Effect of precast pile driving on liquefaction potential mitigation of sandy silts based on CPTu

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ABSTRACT

Precast concrete piles are adopted as a foundation solution in liquefiable silty sand and sandy silt layers of north of Oman Sea shorelines for large diameter liquid tanks. The ground water table is about 6 m deep, and a highly potential liquefiable layer is identified from 7 m and continues to about 12 m deep. This liquefiable layer not only reduces the pile shaft skin friction, but also could have caused damage to slender precast piles as a result of kinematic and inertia shear forces and bending moments, in particular at the intersection of liquefiable and non-liquefiable cohesive layers underneath. The main objective of the paper is to evaluate the effect of densification of sandy silt deposits attributed to pile installation and the possibility of liquefaction mitigation effects due to radial compaction of the soil.

CPTu tests were carried out prior to and after the installation of piles. It is noticed that both q_c and f_s were increased depending on the center-to-center spacing of piles. Liquefaction analysis is carried out on CPTu results before and after piling installation and it is observed that the sandy silt layers are significantly strengthened against liquefaction and the safety factor notably rose above unity after the pile driving operation. The results are compared with triaxial cyclic tests on samples taken from a comparable depth for further investigation, indicating that the mitigation has occurred simply with a 10 percent increase in the relative density of the liquefiable sandy silt layer.

Keywords: Pile driving, CPTu, sandy silt, cyclic triaxial, densification, liquefaction mitigation

1. Introduction

In regions characterized by saturated fine sand deposits and high seismicity potential, liquefaction stands as a critical geo-hazard. It entails the weakening of soil structure and corresponding stiffness due to a systematic increase in pore water pressure and subsequently diminishing effective stress under seismic excitations. The liquefaction occurrences have catastrophic consequences, particularly in industrial areas. Consequently, identifying effective and cost-efficient methods for mitigating liquefaction becomes imperative in ambitious projects.

Various solutions exist to alleviate the adverse impacts of liquefaction, with pile driving emerging as one of the effective options. Pile driving serves to enhance the relative density of liquefiable soil layers through soil structure densification. Additionally, the design of piles includes provisions for transferring superstructure loads to deeper, non-liquefiable soil layers and bearing kinematic forces/moments developed during liquefaction.

The problem of kinematic effects on piles has been studied by Blaney et al. (1976), Kagawa & Kraft (1980), Dobry and O'Rourke (1983), Nikolaou et al. (1995), and Luo & Murono (2001). Determination of the kinematic forces acting on the soil-pile system depends on the liquefaction potential and soil parameters before and during liquefaction. Conventional experiences have held that displacement piles driven into loose and medium dense sands densify the soil structure (Meyerhof 1959, Nataraja and Cook 1983, Bement and Selby 1997, Gianella et al. 2015, Stuedlein et al. 2016 and Stuedlein & Gianella 2017, and Rhyner 2018).

It would have been reasonable to assert that pile driving has the capability to alter grain packing, leading to improvements in mechanical properties and a reduction in liquefaction potential. Consequently, the magnitude of kinematic forces acting on the pile is likely to change. Fakharian et al. (2022) conducted a study assessing the mitigation of kinematic moments associated with precast-driven piles in liquefiable silty sand layers resting on silty clay. The findings showed that the pile arrangement alone was insufficient to counteract the liquefaction consequences, whereas there was a notable increase in the factor of safety, effectively reducing kinematic moments to within acceptable limits.

