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The Application of Dynamic Compaction to HFO Tanks

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Synopsis: Three heavy fuel oil (HFO) tanks with diameters of up to 60 m, a pump station, a pump shed station and a vent stack station have recently been constructed as part of the HFO Tank Farm in Ras Laffan, Qatar. The project was located in an area near the sea with high groundwater level. The ground was composed of 11 to 12 m of silty sand and gravel with cobbles and boulders with diameters up to 300 mm followed by limestone. The preliminary soil investigation using Standard Penetration Test (SPT) indicated that while the soil was generally dense, but a loose layer of sand was identified and soil improvement was stipulated. During later stages, a supplementary geotechnical investigation using the Menard Pressuremeter Test (PMT) indicated that the high SPT blow counts were not representative of the actual ground conditions and that due to the presence of the large cobbles the soil had erroneously been represented as dense. In fact, the soil was loose from the surface down to bedrock. Dynamic Compaction was used to improve the soil's strength and to reduce its compressibility. PMT in conjunction with finite element analysis were used to verify the ground condition after ground treatment.

Keywords: dynamic compaction, ground improvement, soil improvement, Menard pressuremeter test.

1. Introduction

The Qatari industrial city of Ras Laffan, located on the southern shores of the Persian Gulf and 80 km from Doha, is one of the world's largest oil and gas hubs. This industrial complex is continuously and rapidly being expanded to increase the production of gas from the North Field.

One of the projects that has recently been constructed is the Heavy Fuel Oil (HFO) Facility. The project involved the design and construction of an import line, the storage and process area and an export line, along with the necessary utilities and civil works. The storage and process area includes three HFO tanks, a sub-station, a pump shed and other equipment, piping, shelters and other allied facilities. The site plan can be seen in Figure 1.

