The Application of Dynamic Compaction on Marjan Island

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ABSTRACT

Marjan Island is 2.7 million m^2 of development located 27 km southwest of Ras Al Khaimah in the United Arab Emirates. This project has been reclaimed from the Persian Gulf by tipping sand into the sea. Geotechnical investigations indicated that the upper 7 m of ground was composed of very loose to medium dense silty sand interbedded with layers of boulders at different depths. SPT blow counts were recorded to be as low as 4 and Menard Pressuremeter Test (PMT) limit pressure was as low as 70 kPa. Fines content was from 13 to 30%. Preliminary calculations suggested that the in-situ ground conditions could not satisfy the island's main road's settlement criteria and that ground improvement was required. Thus, 198,000 m^2 of the reclamation was treatment by Dynamic Compaction. Pounders weighing up to 20 tons were dropped from 20 m to compact the loose soil. 32 PMT were carried out after ground improvement to verify the achievements. These tests were able to demonstrate that acceptance criteria was readily achieved and that on average the soil's modulus of deformation increased by more than 400%.

Keywords: ground improvement, soil improvement, dynamic compaction

1 INTRODUCTION

Marjan Island, translating to Coral Island, is the first manmade group of islands of its kind that has ever been undertaken in the northern emirate of Ras Al Khaimah in the United Arab Emirates. This project is located approximately 27 km southwest of the city of Ras Al Khaimah and 54 km northwest of the city of Dubai.

As can be seen in the project's master plan, shown in Figure 1, the group of islands are composed of a peninsula followed by four coral shaped islands that are connected together via bridges. The project will consist of low rise villas, townhouses and high rise towers.

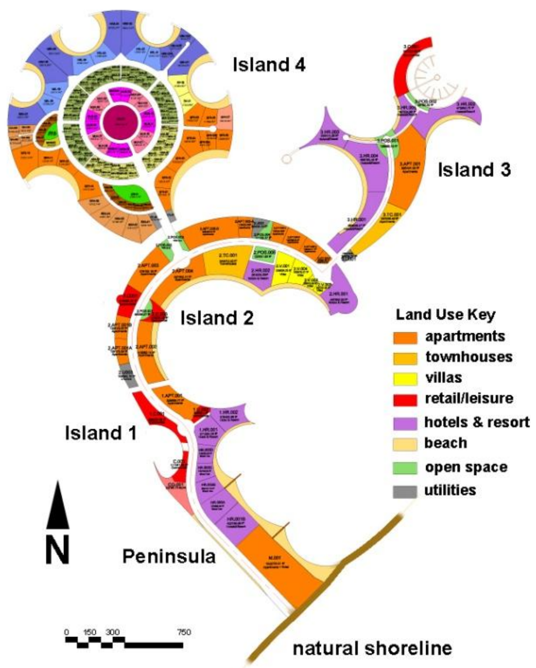


Figure 1. Master plan of Marjan Island (main road corridor shown in white)

2 GROUND CONDITIONS

Unlike most manmade islands in the UAE where land is reclaimed from the sea by hydraulic filling, trucks were used to cart and dump soil more than 3 km into the Persian Gulf to an average elevation of +4 m ACD (Admiralty Chart Datum). Average groundwater was at +2 m ACD.

The preliminary geotechnical investigation on the main road (shown as a white strip in Figure 1) passing through the Peninsula, Island 1 and Island 2 consisted of 37 SPT boreholes drilled down to depths of 2.5 to 16 m. These tests indicated the presence of a fill with heterogeneous strength. On average, in the top 7 m (extending down to elevation -3 m ACD) the fill was composed of very loose to medium dense sand, occasionally interbedded with boulder at different depths. The fines content was variable from 13 to 30% and SPT blow counts were generally low; sometimes as low as 4 and rarely more than 50. The second layer of soil, extending down to -12 m ACD, appeared to possess better mechanical properties. This layer was composed of medium dense to very dense silty sand with occasional interbedded pockets of sandy silt. Fines content was generally from 5 to 30% and SPT was from 10 to more than 50.

