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FEM-DEM study of cyclic behaviour of monopiles for offshore wind turbines

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ABSTRACT: Offshore wind energy plays an important role in the transition to clean energy. Monopiles are the most commonly used foundation for supporting offshore wind turbines. They are subjected to cyclic loading due to waves, currents, and winds during the operational lifetime. Simulation of the cyclic behaviour of monopile is thus crucial for predicting its operational performance and longevity. This study uses the coupled Finite Element Method-Discrete Element Method (FEM-DEM) approach to give a preliminary investigation into the soil-monopile interaction under cyclic loading. The results show that the FEM-DEM method effectively captured the cyclic response, including the non-linear force-displacement relationship and the hysteric behaviour during cyclic loading. In addition, microscopic insights into coordination number and contact normal vector distribution reveal that the contact number and principal contact orientation evolve cyclically in response to repeated loading.

Keywords: Multiscale; FEM-DEM; Monopile; Cyclic loading

1 INTRODUCTION

To meet the energy and climate targets for 2030 and 2050, offshore wind energy, as a source of clean energy, has been considerably growing in the past decades and is expected to continue expanding rapidly.

Among various offshore wind turbine (OWT) foundation types such as monopile, gravity, floating and suction bucket foundations, monopile is the most commonly used foundation type for supporting OWTs in shallower waters at this stage (Offshore wind in Europe, 2020). Monopiles are typically cylindrical steel piles embedded into the seabed to provide support for the wind tower above. They are subjected to cyclic loading due to waves, currents, and winds during the operational lifetime. Understanding the cyclic response of the monopile interacting with surrounding soil mass is important for predicting its operational performance and longevity.

Numerical simulations can provide a cost-effective and efficient alternative to expensive experimental tests (e.g. centrifuge test) and field tests for evaluating the cyclic behaviour of monopiles. The Finite Element Method (FEM) has been widely used to study the soil-pile interaction (Cerfontaine et al., 2016; Wang et al., 2022). To accurately capture the cyclic response, an advanced constitutive model is essential in FEM, especially for long-term cyclic performance (Liu et al., 2020). An alternative approach to FEM is the Discrete Element Method (DEM), which can be used to represent the behavior of granular soils by modeling the interactions between individual soil particles, allowing for a detailed analysis of soil-pile interactions at the microscale. However, the model size in DEM is limited due to the high computational cost associated with simulating large numbers of individual particles (Duan et al., 2017). Hence, the use of DEM is not applicable to boundary value problems that require modeling large-scale domains. Combining the above two methods, namely the coupled FEM-DEM double scale method, offers a promising solution which bypasses the need for phenomenological constitutive laws while making it feasible to address boundary value problems (Guo and Zhao, 2014; Desrues et al., 2019). It uses a DEM representative element to derive the constitutive relationship at each Gauss point, from which the inherent non-linear response of soils under cyclic loading can be captured.

In this study, the coupled FEM-DEM framework described in Desrues et al., 2019 is used to provide a preliminary study on the soil-monopile interaction under cyclic loading. The load-displacement relationship (or so-called p-y response) is presented. Microscopic variables are provided to support the interpretation of the cyclic response.

2 MODEL DESCRIPTION

2.1 Model domain

In this study, the 3D condition is simplified to a 2D plane strain condition by focusing on a layer of soil (Ahayan et al., 2018), as demonstrated in Figure 1. The diameter of the pile (D) is 2 metres. The FE domain under consideration is 32 metres wide and 15 metres long. The soil mass close to the pile has a refined mesh to achieve a higher accuracy, while the area far from the pile has coarser mesh to save computational cost. In total, the soil matrix is discretized into 640 quadrangular elements. It should be noted that, the pile may separate from the surrounding soil mass upon lateral loading. Therefore, an interface element (Cerfontaine et al., 2015) is introduced along the pile, enabling the potential gap between pile and soil elements. Only half of the pile is modelled due to the symmetry.

