Dynamic Compaction of Lateritic Fill for Property Development

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ABSTRACT: Dynamic compaction is a ground improvement technique to densify soils and fill materials by dropping a falling weight called pounder typically made of steel via a crawler crane. The method is to densify the compacted material so that its bearing capacity can be increased, and the settlement can be reduced when additional loads are introduced over the compacted material. Its application has been associated mainly to the compaction of sand deposit or sand fill, construction debris and even sanitary landfill. In this paper, the compaction of lateritic fill using dynamic compaction is presented via two case studies. The first project is the filling of a 23 m deep valley using lateritic soil compacted with dynamic compaction for a heavy industry factory. The second project is the application of dynamic compaction to recompact up to 6 m deep of a filled ground where proper compaction was not done during filling for a housing development project.
Keywords: Dynamic compaction, Menard pressuremeter, lateritic soil, ground improvement.

1. INTRODUCTION

Dynamic compaction (DC) is a ground improvement method to compact soils by heavy tamping which involves repeated dropping of heavy weight called pounder typically made of steel onto the ground surface. This method is also known as dynamic consolidation, heavy tamping, or pounding. The technique at its current form for improvement of large areas was pioneered by Menard (Menard & Broise, 1975) and was extensively tested and optimised hence its safe and economic application today. Since the late 1960s, DC has been developed on the numerous sites all over the world for various soil conditions and for a variety of applications such as roads, airports, seaports and more.

The basic principle behind dynamic compaction (DC) technique consists in the transmission of high energy waves in order to improve weak subsoil. As a result of the impact, the soil is compacted depending on its condition, structure and depth. The energy is transferred to the subsoil by multiple impacts with properly shaped weight (normally steel pounder) with a weight ranging from 10 up to 40 tonnes free falling from a height ranging from 5 up to 40 m. The densification effect when DC is applied on partly saturated soils is analogous to impact (Proctor) compaction in the laboratory while the application of DC on saturated cohesionless soils induces liquefaction and the densification process is like combining blasting and vibro-compaction. It is worthy to note that the effectiveness of DC in saturated fine-grained soils is uncertain (Mitchel, 1981).

Dynamic compaction (DC) has been used successfully for compaction of sand for large scale development or reclamation (e.g., Hamidi et al., 2011 and Bo et al., 2009). This paper presents the application of DC to compact unsaturated lateritic soil for real estate developments on a smaller scale, which is an application less discussed. In this paper, the term “lateritic soil” is used to describe the reddish highly weathered residual soils typically found in tropical or sub-tropical regions, which consists of particles ranging from gravel to clay, usually coated with sesquioxide rich crusts (Oyelami and Van Rooy, 2016). The two projects discussed in this paper are from Malaysia and the lateritic soil is silty in nature. The objective of the paper is to demonstrate that DC can be used successfully to compact lateritic soil for property developments provided proper design and construction control are adopted. The extensive use of Menard pressuremeter in the design and construction control for both projects is presented in this paper.

2. DYNAMIC COMPACTION OF A DEEP VALLEY

2.1 Project Background

A factory for the manufacturing of heavy engineering products is planned to be constructed over a deep valley in Selangor, a state in central area of Peninsular Malaysia west coast. This development is on a piece of land with area of approximately 35,000 m². The land is geologically consisting of lateritic soil and topographically a valley area. The height between the lowest part and the highest part of the valley is about 23 to 28 m within the factory footprint. The valley is also a water catchment area. Therefore, about 1 to 2 m deep of water ponding exists on the lowest part of the valley. From the soil investigation results conducted at different locations within the valley, the subsoil is generally 2 to 4 m thick of medium stiff silty soil with SPT N-value varying from 4 to 9. This layer is underlain by a sandy silt layer with SPT N-value of 50 and above. Figure 1 shows the cross-section and elevation of the valley to be filled for the factory construction.

