Numerical Analysis on Behaviours of Winged Monopile Subjected to Cyclic Loading in a Calcareous Ground

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Abstract. This study is to investigate behaviours of winged monopiles subjected cyclic loading in a calcareous ground through numerical analyses. 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. Triaxial tests on a calcareous ground sampled in Vietnam are carried out prior to the analyses of the load tests to investigate the mechanism behaviours 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 is used to model the ground. Interface elements are employed to simulate the slippage between the pile shaft and the soil. The analysed results show that the resistance of the winged pile is considerably higher than that of the pile without wings.

Keywords: Winged monopile · Calcareous ground · Cyclic load
Numerical study

1 Introduction

In South East Asia sea areas, especially in Truong Sa island of Vietnam, calcareous ground distributes quite popularly. A problematic feature of the calcareous ground is high crushability of soil particles when the soil is subjected to high confining pressure, shear stress and cyclic loading. Monopile foundation is usually used for supporting offshore structures, which are subjected to cyclic loading caused by sea waves and/or winds as well as to vertical loading. In order to improve the shaft resistance, use of winged monopile, in which reinforcement wings are implemented along the outer surface of the pile, is a feasible solution.

Physical and mechanical characteristics of calcareous sands have been summarised 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 on calcareous sediments. Numerical study on behaviours of a single

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pile subjected to cyclic loading in the coral sand was conducted in [3]. Al-Douri and Poulos [4] compared predicted and observed performance of cyclic load tests on small-scale single piles jacked into a dry calcareous sand to study the accumulation of permanent displacement of the piles.

This study is to investigate behaviours of winged monopile subjected cyclic loading in calcareous ground through numerical analyses. 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. Triaxial tests on a calcareous ground sampled in Vietnam are carried out prior to the analyses of the load tests to investigate the mechanical behaviours 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 [5] is used to model the ground.

2 Triaxial Tests of the Calcareous Sand and FEM Simulation

A 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 of the calcareous sand having a relative density, D_r, of 70% were conducted under a confining pressure, p_0, of 150 kPa.

Figure 1 shows the experiment and simulation results of the triaxial tests for monotonic loading. Figure 2 shows the corresponding results for cyclic loading. It is seen from the experimental results that post-peak softening behaviour is observed and the dilatancy is not constant but reduced with the increase of axial strain. Focusing on the experimental result in the case of cyclic loading (Fig. 2a), it is remarkable to see that the accumulative strain increases with number of loading cycles.

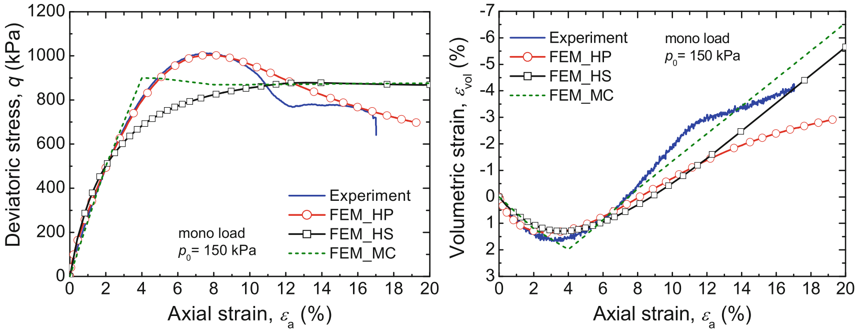

Fig. 1. The experimental and simulation results of the triaxial tests for monotonic loading. (a) Deviatoric stress q versus axial strain ε_a, (b) Volumetric strain ε_{vol} versus axial strain ε_a

To select an appropriate soil model and to evaluate the soil parameters, simulations of the triaxial tests were carried out. In this study, soil models as Mohr-Coulomb (MC), Hardening Soil (HS) [6] and Hypoplastic (HP) are used for the simulations. The FEM