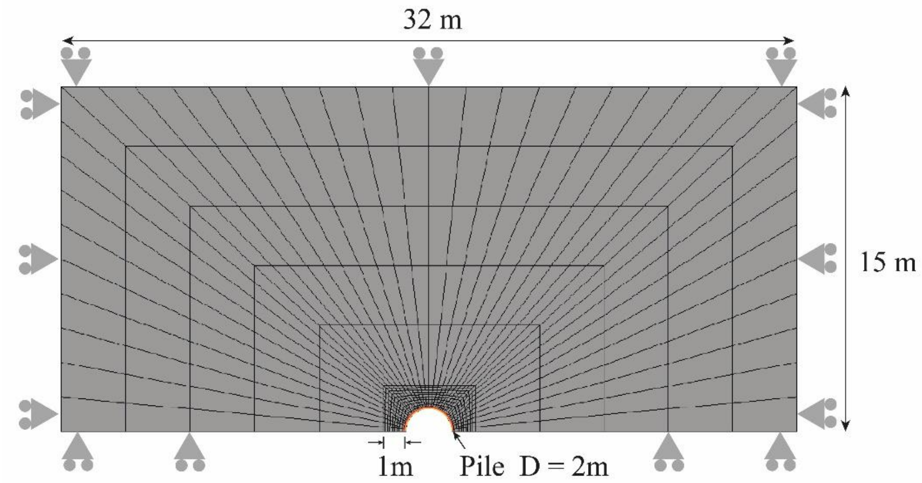

Figure 1. FE domain of a representative soil lay in 2D condition.

2.2 DEM representative volume element

In the presented coupled FEM-DEM framework, a DEM representative volume element (RVE) is used at each integration point to solve the constitutive relationship. An identical RVE is used for all the integration points. To prepare the RVE, 125 spherical grains are generated inside a periodic cell and are subjected to isotropic consolidation until reaching a consolidation pressure of 100 kPa, at which the porosity of the RVE is 0.41. It should be noted that a number of 125 grains in a RVE can lead to large fluctuations in the stress-strain response, a higher number up to 1000 is suggested by Guo and Zhao, 2016. This will be implemented in the future study. A classic frictional contact law is used to solve particle interactions. The grain properties, including particle stiffness (E) and density (ρ), ratio of contact shear stiffness to normal stiffness (K_t/K_n), coefficient of friction (φ), are listed in Table 1. The particle shape effect is not considered in this preliminary study, while it can be addressed by introducing irregular grain shape or rolling and twisting resistance. The grain size ranges from 2 mm to 4 mm with a mean diameter (D_{50}) of 3 mm, as shown in Figure 2. The coefficient uniformity of the particle size distribution (C_u) is 1.45.

Table 1. DEM grain property.

Property	Symbol (Unit)	Value
Stiffness	E (MN/m)	1
Contact stiffness ratio	K_t/K_n	0.3
Coeff. friction	φ	0.5
Density	ρ (kg/m^3)	2650

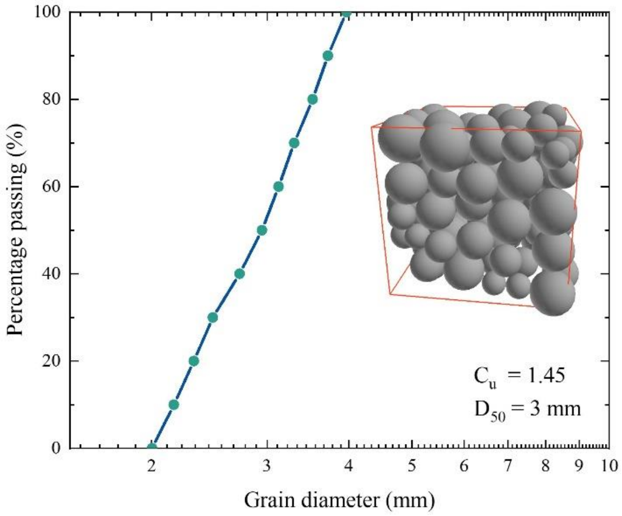

Figure 2. Particle size distribution and illustration of the RVE.

2.3 Cyclic lateral loading scheme

The pile is assumed to be rigid. All the degrees of freedom of the pile nodes are fixed and the pile moves to the right side upon it reaches a maximum displacement which is 3% of the pile diameter. The displacement is defined as the distance between the current location and the original location of the pile as shown in Figure 3. After that, the direction of pile movement reverses to the left and it reverses again until the pile reaches the leftmost position (i.e. 3%D). Such a pattern is repeated to simulate the cyclic movement.

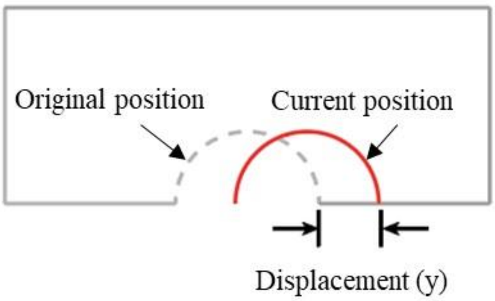

Figure 3. Schematical illustration of the pile movement during the cyclic loading.

3 RESULTS

In this section, the force-displacement response of the pile subjected to cyclic loading is presented and microscopic insights into the RVE are discussed to understand the soil response.

3.1 Force-displacement response

When the pile moves cyclically, it is subjected to the resistance from the surrounding soil mass. This resistance evolves with the pile displacement. Their relationship, i.e., the force-displacement response, is critical for analyzing and designing piles under lateral loading conditions. Figure 4 shows the lateral force-displacement response in the first 3 cycles.

