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Investigation of Dynamic Compaction and Vibro-compaction to Mitigate Liquefaction: A Case Study

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Liquefaction is one of the phenomena that can be triggered by an earthquake. Earthquake causes an increase in pore-water pressure in soil, reducing soil's effective stress to zero or near-zero. In this state, the soil loses its strength and behaves like a liquid. This is known as liquefaction. When soil loses its strength, so it also loses its bearing capacity, causing damage or failure to structures. The soil type that is most prone to liquefaction is loose saturated fine sand. Such soil can be found in many of coastal areas in Indonesia. Indonesia is also one of the most earthquake prone countries in the world, hence liquefaction is one of the natural hazards that Indonesia has to face. Earthquake cannot be prevented, and its occurrence cannot be accurately predicted. Fortunately, liquefaction can be prevented by doing soil improvement to increase the sand density. The two most commonly used ground improvement techniques to increase sand density is dynamic-compaction and vibro-compaction. A case study from Aceh province, where both ground improvement techniques were used, is presented in this paper to compare the performance of dynamic compaction and vibro-compaction.

KEYWORDS Fine sand; Liquefaction; Ground Improvement; Dynamic Compaction; Vibro-compaction

1 INTRODUCTION

Indonesia is an archipelago that is located within the ring of fire region. The ring of fire is a region around the rim of Pacific Ocean where the frequency of earthquakes and volcanic activities are high. As Indonesia is an archipelago, Indonesia has large coastal areas, and many of those coastal areas have loose saturated fine sand. The combination of high earthquake activities and loose saturated sand means Indonesia is prone to liquefaction. Liquefaction is a process whereby soil loses its bearing capacity due to accumulation of excess pore-water pressure induced by earthquake (Figure 1). When the accumulated pore-water pressure, u, is equal to or goes beyond the total stress of soil, σ_v, the effective soil stress, σ_v', becomes zero. When the effective stress becomes zero, shear strength becomes zero, and hence soil loses its bearing capacity. Structures that are built on soil which liquefies will undergo large settlement, damaging the structure or even cause failure. Figure 2 shows a few photographs of damages caused by liquefaction. To mitigate liquefaction problems, sandy soil which has high liquefaction potential needs to be densified.

Figure 3 shows the available ground improvement methods currently available in practice. From the figure, we can see several ground improvement methods suitable for sand, i.e., blasting, dynamic compaction, vibro-compaction, chemical grouting, jet grouting and deep mixing. Amongst all the ground improvement methods available for sand, the most commonly used ones to mitigate liquefaction problems are dynamic compaction and vibro-compaction. In order to check the success of dynamic compaction or vibro-compaction, one can conduct liquefaction potential analysis. Liquefaction potential analysis can be carried out based on standard penetration test (SPT) data (Seed and Idriss, 1971, 1982; Seed et al., 1985; Idriss & Boulanger, 2004; Ishihara, 1985), cone penetration test data (Stark & Olson, 1995), or shear wave velocity test (Andrus & Stokoe, 2000).

In this paper, a case study in which both dynamic compaction and vibro-compaction were used in the same project site is discussed and compared.

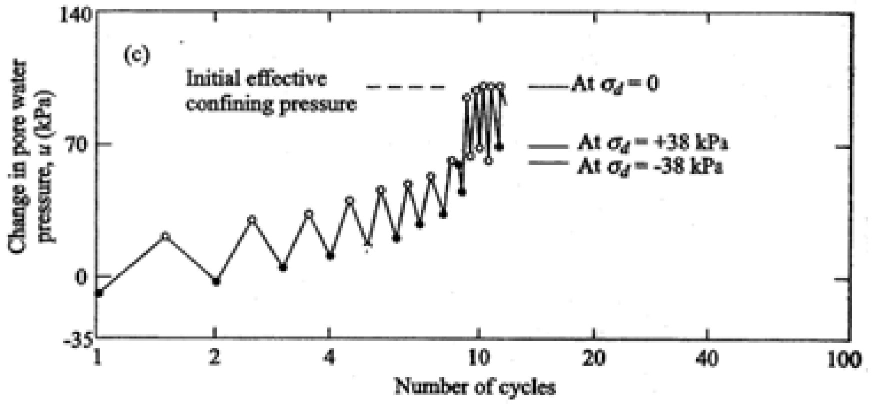


Figure 1. Pore excess accumulation during earthquake (Seed & Lee, 1966).

Figure 2. Destruction caused by liquefaction (Kramer, 1996; Geoengineer, 2015; López-Querol, 2008).

