Optimal Foundation System for a Storage Tank in Liquefiable Soil-A Case Study

Sampat Raj[1], VK Panwar[2] and Sanjoy Bhowmik[3]

[1,2,3]Engineers India Limited, New Delhi, 110066, India
sampat.raj@eil.co.in
vk.panwar@eil.co.in
sanjoy.bhowmik@eil.co.in

Abstract. Storage tanks are constructed in all refinery complexes for the bulk containment of fluids at different stages of the refinery process. This paper presents optimal foundation solution for a storage tank located at Bongaigaon, Assam. Subsoil at the present location consists of top 11m loose to medium dense silty sand which is further underlain by dense sand with fines content less than 15%. The refinery site is located in the highly seismic prone zone and top soil up to substantial depth is susceptible to liquefaction. In order to construct storage tank in such type of soil, it is necessary to provide suitable foundation system for controlling liquefaction and to satisfy the performance requirement. Stone column is one of the ground improvement techniques to increase the bearing capacity and to reduce the total and differential settlements. Ground improvement using vibro stone columns is used to mitigate the liquefaction susceptibility and to minimize the differential settlement of tank foundation. The various aspects of sub soil conditions, design, construction methodology, quality control and hydro test results are discussed in this paper.

Keywords: Storage Tanks, Optimal Foundations, Ground Improvement, Vibro Stone Columns, Hydrotest.

1 Introduction

Tanks are an integral part of refinery and petrochemical industry which are used to store crude oil, petroleum intermediate and end products. The behavior of these flexible structures is closely associated with the strength and deformation characteristics of the subsoil. Any excessive total or differential settlement may cause distress of the tank shell, bottom plates, piping and nozzle connections thus jeopardizing the structural integrity of these structures.

In order to minimize the total and differential settlement, the selection of appropriate foundation system plays a key role. Generally foundation system is decided based on the total estimated settlement under the tank shell. Foundation quality in respect of fixed/cone roof tanks is generally assessed as per the criteria given in Table 1 (Guber, 1974) [5].

Ground improvement becomes imperative in case total settlement at tank periphery exceeds 150mm (for floating roof tanks) and 300mm (for fixed roof tanks).

Table 1. Foundation quality criteria

Category	Maximum Settlement at Shell	Foundation Quality
1	50mm	Excellent
2	50-150mm	Good
3	150-300mm	Fair
4	Over 300mm	Poor (Soil Treatment Required)

An oil storage floating roof tank having 30m diameter and 14.5m height was envisaged at an operational refinery of Bongaigaon, Assam- a state located in northeast region in India which fall under zone of high seismic intensity. Evolving an appropriate foundation system for the proposed tank posed various geotechnical challenges. This includes prevailing subsoil conditions i.e. presence of loose saturated silty sands susceptible to liquefaction and higher ground water table. The selection of optimal foundation system for tank in such type of conditions involved a detailed techno-feasibility assessment.

2 Site Conditions

A detailed subsoil investigation program consisting of boreholes and laboratory testing was carried out to characterize the subsurface soil properties at the project site.

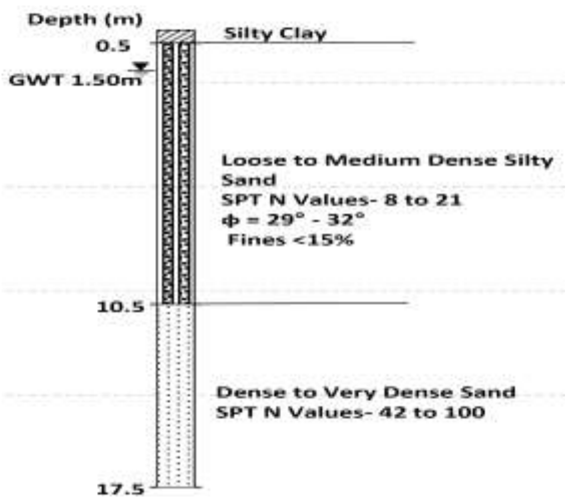

Fig. 1. Generalized soil profile

The soil profile is presented in Fig. 1, which depict that top 0.5m soil is silty clay followed by loose to medium dense silty sand up to 10.5 m depth with SPT N value ranging from 8 to 21 and fines content less than 15%. This layer is underlying by dense to very dense sand mixed with gravels till 18m depth. Ground water table was encountered at 1.50m below the ground level.