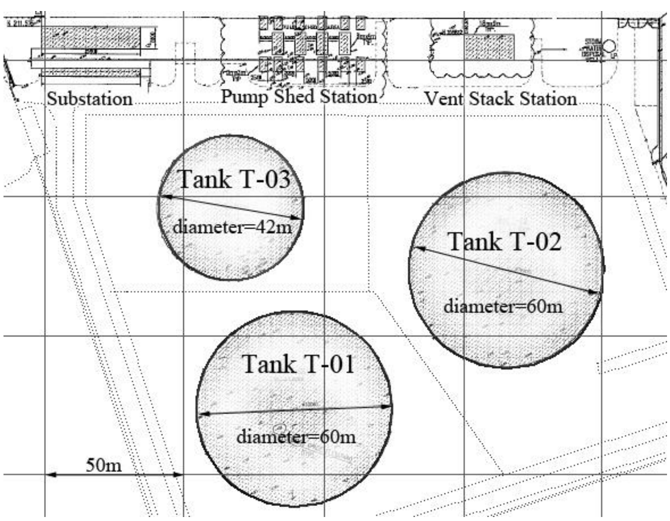


Figure 1: HFO site in Ras Laffan

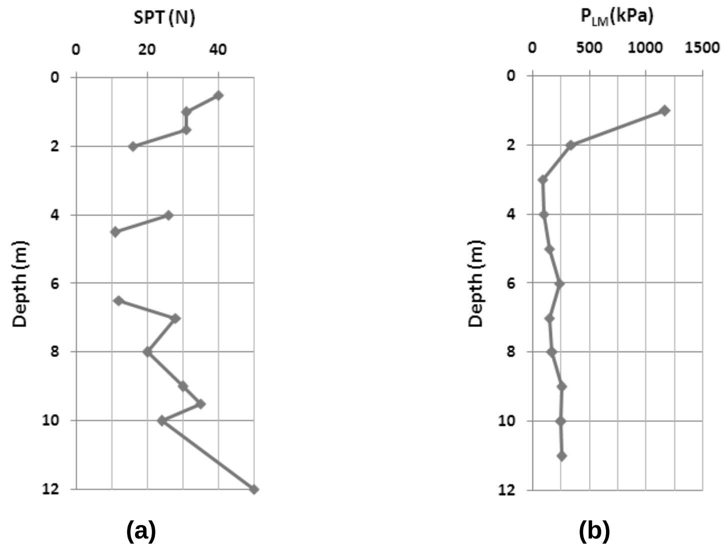


Figure 2: (a) SPT blow counts in borehole BH2B, (b) P_{LM} in PMT T2-01

All tanks were designed to be of fixed roof steel type. The diameters of Tanks T-01 and T-02 were 60 m while Tank T-03 had a smaller diameter of 42 m. The bottom of all tanks was to be at +3.2 m QNHD (Qatar National Height Datum), and the foundations were to be subject to a uniform pressure of 170 kPa.

1.1 Ground Conditions

The HFO site was located in a reclaimed area of the Port. Site survey and initial tests indicated that ground level was generally flat and from +1.2 to +1.8 m QNHD. Groundwater was 0.95 to 2.3 m below ground level.

13 boreholes, 4 per tank and one in the pump station, were drilled and SPT (Standard Penetration Test) was carried out. The upper 12 m of ground appeared to be silty sand and gravel with cobbles. The limited information suggested that fines content was from 8 to 23%. While the SPT blow counts in all boreholes were generally high and in the range of 25 to 50, layers of 1 to 2 m thick with lower blow counts of 11 to 14 were encountered from depths of 5 to 8 m. The SPT blow counts of borehole BH2B is shown in Figure 2(a). It can be noted that testing was aborted for unrecorded reasons at depths of 2.5, 3 and 5 m. The ground then became limestone with USC values mostly recorded to be from 10 to 30 MPa.

At later stages of the project, supplementary field testing by Menard Pressuremeter (PMT) was carried out. These tests were in disagreement with the results of the initial SPT. While SPT blow counts were quite high and suggested the presence of very dense layers, PMT revealed that the soil composition and the presence of cobbles had resulted in the misleading and unrepresentative blow counts. In fact, the PMT limit pressure (P_{LM}) was less than 500 kPa in most depths, signalling that the ground was very loose and with more problems than originally anticipated.

For comparative purposes, PMT T2-01 was carried out in the same location as BH2B. The limit pressure measurements of this test have been graphically shown in Figure 2(b). As can be seen, while the SPT blow counts are indicative of dense to very dense soil, limit pressure readings are only high in the upper most soil layer, possibly due to traffic and movement of equipment. The soil in all deeper layers is loose.

The comparison of the two tests can be an oblique reminder of the fact that SPT was originally developed for sampling soil [1] rather than assessing its strength, and that higher blow counts in gravel and cobble strewn formation grounds are recorded when gravel or cobbles plug the end of the split-spoon [2]. This can lead to false and very misleading interpretations and can result in dangerously under designed foundations.

2. Foundation Solution: Dynamic Compaction

Before the supplementary PMT was carried out and the presence of loose soils throughout the reclaimed site was established, the medium dense sandy layer at the depth of approximately 5 to 8 m was sufficient to apply specific geotechnical measures to ensure the safe transfer of loads from the structures to the ground. Piling, although applicable, was deemed as an expensive solution and ground improvement was preferred as a more competitive alternative.

The project was awarded to a specialist geotechnical contractor who had proposed the application of Dynamic Compaction. The proposed and accepted design criteria for the project were:

- Bearing capacity 170 kPa
- Total settlement 300 mm under a uniformly distributed load of 170 kPa
- Differential settlement 1:180 under a uniformly distributed load of 170 kPa

PMT and finite element analyses were to be used for the verification of design criteria. Interpretation of PMT was carried out using the method of Menard [3].

2.1 Dynamic Compaction

The concept of Dynamic Compaction is to improve the mechanical properties of the soil by transmitting high energy impacts to loose soils that initially have low bearing capacity and high compressibility potentials [4]. The impact creates body and surface waves that propagate in the soil medium. In unsaturated soils the waves displace the soil grains and re-arrange them in a denser configuration. In saturated soils the soil is liquefied and the grains re-arranged in a more compact state. In both cases the decrease of voids will cause the ground surface to subside, and the increase in granular contact will directly lead to improved soil properties.

