STUDY ON MULTI-USE OF AN INTEGRATED OFFSHORE WIND TURBINE FOUNDATION AND COASTAL CAGE NET

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The objective of this study is to investigate the suitable method for the integration of coastal cage net and the offshore wind farm as scour protection. Physical model tests with the scale of 1:36 are carried out in the Near-shore Wave Basin (NSWB) at Tainan Hydraulics Laboratory (THL) with the jacket type foundation and the combination of coastal cage net in the test area. The location in water depth 16m of the foundation is simulated in this study. From the fixed-bed experimental results, it shows that the up-current optimum location of coastal cage net in front of jacket type foundation can have a good effect to reduce current speed under the condition of distance between cage net and foundation being 2 times foundation width (W). However, the up-wave location of coastal cage net in front of jacket foundation, the wave attenuation effect near wind turbine foundation is not so obvious. From the fixed-bed experimental results, the optimum cage net depth is up to 0.75 water depth (3/4h, 12m cage net depth in-situ) for reducing current speed. After the fixed-bed experimental tests, the mobile experimental study on soft scour protection for the jacket type foundation of offshore wind turbine is further conducted.

Keywords: scour protection; cage net; physical model; jacket type foundation

INTRODUCTION

The growing concern in the 1990s over CO^2-forced global warming has given new life to the prospects for greater use of wind turbines because of their credentials as non-polluting generators powered by winds created by solar energy, a renewable resource. Over the past two decades, on-shore wind energy technology has forecasted a ten-fold reduction in cost and currently has become competitive with fossil and nuclear fuels for electric power generation worldwide. As a direct consequence of the Kyoto Protocol there is a new impetus in developing the capacity of offshore wind farms to provide a significant percentage of the target renewable energy quota. Offshore wind energy began in shallow waters of the North Sea where the abundance of sites and higher wind resources were more favorable by comparison with Europe's land-based alternatives. All today's offshore wind farms producing energy are located in shallow waters; they are either founded on monopoles or on gravity based caissons. However, transitional substructure of the offshore wind turbines will be replaced by fixed bottom systems that use a wider base with multiple anchor points like those frequently used in oil and gas industry. Taiwan has plenty of offshore wind power resources in the western Taiwan coastal water area but hasn't yet been developed, not like land wind, where mostly has been set up and arranged. The government arranged the renewable energy proportion to reach the goal than expectation, 15.1% in 2025, including 5.3% of offshore wind power. It reveals the offshore wind power is the most important and urgent of all renewable energy, it increases the most and largest than expectation. However, this amount of electricity from offshore wind energy requires a sizable coastal water area, which is currently shared by various users, including fishermen, shipping lines, recreation and tourism, among others. Thus public acceptance of offshore wind farms is very important for the success of the offshore wind energy development in the western Taiwan coastal water area, and it is necessary for the area to explore the concerns of these different users.

In Taiwan, a range of seabed locations from Chang-Hwa to Yun-Lin, and middle western coast have been licensed for development of offshore wind farms. One of the key factors in setting a building offshore wind farms is the influence of the seabed geology and sedimentary environment on the foundation design and stability over the lifetime of the structure. Regarding foundations for offshore wind turbine, it is well known that in most cases, scouring phenomena occur around the foundations, owing to the presence of the complex supporting structure and inducing changes in the natural flow regime at the sea bed around the supporting structure, leading to increased sediment mobility. Therefore, the objective of this study is to improve understanding of scour behavior and to design the scour protection systems for offshore jacket type foundations located on sandy seabed. In order to describe

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physical processes and influencing factors on scour progressing from a scientific point of view, comprehensive investigations on the scouring phenomena for jacket type foundations have been carried out in this study. A physical model test study has been performed on the occurrence and prevention of erosion holes (scour) around jacket type foundations of offshore wind turbine on sandy soils. The scour around the jacket type offshore wind turbine foundation exposed to wave and current is conducted in the Near-Shore Wave Basin (NSWB, 150m×60m×1.5m) of Tainan Hydraulics Laboratory (THL) with the 1:36 scale fixed-bed and movable-bed experiment. The maximum scour depth and the potential impact scour area around the jacket type offshore wind turbine foundation is analyzed from the result of the mobile bed experiment. Meanwhile this study also evaluates the feasibility of an integrated offshore wind turbine foundation with cage net aquaculture facility in the effect as a soft scour protection.

