

Comparative Analysis of Soil Geometry and Preloading Effects on Soil-Structure Interaction in Cylindrical Tanks

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ABSTRACT

This study examines the impact of preloading on the settlement and stress resultants of cylindrical storage tanks situated on weak soils. The research uses advanced numerical modeling with PLAXIS 3D to explore various soil geometries and preloading values to find their influence on the settlement and structural behavior of the tank. The findings indicate that preloading significantly reduces both the magnitude and differential settlement, thereby enhancing the stability of the tank structure. Specifically, when the intensity of preloading reaches 1.5 times the design loads, the maximum settlement decreases drastically to reach only one-ninth of its original value for the study cases under consideration. The study also compares the effectiveness of preloading with other settlement mitigation techniques, such as stone columns, demonstrating the superior performance of preloading. This study underscores the critical role of preloading as an effective ground improvement technique, offering valuable solutions for mitigating the settlement of circular tanks situated in weak soils to ensure their safety and durability.

KEYWORDS: cylindrical tanks, settlement, soil-structure interaction, PLAXIS 3D, preloading, geotechnical engineering.

1. INTRODUCTION

The settlement of cylindrical storage tanks founded on weak soils is a significant concern in geotechnical engineering, especially in regions with challenging soil conditions. Excessive settlement can lead to structural instability, operational issues, and increased maintenance costs. Therefore, addressing these challenges is crucial for ensuring the safety, durability, and performance of storage tanks. Various techniques have been employed to mitigate settlement in cylindrical storage tanks, including stone columns [1-9] and encased stone columns [10-17]. While these methods have proven effective, there is a growing interest in exploring soil preloading as an innovative strategy to further enhance settlement mitigation [18-27]. Soil preloading involves applying a temporary load to the soil before construction to accelerate soil consolidation and increase soil stiffness, ultimately reducing post-construction settlement. Advanced numerical modeling techniques, such as those implemented in PLAXIS 2D/3D, offer powerful tools for analyzing the behavior of tank-soil systems under various loading conditions. These techniques enable engineers to simulate complex soil-structure interactions and evaluate the performance of different settlement mitigation strategies with high precision.

This study aims to investigate the effectiveness of soil preloading as a settlement mitigation technique for cylindrical storage tanks founded on weak soils. Utilizing advanced

numerical modeling with PLAXIS 2D/3D, the research focuses on the impact of preloading on soil consolidation and settlement reduction. The study provides critical insights into the behavior of tank-soil systems, offering valuable recommendations for optimizing preloading strategies to enhance structural stability and performance.

2. NUMERICAL MODEL

The numerical model of the cylindrical storage tank was developed using PLAXIS 3D, which accurately represents the real structure, as shown in Fig. 1.

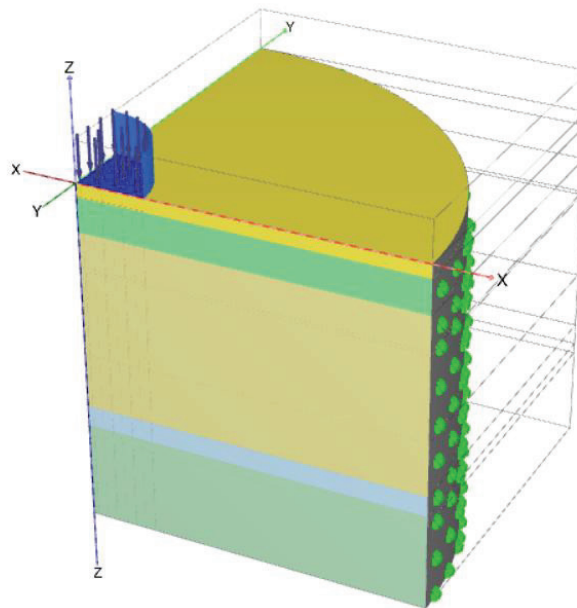


Fig.1: PLAXIS 3D Numerical Model.

2.1. Tank Geometry and Material Properties

The storage tank was modeled as a perfect cylinder with a diameter of 20 meters, a height of 6 meters, a wall thickness of 0.3 meters, and a base thickness of 0.5 meters. The material properties assigned to the tank included a Young's modulus of 2.2×10^7 kN/m², a Poisson's ratio of 0.2, and a unit weight of 25 kN/m³; typical concrete properties are shown in **Error! Reference source not found.** The weak soil profile underlying the tank was defined according to site-specific geotechnical data from the western part of Port Said [29,30], a common practice that involves replacing approximately two meters of the surface soil with a stiff mixture of gravel and sand to improve load-bearing capacity and overall soil stability [28]. The soil profile was divided into a replacement layer and five additional layers, as shown in **Error! Reference source not found.** The first layer, which consists of gravel and sand, extends from 0.00 to 2.00 meters deep. It has a friction angle of 30°, a Young's modulus of 100,000 kN/m², a unit weight of 20.81 kN/m³, a Poisson's ratio of 0.3, and an initial void ratio of 0.50. The second layer, which consists of very soft silty clay, extends from 2.00 to 7.00 meters deep. This layer has a cohesion of 20 kPa, a friction angle of 0°, a Young's modulus of 2,000 kN/m², a unit weight of 16 kN/m³, a Poisson's ratio of 0.4, an initial void ratio of 1.55, an over-consolidation ratio (OCR) of 1.4, a compression index (Cc) of 0.65, and a recompression index (Cr) of 0.15.

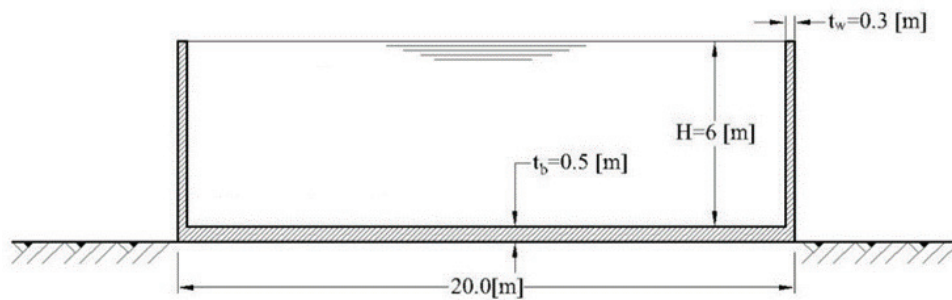


Fig.24: Soil Properties and Modeling.

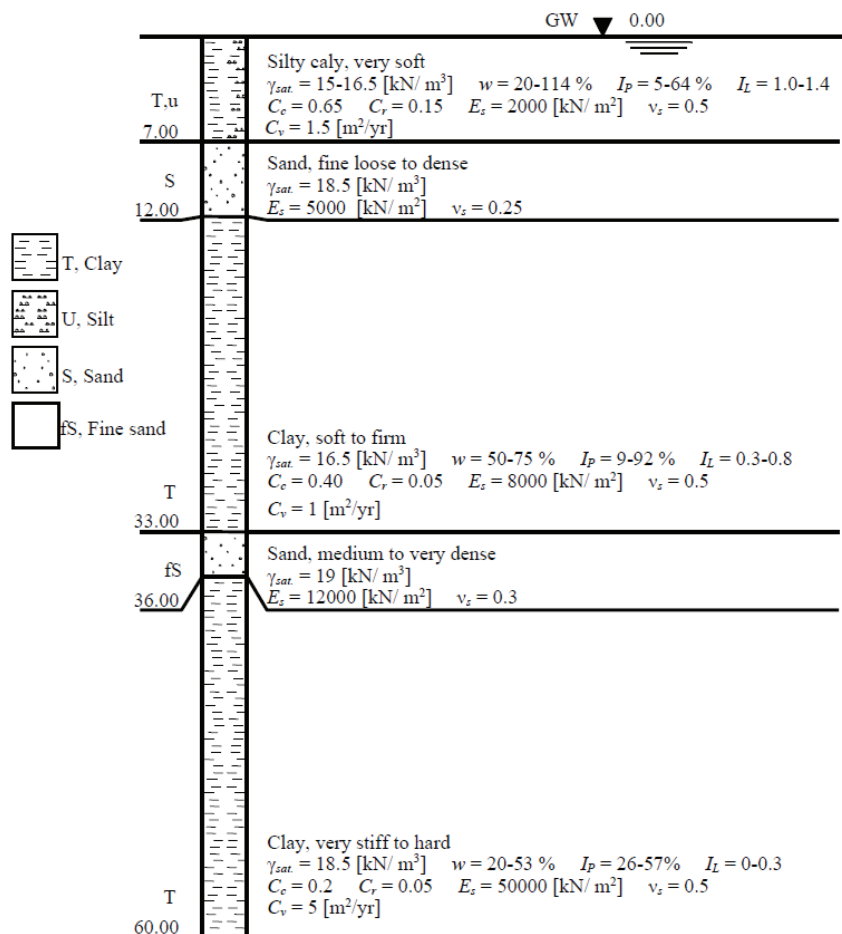


Fig.3: Typical soil properties for Port-Said West [31,32]..

