Remediation of Oil Tank using PLAXIS 3D

A. Gunawan[1]
[1]*Department of Civil Engineering, Bina Nusantara University, Jakarta, Indonesia*
E-mail: agunawan@connect.ust.hk

ABSTRACT: Good and accurate soil investigation is necessary to calculate pile performance with considerable accuracy. Inaccurate or insufficient soil investigation can lead to underestimation or overestimation of pile capacity. For the former case, the design becomes uneconomical, while for the latter case, it can lead to unacceptable settlement, and in worst case scenario, even failure. Recently, there was one such case of an oil tank in East Java. Initial investigation found very dense layer 8 metres below the ground surface until end of investigation depth (30 m depth). Over 300 driven piles were installed to support the tank. Ten piles were tested with Pile Driving Analyzer, and 8 out of 10 did not meet the design capacity. Additional soil investigation later revealed that the very dense layer was only 3 m thick. Below the very dense layer, loose sand was found until 45 m depth. The design was re-evaluated with PLAXIS 3D, and installation of additional piles were required to meet the settlement criterion of 100 mm. However, since it was possible to jack up the oil tank after its settlement, it was decided not to do any remediation.
Keywords: pile, serviceability, soil investigation, numerical analysis.

1. INTRODUCTION

Soil investigation plays a vital role in optimizing a geotechnical design. The number of tests and their depths depends on a lot of factors, namely the load and sensitivity of structure to be constructed, location of hard layers, variability of soil in the area. The location of the tests should be determined by experienced geotechnical engineer in order to achieve the most valuable information with the least tests required. Unfortunately, many project owners, who usually does not come from engineering background, underestimate the importance of soil investigation. They treat them as unnecessary expenses, used only to satisfy the requirement of national standards. However, the cost saving from reducing the number of investigations is far less than the consequences that may occur.

Insufficient or inaccurate soil investigation will require designers to take a more conservative approach, such as taking lower strength and stiffness parameters or higher factor of safety. This makes design inefficient and expensive, often costing more than the money saved from soil investigations. A more dire consequence is when there are unforeseen soil conditions, resulting in excessive settlement, damages or even failures. The repair/remediation cost is usually more expensive than building a new one from scratch.

One recent case was of an oil tank in East Java. Due to inaccurate soil investigation, design capacity of the piles installed was not met. Concern was raised by the project owner, and the design was re-evaluated.

2. PROJECT DETAILS AND PROBLEMS ENCOUNTERED

2.1 Project Information

A 50 m diameter oil tank with 20 Ml (mega litre) capacity was to be built in Tanjung Wangi, East Java, Indonesia. The tank concerned was one of the five tanks to be constructed on site. Three boreholes with SPT (standard penetration test) were carried out to design the five tanks, in which one of the borehole was located in the middle of concerned tank. Three hundred and four driven spun piles (0.4 m diameter) were installed to support this oil tank. Problems were encountered during installation of the piles. Out of the 304 piles installed, 23 of the piles were damaged due to overdriving, while 36 others did not reach their target depth of 10 m. Further increasing the project owner’s concern, the pile capacity test (with Pile Driver Analyzer) reported that 8 out of the 10 piles tested did not meet their design capacity. Thus, the project owner request re-evaluation of the design, and remediation if needed.

2.2 Plan View of the Oil Tank

Figure 1 shows the plan view of oil tank showing the pile layout, as well as the old and new soil investigation location. The 304 piles were spaced 2.5 m apart from each other. For the piles, open circles denote the piles that reached the target depth; red solid circles (36 of them) denote piles with broken pile cap; and blue solid circles (23 of them) denote piles which did not reach their target depth. For the soil investigation, solid square (1 only) denotes the previous borehole location, while the open squares (3 of them) denote the additional soil investigations.

It can be seen that the damaged and short piles (the piles that did not reach target depth) are scattered all around the oil tank, but with majority on the right side of the tank.

Since the old soil investigation was carried out in the middle of the tank, additional soil investigation (BH1) was conducted in its proximity to verify the information provided from existing soil investigation. Another 2 soil investigations were conducted to confirm the uniformity of soil profile under the oil tank.

2.3 Soil Profile (Existing and New Information)

Previous soil investigation showed that the soil in the area consist of sand with varying density. From the ground surface to 3 m depth, medium dense sand was found, followed by dense sand to 7 m depth. From 8 m depth onwards, very dense sand with SPT value over 50 was found. The SPT profile of the previous test is shown in Figure 2. The water table was found 7 m underneath the ground surface.