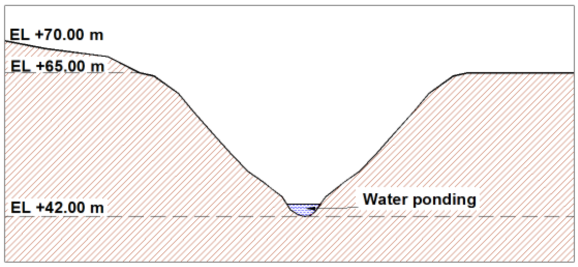

Figure 1 Cross-section of the valley to be filled

The factory is proposed to be built across the valley on EL +65.00 m. The filling of the valley is carried out with the in-situ soil. Thus, cut and fill operations will be conducted at the project site with the cutting of the lateritic soil from the higher areas of the valley being filled to the lower areas of the valley to bring the valley to the final elevation of EL +65.00 m. The initial planning is to compact the cut material using the conventional layer-by-layer compaction method (CCM). For this method, the fill materials shall be placed in layers, and uniformly compacted to achieve dry density of not less than 95% of the maximum dry density at optimum moisture content as determined in the standard Proctor laboratory tests before the next layer is placed and compacted. Loose thickness of each layer shall not be greater than 300 to 400 mm depending on the type of compaction machinery.

Since this project involved large amount of earthmoving, with cutting and filling of a 23 m deep valley with approximately 684,000 tonnes of fill materials, alternative solutions are sought by the developer during the construction stage due to time constraint and concerns over the construction activities to be carried out during monsoon season. The backfilling of the valley is determined as the critical activity and must be completed on time. Time allocated for the backfilling works is 3 months, which means at least one layer of compaction needs to be completed per day if the conventional layer-by-layer compaction method (CCM) is adopted. The developer and earthwork contractor are not confident this can be achieved, especially during monsoon season. Hence, alternative solution using dynamic compaction (DC) is proposed and adopted. A comparison of CCM and DC for this project is shown in Table 1.

Table 1 Comparison between CCM and DC

	CCM	DC
Thickness of compaction layer	0.3 m thick	3 to 5.15 m thick
Number of compaction layer	> 70 layers	5 layers
Duration of compaction	> 3 months	2 months

In this project, dynamic compaction (DC) is applied by dividing the backfilling of the deep valley into five layers. The fill material is placed with thickness ranging from 3 to 5.15 m per layer before DC is carried out. Figure 2 shows the cross-section of the five layers of DC works. It should be noted that the water ponding area is backfilled with crusher run instead of lateritic soil in order for the compaction using DC to be effective. In addition, a layer of crusher run up to 50 cm thick is placed at the top of each layer to be compacted to ensure the compaction works using DC can be carried out without being adversely affected by the heavy rain that occurs during the monsoon season.

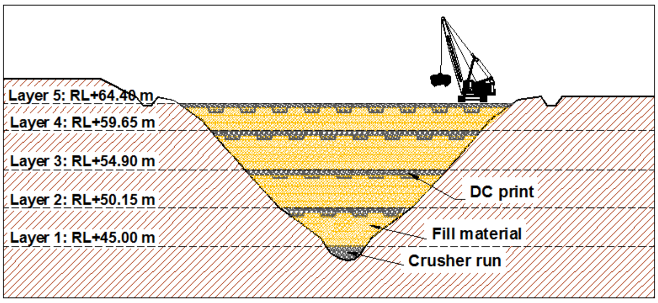

Figure 2 Cross-section of the DC works

2.2 Design and Execution

The Engineer for this project has specified for 50 kPa of safe bearing capacity and maximum allowable settlement of 150 mm, considering raft foundation as the foundation system to be adopted for the factory. Thus, the design and performance criteria at RL +65.00 m after dynamic compaction (DC) works at the fill area are as follows:

- The safe bearing capacity shall be 50 kPa;
- The total post construction settlement shall not exceed 150 mm under the maximum load of 50 kPa;
- The maximum differential settlement shall not be more than 1:500.