The third layer, which consists of fine, loose to dense sand, extends from 7.00 to 12.00 meters deep. It has a friction angle of 30°, a Young's modulus of 5,000 kN/m², a unit weight of 19 kN/m³, a Poisson's ratio of 0.35, and an initial void ratio of 0.50. The fourth layer, which consists of soft to firm clay, extends from 12.00 to 33.00 meters deep. This layer has a cohesion of 20 kPa, a friction angle of 0°, a Young's modulus of 8,000 kN/m², a unit weight of 16 kN/m³, a Poisson's ratio of 0.4, an initial void ratio of 1.10, an OCR of 1.0, a compression index (C_c) of 0.40, and a recompression index (C_r) of 0.05. The fifth layer, which consists of medium to very dense sand, extends from 33.00 to 36.00 meters deep. It has a friction angle of 30°, a Young's modulus of 12,000 kN/m², a unit weight of 19 kN/m³, a Poisson's ratio of 0.35, and an

initial void ratio of 0.50. The sixth layer, which consists of very stiff to hard clay, extends from 36.00 to 60.00 meters' depth. This layer has a cohesion of 20 kPa, a friction angle of 0° , a Young's modulus of 50,000 kN/m², a unit weight of 20 kN/m³, a Poisson's ratio of 0.3, an initial void ratio of 0.72, an OCR of 1.0, a compression index (C_c) of 0.20, and a recompression index (C_r) of 0.05. The permeability coefficient for the first, third, and fifth layers is taken as $0.0202 \times 10^{-3} \text{ m/day}$. For the second, fourth, and sixth layers, the permeability is calculated from the coefficient of consolidation (C_v) using the relationship $C_v = \frac{k}{\gamma_w m_v}$. The coefficients of permeability k_v are 0.0074, 0.0013, and 0.0010 m/year for layers 2, 4, and 6, respectively. These layers are modeled using a combination of Mohr-Coulomb soil model and Hardening Soil Model. Mohr-Coulomb model is used for the gravel, sand, and medium to very dense sand layers, while Hardening Soil Model with undrained (B) conditions is used for the silty clay, soft to firm clay, and very stiff to hard clay layers. The finite element mesh is carefully generated to ensure fine meshing in critical areas (such as the tank base and the upper soil layers) to achieve accurate results while maintaining computational efficiency.

2.2. Boundary Conditions and Loading

Boundary conditions are set to reflect realistic constraints [33]. The bottom boundary is fixed in all directions to represent bedrock, while the vertical boundaries are fixed horizontally but allowed to move vertically to simulate natural soil behavior. This setup prevents lateral movement at the sides while allowing soil settlement or heave as necessary. Loading conditions include the self-weight of the tank and stored material, modeled as a uniformly distributed load on the tank base. The load is applied gradually in stages to simulate the construction process and ensure stability at each step. Additionally, the effects of preloading were modeled by applying a surcharge load over the tank area and removing it after a specified consolidation period to simulate the reduction in settlement due to preloading.

2.3. Mesh Density and Groundwater Table

The finite element mesh is set to medium density to ensure adequate detail in critical areas (the tank base and the upper soil layers) while maintaining computational efficiency. The groundwater conditions are modeled with the groundwater table set at the ground surface, reflecting the high-water table conditions typical of the western part of Port Said.

3. SENSITIVITY ANALYSIS

The soil volume plays an integral role in the accuracy of the results, as the bigger the soil volume of the model, the higher the accuracy. However, it produces more nodes and elements and consumes more time to run the analysis, so it is important to figure out the suitable soil width and the depth of the soil to ensure acceptable accuracy and time consumption for analysis. In this section, we study the effect of width and depth of soil geometry on the soil-structure interaction of the cylindrical tank.

3.1. Soil Width/Tank Diameter Ratio (b_s/D)

This section investigates the suitable soil width/tank diameter ratio (b_s/D) for the model to ensure accurate settlement and internal forces for the cylindrical tank.

3.1.1. Base Center Settlement S_c

Error! Reference source not found.4. shows the variation of settlement at the base center with b_s/D ratio. The settlement at the base center increases considerably as the soil width gets bigger. The percentage increase ranges from 74.59% to 100% for the b_s/D ratio varying from 2 to 7, respectively. When b_s/D is greater than 5, the settlement of the tank center is hardly affected by further changes in the b_s/D ratio.

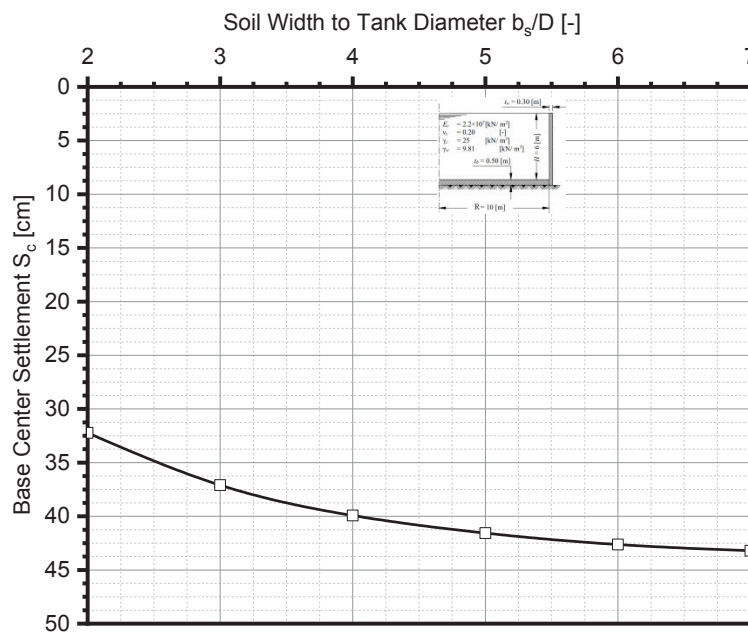


Fig. 4: Effect of variation b_s/D on base center settlement.

3.1.2. Radial Moment Across the Base M_{base}

The maximum radial moment across the base increases by 79.66%, 91.55%, 96.72%, 100%, 99.70%, and 100% of the tank base radial moment for b_s/D values of 2, 3, 4, 5, 6 and 7, respectively, as shown in **Error! Reference source not found.**5. At a value of $b_s/D > 4$, the maximum radial moment across the base appears to have no significant effect. In the same manner, the minimum radial moment across the base increases by 90.12%, 96.02%, 97.25%, 99.93%, 99.18%, and 100% of the tank base radial moment for b_s/D values of 2, 3, 4, 5, 6 and 7, respectively, as shown in **Error! Reference source not found.** At a value of $b_s/D > 4$, the minimum radial moment across the base appears to have no significant effect. As shown in Figs. 5 and 6, the radial moments exhibit minimal sensitivity to variations in the b_s/D ratio after it surpasses the value of 5.

3.1.3. The Meridional Moment in the Wall M_s

The maximum meridional moment in the wall increases by 99.91%, 100%, 100%, 99.91%, 99.91%, and 100% for b_s/D values of 2, 3, 4, 5, 6 and 7, respectively, as shown in **Error! Reference source not found.** At all values, the maximum meridional moment in the wall appears to have no significant effect. The minimum meridional moment in the wall increases by 88.53%, 95.70%, 98.44%, 100%, 99.61%, and 99.61% for b_s/D values of 2, 3, 4, 5, 6 and 7, respectively, as shown in **Error! Reference source not found.** At a value of $b_s/D \geq 2$, the minimum meridional moment in the wall has no significant effect. The suitable

b_s/D seems to be five, given an acceptable accuracy for settlement and all internal forces in the tank.

