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An Investigation on the Utilization of Sand Cushions as Scour Protection for Offshore Wind Turbines

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ABSTRACT

The lifelong operation of offshore wind turbines requires thorough investigations into the safety and stability of their substructures, especially when working against natural hazards. Scour is widely accepted as one of the most significant factors causing foundation deficiencies. To protect offshore wind turbines from scour effectively and economically, sand cushions are widely used but not comprehensively investigated in wind farm projects in China. This paper presents research on the effect and stability of using sand cushions as scour protection for foundations of offshore wind turbines. Flume tests on scour around monopile foundations with and without protection have been carried out. To simulate the working environment of an offshore wind turbine, the combined current and wave was employed during the experiments. Together with field investigations, this study focused on the interaction among water, substructure, countermeasures, and sediments to investigate the mechanism and failure model of sand cushions further. It can be found that the sand cushion can be a good choice to protect underwater structures for a short time rather than a long term. The sand cushion may fail when a weak spot or crack appears. The long-term stability of the sand cushions should be considered. In addition, the sand cushion needs to be designed according to the scour mechanism to be more economical.

KEYWORDS: scour, countermeasures, sand cushion, offshore wind turbine

INTRODUCTION

Offshore wind is widely identified as a considerable indigenous and sustainable resource. According to the report by GWEC (2021), 2020 was a fruitful year for the global offshore wind industry, with new installations of up to 6.1 GW in total, to which China contributed 3.1 GW. And that was the third year in a row that China had led the world in new installations under financial and policy support from the government, especially the carbon peaking and carbon neutrality goals.

The monopile, whose diameter is usually 3 to 8 m, is the typical foundation of offshore wind turbines (Huang and Li, 2012; Qiu, 2000; Depina et al., 2015). During the construction and service life, horseshoe vortex and vortex shedding would occur around the foundations due to the current-structure interaction in the complex marine environment, which leads to local scour at monopiles. It is considered one of the most critical structural stability problems of offshore wind turbines. However, this would result in a deterioration of bearing performance and a change in natural vibration frequency, bringing serious risks to the turbines' safe operation (Zhang et al., 2017; Søren and Ibsen, 2013).

The protection and failure mechanism of various countermeasures have been studied by researchers, aiming to reduce the impact of scour efficiently and economically (Liang and Wang, 2014; Chiew, 1995; Wang et al., 2017; Tang et al., 2022). The countermeasures can be mainly divided into active and passive methods. Sacrificial piles and collars, for instance, are the active protection methods that reduce the scour via changing the current system and weakening the flow. As for passive methods, improving the resistance of the seabed material is the key, such as riprap and sand cushion. Sand cushions, a kind of geotextile filling bag, used to be utilized in seawall construction, and it has been gradually used in wind farm projects nowadays (Wang et al., 2020). It is considered beneficial for the seabed to be covered by cushions to obtain better resistance to the coming flow and erosive force so that the scour around monopiles could be reduced. However, the mechanism and failure model of sand cushions has not been fully studied yet. Therefore, this study aims at the failure mechanism of the utilization of sand cushions by using the flume tests. Recommendations have been provided for the design of this kind of method based on the results.

EXPERIMENTAL SETUPS

Flume tests are widely used to investigate scour-related issues, such as the mechanism of scour process, and the prediction of the scour depth. and the effect of scour protection. A significant number of useful results were obtained based on the flume tests. All the tests in this paper were carried out in the flume at Tongji University, as shown in Figure 1 (a) (Wang et al. 2017). The flume tank is 50 m long, 0.8 m wide, and 1.2 m deep, while the bottom of this flume is made of concrete, and the side walls are made of steel, with windows of 20-mm-thick transparent glass installed in two side walls to allow the flow and scour process to be observed (Wang et al. 2022). A sand basin is also provided by the flume as the testing section, which is 2.7 m long, 0.7 m wide,

and 1.0 m deep. To measure the three-dimensional flow velocity at a specific location, ADV was used in the test, placed as Fig 1 (b) shows.

(a)

(b)

Fig 1 Experimental Setups: (a) Flume tank; (b) Arrangement of ADV

To estimate the scour protection capacity of the sand cushion for the monopile, the scour protection experiment was carefully designed. Since the flume tests usually follow the gravity similarity law, which means to satisfy the Froude Number equality between the model and the prototype:

