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DEM Investigation of Sediment Densification Effect Induced by Mangrove-Inspired Skirt Piles

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ABSTRACT

Mangrove forests stabilize sediments against coastline erosion due to their dense root system. Inspired by such unique characteristics, a ring of mini skirt piles that mimic the mangrove root structure has been proposed, which aims to potentially densify the sediments around the centered monopile and therefore increase the anti-scour potential of the pile system. To test the hypothesis, numerical simulation using the discrete element method (DEM) has been carried out to evaluate the sediment densification effect due to the soil plugging effect during the skirt pile installation process. The displacement and stress states of the surrounding sediments have been analyzed to investigate the pile-sediment interaction at the particle-scale level.

INTRODUCTION

Local scour has been acknowledged as the most important cause that affects the structural integrity of coastal infrastructures (e.g., monopile foundations, bridge piers, and other underwater foundations). Scour occurs as the sediments erode around the foundation induced by flow or wave, consequently, affecting the foundation's stability and resulting in structural failure. Most documented measures to mitigate scour were only focused on the either hydraulic or geotechnical perspectives, such as using sacrificial pile to reduce the incoming flow velocity/wave strength (Melville and Hadfield, 1999; Wang et al., 2017; Li et al., 2022b) or using (cemented) riprap to suppress the sediment from removal (Chiew, 1992; Nielsen et al., 2013). These aforementioned methods, however, inevitably require constant monitoring and the cost is not desirable. Therefore, a more sustainable countermeasure for scour mitigation is needed for further exploration.

In nature, mangrove forests exhibit impressive performance in terms of coastal protection due to their unique prop root structure (Kazemi et al., 2017). Inspired by the mangrove root system, our current studies proposed to use a group of mangrove-inspired skirt piles to mitigate scour around the centered monopile foundation, and the scour depth and volume can be reduced up to approximately 60% and 85%, respectively, depending on the skirt pile's geometry-height, spacing, and number of layers (Li et al., 2022a; Li et al., 2024). The installation of the skirt pile provides both hydraulic and geotechnical benefits as part of the scour countermeasure, in which the developed soil plug in the skirt pile during the installation process facilitates the surrounding sediment movement and therefore increases the relative density of the soil particles between the skirt pile and the centered monopile, such effects have been widely tested in our previous studies using the flume experiments and 2D DEM simulations incorporating cavity expansion method (Li et al., 2024). The objective of this study is to explore the pile-sediment interaction from a 3D perspective and advance the understanding of soil plug formed in skirt piles on the densification effect of surrounding sediment.

3D DEM MODEL IMPLEMENTATION

Model setup and input parameter. Commercial DEM code PFC 3D (Itasca, Version 6.0) is used in this study to investigate the pile-sediment interaction during skirt pile installation. A preliminary 3D DEM simulation is presented in Figure 1. The model has a dimension of 1.8 m x 1.8 m x 0.45 m, and the outer diameters of the monopile and skirt piles are 0.25 m and 0.03 m, respectively. A servo-control mechanism has been implemented on each sidewall during the pile installation to alleviate the boundary effect. The sediments are divided into three parts to save computational cost. For the inner layer (denoted in green) with a dimension of 0.32 m, the particle diameter is between 0.007-0.008 m; For the middle layer (denoted in red) with a dimension of 0.5 m, the particle diameter is between 0.0085-0.011 m. Relative larger particles (diameter between 0.013-0.014 m) are used in the rest outer layer (denoted in blue).

