Directors' research and development activities

Performance of winged monopile in calcareous sand ground

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Abstract

This study aims to investigate the behaviors of winged monopiles subjected to cyclic loading in a calcareous sand through numerical analysis. Axial load tests (push-in or pull-out) of monopiles with and without wings in a calcareous ground are simulated using a three-dimensional finite element software, PLAXIS 3D. Prior to these simulations, triaxial tests on a calcareous sand sampled from Vietnam were carried out to investigate the mechanism behaviors of the calcareous sand, aiding in the selection of an appropriate soil model and the evaluation of the corresponding soil parameters. The hypoplastic model was adopted to simulate the sand. Interface elements were employed to simulate the slippage between the pile shaft and the soil. The analyzed results show that the resistance of the winged pile is considerably higher than that of the pile without wings.

1. Introduction

In the sea areas of Southeast Asia, especially around Truong Sa Island in Vietnam, calcareous sand is quite commonly distributed. A problematic feature of the calcareous sand is high crushability of soil particles when subjected to high confining pressure, shear stress, and cyclic loading. A monopile foundation is usually used for supporting offshore structures subjected to cyclic loading caused by sea waves and/or winds as well as to vertical loading. To improve the shaft resistance, the use of a winged monopile, where reinforcement wings are implemented along the outer surface of the pile, is a feasible solution.

The physical and mechanical characteristics of calcareous sands have been summarized in [1, 2]. In a natural state, calcareous sediments behave differently from terrestrial silica sands, the most significant distinguishing feature being their tendency to exhibit volume reduction upon shearing, even at relatively low normal stresses. It was pointed out in [2] that the tendency for volume reduction due to shearing plays a dominant role in the foundations of calcareous sediments. A numerical study was conducted on the behavior of a single pile subjected to cyclic loading in the coral sand [3]. Al-Douri and Poulos [4] compared the predicted and observed performance of cyclic load tests on small-scale single piles jacked into dry calcareous sand to study the accumulation of permanent displacement of the piles.

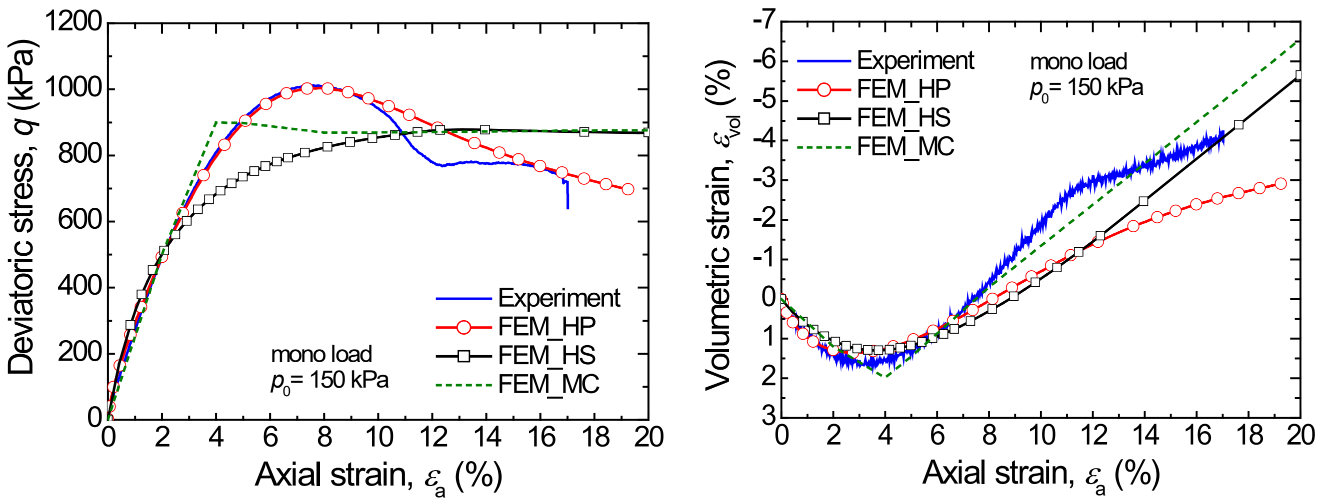
This study investigates the behavior of winged monopile subjected to cyclic loading in calcareous ground through numerical analysis. In the analyses, axial load tests (push-in or pull-out) of monopiles with and without wings in a calcareous ground are simulated using a three-dimensional finite element program, PLAXIS 3D [5]. Triaxial tests on a calcareous ground sampled in Vietnam are carried out prior to the analyses of the load tests to investigate the mechanical behavior of the calcareous ground and to select an appropriate soil model as well as to evaluate the corresponding soil parameters. In this study, the hypoplastic model [6] is used to model the ground. Interface elements are employed to simulate the slippage between the pile shaft and the soil. The analyzed results show that the resistance of the winged pile is considerably higher than that of the pile without wings.

