Experimental Study of Pile Installation and Cyclic Behaviour in Yellow River Silt

Zhe Zhang*, Teng Wang

Offshore Engineering Department, China University of Petroleum, Qingdao, ShanDong, 266580, China
* 15763948182@163.com

Abstract. The pile foundation is often affected by friction fatigue during pile installation and cyclic loading. In order to study the fatigue behavior of it, the installation and cyclic experiments were carried out using pile foundation model test device. The effects of cycle numbers, cumulative displacement on the pile load performance were studied in the experiments. The results show that the friction fatigue appears with different degrees on pile installation and cyclic process. During installation from soil surface, the soil plug increases and eventually remains constant, and the pile head load increases with the increase of penetration displacement, while the horizontal stress on pile shaft decreased with the increase of $h/R$ because of lower relative displacement. In the cyclic load stage, pile head load and base resistance stresses decrease rapidly in the 5 cycles and gradually restore to 68% and 112% respectively, while the horizontal stress reduces to stable in cyclic load and the fatigue behavior is more significant with lower value of $h/R$ due to the higher degree of soil particle breakage.

1. Introduction

The pile foundation of marine structures is subjected to cyclic loadings from the field installation operation on the wind and wave of sea environment. The skin friction mobilized on the pile due to pile/soil interaction decreases with the loading cycles. This characteristic behaviour is referred to friction fatigue [1], which was observed in both model-scale and full-scale pile tests [2-4].

Pile tests reported by Lehanne et al. (1993), Chow (1997) and Jardine et al. (2013a) showed that the local shaft failure is governed by the Coulomb failure criterion which depends on the size and shape of the sand grains and the roughness and hardness of the pile surface[5-7]. Lehane and Chow have shown that the peak shaft resistance [2, 6] $\tau_f$ is given by

$$\tau_f = \sigma'_r \tan \delta_f$$

$$\sigma'_r = \sigma'_{hs} + \Delta \sigma'_d$$

where $\sigma'_r$ is horizontal stress at failure, which comprises two components, the stationary horizontal effective stress $\sigma'_{hs}$ and a dilation component $\Delta \sigma'_d$; and $\delta_f$ =interface friction angle. Jardine and Chow have proposed the following best-fit relationship [8, 9]:

$$\sigma'_{hs} = 0.029 q_c (\sigma'_v / P_{adm} )^{0.12} (h/R)^{-0.38}$$

(3)
where $\sigma'_v$ = vertical effective stress; $P_{\text{atm}}$ = atmospheric pressure; and $R$ = pile radius. $q_c$ reflects the combined effects of the soil density and stress level on the value of $\sigma'_{hs}$, while the $h/R$ term takes account of the friction fatigue effects. Boulon and Foray and others have shown that cavity expansion theory can be used to estimate the increase in the horizontal effective stress due to dilation [10]:

$$\Delta \sigma'_{rd} = 4G\Delta h / D$$

(4)

where $G$ = shear modulus; $\Delta h$ = horizontal displacement of a soil particle at the pile-soil interface; and $D$ = pile diameter.

Uesugi and Kishida’s laboratory interface shear demonstrated that the volume changes induced by interface shearing develop within a narrow band positioned close to the interface [11]. Thus, pile shaft friction degradation was further investigated using constant normal stiffness (CNS) conditions in the direct shear apparatus to examine the influence of relative density, sand type, surface roughness, normal stress and normal stiffness on the monotonic, cyclic and post-cyclic responses [12-15].

Through the study of the monotonic and cyclic shear of soil, especially the constant stiffness interface shear test, the characteristics of the soil element at the pile shaft can be better understood.

Through the study of interface shear test, it can be seen that the interface between pile and soil will undergo physical evolution and obvious shear volume change under cyclic shear which is characterized by the breakage and rearrangement of soil particles at the micro level and the change of normal stress at the macro level, and higher constant normal stiffness may cause higher degree of soil breakage which means higher degree of friction fatigue effect [16].

In summary, the fatigue degradation of pile shaft resistance refers to the lower level of shaft resistance less under cyclic load than that without cyclic load, which is different from the ultimate shaft resistance which falls to the residual value due to the large relative pile-soil displacement. Although there is an increasing focus on the mechanisms of friction fatigue of soil recently, most of the studies conducted aim at the sandy soil and there is a lack of studies on the friction fatigue of silt.

In this paper, the installation and cyclic experiments are carried out using pile foundation model test device and the results are analysed. The effects of cycle numbers, cumulative displacement on the pile load performance are studied in the pile installation and cyclic load stage. The characteristics of pile foundation load variation under cyclic loading and the influence of cyclic loading on static bearing capacity are studied and also the change of pile shaft normal stresses are considered in the experiment for better understanding the friction fatigue behaviour.