To verify this data, 1 new borehole was drilled beside the existing borehole, and another 2 at the north east corner and south west corner of the tank. The new investigations revealed that only the top 6 meters of sand were in a dense to very dense state. Below this depth, loose sand was encountered up to 45 m depth, where the sand starts to increase in density. The SPT profile of the new tests is also shown in Figure 2 for comparison. The water table was found at 6 m underneath the ground surface, similar to the previous investigation.

The new investigations unfolded the reason as to why the piles tested did not meet their design capacity. The piles that were meant to be end-bearing piles were in fact floating piles. The short piles were caused by the very dense layer, and the piles were not able to be driven past this layer. The damaged piles were caused by overdriving when attempting to penetrate this very dense layer. Re-evaluation of the oil tank was conducted based on the new information.

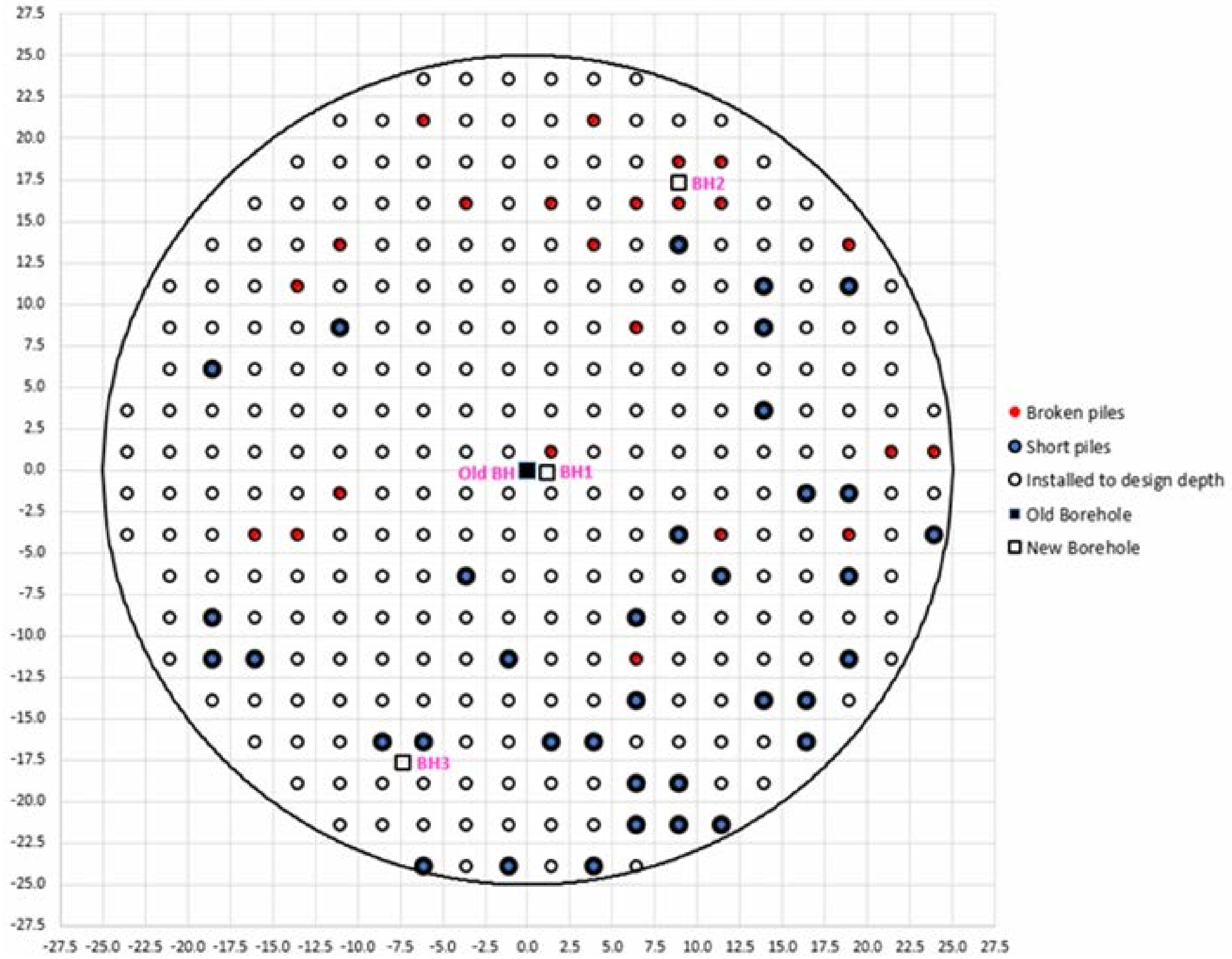

Figure 1 Layout of installed piles

3. RE-EVALUATION OF OIL TANK PERFORMANCE

3.1 Bearing Capacity

Firstly, bearing capacity of the oil tank was evaluated ignoring any of the existing piles (i.e. raft only). The calculation was done using Terzaghi's bearing capacity formula for circular foundation (Terzaghi, 1943).

$$q_u = 1.3\, cN_c + qN_q + 0.3\, \gamma BN_\gamma \quad (1)$$

where q_u is the unit bearing capacity, c is soil's cohesion, q is surcharge above the foot of foundation, γ is unit weight of soil below the foundation, B is the width/diameter of foundation and N_c, N_q and N_γ are the bearing capacity factors.

Since the soil was sand and the foundation was to be founded on the ground surface, c and q = 0, making the first 2 terms in the equation equal to zero. Taking friction angle of sand as 30^o, and effective unit weight of sand = 8 kPa, the bearing capacity can be calculated as q_u = 2300 kPa. The weight of the 21 Ml oil tank is 210,000 kN, giving a pressure underneath the oil tank as 107 kPa. Adding the weight of 0.6 m of raft (pile cap) supporting the oil tank (0.6 x 24 = 14.4 kPa), the total pressure underneath the oil tank is 121.4 kPa. This gives a factor of safety of almost 20, hence bearing capacity is not a problem.

3.2 Liquifaction Analysis

Since the oil tank is to be founded on sand, liquefaction analysis to be analysed. The liquefaction potential is analysed using correlation of cyclic stress ratio versus SPT values by Seed et al. (1985). First the cyclic stress ratio (CSR) has to be calculated using the formula:

