Vibro replacement stone columns for large steel storage tanks in Vietnam

Colonnes ballastées pour des grands réservoirs de stockage en acier au Vietnam

Selvaganesh Selvaraju, Zhi Wei He, Kam Weng Leong
Keller, GeoSS, Singapore, selvaganesh@kellersing.com.sg, hezhiwei@kellersing.com.sg, leongkw@kellersing.com.sg

ABSTRACT: A mega refinery and petrochemical plant has been built in Vietnam, with steel storage tanks of diameters up to 89 m and height of 20 m. The allowable settlements of tanks are based on API653 standard. Prior to construction, soil investigation by Cone Penetration Tests (CPTs) were done along tank circumference at 10m intervals and at tank centers and 5 – 10 boreholes (BHs) were done for each tank. Laboratory tests were conducted on soil samples collected at site. Typical soil profile below tanks consists of 2-3m thick stiff silty soil, followed by 5–6m thick loose to dense sandy soil, then 8–9m thick soft to firm clay which has a 1-2m thick medium dense to very dense sandy soil layer interspersed at certain locations, underlain by stiff to very stiff silty soil. In this design and build project, Vibro Replacement stone columns were installed till the bottom of soft to firm clay. Currently, hydrostatic tests have been completed for all tanks. The measured settlements are well within the settlement criteria. In this paper, the soil profile information and vibro replacement design adopted for tanks are illustrated. Tank settlement prediction and hydrostatic test results will be presented and discussed.

RÉSUMÉ: Une méga raffinerie et usine pétrochimique ont été construites au Vietnam, avec des réservoirs de stockage en acier d'un diamètre allant jusqu'à 89m et une hauteur de 20m. Les tassements admissibles des réservoirs sont basés sur la norme API653. Avant la construction, des investigations de sol au Pénétromètre statique (CPT) ont été réalisés à la fois le long de la périphérie des réservoirs avec un intervalle de 10 mètres ainsi qu'au centre des réservoirs. De 5-10 sondages au pénétromètre dynamique (SPT) ont également été réalisés pour chaque réservoir. Le profil de sol typique sous les réservoirs est de 2-3m d'épaisseur de limons raides, suivi de 5-6m d'épaisseur de sable lâches, puis 8-9m d'épaisseur d'argile molle à raide intercalée de couches de sables moyennement denses à très denses en certains points, le tout reposant sur un sol raide à très raide. Actuellement, des essais hydrostatiques ont été effectués pour tous les réservoirs. Les tassements mesurés montrent qu'ils sont bien en deçà du critère de tassement requis. Dans cette publication, des informations sur le profil de sol ainsi que sur le dimensionnement des colonnes ballastées considéré sont illustrés. Les prévisions de tassements des réservoirs et les résultats des essais hydrostatiques seront expliqués.

KEYWORDS: Steel storage tank, Vibro Replacement, stone column, hydrostatic test, differential settlement

1 INTRODUCTION

By the end of 2012, Vietnam had one operating petrochemical refinery with a capacity of 130 thousand barrels per day, which was below domestic demand for refined oil, and made it dependent on imports (World Energy Outlook Special Report, September 2013). Due to falling production and rising demand for domestic energy requirements, Vietnam is projected to become a net importer of crude oil from 2019 (Vietnam Oil and Gas Report, Q3 2016). To meet the growing demand, capacity of existing refinery is being increased and new refineries being proposed. These refineries will store both crude and processed oil and also the by-products. Hence storage tanks are indispensable in such refineries. Predominantly, these storage tanks are made of steel to take advantage of the ductile nature and better resistance with respect to deformation and hoop stress. In addition, these steel tanks are flexible and tolerant to differential settlements (He at al. 2015). This makes a flexible foundation solution like ground improvement a suitable alternative foundation for steel tanks.

This paper discusses the application of deep vibro replacement stone columns as foundation solution for storage tanks in one such petrochemical plant development in Vietnam.

