FEM Model

2.2.1 Utilized Software

Three-dimensional steel storage tank subjected to uneven settlements has been analyzed by using ABAQUS, a commercially available finite element program, and the settlement was coded in FOTRAN. ABAQUS is a general purpose finite-element analysis program developed by Hibbitt, Karlsson & Sorenson, Inc. (HKS, 1998 and 2000). It includes three core products: ABAQUS/Standard, ABAQUS/Explicit, and ABAQUS/CAE. ABAQUS/Standard was used to perform three-dimensional simulation of uneven settlement on the steel storage tank behavior.

2.2.2 Geometry Of Tank And Material Definition

Having considered the ratio of thickness to radius of the tank, quadrilateral shell elements with four nodes (S4) were used to model the cylinder and most of bottom and top shell, while for some parts of roof and bottom especially for the center of them triangular elements (S3R) were used. Top angle was modeled by beam elements (B31OS) and soil was modeled by spring elements (spring1) that could only tolerate pressure and could not stand tension. The kinematic behavior of steel was used in this investigation. Top angle steel is ST_37; annular plate (annular plate is the part of bottom plate that is placed below the shell and usually has more thickness or is made of stiffener steel), in this project it is made of stiffener steel, And is made of A 516M (A516) and material of the other parts of the tank is A 283M (A283). The diameter to height ratio of the tank is of order 4, and the slenderness ratio (radius to thickness) of the tank is order of 1000 (for the first course) to 3750 (for the last course). And Bottom plate has 10mm thickness.

Table 4. The carbon steel is used in the steel tank.

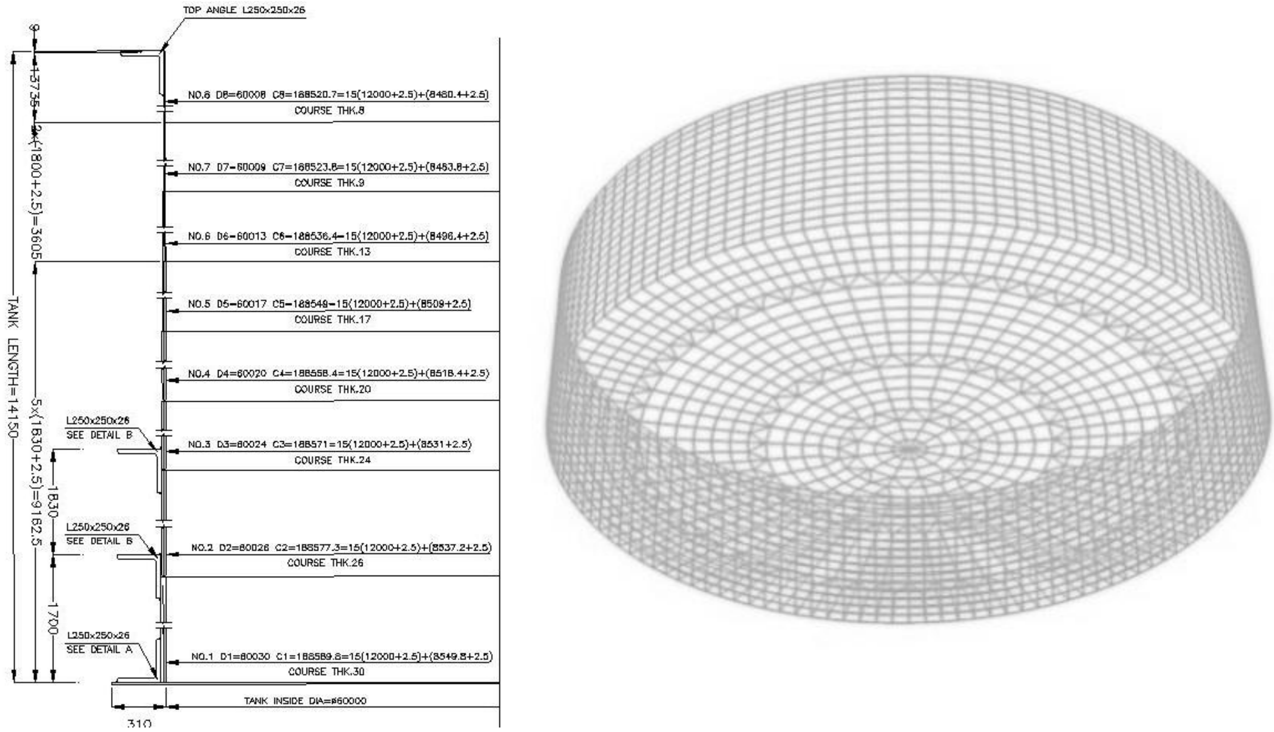
Steel	F_y (MPa)	$allowable\ stress$ (MPa)	ε_y	E_s (MPa)	E_p (MPa)
ST_37	240	144	0.0011	2.1×10^5	1.05×10^3
A 283M(A283)	205	123	0.00097	2.1×10^5	1.05×10^3
A 516M(A516)	220	132	0.001	2.1×10^5	1.05×10^3