$$CSR = 0.65 \times a_{max}/g \times \sigma_0/\sigma_0' \times r_d \quad (2)$$

where a_{max} is the peak ground acceleration, g is gravity, σ_0 is total stress, σ_0' is effective stress and r_d is reduction factor that ranges from 1 at the ground surface, to 0.9 at a depth of 9.6 m. The peak ground acceleration for 10% exceedence in 50 years at Tanjung Wangi is between 0.2 to 0.25 g (Irsyam et al., 2017). By knowing the location of water table, and soil density (Table 1), the CSR can be calculated at any depth. Then, minimum SPT values that does not cause liquefaction under a given CSR can be derived from the chart shown in Figure 3. Before comparing the derived SPT values with field data, the SPT values from the field have to be corrected to 60% energy transferred at 1 atmospheric pressure of overburden. The method to correct the SPT values is given in Peck et al. (1974).

From the evaluation, it was found that the top 6 meters of sand does not liquefy, while the next 25 meters liquefy under 0.25 g acceleration. However, this does not immediately mean that the oil tank is susceptible to liquefaction damages. Ishihara (1985) state that liquefaction damages is also dependent on the thickness of non-liquefied layer. If there is sufficient thickness of non-liquefied soil above the liquefied layer, there will not be liquefaction-induced damages. Based on the chart proposed by Ishihara (1985) shown in figure 4, for 0.25 g acceleration, as long as the non-liquefied layer is thicker than 4.5 m, there is no liquefaction-induced damages. Hence, the oil tank is deemed safe from liquefaction problems.

3.2 Settlement Analysis

To evaluate the settlement of the oil tank, a finite element software, PLAXIS 3D was used. The soil profile used was idealised using the 3 new SPT data, shown by the dashed line in Figure 2.

3.2.1 Constitutive Model and Soil Parameters

The soil model used was Mohr Coulomb, and soil parameters were based on the SPT values. The friction angle and unit weight were estimated using a table by Bowles (1977), while the Young's modulus was estimated by a correlation given by Stroud (1989). Stroud (1989) gives the following correlation:

$$E'/N = 1 \text{ MPa} \quad (3)$$

where *E'* is the Young's modulus, and *N* is the SPT values. The correlation given was for foundation with factor of safety of 3. For foundation with higher factor of safety, higher ratio of *E'/N* can be used. For this case, *E'/N* = 1.2 was chosen. The soil parameters are summarized in Table 1.

