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Multiphase deep vibro solution for biodiesel plant expansion in Singapore

Solution vibro profonde multiphasé pour l'expansion de l'usine de biodiesel à Singapour

Selvaganesh Selvaraju, ZhiWei He & Kam Weng Leong

Keller Foundations (S E Asia) Pte. Ltd, Singapore, selvaganesh@kellersing.com.sg

ABSTRACT: A state-of-the-art biodiesel plant in Singapore proposed its expansion plans in 2018 comprising various structures such as steel storage tanks, pipe racks, and ancillary structures. The foundations of storage tanks are to be designed to satisfy a stringent differential settlement criteria of 13mm over 10m of circumference prescribed by API standard 650, while other structures are to satisfy a criteria of 30mm over 10m span. The soil profile consists of a top layer of firm to stiff silty clay, followed by loose to medium dense sand. The sand layer is underlain by firm marine clay followed by stiff-very stiff clay. Underneath the firm clay layer are residual soils of Jurong formation with SPT N more than 50. An innovative 3-phase deep vibro techniques scheme is adopted to treat the 3 main types of soil in the cross section: Phase 1 Vibro stone columns to treat bottom firm clay; Phase 2 Vibro compaction of over-lying loose-medium dense reclaimed sand; Phase 3 Vibro stone columns to treat firm to stiff silty clay near the surface. Hundreds of Cone Penetration Tests (CPTs) are carried out to capture soil variation and design the treatment depths precisely catering to the varying soil conditions. In this paper, the deep vibro techniques solution would be described with predicted settlements compared with actual monitored settlements during hydrostatic test. With deep vibro techniques, estimated carbon savings is about 77% compared to a driven piling solution, the details of which are presented.

RÉSUMÉ : Une usine de biodiesel ultramoderne qui existe actuellement à Singapour prévoit son expansion. Il se compose de diverses structures telles que des réservoirs de stockage en acier de diamètre, des supports de tuyaux et des structures auxiliaires. Les fondations des réservoirs de stockage, par exemple, doivent satisfaire à un critère de tassement différentiel rigoureux de 13 mm sur 10 m de circonférence prescrit par la norme API 650, tandis que d'autres structures doivent satisfaire un critère de 30 mm sur 10 m de portée. Le profil du sol se compose d'une argile molle-ferme de 4 à 5 m d'épaisseur, suivie de 10 à 20 m de sable lâche à moyennement dense, suivi d'une argile molle à ferme de 3 à 6 m d'épaisseur, reposant sur de l'argile rigide à très rigide, suivi de la formation Jurong de SPT N plus de 50. Un tel profil de sol variable a nécessité un schéma innovant de techniques vibro profondes en 3 phases pour traiter les 3 principaux types de sol dans la section transversale : Phase 1 Colonnes de pierre Vibro pour traiter l'argile molle-ferme du fond ; Phase 2 Vibro-compaction de sable récupéré de densité moyenne et meuble surplombant ; Phase 3 Colonnes en pierre Vibro pour traiter l'argile molle-ferme près de la surface. Un vaste programme d'investigation des sols comprenant des centaines de tests de pénétration au cône (CPT) a été réalisé pour capturer la variation du sol et concevoir les profondeurs de traitement répondant précisément aux différentes conditions du sol. Dans cet article, la solution des techniques de vibro profonde sera décrite avec des tassements prédits par rapport aux tassements réels surveillés pendant le test hydrostatique. Avec les techniques de vibro profond, les économies de carbone estimées sont d'environ 77% par rapport à une solution d'empilage entraîné, dont les détails sont présentés.

KEYWORDS: Vibro stone columns, Vibro compaction, multiphase ground improvement, API standard 650.

1 INTRODUCTION

Globally, 18% of the energy consumed for heating, power, and transportation was from renewable sources in 2017. Nearly 60% percent came from modern renewables (i.e., biomass, geothermal, solar, hydro, wind, and biofuels) and the remainder from traditional biomass. Renewable energy made up 26.2% of global electricity generation in 2018. That is expected to rise to 45% by 2040 (<https://www.ren21.net/reports/global-status-report/>). Especially in the field of passenger transportation, which globally consumes 25% of all energy produced (U.S. EIA, International Energy Outlook 2016), use of renewable energy sources can reduce carbon emissions. One such product is biodiesel which is manufactured by recycling domestic wastes and vegetable oils. Advantage of using biodiesel is that it helps in recycling the domestic wastes which otherwise are a hassle to handle especially in developing countries. This paper discusses the application of an innovative multiphase deep vibro techniques solution as foundation solution for the expansion of a state-of-the-art biodiesel manufacturing plant in Singapore.

