

# CPTU characteristics and liquefaction resistance of reclaimed land by dynamic compaction

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**ABSTRACT:** This paper presents results of an extensive field investigation of a hydraulically-filled sandy site with piezocone penetration testing before and after ground improvement by dynamic compaction (DC). The focus of the paper is to examine the effect of DC on the piezocone penetration sounding characteristics and liquefaction resistance at the site. The results show that DC can increase the cone tip resistance ( $q_c$ ) and sleeve friction ( $f_s$ ) of soils in the expected depths of improvement (roughly from 2 m to 10 m). However, the soil behavior type largely remains unchanged. The liquefaction resistance is increased significantly for the predominately silty sands at this site.

## 1. INTRODUCTION

Several large reclaimed lands were created by hydraulic filling along the offshore of western Taiwan. Those reclaimed lands are generally created by hydraulic filling of the dredged material, mostly consisting of loose silty fines sands. Coupling with high groundwater table and active seismicity, these lands generally have a high potential for liquefaction. To mitigate possible liquefaction hazards, it is essential to densify the reclaimed lands. For ground improvement over a large area, dynamic compaction (Mayne et al., 1984; Chang et al., 2002) is often employed. Dynamic compaction method was introduced by Menard in 1972. The general theoretical framework and the way the procedure is carried out were initially established by Menard and Broise (1975). The effectiveness of dynamic compaction for ground densification depends on several factors, such as the type of soils, the depth to the groundwater table, and the tamping pattern and parameters (grid dimensions, number of passes, weight of tamper, height of drop, number of drops, etc.). In many cases, trial tamping program (pilot test) may be needed.

In practice, *in situ* testing such as standard penetration test (SPT) or cone penetration test (CPT) is often employed to investigate the site before and after dynamic compaction. CPT is particularly suitable for such investigation because of its capability of continuous profiling and superior measurement repeatability over other *in situ* tests. In fact, it has become the most commonly used technique for quality control of field compaction projects (Massarsch and Fellenius, 2002).

In this paper, a case study of the effect of dynamic compaction at a reclaimed land for mitigation of liquefaction hazards is presented. Numerous piezocone penetration (CPTu) soundings were conducted before and after dynamic compaction. The emphasis of the paper is placed on the examination of the cone penetration sounding characteristics and liquefaction hazards at the site before and after dynamic compaction.

## 2. SITE GEOLOGICAL CONDITIONS

The study site is located in the Taichung Harbor Port, Taiwan, a man-made harbor, which is designated for crude oil-related chemical industrial park. This site is a reclaimed land that was created by hydraulic filling. Field investigations show that the groundwater table is located at approximately 3.0 m to 3.8 m below the ground surface. The layout of bored holes and cone penetration (CPT) soundings before the ground improvement work at the site is depicted in Figure 1. Based on bored holes information and CPT soundings, the subsurface soil profiles are depicted with Figure 2. Basically, the subsurface to a depth of 20m at the site consists of the following layers:

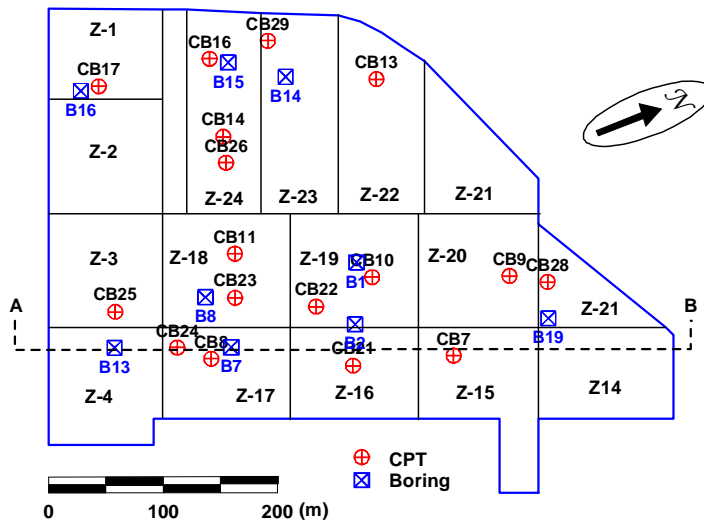


Figure 1. Layout of field tests before the ground improvement work.