Besides various stakeholders are involved in the marine environment and be interested in, and have different opinions about offshore wind energy. Fishermen are an important stakeholder group, since the livelihoods of commercial fishermen could be significantly affected by the installation of offshore wind turbines. Thus this study takes the consideration of the concept of the usage of integrative coastal space to combine offshore wind turbine and coastal cage net, to analyze different distance and optimum cage net depth and furthermore to discuss these factors of coastal cage net which could slow down the erosion around wind turbine foundation or not. Meanwhile, it could be deeply understood that the local stakeholders' opinion about combining offshore wind energy with coastal cage net aquaculture.

HYDRODYDYNAMIC AND MORPHOLOGIC BACKGROUND

Offshore wind turbines are currently perceived as one of the most environmentally friendly sources of electrical power and a non-polluting renewable resource that causes minimal human, ecological and environmental impacts. Offshore wind farms are now being proposed for, or built in, increasingly hostile hydrodynamic environments. Many prospective or potential sites for offshore wind turbine parks are located on seabed of mobile sediments in mid-western coast area of Taiwan (Chang-Hwa and Yun-Lin water area). Thirty sets of 3.6MW (or 5MW) jacket type offshore wind turbines will be established under the plan of Taiwan Power Company (TPC) before 2015. The range of water depth for this offshore wind turbine park is located from 10m to 20m with mild slope bottom(s=1/150~1/600). The sediment in-situ is fine sand of a median diameter of d_{50}=0.2mm, specific gravity γ_s=2.65. The wind turbine foundation of the 16m water depth (shown in Fig. 1) is simulated respectively in this study. Although the life cycle of the wind park is 20 years, however, due to the consideration of extreme wave loading, the model has to be performed in 1:100 year return period typhoon wave for short-term impact and critical monsoon wave for long-term loading. The maximum local current of this area is 1.0 m/s which is a depth averaged current for both tidal and wind driven current. The angle between the incident wave and current is around 90°. Due to high tidal range of the studied area, different water level is also considered for every test.

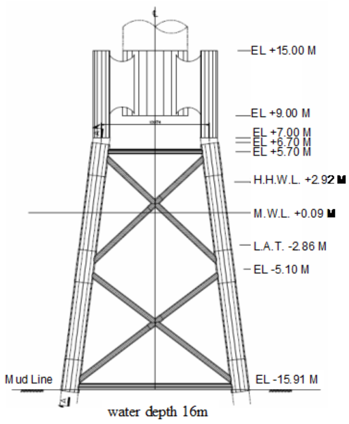


Figure 1. Sketch for the 16m water depth of the jacket type wind turbine foundation. (EL, Elevation; LAT, lowest astronomical tide; MWL, mean water level; HHWL, higher high water level)

Two series of physical model tests with a 1:36 scale fixed-bed and movable-bed experiments in this study. The aim of the first test series is to investigate the optimum location and depth of coastal cage net to reduce the hydrodynamic condition (wave or current) around the jacket type wind turbine foundation by the fixed-bed experiments. The other series of the tests is to aimed at the differences for the greatest magnitude of local scour and potential scour area in the sand bed around the jacket type foundation without/with the optimum location and depth of coastal cage net by movable-bed experiments. The layout of the 27 m × 19 m wave-current basin for the fixed-bed experimental setup is shown in Fig. 2. The wave flume passes from right to left, and the current-generation flume circulates from the downside to the upside. The test area with the models of the jacket-type foundation and coastal cage nets within the water depth of 16 m in the field site is at the junction of these two flumes. The physical modeling is carried out in this wave-current basin at the THL with a scale of 1:36. Froude's law is obeyed in the fixed-bed experiment, the mobile bed experiments are tested based on the Shields Number. Thus based on Shields Number simulation, the sediment used in this experiment is light density coal (specific gravity of coal, γ_c = 2.02) of a median grain size of d_{50} = 0.15 mm, and the model sand bed is 0.35 m deep, 7.0 m long and 5.4 m wide. The equipment and measurement systems used in this experiment include an irregular wave maker, a current generation system, electrical capacitance wave gauges, acoustic doppler velocimeters (ADV) and an ultrasonic bottom profiler moved by the carriage table (7 m × 6.0 m). Before and after the wave-current action for several runs in each test, the bottoms of model sand bed are scanned line by line along the carriage table. Then the topography evolution sea bottom and the scour around jacket type foundation can be analyzed from the measurement data of ultrasonic bottom profiler.