2 EXISTING PLANT AND ITS EXPANSION

The plant is located in the western part of Singapore where soil condition is predominantly reclaimed since the early 1990s. The layout of the existing plant in conjunction with two new plots for

expansion on the southern and western side of the existing plant is shown in Figure 1. The existing plant was constructed with foundation for various structures supported on deep vibro techniques. With the satisfactory performance of structures in existing plant, deep vibro techniques were again adopted to support similar structures in the expansion. The following sections will give a comparative description of the soil conditions, structures, treatment scheme and design of deep vibro techniques solution for the expansion area and the existing plant.



Figure 1. Site layout showing the existing plant and new expansion area.

The following sections will describe the soil conditions, structures, deep vibro techniques scheme adopted at the existing plant first followed by the new expansion.

3 EXISTING PLANT ON DEEP VIBRO TECHNIQUES

The existing plant, commissioned in the year 2011, was constructed between 2008 and 2011 with deep vibro techniques as the foundation solution to support structures such as storage tanks, pipe racks, lighter structures, open areas, and roads. More details about the existing plant are described in the following sections with specific focus to storage tanks.

3.1 Soil conditions

The soil condition at the existing plant consists of loose to medium dense reclaimed sand to a depth of about 15-19m with a cone resistance $q_c \approx 5-10$ MPa underlain by a soft to firm marine clay layer up to depths of 20-24m depths with $q_c \approx 0.5-1$ MPa. Beneath this sand layer are stiff to hard silts with SPT $N=24-60$ and $q_c \approx 1-3$ MPa up to depths of 24-30m. This is underlain by residual soils of Jurong Formation with SPT $N > 60$. The idealised soil profile and soil investigation layout of the existing plant's tank farm is shown in Figure 2. On an average 4-5 Cone Penetration Tests (CPTs) were carried out for each tank prior to design to determine the soil conditions.

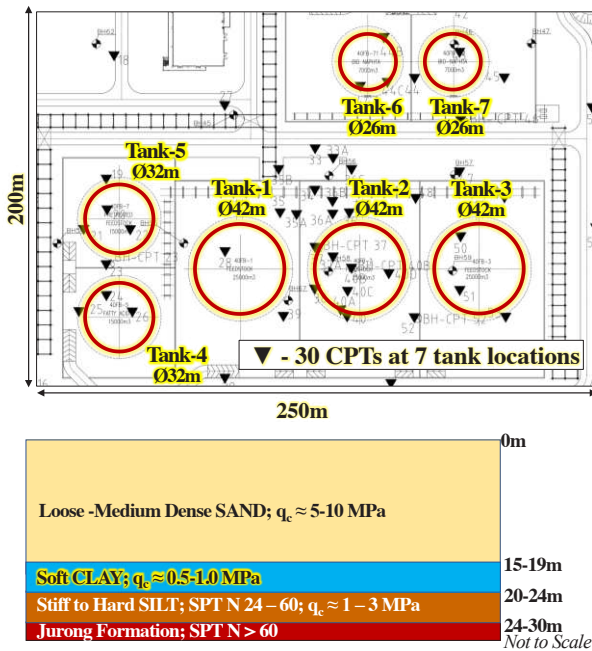


Figure 2. (Top) Soil investigation layout for tanks at existing plant; (Bottom) Typical soil profile based on CPTs and boreholes.

3.2 Structures, loading and performance criteria

The structures supported on deep vibro techniques improved ground at existing plant consisted of storage tanks, pipe racks, lighter structures, open areas, and roads. The design loading and settlement criteria of structures at existing plant and expansion area are summarized in Table 1 and Table 2.

3.3 Deep vibro techniques solution

Based on the soil conditions studied from reports of soil investigation, a two-phase deep vibro solution comprising of vibro compaction and vibro stone columns was adopted. In the first phase vibro stone columns were installed in the bottom soft clay layer. In the second phase, vibro compaction was carried out to densify the loose reclaimed sands above the stone columns treated soft clay layer. The adopted deep vibro techniques scheme is schematised in Figure 3. Vibro stone columns (denoted 1-VSC) were installed by deploying a crane hung system called the Alpha-S by the bottom feed method. After installing vibro

stone columns, another crane hung system setup with the depth vibrator is moved to the area to carry out vibro compaction works (denoted as 2-VC).

Table 1. Structures, design loading and performance criteria

Structures	Design loading (kPa)	Settlement criteria (mm)
Tanks	265	EEMUA 159
Pipe racks	20*	25
Ancillary structures	20*	50

*Uniformly distributed equivalent loading of 20kPa.

