Journal of Civil Engineering and Urban Planning (2025)
Clausius Scientific Press, Canada

DOI: 10.23977/jceup.2025.070207
ISSN 2616-3969 Vol. 7 Num. 2

# *Cumulative Degradation Laws of Coupled Bearing Characteristics between High-Piled Wharves and Foundations under Cyclic Loading*

**Run Liu[1], Chunyang Su[1], Ruohan Sun[2]**

*[1]State Key Laboratory of Hydraulic Engineering Intelligent Construction and Operation, Tianjin University, Tianjin, China*
*[2]Tianjin University of Technology, Tianjin, China*

***Keywords:*** Cyclic Loading, High-Piled Wharf, Load Transfer, Degradation of Bearing Capacity

***Abstract:*** With high-piled wharves in port engineering facing long-term cyclic loading challenges, studying the cumulative degradation laws of pile-soil system bearing characteristics becomes critical for engineering safety. Through model tests and numerical simulations, this paper systematically investigates the degradation mechanisms of coupled bearing characteristics between high-piled wharves and foundations under cyclic loading. Static/dynamic triaxial tests reveal the influence of load amplitude and cycle count on the strength weakening of pile-surrounding soil. Numerical simulations clarify the coupling mechanism of load transfer paths and soil response, as well as bearing capacity degradation mechanisms.

## 1. Introduction

In recent years, China has actively promoted its maritime strategy and accelerated the development of cross sea engineering and port construction. As core supporting structures, pile foundations transfer vertical loads to surrounding soil layers and end-bearing strata through pile-soil interaction, significantly enhancing bearing capacity while controlling settlement. Horizontal loads are transferred to surrounding soil via pile shafts, forming a constraint system that improves lateral resistance and anti-overturning capability. However, long-term cyclic wave loads in marine environments, combined with sudden loads from earthquakes and vessel impacts, gradually weaken pile foundation performance. This necessitates urgent research on bearing capacity degradation mechanisms under cyclic loading for pile-soil coupled systems.

For horizontal cyclic loading on offshore pile foundations, scholars have investigated soil weakening and single-pile coupled bearing characteristic degradation through theoretical analysis, experimental studies, and numerical simulations. Long and Vanneste (1994)[1] proposed cyclic weakening characterization methods based on soil stiffness reduction and static *p*-*y* curves. Rosquoet (2007), Leblanc(2010), and Zhu(2016)[2–4] established empirical formulas for cumulative deformation and stiffness softening via centrifuge tests. Achmus (2009), Zhang(2020) et al.[5–6] developed numerical analysis methods for pile-soil cyclic interaction using sand stiffness degradation models, enabling efficient coupled simulation.

Current research gaps remain in understanding pile-soil coupled bearing degradation mechanisms. This paper systematically reveals load transfer mechanisms, soil stiffness degradation laws, and cumulative attenuation characteristics of pile-soil coupled bearing capacity under cyclic loading through model tests and numerical simulations, providing theoretical support for marine engineering pile foundation design.

## 2. Model Test Study

### 2.1 Experimental Setup

To investigate the dynamic response of single-pile foundations and soil under cyclic wave-current loading, small-scale indoor model tests were conducted using a custom-developed eccentric gear cyclic loading device (Fig. 1).

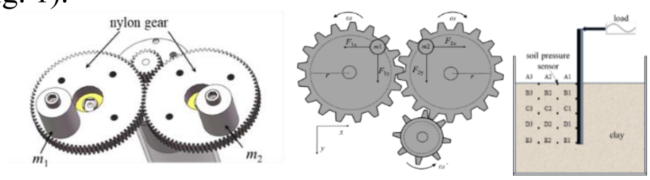



Fig.1 Test apparatus

Coastal soft clay was selected with physical parameters listed in Table 1.

Table 1 Clay physical properties

| $G_s$ | $w_L$(%) | $w_P$(%) | $\rho$/g·cm$^{-3}$ | $e$ | $\rho d$/g·cm$^{-3}$ | $w$(%) |
|---|---|---|---|---|---|---|
| 2.73 | 35.60 | 15.37 | 1.80 | 0.95 | 1.40 | 35.7 |

Static and cyclic loading tests were performed under conditions listed in Table 2.