3 Liquefaction Susceptibility Analysis

Liquefaction is a phenomenon which occurs when a saturated or partially saturated soil substantially loses strength and stiffness in response to an applied stress such as shaking during an earthquake or other sudden change in stress condition, in which material that is ordinarily a solid behaves like a liquid.

The proposed site lies in zone V as per the seismic zoning map of India (IS:1893-2016, Part 1) [1]. An Earthquake magnitude of 7.5 was considered for analysis. Design ground water table was considered at 1.0 m depth below finished ground level. The peak horizontal ground acceleration value for the site was taken as 0.36 g.

A liquefaction analysis was carried out based on the empirical procedure developed by Seed & Idriss (1971) [9]. For the analysis of liquefaction potential, cyclic stress ratio (CSR) and cyclic resistance ratio (CRR) were evaluated using the corrected SPT blow counts and fines content data for the silty sand. Fig. 2 illustrates the induced CSR and CRR with respect to depth. From the expression FOS = CRR/CSR, it was concluded that soil was susceptible to liquefaction up to the depth of 10m under an event of earthquake.

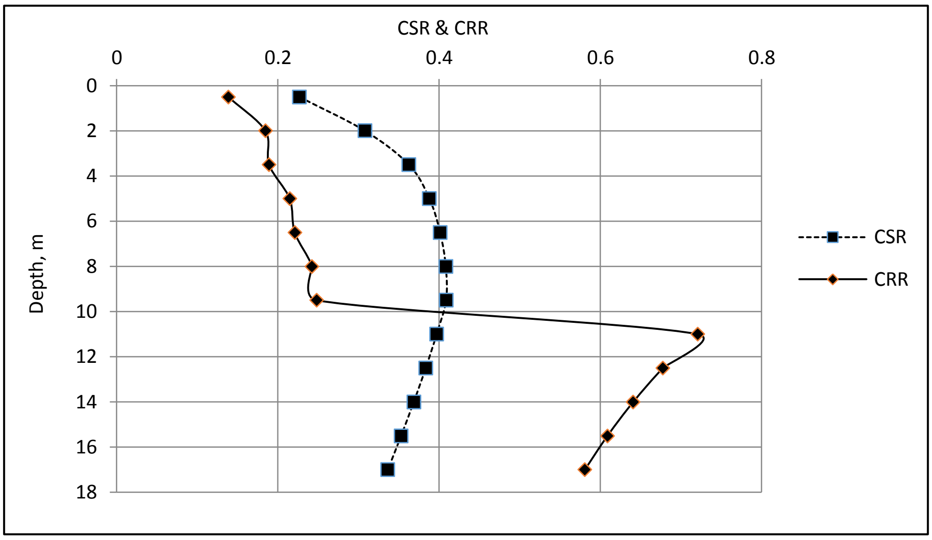

Fig. 2. CSR and CRR with depth (pre stone column installation)

4 Foundation System For Tank

Based on the critical review of subsoil condition and performance criteria, various foundation options had been explored such as pile foundation, dynamic compaction, vibro stone columns etc.

Foundation system pile with pile cap generally proves very costly. Foundations using dynamic compaction generate severe vibrations which may hamper the performance and the life of the existing nearby structures. In the operational plants this method is generally not suitable due to safety related issues.

Ground improvement using vibro stone columns was considered as most appropriate solution compared to other foundation solutions. It is a technique in which coarse grained materials is poured into ground using vibrating tools to form a vertical column. This technique improves the bearing capacity of the soil and decreases the total and differential settlements.