2 LOADING AND PERFORMANCE CRITERIA

This petrochemical plant has been in development since 2013 and is scheduled to be commissioned by July 2017. The soil investigation works started in early 2013 and completed by end of 2013. Ground improvement works for tank foundations started in first quarter and completed in last quarter of 2014. Stone columns were adopted as foundation solution for 12 tanks, with dimensions and design loading for ground improvement summarized in Table 1.

Table 1. Tank dimension and loading information

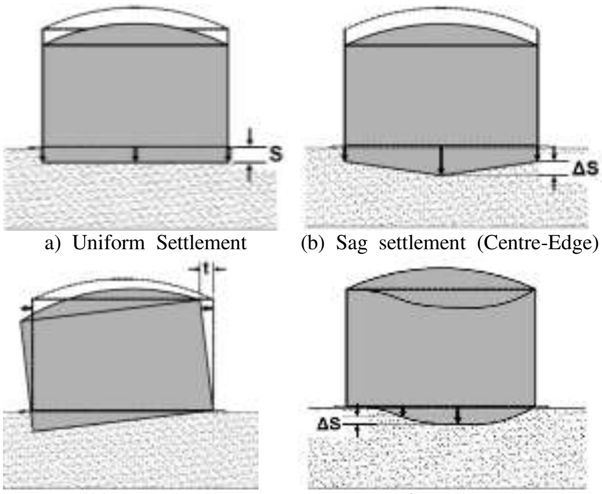
Tank ID (m)	Diameter (m)	Height (m)	Design loading (kPa)
Tank 1	24.0	14.0	200
Tank 2	24.0	14.0	200
Tank 3	30.6	19.3	200
Tank 4	36.6	20.0	200
Tank 5	45.7	15.0	200
Tank 6	89.0	19.9	200
Tank 7	89.0	19.9	200
Tank 8	89.0	19.9	200
Tank 9	89.0	19.9	200
Tank 10	89.0	19.9	200
Tank 11	89.0	19.9	200
Tank 12	89.0	19.9	200

The required performance criteria for the tanks founded on ground improvement is summarized in Table 2.

Table 2. Performance criteria for tanks on ground improvement

Tank Diameter (m)	Allowable total settlement at edge (mm)	Allowable differential settlements		
		Sag	Circumferential	Tilt
$D \geq 25$	300	D/300	13mm per 10m	D/200
$25 > D \geq 10$	150	D/300	13mm per 10m	D/200
$D < 10$	50	D/300	13mm per 10m	D/200

Generally, tank settlement can be classified as uniform and differential settlement. Typical scenarios of tank settlement are explained in subsequent paragraphs and represented in Figure 1.



a) Uniform Settlement (b) Sag settlement (Centre-Edge)

(c) Tilting Settlement (d) Circumferential settlement

Figure 1. Different modes of tank settlement

Uniform settlement: When soil condition is relatively uniform, a storage tank will settle uniformly. There may be no significant problems to tank performance if the tank settles uniformly as illustrated in Figure 1a, except it is possible that pipe connection to tank could be overstressed by tank settlement relative to the pipe connected to other equipment.

Differential settlement is detrimental to tank performance. With respect to tank performance, differential settlement can be classified into 3 categories: sagging, circumferential and tilting settlement. Sagging settlement is commonly referred to as centre-to-edge differential settlement and refers to uneven settlement of tank bottom plate as shown in Figure 1b. If sag settlements are large, tank bottom plate can buckle leading to distress and separation of fillet welds between them. Tilting settlement causes rotation of the tank in a rigid tilted plane as depicted in Figure 1c. This will cause an increase in liquid level on one side of the tank and hence an increase in hoop stress on the shell. Excessive tilting can cause binding of the peripheral seals in a floating roof and inhibit roof travel. Circumferential differential settlement may cause tank shell settle in a non-planar configuration as schematized in Figure 1d inducing additional stresses in the tank shell. The out-of-plane settlement at the bottom of the tank and shell will cause the upper parts of the walls deflect inward or outward producing "ovalisation" of the tank. In the case of floating roof, this settlement could also affect tank nozzles that have pipes attached to the tank.

For this project, the most stringent criterion is the 13mm per 10m circumferential differential settlement limit. A different circumferential settlement assessment methodology was proposed based on API Standard 653 (2009) to satisfy this requirement. It will be further explained in more detail in sections 4 and 5.