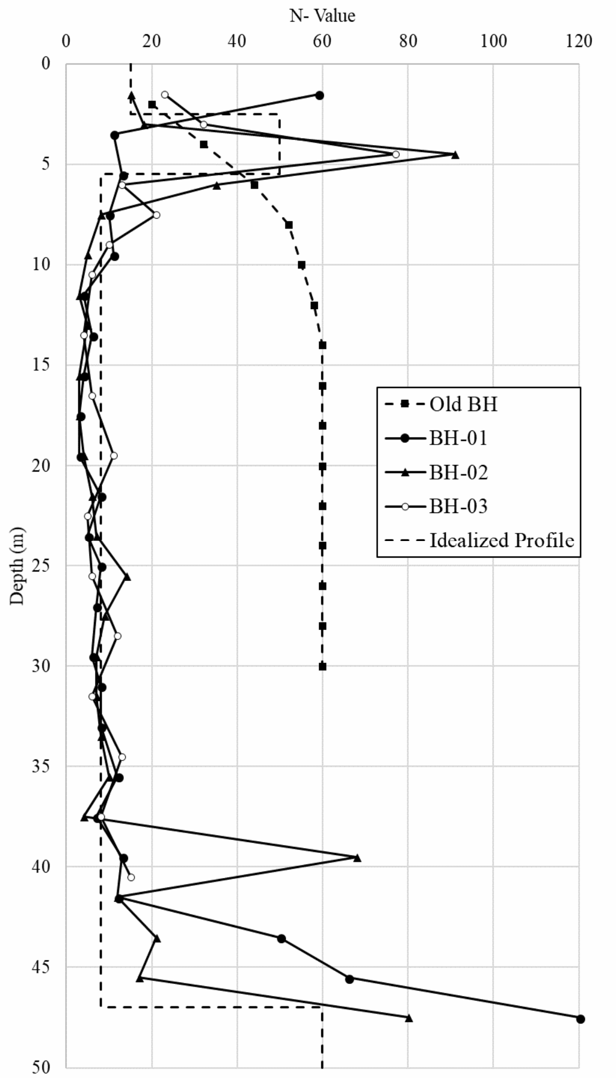

Figure 2 Existing and new SPT N values

Table 1 Soil Profile and Parameters Used for Analysis

Depth (m)	SPT Values	Unit weight (kN/m^3)	Friction angle (^{o})	Young's Modulus (MPa)
0.0-2.5	15	18	30	18000
2.5-5.5	50	19	27	60000
5.5-47.0	8	16.5	28	9600
47.0-70.0	60	20	40	72000

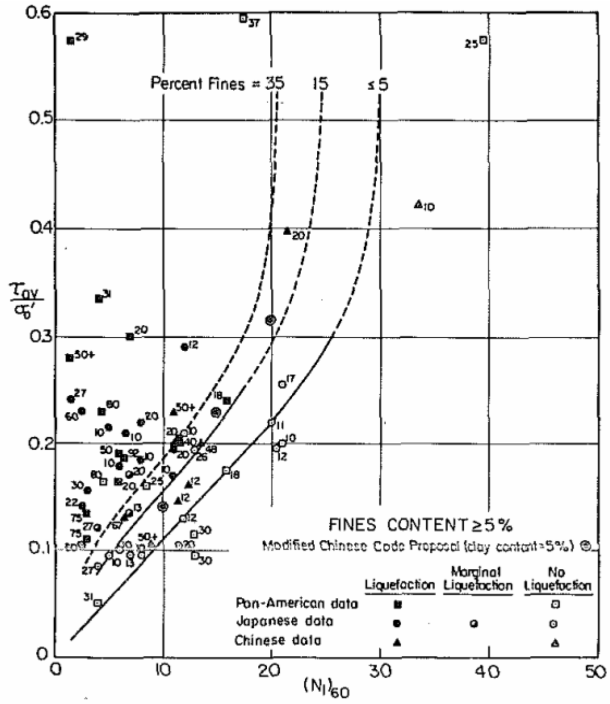

Figure 3 Relationship between stress ratio causing liquefaction and N-values for silty sands (Seed et al. 1985)