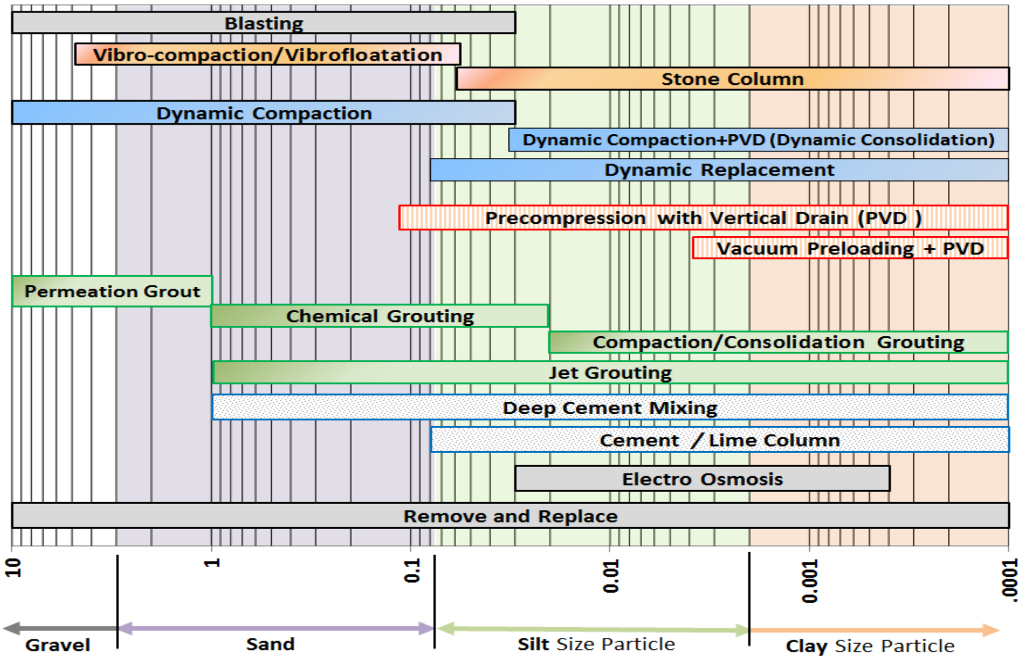


Figure 3. Selection of soil improvement methods based on grain size (SNI 8460:2017).

2 INTRODUCTION TO DYNAMIC COMPACTION AND VIBRO-COMPACTION

Compaction is defined as the process of densifying soil by using external compactive effort. Dynamic compaction is a ground improvement method in which the external compactive effort is applied by dropping a heavy weight (usually 6 to 30 tons) from a certain height (usually 3 to 7 m) (Lukas, 1995; Nicholson, 2015). This technique was first developed by Menard in the 1970s (Gambin, 1979; Menard & Broise, 1975). Figure 4 shows the apparatus required as well as the process of dynamic compaction.

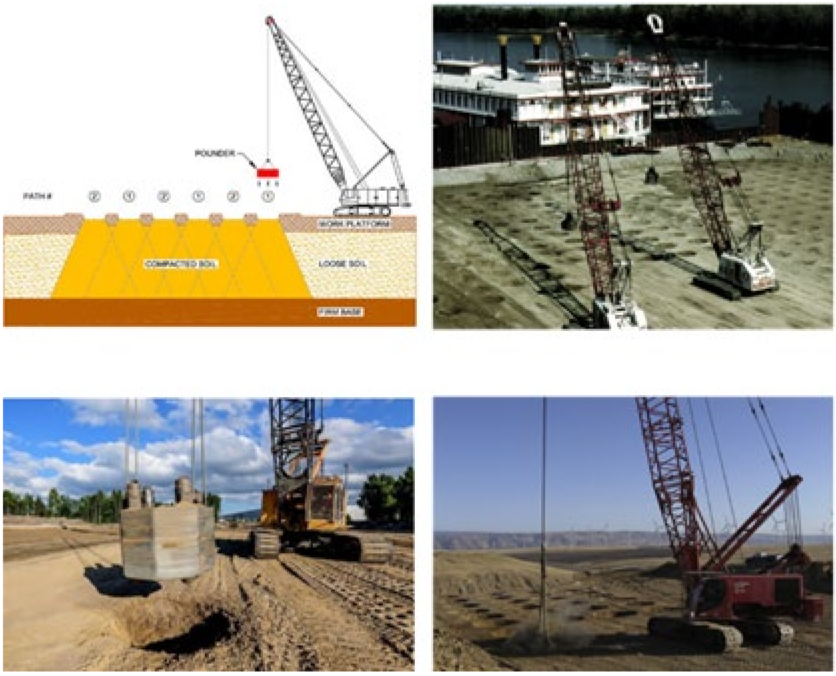


Figure 4. The apparatus for dynamic compaction (Nicholson, 2015; Patel, 2019).

This method is very suitable for granular soil with no cohesion, regardless of whether the soil is saturated or unsaturated. Dynamic compaction is also suitable for compacting gravelly fill material, industrial waste and even household waste. However, this technique is not suitable to be directly used on fine-grained soil, such as silt or clay. To allow dynamic compaction to be used on fine-grained soil, modification has to be made. Example of modification that can be used are adding gravels on the ground surface to be tamped by the hammer. Another modification that can be made is by installing vertical drain to accelerate consolidation process. The latter modification is not recommended by the author.