Dynamic Compaction has already been used in numerous tank projects, such as a tank farm constructed on reclaimed ground in Hong Kong [5] and an LNG tank in Ras Laffan itself [6].

Based on the foundation dimensions of the tanks and the depth of treatment it was decided to apply heavy Dynamic Compaction using a 23 ton pounder. As most heavy duty cranes do not have the ability to lift this pounder, a special crane with the ability to simultaneously lift the pounder using two winches was employed.

Prior to commencing ground improvement a calibration which included 3 heave and penetration tests was carried out to optimize design. Although it is common practice to carry out the calibration outside the project’s treatment area, due to space limitations, in this project the calibration was performed within the tank boundary. Ground surface levels due to pounder impact after 22 blows in HPT-01 which was carried out during the first phase of compaction is shown in Figure 3. For this purpose the pounder with a 1.9x1.9 m^2 base was dropped from 22 m. In addition to measuring the crater’s upper diameter and depth in four corners, changes in ground elevation was also measured up to a distance of 6 m in three directions.

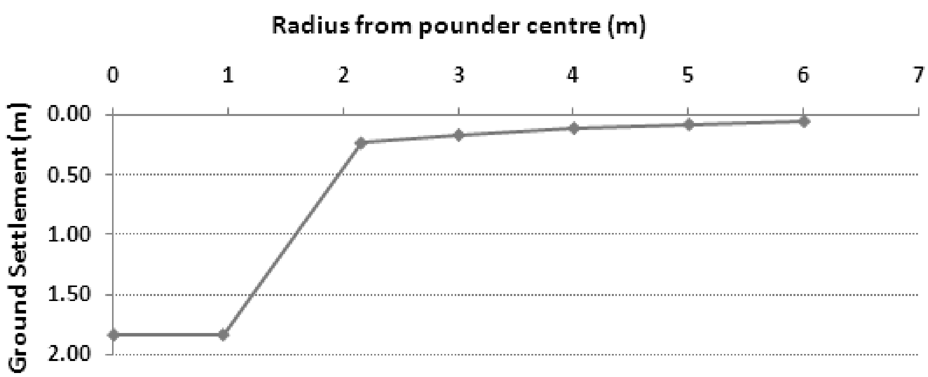
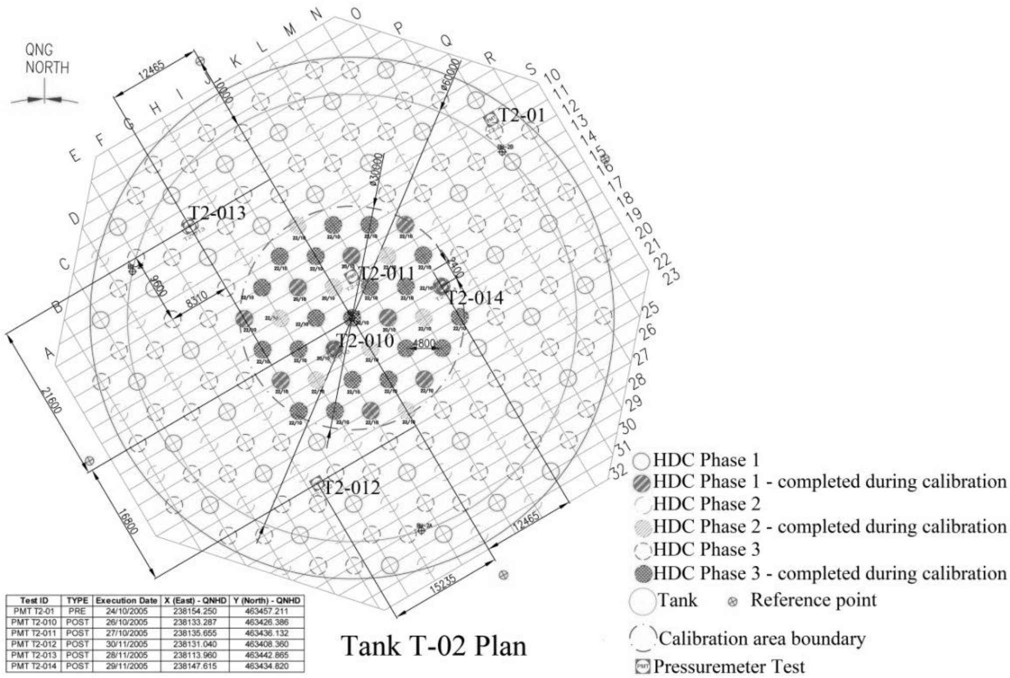