Table 2 Test conditions

| Group | Loading Type | Load Amplitude | Cycles |
|---|---|---|---|
| 1 | Static | — | — |
| 2 | Static | (0.2–0.8)×Ultimate bearing capacity | — |
| 3 | Cyclic | (0.2–0.8)×Ultimate bearing capacity | $10^2$–$10^4$ |

Group 1 determined initial horizontal ultimate bearing capacity via static displacement loading. Group 2 revealed load transfer patterns through static soil pressure data. Group 3 analyzed cumulative degradation effects by comparing pre/post-cyclic bearing capacities.

### 2.2 Results

The load-displacement curve (Fig. 2) showed an ultimate bearing capacity of 4.5 kN, used as the reference for subsequent tests.

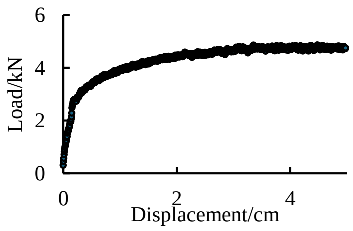
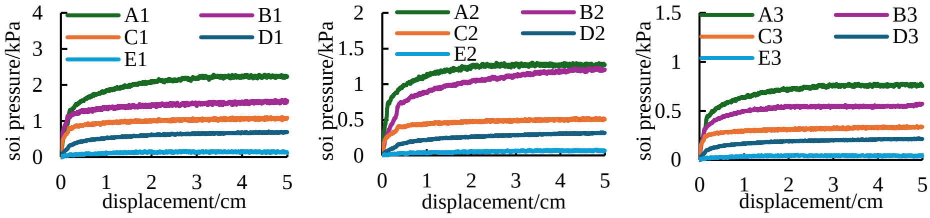


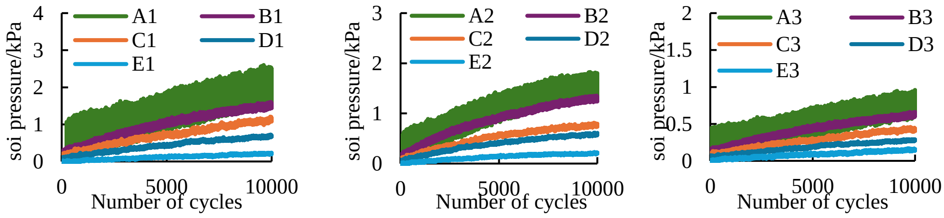

Fig.2 Load-displacement curve

Taking the horizontal load and load amplitude of 0.8 times the ultimate bearing capacity applied in experimental groups 2 and 3 as an example for analysis, the test results are shown in Figures 3 and 4.




(a) (b) (c)

Fig.3 Soil pressure under static loading




(a) (b) (c)

Fig.4 Soil pressure under cyclic loading

Figure 3-4 shows that the horizontal static load and cyclic load are transmitted to the surrounding soil through the pile body, and their transmission effect decreases with increasing burial depth and pile center distance.

Figure 5 shows that cyclic loading significantly reduces the ultimate bearing capacity of pile foundations, and the greater the load amplitude, the more pronounced the weakening of the bearing capacity.

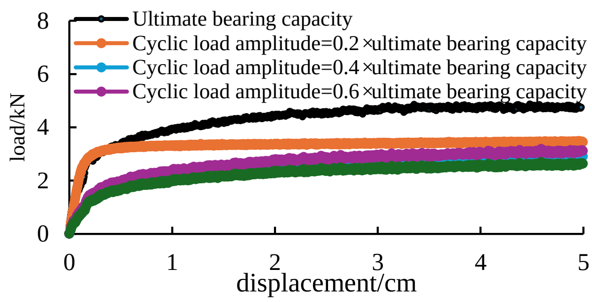



Fig.5 Post-cyclic ultimate bearing capacity

## 3. Numerical Analysis

### 3.1 Model Validation

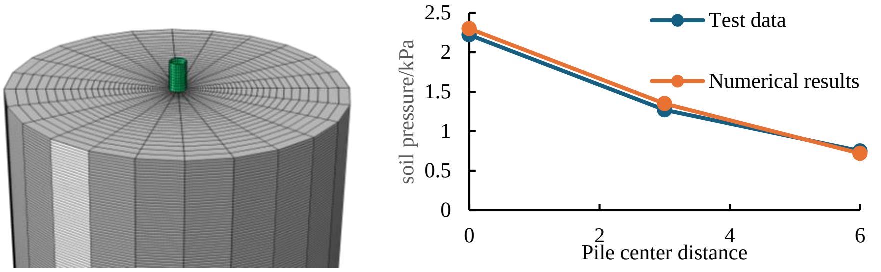



Fig.6 Numerical model and validation

A finite element model replicating experimental conditions was established (Fig. 6). Validation showed excellent agreement with test results, confirming model reliability.