F_y = yield stress

ε_y = yield strain

E_s = elastic modules of steel

E_p = plastic modules of steel



(a) (b)

Figure 5. (a) The shell of the steel storage tank, (b) the symmetric mesh of bottom and shell of the steel tank.

2.2.3 Process of Loading

Three successive steps for applying load was considered, in the first step the load of the weight of steel tank was considered, in the second step the pressure of water was applied and in the last step the settlement effect was coded.

2.3 The Effect of Uneven Settlement on The Steel Storage Tank

Maximum acceptable settlement due to maximum-in plane stress was 384mm and the maximum stress occurs at the base of shell. The other noticeable criteria in this project is: the maximum strain must be less than .006 in the shell that is 6.08e-4 in 368mm settlement, the horizontal displacement of the tank must be less than .0016 of the diameter of the tank which is equal to 96mm.

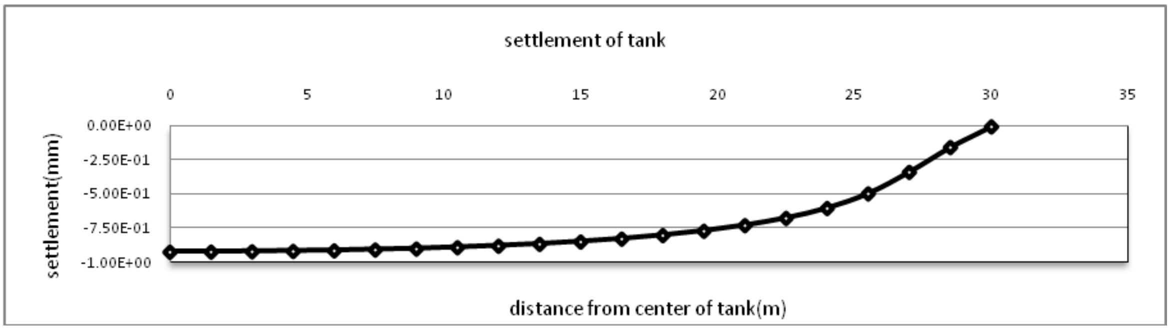


Figure 6. Calculated differential settlement in the tank area (consolidation settlement).

Δ_{max} = 1.96 meter that means the uniform settlement of tank is about 1.04 meter.

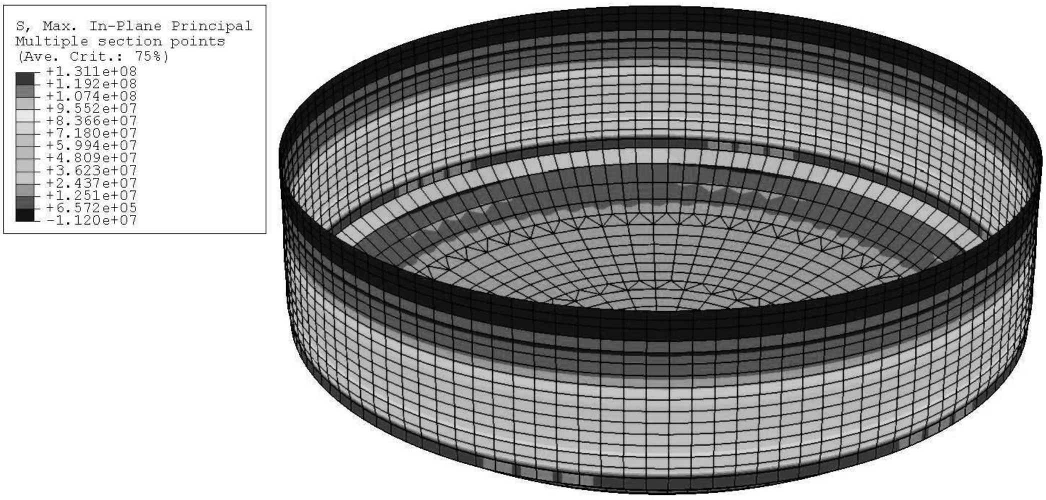


Figure 7. Tank bowl-shaped settlement.