2. Experiment equipment and methods

2.1. Foundation preparation and Test equipment

The foundation soil is made of Yellow River silt taken from 15 meter depth which has the soil density $\rho = 15.79 \text{KN/m}^3$ and the friction angle $\delta = 39^\circ$. It has some special characteristics which are very different from those for sand, which has homogeneous particle size (centralized in 0.005-0.075mm), high degree of roundness and porosity, and poor interlocking with each other. Figure 1 shows the particle size distribution curve of the foundation soil. The pore water pressure formation and dissipation behaviour of silt differs from sand because silt soil is less permeable than sandy soil, thus the friction fatigue behaviour of it needs discuss.

In the formal filling process, the foundation is prepared by layered filling and compaction method. After the foundation filling process is completed, the foundation is slowly saturated by the pipe network water at the bottom of the model bin. In order to assure the saturation effect, the whole saturation process lasts for two weeks. Model soil bin system, loading system and data acquisition system are included in the pile foundation model test device in the research. It is can be used to conduct comprehensive experimental research on various pile foundation problems. The loading system is used to apply displacement control and exert vertical monotonic and cyclic loads. The main
body of the model soil bin is a box-shaped steel structure with a dimension of 2 x 1.2 x 1.2 m, as shown in Figure 2.

![Particle size distribution curve of Yellow River silt (sample depth=15m).](image)

**Figure 1.** Particle size distribution curve of Yellow River silt (sample depth=15m).

### 2.2. Model Pile and Sensor Setting

The pile used in model pile experiment is seamless steel pile. The stress level of filling soil in soil bin is small and the stiffness ratio of pile to soil is large. It is a rigid pile with a length of 1 m, a diameter of 100 mm and a wall thickness of 6.5 mm, as shown in Figure 2. Before the beginning of the experiment, force sensor is arranged on the top of the pile, soil pressure sensors are arranged on the pile shaft and the pile end. The full range calibration is carried out for all sensors, and the results show good linearity and repeatability. In order to reduce the possible influence of non-uniformity, the sensors are arranged on the one side of the pile shaft, and the sensors and the specific installation method are shown in Figure 3.

### 2.3. Experiment scheme

The monotonic loading test and cyclic loading test of the model pile are carried out by using the model test loading device of the pile foundation device mentioned above. The load-displacement characteristics of model piles during installation can be obtained by the monotonic loading test of model piles. The purpose of cyclic loading test is to study the influence of cyclic number and displacement amplitude on cyclic loading characteristics of single pile. During the loading process, the sensors are continuously monitored to obtain the variation rules of pile top load, pile side load and pile end load. The specific test scheme is shown in Table 1.

| Experimental type       | Monotonic installation | Cyclic loading |
|------------------------|------------------------|----------------|
| Load rate (mm/s)       | 5                      | 2              |
| Load displacement (mm) | 650                    | -              |
| Cyclic Amplitude (mm)  | -                      | 5              |
| Cyclic number          | -                      | 100            |

Table 1. Load Types and Contents of Experiments.
3. Test results and analysis

Figure 4 shows the variation of pile load with cumulative displacement during pile foundation installation and the change of plug height is taken into account in the penetration process. As shown in Figure 4(a), it can be seen that the height of plug increases with the penetration depth. When the penetration depth reaches 440 mm, the height of plug remains unchanged, and the soil in the pile undertake certain pile resistance. When the pile penetrates into the soil surface, the pile head reaction increases rapidly, and the soil failure happens after the penetration depth reaches 0.1D, after that the pile head reaction remains unchanged with the increase of displacement for a bit of displacement, which can be seen from Figure 4(b). The pile head reaction increases exponentially until the end of penetration when the penetration displacement continues to increase. The pile end resistance and the pile side friction bear part of the pile load respectively. The base resistance show a similar law with the increase of penetration depth with the pile head reaction. As shown in Figure 4(c), the base resistance increases linearly to 78kpa within 20 mm and then increases exponentially to 265kpa with the cumulative displacement. Horizontal stress on the pile shaft increases with the increase of penetration depth. However, in Figure 4(d), the change of horizontal stress of different value of $h/R$ is not same that the maximum horizontal stress decreases with the increase of $h/R$. This indicates that the soil at different soil layers produce different degrees of horizontal stress along pile shaft with the increase of relative cumulative displacement of pile and soil interface. The larger $h/R$, the smaller the corresponding horizontal stress on pile shaft and the smaller the side friction of pile side are.
Therefore, it can be seen that in the process of monotonous installation of pile foundation, the pile shaft friction is related to \( h/R \) as the penetration proceeds. The larger the \( h/R \), the smaller the relative cumulative displacement of pile-soil interface, the smaller the maximum horizontal stress of pile shaft, and the smaller the pile shaft resistance are if the pile installation from the surface to certain depth.

Figure 4. The variation of pile load with cumulative displacement during pile foundation installation.