As for vibro-compaction, also known as vibro-flotation, the compaction process is carried out by inserting vibrating poker (Figure 5) into the soil layer to be compacted. This technique is suitable for sandy soil above or below the ground water level (Kirsch and Kirsch, 2000). Vibro-compaction can increase the shear strength of soil, reduce compressibility, and in earthquake prone areas, reduce liquefaction potential. In order for vibro-compaction to be successful certain conditions have to be met. In saturated sand, the vibration has to be strong and quick enough to induce pore-water pressure equal to the total stress of the soil. Meaning, the vibro-compaction is used to induce liquefaction around the vibrating poker. When the soil is temporarily liquefied, this state allows easier arrangement of soil particles, achieving a tighter and denser packing upon dissipation of pore-water pressure (Figure 6). In unsaturated conditions, the vibration has to be strong enough to overcome the shear strength of soil, allowing soil particles to move and rearrange to a denser state. In the case whereby water jetting is used, the flow rate has to be high enough to allow local saturation of soil. Then, just like in saturated state, the vibration can induce temporary liquefaction to densify the soil.

Figure 5. Different types of vibrating poker.

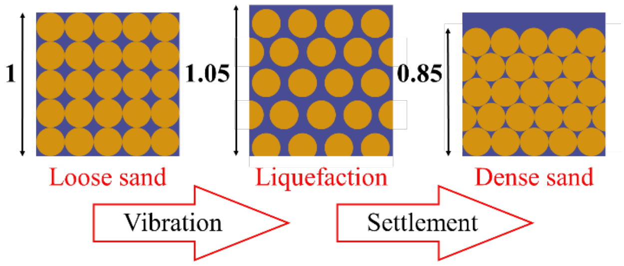


Figure 6. Densification scheme of loose saturated sand.

Another thing to be aware of when executing dynamic compaction or vibro-compaction is buildings in the proximity of area to be improved. Vibration induced by dynamic compaction or vibro-compaction can disturb the comfort of those living nearby, and in more severe case, can even induced damage to nearby structures. Therefore, it is recommended to conduct trial test and measure the vibration induced at several distances. The vibration induced can be monitored using vibration monitoring. The data can then be evaluated using criteria developed by Richart et al. (1970). One can refer to Gouw (1989), Gouw et al. (2013), Greenwood (1970) and Nicholson (2015) for more detailed information on dynamic compaction and vibro-compaction.

3 CASE STUDY OF DYNAMIC COMPACTION AND VIBRO-COMPACTION

3.1 Project Background

The project was located in Arun beach, Lhokseumawe, Aceh, Indonesia. In the 1990s, a few liquified natural gas (LNG) tank, with a diameter of 70 m and a height of 26 m, was to be built on the reclaimed area of Arun beach. The tanks were to be built adjacent to one another. Soil investigation revealed that the soil conditions below the tanks to be built were relatively consistent. Figure 7 shows the soil profile. The soil was predominantly sand with varying degree of fine contents, ranging from 5 to 15%. At depth 3 to 6 m, a thin clayey sand lens of about 1 m thick was found. The SPT blow count varied between 5 to 30 for most of the soil depth investigated.

The design requirement for the project was to prevent liquefaction against an earthquake with peak ground acceleration of 0.18g, and earthquake moment magnitude of 7.5. Figure 8 shows the results from liquefaction potential analysis. It can be seen that almost half of the SPT data lied below the liquefaction boundary, i.e., the soil on site had high liquefaction potential. In addition to the liquefaction problem, differential settlement was also anticipated due to varying stiffness of soil. Thus, it was decided to improve the soil up to 16 m depth.

Thanks to the owner's appreciation in advancement in technology, the owner was willing to apply two ground improvement techniques for this project. One of the tanks was improved with dynamic compaction, while an adjacent tank was improved by vibro-compaction. By conducting two ground improvement techniques adjacent to one another, the effectiveness of the two methods in mitigating liquefaction can be compared. In those days, this project was also one of the first application of dynamic compaction, as well as vibro-compaction in Indonesia.

