Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-2279

Effect of precast piles on densification of sandy silt deposits and improvement of load-movement response of piles

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ABSTRACT: This study investigates the performance of driven piles installed underneath large-diameter spherical tanks supported by ring foundations. The soil profile is comprised of 13 m of a sandy silt and silt overlying a thick layer of silty clay. The CPTu data interpretations as well as dynamic triaxial tests have shown that the sandy silt layer below the ground water surface is prone to liquefaction. To mitigate the liquefaction risks as well as reducing the total and differential settlements of the tank foundations, precast piles were installed across the foundation. CPTu tests were performed “before” and “after” pile installation to evaluate the improvements associated with pile installation. Additionally, DLT as well as SLT tests were performed on the single “test piles” and “construction piles” to assess the behavior of a pile when surrounded by adjacent piles. Results indicate considerable densification of sandy silt layers. Furthermore, single piles loaded within a group exhibited a marked increase in load-movement response compared to the isolated single piles, attributed to the enhanced soil properties resulting from the pile installation. Moreover, the CPTu interpretations as well as dynamic triaxial tests have indicated that the liquefaction potential has mitigated after the pile installation.

KEYWORDS: Displacement pile, pile load tests, CPTu, sandy silt, soil densification, load-movement response.

1 INTRODUCTION

As a result of the higher demands on exporting economic products and importing necessary resources, the construction of industrial structures along coasts and ports has become inevitable. However, the substructural and geotechnical characteristics of coastal areas often lead to challenges in constructing heavy industrial structures. One of the most significant challenges is the settlement of such structures, which can cause damages to superstructure and installations. These problems are intensified by the high groundwater levels near coastal areas, and if neglected, they can render the facilities non-operational and cause economic losses.

One of the solutions to this issue is the use of deep foundations underneath the large and heavy structures. Loads can be transferred to deeper soil layers through piles, allowing the construction of heavy structures on weak soils. In addition to transferring loads to stronger underlying layers with lower settlement potential, driven piles densify the surrounding soil during installation, thereby significantly increasing the load-bearing capacity.

The densification of surrounding soil due to pile driving in sandy and clayey deposits was studied by several researchers (Haddad et al. 2012, Fakharian et al. 2013). Orrje and Broms (1967) and Fakharian et al. (2022) investigated the effects of pile driving in clay. Their results indicated that pore water pressure decreased, and undrained strength increased over time, while the magnitude of the shear strength increase diminished with distancing from the pile due to the pile driving. Poulos (1994) examined horizontal and vertical soil deformations, forces, and induced moments due to pile driving to assess potential damage to adjacent piles. Alves and Lopes (2001) proposed an equation for predicting the relative density of sand surrounding a driven pile, which is a function of the initial soil density and pile diameter. Hunt et al. (2000) monitored shear wave velocity in soft clay before and at various time intervals after pile driving to study its effects. They also investigated pore water pressure increase and lateral soil deformation around the pile. Jardine et al. (2013) studied stress changes around driven piles using instrumentation in a sand-filled chamber. They found that stresses increased near the pile tip during driving but decreased after the tip passed. Shalabi and Bader (2014) demonstrated that pile driving in sand increases soil density, relative density, and friction angle around the pile. The extent of these increases depends on the initial soil porosity (pre-driving density).

However, pile group behavior differs from that of a single pile due to interactions between piles, soil, and the pile cap. Butterfield and Banerjee (1971a), (1971b) analytically studied the effects of soil stiffness, pile cap rigidity, pile length, and pile slenderness on group settlement. Davis and Poulos (1972) investigated the settlement of a single pile due to the loading of an adjacent piles and introduced the group efficiency factor for calculating pile group settlement, which depends on pile cap rigidity and pile spacing. Randolph and Wroth (1979) used analytical relationships to study deformations and settlement of piles and surrounding soil for rigid and flexible piles in homogeneous and non-homogeneous soil. They then derived an interaction factor for pile groups based on the soil settlement profile. Also, a number of investigations were carried out to study the effect of group response using numerical methods (Yang and Jeremić 2003, Freitas et al. 2015, Modarresi et al. 2016, Chen et al. 2019, Han et al. 2019).