According to Figure 6, it can be seen that establishing a model can simulate the experimental results well, proving the reliability of the model. Subsequent research will be carried out based on this model.

### 3.2 Parametric Study

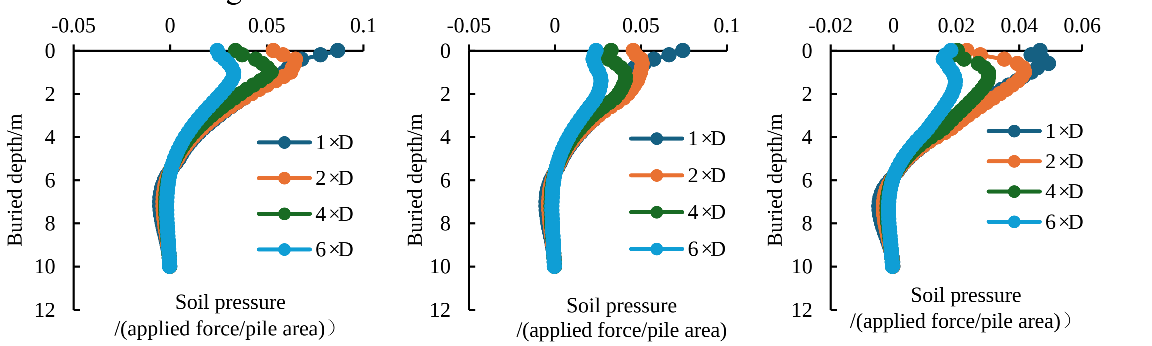
Numerical simulations under various conditions (Table 3) revealed.

Table 3 Simulation conditions

| Case | Pile Length (m) | Diameter (m) | Embedment Depth | Load Position | Ultimate Capacity (kN) | Load |
|---|---|---|---|---|---|---|
| 1 | 20 | 0.25 | 0.5 ×pile length | 0.75 ×free length | 50 | (0.1,0.2,0.5)×ultimate bearing capacity |
| 2 | 10 | 0.1 | 0.5 ×pile length | 0.75 ×free length | 4 | |
| 3 | 10 | 0.1 | 0.5 ×pile length | 0.75 ×free length | 4 | Cyclic load amplitude =0.1 × ultimate bearing capacity |

(1) The influence of horizontal load

Taking condition 1 as an example of the influence of horizontal load, the normalized results of soil pressure are shown in Figure 7.




(a) 0.1×Ultimate bearing capacity (b) 0.2×Ultimate bearing capacity (c) 0.5×Ultimate bearing capacity

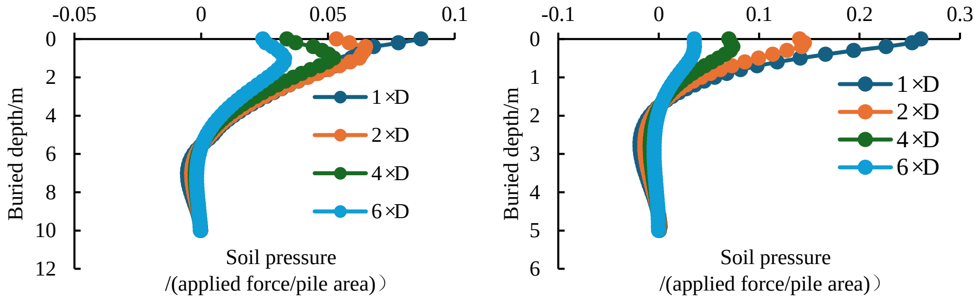
Fig.7 Distribution of soil pressure at different pile center distances in working condition 1

According to Figure 7, it can be seen that the size of the load has little effect on load transmission, with the main difference reflected in the position of the topsoil. The larger the applied load, the smaller the soil pressure on the topsoil, and the response of the soil pressure gradually develops downwards with the increase of the applied load. At the same time, the location of the inflection point is also at a deeper position.

(2) The influence of aspect ratio

Taking condition 1 and condition 2 as examples to compare and study the influence of aspect ratio, the normalized results of soil pressure are shown in Figure 8.

From Figure 8, it can be seen that the aspect ratio has a significant impact on load transfer. The larger the aspect ratio, the easier the load transfer is to concentrate in the upper part of the soil layer, and the location of the inflection point is also closer to the surface of the soil.