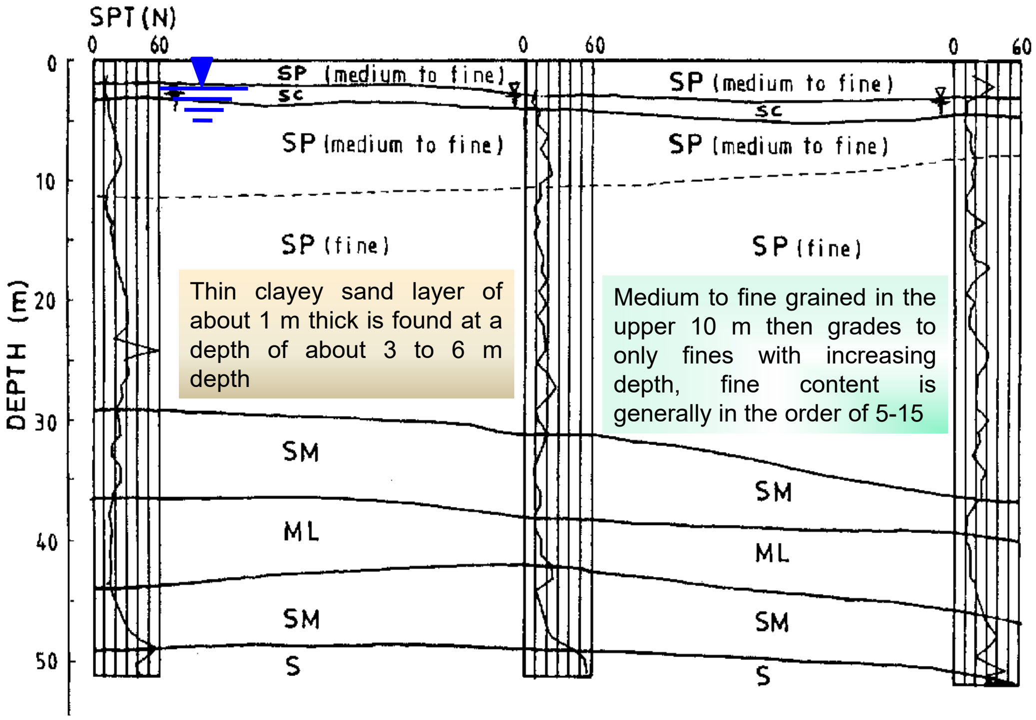


Figure 7. The soil profile at LNG project.

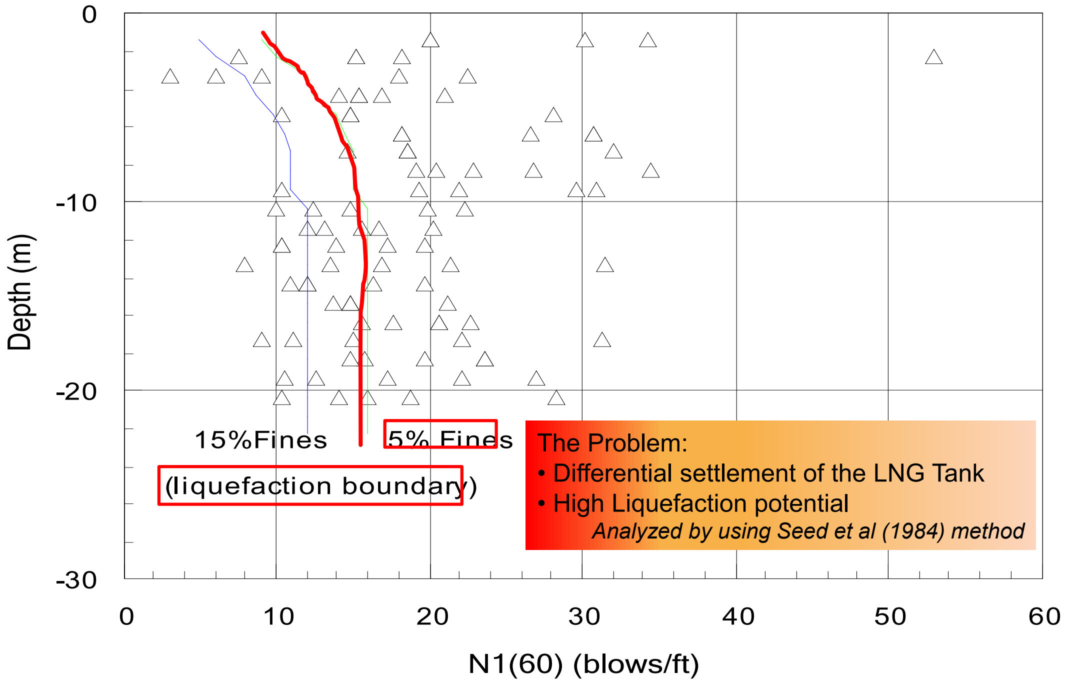


Figure 8. The result of liquefaction potential analysis.

3.2 Dynamic Compaction

For a target improvement depth of 16 m, the dynamic compaction specified was a tamper weighing 160 kN (tamper area = 2 x 2 m) with a drop height of 25 m (Figure 9).

The tamping was carried out in two phases. In the first phase, the tamping was carried out in 8 x 8 m grid, shown as white circles in Figure 10. In the second phase, the tamping was done in the middle of the first phase grid, shown as black circles in Figure 10. The radius to be improved (R_i) were calculated by adding half of the target improved depth (D_i) to half of the LNG tank radius (R_{tank}). The formulation is shown in equation 1.

$$R_i = R_{tank} + 0.5D_i \tag{1}$$

After both phases were completed, an ironing tamping phase was conducted. The purpose of ironing tamping was to densify the soil near the ground surface. For the ironing tamping, the same tamper was used, however the drop height was reduced to 5 m. Overall, the cumulative compaction energy applied was 2000 kNm/m^2, resulting in settlement between 22 to 28 cm.

Figure 11 shows the comparison of SPTs conducted before and after the dynamic compaction. It can be seen that significant improvement was achieved, only 4-5 SPT data points were still located below the liquefaction boundary. The 4-5 SPT data points which were still below the liquefaction boundary was deemed low risk. In 2004, the project was struck by the infamous 2004 Sumatra earthquake, which had a magnitude of more than 9. Despite suffering from earthquake which was higher than the initial design, measurement and surveying after the earthquake showed that the LNG tank did not suffer from any damage, functional nor structural. Proving the effectiveness of dynamic compaction.

Figure 9. The documentation of dynamic compaction during tamping.