3 SUBSOIL CONDITIONS

Extensive boreholes (BHs) and Cone Penetration Tests (CPTs) were done at the tank farm location, with CPTs at every 10m arc length along tank circumference. Therefore, localized soil conditions can be better captured and the impact could be envisaged early in design stage. A typical arrangement of 10 BHs and 30 CPTs for an 89m diameter tank (Tank 8) is shown in Figure 2.

3 .1 *Soil profile*

To understand the overall soil conditions at this tank, the results of borehole SPT N values and CPT q_c values are presented in an idealized soil profile at the tank circumference as shown in Figure 3 and tabulated in Table 3. For the depths where CPT cone did not reach due to hard soil conditions, borehole SPT N values were used. It is noted that at CPTs 1 to 9 and 20 to 25 along the circumference, there is a layer (ID – 3a) of medium dense to dense sand with SPT N = 10– 50 and cone resistance q_c = 4 – 30 MPa. These zones with relatively higher overall stiffness due to the presence of dese sand layers in between, are expected to give lesser edge settlements compared to other zones at CPTs 10 -19 and 26 – 29.

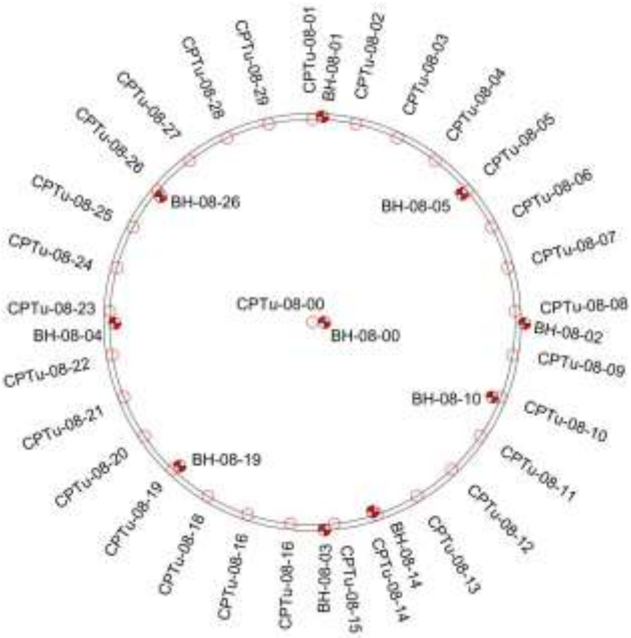


Figure 2. Typical borehole and CPT layout for 89m diameter tank (Tank 8)

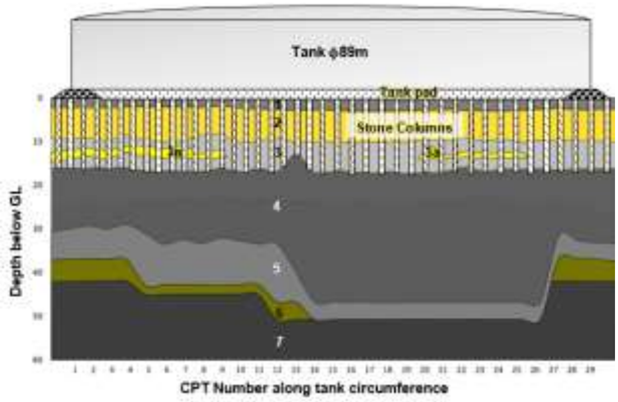


Figure 3. Soil profile under circumference of 89m diameter tank

Table 3. Soil information

ID	Soil type	Depths (m)	SPT N	q_c (MPa)
1	Firm – Stiff Clay	0 – 3	2 – 18	0.3 – 12
2	Loose-Dense Sand	3 – 9	6 – 41	3 – 25
3	Soft - Firm Clay	9 – 18	1 – 9	0.4 – 2
3a	M.Dense–Dense Sand	13 – 15	10 – 50	4 – 30
4	Stiff – Hard Clay	18 – 32	15 – 36	1 – 4
5	Stiff Clay	32 – 50	10 – 20	-
6	M.Dense–Dense Sand	38 – 50	9 – 35	-
7	Hard Clay	42 – 60	> 40	-

3 .2 *Ground Water Table*

The average ground water level was at a depth of 2.5m below existing ground level as revealed by soil investigation report. This was used in the design calculation.

