Smart Geotechnics for Smart Societies – Zhussupbekov, Sarsembayeva & Kaliakin (Eds)

Difference in cyclic lateral loading behavior of a monopile on sandy and clayey grounds

K. Nakai
Nagoya University, Nagoya, Aichi, Japan

M. Ito & S. Sato
Obayashi corporation, Tokyo, Japan

ABSTRACT: As the market for renewable energy continues to expand, expectations for offshore wind power are growing. Monopiles, the most common type of offshore wind turbines foundation, are subjected to cyclic lateral loading due to wind and ocean waves during their service life. Therefore, it is desirable to accurately understand the cyclic loading characteristics of monopiles for design purposes. In this paper, we attempted to understand the difference in cyclic loading behavior of a monopile on sandy and clayey grounds through both model experiments and finite element analysis. As a result, it was confirmed that the lateral displacement of the sandy ground was gradually suppressed by the densification in front of the pile during cyclic loading. On the other hand, the clayey grounds showed rapid increase of displacement if the soil was disturbed by large cyclic loading.

1 INTRODUCTION

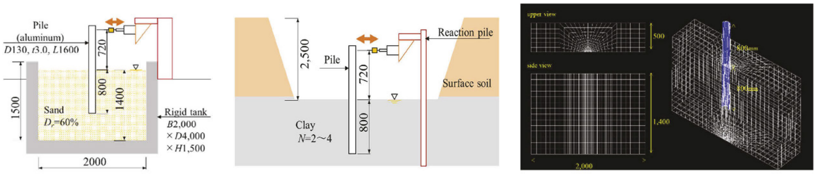
As the market for renewable energy continues to expand, expectations for wind power are growing. In Japan, there are few suitable sites for wind power generation on land, so offshore wind power generation is expected to become more popular. Monopiles, the most common type of offshore wind turbines foundation, are subjected to cyclic lateral loading from wind and ocean waves during their service life. Therefore, it is desirable to accurately understand the cyclic loading characteristics of monopiles for design purposes. Large-scale wind farms have been already constructed in Europe, and many studies have been accumulated. However, most of the studies on the behavior of monopiles subjected to cyclic loading have been conducted on sandy grounds (Long et al. 1994, Liao et al. 1999), and few studies have been conducted on soft clayey grounds which frequently exist around Japan. The purpose of this paper is to understand and compare the cyclic lateral loading behavior of a monopile on sandy and clayey grounds through model experiments and FEM analysis.

2 OUTLINE OF MODEL EXPERIMENTS AND NUMERICAL ANALYSIS

Schematic diagrams of the model experiment are shown in Figures 1a, b. The model pile was made of aluminum with an outer diameter of 130mm, a wall thickness of 3.0mm, and a length of 1,600mm, about 1/50th the scale of the real pile. The sandy ground was made of Nikko silica sand No. 6 in a rigid soil tank to achieve a relative density of 60%. The clayey ground was excavated from the surface soil at the outdoor test site to expose clay with N-values of 2 to 4. In both cases, a model pile was installed into the ground with a penetration depth of 800mm. Lateral loading was conducted by an electric jack 720mm above the ground surface.

DOI: 10.1201/9781003299127-335

The analysis code used was a soil-water coupled finite deformation analysis (Noda et al. 2008) employing elasto-plastic constitutive model; SYS Cam-Clay model (Asaoka et al. 2002), that can describe the mechanical behavior of various soils from sand to clay within a same theoretical framework. FEM mesh is shown in Figure 1c. The mesh was prepared with reference to the rigid soil tanks used in the model experiments, and a half-section model was used considering the symmetricity. The same mesh was used even for clayey ground. Here, the distance from the monopile to the boundary of the analysis domain is more than 3φ for a pile diameter of φ130mm, so the difference in boundary conditions was considered to have less effect. The material constants and initial conditions were determined from the results of laboratory tests (standard consolidation and triaxial compression tests) conducted under the same conditions as the model experiments. The monopile was assumed to be a linear elastic body using solid elements, and the elastic constants of aluminum were used to obtain the same conditions as in the model experiment.

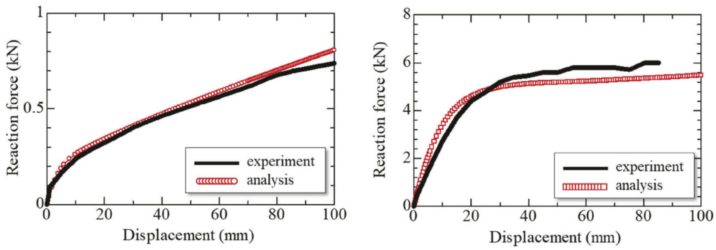


(a) sandy ground (b) clayey ground (c) FEM mesh

Figure 1. Schematic diagram of model experiments and FEM analysis.