1) Silty fine sand layer: roughly from the ground surface to a depth of 8 m. It mainly consists of gray silty fine sand, with trace of silty clay and sandy silt. The SPT blow counts are generally in the range of 4 to 32, with an average of approximately 10. The unit weight of the soil is  $18.3 \text{ kN/m}^3$  and the natural water content ranges from 22.4% to 26.2%. This layer is best characterized as loose sand.

2) Silty sand or sandy silt: roughly between the depths 8 m and 20 m. This layer mainly consists of gray silty fine to medium sand, with layers of sandy silt. The SPT blow counts are generally in the range of 12 to 32, with an average of 21. The unit weight of the soil is  $19.1 \text{ kN/m}^3$  and the natural water content ranges from 24.7% to 27.6%. This layer is best characterized as medium dense sand.

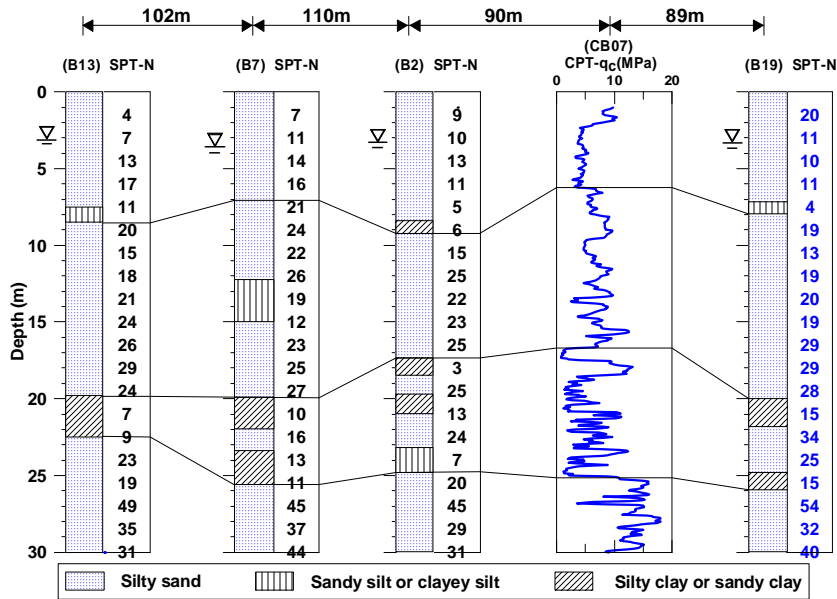


Figure 2. Soil profile along the A-B section at the site.

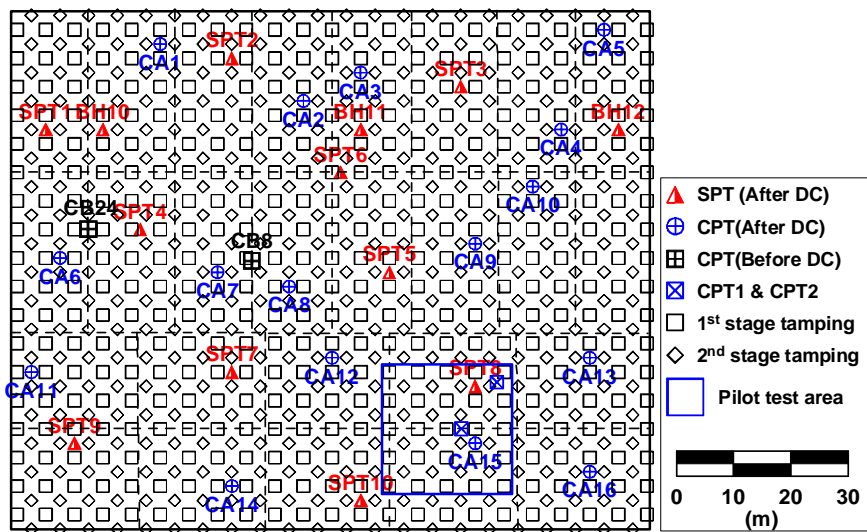


Figure 3. Scheme of pilot test and the geometrical arrangement of the impact points.