Table 2. Performance criteria for tanks based on EEMUA 159

Differential settlement	Criteria
Centre – Edge	1.833% tank diameter
Planar Tilt	1/100 of tank height
Differential settlement	Criteria
Out-of-verticality	1.0% tank diameter
Circumferential	100mm over 10m of circumference

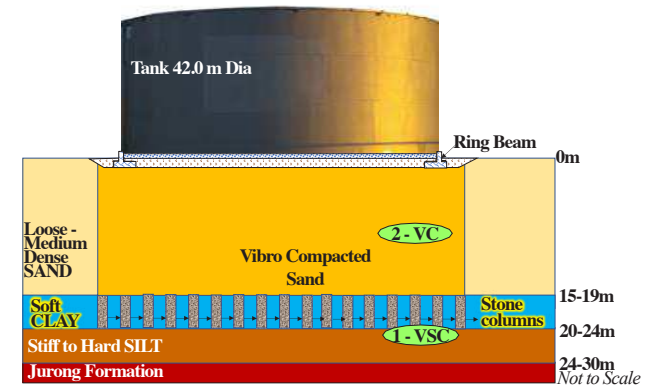


Figure 3. Soil condition and treatment scheme for a typical 042m tank at existing plant

3.3 Tank settlements – design prediction and measurement

The improved properties of the stone columns treated soil were estimated according to Priebe (1995) method by establishing an improvement factor. A detailed description of estimation of improved stiffness of stone columns treated soils is presented in He et al. (2015). Based on Priebe (1995) method, the composite stiffness of the stone columns improved ground is estimated using Eq.1, where E_c = composite modulus in kPa, E_s = modulus of in-situ soil in kPa and n = improvement factor estimated based on Priebe (1995). The improved stiffness (constrained modulus, M_o) of the vibro compacted sand is estimated based on Lunne and Christophersen (1983) (see Eq. 2, 3 & 4).

$$E_c = E_s \cdot n \quad (1)$$

$$M_o = 4q_c \text{ MPa} \quad \text{for } q_c < 10 \text{ MPa} \quad (2)$$

$$M_o = 2q_c + 20 \text{ MPa} \quad \text{for } 10 \text{ MPa} \leq q_c < 50 \text{ MPa} \quad (3)$$

$$M_o = 120 \text{ MPa} \quad \text{for } q_c \geq 50 \text{ MPa} \quad (4)$$

Based on the methodology described above, the estimated total edge settlements for various tanks are summarised in Table 3. The total tank edge settlement was estimated to be about 60 – 130mm during hydrostatic test and 50 – 120mm post hydrostatic test. Based on 20-26 numbers of settlement markers, observed tank edge settlements during hydrostatic test, varied between 20 – 80mm. The circumferential plot of settlements presented in Figure 4 shows observed tank edge settlements of 50 – 120mm which is well within design prediction. The observed settlements during hydrostatic test was quite uniform settlement at the tank edge and satisfied the stipulated differential settlement criteria.

Table 3. Settlements at tank edge prediction and actual

Tank dia	During hydrostatic test (mm)		Post hydrostatic test (mm)	
	Prediction	Actual	Prediction	Actual
26 - 42m	60 – 130	20 – 80	50 – 120	NA.

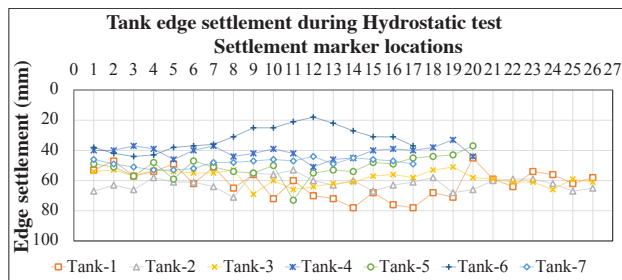


Figure 4. Edge settlements during hydrostatic for Tanks 1 – 7

4 EXPANSION AREA ON DEEP VIBRO TECHNIQUES

In 2019, expansion of the existing plant was proposed at two new plots on the southern and western side of the existing plant. This expansion is expected to increase the production capability of the plant to meet the growing demand for the renewable fuel. The successful application of deep vibro techniques in the existing plant to support important structures was instrumental in the developer willing to explore deep vibro techniques for the expansion area as well. The upcoming sections describe the highly varying soil conditions, structural loading, settlement criteria and observed tank settlements compared with design prediction.

4.1 Soil conditions

Based on the available soil investigation data, the soil conditions at the expansion area are found to be similar to those at the existing plant with certain differences. The bottom clay layer between depths of 20 – 25 m, found in the existing plant, is also observed in the expansion area. This layer appears to be firm in consistency and not as soft as it was during the construction of the existing plant in 2007-08. Unlike the existing plant where the top surface is clean reclaimed sand, at certain areas in the expansion area a fill layer is observed comprising of silts and clays that are uncharacteristic of a typically reclaimed land in Singapore.

