Application of Dynamic Surcharging for Construction of Tanks on Reclaimed Ground

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Synopsis: Palm Jumeira is a reclaimed island off the coast of Dubai. While almost all heavy structures built on this island have been piled, the heaviest non-piled structures that have been constructed are two sewage treatment tanks that have used a unique and innovative Dynamic Surcharging ground improvement solution for their foundation systems. For each tank, a 4 m high surcharge was initially placed on the tank's area and left in place for several days. Then dynamic surcharging was performed by dropping the pounder at the periphery of the surcharge embankment to induce additional settlements. The surcharge was then removed, the ground level reduced, print locations additionally excavated, and dynamic compaction was carried out. Post ground improvement Menard Pressuremeter Tests (PMT) and finite element calculations demonstrated that acceptance criteria were achieved.

Keywords: dynamic compaction, dynamic surcharging, ground improvement, pressuremeter test.

1. Introduction

Palm Jumeira is a group of man-made islands that has been reclaimed off the coast of Dubai, UAE. The reclamation shape consists of a tree trunk, a crown with 17 fronds, three surrounding crescent islands that form an 11 km long breakwater and two identical smaller islands that are in the shape of the logo of project's developer on the sides of the trunk. In all, 94 million m^3 of sand and 7 million m^3 of rock has been used in this project. Calcareous sand was dredged from the Persian Gulf using trailing suction hopper dredgers [1]. When possible, the hopper was discharged by means of a big door located on the bottom of the hull, but when the water was shallow, the dredger sprayed the sand and water mixture onto the reclamation by rainbow discharge.

The variation in fill densities achievable by hydraulic placement is large and closely related to the placement method whereas hopper placed sand is denser than pipeline placed sand [2]. Sand deposited by hydraulic filling below water level generally has a low to medium relative density of about 20 to 60% due to the loose packing from self-weight sedimentation of sand particles under water [2, 3]). The zone with the least strength could be expected to be just beneath water level if fill is placed by subaqueous discharge through hydraulic pumping [4]. Sand placed above water table by hydraulic filling has a high relative density of 60 to 80% because of dense packing from downward seepage and reduction in void ratio as a result of sliding and rolling of the sand particles mixture [3].

Due to the low strength and high compressibility of the soil, ground improvement by vibro compaction was carried out at Palm Jumeira. Even then, heavily loaded structures were constructed on piles. The two sewerage treatment plant (STP) tanks were the only heavily loaded structures that are found on improved ground by a unique an innovative combination of techniques.

2. STP Tanks

2.1 The Tanks' Description and Ground Conditions

As shown in Figure 1, there is a sewerage treatment plant at the tip of each of the lower crescents of Palm Jumeira. The lots were designated A-A and G-G, and each plant included one reinforced concrete tank with a diameter of 35.1 m Each tank was subject to a total uniform load of 120 kPa.

Figure 1: Location of the two sewerage treatment plant on Palm Jumeira

While no geotechnical investigation was available for Lot G-G, two SPT boreholes and two CPT were available not very far from Tank A-A's location. The boreholes indicated that the upper crust of the soil was generally very dense with SPT blow counts (*N*) up to 28. The deeper layers of soil were less dense, with minimum *N* in the upper 8 m of soil being as low as 5. The soil then appeared to become denser with a minimum *N* of 18 and exceeding 50 at the depth of 13 m. The fines content of the soil in these two boreholes were from 2 to 10% in the upper 13 m of soil, but increased to 22% at the depth of 14.5 m. Ground level was at +4 m RL (reduced level) and groundwater was at the depth of about 3 m. CPT resistance, q_c, in the upper 2 m of sand was as high as 25 MPa. The soil then became loose with q_c dropping to as low as 3 to 4 MPa down to the depth of about 13 m where refusal was achieved. Although the SPT and CPT results suggested that the soil was clean sand, fines content as high as 30% was observed in a number of boreholes that were not very far from the project.

At later stages, four SPT boreholes were drilled in the centre and three sides of Lot A-A's tank. These boreholes showed that the upper 3 m of sand was very dense, but the soil then became very loose to medium dense at water level. Blow counts at the depth of 3 to 8 m varied from as low as 4 to as high as 14 and then *N* fell in between the range of 11 to 20 to the depth of about 12 to 13 m where N then exceeded 50. The average fines content of the 38 samples that were extracted from the four boreholes generally ranged from 16 to 21% and up to 30%. This was much more than the average 5% that was indicated by the preliminary geotechnical investigation.