The bearing capacity and settlement calculations are carried out using the methods outlined in D.60.AN General Memorandum on the "Interpretation and Application of Pressuremeter Test Results to Foundation Design" published in Sols-Soils No.26 (Menard, 1975). These methods rely very much on the accuracy of the soil modulus and limit pressure obtained from in-situ soil test. Therefore, Menard pressuremeter has been specified as the pre-treatment and post-treatment tests for this project. Based on the calculations conducted, to comply with the above performance criteria, the compacted laterite fill for each layer should have the following properties:

- Harmonic mean pressuremeter modulus, $E_M \geq 6{,}000$ kPa;
- Geometric mean limit pressure, $P_L \geq 600$ kPa

In this project, the spacing of the dynamic compaction (DC) prints is 5 to 6 m. The DC works is carried out in 2 phases, the main phase and the ironing or overlapping phase. The steel pounder weight is 15 tonnes and the drop height is 20 m. The DC works has been carried out using two lattice-boom cranes with capacity to lift the 15 tonnes steel pounder up to 20 m. Figure 3 shows the DC rig setup for the compaction of the valley. This photograph is taken during the DC works at RL +45.00 m, where the water ponding area has been filled with 3 m thick of crusher-run and to be improved with DC.

Figure 3 DC rig setup for deep valley compaction

2.3 Pressuremeter Test Results

More than 30 Menard pressuremeter tests (PMT) have been carried out during the execution of the dynamic compaction (DC) works for this project as part of the quality control and quality assurance requirements. Figure 4 shows the typical result from the pressuremeter test comparing the pressuremeter modulus, E_M and limit pressure, P_L before DC works (i.e., Pre-PMT-02) and after compaction with DC (i.e., Post-PMT-B (outside)). This test is carried out at level RL +50.15 m (i.e., after the second layer of fill material, specifically the lateritic fill is compacted using DC). In addition, it should be noted that the post-treatment PMT is conducted in between DC prints.

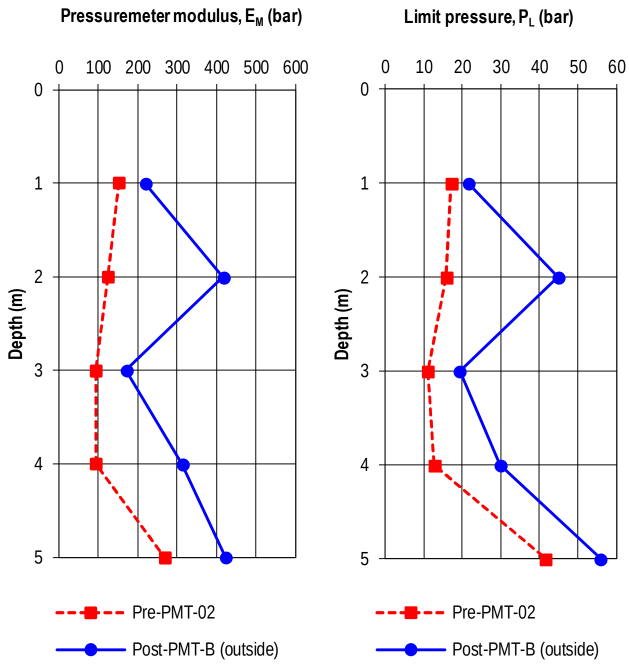

Figure 4 Pressuremeter test results at RL +50.15 m

The PMT test results clearly show that the DC works has significantly increase the E_M and P_L of the lateritic soil. The E_M and P_L after DC compaction are as follows:

- Harmonic mean pressuremeter modulus, E_M = 27,180 kPa;
- Geometric mean limit pressure, P_L = 3,150 kPa

These values exceed the required values (i.e., acceptance criteria) by more than 4.5 times. This means the DC has been successfully implemented on the lateritic fill.

3. DYNAMIC COMPACTION OF A FILLED GROUND

3.1 Project Background

This project is a housing development consists of double storey link houses and shop houses. It is situated in Kedah, a state located in the north-western part of Peninsular Malaysia. The project is to be built on a land area of approximately 34,000 m². The existing land elevation varies from RL +20.00 m to RL +30.00 m. Cut and backfilling works is performed to achieve the final building platform of RL +26.00 m.