A typical soil profile, as summarised in Figure 5 (Top), at the expansion area consists of firm to stiff sandy to silty clay with $q_c \approx 0.5-1.0$ MPa upto 5-6m depths. This fill material is sometimes found to be loose silty to clayey sands with $q_c \approx 2.5-6.0$ MPa. This is underlain by loose to medium dense sand to depths of 19.5–20.5m with $q_c \approx 3.0-11.0$ MPa, followed by firm clay with $q_c \approx 0.9-1.5$ MPa to depths of 21.5–24.0m. This sand layer is followed by a layer of stiff to hard clay layer between 22.0–31.5m depths with $q_c \approx 2.0-5.5$ MPa followed by residual soils of Jurong Formation with SPT $N \geq 50$ which is resting on sedimentary rock of grade S(III) siltstone and sandstone.

4.1.1 Top fill layer

Preliminary soil investigation data showed the extent of this top fill layer was rather heterogenous and widespread. The bottom levels of the top fill layer across the tank locations are summarised in the form of a contour in Figure 5. While there were 12 tanks in the expansion area, the case study in this paper focusses on the main tank farm of 8 tanks with diameters of up to 38m.

Considering an average current ground level of about 104mRL the thickness of the top fill layer varied from 0.5 – 7m across the tank farm. The soil type and properties of this top fill layer was found to be highly heterogenous and of mixed nature

– sandy silts to silty clays. Considering the presence of this layer was prevalent and varying in the tank farm area, the extent and depth of this layer had to be identified carefully in the expansion area to ensure the tanks do not undergo excessive settlements during their operation lifespan. It was important that a carefully planned soil investigation scheme is carried out before design and execution of deep vibro techniques.

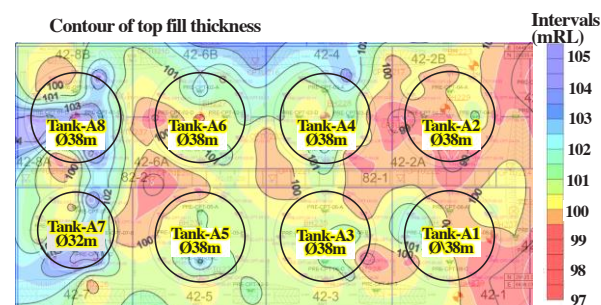
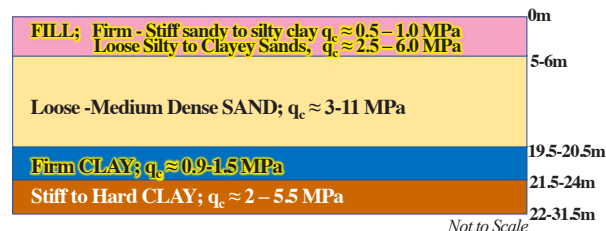


Figure 5. (Top) Typical soil profile across the tank farm; (Bottom) Contour of top fill layer thickness at tank farm area with tank shell outline shown in black rings.

4.2 Structures, loading and performance criteria

The loading and performance criteria for the structures to be built in the expansion area are similar to those in the existing plant except that the tanks are designed compliant to API standard 650 as summarised in Table 3.

Table 3. Structures, design loading and performance criteria

Structures	Design loading (kPa)	Settlement criteria (mm)
Tanks	265	API Standard 650
Pipe racks	20*	25 [§]
Light structures, Open areas, and roads	20*	50

*Uniformly distributed equivalent loading of 20kPa.

[§]With a differential settlement criterion ≤ 15 mm with respect to tank edge

This code specifies a stringent circumferential settlement criterion of 13mm over 10m of circumference during hydrostatic test monitoring which was adopted as the design criteria. Even though there were no requirements for total and centre-to-edge differential settlement or planar tilt as stipulated by API standard 650, the circumference differential settlement criteria of 13mm over 10m was about 7.6 times more stringent than that based on EEMUA 159 as tabulated in Table 4.

Table 4. Loading and performance criteria for tanks at expansion area based on API standard 650 compared with

Structures	Design loading (kPa)	Differential settlement over 10m of circumference	
		Existing plant (EEMUA 159)	Expansion area (API standard 650)
Tanks	265	100mm	13mm

4.3 Deep vibro techniques solution at expansion area

As described in earlier sections, the soil condition was highly varied due to presence of top mixed fill. Hence, in order to satisfy

the stringent settlement criteria, a clear understanding of the soil condition was needed prior to design. As a first step towards a solution, a detailed cone penetration testing scheme was prescribed for each of the tanks as stipulated by Selvaraju et al. (2017) for application of vibro replacement stone columns for storage tanks with similar circumferential settlement criteria.