This contour shows that maximum stress happens at the base of shell and the stress reduces in the height of shell.

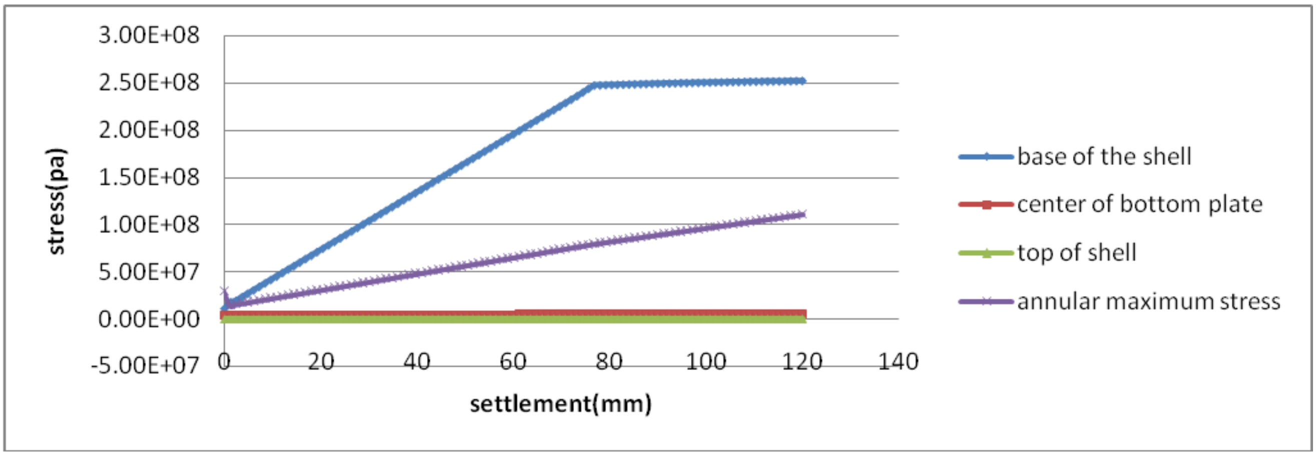


Figure 8. Stress of tank versus bowl-shaped settlement.

The curves show that the slope of base of shell suddenly reduces after 771mm settlement, because the stress is more than the yield stress of the steel. The numerical results dictate that the bowel-shaped settlement has more effect on the base of shell than the other part of steel tank. Concluding, the acceptance criterion of this type of settlement is stress in the base of shell. Figure 9 shows the horizontal displacement of the top of shell decreases when the settlement of tank increases.

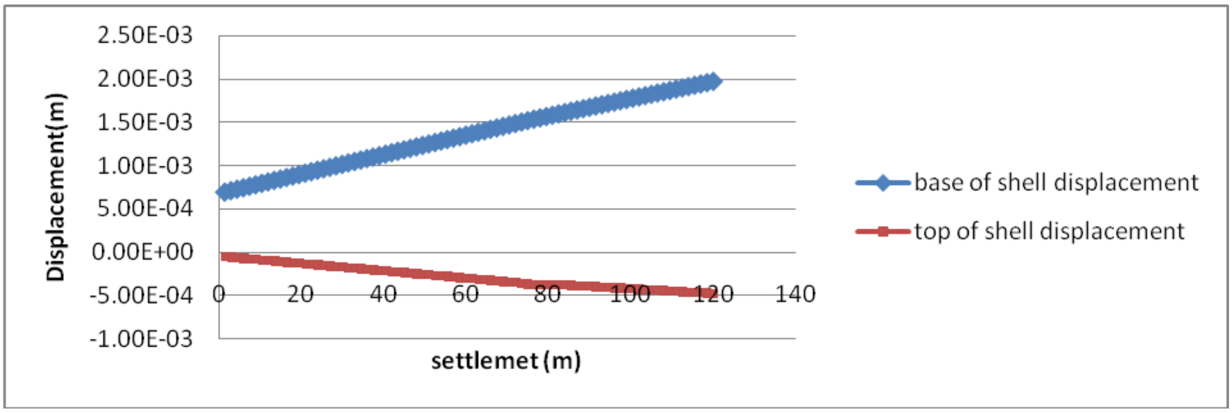


Figure 9. Shell displacement versus bowl-shaped settlement.