4 STONE COLUMNS TREATMENT SCHEME AND SETTLEMENT PREDICTION

Based on the soil information and required performance criteria, Vibro Replacement by stone columns was used as ground improvement solution for the tank. The treatment was done in the area under the tank footprint, as well as a 3m wide ring outside. The adopted treatment scheme is shown in Figure 4. The design spacing of stone columns is 2.5m c/c square grid arrangement. The stone columns treatment depth was proposed by zoning based on individual CPTs with a maximum depth of about 18m.

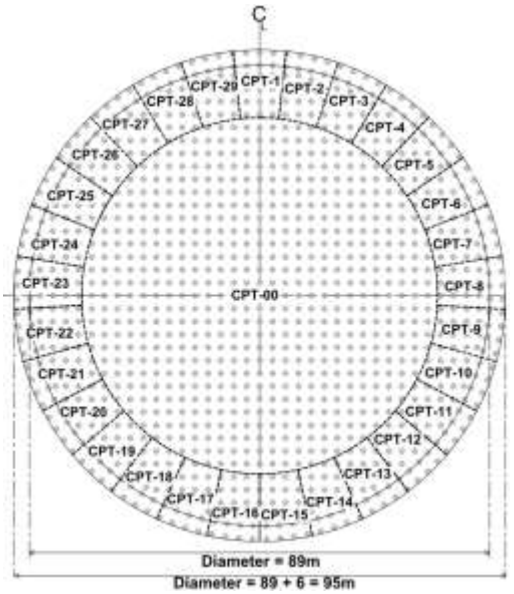


Figure 4. Adopted stone columns treatment scheme based on CPT zoning

The well-known Priebe (1995) method was adopted in the settlement analysis. An improvement factor is established from treatment scheme and property of stone columns and in-situ soil. Then, tank settlements are calculated accordingly using composite modulus for treated soil. Tölke's theory of stress distribution under footings was used to estimate vertical stress under loaded area and settlements are thus calculated. The tank centre and edge settlements under design load of 200kPa were estimated for soil profile shown in section 3.1.

The tank settlements were estimated and are summarised in Table 4a, 4b and 4c. Summary of comparison is shown in Table 4a, 4b and 4c. The predicted edge settlements range from 170mm to 275mm, which are less than the limit of 300mm. The predicted maximum sag settlement is 141mm, which is less than the limit of 297mm (D/300). The maximum tilt is found to be 105mm which is within the limit of 445mm.

Table 4a. Predicted edge settlement

Location at Tank	Range of estimated settlement (mm)	Estimated maximum settlement (mm)	Allowable (mm)	Remarks
		Edge	Edge	
Edge	170 - 275	275	300	OK.

Table 4b. Predicted sag settlement

Location at Tank	Range of estimated settlement (mm)	Estimated max sag settlement (mm)	Allowable (mm) D/300	Remarks
		Centre-Edge	Sag	
Centre	311	141	297	OK.
Edge	170 – 275			

Table 4c. Predicted tilt settlement

Location at Tank	Range of estimated settlement (mm)	Estimated max tilt settlement (mm)	Allowable (mm) D/200	Remarks
		Edge-Edge	Tilt	
Edge	170 - 275	105	445	OK.

5 HYDROSTATIC TEST – RESULTS & DISCUSSION

Hydrostatic test is normally carried out to check the water tightness and integrity of the tank. It serves the purpose of pre-loading the tank as well. In this project, settlement of ground was observed to check the performance of ground improvement. Water was filled in stages of 0%, 25%, 50%, 75% and 100% of tank height. At each stage, the tank edge settlements were measured at thirty-two settlement markers installed at equal intervals along the tank circumference. The water was held at full height for about 3 days before dewatering. Hydrostatic test for this tank started on 8 September 2015 and completed on 24 October 2015. The tank edge settlements measured during different stages of water loading are presented in Figure 5.

