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Experimental study on the wave-trapping phenomenon over three-dimensional topographic structures

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1 Introduction

Topographic variation is considered one of the key mechanisms for the generation of extreme waves, a phenomenon that has attracted considerable research attention in recent years [1, 2, 3, 4]. Topography concentrates wave energy through geometric constraints, while also amplifying it by resonance when its dimensions match the characteristic wave scales [5, 6, 7]. However, existing research has predominantly focused on two-dimensional (2D) topography, leaving the role of three-dimensional (3D) topographic features in the generation of extreme waves underexplored. To investigate the influence of three-dimensional topographic effects, a series of experiments were conducted to simulate the evolution of waves with varying periods and wave steepnesses over a three-dimensional seabed. Cylinder and frustum models were used to simulate three-dimensional topographies, characterized by abrupt depth variations and slopes, respectively.

2 Experimental Setup

The experimental setup of the submerged three-dimensional topography is shown in Fig. 1, comprising a cylinder and a frustum. The cylindrical model, with a diameter of $D = 4$ m and a height of $H = 0.46$ m, was used to investigate the condition of abrupt depth changes. Besides, a frustum model of height $H = 0.46$ m, top diameter $D_1 = 4$ m (same as the cylinder), and bottom diameter $D_2 = 6.3$ m (giving a $1 : 2.5$ slope) was used to simulate the 3D topography with slopes. The measured data was captured using the capacitive-type gauges deployed around the cylinder model. This experiment investigates how dispersive waves interact with sudden changes in three-dimensional bathymetry over a series of parametric analysis, and then trigger the wave-trapping phenomenon to form extreme waves.

3 Results

Figure 2 illustrates the spatial distribution characteristics of the exaggeration factors along the axis of symmetry of the wave basin for a cylinder model under different cases. The exaggeration factor, which compares the measured wave height over the topography with the incident wave height without the topography, serves as a direct indicator of wave energy enhancement. It is evident that the maximum exaggeration factors appear at the trailing edge of the cylinder, validating the wave-amplification effect of the 3D circular sill. Case 2 shows the highest peak value, and the wave period in this case is obtained based on the resonant solution by the long wave theory [5]. The minimal downstream amplification in Case 2 indicates wave trapping within the trailing edge, supporting the numerical results of Renzi [6]. To further investigate the

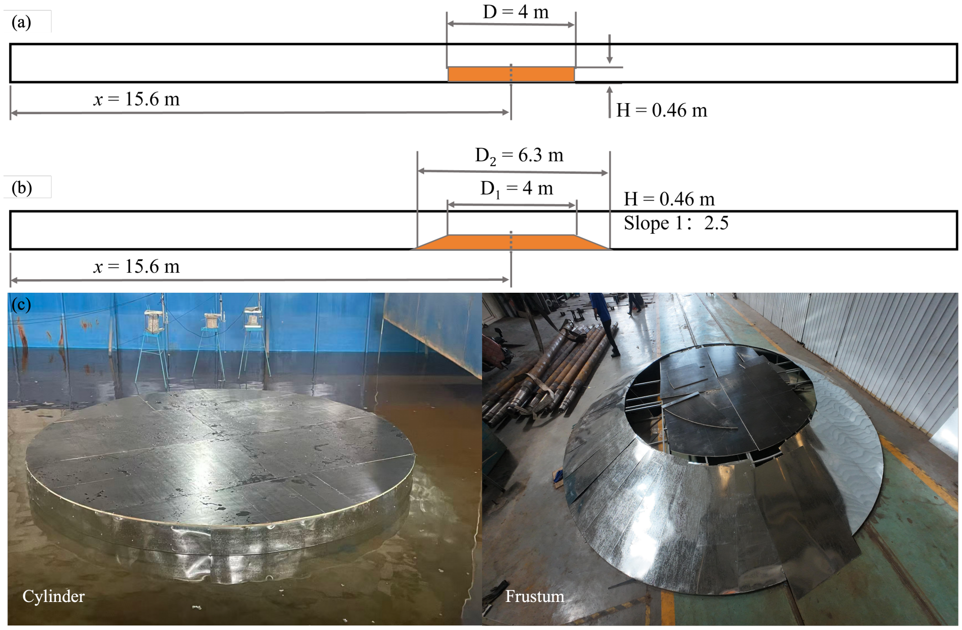

Figure 1: Schematic diagrams of the experimental models (a: cylinder, b: frustum) and a photograph of the as-built bottom topography (c) in the wave basin.