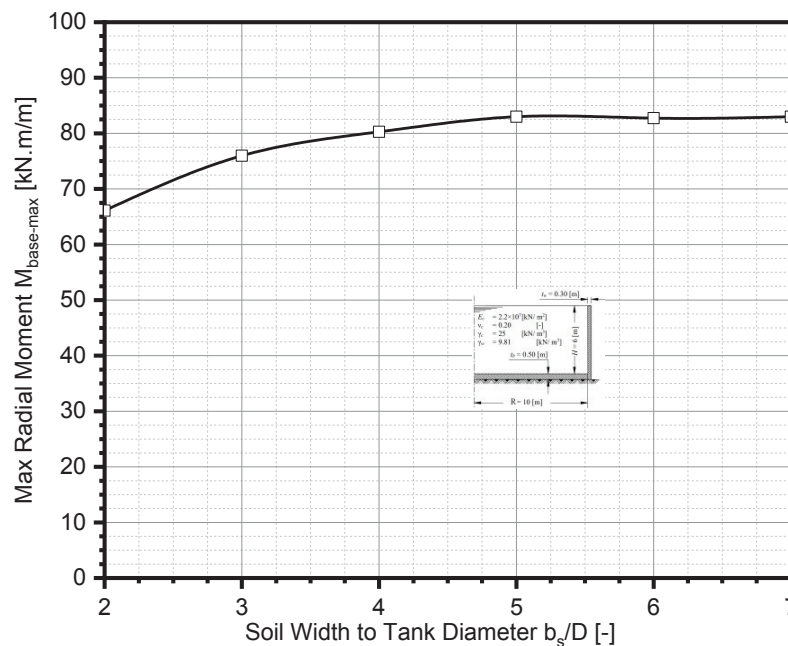


Fig.5: Effect of variation b_s/D on Max radial moment.

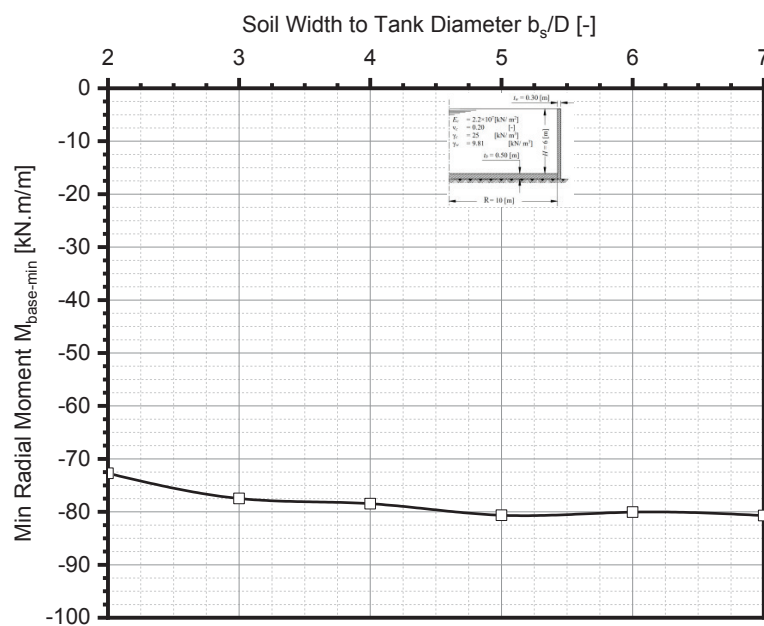


Fig.6: Effect of variation b_s/D on Min radial moment.

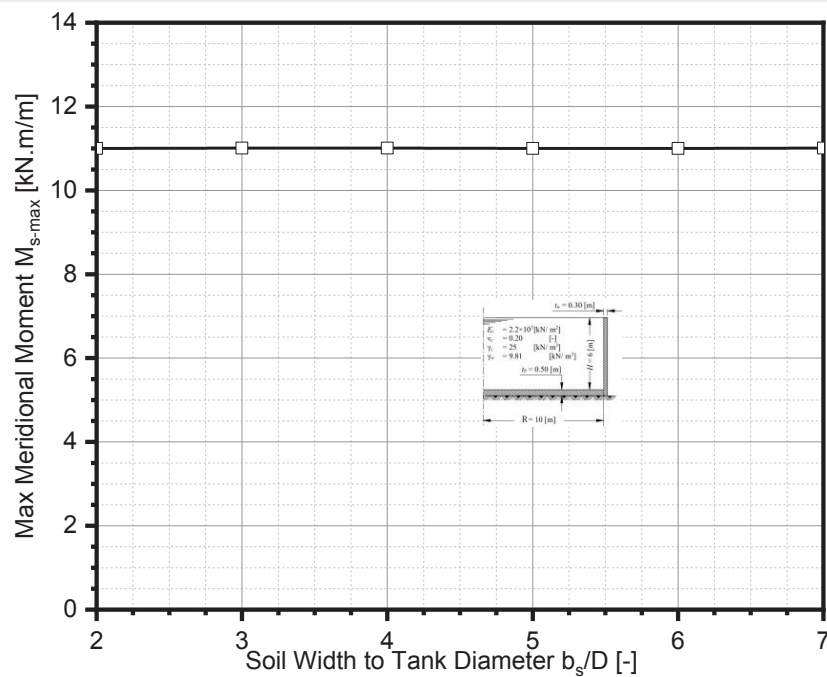


Fig.7: Effect of variation b_s/D on Max meridional moment.

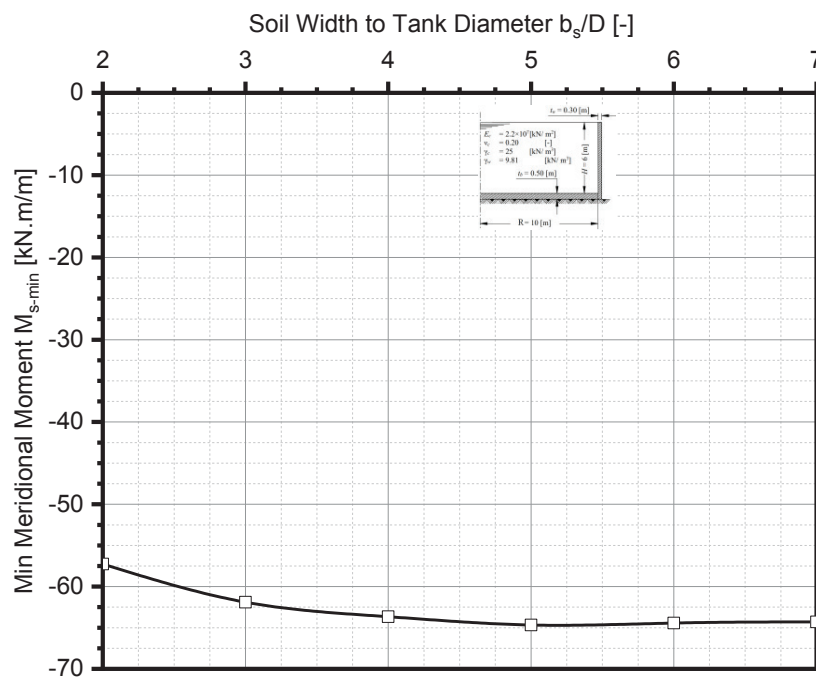


Fig. 8: Effect of variation b_s/D on Min meridional moment.

3.2. The Depth of the Soil Model

This section investigates the suitable soil depth/radius ratio for the model to provide suitable accuracy on settlement and internal forces of the structure.

3.2.1. Settlement at the Base Center S_c

Error! Reference source not found. shows the settlement under the center of the base increases by 42.54%, 74.74%, 89.27%, 95.98%, 98.30%, 99.31%, and 100% for D_s/R values of 1, 2, 3, 4, 5, 6 and 7, respectively. At a value of $D_s/R \geq 5$, the base center settlement appears to have no significant effect.