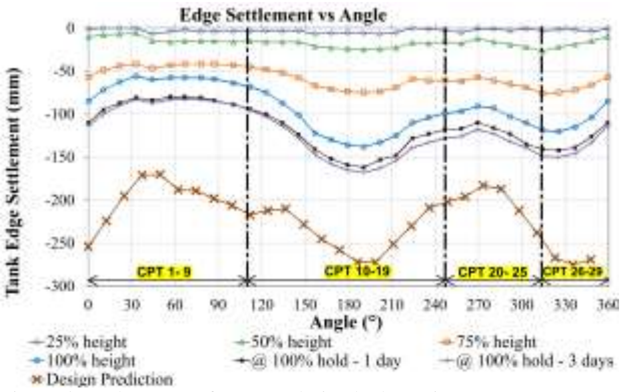


Figure 5. Settlement performance during hydrostatic test

5.1 *Results and Inferences*

The measured tank edge settlements were well within design prediction. At the end of 3 days of 100% water holding, a smoother trend compared to the design prediction is shown. The settlement trend along the tank edge was effectively captured by the analysis.

The availability of extensive number of CPTs along the tank circumference supplemented by borehole logs helped to identify the variable soil conditions and propose treatment accordingly. For instance, zones at CPTs 1 – 9 and 20 – 25 showed dense sand layers interspersing with firm silty clay layer. Hence during design, smaller stone column diameters of 0.6 – 0.7m were employed at the dense sand layers. For the remaining zones represented by CPTs 10 - 19 and 26 – 29 where firm silty clay layer was present until treatment depth without the intermediate dense sand layer, the treatment was locally strengthened with larger stone columns diameters of 0.9 – 1.1m in the firm silty clay layer. Hence the zones represented by

CPTs 10 – 19 and 26 - 29 were predicted to show larger tank edge settlements compared to remaining zones denoted by CPTs 1 – 9 and 20 – 25. Subsequently, similar trend was observed during hydrostatic test settlement monitoring as shown in Figure 5. Nevertheless, the measured settlements at all tank locations could satisfy total edge settlement, sagging and tilting differential settlement as explained in section 4.

5.2 *Circumferential settlement assessment*

To estimate the circumferential differential settlement, method described in API 653 (2009) which is also outlined by Leung and Leong (2014) and He et al (2015) was employed. Using this method, circumferential differential settlement is calculated in terms of ***out-of-plane deflection*** from a cosine curve fitted for the observed tank edge settlements during hydrostatic test. Out of plane deflection at a point i along the tank circumference is calculated using equation (1). Out of plane settlement at any point i, U_i is the difference between the estimated design tank edge settlement and the corresponding value from fitted cosine curve. To apply the above method of estimation of out-of-plane deflection, the plane is determined first. The plane is defined as an optimum cosine curve derived from $a+b\cos(\theta+c)$. The parameters a, b and c are determined by least squares methods using actual monitored edge settlements.

$$S_i = U_i - (\tfrac{1}{2}\, U_{i-1} + \tfrac{1}{2}\, U_{i+1}) \qquad (1)$$

S_i = Out of plane deflection at point i

U_{i-1}, U_i and U_{i+1} = Out of plane settlement at point i-1, i and i+1 along tank circumference

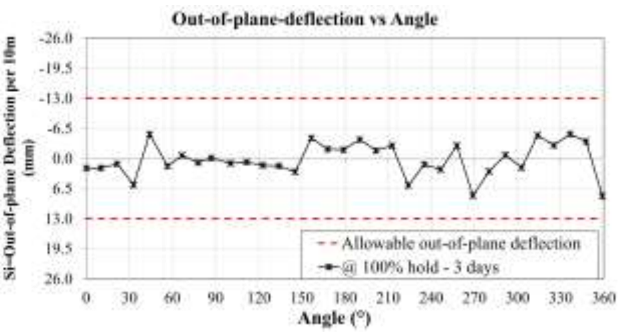


Figure 6. Circumferential differential settlement during hydrostatic test

Based on this methodology, the circumferential differential settlement was estimated at each of the settlement monitoring locations and shown in Figure 6. It was found to be within the allowable limit of 13mm over 10m length of circumference.