For example, the response of silty layers to liquefaction remains contentious, contingent upon whether they exhibit sand-like or clay-like behavior. Additionally, the quantity and spacing of piles can affect the densification of subsoil layers. This underscores the necessity for supplementary studies to be conducted on this matter. This study investigates the impact of pile driving in silty sand/sandy silt layers, focusing on a case study with a significant number of piles. To ensure accuracy, the evaluation includes CPTu and cyclic triaxial tests conducted before and after pile driving. CPTu tests were conducted among the driven piles and in adjacent areas with a reasonable distance serving as a reference to represent the initial conditions before pile installation. Additionally, cyclic triaxial tests were performed on soil samples obtained from the relevant depths, with remolding based on the relative density (D_r) determined from CPTu tests representing conditions before and after pile driving at that specific depth. Both *in-situ* and laboratory tests demonstrate that pile driving substantially enhances soil densification and safety factors against liquefaction in sand-like silty layers.

2. Location and geotechnical condition

The study site is situated along the northern shorelines of the Oman Sea, in an industrial area in the vicinity of Jask City in southern Iran. The area is located 300 m away from the sea and consists of very fine sand, sandy silt, and silty clay sediments. The peak ground acceleration (PGA) with a period of 475 years is estimated equivalent to 0.36g based on site-specific seismology. Therefore, liquefaction of the fine sands and sandy silt layers is threatening the stability of heavy structures such as large-diameter liquid tanks.

An extensive geotechnical investigation was carried out at the site study including *in-situ* tests (e.g., CPTu) and extensive laboratory investigation. CPTu tests were executed prior to (as a reference test) and after the installation of piles to evaluate the effect of pile execution on liquefaction hazard mitigation. Subsurface layers of soil mostly consist of frictional fine sand and sandy silts in the upper layers and cohesive soil containing clay and silty clay in deeper layers.

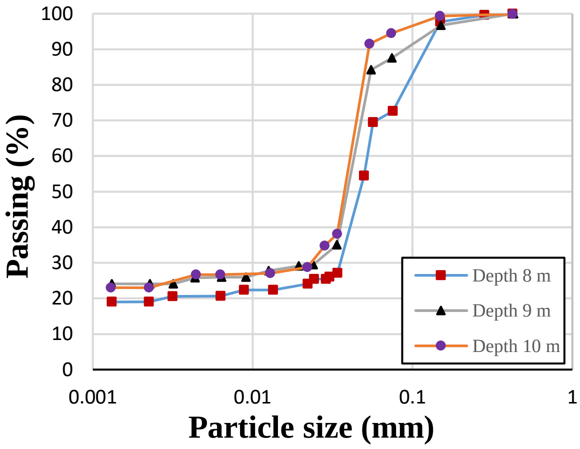

Figure 1. Grading curves at depths 8, 9 and 10 m

The concentrated zone of this paper is mainly between 7 to 12 m which mostly consists of frictional sandy silt and silt mixtures. Underneath is a soil layer consisting of low plasticity clay extended to about 30 m depth. The particle size distribution curves are illustrated in Fig. 1 highlighting that the particle size reduces with depth from 8 to 10 m. The percentages of clay, silt, and sand at each depth are summarized in Table 1, indicating that the sand content has decreased and the silt content has increased from 8 to 10 m.

Table 1. Different soil constituents at three depths

Depth (m)	Clay (%)	Silt (%)	Sand (%)
8	19.2	53.3	27.5
9	24.1	63.3	12.5
10	23.2	71.4	5.4

3. CPTu data and classification

According to the soil behavior type index based on CPTu test, the updated unified methodology developed by Robertson (2009) is utilized. As shown in Eqs. (1) and (2), to normalize the tip and sleeve friction resistance (i.e., Q_t and F_r respectively) the effective vertical stress is employed.

$$Q_t = \frac{q_t - \sigma_{v0}}{\sigma'_{v0}} \qquad (1)$$

$$F_r = \left[\frac{f_s}{q_t - \sigma_{v0}}\right] \times 100\% \qquad (2)$$

where f_s is sleeve friction, σ_{v0} and σ'_{v0} are *in-situ* total and effective overburden stresses, respectively, and q_t is CPT corrected cone resistance computed as Eq. (3).

$$q_t = q_c + u_2(1 - a) \qquad (3)$$

where the parameter "a" is the net area ratio of the CPT cone determined from laboratory calibration, mostly assumed between 0.7 and 0.85. The groundwater table is evaluated through site investigations as well as observations in the boreholes indicating a depth of about 6 m from the ground surface. Data acquired from CPTu tests before the pile driving (B-PD) and after the pile driving (A-PD) are depicted in Fig. 2 in which the soil type classification is evaluated through Robertson's method (i.e., Robertson 2009) and shown next to CPTu data and pore pressure profiles.