2. Triaxial Tests of The Calcareous Sand and FEM Simulation

The calcareous sand collected from Truong Sa Island in Vietnam was used in this study. Only soil particles having a particle diameter, d, smaller than 4.75 mm were used in the experiments. Triaxial monotonic and cyclic CD compression tests on calcareous sand with a relative density, Dr, of 70% were conducted at a confining pressure, p_0, of 150 kPa. Cylindrical specimens with a height of 100 mm and a diameter of 50 mm were used in the tests.

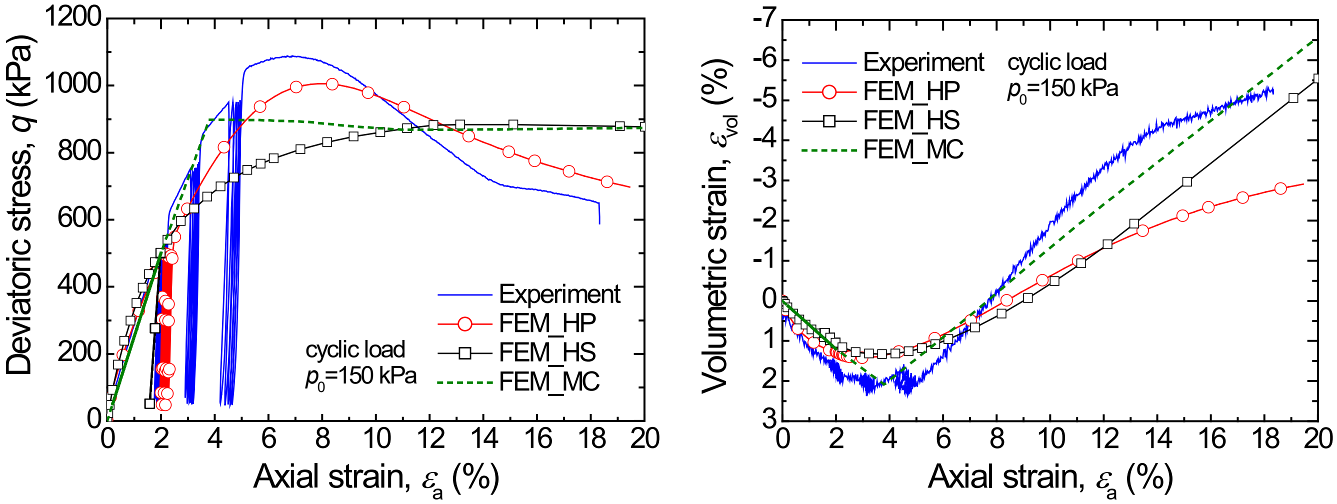
Fig. 1 and 2 show the experimental and simulation results of the triaxial tests for monotonic and cyclic loading, respectively. The experimental results indicate that post-peak softening behavior is observed, and dilatancy decreases with increasing axial strain. Specifically, in the case of cyclic loading (Fig. 2a), the accumulative strain increases with the number of loading cycles.

Simulations of the triaxial tests were carried out to select an appropriate soil model and to evaluate the soil parameters. In this study, soil models such as Mohr-Coulomb (MC), Hardening Soil (HS) [7] and Hypoplastic (HP) were used for the simulations. The FEM simulations results of the triaxial tests are also shown in Fig. 1 and 2. It is evident that MC and HS models cannot simulate the post-peak softening behavior (Figs. 1a and 2a) and the reduction of dilatancy (Figs. 1b and 2b) with increasing axial strain, ε_a. In particular, the MC and HS models are unable to simulate the accumulative strain due to cyclic loading (see Fig. 2b). Meanwhile, the HP model [6] generally simulated the measured q vs. ε_a of the calcareous sand well, both qualitatively and quantitatively, although there are differences in dilatancy curves between the experiments and the simulations. The hypoplastic model will be employed for model ground in numerical analyses of monopiles, which are presented in Section 3.