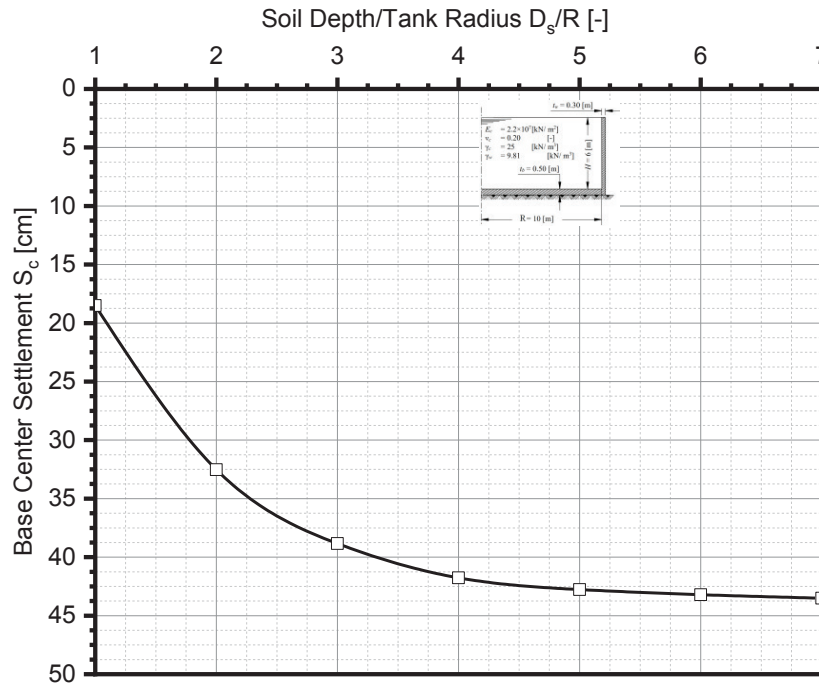


Fig. 9: Effect of variation D_s/R on base center settlement.

3.2.2. Radial Moment Across the Base M_{base}

The maximum radial moment across the base increases by 84.92%, 95.52%, 100%, 98.34%, 94.08%, 97.90%, and 96.96% for D_s/R values of 1, 2, 3, 4, 5, 6 and 7, respectively, as shown in **Error! Reference source not found.** At a value of $D_s/R \geq 2$, the maximum radial moment across the base appears to have no significant effect. The minimum radial moment across the base increases by 79.15%, 100%, 94.95%, 89.56%, 94.09%, 86.58%, and 79.68% for D_s/R values of 1, 2, 3, 4, 5, 6 and 7, respectively, as shown in **Error! Reference source not found.** At the value of $D_s/R \geq 2$, the minimum radial moment across the base appears to have no significant effect.

3.2.3. The Meridional Moment in the Wall M_s

The maximum meridional moment in the wall increases by 98.19%, 100%, 98.97%, 93.02%, 95.43%, 94.83%, and 92.59% for D_s/R values of 1, 2, 3, 4, 5, 6 and 7, respectively, as shown in **Error! Reference source not found.** At all values, the maximum meridional moment in the wall appears to have no significant effect. The minimum meridional moment in the wall increases by 92.70%, 100%, 93.24%, 81.97%, 82.01%, 79.14%, and 78.10% for D_s/R values of 1, 2, 3, 4, 5, 6 and 7, respectively, as shown in **Error! Reference source not found.** At a value of $D_s/R \geq 3$, the minimum meridional moment in the wall has no significant effect.

The suitable D_s/R seems to be five, given an acceptable accuracy for settlement and all internal forces in the tank.

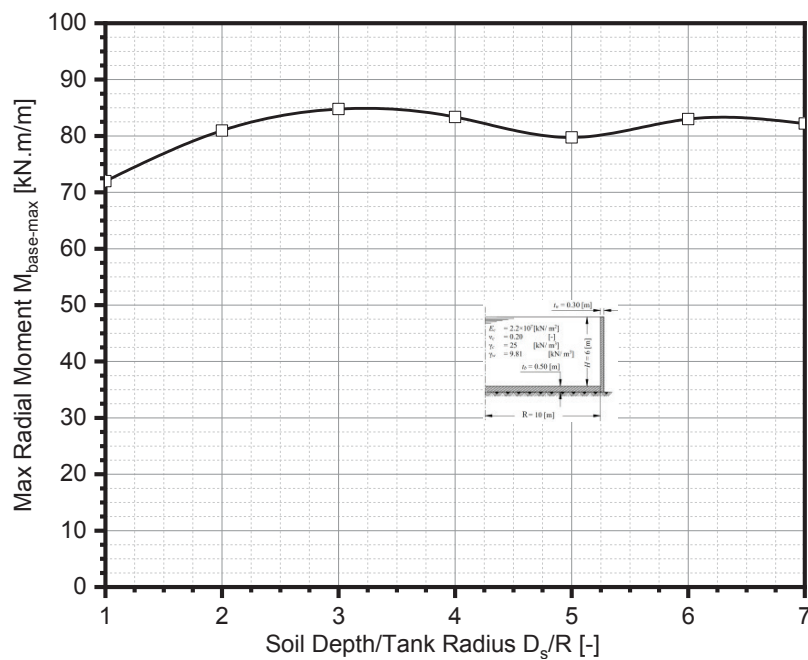


Fig. 10: Effect of variation D_s/R on Max radial moment.

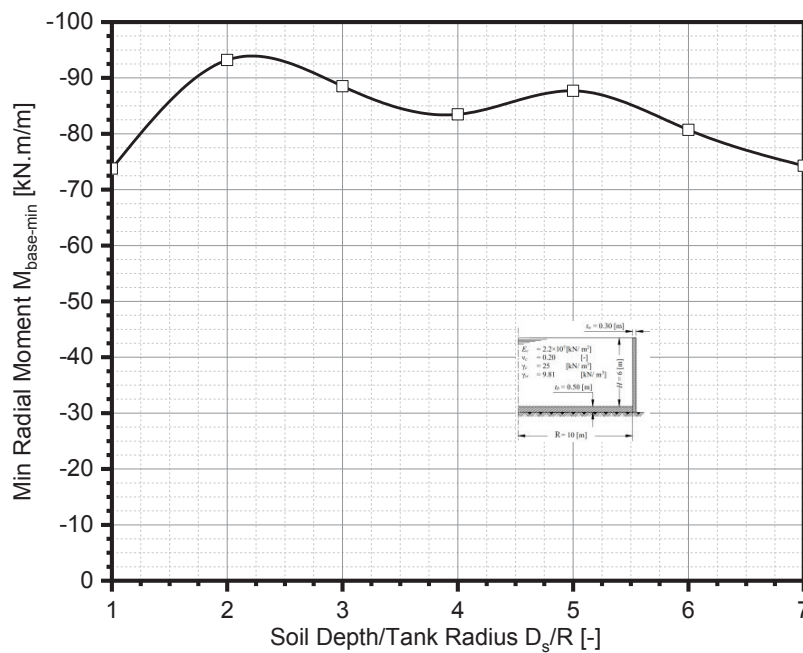


Fig. 11: Effect of variation D_s/R on Min radial moment.

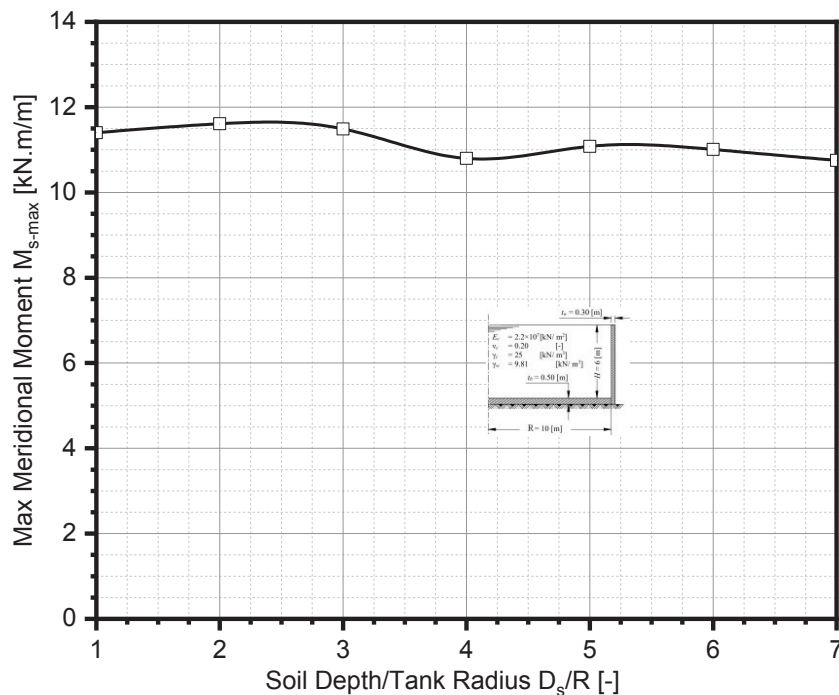


Fig. 12: Effect of variation D_s/R on Max meridional moment.