Two Menard Pressuremeter Tests (PMT) were also carried out in Lot A-A. Testing started below sea level. Limit pressure, P_{LM}, was from less than 100 to about 700 kPa. Pressuremeter Modulus, E_M, was measured to be from less than 1 to 6 MPa.

In Lot G-G, 5 SPT and 3 PMT were carried out. SPT was performed from the depth of 4 m. The tests showed that soil was loose to medium dense sand down to about 9 to 12 m with *N* in the range of 6 to 16. The soil then became denser with *N* increasing to 16 to 40. Fines content ranged from 5 to 25% and with an average of 13%. P_{LM} from the depth of 4 to 13 m ranged from as low as 100 to 1,500 kPa.

2.2 Foundation Solution

Preliminary studies indicated that raft foundations could not be used for the tanks without the implementation of specific foundation measures. Piling and ground improvement were both deemed as possible alternatives; however piling was quickly disfavoured due to the associated high costs. Different ground improvement techniques were considered. Soil improvement acceptance criteria for a tank foundation level at level +2.5 m RL was developed as:

- Allowable bearing capacity: 160 kPa with a safety factor of 3
- Differential settlement: 1/750 for a uniformly distributed load of 120 kPa

Several ground improvement techniques were considered. Although vibro compaction was the practiced method of ground improvement on Palm Jumeira, the possible presence of silty sand placed doubt on the applicability of this technique. Stone columns were feasible, but appeared to be costly. Dynamic Compaction was considered as both economical and reliable, but at that time suitable rigs with sufficient lift capacity could not be sourced from the region.

The review of available rigs indicated that the maximum pounder that the rigs were able to lift was limited to 15 tons; thus as a supplement to Dynamic Compaction the appointed specialist geotechnical contractor decided to implement Dynamic Surcharging to enhance the achievable results at depth. Dynamic surcharging is the combined effect of static loading and high energy impacts to create acceleration in the soil under the static loading in such a way as to include a shearing process around the surcharge fill. This will result in the reduction of load spreading which was initially caused by the high strength of the upper layers. Further, vibrations and increasing of the pore pressure under the tank will result in a reduction in friction between the granular particles of the soil and ultimately lead to the collapse of the foundation soil under the influence of Dynamic Surcharging.

In this technique a surcharge is initially placed over the treatment area and Dynamic Compaction is performed. Although granular materials settle under static loads, as dynamic shear modulus has been found to decrease significantly with increasing values of shear strain amplitude [5], it can be expected that introducing vibration will increase the amount of settlement under the surcharge. Furthermore, the rate of consolidation of fine soils is most when the pore water pressure is high, and it is possible to increase the rate of consolidation back to previously high values by inducing pore water pressure through vibration.

2.3 Application of Ground Improvement

For each tank, initially four settlement monitoring plates were installed on ground. One plate was installed in the centre of the tank and the other three were installed at 120^o angles from one another on a ring with a radius of 17.5 m.

4 m of surcharge was placed evenly over an area with a base diameter of 44.2 m. The diameter of surcharge on its top was 32.2 m. Thus, the approximate volume of the surcharge was $4{,}700m^3$. Assuming an in-situ unit weight of 17 kN/m^3, the total weight of the surcharge can be estimated to be 80 MN. Noting that tank foundation level was +2.5 m RL, the overburden soil added another 25 MN to the surcharge. Although the pressure on foundation level from 4 m of surcharge and 1.5 m of overburden was 93.5 kPa which is equivalent to 78% of the tank's total load, the 105 MN of load equates to approximately 90% of the tank's total load.

As shown in Figure 2 and Figure 3, the settlements of Tanks A-A and G-G were recorded during placement of the surcharge. Due to logistical difficulties the surcharge in Lot G-G was placed over a longer period. It can be seen that the plates have settled reasonably pro rata with surcharge height. Once backfilling was completed, the surcharge was left in place for 5 additional days. It can be seen that then the settlement rate had considerably decreased and for practical purposes it can be estimated that, for example, in Lot A-A the ground could have been subject to an additional maximum settlement of 5 mm in the long run.

Before commencement of dynamic surcharging 26 prints on a circle with a diameter of 49.2 m were excavated by about 1 m to increase the depth of influence and each print was compacted by drooping a 15 ton pounder 30 times on it. This was repeated 6 times in Lot A-A and 5 times in Lot B-B.