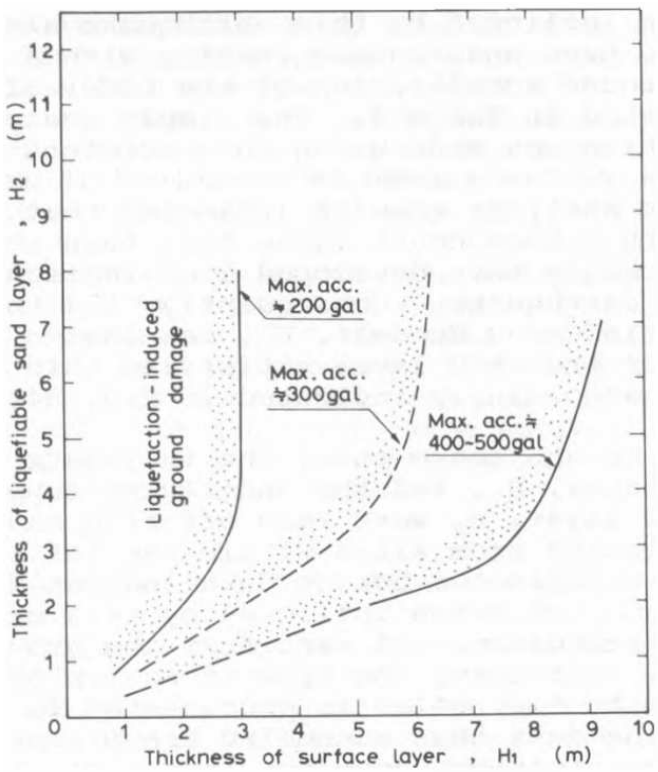

Figure 4 Boundary curves for site identification of liquefaction-induced damage (Ishihara, 1985)

3.2.2 Numerical Model

The numerical model used is shown in Figure 5. The model had a dimension of 150 x 150 x 70 m (length x width x height), with the oil tank located in the center of the model. The piles were modelled as embedded beam elements (Brinkgreve et al., 2017). The broken piles were not modelled, while the short piles were modelled as they were on site. The raft was modelled as plate elements, and the weight of the oil tank was modelled as a distributed load.

3.2.3 Properties of Embedded Beam and Plate

In PLAXIS, the required inputs for embedded beam are Young's modulus, unit weight, diameter, maximum axial skin resistance and base resistance. The young's modulus and unit weight are 28 GPa, and 24 kN/m^3 respectively, typical values for reinforced concrete. The diameter of pile was 0.4 m as previously mentioned. In PLAXIS, the axial skin resistance is automatically calculated, but not the base resistance. The base resistance has to be calculated manually and inserted as input. For the axial skin resistance, only the limiting value is required.

Base resistance of pile was calculated using correlations tabulated by Poulos (1989). Decourt (1982) gave a correlation for driven pile in sand as:

$$f_b = 400 \text{ x N kPa} \quad (4)$$

where f_b is the unit base resistance and N is the average SPT values in the local failure zone.

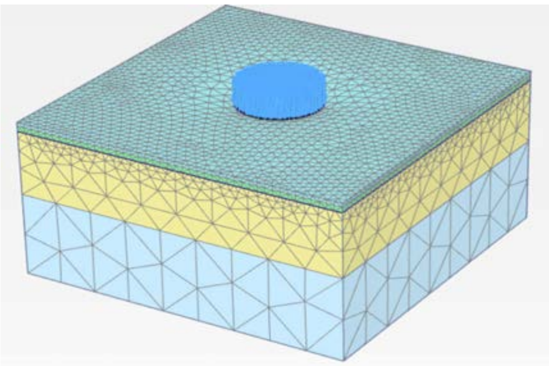

Figure 5 Finite element mesh used

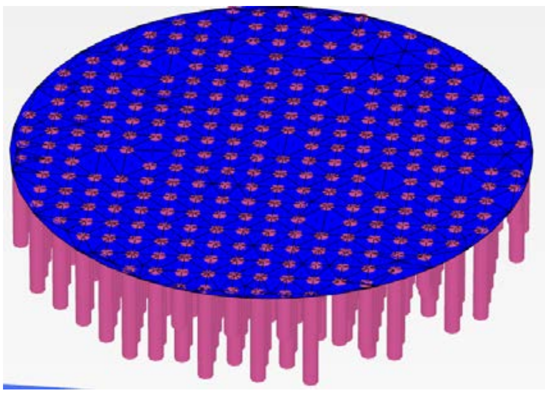

Figure 6 Zoomed in view of foundation piles and pile cap

The limiting shaft resistance was also calculated based on Decourt (1982), whereby he gave the correlation

$$f_s = 3.3 \text{ x N kPa} \quad (5)$$

where f_s is the unit shaft resistance and N is the SPT values at certain pile depth.