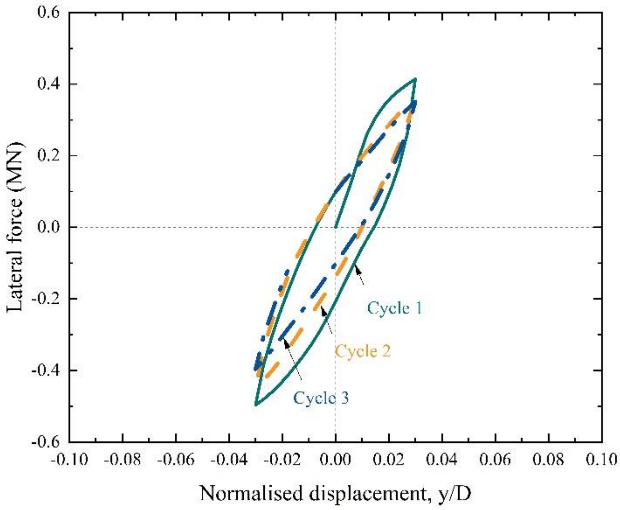

Figure 4. Force-displacement response of the FEM-DEM model for three consecutive displacement controlled cycles.

It can be found from Figure 4 that the non-linear response can be identified when the pile moves to the right. This non-linear behaviour aligns with the experimental results reported by Byrne et al., 2020; Wang et al., 2022, among others. The model can capture accurately the hysteric behaviour of soils. Specifically, in the first cycle, the force-displacement curve does not form a closed loop. At the end of the first cycle, upon returning to its initial position, the lateral force is non-zero, indicating that the stress state is not uniform. This can be further supported by the stress distribution around the half pile. Figure 5 plots the normal stress distribution along the half pile at four selected states, from A to D in the first cycle. It can be seen that the normal force acting on the pile evolves with the displacement. At the end of the first cycle (point D in Figure 5), the stress distribution is not uniform due to the plastic deformation accumulated in the first cycle.

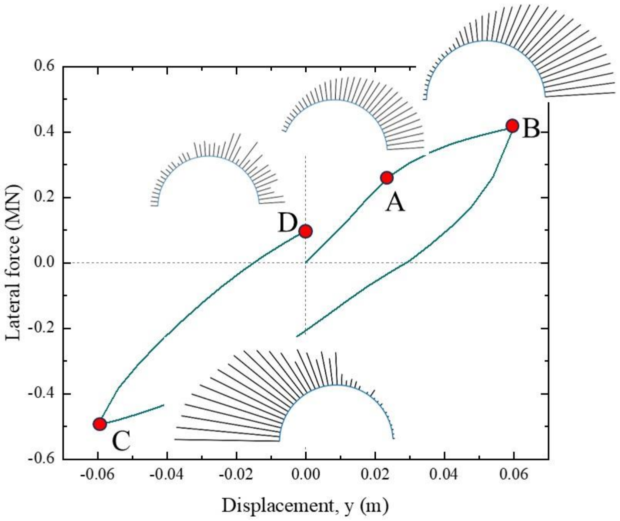

Figure 5. Normal stress distribution along the half pile at four selected states in the first cycle.

At each subsequent loading cycle, there is a noticeable reduction in the lateral force for a given displacement (see Figure 4), suggesting a degradation of stiffness or softening of the soil around the pile. This behaviour is characteristic of soils subjected to cyclic loading, where the soil gradually responses to repeated loads through rearrangement of particles, leading to a change in soil properties and resistance. The rearrangement of particles are investigated in the following section.

3.2 Insights into the RVE behaviour

Microscopic insights into the RVE behaviour are conducted in this section to support the understanding on how soil grains around the pile response to the cyclic loading.

The coordination number (CN) describes the average contacts per grain and is widely used to characterize the microstructural state of a granular packing (Zhang and Dieudonné, 2023;). CN is defined as:

$$CN = \frac{2C}{N} \quad (1)$$

where C is the number of contacts and N is the number of particles.

Two RVEs (locations are indicated in Figure 6) are selected and their evolution of CN is compared. It can be found that the evolution of CN of the two RVEs shows a cyclic pattern, although they exhibit opposite phases. The CN of RVE1 first decreases and then increases in a cyclic pattern. In contrast, CN of RVE2 initially increases and then decreases. This difference in the evolution of CN arises from the fact that RVE1 is subjected unloading followed by loading, while RVE2 undergoes loading followed by unloading. In the loading phase, the RVE packing rearranges and tends to form a denser contact network (i.e. increase in CN) to bear the increased load at the location of the RVE due to the pile movement. In the unloading stage, it is characterised as loosing of contact. The difference in the evolution trend of CN is more clear at the end of the cycles, as indicated by the circular symbols in Figure 6. With cycles increases, CN of RVE1 generally shows a decreasing trend while CN of RVE2 gradually increases. This suggests that the evolution of trend of CN is related to the initial loading condition.