Despite the dominant adverse effects in pile group loading, there are also beneficial effects that, if properly considered, can lead to a more economical pile group design. One of the favorable effects, which has received little attention, is the influence of adjacent precast pile installation on the load response of a single pile, distinct from the effect of pile driving on its own behavior. The main objective of this study is evaluating the effect of precast pile installation on the surrounding piles responses in pile groups embedded in silts and sandy silt deposits. A large data set comprised of CPTu, pile dynamic/static load tests “before” and “after” pile group execution is used for interpretations and manipulations of the pile installation effects, specifically on skin frictional resistance as well as load-movement response of the piles.

2 LOCATION AND GEOTHECNICAL CONDITION

The study area covering approximately 700 hectares and is situated near Jask city in Hormozgan Province, southern Iran, at an approximate distance of 300 meters from the northern coasts of the Oman Sea (Figure 1). Located within the Zagros orogenic zone, the area exhibits complex geological features typical of regions with active tectonics. The subsurface mainly comprises marl, sandstone, and silty/clayey sediments, which serve as the foundation soil for this investigation. According to site-specific seismic studies, peak ground acceleration (PGA) associated with a 475-year return period is estimated at 0.36g, indicating that the area lies within a seismically active zone.

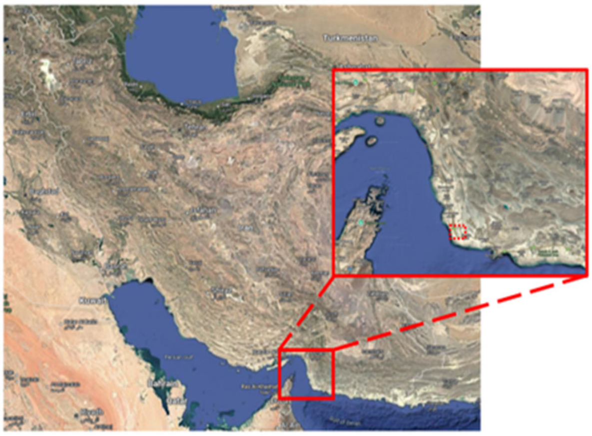

Figure 1. Study site location.

A variety of tests were carried out to evaluate the geotechnical characteristics and soil conditions, including both *in situ* and laboratory investigations such as SPT, CPTu, soil classification tests and typical mechanical tests including odometer, uniaxial and triaxial tests. The results provided a comprehensive understanding of the soil profile and its physical and mechanical properties at different depths. The CPTu tests were executed "before" and "after" pile installation. The CPTs after pile installation were performed within the zone of driven piles at various spacing intervals.

On the basis of the geotechnical data, the 700-hectar site was divided into four zones based on variations in the soil stratification (Figure 2). The scope of this study is focused on Zone 2. The soil profile in Zone 2 is composed of a combination of silt and sandy silt extending to a depth of around 13 meters, beneath which medium stiff to stiff layers of clay and silty clay are encountered. Furthermore, a clay lens is located at an approximate depth of 4.5 to 5.5 meters (Figure 3).

Sphere tanks having different diameters from 22 to 24.5 m are supported by ring foundations (Figure 4). Precast 400 mm square piles were driven beneath the ring foundations in an annular layout having three rows. The spacing between piles is 1.6 m 2 m depending on design requirements leading to s/d ratios of 4 and 5, respectively.

An outline of geotechnical and extensive pile testing program is presented in the following section.

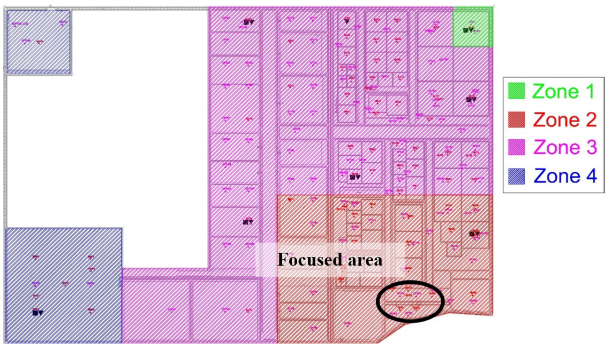

Figure 2. Focused zone in the study site.