### 3. DYNAMIC COMPACTION WORK

Dynamic compaction was selected for ground improvement. The site was divided into 15 zones, each with an area of approximately 10000m<sup>2</sup>. Figure 3 shows the typical layout of the dynamic compaction patterns and the *in situ* test locations. The square symbol represents the locations of the first stage tamping, and the rhombus symbol represents the locations of the second stage tamping. The smaller square area (440 m<sup>2</sup>), shown at the lower right corner of Figure 3, is a pilot (trial) test area. The weight of tamper is 25 tons and the drop height is 20 m. In each stage, the number of drops is selected at 10 based on the trial tamping for effectiveness.

According to the cases studied the above parameters were widely used in Taiwan. These parameters were also confirmed by the pilot test.

#### 4. CPTU CHARACTERISTICS BEFORE AND AFTER DC

These prior CPTu soundings along with the post-compaction penetration soundings at near-by locations in these zones provide a basis for an examination of the soil characteristics as altered by dynamic compaction. The variations in the soil characteristics as reflected by the changes in cone tip resistance ( $q_c$ ), sleeve friction ( $f_s$ ), and penetration porewater pressure ( $u_2$ ), are summarized in the following.

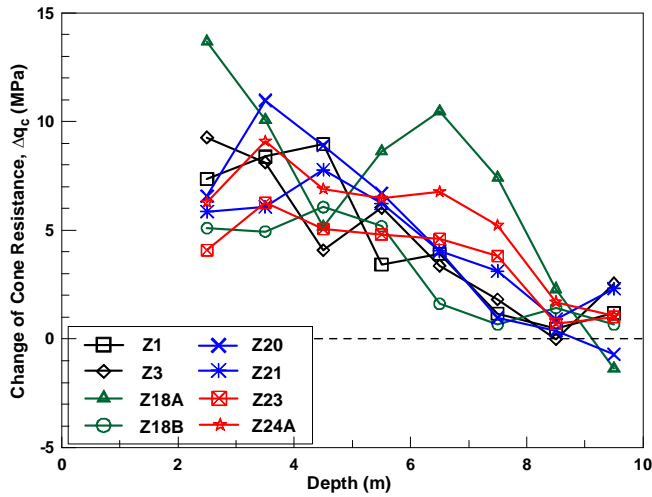


Figure 4. Average change in  $q_c$  versus depth.

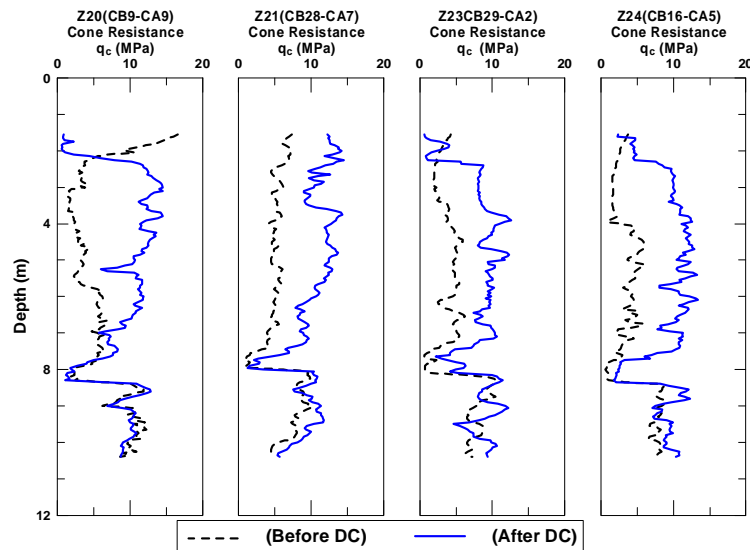


Figure 5. Change in the  $q_c$  profiles before and after dynamic compaction.