(1a) Deviatoric stress q versus axial strain ε_a (1b) Volumetric strain ε_{vol} versus axial strain ε_a

Fig. 1. The experimental and simulation results of the triaxial tests for monotonic loading.



(1a) Deviatoric stress q versus axial strain ε_a (1b) Volumetric strain ε_{vol} versus axial strain ε_a

Fig. 2. The experimental and simulation results of the triaxial tests for cyclic loading.

3. Numerical Analysis of Monopiles in Calcareous Sand

3.1. Description of Numerical Model

Case studies considered in this paper are close-ended monopiles with and without wings, subjected to vertical loading (push-in or pull-out loading) in calcareous sand ground. The monopiles made of steel have a total length of 25 m, with 24 m embedded and 1 m free-standing. They have an outer diameter of 1 m and a pile wall thickness of 0.015 m. The reinforcement wings of the winged pile have a width of 0.5 m (0.5D), with an opening angle of 120 degrees and a thickness of 0.01 m. The wings are spaced at 1 m interval, as shown in Fig. 3.

Model ground in this numerical study consists of calcareous sand, with properties presented in the Section 2. Groundwater influences the initial effective stress conditions, although for simplicity, a fully-drained condition was assumed during loading, resulting in uncoupled analyses. Fig. 4 shows the dimensions of the model ground. The side boundary extends laterally to 6 m (6*D*, *D* is the pile diameter) from the pile axis with restrained (fixed) horizontal displacements applied. The base boundary, located 10 m (10*D*) from the pile tip, has restrained vertical and horizontal displacements applied.

To model the pile, a hybrid model was used, consisting of a beam element surrounded by solid elements, according to Kimura and Zhang [8]. In the hybrid model of this paper, beam element carried a large proportion of the axial stiffness, *EA*, and bending stiffness, *EI* of the pile.

Interface elements were assigned along the pile shaft to simulate the slippage between the pile and the ground. An innterface cohesion of 1 kN/m^2 and an interface angle of 32 degrees were assumed, based on the triaxial test results and the strength interface reduction factor of 0.67.

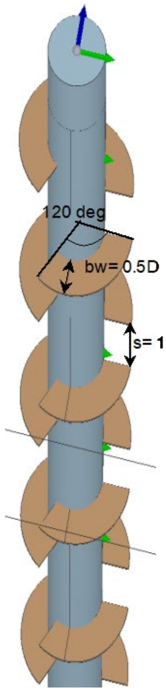


Fig 3. Dimensions of reinforcement wings.

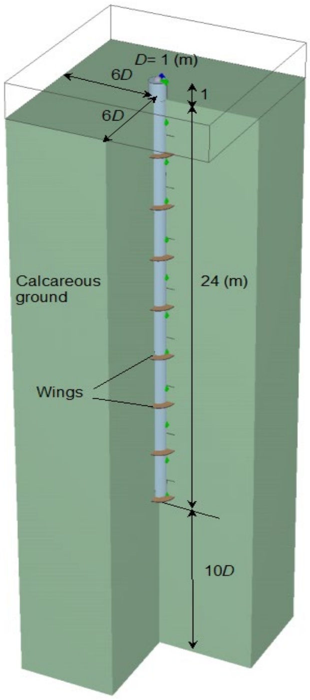


Fig 4. Dimensions of the model ground.

3.2. Numerical Results and Discussions

Fig. 5 shows the analyzed results for the monopiles (with and without wings) subjected to push-in loading including monotonic and cyclic load. Clearly, the winged-pile shows much greater resistance than the pile without wings under both monotonic and cyclic loading. Firstly, consider the load-settlement curves of the pile without wings. It is interesting to notice the difference in the pile resistance, which is influenced by loading types. The resistance of the pile after the cyclic loading decreases compared with that of the monotonic loading. Meanwhile, in the case of winged-pile, the pile resistance is almost the same between the monotonic and cyclic loading cases.