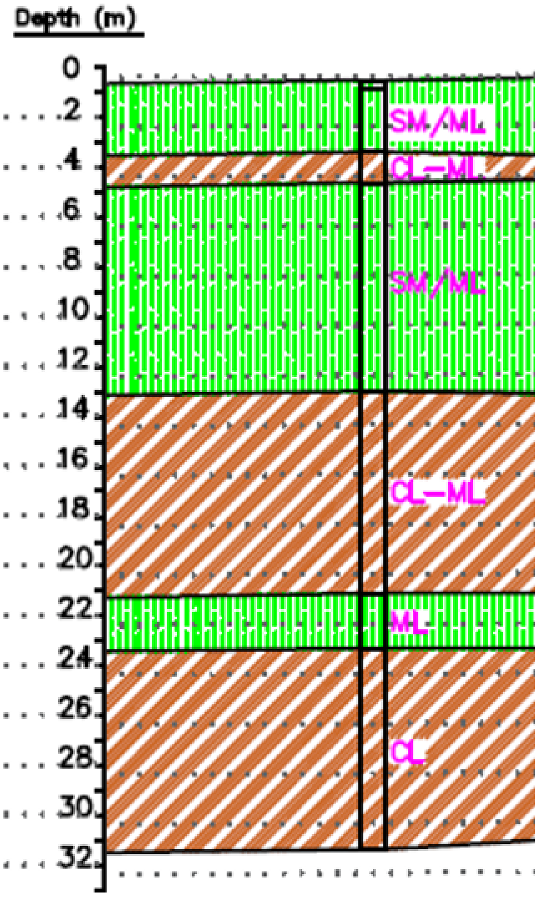

Figure 3. Soil profile of Zone 2

Figure 4. View of ring foundations and precast piles.

3 TEST CONFIGURATION AND METHODOLOGY

3.1 *Geotechnical tests*

The CPTu is particularly favored in pile-related research and design applications due to the continuous data output and its mechanical similarity to pile driving (Valikhah et al. 2019, Haque et al. 2020). The penetration mechanism of the CPT closely resembles that of driven piles, making it especially suitable for assessing pile drivability and estimating pile bearing capacity. Moreover, the analogies between CPT resistance and an actual pile resistance enhances its applicability in pile driving projects, making it a preferred tool in both research and practice.

In order to evaluate the influence of pile driving on soil improvement of the upper 13 m comprised of silty sands and sandy silts, CPTu tests were performed at two distinct stages: (1) during geotechnical study across the study site and at location of significant structures such as tanks; (2) after pile installation in between the piles as shown in Figure 5. They are referred in this paper as "before" and "after" pile driving, respectively (as indicated in Figure 6). The objective was to evaluate the effect of pile installation on both pile ultimate load as well as mitigation of liquefaction as a result of increase in density.

Figure 5. CPTu performing among piles "after" pile driving.

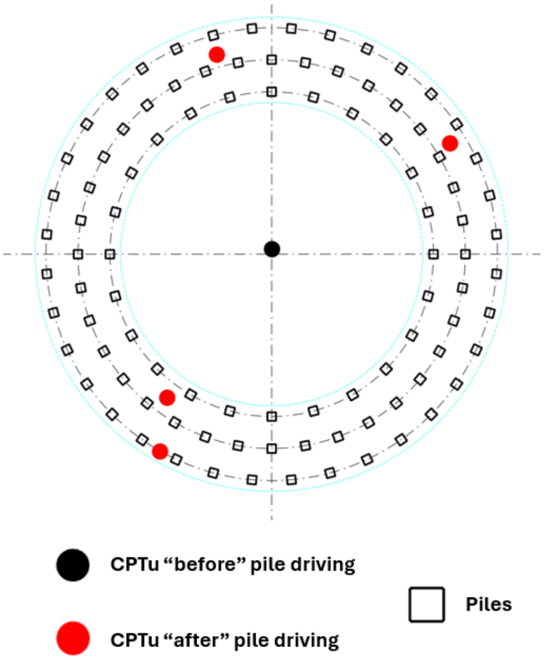

Figure 6. CPTu points "before" and "after" pile driving for a tank with s\d=4.