In addition to the preliminary soil investigation data from 14 boreholes and 11 CPTs in the tank farm, an additional 134 CPTs were carried out for the 8 tanks. For a typical tank of 38m diameter, 17 CPTs were carried out for each tank out of which 12 CPTs were placed along the circumference and remaining 5 CPTs inside the centre of the proposed tank footprint. The layout of CPTs at the tank farm zone of the expansion area is shown in Figure 6. The CPTs at the circumference were spaced 10m apart from one another to check the soil profile carefully along the circumference to design the deep vibro techniques scheme complying to the tank performance criteria, especially at the tank circumference.

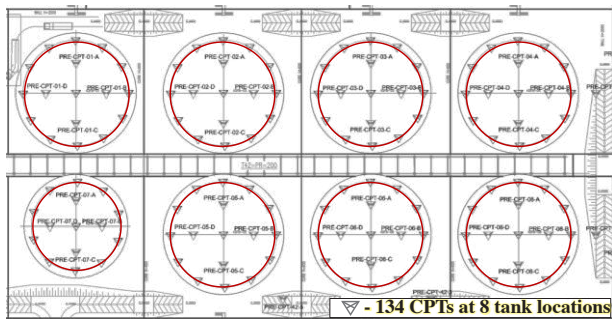


Figure 6. Layout of CPTs at the tank farm in expansion area

The abundant soil profile information known with detailed CPT scheme further aided by the existing boreholes information were key to understand the soil profile variation. As shown in Figure 7, a customised zoning of treatment depths varying from d1 to d17 based on CPT demarcation was visualised even during the early design stages to capture the soil variation to the best of the available information. While it is important to understand the soil profile at the circumference, it is also important to treat the centre of the tank footprint well enough to leave no top fill layer or bottom firm clay untreated. Hence the zoning was not only focussed on circumference but also under the centre of the tank.

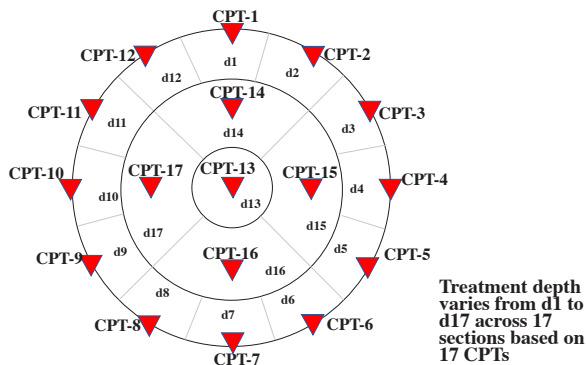


Figure 7. Typical CPT layout and treatment zoning for a typical 38m diameter tank in expansion

The three main soil types (bottom clay, reclaimed sand, and top fill layer) observed in the cross section were different in nature and varied in strength and consistency. Hence a customised treatment scheme was envisaged catering to layer properties rather than adopting one type of treatment for the entire soil profile. Hence the design treatment scheme consisted of a three-phase deep vibro techniques scheme as shown in Figure 8. The first two phases of this scheme are similar to the treatment scheme adopted for the existing plant where the vibro

stone columns (denoted 1-VSC in Figure 8) were installed by the crane hung system Alpha-S system by bottom feed method in the bottom firm clay layer between depths of up to 25m. Prior to this, a phase of preboring was carried out to loosen the sand layer to facilitate the penetration of the stone columns installation in the first phase. After the installation of the first phase of stone columns, the second phase comprised of vibro compaction works in sand layer (denoted as 2-VC in Figure 8) using a crane hung system as well but setup with the depth vibrator meant for vibro compaction. Further to this, a third phase was carried out where vibro stone columns were installed in the top fill layer (denoted as 3-VSC in Figure 8) using an in-house vibro replacement rig (called Vibrocatt) which are typically common in treating soft clays as described by He et al (2015).

As the treatment was done in three phases, three different optimised grid spacing were designed for vibro stone columns (VSC) and vibro compaction (VC) to satisfy the performance criteria and at the same time not overtreating the soil. For instance, the bottom firm clay was treated with a wider spacing grid of stone columns as layer was firm, whereas the top fill layer which seemed recently placed, was treated with a tighter grid spacing stone columns. The adopted three phase deep vibro techniques scheme for a typical tank in the expansion area is schematically illustrated in Figure 8.