4. Liquefaction analysis

4.1. CPT-based analysis

CPT-based probabilistic correlations for the triggering of liquefaction in sands and silty sands have been developed by a number of investigators (e.g., Boulanger & Idriss, 2014). The cyclic softening and liquefaction potential are assessed using a methodology proposed by Robertson & Wride (1998), derived from the foundational work of Seed & Idriss (1971). This approach estimates the cyclic stress ratio (CSR) induced by seismic events and can be compared with the cyclic resistance ratio (CRR) of the soil, so that liquefaction may occur in the case of CSR>CRR. The procedure estimates CRR based on soil classification as "Sand-like"

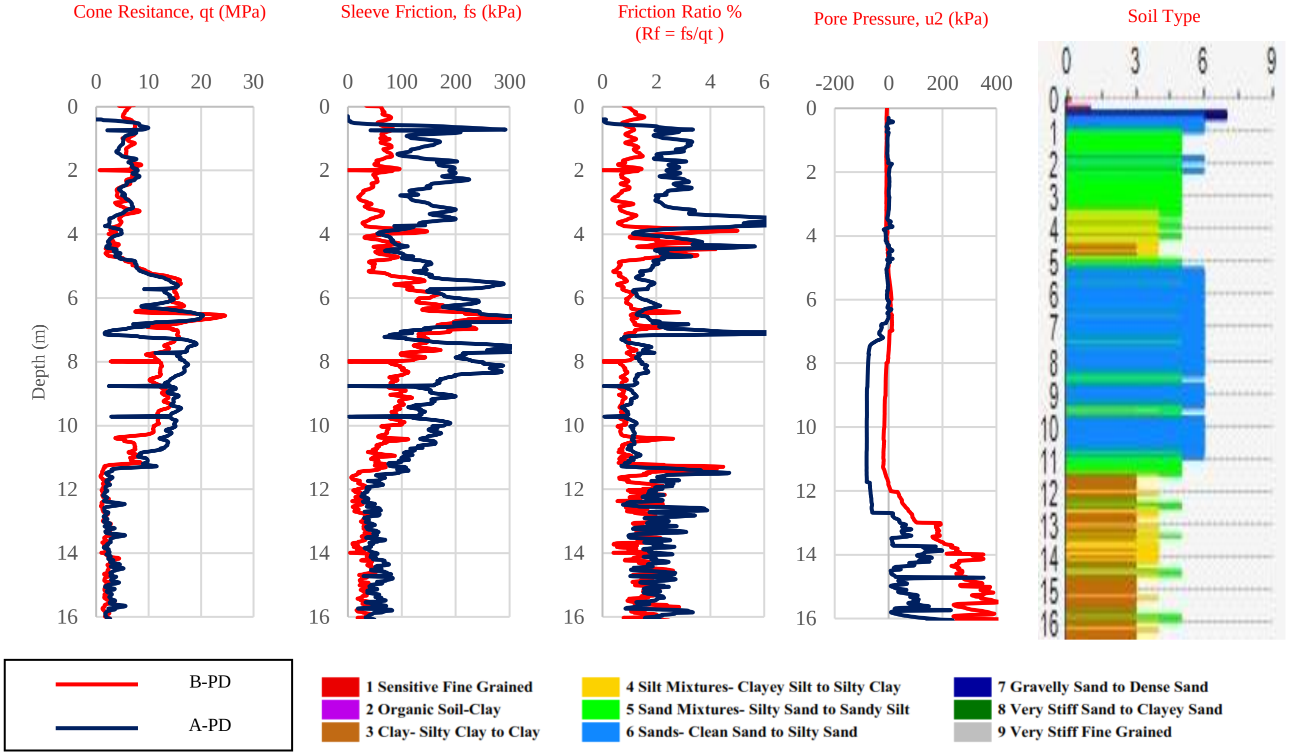

Figure 2. Cone resistance, sleeve friction, friction ratio, and pore pressure profiles accompanied by soil classification from CPTu tests before (B-PD) and after the pile driving (A-PD)

or “Clay-like”, with the defining boundary at I_c=2.6, as defined by Robertson (2009).

Upon thorough analysis of cone penetration test (CPT) data and interpretations, it was evident that the soil at depths of 7 to 12 m exhibits a clear reduction in CRR implying the liquefiable soil layers.

According to Robertson (2009), the SBT chart depicted in Fig. 3 at the depths of 8 m and 10 m primarily comprises sandy-silt composition consisting of particle size distribution shown in Fig. 1. The relocation of B-PD and A-PD data on the SBT chart indicates soil densification as a result of the precast pile installation with embedment depths ranging from 12 m on peripherals to 16 m near the foundation core.

Measures were taken to assess the mitigation of liquefaction risk, with the implementation of pile driving effects followed by subsequent CPT assessment conducted within the space between adjacent piles. The results, as illustrated in Fig. 4, signify a notable increase in terms of liquefaction resistance. In other words, the cyclic resistance ratio (CRR) exceeded the cyclic stress ratio (CSR) after the pile-installation-induced densification, leading to a greater safety factor against liquefaction.