3.2 *Pile tests*

A comprehensive test pile program was planned and carried out at the study site at two stages, including: (1) Test Pile Study, and (2) Tests on Working Piles. Both Dynamic Load Tests (DLT) and Static Load Tests (SLT) were performed on piles at each stage. The stage 1 was undertaken to achieve a more economical and efficient design. The test pile study usually allows for reducing the length of the working piles, resulting in cost and execution time savings and easier pile installation.

For driven piles, DLT is one of the most commonly used methods to evaluate pile behavior and to separately assess bearing capacity components, such as tip resistance and shaft resistance. It is a rapid and cost-effective test performed by applying impact loads—typically using a hammer—while measuring strain and acceleration at the pile head (Goble and Likins 1996, Fakharian 2000, Attar and Fakharian 2013, Fakharian et al. 2014, Moayedi et al. 2017). The collected data are analyzed using wave equation-based methods (such as CAPWAP) to estimate the load-bearing performance and stress distribution. DLTs during the test pile study of sage (1) were conducted during pile installation, at the end of driving (EOD), and at Restrike with multiple intervals afterward (BOR and EOR) to investigate the soil setup effects. The tests were carried out using a Pile Driving Analyzer (PDA), which enables real-time monitoring and analysis during and after pile driving.

Static load tests (SLT) were also performed on selective number of piles both during test pile study and onto the working piles and attempted to continue to plunge failure to achieve complete load–movement responses, to have a direct measure of both ultimate capacity and pile stiffness. DLTs were performed on all the test piles at different post-driving stages, while SLTs were conducted on a subset of these piles.

Following the final design and along with placement of the working piles, DLTs were carried out on 10% of the working piles at various time intervals after installation, and SLTs were conducted on 0.3% of them. Subsequently, several CPTs were performed between the installed piles to examine the effects of pile driving on the improved density and strength of the surrounding soil across different depths.

4 RESULTS AND INTERPRETATIONS

4.1 *CPTs (before and after pile driving)*

The CPT locations "after" pile driving as well as the pile layout in one of the ring foundations are illustrated in Figure 7. Two types of pile arrangement were adopted in design phase having pile spacing of s/d = 4 and s/d = 5. The difference is intended to illustrate the influence of pile spacing on the behavior of a single pile surrounded by other piles within the group. Figure 8 compares post-driving sleeve friction (f_s) from CPT results with a CPT REF for both spacing conditions. The black line in each graph shows the CPT REF related to "before" pile driving. All the color lines are related to different CPT results "after" pile installations among them. The results clearly indicate higher values of f_s in both s/d of 4 and 5, while the spacing ratio of 4 exhibits higher values. Figure 8 also shows the increase in average f_s values "after" pile driving, compared to the reference CPT. It is evident that the most significant rise in f_s is attributed to the frictional layer between approximately 5 and 13.5 m depth, where the percentage of sand particles is higher compared to the layers above. Below 13 m is the CL-ML layer where increase in f_s is less significant.

The higher values of f_s at the CPT points among the piles as compared to the REF CPT points could have two advantages: (1) mitigation of liquefaction potential between GWT at depth 6 m to 13 m; the details of this improvement were presented in Fakharian et al. (2024); (2) increase in pile ultimate load and pile stiffness. The evidences of increase in pile capacity and stiffness are presented in the following subsections.

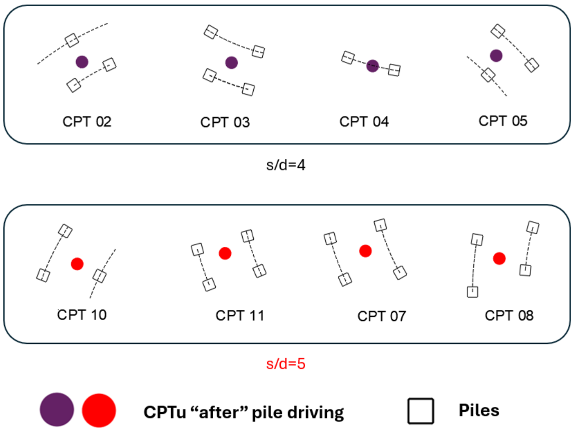

Figure 7. CPTu locations among the piles after pile driving.