Vibro stone columns densify the area beneath the tank and also act as drainage which dissipate the excess pore water pressure in the event of earthquake and mitigate the liquefaction susceptibility. The introduction of stiffer material (stone) can potentially carry higher stress levels and thereby reduce stresses in the liquefiable soil (Priebe, 1991) [7]. Consequently, CSR is reduced. The CSR reduction may be estimated using several approaches developed by Priebe (1998) [8], Baez and Martin (1993) [3] and Goughnour and Pestana (1998) [4].

5 Stone Column Design Considerations

The critical parameters for the design of most efficient vibro stone columns are finished diameter of the stone columns, stress concentration factor (n), pattern of installation and area replacement ratio (a_s). The spacing of the stone columns was decided based on the method suggested by Priebe, H.J. (1998) [8] to mitigate the liquefaction potential of the subsoil. Angle of internal friction of the stone, φ_s, was taken as 42°.

The length of the stone column was decided in such a way that it extends through the liquefiable zone and rest in the competent soil strata which is 12m from the finished ground level. Finished diameter of the stone column was 800 mm with triangular grid pattern since it yields the densest packing. Spacing of the stone columns inside the tank periphery was 1.80m and along the periphery of the tank was 1.50m. Total nos. of stone columns were 451 which were decided based on the equivalent area of the stone column. Typical stone column layout is shown in Fig. 3.

Settlements corresponding to hydrotest loading have been estimated about 70mm at tank center and 40mm at tank shell. However, during seismic event tank would experience inordinate total settlement and large differential settlements that would severely affect the performance of floating roof tank.

Settlement after the installation of the stone columns was estimated by applying the improvement factor (n_o) as suggested by Priebe, H.J. (1995) [6]. Post treatment settlements at the center and periphery have been worked as about 38mm and 21mm respectively.

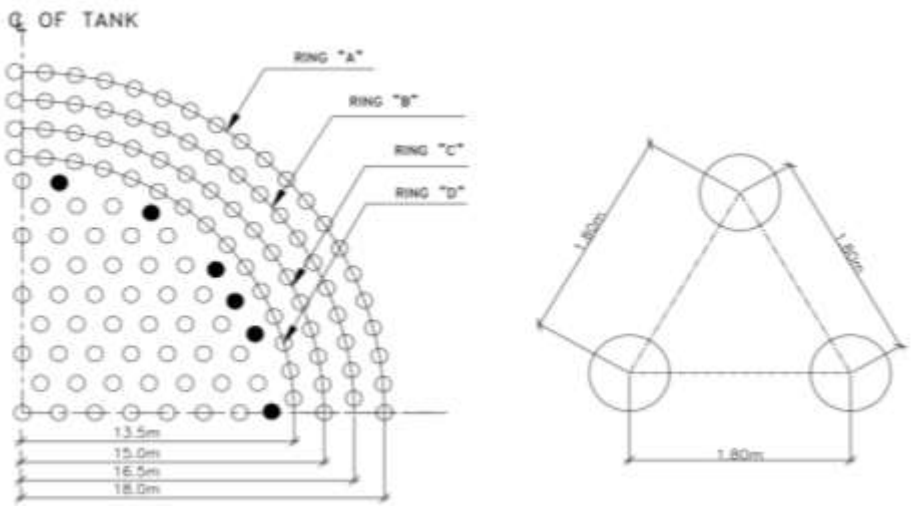

Fig. 3. Stone column layout in a tank quadrant

6 Load Testing

An initial stone column group test was carried out at a trial test site in the close vicinity of proposed tank location to verify the stone column design. The initial stone column test was conducted on a group of three columns.

Additional columns were installed surrounding the test column to simulate the field conditions of compaction of the intervening soil. The load test plan developed for the initial stone column test is presented in Fig. 4.