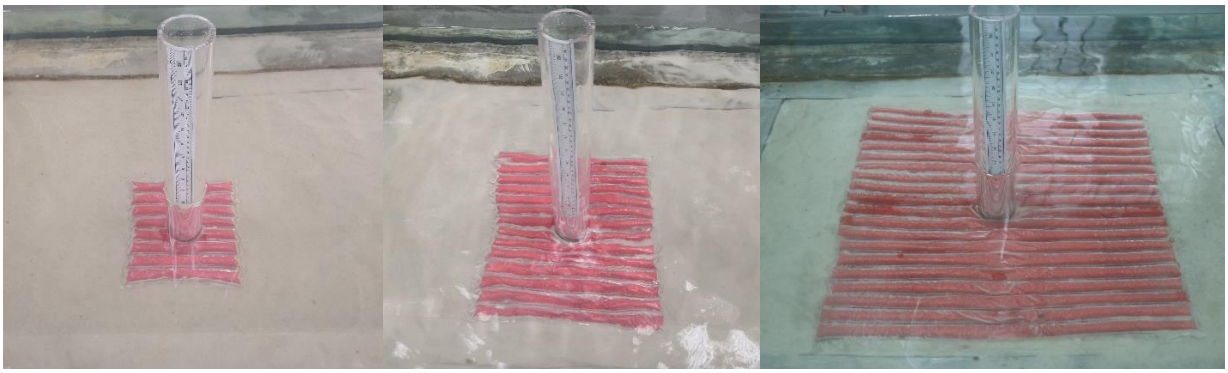
$$\frac{V_m}{\sqrt{gL_m}} = \frac{V_p}{\sqrt{gL_p}} \tag{1}$$

where g is the gravity acceleration; V and L are the velocity and size of the object, respectively; the subscripts m and p represent the model and prototype, respectively; $L_p/L_m=\lambda_L$ is the length scale.

Additionally, Ataie-Ashtiani and Behesti (2006) suggested that the model size should not be larger than 12% of the flow section to avoid the influence of the blockage effect. Whitehouse (1998) also recommended that the ratio of the width of the flume to the width of the model should be greater than 6. To meet the standard, the similarity, $\lambda_L=\lambda_H=100$, was selected in this study. As for the particle diameter in the test, the total sediment transport modeling similarity law proposed by Dou (1977) was used. Besides, to reduce the scale effect that the structural model size may have on the sediment, the ratio of the model diameter to the median sediment diameter should be greater than 50 (Melville and Chiew, 1999). Consequently, the median particle size, d_{50}, of the sand was selected as 0.15 mm. Based on the sediment incipient velocity formula (Dou, 1999), the preliminary test was conducted at first to ensure the best functioning conditions and test results during the operation of the flume. The flow velocity of 20 cm/s was selected as the test velocity condition after the pre-experiment, assuring that the process in the tank was clear water scour.

The prototype of the offshore wind turbines is of the diameter which is 6 m, and the water around piles is 9 ~ 20 m deep. According to the design work, 15 m was taken as the average water depth, and a square sand cushion of 30 m width was arranged around the pile. According to formula (1) and based on the geometric scale 100, the diameter of the model made by organic glass, the

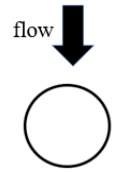
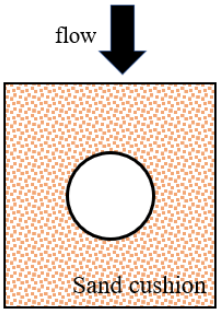
water depth, and the width of the sand cushion should be D = 6 cm, d_s = 15 cm, and L = 5D = 30 cm, respectively. And two extra groups (L = 10D = 60 cm and L = 3D = 18 cm) were added, aiming to discover the effect of the covered the sand cushion range on the scour protection. The arrangement of the pile and sand cushion in the flume test is shown in Fig. 2. More details of the experiment are shown in Table 1.



(a) width=18cm **(b) width=30cm** **(c) width=60cm**

Fig 2 The arrangement of the pile and sand cushion

Table 1 Detailed experiment plan

Protection	Arrangement	Water depth h (m)	Pile diameter D (cm)	Cushion width a (m)	Median diameter d_{50} (mm)
Without protection		0.15	6	/	0.15
Sand cushions		0.15	6	3D	0.15
		0.15	6	5D	0.15
		0.15	6	10D	0.15

RESULTS AND DISCUSSIONS

For the test of sand cushion (L = 30 cm and L = 60 cm), the upstream flow was affected by the water resistance from the monopile, and consequently, the downward stream, as well as the reverse vortex, was created. The stream and the vortex would influence the bottom of the cushion, which eliminated the scouring force of the downward stream effectively. And because the coverage area is of a certain scale, exceeding the scope of the horseshoe vortex current system around piles and

the wake flow vortex current system behind piles, sediments under the sand cushion didn't show an evident scour phenomenon. Especially influenced by the thickness of the cushion, the upper surface is slightly beyond the surface of the sediment, which makes part of the sediment particles get deposited on the water-side face and move from the frontier to two flanks of the cushion when the stream close to the sediment bed carrying the upstream particle passed by the upstream face of the cushion. The moving direction of the particles is shown in Fig. 3 (a). Other sediment particles kept moving along the flow, and some of the particles were deposited midway. However, because of the smoothness of the sand cushion surface, deposited particles on the surface will be carried away again by the continuous flow. On the other hand, since the sand cushion around the pile was of certain roughness and part of the sediment particles rushed out through the gap between the cushion and the pile, some particles will still get deposited around the pile on the adjacent part of the cushion when the scour reaches the equilibrium state (Fig. 3(b)).