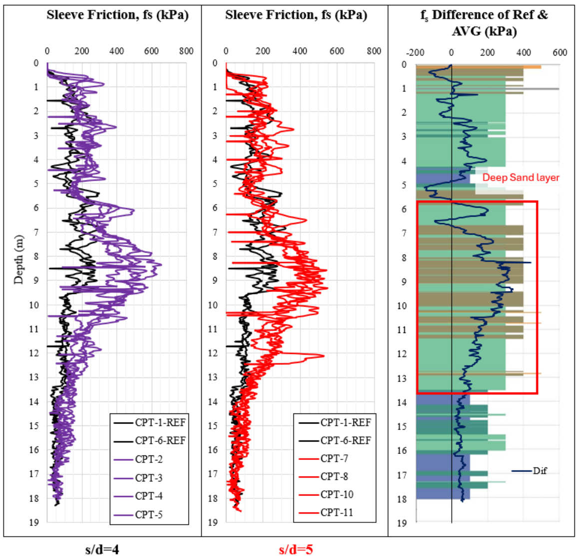

Figure 8. Comparison of CPT results “before” and “after” pile installation.

4.2 *Static Load Tests (SLT)*

The load-movement plots from static load test results clearly highlight the substantial impact of pile driving on the behavior of a single pile. As illustrated in Figure 9, the load-movement response of an 18.7 m Test Pile (TP-21) differs notably from that of the Working Piles. The ultimate resistance of the 18.7-m Test Pile, calculated using the Davisson Offset Limit method (Davisson 1972), is approximately 2,200 kN, while the Working Piles, with embedment depths ranging from 12.5 to 15.3 meters, exhibit ultimate resistances between 2,600 and 3,500 kN. In addition, the stiffness of the 18.7-m Test Pile is found to be similar to that of the shorter 12.5-m Working Pile. The ultimate load and stiffness of all other working piles are considerably greater that the test pile, despite the fact that they are having shorter lengths.

4.3 *Dynamic Load Tests (DLT)*

Performing signal matching analysis using CAPWAP on DLT results enables the separation of shaft and tip resistances, offering a more detailed understanding of the pile behavior. The outcomes of the PDA tests are presented in Figure 10 where shaft resistance variations are plotted against depth for two groups of piles: (1) test piles, and (2) working piles. To ensure a fair comparison and also minimizing the influence of soil setup, only the dynamic test results obtained between 7 and 60 days “after” driving are considered for comparison purposes.

Figure 10 clearly indicate that the working piles have achieved considerably higher shaft resistances, with the most notable increase occurring at the depth of 5 to 13 m, corresponding to the silty sand layer for which higher f_s values were measured in CPT tests “after” pile installations compared to CPT REF. The red shading zone in Figure 10 presents the shaft friction distribution after the soil setup for the single piles, while the blue shading zone is attributed to the frictional resistance of the working piles.

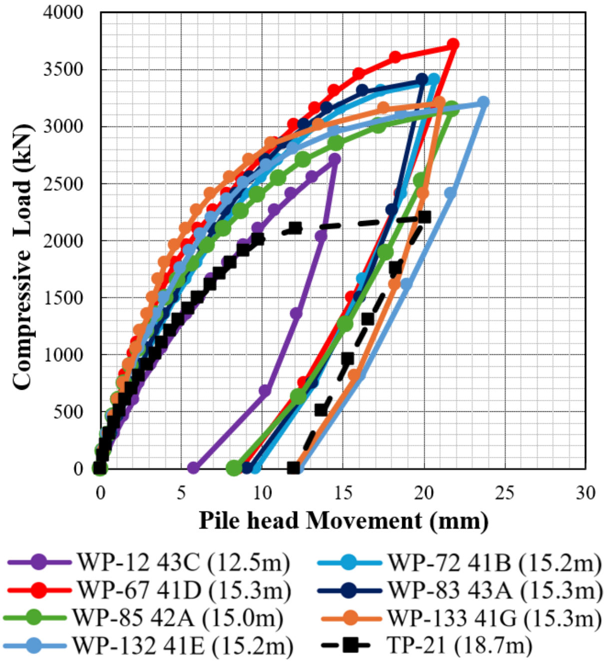

Figure 9. Static load test plots of “Test Pile” and “Working Piles”.