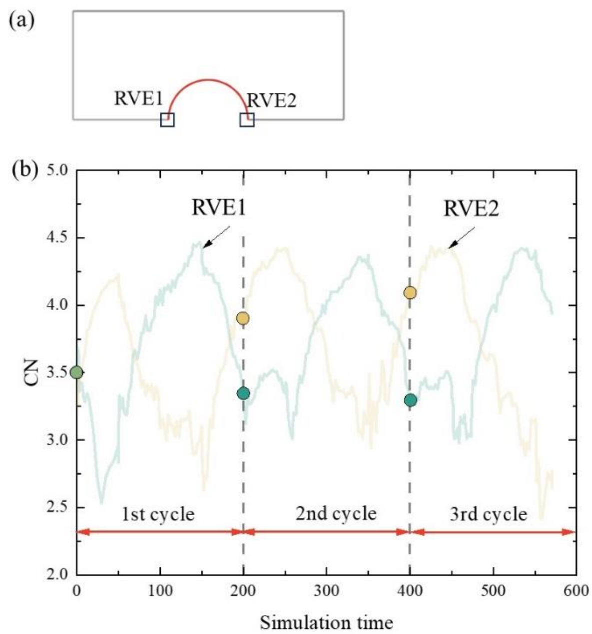

Figure 6. (a) Demonstration of the location of the two selected RVEs; (b) Evolution of coordination number of the two selected RVEs during the cyclic loading.

Apart from the evolution of CN, the arrangement of particles can also be characterized from the contact orientation. Figure 7 shows the distribution of contact normal vectors of RVE1 and RVE2 at three states where the pile is at the original position, rightmost position (corresponds to position B in Figure 5) and leftmost position (corresponds to position C in Figure 5) respectively in the first cycle. It can be seen that the principal contact orientation, i.e., the direction of the major axis of the ellipse, evolves with the pile location. When the RVE is subjected to compressive force, the particles in that RVE rearranges and the principal contact orientation tends to align with the loading direction. In a unloading phase, the principal contact orientation rotates. It should be noted that the contact normal vector distribution is not isotropic due to the low number of particle. More particles in a RVE will be used in the future work.

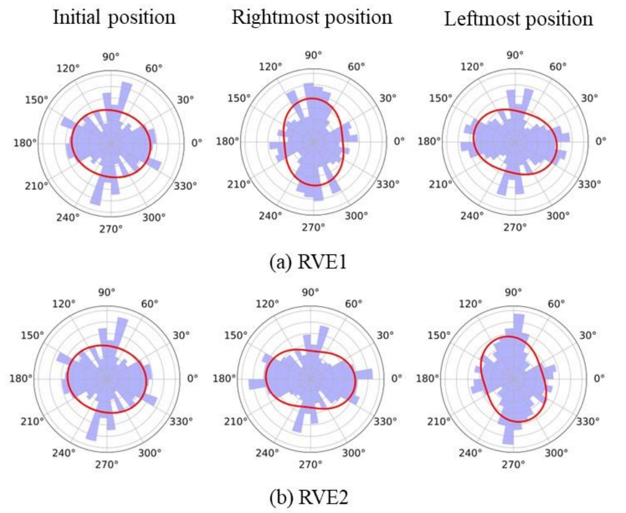

Figure 7. Evolution of distribution of contact normal vector for (a) RVE1 and (b) RVE2 in the first cycle.

4 CONCLUSIONS

This study provides a preliminary investigation into the soil-pile interaction under cyclic loading using the coupled FEM-DEM approach. It demonstrated that the FEM-DEM method can effectively capture the cyclic response, including the non-linear force-displacement relationship and the hysteric behaviour during cyclic loading. A degradation of soil stiffness upon cyclic loading was found. Additionally, microscopic insights on coordination number and contact normal vector distribution were examined to understand how the soil particles around the pile rearrange in response to cyclic loading, revealing the dynamic adjustments in particle contact number and orientations. In the future work, the mesh size effect will be analysed and the model will be refined by increasing particle number in RVE and extending the analysis to a broader range of loading conditions.

AUTHOR CONTRIBUTION STATEMENT

Aoxi Zhang: Data curation, Investigation, Formal Analysis, Writing- Original draft. **Cyrille Couture**: Software, Methodology, Writing – review & editing. **Frédéric Collin**: Supervision, Conceptualisation, Funding acquisition, Writing – review & editing.

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