It can be seen in Figure 2 and Figure 3 that Dynamic Surcharging has increased the settlements of Tank A-A and Tank G-G respectively by 1.6 to 5.2 and 1.3 to 3 times the value of the static settlements. The maximum effect was on the periphery where impact wave amplitudes were greatest. Also, although the maximum differential settlement of outer monitoring plates of Tank A-A were 7 mm at the end of static surcharging, the maximum differential settlements during Dynamic Surcharging increased by 4 times to 40 mm. This suggests the possibility of large differential settlements under seismic and vibratory loads in untreated areas of the same ground.

Once Dynamic Surcharging was completed the surcharge fill was removed and the ground was excavated within a diameter of 41.2 m to working platform level at +2.8 m RL. The excavation sides sloped outwards such that the top of excavation had a diameter of 46 m.

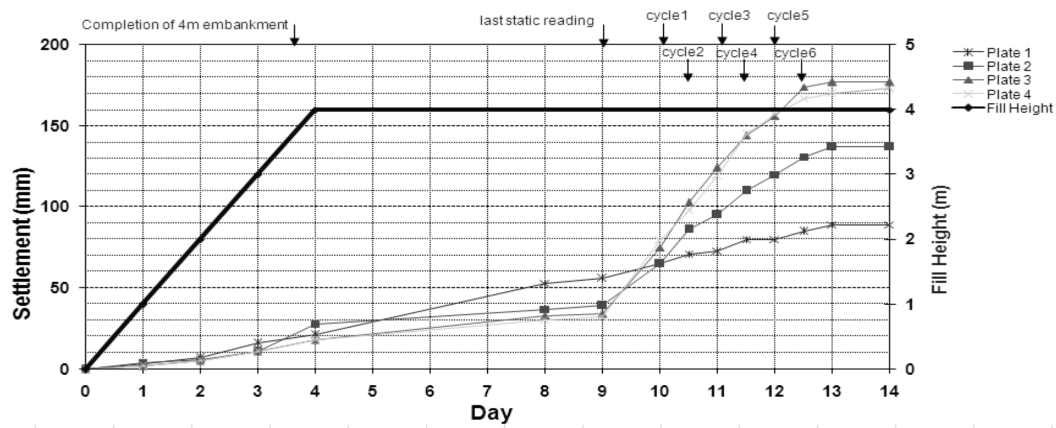

Figure 2: Ground settlement in Tank A-A during static and dynamic surcharging

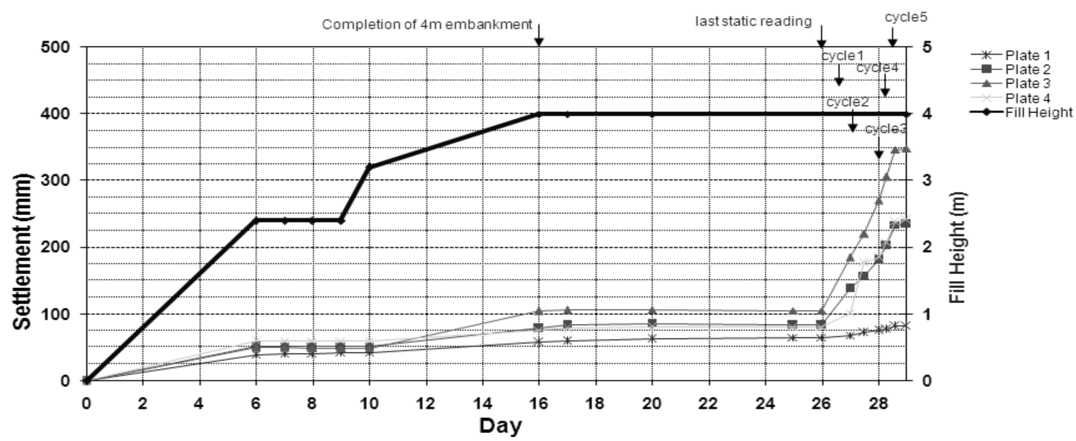

Figure 3: Ground settlement in Tank G-G during static and dynamic surcharging

Dynamic Compaction was carried out on prints located in the centre of the working platform and on 4 concentric rings around the central print. Each print was further excavated by about 1 m to facilitate pounder penetration and to increase the depth of influence. 150 m^3 of crushed rock and cobbles was added to the total of 58 prints in each tank. This amounts to about 2.6 m^3 of rock per print or an equivalent of approximately 0.13 m of rock per every metre of ground within the treatment radius. This amount of stone is insufficient to efficiently increase the ground strength, but was used to increase soil permeability. Pounder drop height during the first and second phases of compaction was 20 m. A lesser impact energy was used during the ironing phase.