The average shaft resistance (R_s) was computed for both pile types. For the test piles, the average R_s is 69 kPa, while for the working piles, it has increased to reach 151 kPa, indicating a remarkable rise. This substantial increase highlights the influence of adjacent piles driving on enhancing the shaft resistance through mechanisms such as soil densification as well as increases in lateral confinement.

Based on the results of the DLT tests and the derived shaft resistance values at different depths using signal matching analysis, it can be observed that the working piles, despite having shorter embedment depths, have exhibited equal or higher shaft resistances (R_s) compared to the test piles. For further clarifications, the average R_s values for all piles are plotted in Figure 11. It is evident that the average R_s for the working piles is higher than that for the test piles. This difference in average R_s reflects the influences of adjacent pile driving on the behavior of a single pile.

Further analytical and numerical studies are underway to explore the effect of pile driving on soil improvement in sandy silts and silty sands through cavity expansion theories. From design point of view, it would have been important to propose analytical solutions on the effect of multiple pile penetration on the improved skin friction of a center pile depending on depth (confinement), pile arrangement and spacing, pile driving sequence, silt content, initial relative density, etc.

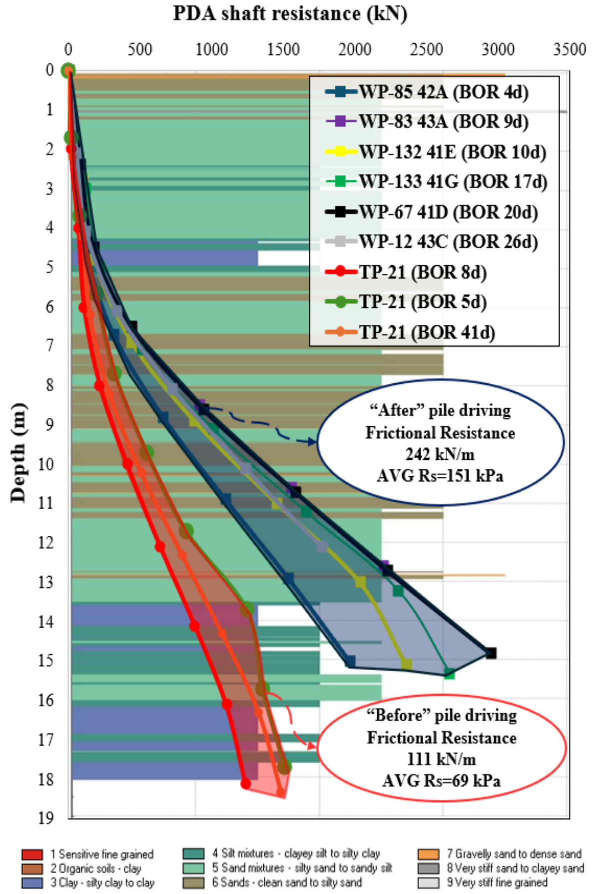

Figure 10. DLT shaft resistance results of "test" and "working" piles.