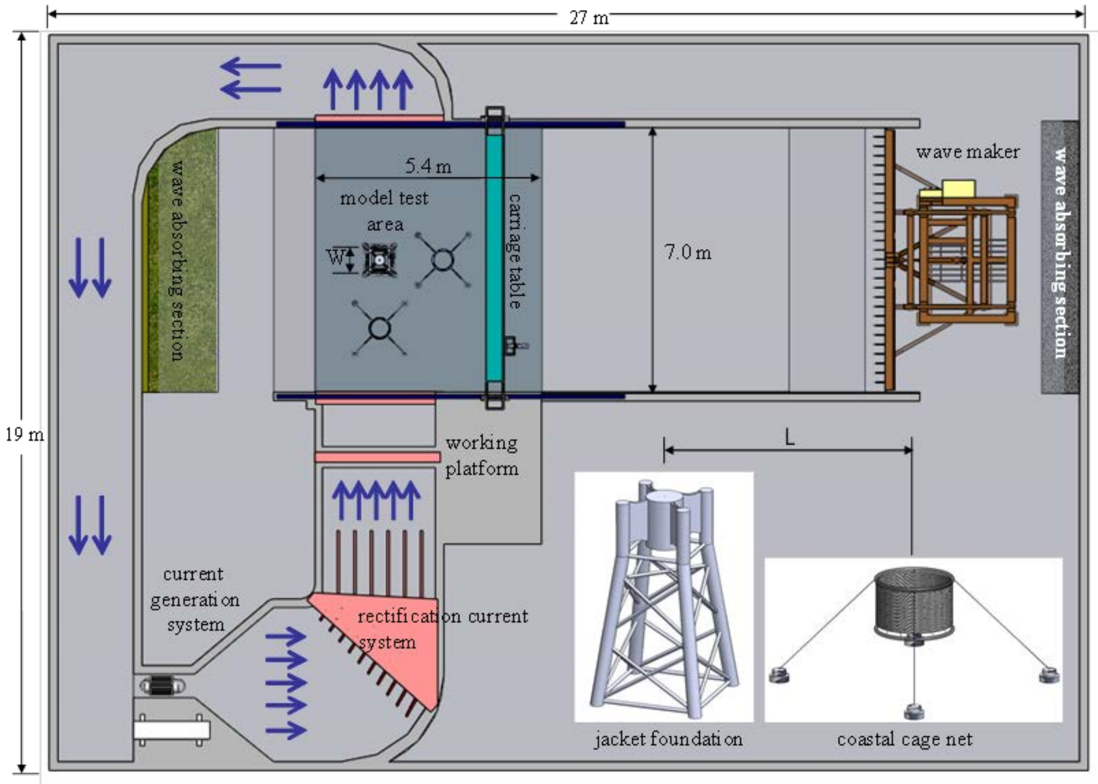


Figure 2. A sketch of the experimental setup for the jacket type foundation and coastal cage net.

FIXED-BED EXPERIMENTS FOR WAVE AND CURRENT HYDRODYNAMIC TEST

When the occurrence or uncertainties of a local scour hole around the foundation of wind turbine are not desired, preventive or remedial countermeasure can be applied. Almost all of today's knowledge about scour behavior and the strategy of scour protection are based on physical experiment carried out in flumes in co-directional waves and current, with two-dimensional waves. Typically, the traditional hard scour protection will be realized by using layers of natural and crushed rock which are increasing in size when going up from the seabed. The lowest layer of rock, which is small enough to restrain the soil, can be replaced by a geo-textile.

Thus, this study also considers the concept of the usage of integrative coastal space to combine offshore wind turbines and coastal cage nets, to analyze different distances and optimum cage net depths and, furthermore, to discuss these factors of coastal cage nets, which could slow down the erosion around wind turbine foundation. The cage net diameter is 18 m, which is the same as the outer width (W) of the jacket-type foundation. The tested cage net depths are 4 m, 8 m and 12 m, which are

1/4, 2/4 and 3/4 of the water depth (h) of 16 m in the field site. All the test conditions of the fixed-bed experiment in this study are shown in Table 1.

Table 1. Test conditions of the fixed-bed experiment.