3 Analysed Data from Site Monitoring

As it mentioned, the tank had been gradually filled with water for preloading, during this process all deformations in base and shell of the tank had been monitored daily to avoid from any disruptive deformations. In this section the settlement of the base when the tank was filled, presents in figure 10. Figure 11 presents the nodes of base which the settlement monitored.

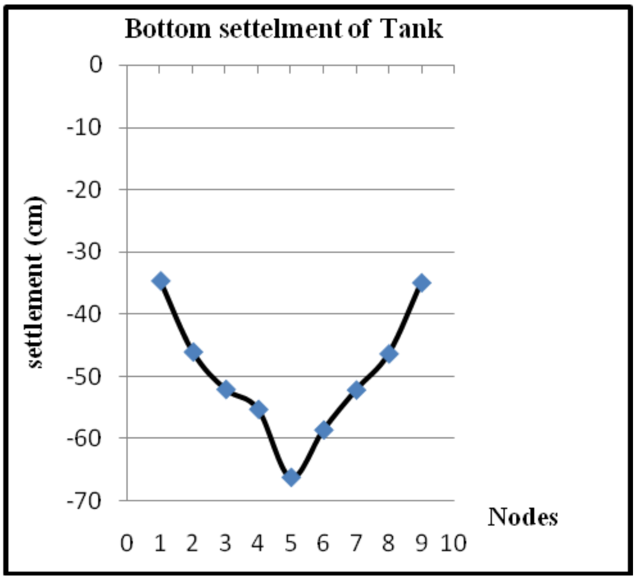


Figure10. Settlement of base node when the tank was filled.

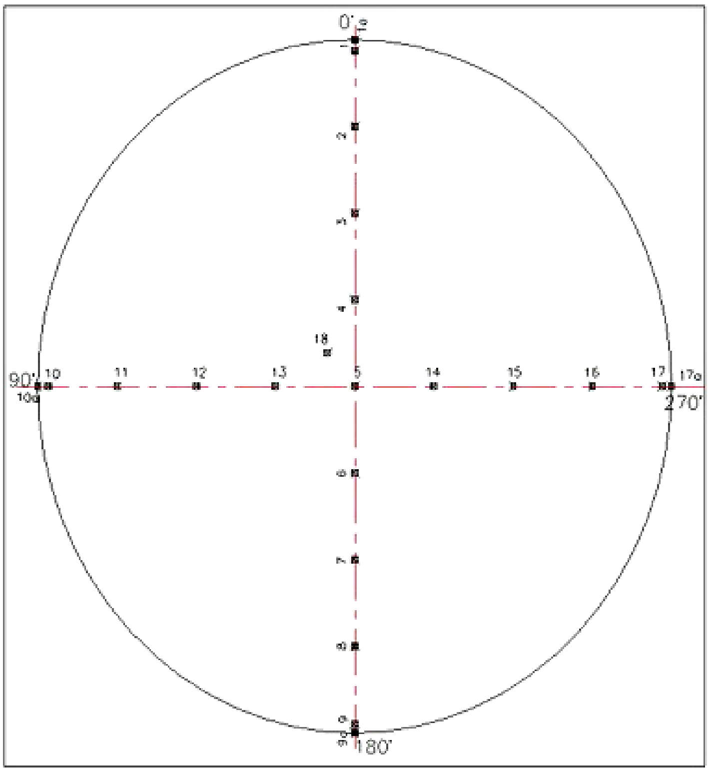


Figure 11. Nodes of the base.

4 Conclusion

All design and site monitoring present that preloading with water is done successfully. Settlement which was measured in site is matched to the design and FEM model. Moreover, final monitoring of base and shell tank shows that final settlement and differential settlement did not damage tank elements and tank is prepared to get in service. So, this paper presents that preloading with water can be used instead of other soil improvement methods for fine soli in tank farms, to reduce construction time and project expenses.

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