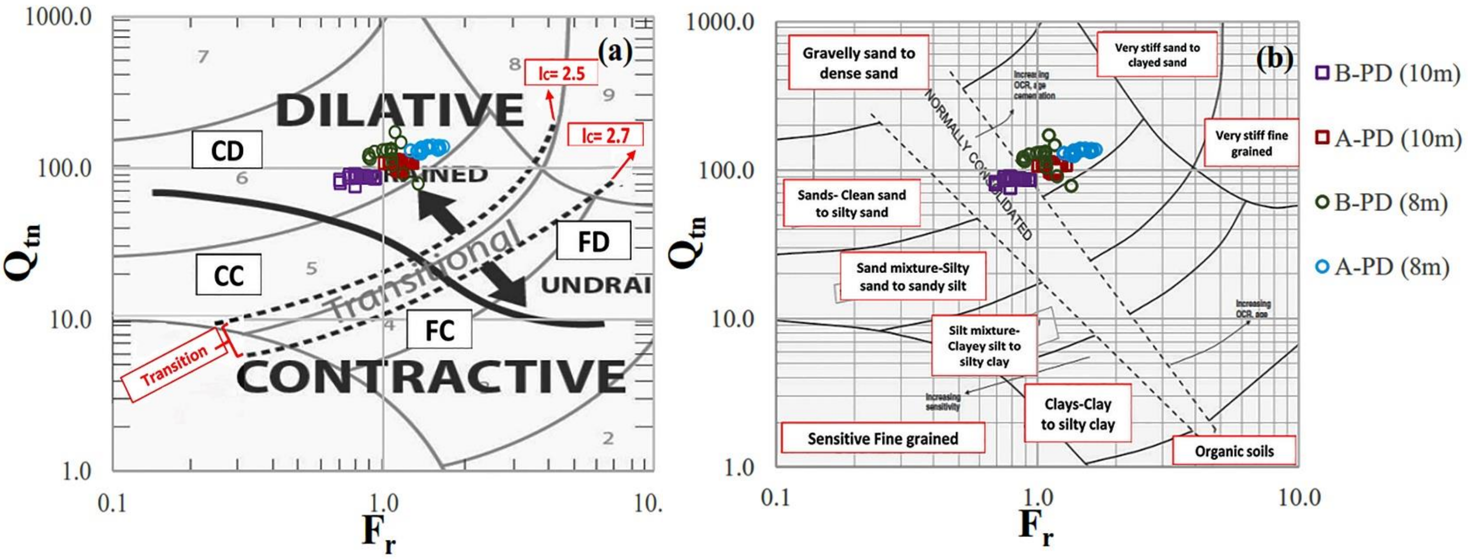

Figure 3. Data points of depths 8 and 10 m on Soil Classification Charts of Robertson (2009): a) normalized Soil behavior classification; b) soil classification, indicating movement of points to becoming denser, hense more dilative after the pile driving

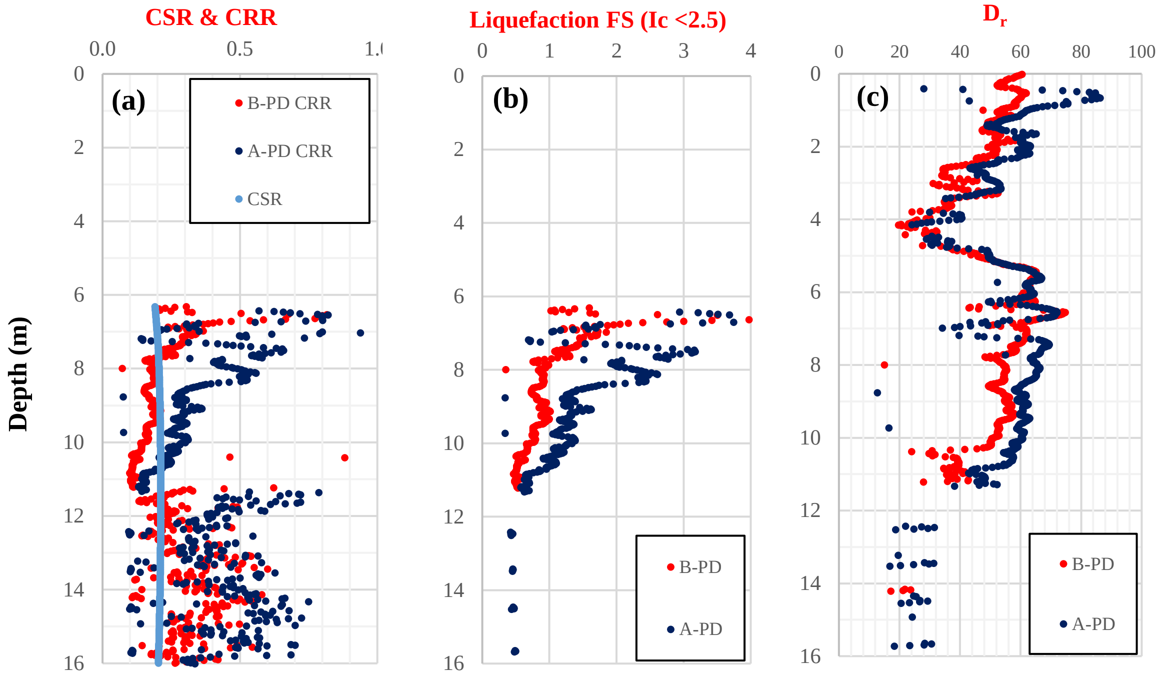

Figure 4. Improvement of liquefaction potential risks below GWT based on CPTu after pile driving: a) CSR & CRR, b) Liquefaction Factor of Safety, and c) relative density (B-PD: brefore pile-driving); A-PD: after pile-driving)

Notably, the subsequent liquefaction potential decreased significantly after pile driving as CPT evaluation indicated. This demonstration underscores the applicability of pile driving as an effective, viable strategy for strengthening soil stability and mitigating liquefaction susceptibility of fine sands and sandy silts.