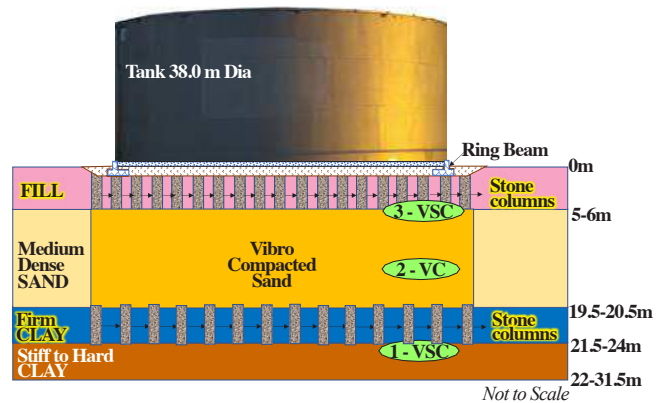


Figure 8. Soil condition, treatment scheme for a typical tank at expansion area.

4.4 Tank settlements – design prediction and measurement

The design methodology adopted to predict tank settlements is same as that adopted in existing plant – using Priebe (1995) method for stone columns treated soil and using the correlation based constrained modulus for the vibro compacted sand. The design settlement prediction initially was based on a given tank loading of 265kPa. During hydrostatic test, the actual maximum water height was only about 20m. As the settlement due to structural loads from the tank is generally minimal ($\approx 5\%$) compared to the tank fluid load, it was assumed that the predominant loading experienced by the ground would be tank fluid load estimated to be about 200 kPa ($20\text{m} \times 9.81\text{kN/m}^3 \approx 200\text{ kN/m}^2$ or 200 kPa). Hence the settlement prediction during hydrostatic test and total settlement presented here are based on a loading of 200kPa to compare with observed settlements at the end of hydrostatic test done with 20m of water height. The tank's edge settlement at various stages of the hydrostatic test (water heights of 25%, 50%, 75%, 100%, 100% holding at 1, 5 and 10 weeks) for a typical tank are presented in Figure 9.

The observed tank edge settlements at various stages until 100% water height held for 10 weeks (2.5 months) were uniform and showed good stabilisation as substantiated by the fact that the difference in tank edge settlements between different stages kept reducing and showed very minimal increase between the readings at 100% held for 5 weeks and 10 weeks. In addition, the stabilised tank edge settlements at the final stage were quite

matching to the tank circumferential settlement predicted to occur at the end of the hydrostatic test. This showed that the design methodology adopted was quite appropriate for the design of deep vibro techniques scheme and prediction of tank settlements. The difference between the maximum tank edge settlement at hydrostatic test and the total settlement is the anticipated long-term settlement which is expected to occur during the tank service life and based on the observed trends which are close to the predicted values. It could be concluded that tank edge settlements were well within design prediction and resulted in satisfactory tank performance during hydrostatic test.

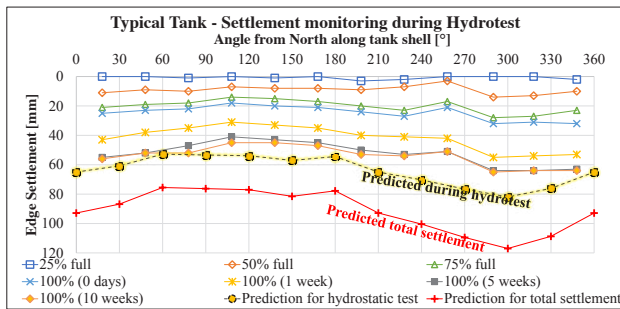


Figure 9. Tank edge settlements – prediction vs actual

To assess the circumferential differential settlement, the methodology suggested by Leung and Leong (2014), He et al. (2015) and Selvaraju et al. (2017) was adopted in the design calculations. Using this method, circumferential differential settlement is calculated in terms of out-of-plane deflection from a cosine curve fitted for the tank edge settlements. Out of plane deflection at a point “i”, along the tank circumference is calculated using Eq. (5) where S_i is the out of plane deflection at point i and U_{i-1} , U_i and U_{i+1} are out of plane settlements at points i-1, i and i+1 are the differences between the estimated design tank edge settlement and the corresponding value from fitted cosine curve at points i-1, i and i+1 along the tank shell. Under this method, an optimum cosine plane is derived of the form $a+b\cos(\theta+c)$; parameters a, b and c are determined by least squares methods using actual monitored edge settlements to limit the out of plane deflection to not more than 13mm over 10m of circumference.

$$S_i = U_i - (1/2 U_{i-1} + 1/2 U_{i+1}) \quad (5)$$

The out of plane deflection was calculated at various points along the circumference of the tank based on the above methodology and presented in Figure 10 in comparison with the out of plane deflection values for the stabilised actual tank edge settlements at the end of hydrostatic test. As observed from Figure 10, the out of plane deflection values for actual tank edge settlements were within the allowable limits of 13mm over 10m of circumference, and more uniform and lesser in absolute magnitude than the predicted values from design. Hence both the total tank edge settlement and circumferential settlement observed were satisfactory and in line with prediction.

