Geotechnical Design Considerations of Ground Storage Tanks in Southeast Texas and Louisiana

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Abstract: Geotechnical Design considerations of large diameter ground storage tanks are of significant interest to practicing geotechnical engineers in the Texas and Louisiana Gulf Coast dominated by the Oil, Gas and Chemical industries. In this paper, general geotechnical analysis and design methodologies are presented and comparisons are made using two case histories to evaluate how well the predicted tank performances match with observed tank performances.

1. Introduction

Large diameter steel storage tanks are frequently constructed within various oil and gas refineries owned by large oil and gas companies situated along the Texas and Louisiana Gulf Coast to store crude oil products. The Beaumont clay formation along the southeast Texas Gulf coast and parts of Louisiana and relatively softer soil deposits found near the Mississippi river in southeast Louisiana pose a unique challenge to geotechnical engineers regarding prediction of tank performances on these soil deposits. Geotechnical design considerations of ground storage tanks typically involve stability and settlement considerations. General bearing capacity theories and conventional settlement computation methods are available in common literature, which can be used to predict stability and settlement of storage tanks but relatively fewer case histories are available to compare the correlation between prediction and reality. In this paper, geotechnical stability and stability evaluation methods typically followed by local practitioners and it is demonstrated how the evaluation methods can be carefully applied to predict observed tank performance and settlements with reasonable accuracy for practical purposes.

2. Foundation Soils Characteristics

The Beaumont clay formation (William and Fotch, 1982, Mahar and O'Neill, 1983, William, 1987) is a unique soil formation consisting primarily of deltaic deposits of stiff to very stiff or hard clays and sandy clays intermixed with layers of silty sand layers. The cohesive soils of Pleistocene geologic age are moderately to heavily desiccated and therefore moderately to heavily over-consolidated. On the contrary, relatively recent deltaic deposits along the Mississippi river in Southeast Louisiana are generally found to be about normally consolidated to lightly over-consolidated.

3. Objectives

The objectives of this paper is to discuss various published methods available to evaluate tank stability and settlement evaluation, discuss the methods practitioners typically use locally to perform these evaluations, to discuss advanced numerical analysis methods for these evaluations and to compare the predictions with observed tank performances via two case histories.

4. Tank Stability Evaluation

Ground storage tank stability is typically analyzed using hydrotesting conditions. Ground storage tank stability is typically controlled by the undrained shear strength of the supporting soil. Tanks supported on ringwall foundations should satisfy three (3) separate bearing capacity concerns: (1) base shear failure (deep stability) (2) edge shear failure and (3) adequate ringwall bearing capacity with regards to punching shear failure. Unless a significant portion of the soil column is weak, base shear is typically not a critical issue. Base and edge shear stability issues and evaluation procedures are discussed in detail by Duncan and D'Orazio (1984). The mechanism of base shear failure is very similar to the mechanism for bearing failure of a shallow footing on clay. In this mode of failure, the entire tank acts as a single unit in which the entire base of the tank undergoes downward movement while the foundation soils are squeezed outward laterally from beneath the tank. The recommended factor of safety based on Appendix B in API Standard 650 and by Duncan and D'Orazio (1984) varies significantly. In the case of edge shear, the near surface soils shear allowing a small section of the tank to distort, deform and subsequently rupture. Edge shear failure is possible because a steel tank is relatively flexible and when local failure occurs, a portion of its perimeter moves independently of the adjacent tank base area. Edge shear failure is the most common mode of bearing failure for ground storage tanks supported on shallow foundation systems. The recommended factor of safety based on Appendix B in API Standard 650 and by Duncan and D'Orazio (1984) varies significantly. For punching shear, as the load increases on the ringwall, vertical movement of the ringwall is accompanied by compression of the foundation soil directly underneath the ringwall. With continued downward movement, the foundation soils shear around the ringwall perimeter. To the best of Author's knowledge, the factor of safety for tank ringwall bearing capacity is not well defined in API Standard 650. It should be noted that Duncan and D'Orazio (1984) procedures do not consider soil-structure interaction, change of base pressure distribution due to presence of tank bottom plate and presence of tank ringwall. More rigorous finite element methods can be used to more accurately evaluate tank stability. Generally Duncan and D'Orazio (1984) methods result in conservative factor of safety. It can be seen that depending on the method used, the prediction of hydrotest stability factor of safety could vary significantly.