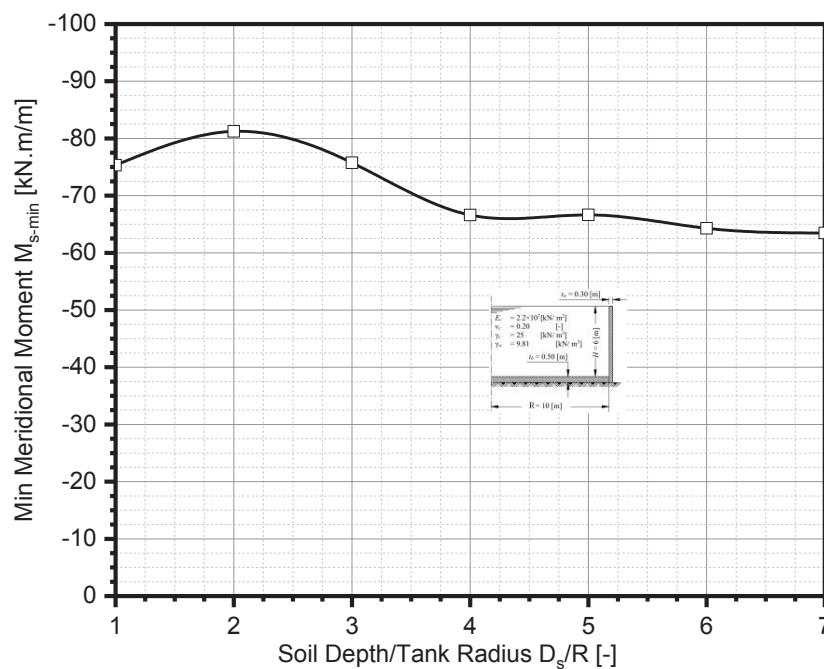


Fig. 13: Effect of variation D_s/R on Min meridional moment.

4. NUMERICAL ANALYSIS AND DISCUSSIONS

This section explores three primary techniques: preloading, stone column and encased stone column. By examining their impact on settlement and internal forces, and comparing

their effectiveness, this study aims to provide practical insights for optimizing the stability and performance of cylindrical storage tanks.

4.1. Effect of Soil Preloading

Preloading of soft clay is one of the most popular, effective, and economical methods used to increase the shear strength of soft soil and control its post-construction settlement [34]. This section investigates the effect duration and value of soil preloading to seek the maximum improvement of soil strength. The investigation of soil preloading value shall be divided into three loads (1x, 1.25x, 1.5x) where “x” is the tank's full total load for 30 days.

4.1.1. Soil Settlement Before Construction

Error! Reference source not found. shows the behavior of the soil settlement before construction for different values of soil preloading value of 30 days duration. It can be observed that the relationship is almost linear until the load reaches to the limit of 1.5 times. It noted that the settlement of the soil increases by 79.85%, 104.72%, and 139.33%, respectively, to the total settlement of the tank without the preloading process for values 1 time, 1.25 times, and 1.5 times of the total tank load as soil preloading, respectively.

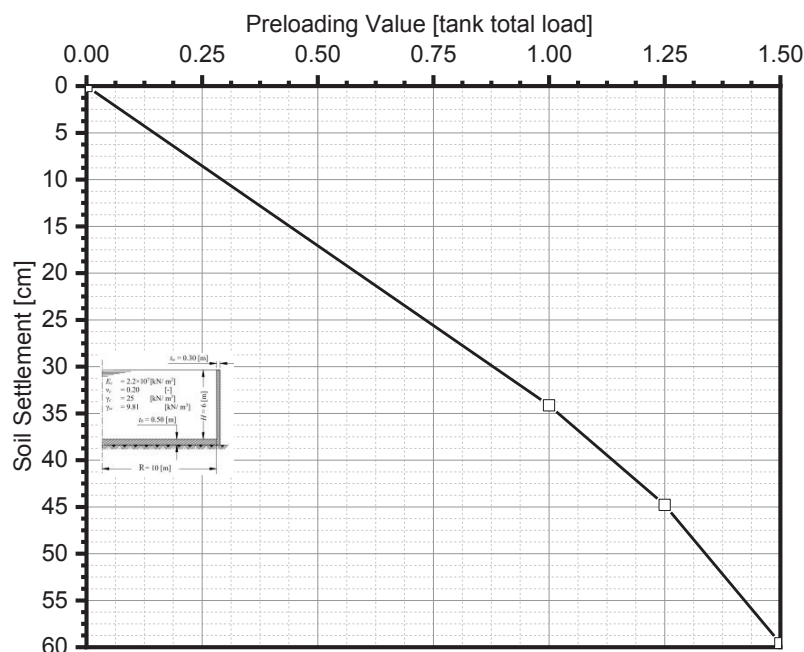


Fig. 14: Variation of settlements of soil (positive when downward) for different values of preloading.

4.1.2. Base Center Settlement S_c

Error! Reference source not found. presents the behavior of base center settlement under the effect of soil preloading value. It can be observed that the soil preloading value significantly affects the base center settlement of the tank until soil preloading is greater than 1.25 times the tank load. It does not have any significant effect. It noted that the total settlement under the center of the tank base decreases by 72.43%, 87.35%, and 88.71% for values 1 time, 1.25 times, and 1.5 times of the total tank load as soil preloading, respectively.

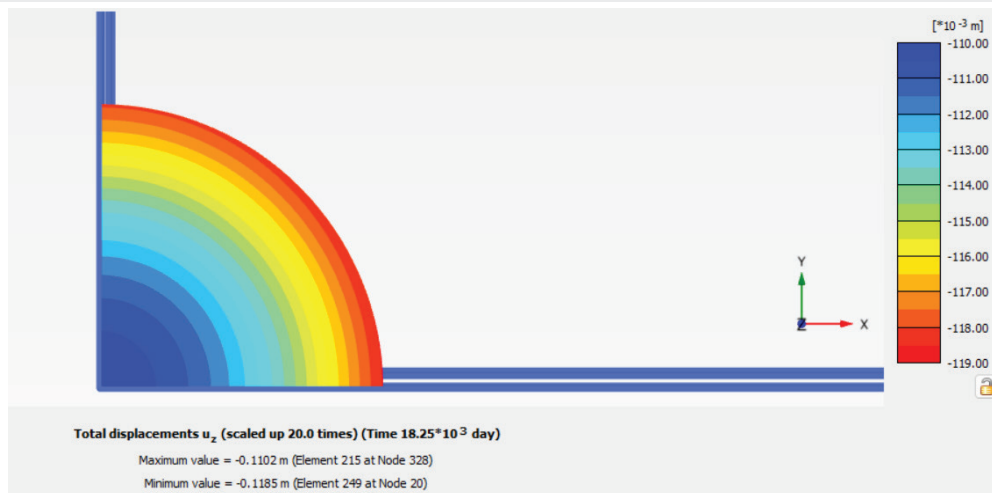


Fig. 15: PLAXIS 3D - base settlement under preloading equivalent to full tank load.

4.1.3. Radial Moment Across the Base M_{base}

The maximum radial moment across the base decreases to 56.11%, 87.71%, and 94.38% of the tank base radial moment without the preloading process for values 1 time, 1.25 times, and 1.5 times of the total tank load as soil preloading, respectively, as shown in **Error! Reference source not found.** The minimum radial moment across the base decreases to 66.62% and 99.48% and increases to 112.75% of the tank base radial moment without the preloading process for values 1 time, 1.25 times, and 1.5 times of the total tank load as soil preloading, respectively, as shown in Figs 17 & 18

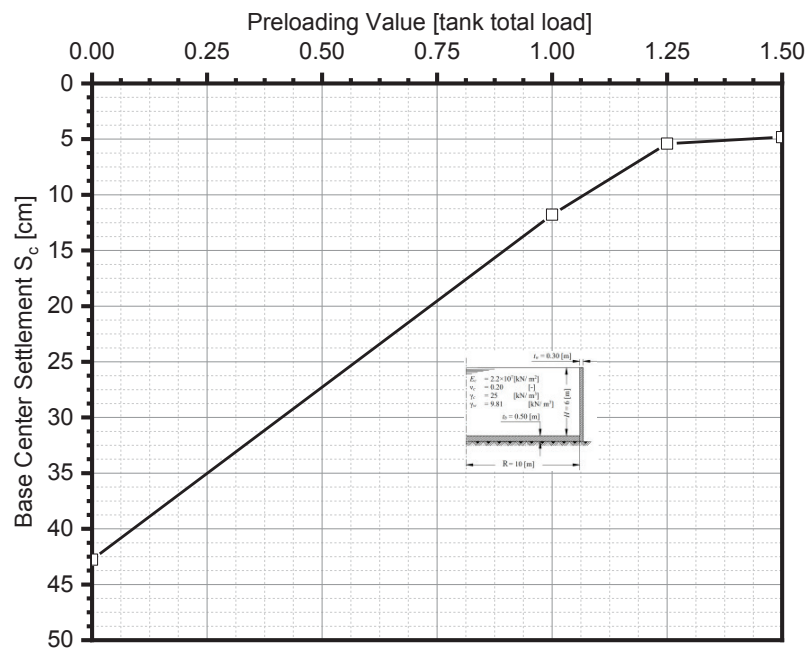


Fig. 16: Variation of center settlements in the base plate (positive when downward) for different values of preloading.