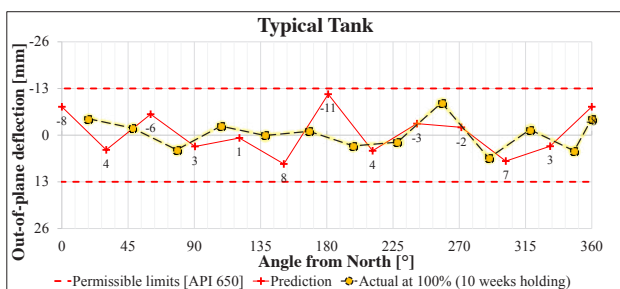


Figure 10. Out of plane deflection at tank edge – prediction vs actual

The general smoother nature of the actual out of plane deflections is due to the soil structure interaction phenomenon whereby some differential settlements are absorbed by the tank steel shell which is generally quite ductile in nature and can accommodate settlements better than rigid structures. From the results presented, it could be summarised that both in the existing plant and in the expansion area, despite the challenging soil conditions, deep vibro techniques proved to be a suitable foundation solution to support structures designed with a reasonable settlement criterion.

5 SUSTAINABILITY AND CARBON FOOTPRINT OF THE DEEP VIBRO TECHNIQUES SOLUTION

As mentioned in the previous sections, the end-product to be manufactured by this state-of-the-art plant is a renewable biodiesel which is slated to be used across all sectors especially transportation and even in strategic sectors such as aviation. While the product to be manufactured is itself eco-friendly, it is also equally important and relevant that the construction of such a plant is also eco-friendly or in other words “sustainable”. The upcoming paragraphs explain the estimated environmental impact, in terms of carbon emission, that could possibly be caused by deep vibro techniques in comparison with commonly adopted foundation solution like piling.

5.1 Sustainability and its importance in construction industry

Sustainability can be defined as the processes and actions through which one strives to meet the needs of the present without compromising the ability of future generations to meet their needs (Brundtland report, 1987). In 2005, the World Summit on Social Development identified three core areas that contribute to sustainable development – economic development, social development, and environmental protection. Construction industry accounts for 36% of worldwide energy usage, and 40% of CO₂ emissions (International Energy Agency, 2019. Global Status Report for Buildings and Construction 2019). Construction can also result in hazardous waste, and the improper disposal of such waste can result in pollution that affects not just the environment, but also the health of people living in that area. The heavy machinery used in construction still rely heavily on fossil fuels, and even inefficient electricity use can result in the unnecessary burning of fossil fuels further down the energy supply line. Hence it is important to monitor and reduce the CO₂ emissions in construction projects.

5.2 Calculation of carbon emissions using CO₂-equivalents

The concept of embodied CO₂ is useful as it provides an indication of the amount of Green House Gases (GHG) emitted by an activity of production process (Egan and Slocombe, 2009). Embodied carbon calculations therefore require an understanding of all the materials, or ingredients, within the products, and all activities related to those materials, such as processing and transport. The term carbon dioxide equivalent CO₂e is a standard unit for measuring carbon footprints. The idea is to express the impact of each different greenhouse gas in terms of the amount of CO₂ that would create the same amount of warming. That way, a carbon footprint consisting of various greenhouse gases can be expressed as a single number. The European Federation of Foundation Contractors (EFFC) and Deep Foundations Institute (DFI) have developed a sector-specific carbon accounting methodology and associated “carbon calculator” for foundations and geotechnical works intended to be an internationally adopted tool for ground engineering works. In 2011, a working group comprising of geotechnical contractors, funded by EFFC and DFI, tailored a methodology to allow a Microsoft® Excel version of the calculator. With various research and development, by year 2016 a version 3.0 of the

EFFC-DFI Carbon Calculator was released to help engineers and planners calculate the CO₂e involved in a construction project. The detailed procedure to calculate the CO₂e is described in the EFFC-DFI Carbon Calculator Methodological & User Guide version 2.2.