16 Menard Pressuremeter Tests (PMT) were also later carried out as part of a supplementary geotechnical investigation. Limit pressure (P_L) in these tests also indicated that the ground was sometimes very loose in the upper 7 m. The lowest P_L was recorded to be as low as 70 kPa. Although due to truck traffic the upper metre or two of the ground was generally very dense and P_L of more than 1000 kPa was commonly observed, the limit pressure of the deeper layers was commonly less than 600 kPa. Similarly while Menard Modulus (E_M) was generally 4 to 8 MPa at depths of 2 to 7 m, yet values of less than 1 MPa were occasionally encountered.

2.1 Interpretation

According to Menard (1975) natural unconsolidated soil or young fills will undergo large settlements with time, even if they are very lightly loaded. The self bearing condition of a soil; i.e. the minimum value of the soil parameters that a soil must have so as not to settle under its own weight, can be related to physical or mechanical properties of the soil. Menard's experience shows that the limit pressure is a suitable characteristic and for sand and sand with gravel the net limit pressure defined as the difference between the limit pressure and the at rest horizontal earth pressure at depths less than 10 m must be at least respectively 600 kPa and 800 kPa to prevent creep settlement. For depths greater than 10 m these figures have to be increased. Menard proposes to estimate the self weight settlement of soft or loose soils during a period of one year as a first approximation using Equation 1.

$$w \sim \frac{h}{1000} \frac{1 - {}^{\alpha P'_L}/_2}{{}^{\alpha P'_L}/_2} \tag{1}$$

w= self weight settlement (cm)
h= layer thickness (cm)
P'_L= net limit pressure (bars= 100 kPa)

Assuming creep due to the soil's self weight will reach stabilisation after t years, and assuming that creep will decrease logarithmically, self weight settlement, w_n, in year n will be:

$$w_n = w_{year\ 1} \frac{\ln\left(\frac{t+1}{n}\right)}{\ln(t+1)} \tag{2}$$

Instead of summing up creep settlement throughout the years, it is possible to alternatively estimate the total settlement of m layers, each H metres thick, due to an increase of the layers' limit pressures using Equation 3 (Hamidi et al, 2010b).

$$s = \frac{0.03}{\log 2} \sum_{k=1,m} H_k \log \left({(P_L)_{\text{after}}}/{(P_L)_{\text{before}}} \right)_{\text{k}} \tag{3}$$

Thus, it can be estimated that a one metre thick layer of sand with an initial limit pressure of say 400 kPa will undergo 17.5 mm of creep settlement for its P_L value to reach stability at 600 kPa.

2.2 Geotechnical Concerns

The heterogeneity in soil strength and the presence of loose spots near dense spots indicated that it was possible for the ground to undergo large differential settlements due to the self weight of the soil without external loading. Structural and traffic loads further increased the risks of failure due to excessive ground deformations and insufficient bearing capacity.

The geotechnical concerns were considered to be of high priority for the main road corridor that went through the Peninsula, Island 1 and Island 2 (refer to Figure 1). Hence, the project management team approached geotechnical specialist contractors to propose solutions for mitigating the geotechnical concerns.

3 GROUND IMPROVEMENT SOLTUION: DYNAMIC COMPACTION

After the review of all proposals the project's management team and consultant awarded the project to a specialist ground improvement contractor who had proposed the application of dynamic compaction.

The concept of this technique 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 (Hamidi et al., 2009). The impact energy is delivered by dropping a heavy weight or pounder from a significant height. The pounder weight is most often in the range of 8 to 25 tons although lighter or heavier weights are occasionally used. Drop heights are usually in the range of 10 to 20 m although 40 ton pounders have been dropped from 40 m (Mayne et al., 1984).