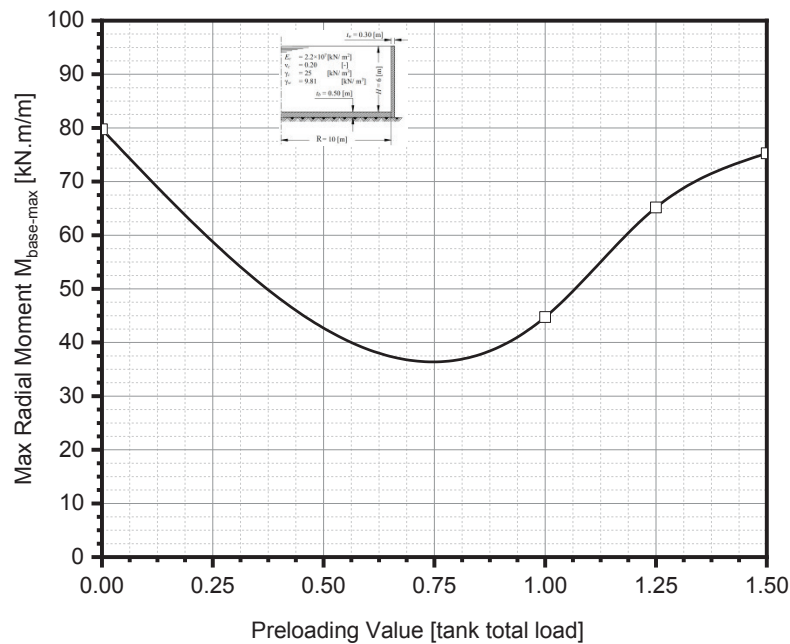


Fig. 17: Effect of variation preloading value on Max radial moment.

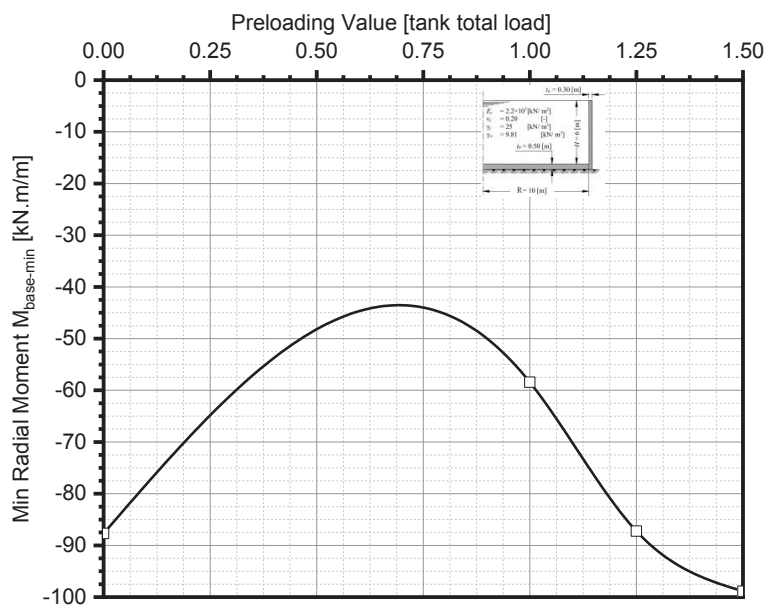


Fig. 18: Effect of variation preloading value on Min radial moment.

4.1.4. The Meridional Moment in the Wall M_s

The maximum meridional moment in the wall increases to 439.98%, 639.53%, and 715.88% of the tank wall meridional moment without the preloading process for values 1 time, 1.25 times, and 1.5 times of the total tank load as soil preloading, respectively, as shown in **Error! Reference source not found..** The minimum meridional moment in the wall decreases to 2.92%, 4.64%, and 5.39% of the tank wall meridional moment without the preloading process for values 1 time, 1.25 times, and 1.5 times of the total tank load as soil preloading, respectively, as shown in **Error! Reference source not found.**

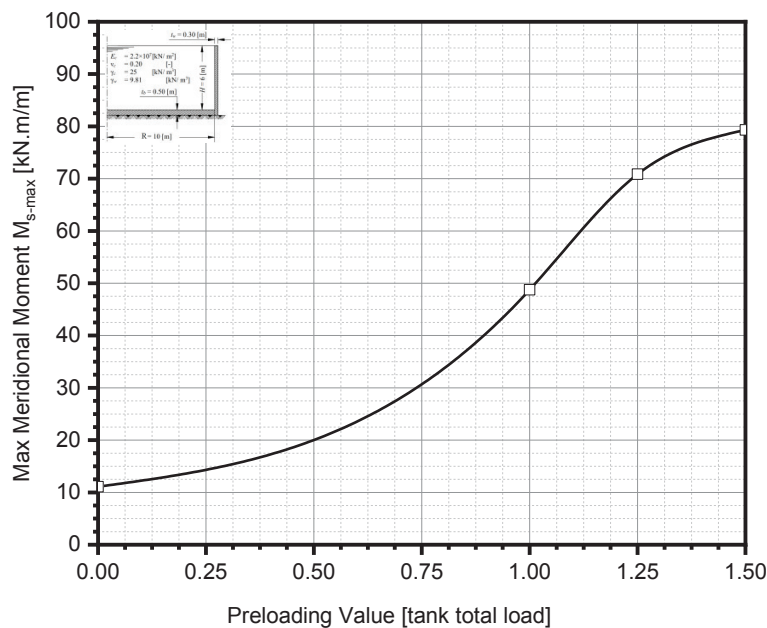


Fig. 19: Effect of variation preloading value on Max meridional moment.

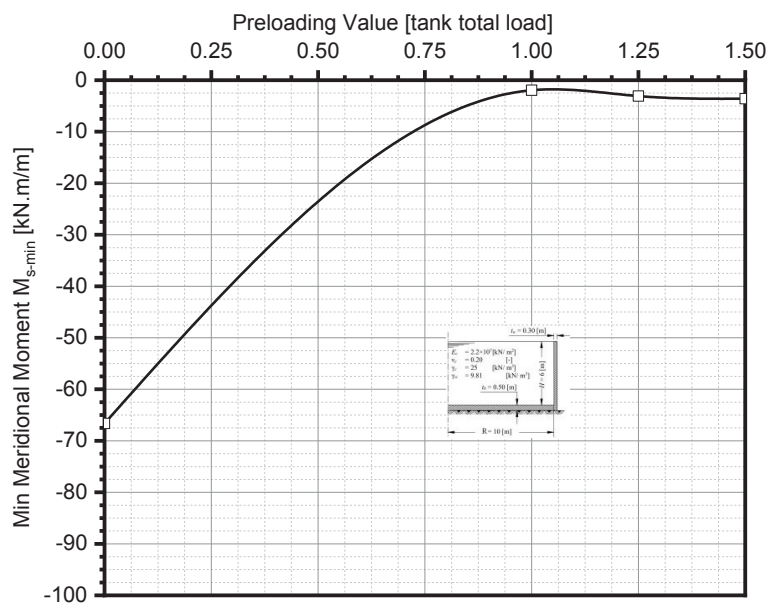


Fig. 20: Effect of variation preloading value on Min meridional moment.

4.1.5. Tangential Force in the Wall N_θ

The maximum tangential force in the wall increases to 198.81%, 226.99%, and 238.38% of the tank wall tangential force without the preloading process for values 1 time, 1.25 times, and 1.5 times of the total tank load as soil preloading, respectively, as shown in **Error! Reference source not found.** The minimum tangential force in the wall increases to 112.15%, 139.77%, and 166.01% of the tank wall tangential force without the preloading process for values 1 time, 1.25 times, and 1.5 times of the total tank load as soil preloading, respectively, as shown in Fig.22.