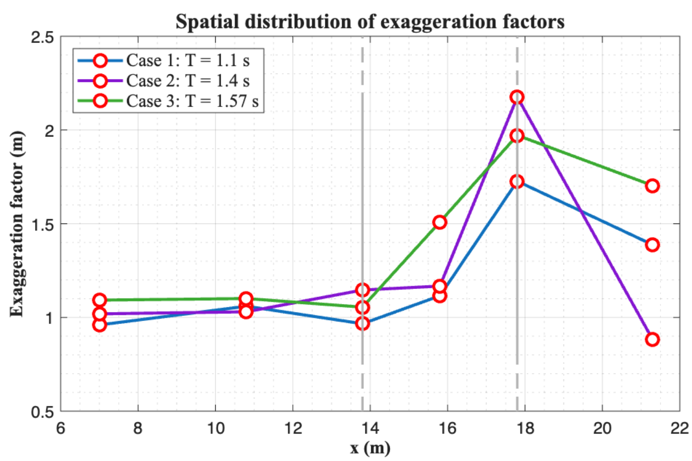

Figure 2: Spatial variation pattern of exaggeration factors.

distribution characteristics of the wave hydrodynamic characteristics, the detailed distribution information will be analyzed via more experimental results.

The maximum values of the normalized wave amplitudes at various spatial locations in case 1 and case 2 is presented in Figure 3, with the color bar on the right indicating the magnitude of the normalized amplitudes, and the red dashed circle indicates the top profile of the cylindrical model. The cylindrical model induces wave amplification under various conditions and is predominantly located above and downstream of the cylinder. However, at gauges 30, 32, and 33 located laterally behind the cylinder, a significant reduction in wave amplitude is observed. The decrease stems from three-dimensional effects induced by the geometries, which cause wave refraction as the waves propagate across the submerged cylinder. For non-resonant cases, the maximum normalized wave amplitudes occur at gauge 31 downstream of the cylinder, while significant amplification is also observed at gauge 10, located 3.5 m behind the rear edge of the cylinder. In contrast, under resonant conditions, the maximum normalized wave amplitudes are located at gauge 9 above the rear