Figure 5 shows the variation of pile foundation load with cumulative displacement and cyclic times during cyclic loading. In Figure 5a, it can be seen that in the initial stage of cycling, the reaction force at the pile head decreases rapidly with the increase of accumulated displacement. When the accumulated displacement reaches 70 mm, the pile head load reduced to the lowest value of 0.4, and the cycle number is about 5 times. At this time, the soil at the pile end may liquefy and the bearing capacity of the soil decreases which result in the degradation of pile head load. With the increase of accumulated displacement, the normalized normal stress recovers to a certain extent, and it stabilizes to 68% of the original level finally. The hysteretic curve formed by cumulative displacement and pile end reaction is shown in Figure 5(b). At the beginning of the cycles, the hysteretic curve forms the largest area while the area decreases with the number of cycles increasing. The area of the hysteretic curve increases after the number of cycles exceeds five, indicating that the energy accumulated by the cycle and recovery of the soil strength. With the increase of cumulative displacement, the recovery of pile head reaction may be related to the gradual compaction of soil at the pile end during cyclic loading.
Hence, the pile shaft resistance of decreases gradually with the increase of accumulated displacement, and finally reaches a stable state. The phenomenon of friction fatigue is related to the height above the pile end. The smaller value of h/R, the more significant the effect of friction fatigue will be. Because the particle breakage is more significant with higher stiffness of the soil layer which result in more notable friction fatigue behaviour on the pile shaft[16].

![Figure 5](a). Variation of pile foundation load with cumulative displacement and cyclic times during cyclic loading

4. Conclusion
In the process of monotonous installation of pile foundation, the pile shaft friction is related to h/R as the penetration proceeds. The larger the h/R, the smaller the relative cumulative displacement of pile-soil interface, the smaller the maximum horizontal stress of pile shaft, and the smaller the pile shaft resistance are if the pile installation from the surface to certain depth. In the cyclic stage, the pile shaft resistance of decreases gradually with the increase of accumulated displacement, and finally reaches a stable state. The phenomenon of friction fatigue is related to the height above the pile end. The smaller value of h/R, the more significant the effect of friction fatigue will be. Because the particle breakage is more significant with higher stiffness of the soil layer which result in more notable friction fatigue behaviour on the pile shaft.

References
[1] Heerema, E P. (1980) Predicting pile drive ability: heather as an illustration of the friction fatigue theory. Ground Engineering, 13(2): 15–37.
[2] Lehane, B.M. (1992) Experimental investigations of pile behaviour using instrumented field piles. Imperial College, London.
[3] White, D. J., Lehane, B.M. (2004) Fiction fatigue displacement piles in sand. Géotechnique, 54(10): 645–658
[4] White, D. J. (2005) A general framework for shaft resistance on displacement piles in sand. In: Proceedings of the 1st International Conference on Frontiers in Offshore Geotechnics. Perth, Australia. 697–703.
[5] Lehane, B.M., Jardine, R.J., Bond, A.J., & Frank, R. (1993) Mechanisms of shaft friction in sand from instrumented pile tests. Journal of Geotechnical Engineering, 119(1): 19-35.
[6] Chow, F.C. (1997) Investigation into Displacement Pile Behaviour for Offshore Foundations. PhD thesis, Imperial College London, London, UK.
[7] Jardine, R.J., Zhu, B.T., Foray, P. & Yang, Z.X. (2013) Measurement of stresses around closed-ended displacement piles in sand. Géotechnique. 63(1): 1-17.
[8] Jardine, R.J., Chow, F.C. (1996) New design methods for offshore piles. Marine Technology Directorate. Paris.

[9] Jardine, R.J., Standing, J.R., Kovacevic, N. (2005) Lessons learned from full-scale observations and the practical application of advanced testing and modelling. In: Keynote paper, Proc. Int. Symp. On Deformation Characteristics of Geomaterials, Lyon, pub Balkema, Lisse, 201-245.

[10] Boulon, M., and Foray, P. (1986) Physical and numerical simulation of lateral shaft friction along offshore piles in sand. In: Proc., 3rd Int. Conf. on Numerical Methods in Offshore Piling, Institut Francais du Petrol, Nantes, France, 127–147.

[11] Uesugi, M., Kishida, H. (1986a) Influential factors of friction between steel and dry sands. Soils and Foundations, 26(2): 33–46.

[12] Ooi, L. H., Carter, J. P. (1987) A constant normal stiffness direct shear device for static and cyclic loading. Geotechnical Testing Journal, 10(1):3 -12.

[13] Fakharian, K., Evgin, E. (1997) Cyclic Simple-Shear Behavior of Sand-Steel Interfaces under Constant Normal Stiffness Condition. Journal of Geotechnical & Geoenvironmental Engineering, 123(12):1096-1105.

[14] Mortara, G., Mangiola, A., Ghionna, V. N. (2007) Cyclic shear stress degradation and post-cyclic behaviour from sand-steel interface direct shear tests. Canadian Geotechnical Journal, 44(7):739-752

[15] Pra-Ai, S., Boulon, M. (2017) Soil–structure cyclic direct shear tests: a new interpretation of the direct shear experiment and its application to a series of cyclic tests. Acta Geotechnica, (1):1-21.

[16] Feng Da-kuo, Zhang Jian-min, Hou Wen-jun. (2010) Progressive test investigation on 3D behavior of gravel structure interface. Journal of Earthquake Engineering and Engineering Vibration, 30(6): 154—161.