Pounder penetration and the outer crater diameter for each print location was measured during the first two phases of Dynamic Compaction. In the first phase of Tank A-A, the average pounder penetration depth and average upper diameter of crater were respectively 1.7 m and 5 m. In the second phase, these numbers reduced significantly to 0.4 m and 2.3 m. the diameter of the crater at the base could be assumed to be equal to the pounder's dimension; i.e. 1.7 m.

At the end of Dynamic Compaction, the ground level in Tank A-A had dropped to +2.25 m RL. Noting that 150 m^3 of stone equivalent to a thickness of 0.13 m had been added, it can be calculated that the ground had settled 0.68 m in addition to the settlements induced by Dynamic Surcharging. Settlement induced by Dynamic Compaction in Tank G-G was 0.64 m. Although the magnitude of this settlement is much larger than what was measured during Dynamic Surcharging, it should be recalled that Dynamic Surcharging was aimed at reducing the settlement of the deeper layers that may have been unreachable with Dynamic Compaction using a 15 ton pounder.

2.4 Verification

Upon completion of Dynamic Compaction and levelling of the site, 4 PMT were carried out in Tank A-A and 3 were performed in Tank G-G. P_{LM} and E_M before and after ground improvement are shown in Figure 4. As could have been predicted the most improvement has occurred down to the depth of about 8 to 9 m; however due to the combination of Dynamic Surcharging and pre-excavated Dynamic Compaction P_{LM} at the 5 m depth (from original ground level) in Tank A-A has increased by approximately 380% and even at the depth of 10 m, P_{LM} shows an increase of about 70%. Furthermore, the minimum P_{LM} value after improvement is greater than 600 kPa which demonstrates that the young hydraulic fill is no longer subject to creep due to self weight [6].

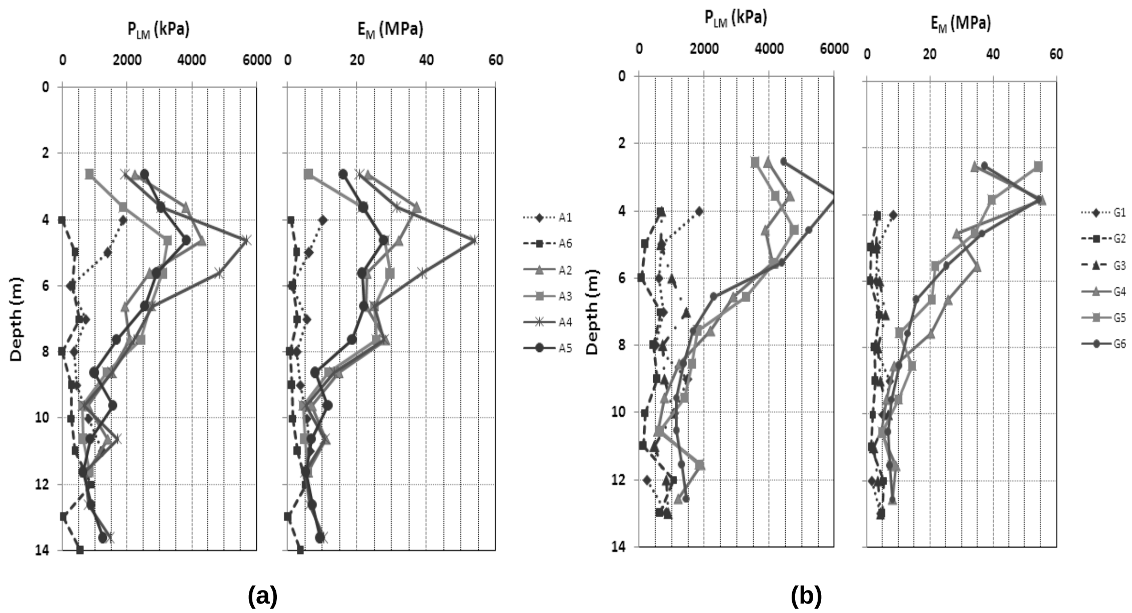

Figure 4: Pre (red) and post (green) ground improvement results, (a) Tank A-A (b) Tank G-G