<table>
<tr><th>current (m/s)</th><th>wave height H (m)</th><th>wave period T (sec)</th><th>water depth h (m)</th><th>location of cage net (W)</th><th>depth of cage net</th></tr>
<tr><td>0.083</td><td>0</td><td>0</td><td rowspan="16">0.444</td><td rowspan="3">---</td><td rowspan="3">---</td></tr>
<tr><td>0.167</td><td>0</td><td>0</td></tr>
<tr><td>0.250</td><td>0</td><td>0</td></tr>
<tr><td>0.083</td><td>0</td><td>0</td><td rowspan="3">up-current side 2、4、6、8</td><td rowspan="3">1/4h、2/4h、3/4h</td></tr>
<tr><td>0.167</td><td>0</td><td>0</td></tr>
<tr><td>0.250</td><td>0</td><td>0</td></tr>
<tr><td>0</td><td>0.1</td><td>1.2</td><td rowspan="5">---</td><td rowspan="5">---</td></tr>
<tr><td>0</td><td>0.1</td><td>1.4</td></tr>
<tr><td>0</td><td>0.1</td><td>1.6</td></tr>
<tr><td>0</td><td>0.1</td><td>1.8</td></tr>
<tr><td>0</td><td>0.1</td><td>2.0</td></tr>
<tr><td>0</td><td>0.1</td><td>1.2</td><td rowspan="5">up-wave side 2、4、6、8</td><td rowspan="5">1/4h、2/4h、3/4h</td></tr>
<tr><td>0</td><td>0.1</td><td>1.4</td></tr>
<tr><td>0</td><td>0.1</td><td>1.6</td></tr>
<tr><td>0</td><td>0.1</td><td>1.8</td></tr>
<tr><td>0</td><td>0.1</td><td>2.0</td></tr>
</table>

From the fixed-bed experimental results, it is shown that the up-current optimum location of coastal cage nets in front of the jacket-type foundation can have a good effect at reducing the current speed under the conditions that the distance between the cage net and foundation is two-times the foundation width (W), see Fig. 3. The optimum cage net water depth is up to 3/4h for reducing the current speed. When farther away from the foundation or high current velocity (0.25 m/s), the current reducing effect is not obvious. However, with the up-wave location of the coastal cage net in front of the jacket type foundation, the wave attenuation effect near the wind turbine foundation is not so obvious. From the fixed-bed experimental results, the optimum cage net water depth is up to 0.75 (3/4 h, 12-m cage net depth in-situ) for reducing the current speed.

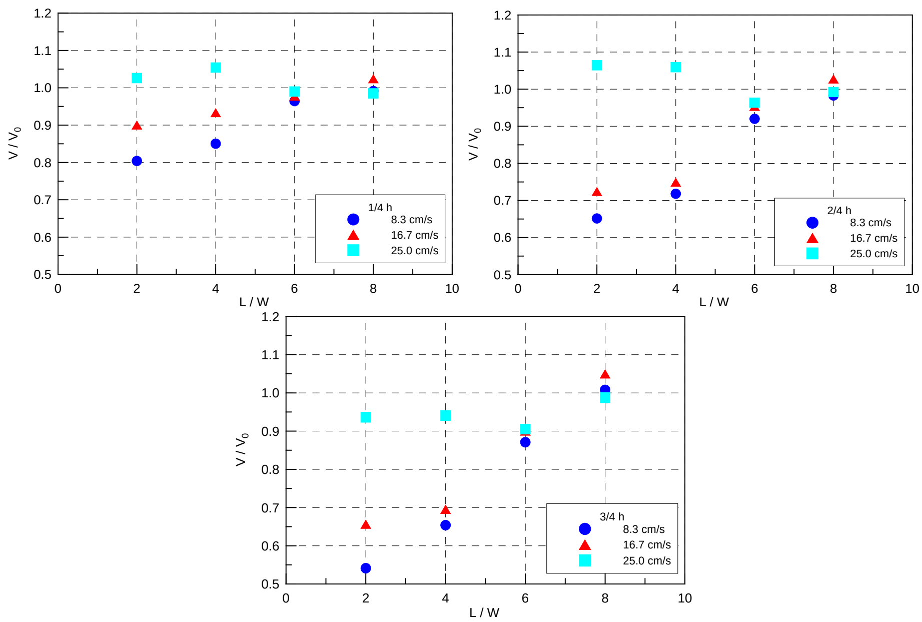


Figure 3. The cage net effect of different current speed under the cage net depth and location for reducing the current speed.