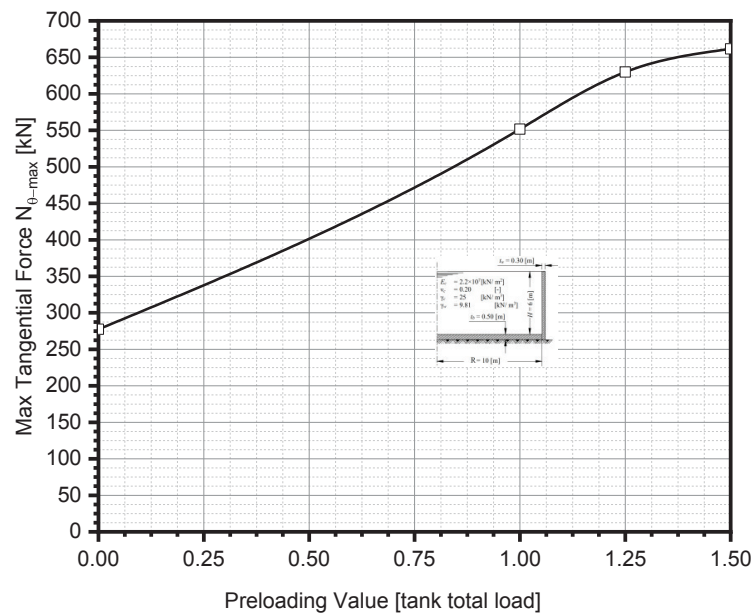


Fig. 21: Effect of variation preloading value on Max tangential force.

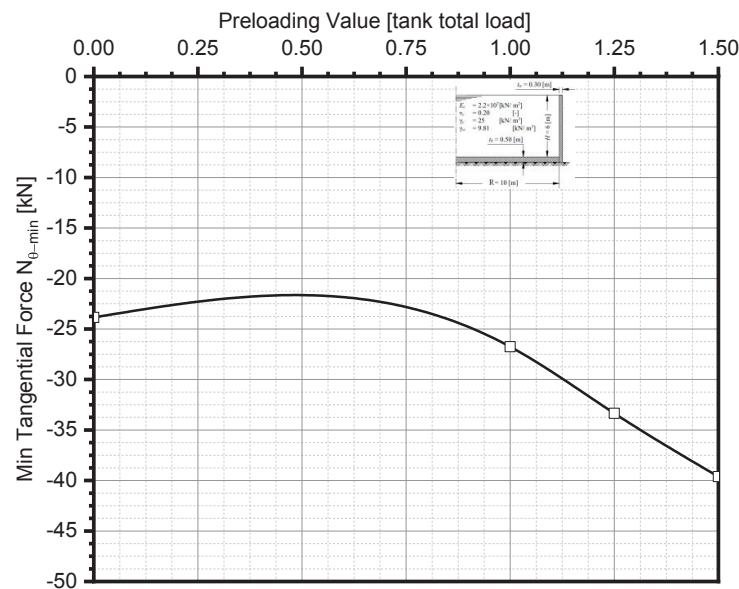


Fig. 22: Effect of variation preloading value on Min tangential force..

4.2. Alternative Settlement Mitigation Technique

The efficiency of two commonly used settlement mitigation techniques, which are stone columns and encased stone columns, are compared in a previous study [33]. **Error! Reference source not found.** presents the settlement-time responses over a 20-year period at the center of the circular base. The stone column techniques, both with and without encasement, are evaluated for a 1.5-meter diameter and 50-meter height stone column with the tank base on the ground surface. The settlement-time responses for both stone column techniques are similar, with slightly larger settlement without encasement due to lower stiffness. Most settlement occurs initially, with a significant consolidation rate in the first few years, followed by a drastic reduction with only about 3% of the final settlement occurring over the next 18 years.

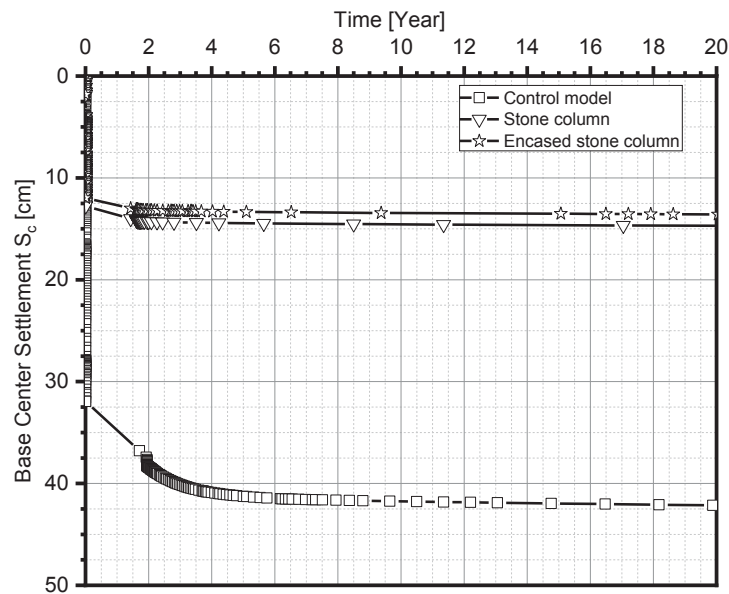


Fig. 23: Settlement response at the tank center for two different mitigation techniques [33].

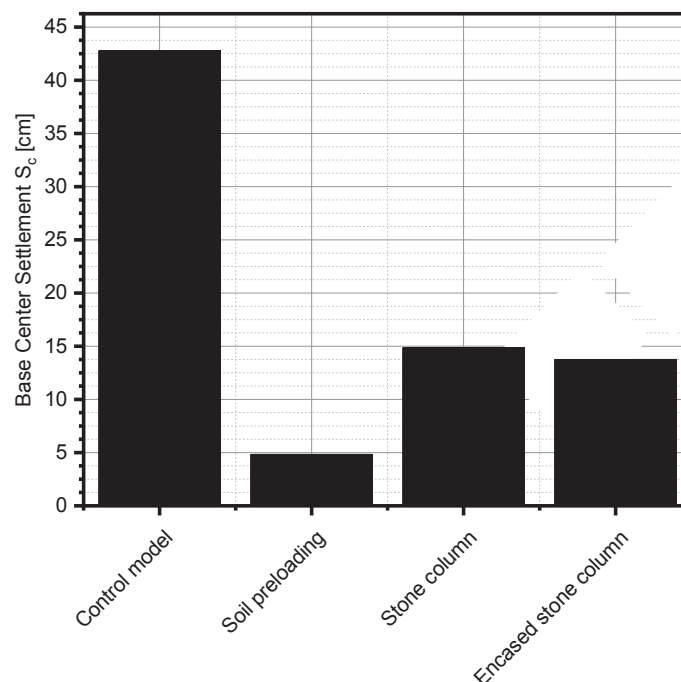


Fig. 24: Comparison of settlement mitigation techniques.

Error! Reference source not found. compares the effectiveness of different settlement mitigation techniques over a 20-year period, including the control model, soil preloading, stone columns, and encased stone columns. The control model, representing no mitigation, shows the highest settlement (approaching 45 cm) highlighting the significant issues that arise when no intervention is applied. Among the mitigation techniques, soil preloading emerges as the most effective as it reduces settlement to shorter than 10 cm. This method accelerates soil consolidation and enhances soil stiffness, providing substantial reductions in settlement.

Encased stone columns also reduce settlement to approximately 20 cm, benefiting from the added stiffness provided by the encasement. Regular stone columns show moderate effectiveness, reducing settlement to around 25 cm. Overall, the analysis underscores the superior performance of soil preloading in mitigating settlement, followed by encased stone columns as it is the least effective method among the methods studied.