Figure 3: Measured ground deformation during heave and penetration test HPT-01



Test ID	TYPE	Execution Date	X (East) - QNHD	Y (North) - QNHD
PMT T2-01	PRE	24/10/2005	238154.250	463457.211
PMT T2-010	POST	26/10/2005	238133.287	463426.386
PMT T2-011	POST	27/10/2005	238135.655	463436.132
PMT T2-012	POST	30/11/2005	238131.040	463408.360
PMT T2-013	POST	28/11/2005	238113.960	463442.865
PMT T2-014	POST	29/11/2005	238147.615	463434.820

Figure 4: Layout of dynamic compaction works and PMT testing

It can be seen that, as also reported by Hamidi et al (in print), pore water pressure in granular saturated soils that allow water to drain rapidly drops sufficiently to allow the soil to consolidate within the impact zones. However, had the pore water pressure remained too high, instead of consolidating the ground, further impacts would have only displaced the soil under the pounder into the surrounding zone and would have caused the ground around the impact point to heave.

As shown in Figure 4 and based on the preliminary design, calibration and calculations, Dynamic Compaction in the tank areas was applied in 3 phases with the final grid being an equilateral triangle with 4.8 m sides. Ground improvement was carried out with on offset width of 4 m beyond the tanks' boundaries.

Upon mobilisation and completion of calibration, Dynamic Compaction works for the three tanks and three buildings was completed in less than 4 weeks.

2.2 Verification

P_{LM} and E_M (Menard Modulus) values of one of the post Dynamic Compaction PMT in Tank T-02 is shown and compared with a test (PMT T2-01) carried out before ground improvement. Post soil improvement P_{LM} can be used to calculate ultimate bearing capacity given by Menard [3] as shown in Equation (1).

$$q_l - q_o = k(P_{LM} - P_o) \tag{1}$$

q_l= ultimate bearing capacity
q_o= overburden pressure at the periphery of the foundation level after construction
k= bearing factor varying from 0.8 to 9 according to the embedment, the shape of the foundation and the nature of the soil.
p_o= at rest horizontal earth pressure at the test level (at the time of the test)

When the foundation rests on soil with variable P_{LM}, the equivalent limit pressure is defined as the geometric mean of the values:

$$P_{LM} = \sqrt[3]{P_{LM1} P_{LM2} P_{LM3}} \tag{2}$$

P_{LM1}= geometric mean of the values measured in the section from +3*R* to +*R* above foundation level
P_{LM2}= geometric mean of the values measured in the section from +*R* to -*R* above foundation level

P_{LM3}= geometric mean of the values measured in the section from $-R$ to $-3R$ above foundation level
$2R$= width of the foundation.

Noting that the tank will be on the ground surface, k=0.8, Equation 1 may be rewritten as

$$q_l = 0.8P_{LM} \tag{3}$$

We can conservatively exclude the high P_{LM} values of the bedrock in the calculation and calculate the geometric mean of P_{LM} to be 1,853 kPa. Thus, after applying a safety factor of 3, the allowable bearing capacity is calculated to be 618 kPa; more than 3.6 times the required value.

The comparison of PMT before and after (PMT T2-013) Dynamic Compaction for Tank T-02 are shown in Figure 5. It can be seen that the limit pressure and Menard modulus of the soil has increased several folds and a soil that originally had very low strength parameters has become very dense with equally high parameters.