MOVABLE-BED EXPERIMENTS FOR WAVE AND CURRENT TEST

Scouring is herein considered to be the lowering of the bed in the vicinity of a marine structure due to local accelerations and decelerations of the near-bed velocities and the associated turbulence (vortices), leading to an increase of the local capacity for sediment transportation. Generally, the near-bed flow around the vertical pile consists of a horseshoe vortex generated at the up-current side of the pile and vortices generated at the lee-side of the pile. Currently, with 181 out of 295 foundations of offshore wind turbines, the monopole is the preferred foundation option. Among these foundations, 169 are driven in sandy soils, which can be more or less susceptible to scouring. As a rule of thumb, confirmed by experience with other structures, the scour hole can reach a depth of 1.5 times the pile diameter (D). Based on experimental data, Sumer et al. found a circular pile to have a maximum scour depth ($d_{s,max}$) up to 1.3 times the pile diameter (D). De Bruyn studied the scour process near a vertical pipe in current and wave conditions. The bed material was natural sand with d_{50} = 0.2 mm. The water depth in the experiment was 0.3 m. The depth-averaged velocity up-current of the pipe was 0.4 m/s (mobile bed, $U/U_{cr} > 1$). The maximum scour depth ($d_{s,max}$) around the pipe was found to be 1.9D for a current and breaking waves.

However, the jacket type foundation basic design is a non-general, single shape. Therefore, the problem of the scouring of the nearby jacket-type foundation caused by external forces under the waves and current will be a more complex phenomenon than for single vertical piles. Meanwhile, when we consider the local scouring around offshore structures under the interaction of waves and current, a numerical model is still difficult to simulate. Only with on-site monitoring and hydraulic model tests could the scour ranges and the maximum scour depth around the jacket type foundation be explored.

After the fixed-bed experimental tests, the movable-bed experimental study on the soft scour protection for the jacket type foundation for offshore wind turbines is further conducted. The equipment and measurement system used in this mobile bed experiment include the same system used in the fixed-bed experiment together with the ultrasonic bottom profiler moved by the carriage table. The ultrasonic bottom profiler system used in this experiment is the 5-MHz Ultrasonic Ranging System from SeaTek Company; its ultrasonic probe can continuously measure the dynamic changes in the bottom profiler. There are 12 transducers included in this system, and all of the transducers are housed in stainless steel housings. The transducers operate at 5 MHz, have a half beam angle of 0.9 degrees and a transducer diameter of 1 cm. The closest range measurement of this system is 3 cm; the furthest range is 110 cm; the measurement accuracy is 1 mm. When measuring the bottom profiler, the jacket type foundation model could be taken up, and then, the changes in the surrounding and the inside seabed of the jacket type foundation model could be thoroughly measured. Before and after the wave-current action for several runs in each test, the bottoms of the model sand beds are scanned line-by-line along the carriage table. Then, the evolution of the topography of the sea bottom and the scouring around the jacket-type foundation can be analyzed from the measurement data of the ultrasonic bottom profiler. In general, a coastal topography test model and the sedimentation between the model and the field must meet the mobility number (or Shields parameter) similarity. In order for the currently used model bottom material (coal) to completely satisfy the mobility number (or Shields parameter) similarity, the scale of the waves and current should be adjusted to be much larger than 1/36 for incipient sediment transportation. However, due to our experimental conditions, the bottom current (U) still satisfies $U > U_{cr}$, in which U_{cr} is the critical bottom incipient velocity. Therefore, each test in our experiments is continually conducted at equilibrium scouring (i.e., the maximum scouring depth does not change again). All the test conditions of the movable-bed experiment in this study are shown in Table 2.

Table 2. Test conditions of the movable-bed experiment.