(a) deposited in front of cushions **(b) deposited around monopile**

Fig 3 Results of sand cushions protection for large-scale monopile

As for the sand cushion, which is 18 cm wide, the mechanism of scour protection was the same as larger ones. Though the surface of the cushion around the pile could efficiently reduce the impact of the downstream flow, the covering area was smaller than the horse-shoe vortex-influenced area. Consequently, the sediment in front of the cushion was continuously scoured by the current vortex system, followed by the local hollow zone appearing at the middle of the cushion frontier. More sediment particles rushed out from the hollow zone because of the continuous scour. The zone gradually extended towards the flank sides and developed into the scour hole, as Fig. 4 shows. After this, the particles rushing out from the hole would gradually move toward the flanks and get deposited (Fig. 5(a)), and the deposited area slowly moved to the downstream direction (Fig. 5(b)). Theoretically, the cushion could deform with the sand bed collaboratively since it is of comparatively high softness. But the area of the cushion in this experiment group was not big enough for the stiffness to avoid not being influenced by the center area of the single pile, so the cushion of small size is hard to adapt to the deformation of the sand bed, which led to the final development of the scour hole.

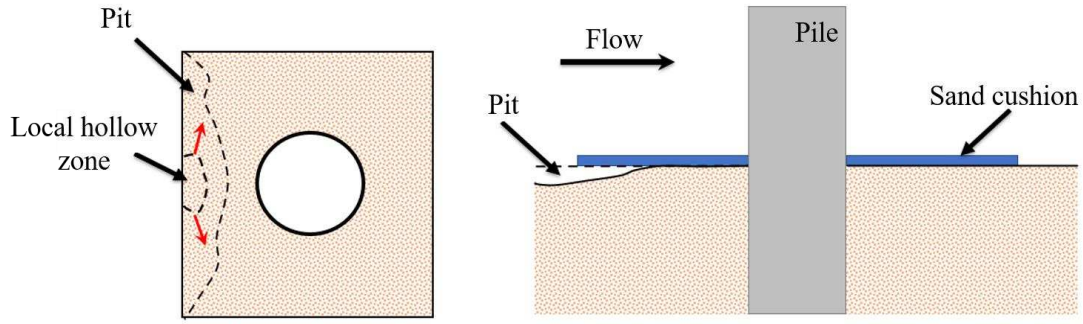
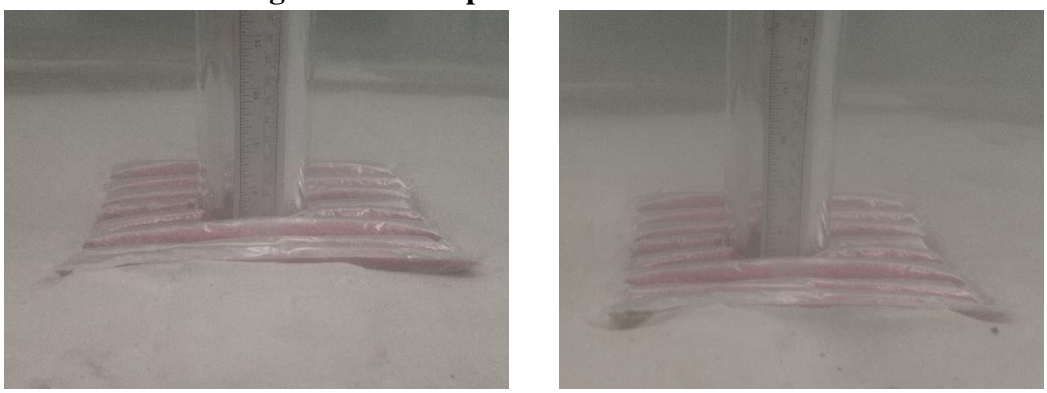


Fig.4 The development of the hollow zone



(a) deposited at two flanks of sand cushions **(b) deposited soils move backward**

Fig 5 Results of sand cushions protection for small-scale monopile

Technical Code for Application of Geosynthetics in Water Transport Engineering is widely used in China to determine the scale of the sand cushion. Considering the predicted scour depth and the shape of the hole, the calculative formula of lateral length (protected structure not included) of the sand cushion can be given as:

$$L \geq k_p \Delta h_p \sqrt{1+m^2} \tag{2}$$

where k_p is the coefficient of the wrinkle, normally as 1.1~1.3; Δh_p is the predicted scour depth; m is the coefficient of the stability of the riverbed slope, $m = cot\alpha$, α is the angle of the foot of the slope after the scour.