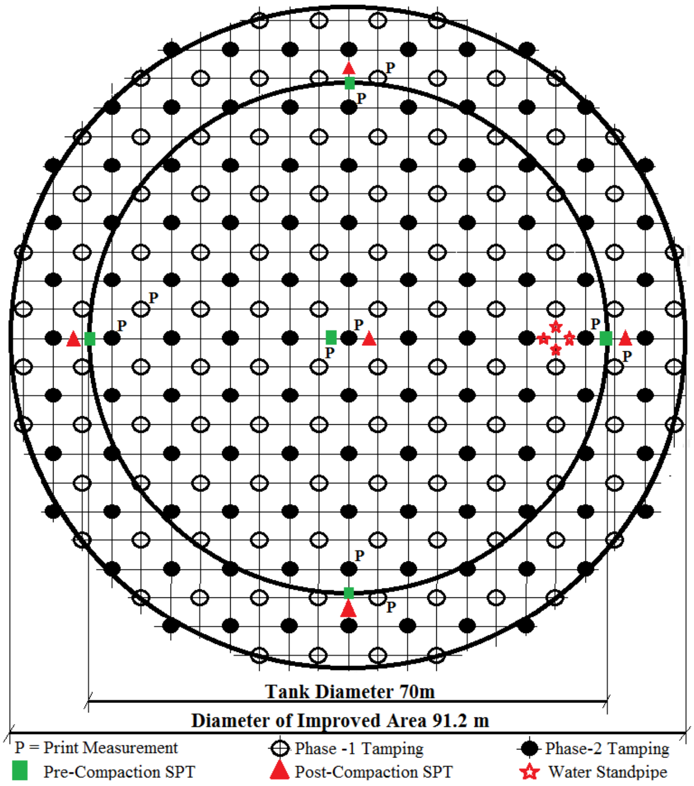
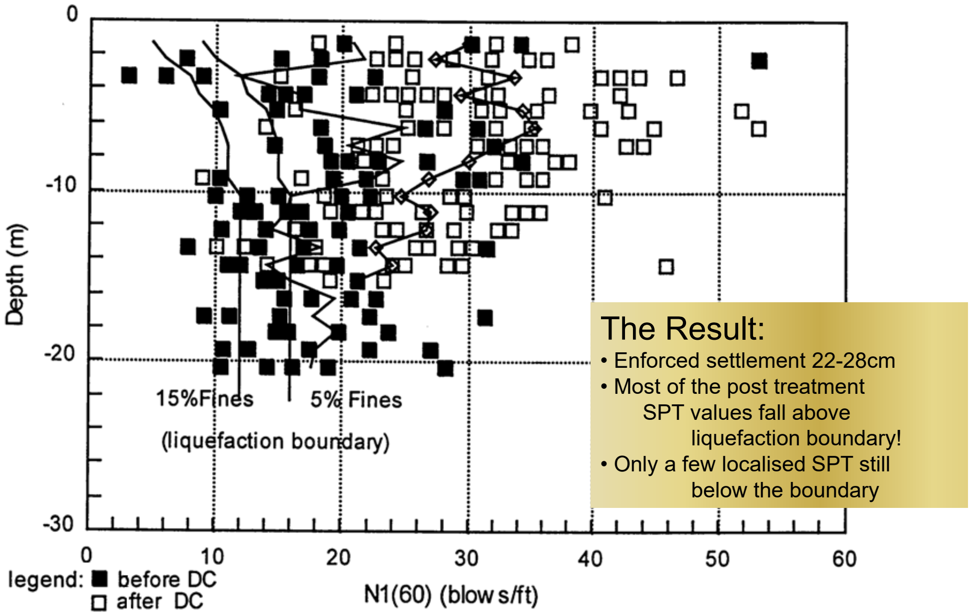


Figure 10. Arrangement of tamping coordinates for dynamic compaction.

From Figure 11, it can be seen that the effectiveness of compaction reduced with depth. The data in Figure 11 is further analyzed to evaluate the degree of improvement in dynamic compaction. The degree of improvement is calculated by dividing the post-compaction SPT blow count with pre-compaction SPT blow count. The degree of improvement is shown in Figure 12. It can be seen that the higher the pre-compaction SPT blow count, the lower the degree of improvement. From this data, dynamic compaction was only effective in improving sandy soil with a pre-compaction SPT blow count of less than 30.



The Result:
- Enforced settlement 22-28cm
- Most of the post treatment SPT values fall above liquefaction boundary!
- Only a few localised SPT still below the boundary

Figure 11. The comparison of NSPT before and after dynamic compaction.