3 MONOTONIC LATERAL LOADING BEHAVIOR

Figure 2 shows the reaction force-displacement relationship at the loading point for the monotonic lateral loading test conducted on sandy and clayey grounds. The analytical results for both grounds reproduce the experimental results well. Comparing the two grounds, the clayey ground had a clear ultimate bearing capacity *Pu*, while the sandy ground continued to increase lateral load. Based on the experimental results, *Pu* = 0.82kN for the sandy ground and *Pu* = 5.9kN for the clayey ground were determined.



(a) sandy ground (b) clayey ground

Figure 2. Monotonic loading behavior by model experiment and FEM analysis.

4 CYCLIC LATERAL LOADING BEHAVIOR

Cyclic lateral loading tests were conducted at amplitudes of 0.1*Pu*, 0.3*Pu* and 0.5*Pu* based on the ultimate load *Pu* obtained from the monotonic loading tests. The 0.1*Pu* assumes ocean waves at ordinary conditions, while the 0.3*Pu* and 0.5*Pu*, storm waves. The loading was given in the form of a one-sided triangular wave, and the periods are assumed to be 6, 11 and 16 seconds for 0.1*Pu*, 0.3*Pu* and 0.5*Pu*, respectively, as average values of the assumed external forces.

Figure 3 shows the relationship between the displacement increase rate at ground surface $\delta N/\delta N_1$ and the number of cycles N in the model experiments (where δN and δN_1 are the displacement at the Nth and 1st cycles, respectively). The lateral displacement increased with the number of cycles for both grounds. For the sandy ground, the displacement tended to converge showing linear relation on the one-logarithmic graph. Moreover, the increase rate did not change significantly regardless of the amplitude. On the other hand, for clayey ground, the increase rate became large with the amplitude, and the lateral displacement increased rapidly during the cycles. In addition, the larger the amplitude, the more rapidly the displacement increased after a smaller number of cycles. The analytical results are shown in Figure 4. Although the number of cycles at which the displacement began to increase is slightly smaller for clay, the analytical results captured the trend of the experimental results well, as the increase rate was linear for the sandy ground and the displacement increased rapidly for the clayey ground.

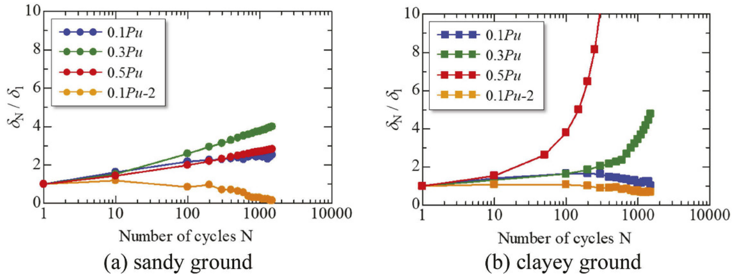


Figure 3. Relationship between displacement increase rate and number of cycles (model experiments).

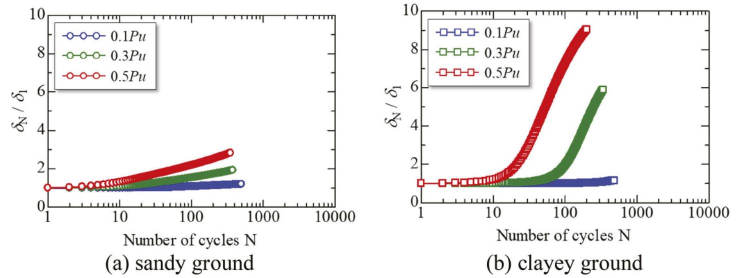


Figure 4. Relationship between displacement increase rate and number of cycles (FEM analysis).