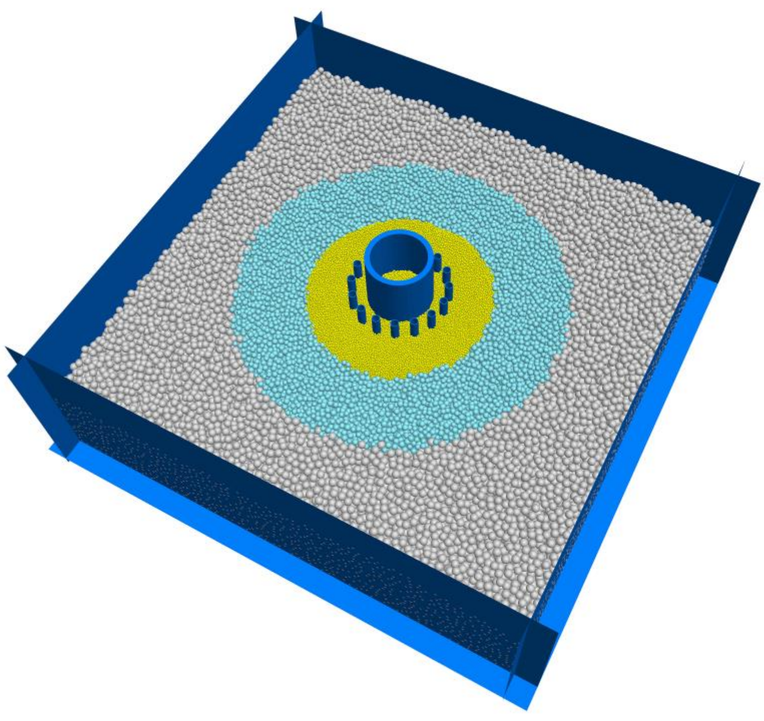

Figure 1. DEM model setup and layout of the pile system

Therefore, approximately 530,000 particles have been generated in the DEM model. A total of 16 skirt piles are located around the centered monopile, which aims to densify the surrounding sediments and increase strength to resist scour from the geotechnical benefits of the proposed design. The embedded rolling resistance linear contact model has been used in the DEM model to simulate the angularity effect of particles. For completeness, the input parameters are summarized in Table 1.

Table 1. Input parameters in the DEM model

Input parameters	value
Particles	
Normal stiffness (N/m)	$1x10^{8}$
Shear/Normal stiffness ratio	0.2
Friction coefficient	0.4
Rolling friction coefficient	0.15
Density (Kg/m^3)	2650
Damping ratio	0.7
Wall	
Normal stiffness (N/m)	$1x10^{10}$
Shear/Normal stiffness ratio	0.2
Friction coefficient	0.2

Plug effect in the skirt pile. The soil plug effect occurs during the open-ended pile installation, in which soil mass enters the inside of the pile and gradually forms a soil column, the friction between the soil column and the pile interior wall is accumulated gradually which consequently enables the pile "plugged" and acting as a closed-ended pile, preventing the following soil mass from entering in the subsequent installation stage (Lehane and Gavin, 2001). The extra soil that does not enter the pile will be laterally pushed away as the advancement of plugged pile installation and there is a tendency for the surrounding sediment to be densified (Liu et al., 2012). In addition, the plug effect is more likely to occur in a slim pile rather than a large-diameter pile. Accordingly, it is hypothesized that if the spacing between the monopile and skirt pile is close enough, the use of the skirt pile would encourage the development of the plug and promote the sediment displacement in the vicinity of the monopile and therefore enhance the sediment strength to resist scour.

In the DEM simulation, the monopile was installed to the depth of 0.3 m at a constant rate of 0.05 m/s to keep the system in the quasi-static condition, followed by the installation of the skirt piles to the same depth and rate. It is hypothesized the installation of slim skirt piles would facilitate the formation of soil plugs, as a result, densifying the sediments between the monopile and the plugged skirt piles.

RESULTS AND DISCUSSIONS

Evolution of soil plug. A cross-section plot is presented in Figure 2 to demonstrate the development of soil plug formed in the skirt piles at various embedded depths. It can also be noticed that the soil plug does not occur in the monopile due to its relatively larger diameter and shallow embedded depth, which is consistent with the findings in Liu et al. (2019), while the plug effect easily occurs in the slim skirt piles (the height of the interior soil column is smaller than the skirt pile embedded depth of 0.1 m), and such a phenomenon becomes more significant as the skirt piles are installed to a deeper embedded depth. Accordingly, the sediments between the skirt piles and the centered monopile are expected to be squeezed and densified during the skirt pile installation, resulting in the enhancement of strength and anti-scour potential in the erodible area around the centered monopile foundation.