For the plate element, the required inputs are thickness, unit weight, Young's modulus and Poisson's ratio. The thickness used was 0.6 m, the same as that planned. Unit weight and Poisson's ratio are 28 GPa and 0.2 respectively, typical values for reinforced concrete.

3.2.4 Modelling Procedure

The modelling of the oil tank followed the following procedure:

1. Generation of initial stress by K_0 procedure
2. Installation/activation of piles
3. Installation/activation of plate
4. Activate surcharge load

3.2.5 Evaluated Settlement

Figure 7 shows the settlement contour of oil tank if the oil tank was to be constructed as it was. The maximum settlement is located in the middle of the tank and minimum settlement is located in the edge of the oil tank. The maximum and minimum settlement are 330 mm and 230 mm respectively. The settlement was higher than the tolerable settlement of 100 mm. Therefore, improvement was required.

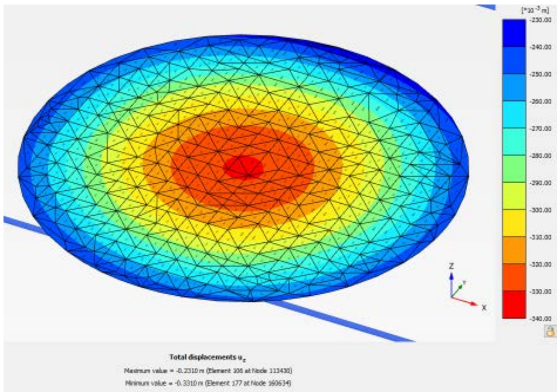

Figure 7 Evaluated settlement distribution without improvement

4. PROPOSED REMEDIATION

In order to reduce the settlement to the acceptable settlement, it was proposed to install additional piles with longer length in between the existing piles. The additional piles were to be driven pile with pre-drilling to 6 metres depth. This was planned to ensure that no piles were damaged while penetrating the very dense layer from 2.5 to 5.5 m depth. Several configurations were attempted to optimize the design, while meeting the settlement criterion. Only the final configuration is presented in this paper.

Figure 8 shows the final proposed layout of additional piles. One center pile and four 'rings' of additional piles were designed. The additional piles were designed to be 0.6 m diameter. The center pile and innermost ring of piles (1st ring: shown by blue diamond in Figure 6) had a depth of 47 m, i.e. founded on the very dense sand layer. The innermost ring of piles consisted of 12 piles and were located 5 m from the center of the foundation. The second innermost ring of piles (2nd ring: shown by green squares) consisted of 24, 40-m long piles to be located 10 m from the center of the foundation. The second outermost ring of piles (3rd ring: shown by blue diamond) had the same depth as innermost ring of piles, i.e. 47 m. The second outermost ring of piles consisted of 36 piles, located 15 m from the center of the foundation. The outermost ring of piles (4th ring: shown by orange triangle) had a depth of 30 m and consisted of 48 piles. This gave a total of 121 additional piles.

The embedded beam properties of the additional piles were evaluated using the methods laid out in section 3.2.3. The numerical procedure was identical to those written in section 3.2.4.