5.3 Estimation of CO₂-equivalents for deep vibro techniques in comparison with piling

Based on the EFFC-DFI carbon calculator version 3, total carbon emissions in terms of greenhouse gas (GHG) CO₂e estimated for the deep vibro techniques solution for the tanks in the southern area of the expansion area was about 1,152 tCO₂e. This is contributed by various factors such as energy, materials, freight etc.. The contribution of various factors is illustrated in Figure 11.

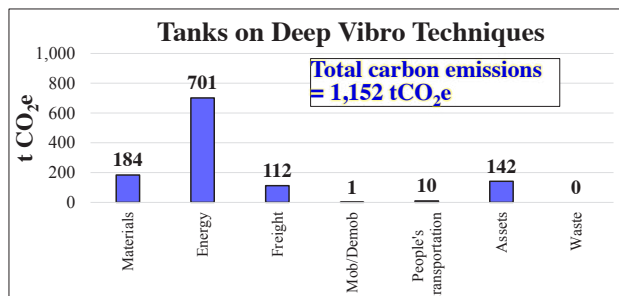


Figure 11. Carbon emissions in CO₂e for deep vibro techniques solution

The actual carbon emissions in the form of CO₂e for deep vibro techniques were estimated using actual project data such as total installed linear metres of deep vibro techniques (VC and VSC), associated materials, fuels used, transport and other factors used were documented in detail throughout the project. For comparison with deep vibro techniques, a fictitious driven pile design scheme was assumed with pile diameter of 600mm at centre-centre square grid spacing of 2.5m for depths of 25m. The assumed pile depth of 25m is on the conservative side, as while using driven piles, the piles need to be installed to much stiffer stratum than that observed at 25m depth at this project. The adopted 25m depth is on the conservative side and purely for comparison purpose with the deep vibro techniques' calculated carbon emissions (CO₂e).

The carbon emissions for the tanks foundation if driven piling solution was adopted would have been about 4,622 tCO₂e. From a simple but lower bound estimate of carbon emissions with driven piling solution, for the tank farm area estimated carbon emissions based on deep vibro techniques, is about 3,470 tCO₂e lesser than a case if driving piling had been adopted. Hence deep vibro techniques achieved a significant 75% reduction in carbon emissions as presented in Figure 12.

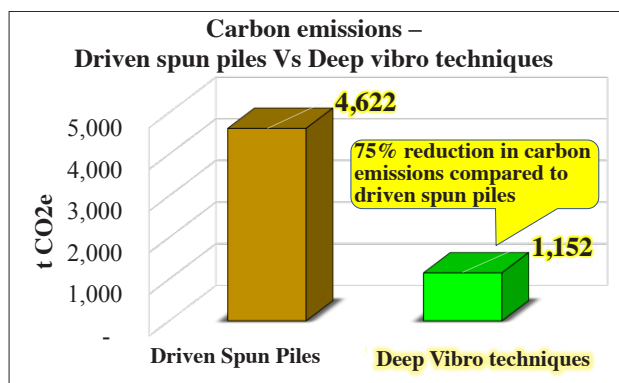


Figure 12. Carbon emissions – Driven piles vs Deep Vibro Techniques

5.4 Equivalencies analogous to the carbon savings

At the tank farm area, nearly 3,600 tCO₂e was reduced by adopting vibro techniques compared to a case if driven spun pile had been adopted. To put this tremendous savings in perspective, the following equivalencies are presented in Figure 13. The amount of carbon emissions saved by adopting deep vibro techniques is equivalent to burning fossil fuels which will fuel an average car driving 359 times around the earth (which is roughly 14 million kilometres) or equivalent to powering about 1,296 homes in Singapore Housing Development Board units. And more importantly, this saving is also equivalent to planting about 4,701 acres (1,903 Hectares) of forests cover increase in a year, which is almost 2.6% of the area of Singapore.



Figure 13. Positive impact of emissions reduced by deep vibro techniques

By analysing the significant reductions achieved by deep vibro techniques coupled with the positive environmental impact that is evident from the equivalencies presented, it is evident that deep vibro techniques are a sustainable and eco-friendly foundation solution.

6 CONCLUSION

The successful application of deep vibro techniques for a biodiesel plant in Singapore was described for the existing plant in 2008 as well as its ongoing expansion beside the existing plant. The ground improvement design process along with the settlement prediction methods were described. The observed tank edge settlements at the end of the hydrostatic test were presented which were found to be well within the design prediction. In addition to total tank edge settlements, the observed circumferential differential settlements were also in line with design prediction. Therefore ground improvement solution comprising of multiphase deep vibro solution satisfied the total settlement as well as the stringent circumferential differential settlement criteria. Hence deep vibro techniques solution could be an eco-friendly and sustainable alternative to driven piling solution providing significant carbon footprint reduction.

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