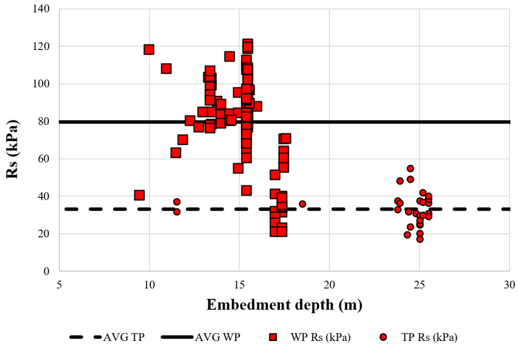

Figure 11. Comparison of skin frictional resistance between TPs and WPs

5 CONCLUSIONS

The extensive geotechnical and pile testing data of the study site including the results of CPT tests conducted "before" and "after" pile driving, along with SLT and DLT data obtained from both isolated test piles and working piles in a group revealed significant improvement as a result of pile installation in sandy silt layers. The comparison of CPT results "before" and "after" pile driving clearly demonstrate that pile driving leads to densification of the surrounding soil, resulting in increased CPT sleeve friction (fs). Furthermore, it was observed that closer pile spacing produced a higher increase in f_s values indicating the role of pile spacing on the behavior of single pile within a group.

In the same manner, due to the densification effects from adjacent driven piles, a single pile surrounded by other piles exhibited higher bearing capacity and load-movement response compared to an isolated pile. The stiffness of the surrounded piles is noticeably higher than that of single isolated pile. This behavior was consistently confirmed by both SLT and DLT test results, indicating that group effects in driven piles can enhance pile performance through improved soil confinement and strength.

DLT test results interpretations and CPTu data show that significant soil improvement occurs in sand and silty sand layers under high confinement stress, while only a minor increase in f_s is observed in the underlying cohesive layers.

The findings provide critical insights into optimizing and further understanding the contribution of precast piles as soil improvement means as well as increase in bearing capacity and stiffness of the piles, even in frictional deposits having high percentage of silt content.

It should be clarified however, that the increase in pile ultimate load and stiffness within the group does not mean that the response of a pile in the group is stiffer than a single pile, when all the piles are loaded simultaneously as a result of surcharge loading from the structure. It is well understood that pile group effect makes the response softer than a single pile. However, the increase in capacity and stiffness of a pile within the group should be considered when expanding the load-movement of a single pile to that within the group, before evaluating the pile group response and settlement calculations.

6 ACKNOWLEDGEMETS

The authors would like to acknowledge Enerchimi Inc., Tadbir Sahel Pars, and Morvarid Makran Inc. for financing the extensive site investigation and dynamic/static pile test study of the study site. Special thanks are also due to Pars GeoEnviro Inc. for performing the elaborate site and laboratory studies with special care to provide high quality data.

7 REFERENCES

Alves, A. and Lopes, F. 2001. A contribution to the study of compaction piles in granular soils. *PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON SOIL MECHANICS AND GEOTECHNICAL ENGINEERING*, AA BALKEMA PUBLISHERS.

Attar, I. H. and Fakharian, K. 2013. Influence of soil setup on shaft resistance variations of driven piles: Case study. *International Journal of Civil Engineering, Transaction B: Geotechnical Engineering* **11**(2): 4-5.

Butterfield, R. and Banerjee, P. 1971a. The problem of pile group–pile cap interaction. *Geotechnique* **21**(2): 135-142.

Butterfield, R. and Banerjee, P. 1971b. The elastic analysis of compressible piles and pile groups. *Geotechnique* **21**(1): 43-60.

Chen, Y., Lu, F., Namdar, A. and Cai, J. 2019. Working mechanism of pile group with different pile spacing in dense sand. Adv. *Civ. Eng* **2019**: 5376594.

Davis, E. and Poulos, H. 1972. The analysis of piled raft systems. *Australia Geotechnique Journal* **2**(1): 21-27.

Davisson, M. 1972. High capacity piles. *Proc. Innovations in Found. Const.* **52**.

Fakharian, K. 2000. A case study on the application of pile driving analyzer (PDA) and CAPWAP analysis to bearing capacity of piles. *ISOPE International Ocean and Polar Engineering Conference*, ISOPE.

Fakharian, K., Attar, I., Sarrafzadeh, A. and Haddad, H. 2013. Contributing factors on soil setup and the effects on pile design parameters. *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*.