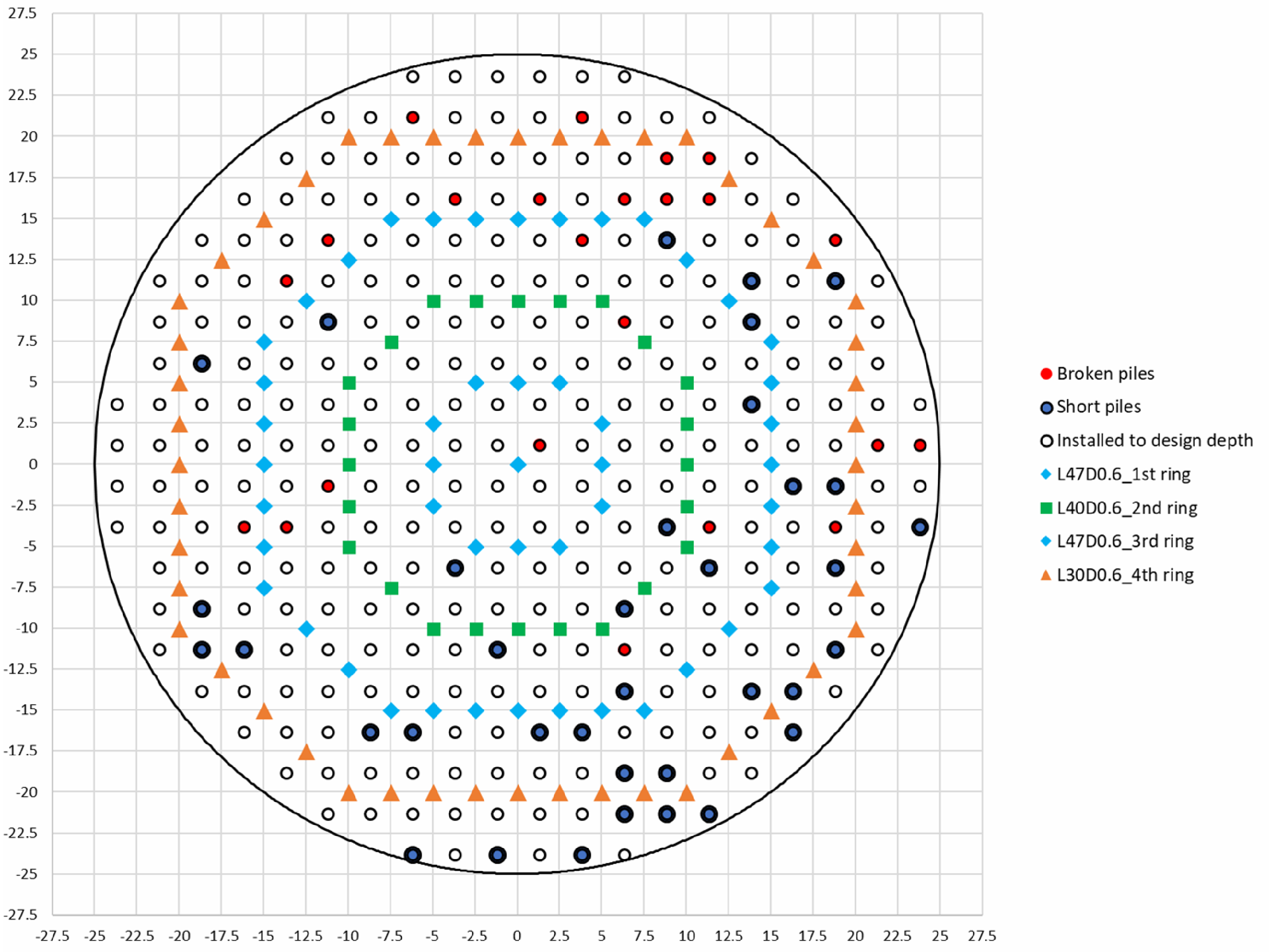

Figure 8 Plan view of the oil tank with additional piles installed

Figure 9 shows the settlement contour of oil tank with the additional piles. The maximum and minimum settlement were 90 mm and 80 mm respectively, with the maximum settlement (shown in red) located at the corners of the tank and minimum settlement (shown in blue) located at the second outermost ring of piles. With the added piles, the settlement was reduced from 330 mm to 90 mm. The differential settlement was also reduced from 100 mm to 10 mm.

5. EVALUATING EFFECTIVENESS OF ADDITIONAL PILES ONLY

To evaluate the effectiveness of 'additional' piles, additional run was conducted without the existing piles (i.e. the oil tank is to be founded only on the 121 piles).

Figure 10 shows the settlement contour of the oil tank, if it were to be founded only on the 'additional' 121 piles. It can be seen that the settlement magnitude is similar, in fact the oil tank founded on the 121 piles without the existing 304 piles had slightly lower settlement than the one with existing 304 piles (refer to Figure 9). This is due to pile group efficiency (Poulos, 1989). For the analysis with existing piles included, the center to center spacing between 2 adjacent piles were as close as 1.25 m, which is only twice the diameter of 'additional' piles. Whereas, if the existing piles did not exist, the piles would have 2.5 m spacing, which is more than 4 times the diameter. Therefore, the 'additional' piles would be more efficient without the existing piles, and hence less settlement.