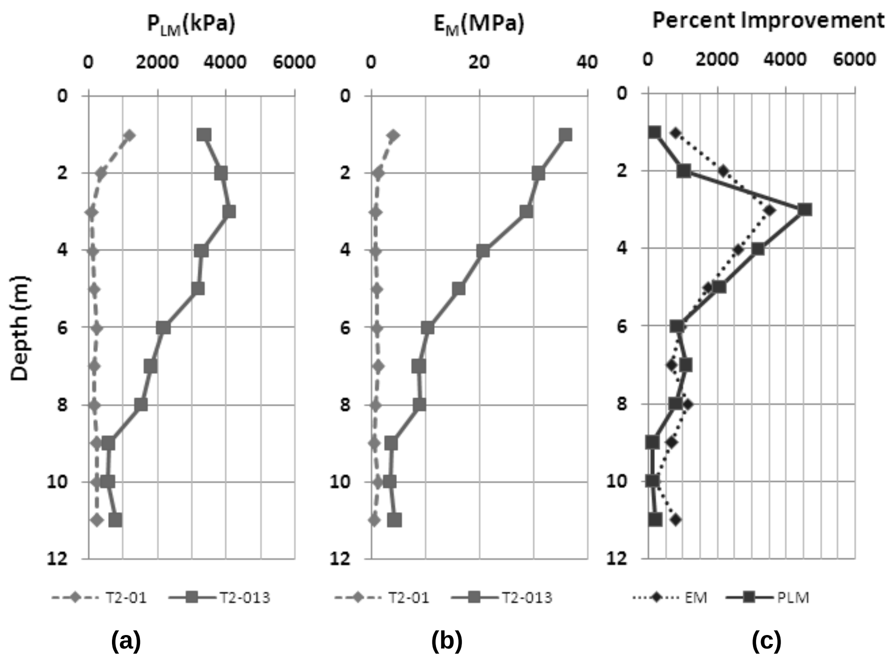


Figure 5: Comparison of PMT parameters before and after Dynamic Compaction (a) P_{LM}, (b) E_M and (c) percentage of improvement of P_{LM} and E_M

Although earlier literature [7] suggests that Dynamic Compaction can increase the soil's limit pressure to 2.4 MPa and improve the parameters by about 400%, Hamidi et al. [8] have previously shown that the mentioned figures are somewhat conservative and higher limit pressures and larger percents of improvement can be obtained. The comparison of PMT parameters before and after Dynamic Compaction in this project also support Hamidi et al.'s findings, and it can be seen that, at least in the case of very loose soils, application of extra blows can increase the improvement ratio of the soil to more than what was reported earlier. Indeed, it can be observed that more than 500% of improvement was measured at the depth of 8 m.

Conservative finite element calculations based on an envelope of the lowest results of all tests were able to demonstrate that settlement criteria had also been satisfied. The tanks were then constructed and ground improvement put to actual testing during the hydrotest. Of the 32 points on the shell of Tank T-02 whose settlements were measured during the hydrotest, maximum and minimum total settlements were from 13 to 26 mm with differential settlement between any two points (5.89 m apart) limited to 4 mm or less than 1 in 1,472 which is well below the 1:180 limit of the design criteria.

3. Conclusions

The HFO ground improvement project has been a good reminder that a proper geotechnical soil investigation for a project should be selected with consideration of the ground composition. While PMT has revealed that the HFO site was located in a reclaimed area containing loose material down to the depth of about 11 m, due to the presence of large diameter granular material, SPT gave an erroneous representation of the actual ground conditions.

The depth of treatment and dimensions of the tanks required heavy Dynamic Compaction to be carried out using a 23 ton pounder that was dropped from 22 m. The heave and penetration test was able to demonstrate that compaction energy was efficiently able to compact the soil without any heaving around the print location.

Compaction results have been quite impressive and it can be seen that even at the deepest layers at 11 m, improvement was substantial. Maximum percentage of improvement was much more than what is suggested by earlier literature dating back to the 1990s. This may be due to very loose initial ground conditions or the utilisation of specially designed cranes that have the capacity to lift much heavier pounders than what was possible before.

In addition to the PMT testing and finite element calculations, full scale hydrotest was performed for each tank. This test was able to demonstrate that both total and differential settlements were considerably less than design criteria.

4. Acknowledgement

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5. References

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