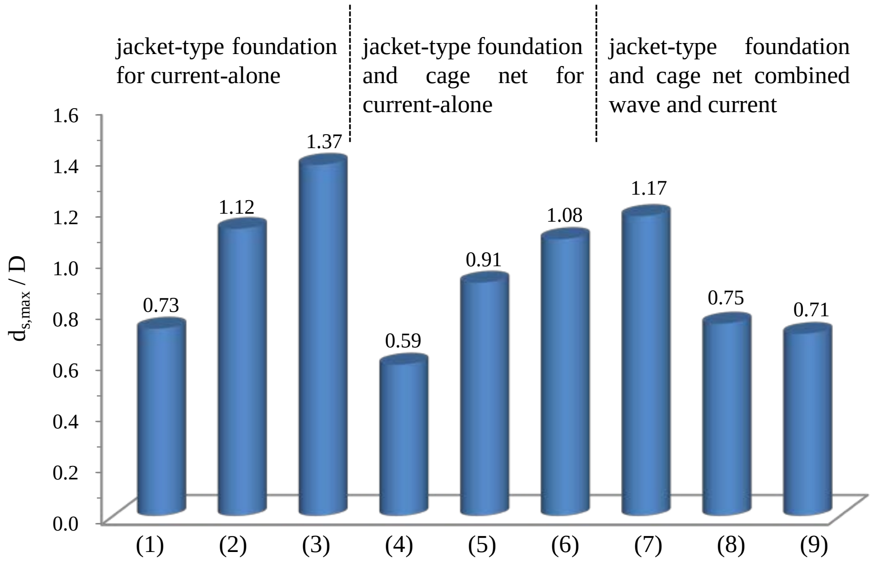
current (m/s)	wave height H (m)	wave period T (sec)	water depth h (m)	location of cage net	depth of cage net
0.083	0	0	0.444	---	---
0.167	0	0			
0.250	0	0			
0.083	0	0		up-current side 2W	3/4h
0.167	0	0			
0.250	0	0			
0.167	0.214	1.95	0.401	---	---
0.167	0.214	1.95		up-current side 2W	3/4h
0.167	0.214	1.95		up-current and up-wave side 2W	3/4h

From Table 3 and Fig. 4, the evolution of the maximum scour depth with the different test conditions for the jacket type foundation is shown. For the current-alone case (a current of 0.25 m/s), the scour hole can reach a maximum depth ($d_{s,max}$) of 1.37 times the pile diameter (D) of the jacket type foundation without the coastal cage net. However, if we locate the coastal cage net in front of the wind turbine on the up-current side optimum position (2W), the maximum scour depth can be reduced to 1.08 D, and the redeposition phenomenon occurred inside the jacket-type foundation; see Fig. 5. Regarding the combined typhoon wave and current loading tests, the maximum scour depth can be from 1.17 D (without the cage net) to 0.75 D (one cage net at the up-current side) or 0.71 D (one cage net at the up-current side, another one at the up-wave side), see Fig. 6. Therefore, the cage net can reduce the current rate and scouring around the jacket type foundation.

Table 3. The maximum scour depth around the four piles of the jacket-type foundation and the coastal cage net (a water depth of 16 m) under different hydrodynamic conditions. (D = 2.08 m)

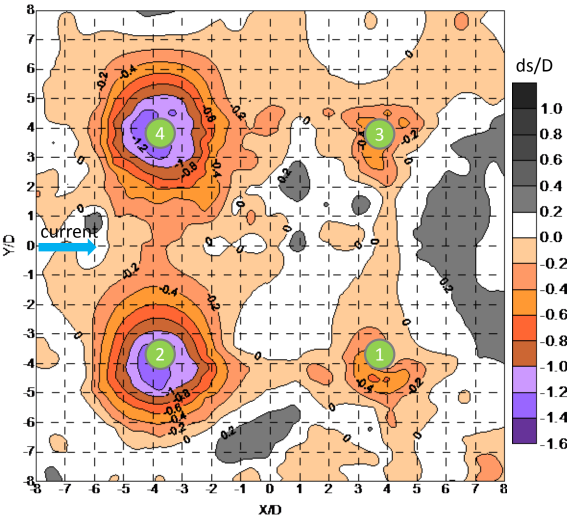
test case	d_{s1}/D	d_{s2}/D	d_{s3}/D	d_{s4}/D	test case	d_{s1}/D	d_{s2}/D	d_{s3}/D	d_{s4}/D
current of 0.083 m/s	0.35	0.66	0.40	0.73	0.083 m/s cage net	0.26	0.59	0.31	0.53
current of 0.167 m/s	0.61	1.12	0.76	1.11	0.167 m/s cage net	0.52	0.91	0.53	0.87
current of 0.25 m/s	0.70	1.24	0.62	1.37	0.25 m/s cage net	0.46	1.08	0.46	0.87
wave and current	0.81	1.14	0.79	1.17	wave and current 1 cage net *	0.75	0.65	0.71	0.64
					wave and current 2 cage net **	0.70	0.48	0.45	0.71

*cage net located at the up-current side; ** cage nets located at the up-current side and the up-wave side.