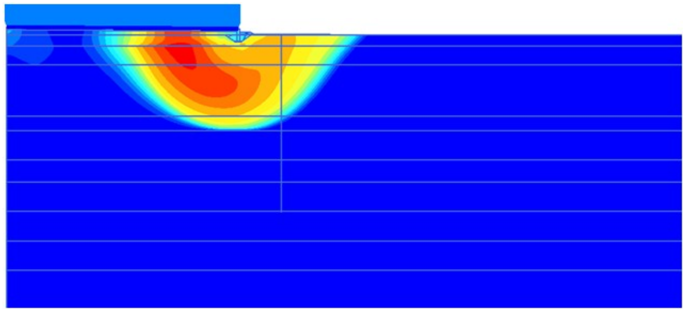
5. Tank Settlement Evaluation

In addition to bearing capacity concerns, the tanks should also perform adequately with regards to settlement from induced hydrotesting and long-term operating conditions. Settlements can be expected due to immediate elastic compression and long-term consolidation of the foundation soils beneath the tank footprints. The hydrotest settlement evaluation requires an undrained elastic modulus, which is a difficult parameter to predict although it has significant influence on predicted hydrotest settlement. Simplified methods are available in literature to predict elastic settlement (Poulos and Davis, 1974) based on an assumed undrained elastic modulus. William and Fotch (1982) used strain influence approach (Schmertmann, 1978) methods to compute an equivalent elastic modulus to obtain elastic settlement. William (1982) also proposed a method based on back calculation of elastic modulus based on observed settlements on Beaumont formation clays as function of tank diameter. Commercial computer programs (Slide, Rocscience) use layer-by-layer elastic modulus approach for elastic settlements where undrained elastic modulus for each clay layer can be estimated using the empirical relations proposed by Duncan and Buchignani (1976). It thus becomes obvious that depending on the method used, the prediction of hydrotest settlement could vary significantly. Long term consolidation settlements are typically estimated using Terzaghi's (1948) theory of one-dimensional consolidation. The load intensity for long-term settlement should be evaluated using average product load in the tanks considering variation in product height in the tank over the service life. Finite element soil-structure interaction can also be used to predict tank settlements for short and long-term conditions using appropriate soil models.

6. Case Histories

<u>Site 1</u>

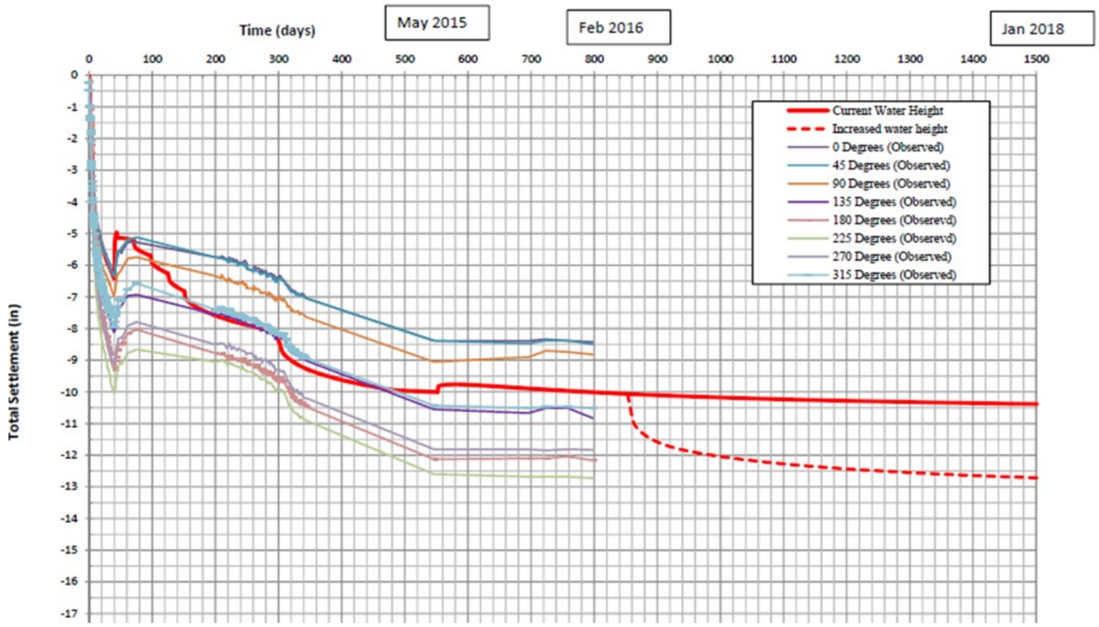
Site 1 is located in Jefferson County, Texas. The new tank that was constructed at the site was approximately 253-ft in diameter with shell heights of 48.6-ft and it stored crude oil product with a specific gravity on the order of 0.94. Shallow concrete ringwall foundation system was considered for support of the tank shells at the project site. Stability analysis of the tank using Duncan and D'Orazio (1984) methods resulted in edge shear factor of safety against stability for hydrotest, which did not meet API requirements. Therefore axisymmetric finite element analysis was performed at Client's request to verify the factor of safety. The finite element analysis resulted in satisfactory factor of safety and the tank was allowed to be constructed at the site. Hydrotest settlements were monitored at points suitably located along the tank ringwall. The estimated hydrotest settlements were in reasonably close agreement with observed settlements.