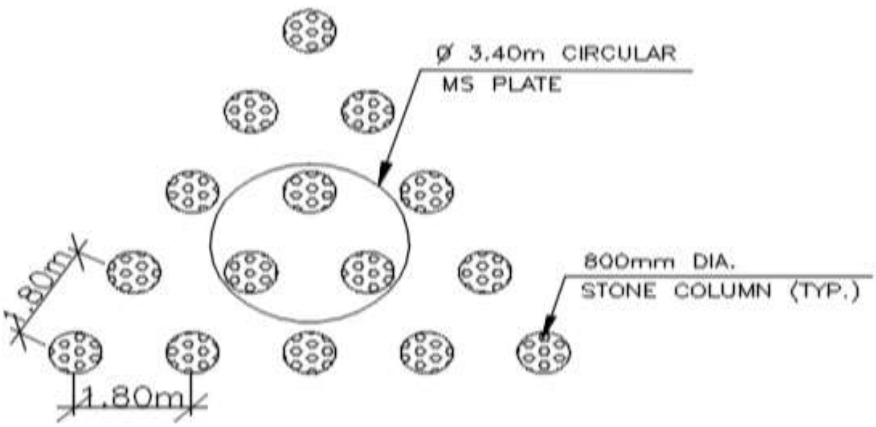

Fig. 4. Plan for group columns load test

The load test was conducted as per the Indian Standard codal provisions of IS 15284 part 1 [2] and the maximum load applied was 1.5 times the design load. The load intensity-settlement behavior of the initial stone column tests is presented in Fig. 5.

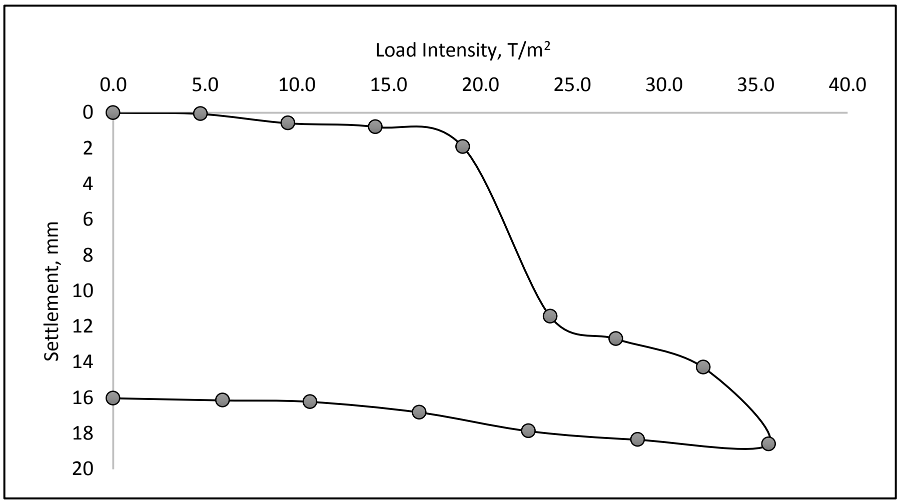

Fig. 5. Load intensity-Settlement curve for group column test

Total settlement at design intensity of 23 t/m^2 was observed to be 11.40 mm and at 1.5 times the design load (i.e. 34.5 t/m^2) was 18.60mm for initial group column test. The observed total settlement at the design intensity was well within the settlement criteria stipulated by IS: 15284-2003, Part 1 (25-30mm for group columns test) [2].

7 Liquefaction Analysis Post Treatment

Post treatment liquefaction analysis was performed according to design procedure by Priebe, H.J. (1998) [8]. The improvement factor (n) which is a function of area ratio and friction angle of column material was calculated as per the Fig. 6. The area ratio for the design column spacing was 5.58 and the improvement factor (n) was 1.98. The reciprocal of this improvement factor ($\alpha = 1/n$) was used to reduce the cyclic stress ratio (CSR) and evaluate the remaining liquefaction potential as per the empirical procedure developed by Seed &Idriss (1971) [9].