Within the planned depth of ground improvement (approximately 10 m),  $q_c$  values increase significantly, especially in depths of 2 m to 7 m. Figure 4 shows the average increase in  $q_c$  values at various depths; typically, the increase ranges from 2

to 10 MPa. The increase in  $q_c$  generally becomes less significant with depth. The possible reason is that either a clayey layer exists or the original  $q_c$  values at this depth (8 m to 10 m) are already quite high ( $q_c \approx 8$  MPa before dynamic compaction) and thus less improvement can be achieved. Figure 5 shows the  $q_c$  sounding profiles before and after dynamic compaction in four zones. It is noted that in some locations, there is virtually no increase in  $q_c$  at a depth of about 8 m. This is likely due to the existence of a thin layer of clayey material.

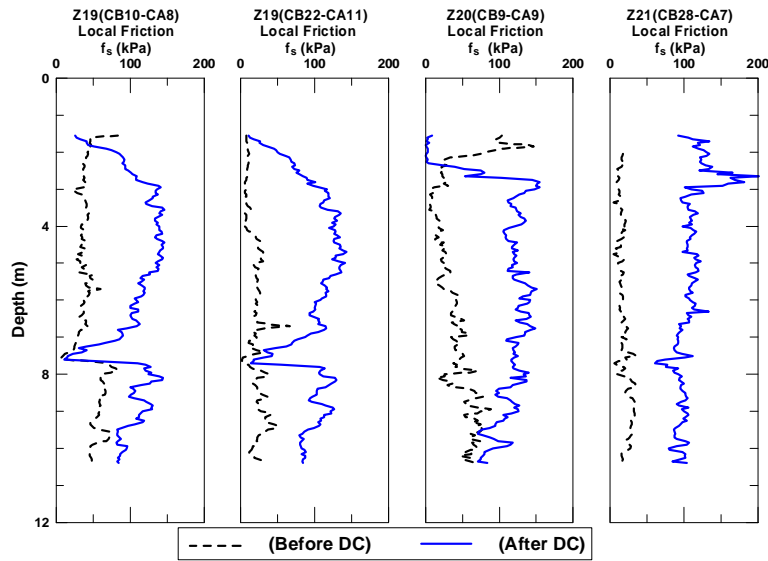


Figure 6. Change in the  $f_s$  profiles before and after dynamic compaction.

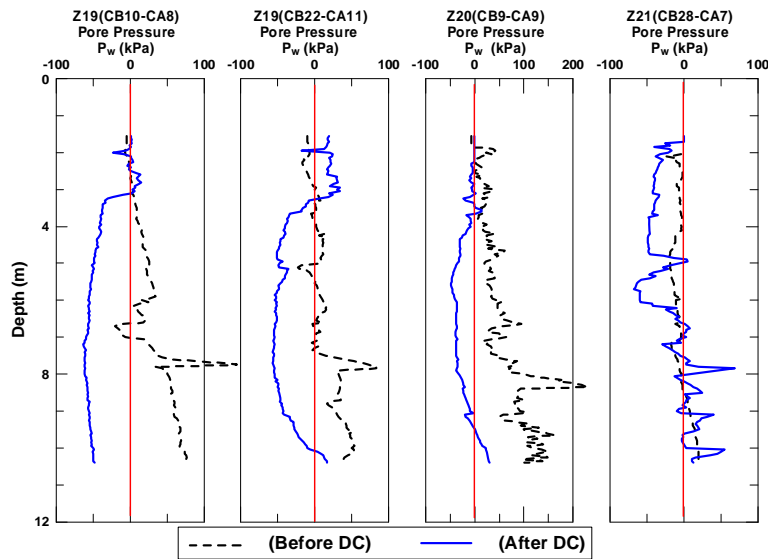


Figure 7. Changes in the penetration porewater pressure at selected locations.