Finite Element Stability Analysis of Tank
Jefferson Parish, Texas

Site 2

Site 2 was located in Ascension parish, Louisiana. The evaluation involved prediction of future tank settlement for an existing pile-supported tank. The existing fire water/clarifier tank was 100-ft in diameter and was supported on driven 14-in diameter x 65-ft long concrete pile group system. The design over flow nozzle level of the tank was 76-ft and the design maximum operating high level was 74-ft. The study utilized geotechnical borings and reports performed by others, miscellaneous previous engineering and geotechnical reports by others as well as a variety of project information furnished by the Client including settlement monitoring of the tanks and other structures. Based on a detailed review of existing information, one additional soil boring was performed adjacent to the existing tank. The primary purpose of this additional boring was to obtain sufficient subsurface data needed to evaluate the compressibility of soils below the pile tip elevation for the tank which was required for detailed settlement analysis. Since construction, the pile supported tank had experienced several inches of settlement during hydrotesting and continued to settle. At the time of the new study, total settlement of the tank foundation measured to date ranged from approximately 8.5-in on one side of the tank to approximately 12.8-in on the opposite side of the tank indicating a significant tilt due to non-uniform settlement of the tank perimeter. In an effort to predict the future settlement of the tank, a detailed time-rate settlement analysis was performed for the new study. The predicted time-settlement responses were in reasonable agreement with the observed time settlement history of the tank allowing the prediction of future tank settlement with confidence.



Time -Settlement Response of Foundation Ascension Parish, Louisiana

7. Lessons Learned

The following are lessons learned from the 2 case histories:

- Undrained elastic modulus based on published literature of Duncan and Buchugnani (1976) produces conservative estimate of tank hydrotest settlement.
- The elastic modulus estimation method suggested by William (1982) appears to produce more accurate results close to observed values.
- Duncan and D'Orazio (1984) methods appear to very conservative for tank stability
- Finite element methods appear to produce more realistic results
- Tank settlement predictions vary using different methods
- The methods used to predict tank performances for the 2 case histories appear to be reasonable producing results close to observed tank performances and tank settlements

8. References

1) Duncan JM and D'Orazio, T (1984) Stability of Oil Storage Tanks – Journal of Geotechnical Engineering, ASCE, Vol. 110, No. 9
2) Williams CE and Focht, JA (1982) Initial Response of Foundations on Stiff Clay – ASCE Convention, New Orleans, LA
3) Williams CB (1989) Evaluated Behavior of Foundations on Stiff Clay – Texas Civil Engineer
4) Duncan JM and Buchignani, AL (1976) An Engineering Manual for Settlement Studies
5) Terzaghi, KV and Peck RB (1948) Soil Mechanics in Engineering Practice
6) American Petroleum Institute Standard 650 – Welded Steel Tanks for Oil Storage