The above inferences show that presence of adequate soil investigation data alerted the designer to adopt a design stone columns catering to the varying soil profile under the tank. Such value engineering based design would not have been possible without adequate soil investigation data in terms of CPTs provided during design stage. This has also been postulated by Daramalinggam et al. (2009).

5.3 *Discussion on future settlements*

Generally, it was noted that measured tank edge settlements were lower than design prediction as seen from Figure 5. This may be attributed to the following reasons.

The tank height is 20m whereas design fluid height inside tank is about 18.53m. Even under full height of water, the imposed loading could be only about 182kPa. Hence settlements estimated using a design loading of 200kPa could be slightly over estimated.

The test was held at full water height only for 3 days due to tight schedule for tank handover. Hence consolidation settlements under tank loading did not occur completely and are still expected to occur in the future. Hence the future settlement monitoring of tank during operation stage is essential.

6 CONCLUSION

Ground improvement by Vibro Replacement has been widely adopted for tank farm foundations in Asia (Raju and Sondermann (2006), Leong and Raju (2007), Raju and Daramalinggam (2007), and Raju (2009)). The salient feature of ground improvement method is that it is a mass improvement concept which involves strengthening of soil mass. The design involves utilizing the improved strength of treated soil rather than conventional pile design concept where load is transferred to deeper hard stratum thus requiring deeper and more expensive foundation solution. As soil stratigraphy plays a major role in the success of ground improvement option, soil investigation data is important in ground improvement design. Availability of extensive soil investigation data will help identifying the areas of concern and exploring avenues of optimization. Hence value based engineering and innovation in design methodology is possible while applying ground improvement coupled with suitable soil data.

For the current project, subsurface soil conditions revealed by extensive CPTs and boreholes under various tanks were studied and elaborated stone column scheme was proposed as foundation solution for each tank. The tank settlements predicted based on designed stone columns scheme satisfied the required performance criteria in terms of total and differential settlements. During hydrostatic tests, the tank settlements were found to be well within the design prediction. The overall tank edge settlement trend followed what was predicted during design. Hence, stone column solution met the performance criteria for the project and proved an attractive alternative foundation solution.

7 REFERENCES

American Petroleum Institute (API). 2009. API Standard 653. *Tank Inspection, Repair, Alteration, and Reconstruction*. API Publishing Services, Washington DC.

Daramalinggam J., Leong K.W. and Partzsch S. 2009. Comprehensive Site Investigation and Construction Monitoring for Tank Farms on Improved Ground. *Ground Improvement Technologies and Case Histories*, Leung C.F., Chu J. and Shen R.F. (eds.), 647-654.

He Z.W., Leong K.W. and Selvaraju S. 2015. Steel Tanks On Deep Vibro Techniques Improved Ground. *Advances in Soft Ground Engineering*. Leung C.F., Ku T. and Chian S.C. (eds.), 387-397.

Leong K.W., and Raju V.R. 2007. The construction and performance of foundations using vibro techniques for an oil storage terminal in Singapore. *Proceedings of 16th Southeast Asian Geotechnical Conference*, Kuala Lumpur, 585-590.

Leung C.F and Leong K.W. 2014. Foundation versus ground improvement in soft soils. *Keynote, Proceedings of Soft Soils 2014*, Bandung, Indonesia, A3-1--A3-14

Priebe H.J. 1995. Design of Vibro Replacement. *Ground Engineering December 1995*, 31-37.

Raju V.R. 2009. Ground Improvement – Principles and Applications in Asia. *Ground Improvement Technologies and Case Histories*, Leung C.F., Chu J. and Shen R.F. (eds.), 43-65.

Raju V.R., and Daramalinggam J. 2007. Optimized foundation systems using deep vibro techniques for large tank farms. *Proceedings of 13th Asian Regional Conference on Soil Mechanics and Foundation Engineering*, Kolkata, India.

Raju V.R., and Sondermann W. 2006. Ground Improvement using Deep Vibro Techniques. *Ground Improvement Case Histories*. Indraratna B and Chu J (eds.), 601-638.