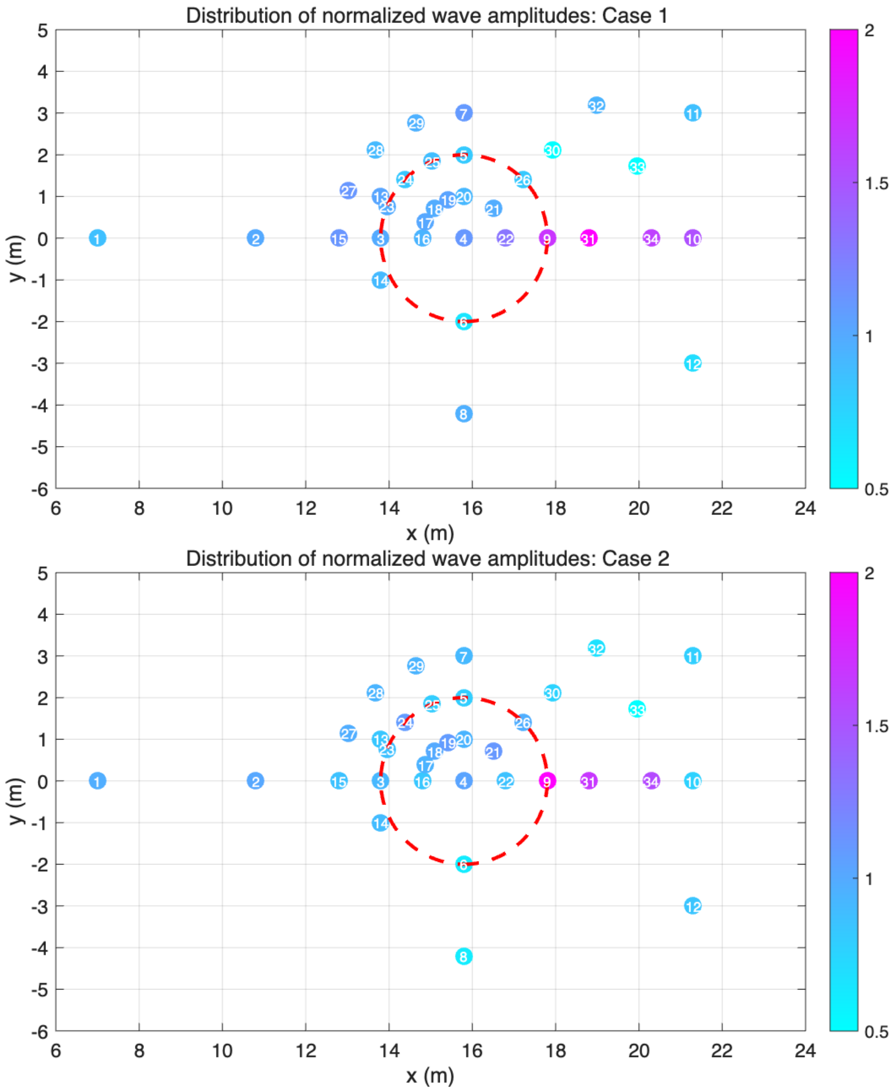

Figure 3: Normalized surface elevations under different spatial distributions.

edge of the cylinder, while the value at gauge 10 shows a decrease. This indicates that while resonance conditions dictate the magnitude of peak wave heights, the normalized wavelength controls the spatial location of maximum amplification.

Figure 4 presents the directional wave spectra in the edge region of the cylindrical model for case 2, where the first row represents the directional spectra at the right-front, right-side, and right-rear edges of the cylinder, while the second row corresponds to those at the front edge, center, and rear edge. It can be observed that the wave energy propagates predominantly along the radial and tangential directions of the cylinder edge, which indicates that the topographic shape exerts an effect of energy concentration. Meanwhile, there is a significant broadening of the frequency bandwidth along the direction of wave propagation, and it presents clear resonant trapped modes at the edge.

4 Conclusions

Laboratory experiments were conducted to study nonlinear wave propagation over these three-dimensional topographic depth transitions. Experimental evidence was first obtained for the wave-trapping phenomenon

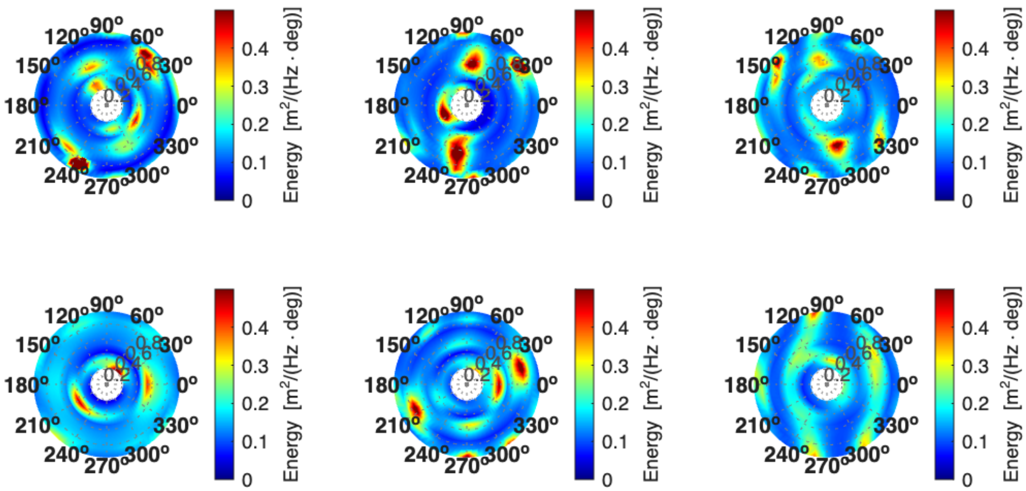

Figure 4: Directional spectra for cylinder model under several positions.

over three-dimensional cylindrical topography and identified it as a potential mechanism for extreme wave generation. The results indicate that the 3D topography induces a wave-trapping effect, confining wave energy above the topography and thus significantly increasing the wave height. Moreover, analysis of the directional wave spectrum reveals that the geometry of this trailing edge not only blocks wave energy from propagating into deeper water but also channels it toward the rear edge region, especially under resonance conditions. The wave propagation direction is significantly influenced by the topography, which suggests the importance of considering three-dimensional effects in coastal engineering applications. More detailed results will be presented at the workshop.

Acknowledgements
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