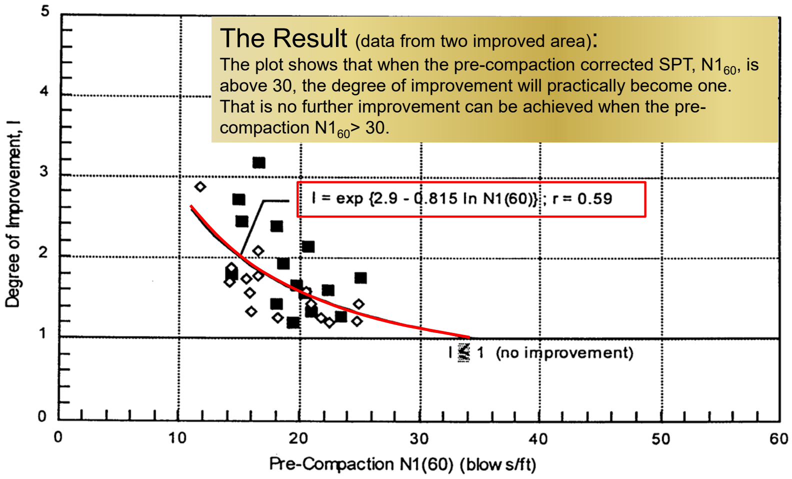

The Result (data from two improved area):
The plot shows that when the pre-compaction corrected SPT, $N1_{60}$, is above 30, the degree of improvement will practically become one. That is no further improvement can be achieved when the pre-compaction $N1_{60}$> 30.

Figure 12. Degree of improvement using dynamic compaction.

3.3 Vibro-compaction

For the adjacent LNG tank, vibro-compaction was also used to improve the sand layer up to 16 m depth. The grain size distribution from the soil layers to be improved is shown in Figure 13. In order to evaluate the suitability of soil with vibro-compaction improvement, a suitability criterion by Brown (1977) was overlaid on the grain size distribution curve. As shown in Figure 13, the sand layer in this project was located in between zone B and zone C. According to Brown (1977), soil with grain size distribution located in zone B is the most suitable for vibro-compaction technique, whilst soil with grain size distribution located in zone C need backfill material, i.e., vibro-replacement. Therefore, the soil in this project required backfill material. The grain size distribution used for the backfill material is also shown in Figure 13.

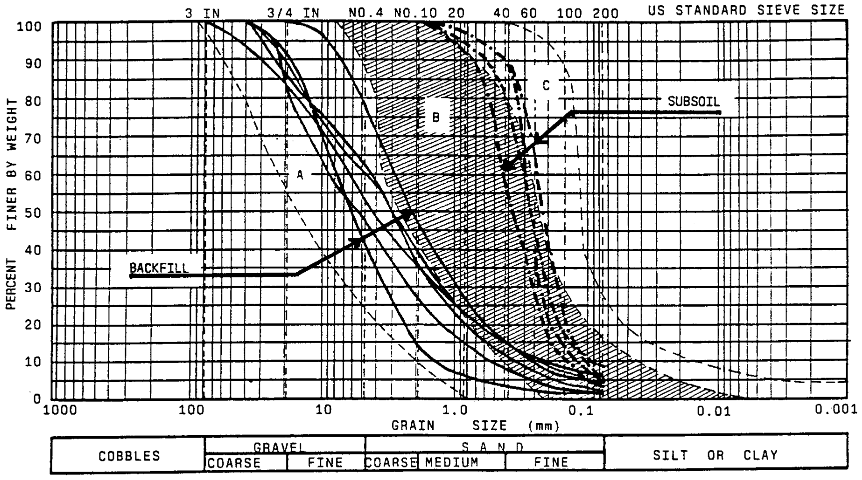


Figure 13. The grain-size of sub soil and backfill material (Brown, 1977).

The vibrating poker used in this project had 30 HP (horsepower), a diameter of 381 mm, length of 1.85 m and a weight of 18 kN. The vibrating poker rotates at a rate of 1800 rpm (rotation per minute), inducing a centrifugal force of 100 kN. The vibrating poker had two sets of water jet located at the tip and upper part of the vibrating poker. During the initial insertion of the vibrating poker, only the water jet at the tip was turned on (Figure 14-2). When the depth of improvement was reached, the water jet at the tip was turned off and the upper water jet was turned on (Figure 14-3). This was to prevent caving in of soil and allow backfill material to be filled into the annular hole created by the insertion of vibrating poker (Figure 14-3). The water jet used had a flow rate of 3000 l/min. As the project site was located near the sea, sea water was used for the water jetting. The compaction process was conducted by slowly extracting the vibrating poker while backfill material is continually added. The extraction rate was maintained below 30 cm/min (Figure 14-3). The backfill material consumed was 0.8 m^3 per meter depth of improvement. The vibro-compaction was carried out in triangular pattern with a spacing of 2.4 m. Figure 14 shows the documentation of vibro-compaction carried out for this project.