6. CONCLUSIONS AND DISCUSSION

In this paper, an oil tank to be founded on 304 piles encountered problem during pile installation. Problems encountered include piles not reaching target depth, damaged piles, and piles not reaching their design capacity. Additional soil investigations revealed that the previous soil investigation was not accurate. PLAXIS3D was used to re-evaluate the oil tank design, and remediation was suggested to meet the initial design criterion.

From the analysis conducted, in order to satisfy the settlement criterion of 100 mm, another 121 piles would be needed, in addition to the existing 304 piles. Further analysis shows that by using only 121 piles, the settlement criterion can be met. In fact, without the existing piles, the 121 piles would perform better and settle less than 425 piles. This shows that more piles do not necessarily means better performance, optimization is required.

This case also highlights the importance of good and accurate soil investigations to an effectiveness of geotechnical design. A good practice is to have the design consultant to supervise the driller to countercheck the borelog. This practice is common in countries with established geotechnical practice, e.g. Australia. Unfortunately, such practice is rarely practiced in Indonesia. Another important thing to note about soil investigation are the numbers of soil tests. Many project owners belittle the importance of soil investigation and try to save cost by limiting the number of soil tests. However, the cost saved by reducing the soil tests is often insignificant compared to the potential cost saving from design optimization. In worst case scenario, the lack of information can lead to failures, and lead to heavy losses in terms of money and time. It is an engineer's duty to inform project owners the importance of soil investigation, as it is the very basis of a geotechnical design.

Due to the urgency and heavy cost to remediate the oil tank, the project owner decided to build the tank as it is. Another reason is that the oil tank can be built to accommodate the settlement. The accommodation can be done by jacking up the oil tank after its settlement, and the foundation can be releveled (Wit, 1991). Furthermore, before the oil tank operation, hydrostatic test (Morera and Makar, 2009) would be conducted, whereby the oil tank would be filled to its full capacity with water. Fortunately, the oil tank is founded on sand, hence the settlement will occur very quickly, and the releveling can be conducted after the hydrostatic test. Little or no settlement is expected after the hydrostatic test, as oil has lower density than water, i.e. the operational weight of oil tank is lower than the hydrostatic test.

In conclusion, a good and accurate soil investigation is required for any construction. Without a good soil investigation, the foundation design will not be optimum, and cost more than a design with proper soil investigation. From this case study, one can also learn that remediation may not be necessary, even though the initial design criteria is not met. It is dependent on the structure, as well as soil condition. However, careful evaluation need to be conducted before making the decision.

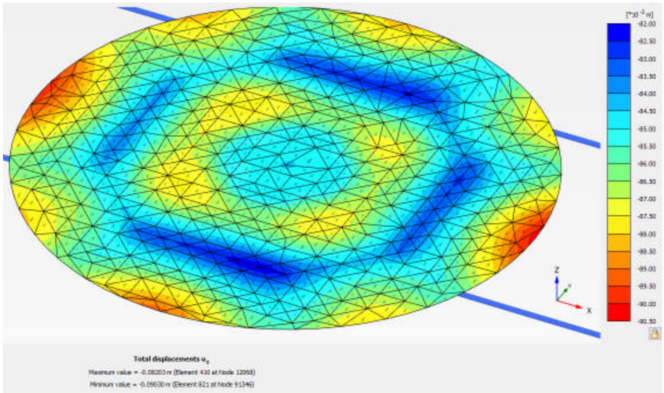

Figure 9 Evaluated settlement distribution with additional piles

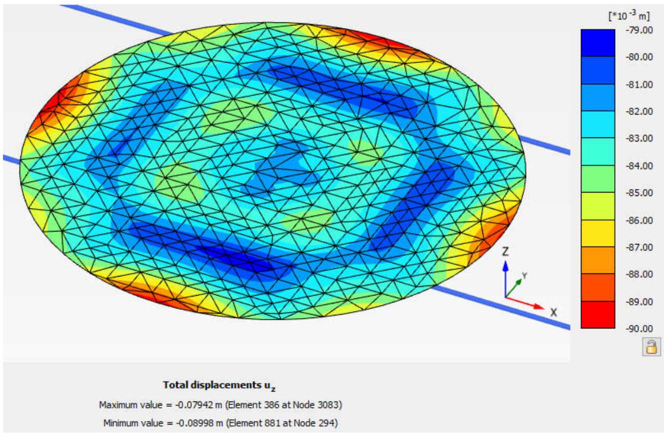

Figure 10 Evaluated settlement distribution with only 121 piles

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