The backfilling works using surrounding lateritic soil from cutting of hill is carried out using the conventional layer-by-layer compaction method (CCM). The lateritic soil is mainly silty. The houses are to be built mainly on the filled ground. In order to meet the required design criteria in terms of bearing capacity and settlement for the buildings to be built on pad footings, compaction of the backfilling soil must be at least 95% of the maximum dry density at optimum moisture content of the soil. The thickness of the fill ranges from 2 to 6 m.

After the backfilling has completed, Mackintosh probe (MP) test is carried out on the ground surface up to 6 m depth or refusal. Figure 5 shows some of the MP test results conducted on site. The test results show that the compaction completed at certain areas within the project site does not achieve the required degree of compaction. This is confirmed by the existence of soft layers (i.e., MP blows count less than 30 blows per 300 mm) within the compacted ground at varying depths up to 4.5 m. It should be noted that for the areas where the refusal is reached before 6 m, the probe is likely to have hit the granite bedrock.

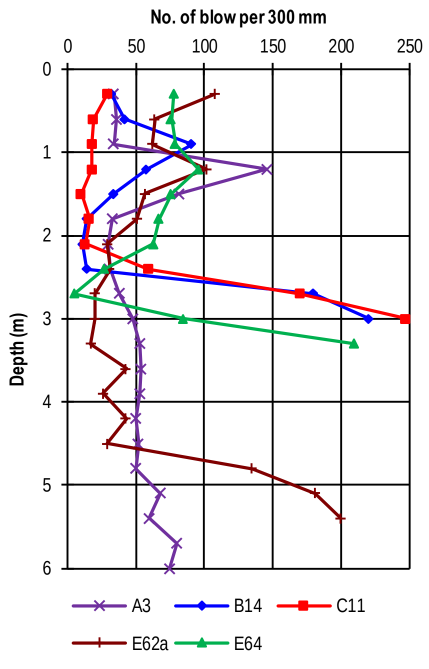

Figure 5 Mackintosh probe test results

From the Mackintosh probe (MP) test results, it is concluded that the ground is non-uniformly compacted. Consequently, the construction of the buildings cannot be started. The developer has considered a few options to solve this issue as follows:

- Change the foundation system from pad footings to piles foundation;
- Excavate the fill material and recompact;
- Deep compaction using dynamic compaction (DC).

Eventually, DC is selected as it is the cheapest and fastest solution among the options available. The deep compaction up to 6 m thick using DC is possible for this project because the filled ground is unsaturated.

3.2 Design and Execution

The foundations for the buildings are originally designed as pad footings with size ranges from 900 mm × 900 mm to 2850 mm × 2850 mm and minimum embedment of 1.2 m. The net allowable bearing capacity of 106 kPa is required throughout the compacted ground. The allowable settlement criteria for the pad footings is shown in Table 2. Following the dynamic compaction (DC) works to recompact the non-uniformly compacted lateritic soil, the Engineer has asked for the same pad footings design and acceptance criteria to be maintained. The maximum treatment depth is limited to 6 m because this is almost the maximum thickness of fill at the project site.

Table 2 Allowable settlement criteria

Criteria	Isolated footings
Angular distortion	1:300
Maximum settlement (i.e., long term settlement after completion of building)	75 mm

The design and calculation for the bearing capacity and settlement are carried out in accordance to the following section in the D.60.AN General Memorandum (Menard, 1975):

- Section 3 Calculation of the bearing capacity
- Section 4.2 General formula for settlement of an isolated foundation (T-0 rule)

Based on the design conducted, in order to meet the bearing capacity and settlement requirements, the acceptance criteria for the dynamic compaction (DC) works are specified as follows:

- Geometric mean limit pressure, P_L, over the improvement depth shall not be less than 500 kPa to achieve the net allowable bearing capacity.
- Harmonic mean pressuremeter modulus, E_M, of the compacted fill shall not be less than 5,000 kPa for the upper 6 m to ensure the allowable settlement criteria can be met.