4.2. Triaxial-based analysis

Cyclic triaxial testing has been extensively utilized since the 1960s for assessing soil liquefaction potential due to its simplicity and widespread applicability (Seed & Lee, 1966). In the undrained cyclic triaxial test, the cyclic stress ratio (CSR) is defined as the ratio between the shear stress (τ_d) and the normal effective stress (σ_c') acting on a plane inclined at 45° to the horizontal plane.

In this study, two thresholds for liquefaction were assumed: $R_u = 0.95$ & $\varepsilon_{DA} = 5\%$. This selection aligns with established criteria in the literature for liquefaction analysis (Ishihara, 1993). Considering the silty nature of the soil, a strain criterion (i.e., $\varepsilon_{DA} = 5\%$) was incorporated due to the potential for cyclic mobility in the soil at the specified densities. Fig. 5 shows relative density at the depth of 10 m using Jamiolkowski (2003) method from CPTu data before the pile driving acquired 52%. The densification caused by pile driving lead to a higher relative density of soil around the pile which is 60% at the depth of 10 m. Samples were prepared according to *in-situ* conditions using the moist tamping method, with densities of 52% and 60%. Moist tamping method is commonly employed for preparing samples in liquefaction investigations (Ladd, 1978; Frost & Park, 2003).

Tests were conducted under stress-controlled condition at a frequency of 0.5 Hz with a CSR=0.25, the CSR calculated for CPT (Robertson, 2009), for comparisons with CPT results. Considering the physical properties of the soil at the depth of 10 m, a confining stress of 100 kPa and a deviatoric stress of 50 kPa were applied based on the seismic potenial of the site (Fig. 6).

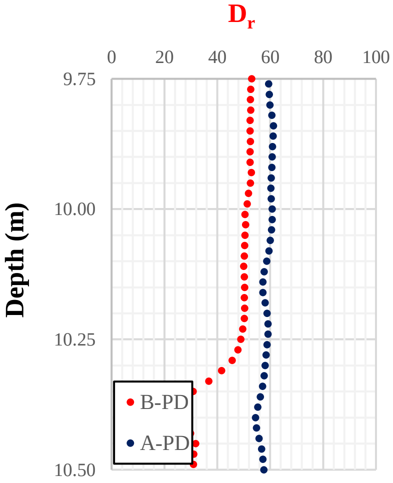

Figure 5. Relative density at depth of 10 m before and after pile driving

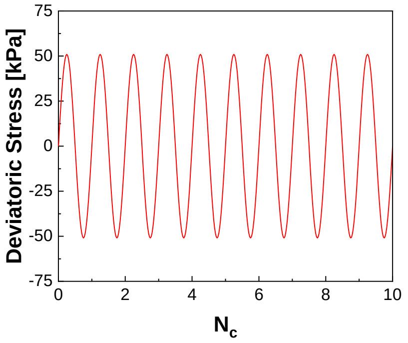

Figure 6. The applied deviatoric stress

As can be seen in Fig. 7, The findings indicates liquefaction occurrence during the 13th cycle for the sample with 52% density, whereas no liquefaction was observed even after 20 cycles in the sample with 60% density. The presented results illustrate an improvement in liquefaction resistance at 60% density, aligning with observations from CPT results. This correlation is evident in Fig. 8. Based on the depth of the specimen tested by the triaxial apparatus, the CPTu test indicates an increase in the liquefaction Factor of Safety from 0.72 to 1.33.