Fakharian, K., Hashemi, M., Kaviani-Hamedani, K., Osouli, A., Vaezian, H., Bahrami, M., Bahrami, T. and Attar, I. 2024. Effect of Precast Pile Driving on Liquefaction Potential Mitigation of Sandy Silts Based on CPTu. 7th International Conference on

Geotechnical and Geophysical Site Characterization (ISC 24). Barcelona.

Fakharian, K., Masouleh, S. F. and Mohammadlou, A. S. 2014. Comparison of end-of-drive and restrike signal matching analysis for a real case using continuum numerical modelling. *Soils and foundations* **54**(2): 155-167.

Fakharian, K., Shafiei, M. and Hafezan, S. 2022. Investigation of soil setup effects on pile response in clay considering overconsolidation ratio and installation method through physical modeling. *Canadian Geotechnical Journal* **60**(4): 488-503.

Freitas, A. C. d., Danziger, B. R., Pacheco, M. and Gerscovich, D. M. S. 2015. 3-D predictions of installation and group effect on driven piles in sands. *International Journal of Geotechnical Engineering* **9**(1): 101-112.

Goble, G. and Likins, G. 1996. On the application of PDA dynamic pile testing. *Proceedings of the Fifth International Conference on the Application of Stress-Wave Theory to Piles, Orlando, FL*.

Haddad, H., Fakharian, K. and Hosseinzadeh Attar, I. 2012. Numerical modeling of setup effects on pile shaft capacity and comparison with an instrumented case. *The 9th International Conference on Testing and Design Methods for Deep Foundations*.

Han, F., Salgado, R., Prezzi, M. and Lim, J. 2019. Axial resistance of nondisplacement pile groups in sand. *Journal of Geotechnical and Geoenvironmental Engineering* **145**(7): 04019027.

Haque, M. N., Abu-Farsakh, M. Y. and Zhang, Z. 2020. Evaluation of pile capacity from CPT and pile setup phenomenon. *International Journal of Geotechnical Engineering* **14**(2): 196-205.

Hunt, C. E., Pestana, J. M., Bray, J. D. and Riemer, M. 2002. Effect of pile driving on static and dynamic properties of soft clay. *Journal of geotechnical and geoenvironmental engineering* **128**(1): 13-24.

Hunt, C. E., Pestana, J. M., Bray, J. D. and Riemer, M. F. 2000. Effect of pile installation on static and dynamic properties of soft clays. Innovations and Applications in Geotechnical Site Characterization**:** 199-212.

Jardine, R., Zhu, B., Foray, P. and Yang, Z. 2013. Measurement of stresses around closed-ended displacement piles in sand. *Géotechnique* **63**(1): 1-17.

Moayedi, H., Mosallanezhad, M. and Nazir, R. 2017. Evaluation of maintained load test (MLT) and pile driving analyzer (PDA) in measuring bearing capacity of driven reinforced concrete piles. *Soil Mechanics and Foundation Engineering* **54**(3): 150-154.

Modarresi, M., Rasouli, H., Ghalesari, A. T. and Baziar, M. H. 2016. Experimental and numerical study of pile-to-pile interaction factor in sandy soil. *Procedia engineering* **161**: 1030-1036.

Orrje, O. and Broms, B. B. 1967. Effects of pile driving on soil properties. *Journal of the Soil Mechanics and Foundations Division* **93**(5): 59-73.

Poulos, H. 1994. Effect of pile driving on adjacent piles in clay. *Canadian geotechnical journal* **31**(6): 856-867.

Randolph, M. F. and Wroth, C. 1979. An analysis of the vertical deformation of pile groups. *Geotechnique* **29**(4): 423-439.

Shalabi, F. I. and Bader, T. A. 2014. Effect of sand densification due to pile-driving on pile resistance. *International Journal of Civil Engineering* **3**(1): 17-30.

Valikhah, F., Eslami, A. and Veiskarami, M. 2019. Load–displacement behavior of driven piles in sand using CPT-based stress and strain fields. *International Journal of Civil Engineering* **17**(12): 1879-1893.

Yang, Z. and Jeremić, B. 2003. Numerical study of group effects for pile groups in sands. *International Journal for Numerical and Analytical Methods in Geomechanics* **27**(15): 1255-1276.