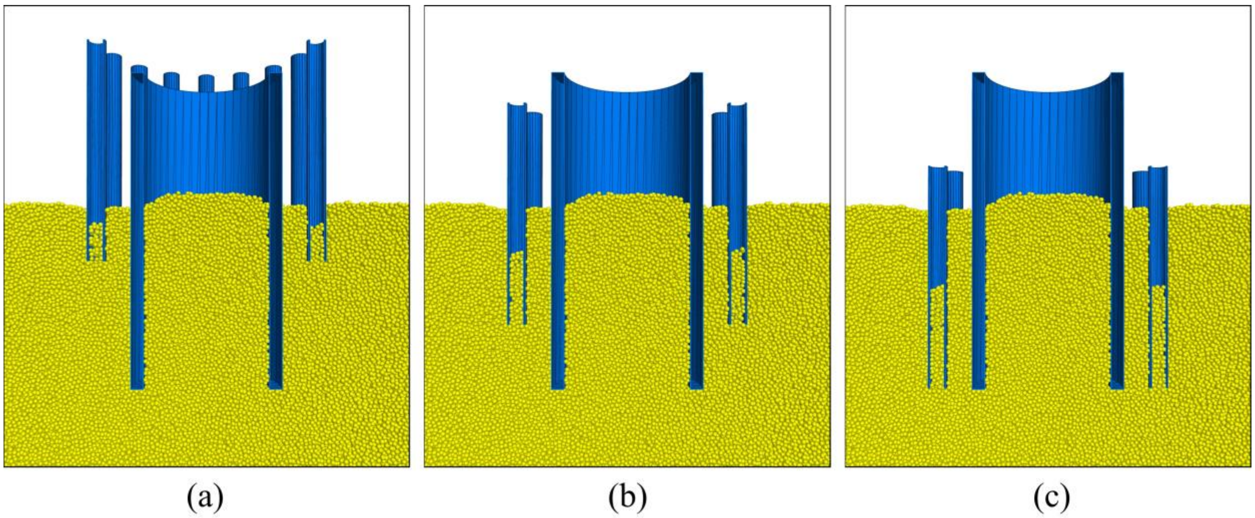

Figure 2. Evolution of soil plug developed in the skirt piles at various embedded depths: (a) 0.1 m; (b) 0.2 m; (c) 0.3 m

Sediment displacement. To highlight the effect of skirt pile installation on the surrounding sediment, the particle displacement has been reset to zero before installing skirt piles to investigate the net movement of sediment due to the soil plug effect. Figure 3 shows the lateral displacement of sediments between the plugged skirt piles and the centered monopile at the final stage (Embedded depth of 0.3 m). The skirt pile behaves like the close-ended pile and prevents the sediment from entering during the installation once the plug is formed. As a result, sediments are being pushed away in the following installation stages, in which the range of lateral displacement is within 1.5 cm. Sediments between the plugged skirt pile and the monopile are being pushed towards the monopile, and the lateral displacement becomes more significant with the depth increment. Subsequently, the densification effect can be expected for the loose or medium-dense sediment. Similarly, sediments behind the skirt pile are being pushed outside of the pile system and a greater displacement has been observed in a deeper location. The displacement beneath the pile tips is less obvious compared to the sediments along the pile surface.