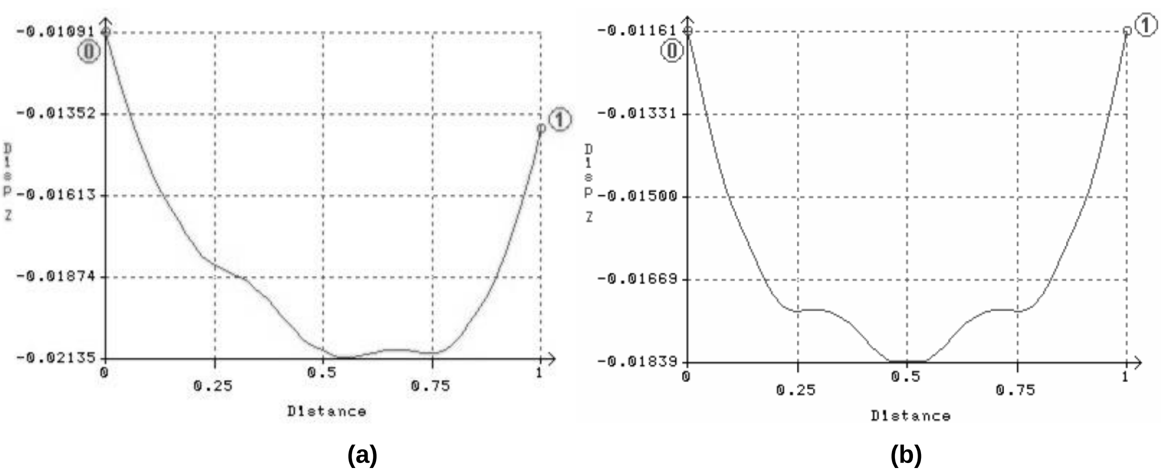

Figure 5: Calculated settlement profile for different conditions under (a) Tank A-A and (b) Tank G-G

Bearing capacity can be calculated using the equation proposed by Menard [6]. In Tank A-A, the geometric mean of the average of the 4 post ground improvement PMT is 1,684 kPa. Conservatively assuming that the deeper layers also have the same value and that the foundation is on ground level, the allowable bearing capacity can be calculated to be 449 kPa which is much more than the required 160 kPa. In Tank G-G, the geometric mean of the average of the 3 post ground improvement P_{LM} is 2199 kPa which is 30% higher than the geometric mean of Tank A-A.

Tank settlements were calculated by taking the tank-soil interaction into account and using finite element analysis (COSMOS/M software). A three dimensional model was analysed for each tank. The three dimensional model was developed in half space due to symmetry.

For Tank A-A, the modelled tank was placed on a 0.5 m thick concrete raft and an upper very dense layer and a lesser dense layer at the bottom. In order to assess differential settlement effects, the ground in the model was made stiffer on one side than the other. To accomplish this thickness of the upper and lower sand layers in the left side of the tank were respectively assumed to be 7.5 m and 3.5 m. On the right side, the upper and lower sand layers were each assumed to be 6.5 m. Young's moduli, E_y, for the sand layers were calculated using the relation between E_M and E_y as proposed by Menard [6]. E_y for the upper and lower sand layers were respectively assumed to be 57.9 and 22.5 MPa. In Tank G-G, the upper and lower sand layers were assumed to be respectively 5 m and 6 m with the same thickness in all locations under the tank. Here, E_y for the upper and lower sand layers were assumed to be respectively 69.6 MPa and 24 MPa.

The result of the finite element analysis is shown in Figure 5 for both tanks. As can be observed that the maximum settlement at the centre of the Tank A-A is 21.35 mm. Minimum tank settlement at the shell is 10.91 mm. Thus, differential settlement over the radius length of 17.55 m is 10.44 mm or less than 1/1,681 which is much smaller than the allowed 1/750 value. Differential settlement from one side to the other side of the tank can be calculated to be 3.13 mm or less than 1/11,200. In Tank G-G maximum settlement in the centre of the tank was 18.39 mm. Shell settlement was calculated to be 11.61 mm; thus differential settlement from the centre to the shell of the tank can be calculated to be 1/5,177.

3. Conclusions

This project has been able to demonstrate the effectiveness of innovatively combining two techniques; i.e. Dynamic Surcharging and Dynamic Compaction, to improve the ground and achieve results that would have been otherwise infeasible with the available equipment.

Dynamic Surcharging was able to induce additional settlement compared to what was realized under static loading conditions. This has not only shown the value of Dynamic Surcharging for increasing induced settlements and soil strength, but is also a reminder that even if settlements are acceptable under static loading conditions, vibration of the ground due to earthquakes or any other source can introduce additional unwanted settlements.

Although the settlement magnitude of Dynamic Compaction was much more than Dynamic Surcharging, the latter has realized critical settlement at depths that would have been treated less effectively with the available equipment.

4. Acknowledgement

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5. References

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