In order to verify the performance criteria are achieved, acceptance test using pressuremeter test (PMT) is specified. Plate load test using 1 m diameter steel plate is also conducted after the DC works to cross-check the PMT results.

The dynamic compaction (DC) works is only proposed at the building footprint. The requirement is to treat the building footprint area so that the pad footings for the double storey houses and shop houses can be constructed at any location within the building footprint. The typical layout of DC prints adopted for the project is shown in Figure 6. The spacing adopted for the main phase DC compaction is 5.2 m centre-to-centre on a square grid and this is followed by the ironing phase. A lattice-boom crane capable of lifting 15 tonnes pounder with 20 m drop height is used for this project to give maximum compaction energy of 300 tonne·m per blow.

3.3 Pressuremeter Test Results

Thirteen Menard pressuremeter tests (PMT) have been carried out in this project. The tests are carried up to 6 m or refusal depth. Figure 7 shows the 3 pre-treatment PMT conducted before dynamic compaction (DC) works. The results show that the thickness of the fill is not uniform and ranging from about 2 to 6 m throughout the development area. In terms of degree of compaction, it is shown that there are localised layers within the lateritic fill which are not properly compacted (i.e., pressuremeter modulus, E_M less than 5,000 kPa). For instance, at depth of 2 m for Pre-PMT-01, at depth of 1 m for Pre-PMT-02, and at depth of 3 to 4 m for Pre-PMT-03.

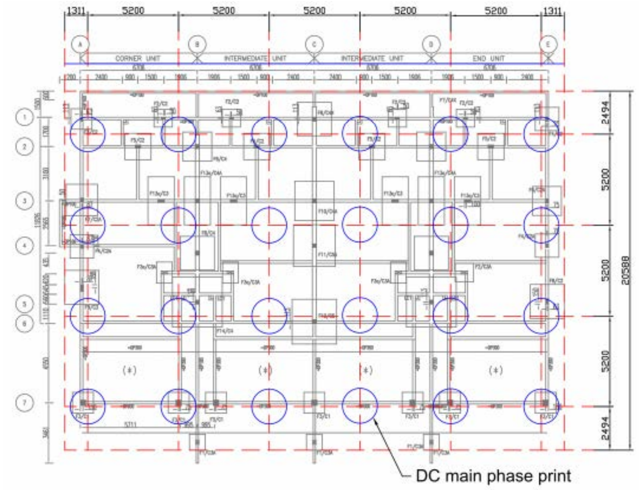

Figure 6 Layout for dynamic compaction (DC) works

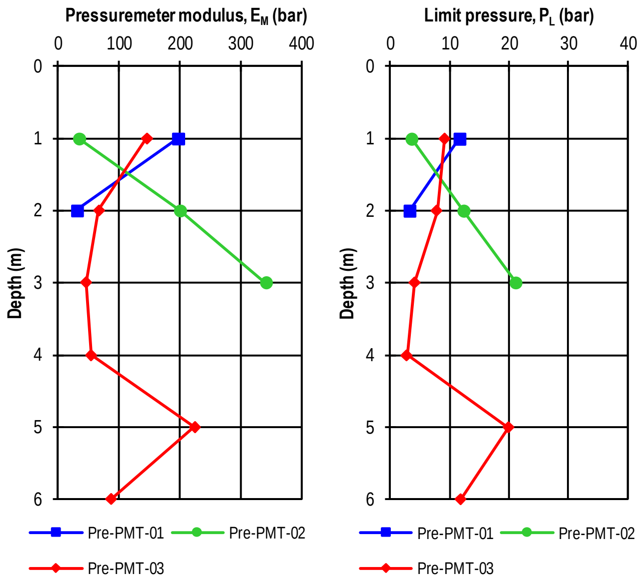

Figure 7 Pre-treatment pressuremeter test (PMT) results

Figure 8 shows the post-treatment pressuremeter test (PMT) conducted at the same location with the pre-treatment PMT after dynamic compaction (DC) works. It is shown that the fill material has been well compacted as demonstrated with the overall increase of the pressuremeter modulus, E_M and limit pressure, P_L. The variability of the lateritic fill is also reduced. Table 3 summarises the harmonic mean E_M and geometric mean P_L of the lateritic fill recompacted using DC method. Clearly, the values of E_M and P_L obtained after DC works exceeded the specified acceptance criteria. Thus, the pad footings can be built confidently within the building footprint area to support the double storey houses and shop houses. It is worthy to note that the plate load test conducted up to 2 times the net allowable bearing capacity (i.e., 212 kPa) recorded a maximum settlement of less than 21 mm.