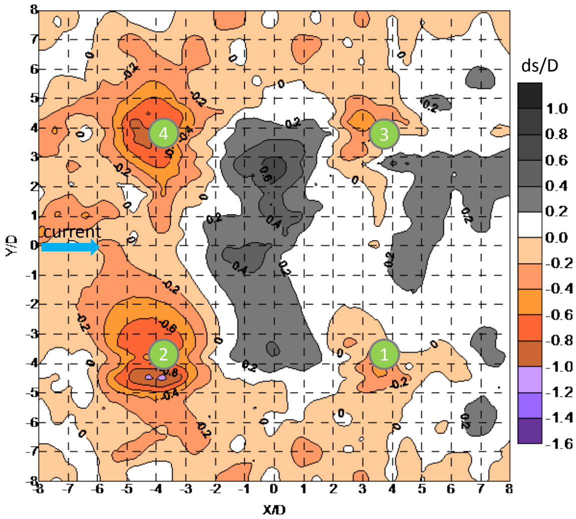


Note: (1) current of 0.083 m/s; (2) current of 0.167 m/s; (3) current of 0.25 m/s; (4) current of 0.083 m/s + cage net; (5) current of 0.167 m/s + cage net; (6) current of 0.25 m/s + cage net; (7) typhoon wave + current of 0.167 m/s; (8) typhoon wave + current of 0.167 m/s + cage net (up-current side); (9) typhoon wave + current of 0.167 m/s + 2 cage net (up-current side and up-wave side).

Figure 4. The maximum scour depths under the different test conditions for the jacket type foundation and coastal cage net.

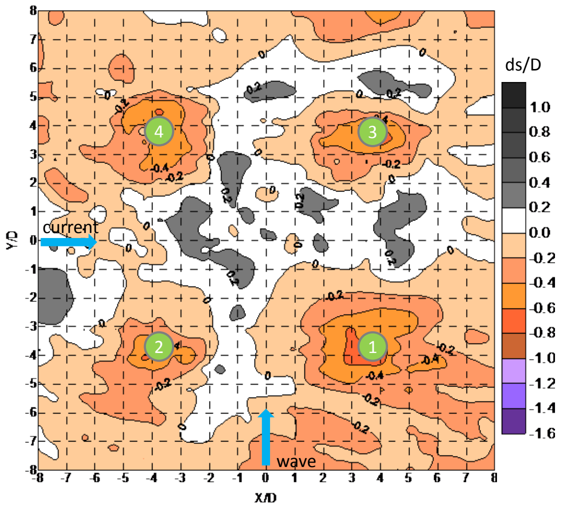


current of 0.25 m/s

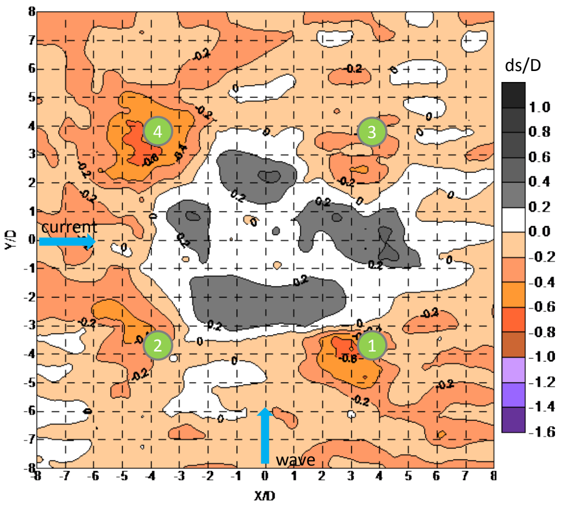


current of 0.25 m/s with cage net

Figure 5. The potential impact erosion area and scouring around four piles of the jacket type foundation and cage net under the current-alone case (a current of 0.25 m/s).



cage net located at the up-current side



cage nets located at the up-current side and the up-wave side

Figure 6. The potential impact erosion area and scouring around four piles of the jacket type foundation and cage net under the wave and current case (wave height of 0.214 m; wave period of 1.95 sec; current of 0.167 m/s).