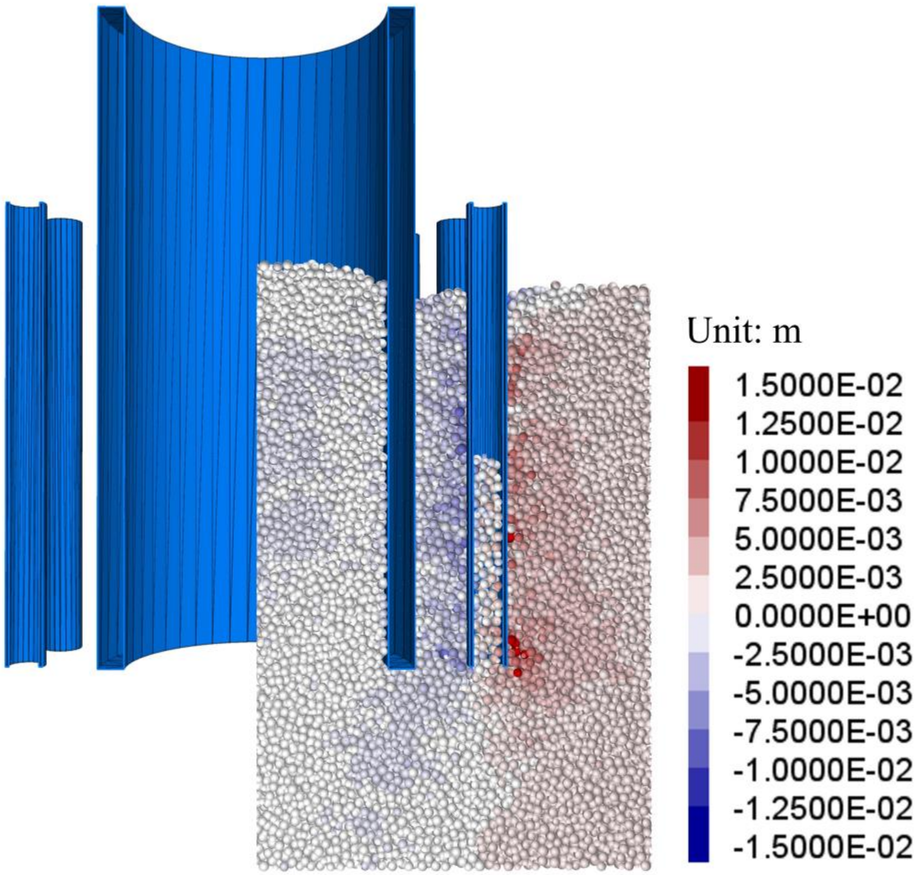

Figure 3. Lateral displacement of sediment between the plugged skirt pile and monopile at 0.3 m embedded depth

Sediment porosity and stress state. A series of measurement circles (MC) have been implemented around skirt piles to monitor the change in the sediment stress state and porosity. Eight MC are deployed at each side of the skirt pile, as shown in Figure. 4a. For the sediments between the monopile and skirt pile, the averaged porosity gradually decreased from 0.42 to 0.395 in the depth of 0.225-0.3 m (denoted in blue), indicating the sediments would have been densified and greater erosion resistance can be expected. A slight reduction of porosity for the sediments near the surface (depth of 0-0.075 m, denoted in red). The lowest porosity (~0.412) occurs for the deeper sediments behind (outside) of the skirt piles before installation, implying relatively dense sediment at the initial state, and consequently resulting in the dilation and porosity increased during the skirt pile installation (denoted in purple).

Figure 5 presents the lateral stress for sediments at various locations during the skirt pile installation. A greater lateral stress (up to 17 kPa) takes place for the sediments in the deeper location (denoted in blue and purple) and becomes weaker for the surface area, indicating the installation of skirt piles disturbs the sediment in a deeper zone compared with surface sediment, this finding is consistent with that in Figures 3 and 4.

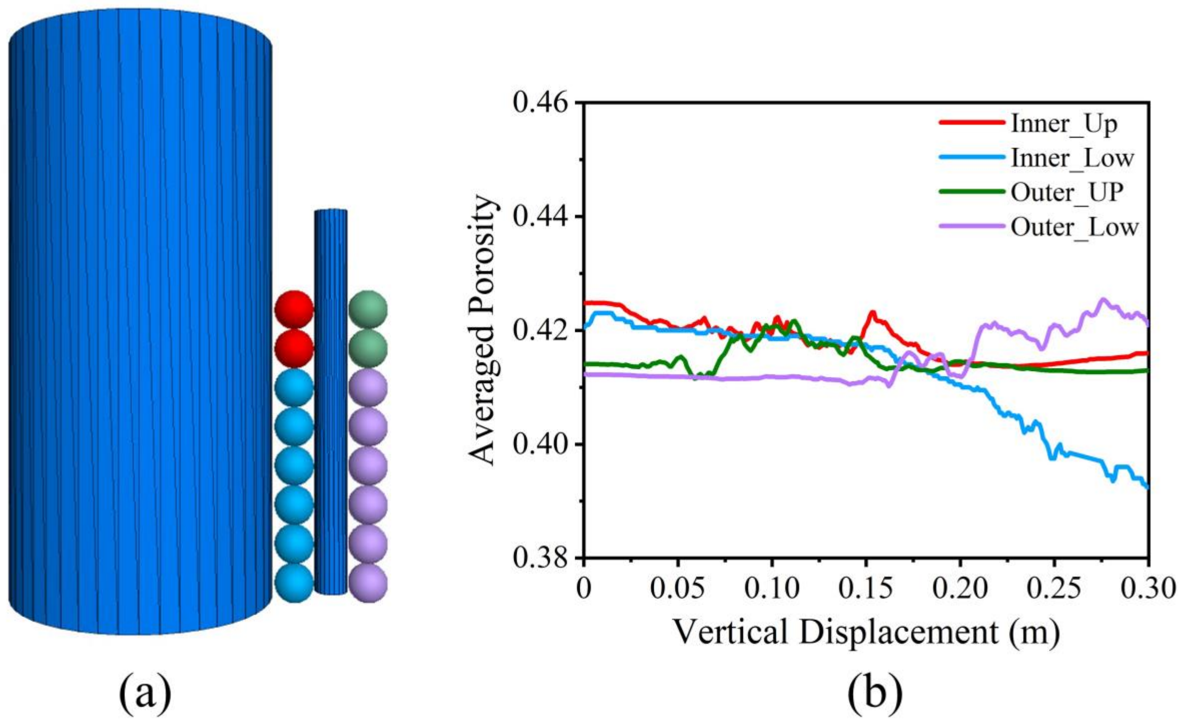

Figure 4. Sediment porosity with embedded depth: (a) Layout of measurement circles; (b) Variance of porosity during installation