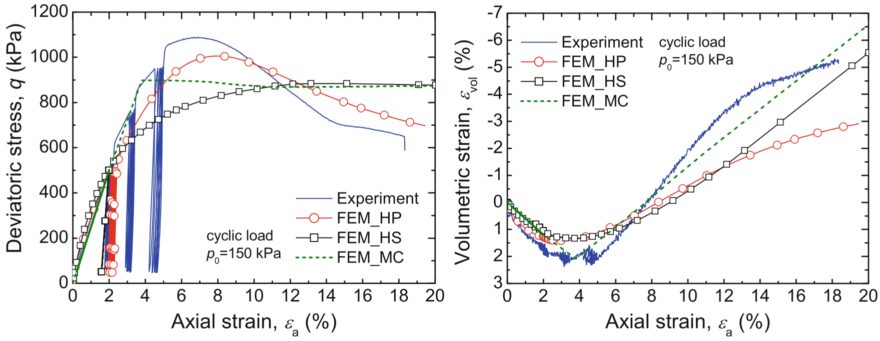

Fig. 2. The experimental and simulation results of the triaxial tests for cyclic loading. (a) Deviatoric stress q versus axial strain ε_a, (b) Volumetric strain ε_{vol} versus axial strain ε_a

simulations results of the triaxial tests are also shown in Figs. 1 and 2. It is obvious to see that MC model and HS model cannot simulate the post-peak softening behaviour (Figs. 1a and 2a) and reduction of dilatancy (Figs. 1b and 2b) with increase in ε_a. Particularly, it is impossible to use MC model and HS model to simulate accumulative strain due to cyclic loading (see Fig. 2b). Meanwhile, HP model [5] generally simulated well the measured q vs. ε_a of the calcareous sand in both quality and quantity, although there are differences in dilatancy curves between the experiments and the simulations. The hypoplastic model having the parameters shown in Table 1 will be employed for model ground in numerical analyses of monopiles, which are presented in Sect. 3.

Table 1. Parameters of the hypoplastic model

φ_c (deg.)	h_s (kN/m^2)	n	e_{d0}	e_{c0}	e_{i0}	α	β	m_R	m_T	R_{max}	β_r	χ	p_t (kN/m^2)	e
40	1×10^5	0.08	0.769	1.267	1.450	0.25	1.8	5	7	4×10^{-4}	0.8	4.5	1.0	0.920

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 a calcareous sand ground. The monopiles made of steel have a total length of 25 m (24 m embedded and 1 m free), 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), an opening angle of 120° and a thickness of 0.01 m and interval spacing between wings is set 1 m, as shown in Fig. 3.

Model ground in this numerical study is calcareous sand having the properties presented in the Sect. 2. Ground water which has an influence on initial effective stress condition of the ground was considered, but fully-drained condition was assumed during loading for simplicity. That is, uncoupled analyses were carried out. Figure 4

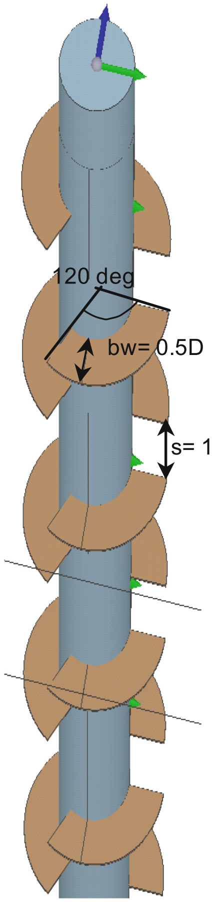

Fig. 3. Dimensions of reinforcement wings

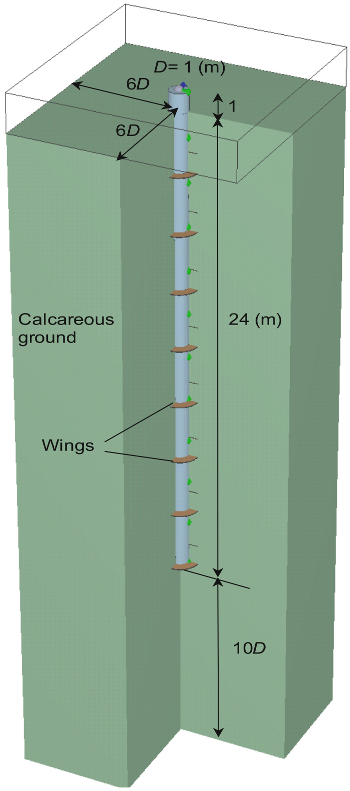

Fig. 4. Dimensions of the model ground

shows the dimensions of the model ground. The side boundary is extended laterally to 6 m (6*D*, *D* is the pile diameter) from the pile axis and applied with restrained (fixed) horizontal displacements. The base boundary is 10 m (10*D*) from the pile tip and applied with restrained vertical and horizontal displacements.