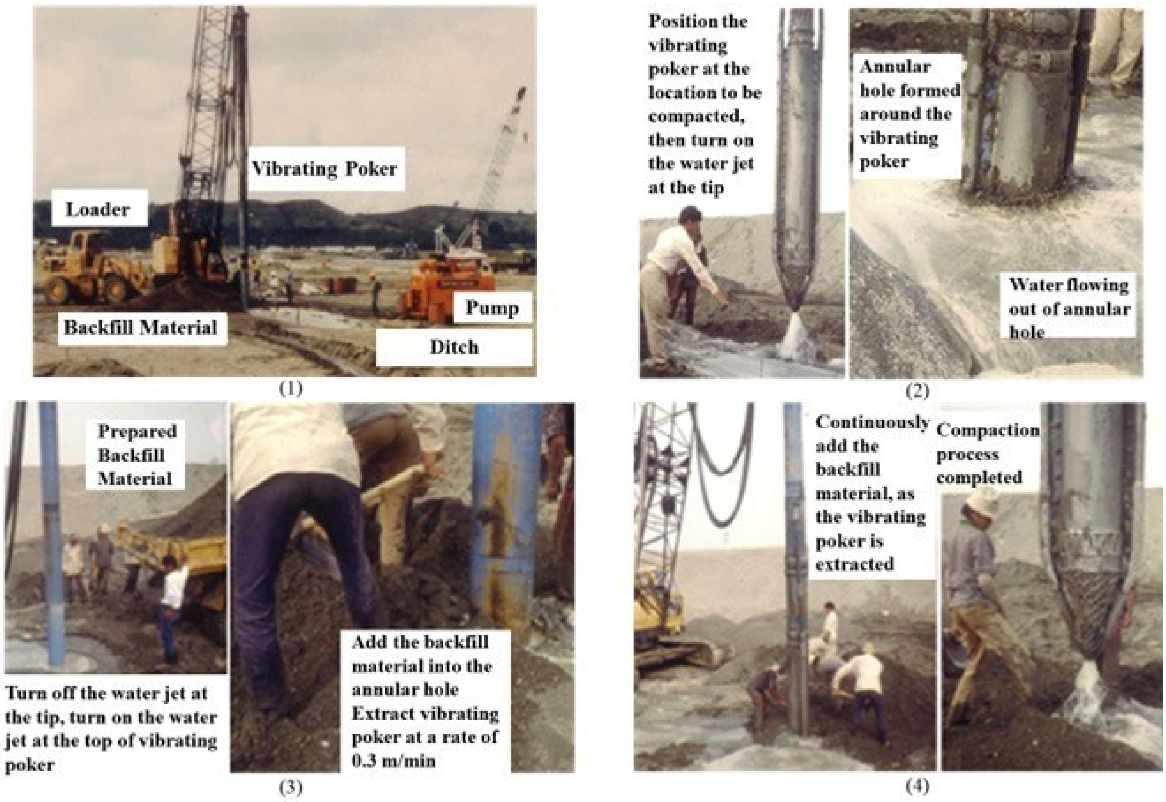


Figure 14. Documentation of vibro-compaction for the LNG tank project: (1) Apparatus for vibro-compaction, (2) Insertion of vibrating poker, (3) backfilling and extraction of vibrating poker, (4) extraction vibrating poker and completion of vibro-compaction

To evaluate the effectiveness of vibro-compaction, SPTs were also conducted after the vibro-compaction improvement. Figure 15 shows the comparison of SPT blow counts before and after vibro-compaction. It can be seen that all SPT blow counts after vibro-compaction were above the liquefaction boundary. This means that there is no liquefaction potential. From the figure, it can also be seen that similar degree of improvement was achieved throughout the 16 m improvement depth. This is contrast to dynamic compaction, in which degree of improvement reduces with depth. Figure 16 shows the degree of improvement produced by vibro-compaction evaluated in the same way as dynamic compaction. Similar to dynamic compaction, vibro-compaction was only effective in improving sandy soil with pre-compaction SPT blow count of less than 30.

The LNG tank improved by vibro-compaction also survived the 26 December 2004 great Sumatra earthquake of 9.1-9.3Mw without suffering any structural or functional damage.

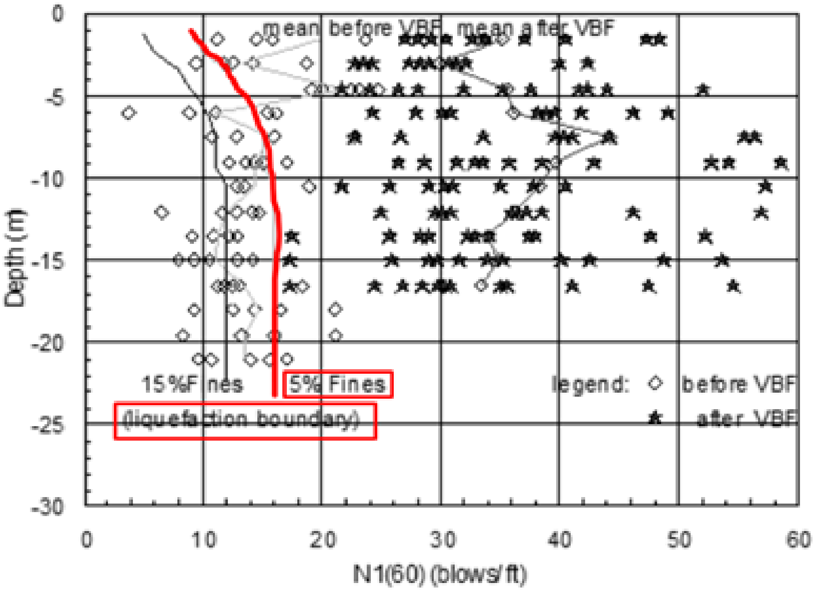


Figure 15. The comparison of SPT blow counts before and after vibro-compaction.