Table 3 Harmonic mean E_M and geometric mean P_L values

	Harmonic mean E_M (kPa)	**Geometric mean P_L (kPa)**
Post-PMT-1	11,100	760
Post-PMT-2	26,100	1,190
Post-PMT-3	11,000	1,000

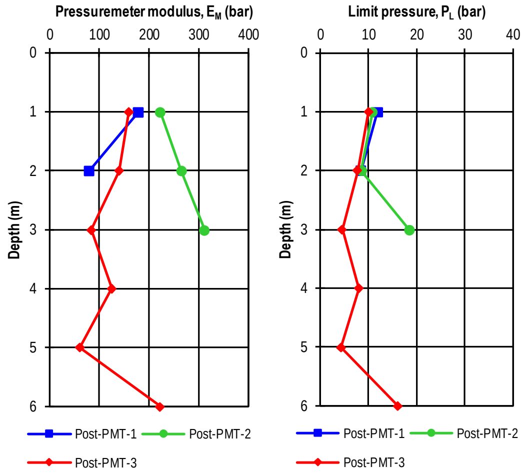

Figure 8 Post-treatment pressuremeter test (PMT) results

4. DISCUSSION

Notwithstanding the uncertainness of dynamic compaction (DC) to treat soil with high fines content, this paper has presented two case studies of the application of DC to compact lateritic fill for property development projects. The main reason for the two projects to be successfully implemented, despite the fill material is mainly silty soil with fines content more than 50%, is because the lateritic fill is unsaturated or partially saturated. Furthermore, for the case of the deep valley compaction, additional construction measure has been taken to minimise the effect of rainwater from wetting the lateritic fill by placing a layer of crusher run on top of each layer of fill to be compacted. This increases the effectiveness of the DC works tremendously. Indeed, DC will not be the go-to solution for the compaction of lateritic fill in property development projects. Nonetheless, it could be an attractive solution under certain conditions as highlighted in the two case studies in this paper. Therefore, property developers and their designers should keep in mind the potential of using DC for their projects, especially when a thick layer of fill is to be compacted.

This paper also discusses on the application of pressuremeter test (PMT) in the design and construction quality control including verification of the design conducted for dynamic compaction (DC) works. The pressuremeter modulus, E_M and limit pressure, P_L from the PMT are the two soil parameters adopted in the settlement and bearing capacity calculations. As such, verification at the project site after compaction works can be done almost instantaneously upon completion of the PMT. If the required E_M and P_L are not achieved, additional compaction works can be conducted. If the specified E_M and P_L are met, the compacted ground can be handed over for next phase of construction. Indeed, PMT is a valuable tool in DC works as it provides the possibility for the designer and constructor to check on the deep compaction works at every metre interval and verification of the design can be done swiftly following the test.

5. CONCLUSION

This paper has presented two case studies of the application of dynamic compaction (DC) for the compaction of unsaturated lateritic fill with high fines content in property development projects. The first case study is the compaction of a deep valley up to 23 m using DC. The 23 m deep valley is subdivided into 5 layers of 3 to 5.15 m to ensure effective compaction using DC. The second case study is the recompaction of a non-uniformly compacted filled ground up to 6 m. In both projects, pressuremeter test (PMT) has been used in the design and construction control. The PMT results show the effectiveness of DC to compact the lateritic fill to the required level in both projects. Indeed, unsaturated lateritic fill with high fines content can be compacted successfully using DC if proper design and construction tools are adopted.

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