In order to model the pile, a hybrid model in which beam element surrounded by solid elements was used, according to Kimura and Zhang [7].

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

The following FEM analysis procedure was adopted:

Step 1: Self-weight analysis of the ground model with the water level at the ground surface. In this study, drained type of soil model was employed.
Step 2: Setting the pile in the ground, and self-weight analysis including the pile. The beam pile elements, the solid pile elements and the interface elements were created.
Step 3: Analysis of loading process. In the analyses, loading of the model was performed by displacement-controlled manner. In each loading cycle, the displacement of the pile top was increased from 0 to 5 mm, then was reduced to 0 mm again. The number of loading cycles was 30 cycles in analyses of cyclic loading. After cyclic loading was applied, the load-displacement analyses were continued until the displacement attained to 100 mm (0.1*D*).

Note here that, the effect of pile installation is not considered in this particular study. This aspect is one of the interests of the authors for further study.

3.2 Numerical Results and Discussions

Figure 5 shows the analysed results for the monopiles (with and without wings) subjected to push-in loading including monotonic and cyclic load. It is obvious to see that the resistance of the winged-pile is much larger than that of the pile without wings in both monotonic and cyclic loading. Firstly, focusing on 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.

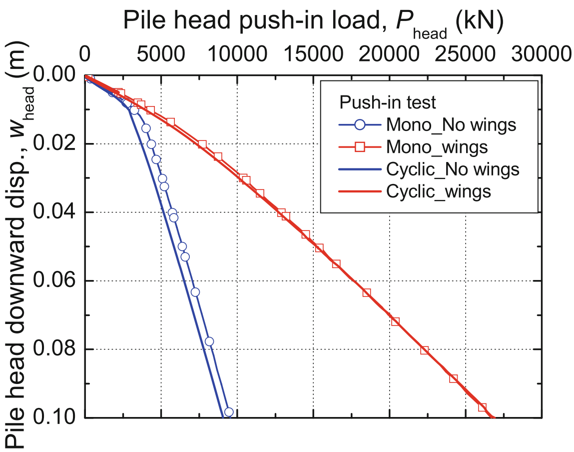

Fig. 5. Load-displacement curves in the case of push-in test

Figure 6 shows the load-displacement curves of the piles in the case pull-out loading. Obviously, the resistance of the wing-pile is much larger 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 to the preserving behaviour 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.

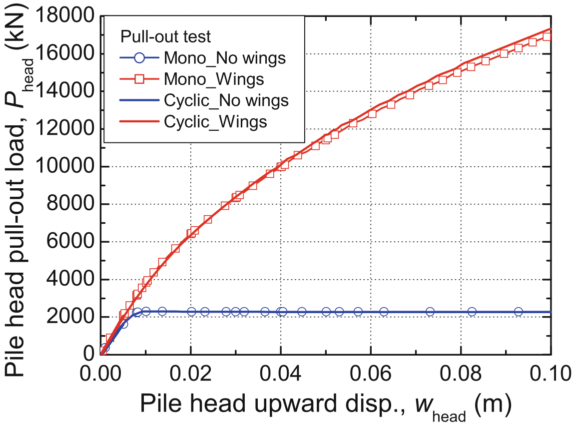

Fig. 6. Load-displacement curves in the case of pull-out test

4 Concluding Remarks

It is derived from this study that it is feasible to employ the Hypoplastic soil model but Mohr-Coulomb or Hardening soil models to simulate the calcareous sand ground, especially in cyclic loading.

The numerical results show that the winged pile has considerably larger resistance than the normal pile without wings, not only in pull-out loading but also in push-in loading tests, indicating the high performance efficiency of the winged pile. In this numerical study, the pile installation effect was not considered. Therefore, experiments through small-scale models and/or full-scale models in which the pile installation effect is considered, are necessary to evaluate the performance efficiency of the winged pile in practice.

Parameter study to investigate the influences of the characteristics of reinforcement wings such as the width of wings, the wing spacing, the inclination angle of wings, etc. on the performance of the pile will be carried out in near future.

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