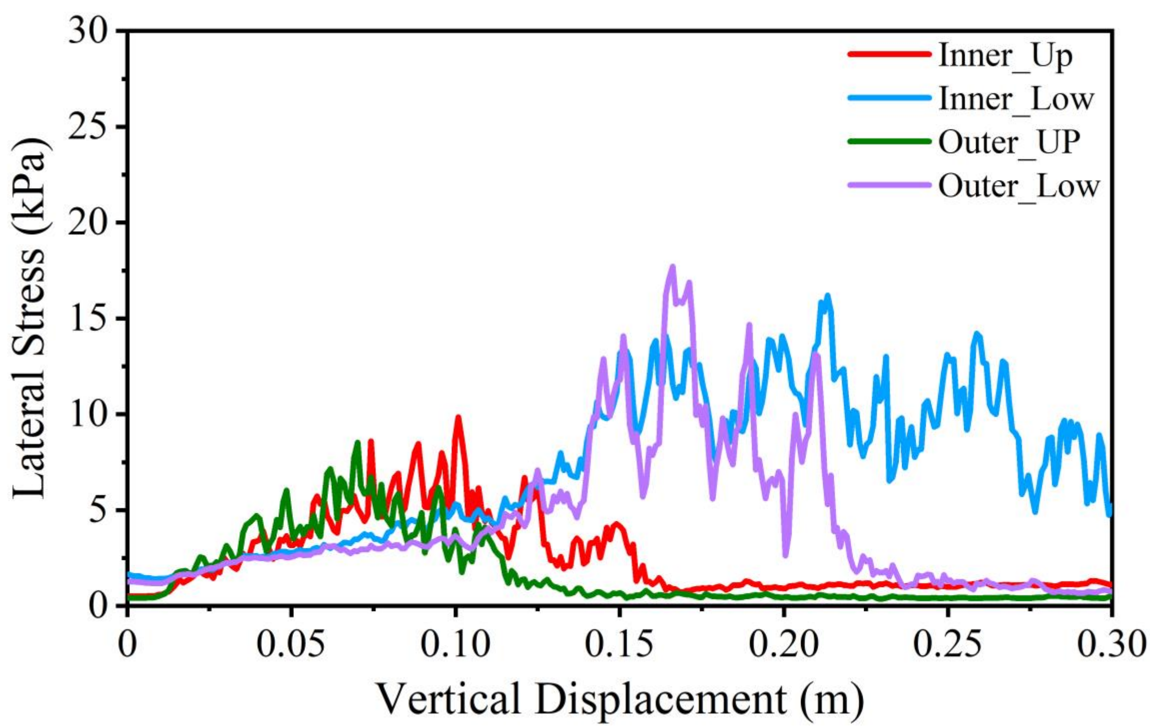

Figure 5. Change of lateral stress with embedded depth

DISCUSSION

Our previous study (i.e., Li et al., 2024) demonstrated that the installation of skirt piles contributes to densifying the sediment around the monopile foundation through a series of 2D DEM simulations and flume experiments. The current preliminary 3D DEM simulations provide the vertical profile of sediment porosity and stress state at various depths. Although installing skirt piles results in the plug forming inside of the skirt pile and therefore reduces the porosity and densifies the sediments at a deep location to resist erosion, such a strengthening effect is less significant for the surface sediments, which also explains why the initial scour rate was similar when using different installation sequences of skirt pile and monopile in the flume experiments (Li et al., 2024). As the porosity reduction is more significant in the deep depth, the geotechnical benefits of using skirt piles (sediment densification) are expected to occur in the later to final stages of scour rather than the initial period.

CONCLUSION

This study presents a 3D DEM modeling of installing mangrove-inspired skirt piles around the centered monopile that aims to densify the erodible sediment around the centered monopile foundation and therefore enhance their strength to resist scour even further. The preliminary simulation studies indicate that the installation of skirt piles can promote the reduction of the sediment porosity and hence densify the soil around the centered monopile foundation. These effects are more obvious for the sediment in a deeper location compared with the surface sediment, implying using skirt piles provides geotechnical benefits for the scour at the later or final stages rather than the initial period. A more sophisticated and systematic simulation will be performed in future studies to optimize the geotechnical benefits of skirt pile usage.

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