STAKEHOLDERS ANALYSIS

In public management and arrangement, the stakeholders are defined as: "anyone, any group or organization which could be effected by the results from the noticed things or resources". According to the standpoint of each stakeholder as well as the importance in a project, used two indexes to divide stakeholders into four categories, including Advocates, Antagonistic, Low Priority, and Problematic, and then established corresponding strategies respectively according to the analysis matrixes of stakeholders. In natural resource management, collaboration management is usually applied to the analyses of stakeholders. Collaboration management is a continually process of coordination, learning, and modification. The 1st stage of the entire process is mainly to organize for the partnership. Through collaboration management, primary stakeholders can play an actually influential role, even enter the management level or participate in decision making, establish a continuous learning-by-doing partnership, fulfill management rules which can be accepted by both parties and which are of legal force of constraint, and continuously advance the capability and responsibility of the stakeholders. In terms of ocean or costal management, the participation of stakeholders should have its original value instead of a measure for smooth management execution or the reinforcement of project persuasion. Besides the above experimental studies, this study also has analysis for stakeholders' opinions on offshore wind energy and coastal aquaculture (Fig. 7) to understand the real demand for adjusting the dilemma of information asymmetry from government and community.

Besides the above experimental studies, this study also has made a preliminary analysis for stakeholders' opinions on offshore wind energy and coastal aquaculture to understand the real demand for adjusting the dilemma of the marine space utilization in the western Taiwan coast. The stakeholders' opinions are collected from four groups, including government, offshore wind farm developers, environmental groups and residents. From this preliminary feasible analysis for stakeholders' opinions, the results show that the four groups can accept the concept of an integration of offshore wind farms and cage net aquaculture for the western Taiwan coastal water utilization. However, a detailed layout for the integration of offshore wind farms and coastal aquaculture should be investigated in the near future.

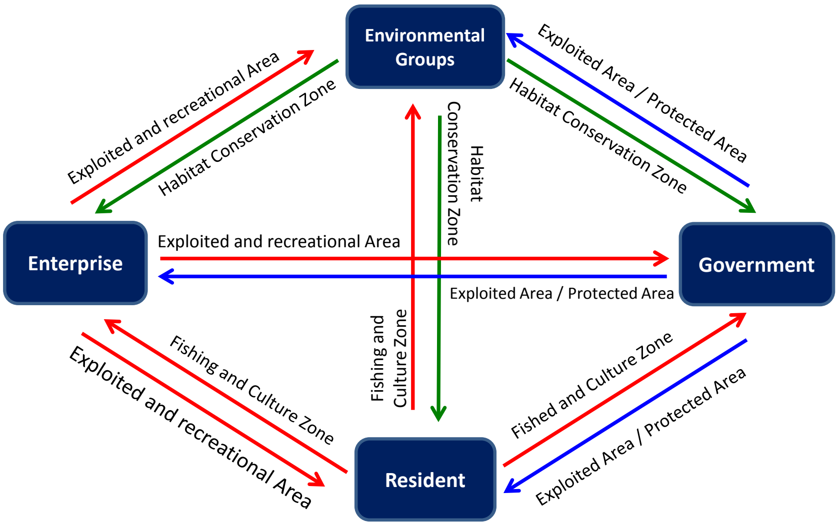


Figure 7. Stakeholders' opinions on offshore wind energy and coastal aquaculture.

CONCLUSION

This paper presents the results of a study regarding the scour around the jacket type offshore wind turbine foundation which is considered to be used in the mid-western coastal wind farm development in TAIWAN. The scour and scour mitigation investigation is carried out in a wave-current basin to provide a deep understanding of flow-structure interaction. The ratio of maximum scour depth to leg diameter (D) of jacket type foundation and the potential impact scour area can be obtained from the results of physical model test. Meanwhile, a traditional hard scour protection is tested and found to be effective in preventing scour around jacket type foundation of offshore wind turbine. Although it is a common practice to apply scour protection at sites with a potential local scour, the analysis of this study indicates that the function of protection is likely to provide a technically acceptable solution. Furthermore, the study of designed solutions with and without scour protection will be investigated by the comparison with respect to technical feasibility, risks and costs in the near future.

Meanwhile, through this study on the integration of jacket type offshore wind turbine foundation and coastal cage aquaculture as a soft scour protection countermeasure, it is helpful to the substantial development of coast water area, and it could be the important reference for future coastal integration development to provide related organizations for the implement of the coastal-line multiple usage of integrating offshore wind energy and coast aquaculture facility. Furthermore, when building the related stakeholders' evaluation system, we will know the important community information to achieve the balance between the coastal development and the livelihood of residents.

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