Figure 6 shows the  $f_s$  profiles before and after dynamic compaction at selected locations. Similar profiles are observed at other locations. The results show that except at the depth of 7 m to 8 m, the sleeve friction increases significantly as a result of dynamic compaction. The exception at the depth of 7 m to 8 m is likely due to

the existence of thin-layer of clayey material. Finally, it should be noted that the increase in both  $q_c$  and  $f_s$  indicate that the dynamic compaction alters soil resistance in both vertical and horizontal directions.

In cohesionless soils, the penetration porewater pressure is usually less than the hydrostatic water pressure, as the soil is in drained state; and in dense sands, the penetration porewater pressure becomes negative. On the other hand, in saturated clayey silt and silty clay, the penetration porewater pressure is usually greater than the hydrostatic water pressure. The change in the penetration porewater pressure after dynamic compaction offers another way to examine the effect of dynamic compaction. Figure 7 shows typical changes in the penetration porewater pressure at selected locations at the site. Similar behaviors are observed at other locations. In general, the soils become denser as a result of dynamic compaction, which is reflected in greater negative penetration porewater pressure.

## 5. VARIATION IN SOIL BEHAVIOR TYPES

Cone penetration involves no sampling, and soil classification according to CPT is different from those carried out according to the Unified Soil Classification System (USCS); soil type determined with CPTu data is referred to as the soil behavior type (Been and Jefferies 1992; Robertson and Wride 1998). In theory, the dynamic compaction generates stress waves that densify the soils, and thus, soil type at depths will not be altered in the process (except at the point of contact where some change in particle size and distribution might be possible). However, the dynamic compaction can alter the values of  $q_c$ ,  $f_s$ , and  $u_2$ , as discussed previously. Thus, it would be of interest to examine the possible variation of CPT soil behavior type.

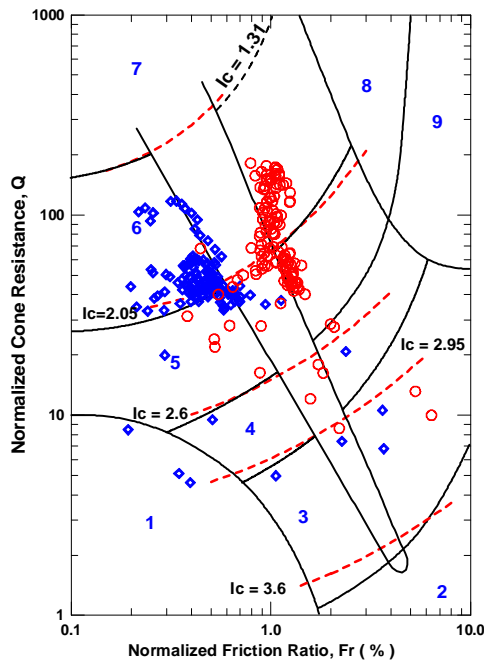


Figure 8. Soil behavioral classification before and after dynamic compaction in zone Z18 (rhombus - before compaction; circle - after compaction).

Figure 8 shows typical CPT results (data points plotted on the soil behavior classification chart) from a selected location before and after dynamic compaction (soundings CB23 and CA14 in Zone 18). Results from other locations reveal similar patterns and are not shown herein. Although the data points have “shifted” from looser state into denser state (mostly become overconsolidated sands as shown in the classification chart), the soil behavior type remains almost unchanged. Before the dynamic compaction, the soils are mostly in the range of type 6 (sands: clean sand to silty sand) to type 5 (sand mixture: silty sand to sandy silt). After the compaction, the classification largely remains the same, although the soils become denser. Another way to examine this change is to compare the profile of soil behavior type index ( $I_c$ ) before and after the compaction. Although some changes in the numerical values of  $I_c$  are observed, the soil behavior types largely remain the same.