Dynamic compaction has been used for the improvement of the mechanical properties of many road projects including the 900,000 m^2 Abu Dhabi New Corniche Road (Varaksin et al, 2004; Hamidi et al., 2010a) and Abu Dhabi to Reem Island Causeway (Hamidi et al., 2010a; Hamidi et al., 2011a).

3.1 Scope of works and criteria

The 198,000 m^2 ground improvement area for the main road was defined within an area of 123,000 m^2 in the Peninsula and Island 1 and 75,000 m^2 in Island 2.

Ground improvement design criteria was specified to be:

1. Maximum total settlement: 25 mm under a uniform load of 20 kPa on the road area

2. Maximum differential settlement: 1:500 between any two points on the road with a distance of 10 m under a uniform load of 20 kPa.

Verification and acceptance of the works was by the Menard Pressuremeter Test (PMT) and interpretation of test results was specified to be by the Menard (1975) method.

3.2 Application of dynamic compaction

At the beginning of the works a calibration dynamic compaction programme consisting of two trials was performed to verify and optimise the ground improvement parameters. In this calibration a 20 ton pounder was dropped from 20 m. Heave and penetration tests (HPT) were performed to measure the amount of ground compaction per drop and PMT were carried out to verify that acceptance had been achieved. More information about the calibration has been reported by Hamidi et al. (2011b).

Dynamic compaction was carried out using 17 and 20 ton pounders that were dropped from two specially designed cranes. Each print location was subject to 5 to 8 blows dropped from 20 m. In the ironing or light dynamic compaction phase the 17 and 20 ton pounders were dropped from 12 m or a 12 ton pounder was dropped from 17 m.

Figure 2. Application of dynamic compaction on Marjan Island

Mobilisation of equipment, ground improvement works and testing were carried out during a period of 5 months. Execution of dynamic compaction is shown in Figure 2.

3.3 Verification

16 PMT were carried out before dynamic compaction. A further 32 PMT were also carried out after ground improvement to verify the ground conditions and to confirm that acceptance had been achieved. Of these post soil improvement tests 14 were on the Peninsula, 5 were on Island 1 and 13 were on Island 2.

For comparative purposes the E_M values of two test locations that were substantially different are shown in Figure 3. Although in reality the distance between these two tests was much more than 10 m, it is of interest to study the total settlements.