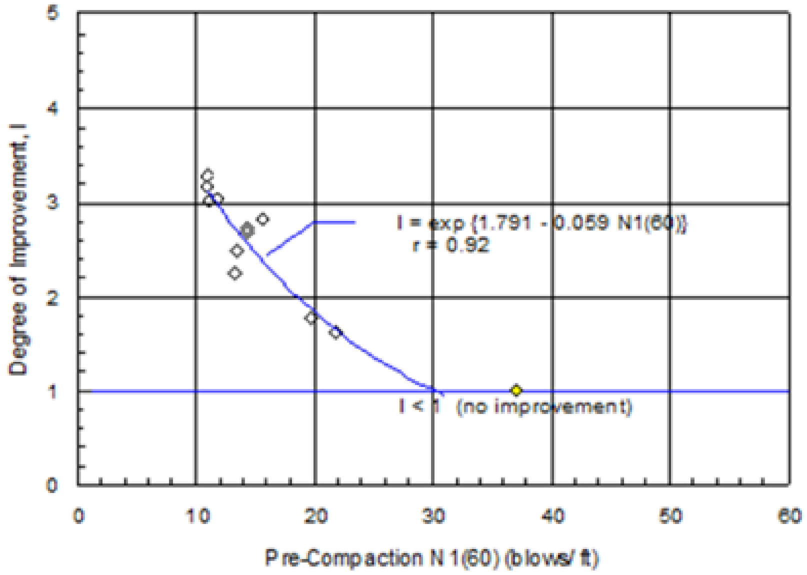


Figure 16. Degree of improvement using vibro-compaction.

3.4 Dynamic Compaction vs. Vibro-compaction

Figure 17 shows the SPT blow counts before and after ground improvement for both dynamic compaction and vibro-compaction. The most obvious difference is the improvement in SPT blow count with depth. For dynamic compaction, the improvement reduces with depth, whereas vibro-compaction shows similar improvement throughout the improvement depth. This shows that compaction energy from dynamic compaction reduces with depth. This is natural as the compaction energy is applied on the surface in the case of dynamic compaction. Different from dynamic compaction, vibro-compaction shows a relatively uniform degree of improvement for all depth. This is because the compaction energy is applied directly from the vibrating poker, which is inserted from the ground surface to the depth of improvement. Therefore, the compaction energy does not reduce with depth. However, both techniques have a limiting capacity in terms of soil that can be improved. Sandy soil with SPT blow count of more than 30 cannot be further improved.

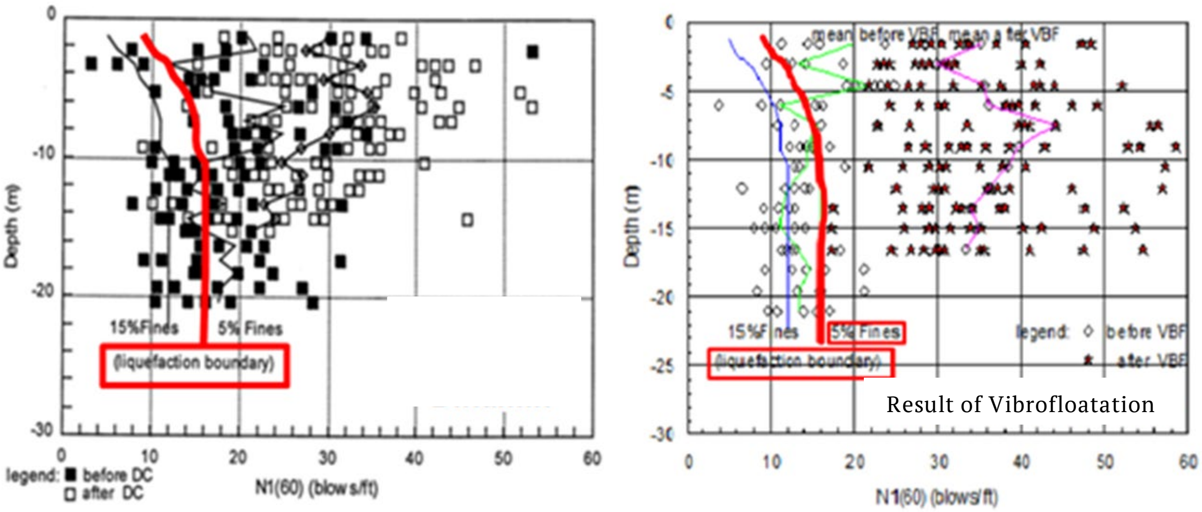


Figure 17. The comparison of dynamic compaction and vibro-compaction results.

4 CONCLUSION

Both dynamic compaction and vibro-compaction are capable of densifying sandy soil and reduces the liquefaction potential. This was proven in the LNG tank project as both the tank improved by dynamic compaction and the tank improved by vibro-compaction both survived an earthquake with magnitude higher than 9. A few things to note, however, is that dynamic compaction suffers from loss of effectiveness with depth. Whereas the effectiveness of vibro-compaction is uniform throughout the improvement depth. Although vibro-compaction seems superior in terms of degree of improvement, vibro-compaction requires tremendous amount of water, and hence cannot be applied in areas where water supply is scarce. Both ground improvement techniques cannot further improve sandy soil which already has SPT blow count of 30 or more.

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