## 6. VARIATION IN LIQUEFACTION-INDUCED SETTLEMENT

One effective way to examine the liquefaction hazards is to compute possible settlements induced by liquefaction. Many investigators have contributed to this subject (Tokimatsu and Seed, 1984; Ishihara and Yoshimine, 1992; Zhang et al. 2002; Cetin et al., 2009). In this paper, the procedure proposed by Ishihara and Yoshimine (1992) is adopted for the analysis of liquefaction-induced settlement, although other methods may also be used. Based on their field observations, Ishihara and Yoshimine (1992) rated the ground damage as “Light to no damage” if the settlement is less than 10 cm, “Medium damage” if the settlement is between 10 cm and 30 cm, and “Extensive damage” if the settlement is greater than 30 cm.

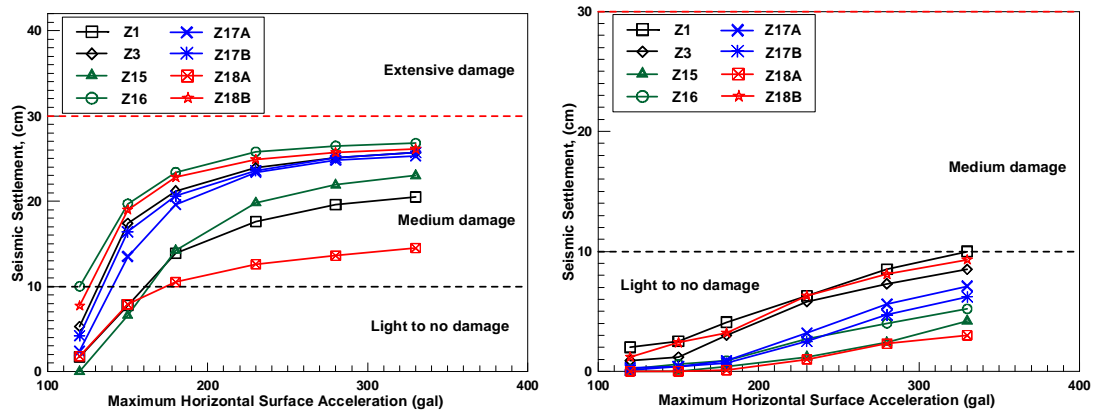


Figure 9. Liquefaction-induced settlement before and after dynamic compaction.

Figure 9 shows the results of the settlement analysis for the site before and after DC. At the  $a_{max} = 230$  gal shaking level, the computed settlements (before DC) all indicate a “Medium damage.” After the dynamic compaction these settlement results all indicate a “Low to no damage” even if  $a_{max}$  is much greater than 230 gal. The effectiveness of the dynamic compaction for reducing the liquefaction hazards at this site is demonstrated. The results are consistent with field observations in the 1995 Hyogoken-Nambu earthquake. Ishihara and Cubrinovski (2005) reported that fewer signs of liquefaction were found in reclaimed deposits that had been treated by

ground improvement measures; only scattered sand boils and smaller settlement of the ground were observed in the areas of compacted fill deposits.

## 7. CONCLUSIONS

A case study of the effectiveness of dynamic compaction at a reclaimed land created by hydraulic filling is presented. The results show that dynamic compaction can increase the cone tip resistance ( $q_c$ ) and sleeve friction ( $f_s$ ) of soils in the expected depth of improvement (roughly from 2 m to 10 m). However, at some depths where thin-layer of clayey soils exist, there is virtually no change in  $q_c$  and  $f_s$ . Furthermore, the change in the penetration porewater pressure ( $u_2$ ) also signals the densification by dynamic compaction. As the sands become more over-consolidated after the dynamic compaction, the magnitude of the negative penetration porewater pressure ( $u_2$ ) becomes more negative. While significant changes in  $q_c$ ,  $f_s$ , and  $u_2$  are observed after the dynamic compaction, the soil behavior type largely remains unchanged. Finally, the changes in liquefaction resistance after the dynamic compaction are observed. The liquefaction-induced settlement analysis results show that the risk is significantly reduced by the dynamic compaction.

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