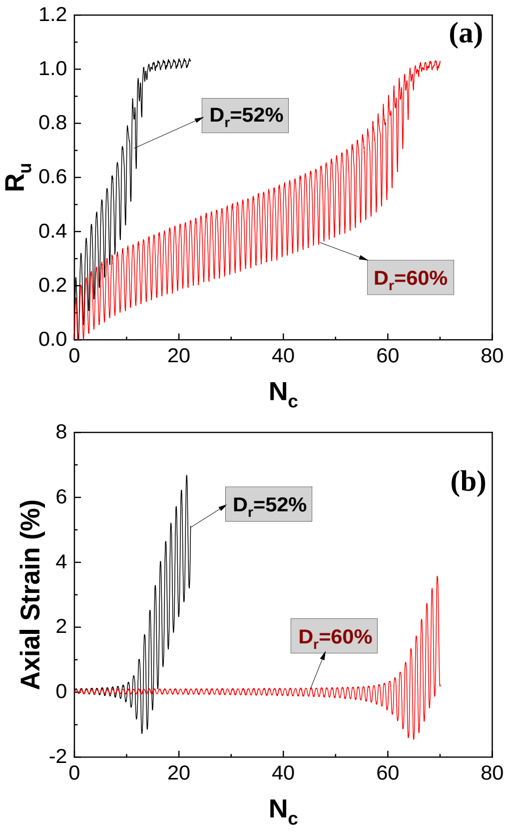

Figure 7. Cyclic triaxial test results for liquefaction poterntial evaluation with D_r values of 52 and 60%: (a) excess pore water pressure ratio; and (b) axial strain, versus numbers of cycles

5. Discussion

There exist numerous methods aimed at mitigating damages amd settlement risks caused by liquefaction in cohesionless soils. These strategies encompass vibrocompaction, rammed aggregate piers (RAP), stone columns, drilled displacement piles, driven displacement piles, and deep dynamic compaction (Han, 2015). They share the common objective of fortifying the soil's resistance against liquefaction-induced stresses and minimizing settlement potential. This is achieved by augmenting soil density, reinforcing load-bearing capacity, and altering mechanical properties of the soil strata. Among the available approaches, precast pile driving has also been considered as a remedial measure to increase the soil density and hence mitigating the liquefaction potential.

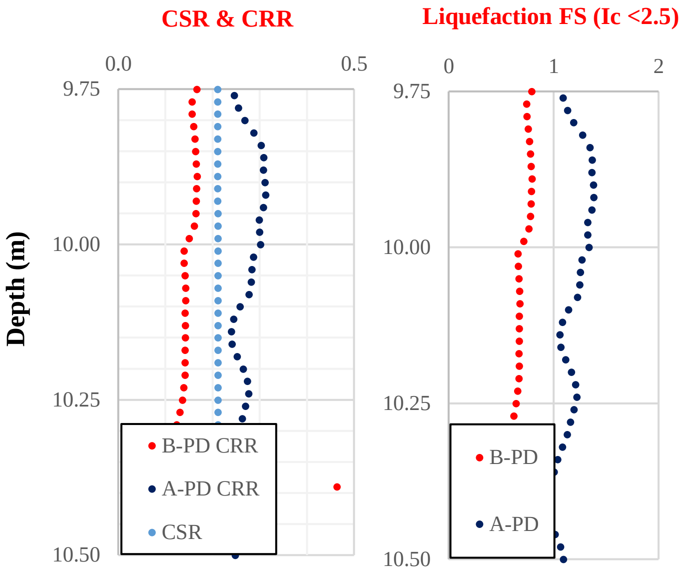

Figure 8. A comparison between liquefaction zone before and after pile driving

The utilization of precast piles in liquefaction mitigation strategies involves driving precast concrete piles into the ground to provide structural reinforcement and stability. Studies have shown that precast pile driving can effectively mitigate liquefaction-induced settlement by transferring loads to a deeper and more stable soil layer, thereby reducing the susceptibility of the soil to liquefaction (Collela et al., 2022). Moreover, the process of pile driving induces soil densification, a fundamental principle rooted in the rearrangement of soil particles into a more compacted state, thereby decreasing the void ratio of the geomaterial (Han, 2015). This densification yields several advantageous outcomes, including increased modulus, strength, and enhanced resistance to liquefaction, concurrently diminishing permeability, and collapsibility. This phenomenon highlights the pivotal role of pile driving in fortifying soil integrity and mitigating liquefaction risks through a systematic compaction mechanisms.