The difference in cyclic loading characteristic between sandy and clayey grounds are discussed in detail. Figures 5 and 6 show the distribution of void ratio change, degree of structure and shear strain after 40 cycles at an amplitude of $0.5Pu$ in sandy and clayey ground, respectively. Here, structure stands for the bulkiness of the soil, which is widely observed in soft soils, and the higher the degree of structure, the more sensitive the behavior. Lowering/collapse of the structure can be regarded as soil disturbance, which causes volumetric compression and decrease in strength. The void ratio change shows that the sandy ground became denser in front of the monopile during cyclic loading. On the other hand, clay with low permeability showed little density change. This indicates that the displacement of the monopile in the sandy ground was gradually suppressed by the density increase during cyclic loading. The distribution of the structure indicates that clayey ground possessed higher degree compared with sandy ground at initial condition. In addition to that, the clayey ground was strongly disturbed during cyclic loading, and the structure around the monopile was lowered over a wide area. Especially in the case of large amplitude, the clay ground was significantly disturbed, and the displacement of the monopile increased rapidly during loading. The shear strain shows that the strain in the sandy ground was concentrated around the pile, whereas that in the clayey ground was spread over a wide area. This tendency was the same as the experimental results, although the details are omitted due to the limited pages.

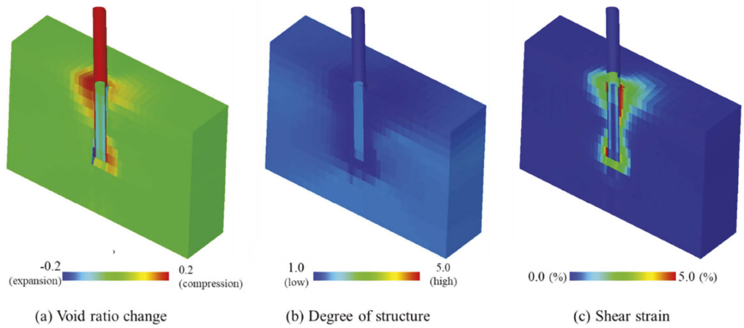


Figure 5. Contour distributions of sandy ground subjected to 40 cycles of cyclic loading with 0.5*Pu*.

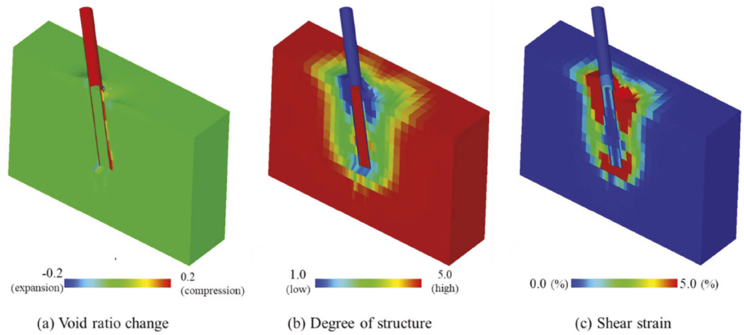


Figure 6. Contour distributions of clayey ground subjected to 40 cycles of cyclic loading with 0.5*Pu*.

5 CONCLUSIONS

We compared the cyclic lateral loading behavior of a monopile on sandy and clayey grounds through both model experiments and FEM analysis. In sandy ground, lateral displacement was gradually suppressed by density increase during cyclic loading. On the other hand, the clayey ground showed rapid increase of displacement if the soil was disturbed by large cyclic loading. In addition, the 0.1*Pu*-2 in Figure 3 was the result of cyclic loading at 0.1*Pu* after a cyclic history of 0.3*Pu*. This result also confirms experimentally that, if the load history is large beforehand, displacement hardly propagates under small amplitude loading.

Comparison between model experiments and FEM analysis has confirmed the validity of the analytical code. Therefore, in the future, this analysis code will be used to study complex stratification alternating clay and sand layers that cannot be reproduced by model experiments, as well as for full-scale studies.

Finally, we would like to thank Prof. Toshihiro Noda (Nagoya University) and Mr. Taku Kurimoto (Obayashi corporation) for valuable advice in the course of this research.

REFERRENCES

Long J. H. and Vanneste Geert. 1994. Effects of cyclic lateral loads on piles in sand, *Journal of Geotechnical Engineering* 120(1): 225–244.

Lin San-Shyan and Liao Jen-Cheng. 1999. Permanents strains of piles in sand due to cyclic lateral loads, *Journal of Geotechnical and Geoenvironmental Engineering* 125(9): 798–802.

Asaoka, A., Noda, T., Yamada, E., Kaneda, K. & Nakano, M. 2002. An elastoplastic description of two distinct volume change mechanisms of soils, *Soils and Foundations* 42(5): 47–57.

Noda, T., Asaoka, A. & Nakano, M. 2008. Soil-water coupled finite deformation analysis based on a rate-type equation of motion incorporating the SYS Cam-clay model. *Soils and Foundations* 45(6): 771–790.