According to formula (2), the lateral length should be approximately 22.8 cm. The 30 cm and 60 cm groups met the standards. However, 18 cm was slightly smaller than the recommended length. Table 2 gives the final scour depth under the three different cushion scales. When the length was 30 cm, rushing soil around the pile made a dominant contribution to the equilibrium scour depth of 0.3 cm, about 6.67% of the depth without protection. With the length increasing from 30 cm to 60 cm, the final scour depth only decreased by 0.1 cm, which indicates that when the scale meets the code standard, the protection improvement by increasing the size is quite limited. When the length was 18 cm, the maximum scour depth was two times that of the 30 cm group. Considering the experiment phenomenon mentioned before, it is obvious that even if the size is smaller than the standard, the cushion can still protect well. Still, the development and the final

shape of the scour hole differ from the 30 cm and 60 cm. And the terrain elevation would be influenced by the scour hole beneath the cushion, forming into the unidirectional slope before the pile. The maximum scour depth was located right before the monopile, which made the anti-sliding calculation of the cushion at the slope in front of the pile a need.

Table 2 Maximum scour depth after protection

Width of sand cushion (cm)	Pile diameter (cm)	Width /Diameter	Maximum scour depth (cm)	
			Without sand cushion	With sand cushion
18	6	3		0.6
30	6	5	4.5	0.3
60	6	10		0.2

***Please note that Width/Diameter here means the ratio of sand cushion width to the pile diameter.**

FIELD INVESTIGATIONS

The sand cushion has been utilized in some practical projects since it has better performance potential during construction and maintenance. In a 150MW wind farm project, the whole sea bed migration and local erosion are obvious in the sea area where the site is located. Monopiles with a 6 m diameter are used as the foundation. The maximum scour depth is about 4 m, and the scour range is 10 m around the pile approximately. To obtain scour protection, the sand cushion was utilized to offer to scour protection. Right after the completion of pile driving, two sand cushions whose size is 18 × 16 m were thrown around the pile to protect it, covering an area of about 540m². It can be referred that the laying range is about four times the diameter. Besides, relevant construction techniques were developed, and the final sand cushion laying deviation was controlled within 0.5 m. In 2015, the sand cushion was successfully implemented for all turbine and booster station foundations. After later inspection, the scour protection effect is proved to be good.

Fig 6 Large-scale sand cushions were transported and hoisted.

As for another offshore wind farm not far from the previous one, the seabed elevation at the site is -23.5m ~ -3.1m, and the terrain in some areas is significantly undulating. The depth and the velocity of the water are 3 ~ 25 m and 0.4 ~ 0.7 m/s, respectively. In this wind farm, the diameter of the monopile used is also 6 m, and before the protection, the majority of wind turbines there were of a scour depth greater than 5 m. After the arrangement of the sand cushion, whose range is about 14 m and a certain amount of the service life, according to the monitoring statistics, 76% of the sand cushions approximately have been playing a protective role, which can be indicated that the sand cushion protection has certain benefits.

CONCLUSION

Based on a series of flume tests, the scour protection mechanism of sand cushions of different sizes was studied. The surface of the sand cushion around the pile can effectively alleviate the impact of the downflow. For the layout range of 5 d and 10 d (d represents the diameter of the pile), due to the large coverage area exceeding the action range of the horseshoe vortex current system around the pile and the wake eddy current system behind the pile, there was no obvious scour phenomenon in the soil beneath the sand cushion. However, as for the comparatively smaller layout range (3d), since it is less than the action range of the eddy current system and the flexibility is relatively small and cannot get deformed together with the sand bed surface. The scour hole would appear in the front of the cushion, and the particles would be deposited on the two sides.

Apart from sand cushions, rock protection, also known as riprap, is widely used. These two countermeasures both have the issue of edge scour. Because sand cushions are huge geotextile filling bags with sand inside, usually the sand can only have limited movement and would not leak out as long as it has been well packaged. Compared to riprap, sand cushions are tended to be of better unity. However, the installation requirements of sand cushions are more strict in practice, especially in the marine environment. In addition, according to the flume test results, it might be possible to allow sand cushions to play a protective role and the edge scour of cushions not to have an influential impact on the foundations by moderately expanding the range.

Overall, the sand cushion performed well in scour protection, and the bigger the size, the better the performance. However, when the size of the sand cushion reaches the recommended design size in the code, continuing to increase the size of the sand cushion has little effect on the improvement of the effect of scour protection. There are also examples of using the sand cushion for scour protection in the wind farm project, and the layout range mainly adopts 2d ~ 4d. After serving for a certain period, based on the monitoring statistics, it is proved that the sand cushion has a certain protective effect.

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