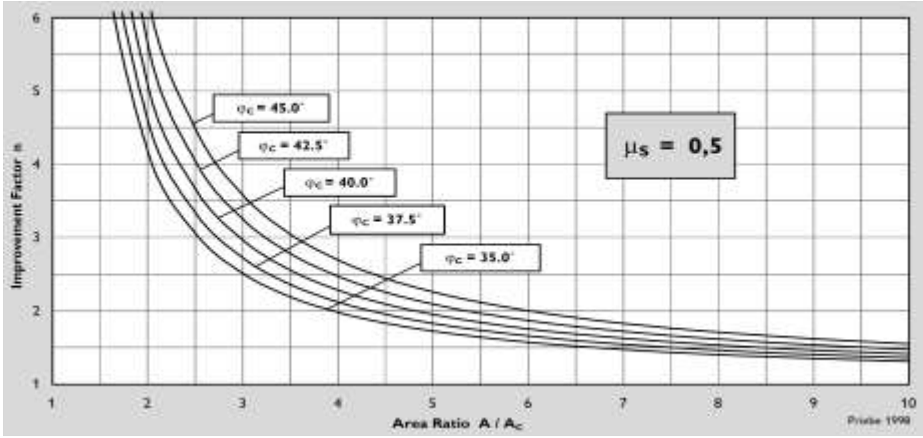

Fig. 6. Design chart for vibro replacement (After, Priebe, H.J., 1998)

Fig. 7 illustrates the induced CSR and CRR with respect to depth. This figure shows that factor of safety is greater than 1.0 that proves the liquefaction potential of the soil is mitigated after installation of stone columns.

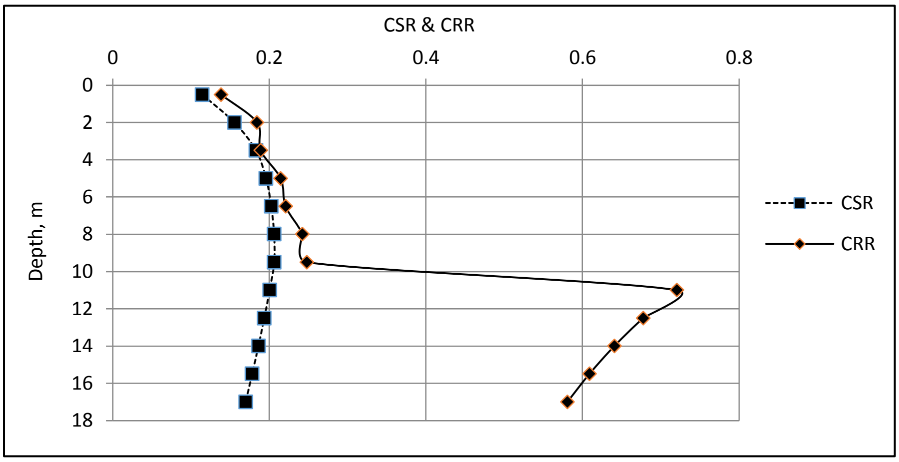

Fig. 7. CSR and CRR with depth (post stone column installation)

8 Hydrotest Results

Tank was hydrotested upto the design height and the settlement readings were recorded at 8 nos. of equidistant peripheral points. The settlement readings are presented in Fig. 8. The maximum actual settlement observed at the tank periphery was 17mm which was well within the allowable settlement limits at tank periphery for floating roof tank.

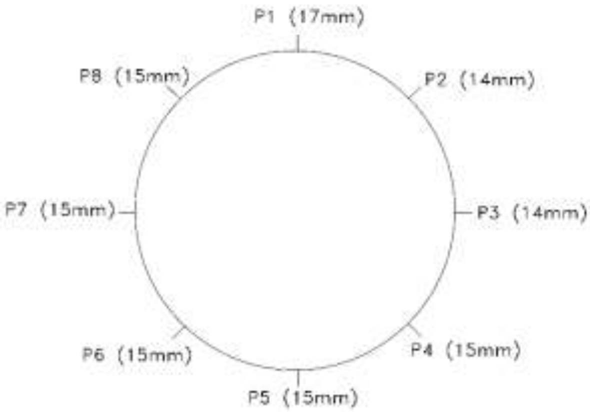

Fig. 8. Observed peripheral settlements

9 Conclusions

The present study demonstrates that ground improvement using stone column is the most optimal foundation solution for storage tanks in liquefiable soil conditions for an operational plant. Extremely close agreement between the predicted peripheral settlement (21mm) and the measured settlement at the tank periphery (17mm) at full hydrotest load confirm the adequacy and reliability of the design parameters and design procedure adopted.

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