5. CONCLUSIONS

To conclude, this study emphasizes the significance of soil-structure interaction in the settlement behavior and internal force distribution of cylindrical storage tanks. It was demonstrated that soil preloading is very effective in mitigating settlement of circular storage tanks and enhancing the stability of tanks founded on weak soils. Key conclusions from the study are:

1. Preloading significantly reduces both the magnitude and differential settlement along the tank base.
2. The study proves that preloading the soil with values between 1.25 and 1.5 times of the total tank load significantly reduces settlement. This finding is essential for refining preloading techniques to improve structural stability.
3. The soil width to tank diameter ratio (b_s/D) and soil depth to tank radius ratio (D_s/R) significantly influence settlement and internal forces. Ratios of b_s/D and D_s/R equal to 5 are found to be optimal for accurate modeling of the interaction between soil and circular reinforced concrete tanks.
4. Among the various settlement mitigation techniques examined, soil preloading emerged as the most effective as it reduces the initial settlement from 42 cm to less than 10 cm. Encased stone columns come next, as it reduce settlement to approximately 20 cm. Regular stone columns, on the other hand, minimize settlement to around 25 cm.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

- [1] Barksdale RD, Bachus RC. Design and construction of stone columns, vol. I. Turner-Fairbank Highway Research Center; 1983.
- [2] Pulko B, Majes B, Logar J. Geosynthetic-encased stone columns: Analytical calculation model. *Geotextiles and Geomembranes*. 2011;29(1):29-39.
Doi:10.1016/j.geotexmem.2010.06.005
- [3] Wang G. Consolidation of Soft Clay Foundations Reinforced by Stone Columns under Time-Dependent Loadings. *J Geotech Geoenviron Eng*. 2009 Dec;135(12):1922–31.
Doi:10.1061/(ASCE)GT.1943-5606.0000178
- [4] Dheerendra Babu MR, Nayak S, Shivashankar R. A Critical Review of Construction, Analysis and Behaviour of Stone Columns. *Geotech Geol Eng*. 2013 Feb;31(1):1–22.
Doi: 10.1007/s10706-012-9555-9

- [5] Deb K, Das AK. Distribution of Stress on Stone Column-Reinforced Soft Soil under Cylindrical Storage Tank. AMM. 2014 Jun 6;567:699–704. Doi:10.4028/www.scientific.net/AMM.567.699
- [6] Das AK, Deb K. Response of Cylindrical Storage Tank Foundation Resting on Tensionless Stone Column-Improved Soil. Int J Geomech. 2017 Jan;17(1):04016035. Doi: 10.1061/(ASCE)GM.1943-5622.0000697
- [7] Killeen MM, McCabe BA. Settlement performance of pad footings on soft clay supported by stone columns: A numerical study. Soils and Foundations. 2014 Aug;54(4):760–76. Doi:10.1016/j.sandf.2014.06.011
- [8] Zukri A, Nazir R. Numerical modelling techniques of soft soil improvement via stone columns: A brief review. IOP Conf Ser: Mater Sci Eng. 2018 Apr;342:012002. Doi:10.1088/1757-899X/342/1/012002
- [9] Muzammil SP, Varghese RM, Joseph J. Numerical Simulation of the Response of Geosynthetic Encased Stone Columns Under Oil Storage Tank. Int J of Geosynth and Ground Eng. 2018 Mar;4(1):4. Doi:10.1007/s40891-017-0122-6
- [10] Raithel M, Kempfert HG, Kirchner A. Geotextile-encased columns (GEC) for foundation of a dike on very soft soils. In: Proc., 7th Int. Conf. on Geosynthetics, Balkema, The Netherlands; 2002.
- [11] Gniel J, Bouazza A. Construction of geogrid encased stone columns: A new proposal based on laboratory testing. Geotextiles and Geomembranes. 2010 Feb;28(1):108–18. Doi:10.1016/j.geotexmem.2009.12.012
- [12] Yoo C. Performance of Geosynthetic-Encased Stone Columns in Embankment Construction: Numerical Investigation. J Geotech Geoenviron Eng. 2010 Aug;136(8):1148–60. Doi: 10.1061/(ASCE)GT.1943-5606.0000316
- [13] Gu M, Han J, Zhao M. Three-dimensional DEM analysis of single geogrid-encased stone columns under unconfined compression: a parametric study. Acta Geotech. 2017 Jun;12(3):559–72. Doi: 10.1007/s11440-017-0547-z
- [14] Zhang L, Xu Z, Zhou S. Vertical cyclic loading response of geosynthetic-encased stone column in soft clay. Geotextiles and Geomembranes. 2020 Dec;48(6):897–911. Doi:10.1016/j.geotexmem.2020.07.006
- [15] Xue J, Liu Z, Chen J. Triaxial compressive behaviour of geotextile encased stone columns. Computers and Geotechnics. 2019 Apr;108:53–60. Doi:10.1016/j.compgeo.2018.12.010
- [16] Gao J, Zhang Y, Wang C, Yuan C. Behavior characteristics of geosynthetic-encased stone column under cyclic loading. Transportation Geotechnics. 2021 May;28:100554. Doi:10.1016/j.trgeo.2021.100554
- [17] Pandey BK, Rajesh S, Chandra S. Time-Dependent Behavior of Embankment Resting on Soft clay Reinforced with Encased Stone Columns. Transportation Geotechnics. 2022 Sep;36:100809. Doi:10.1016/j.trgeo.2022.100809
- [18] Indraratna B, Redana IW. Plane-Strain Modeling of Smear Effects Associated with Vertical Drains. J Geotech Geoenviron Eng. 1997 May;123(5):474–8. Doi:10.1061/(ASCE)1090-0241(1997)123:5(474)
- [19] Indraratna B, Rujikiatkamjorn C, Sathananthan I. Analytical and numerical solutions for a single vertical drain including the effects of vacuum preloading. Can Geotech J. 2005 Aug 1;42(4):994–1014. Doi:10.1139/t05-029
- [20] Hird CC, Pyrah IC, Russell D, Cinicioglu F. Modelling the effect of vertical drains in two-dimensional finite element analyses of embankments on soft ground. Can Geotech J. 1995 Oct 1;32(5):795–807. Doi:10.1139/t95-077

- [21] Lee CF, Lau CK, Ng CWW, Kwong AK, Pang PLR, Yin JH, et al., editors. *Soft Soil Engineering*. 1st ed. Routledge; 2017.
- [22] Dey A, Reddy MA. Compensated Raft Foundation on a Preloaded Soil Improved by Vertical Drains. In: *Ground Improvement and Geosynthetics* [Internet]. Shanghai, China: American Society of Civil Engineers; 2014 [cited 2024 Jun 19]. p. 515–25. Available from: <http://ascelibrary.org/doi/10.1061/9780784413401.051>.
- [23] Hu Y yuan, Yang P. Secondary settlement estimation in surcharge preload subject to time effect of secondary consolidation coefficient. *J Cent South Univ*. 2017 Feb;24(2):341–52. Doi:10.1007/s11771-017-3436-6
- [24] Hammad MS. Application of Prefabricated Vertical Drains in Soft Clay Improvement. *IJEAS*. 2019 Oct 31;6(10). Doi:10.31873/IJEAS.6.10.26
- [25] Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Indonesia, Toha FX. Post Preloading Creep Properties of Highly Compressible Harbor Marine Sediments. *J Eng Technol Sci*. 2017 Jul 31;49(2):163–78. Doi:10.5614/j.eng.technol.sci.2017.49.2.1
- [26] Fan L, Xun Z, Peng S. A Comparative Case Study on Drainage Consolidation Improvement of Soft Soil under Vacuum Preloading and Surcharge Preloading. *Applied Sciences*. 2023 May 8;13(9):5782. Doi:10.3390/app13095782
- [27] Lei M, Luo S, Chang J, Zhang R, Kuang X, Jiang J. The Influences of Vacuum–Surcharge Preloading on Pore Water Pressure and the Settlement of a Soft Foundation. *Sustainability*. 2023 May 7;15(9):7669. Doi:10.3390/su15097669
- [28] El Gendy O. *Behavior of Tanks under Static and Cyclic Loading*. Port Said: Port Said University. 2016.
- [29] El Gendy M, El Gendy A. *Analysis and Design of Slab Foundations by FE-Method-Program ELPLA 10*. GEOTEC Software Inc, Canada. 2015.
- [30] Pelli F, Rossanese A. Settlements Of An Instrumented Landfill On Soft Delta Soil With Vertical Wick Drains. In *ISRM*; 2000. p. ISRM-IS.
- [31] Pelli F, Carletti A. Characterization of soft deposits in the Eastern Nile Delta. In 1998. p. 257–62.
- [32] Abbas SEI. Settlement Mitigation of Cylindrical Tanks Founded on Weak Soil Under Static Loading. *Port-Said Engineering Research Journal*. 2024 Jan 8;0(0):0–0. Doi:10.21608/pserj.2024.249595.1284
- [33] Roesyanto, Iskandar R, Silalahi SA, Fadliansyah. Soil settlement analysis in soft soil by using preloading system and prefabricated vertical draining runway of Kualanamu Airport. *IOP Conf Ser: Mater Sci Eng*. 2018 Feb;309:012024. Doi:10.1088/1757-899X/309/1/012024