Fig. 6 shows the load-displacement curves of the piles in the case pull-out loading, in which the pile resistance is contributed by only the pile shaft resistance. Clearly, the resistance of the wing-pile is much greater than that of the pile without wings. As for the single pile without wings, the shaft resistance attained to the ultimate value of around 2300 kN after the pile head displacement reached about 0.01 m (w/D = 0.01). Meanwhile, the resistance of the winged pile increased with the increase of the pile head displacement and attained a stable behavior even until the displacement reached 0.1 m (w/D= 0.1). The resistance of the winged pile at w/D = 0.1 is 17000 kN which is over 7 times larger than that of the pile without wings, indicating a significant effect of the reinforcement wings on the pile shaft resistance. Note here that the resistance of a pile at $w/D = 0.1$ is considered as the pile capacity in design specification of many countries. The differences in pile resistance between monotonic and cyclic loading are insignificant.

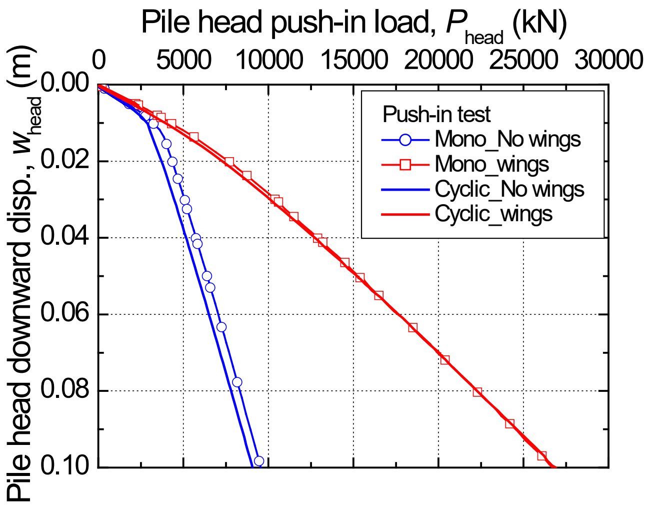


Fig 5. Load-displacement curves in push-in test.

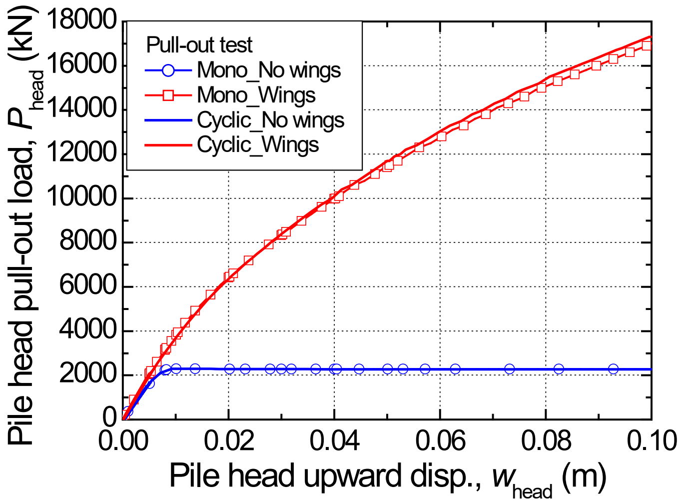


Fig 6. Load-displacement curves in pull-out test.

4. Conclusion

In this study, triaxial tests of a calcareous sand sampled from Truong Sa Island of Vietnam were conducted to investigate the mechanism behaviors under monotonic and cyclic loading. After that, numerical simulations of the triaxial tests were carried out to select an appropriate soil model and evaluate the corresponding parameters for numerical analyses on behaviors of monopiles in the calcareous sand ground.

The results from both experimental and simulation of triaxial tests indicate that the Hypoplastic soil model is more suitable than the Mohr-Coulomb or Hardening soil models for simulating calcareous sand, particularly under cyclic loading.

The numerical results show that the winged pile has considerably greater resistance than the normal pile without wings, both in pull-out and push-in loading tests, indicating its high performance efficiency of the winged pile. However, in this numerical study, the pile installation effect was not considered. Consequently, conducting experiments through small-scale models and/or full-scale models, wherein the pile installation effect is considered, are necessary to evaluate the performance efficiency of the winged pile in practical applications.

References

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