To assess soil densification resulting from pile driving, a Cone Penetration Test (CPT) analysis was conducted onsite before pile installation. Initial CPT results, such as liquefaction analysis indications at a 10-meter depth, prompted laboratory reconstruction of soil samples mirroring *in-situ* conditions on the basis of the CPT data. The 400 mm precast square piles were driven on a square pattern at center-to-center spacing of 2.8 m. The 2.8 m corresponds to a s/B of 7 which is interpreted as a large-spaced pile arrangement, compared for example to more commonly spacings of 3 to 5. The presented CPTu results of after pile driving related to a point at the center point of 4 piles which is in fact the farthest distance from the pile skins in the domain of driven piles. CPTu tests were also carried out at shorter distances to the piles indicating higher compaction and relative density of the sandy silt. Therefore, the interpreted point is deemed to having benefited the lowest cimpaction degree.

Subsequent triaxial testing verified liquefaction susceptibility as observed in CPT results. Following pile installation, a CPT evaluation conducted between piles revealed improved soil mechanical properties and increased resistance to liquefaction. Furthermore, the properties of the reconstituted soil sample for triaxial testing were revised based on updated CPT data, and the results of cyclic triaxial tests confirmed the mitigation of liquefaction risks. This comprehensive investigation examined the impact of soil densification induced by pile driving on liquefaction susceptibility, employing both field and laboratory methodologies.

The findings clearly demonstrate the improved soil mechanical properties and increased resistance to liquefaction, underscoring the efficacy of pile driving in mitigating liquefaction risks in dominantly silty calcarious soils. Previously, it was mostly agreed that precast pile driving could have imporved the density of dominantly sandy soils provided that the pile spacing ratio (s/D) was less than 5. This study revealsed that not only it worked for finer frctional soils such as sandy silts, but it also contrubuted to soil improvemnt up to higher s/D ratios of up to 7.

Static and dynmaic pile load testing plans before and after pile driving on sufficient numbber of piles indicated meaningful increase in pile bearing capacity as well as pile stiffness subjected to axial compressive loads. The details are still under investigation and the results and intrepretations shall be published afterwards.

6. Conclusions

A case study is presented from a construction site having several large diameter steel liquid tanks located near coastlines of Sea of Oman with high risks of seismicity, having a peak ground acceleration ratio of 0.36. A sandy silt layer exist between 7 to 12 m and SPT and CPT data interpretations revealed high potential to liquefaction. Precast pile driving was adopted as a remedial measure for both settlement and differential settlement reduction as well as mitigation of the liquefaction potential of the mentioned depth. CPTu tests were carried out after pile driving for comparison purposes with before pile driving. Samples were taken and reconstituted in the lab to perform cyclic triaxial tests with densities of original *in-situ* condition as well after pile driving. The findings of the study can be summarized as follows:

1. The CPTu data shows increase in both q_c and f_s and reduction in developed excess pore water pressure after pile driving.
2. The correlations indicate an increase of about 10 to 12 percent in relative density in the zone of liquefiable sandy silt.
3. The soil behavior classification charts indicate a more dilative soil is emerged after pile driving.
4. The liquefaction analysis based on CPTu data showed susceptibility to liquefaction before pile driving, but the potential is significantly mitigated after the pile driving.
5. Tiaxial test results on reconstituted samples with the same relative densities of before and after pile driving support the CPTu interpretations.
6. Although the presented CPTu data after pile driving corresponds to the farthest point in the pile group, the increase in density has been sufficiently large to mitigate the liquefaction potential.
7. It is concluded that precast pile driving could be considered as a remedial measure of increasing compaction and hence mitigating the liquefaction potential of frictional soils having large amount of silt content.

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