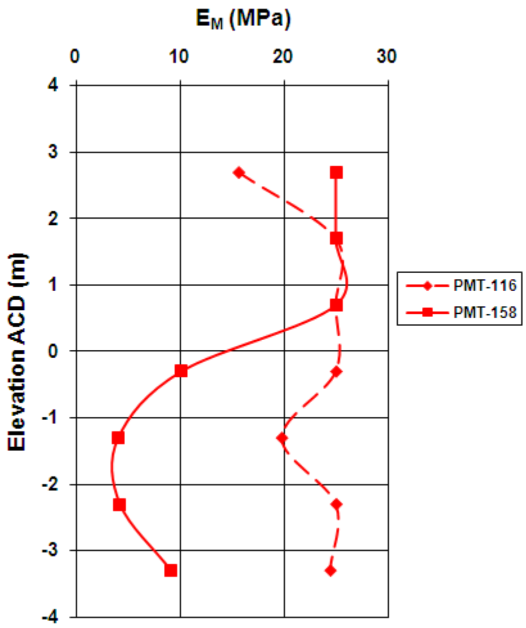


Figure 3.Two post dynamic compaction E_M results

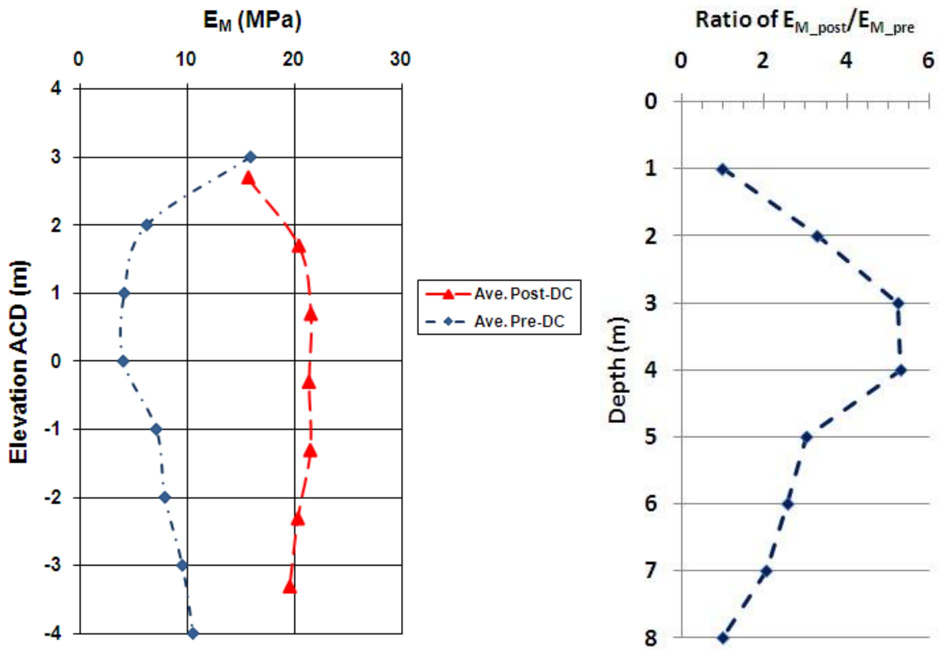
Settlements can be calculated using Equation 4 (Menard, 1975):

$$s = \frac{1.33}{3E_B} pR_o \left(\lambda_2 \frac{R}{R_o}\right)^{\alpha} + \frac{\alpha}{4.5E_A} p\lambda_3 R \quad (4)$$

s= settlement
p= mean contact stress on a rigid footing
R= half of footing width
R_o= a reference length equal to 0.30m
λ_2, λ_3= shape coefficients
E_A and E_B= functions of E_M (Menard, 1975)
α= rheological factor

Assuming a loading area of 100 m by 10.5 m subject to a uniform load of 20 kPa, and conservatively assuming a 20 MPa Menard Modulus for all layers below testing levels, it can be seen that the total settlement of the testing point with lower moduli will result in only 2.2 mm of settlement. This figure itself is much less than the acceptable differential settlement between two points, and demonstrates that acceptance has been achieved..

Figure 4(a) shows the average E_M before and after dynamic compaction. It can be seen that while it is generally expected for the improved test profile to be sickle shaped, it this case because the average E_M before dynamic compaction was least where the improvement is most, the improvement profile appears to be more linear and only slightly curved. However, it can be seen in Figure 4(b) that E_M improvement ratio does appear to be in the shape of a sickle and the maximum improvement was achieved at about half the depth of improvement. The average maximum E_M improvement ratio was 5.31 (431%). Although the authors have observed much higher ratios in some dynamic compaction projects (Hamidi et al., 2010b, Hamidi et al., 2011c) this figure is quite compatible with the indicative upper bound figure of 400% that has been proposed by Lukas (1986, 1995) as a guideline.



(a) (b)

Figure (4). (a) Average E_M before and after dynamic compaction, (b) E_M improvement ratio

4 CONCLUSION

Marjan Island is a reclaimed site that has been realised by dumping sand into the sea by trucks. The geotechnical investigation showed that the soil was of variable strength and very loose down to the depth of about 7 m, and preliminary analysis indicated that the ground was subject to creep settlement due to self weigth and differential settlements. Dynamic compaction was implemented to improve the main road of the Peninsula, Island 1 and Island 2.

Post ground improvement PMT tests were carried out, and were able to demonstrate that ground settlements due to the project's uniformly distributed design load was negligible and much less than the acceptance criteria.

5 ACKNOWLEDGEMENTS

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