(a) Condition 1 (b) Condition 2

Fig.8 Distribution of soil pressure at different pile center distances

(3) The impact of cyclic loading

Taking working condition 3 as an example, the influence of load location was compared and studied, and the results are shown in Figures 9 and 10.

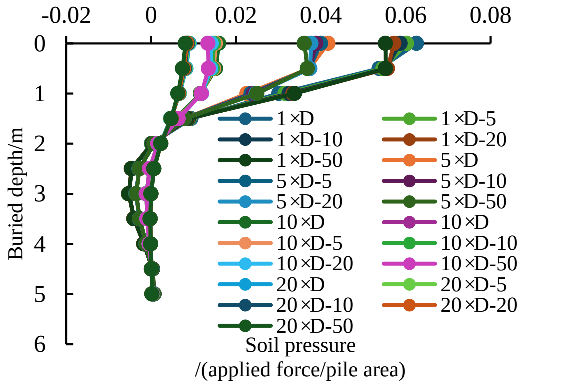



Fig.9 Distribution of soil pressure under cyclic loading

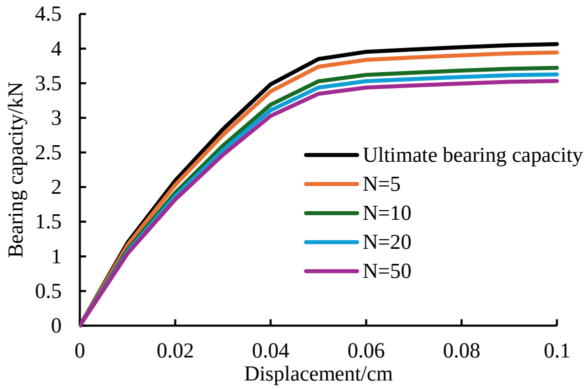



Fig.10 Bearing capacity after cyclic loading

According to Figures 9 and 10, it can be seen that under cyclic loading, the load transfer on the surface soil is greatly affected, which reduces the proportion of load borne by the surface soil and has a relatively small impact on the deep soil. At the same time, after cyclic loading, the bearing capacity is significantly reduced, and the magnitude of the reduction in bearing capacity increases with the increase of the number of cycles.

## 4. Conclusions

Under long-term cyclic loading, the pile-soil coupling bearing characteristics exhibit significant cumulative degradation effects. As the amplitude and number of cyclic loads increase, the stiffness of the soil around the pile weakens, and the load-bearing capacity of the surface soil decreases, resulting in a decrease in the horizontal ultimate bearing capacity of the pile foundation.

The load transfer law is significantly affected by the length to diameter ratio of the pile, as the length to diameter ratio increases, the load transfer is more concentrated in the upper part of the soil layer, and the position of the inflection point becomes shallower.

The weakening effect of cyclic loading on surface soil is much higher than that on deep soil. Under cyclic loading, the surface soil pressure attenuates significantly, while the response of the deep soil changes relatively little. This non-uniform weakening causes the overall bearing capacity of the pile foundation to degrade.

## Acknowledgements

This research was supported by the National Key R&D Program of China (2022YFB2603000).

## References

*[1] Long J, Vanneste G. Effects of cyclic lateral loads on piles in sand[J]. Journal of Geotechnical Engineering, 1994, 120(1): 225-244.*

*[2] Rosquoet F, Thorel L, Gaenier J, et al. Lateral cyclic loading of sand-installed piles[J]. Soils and Foundations, 2007, 47(5): 821-832.*

*[3] Leblanc C, Houlsby G T, Byrne B W. Response of stiff piles in sand to long-term cyclic lateral loading[J]. Géotechnique, 2010, 60(2): 79-90.*

*[4] Zhu B, Li T, Xiong G, et al. Centrifuge model tests on laterally loaded piles in sand[J]. International Journal of Physical Modelling in Geotechnics, 2016, 16(4): 160-172.*

*[5] Achmus M, Kuo Y S, Abdel-Rahman K. Behavior of monopile foundations under cyclic lateral load[J]. Computer and Geotechnics, 2009, 36: 725-735.*

*[6] Zhang C, Zhu Z, Yu Feng, et al. Long Term Horizontal Cyclic Loading Cumulative Deformation of Large-Diameter Single Piles in Sandy Soil [J]. Journal of Geotechnical Engineering, 2020, 42 (6): 1076-1084.*