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Wave load on submerged quarter-circular and semicircular breakwaters under irregular waves

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A R T I C L E I N F O

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A B S T R A C T

Laboratory experiments were conducted to investigate the characteristics of wave loading on submerged circular-front breakwaters due to irregular waves. The wave force spectrum for a semicircular breakwater is similar to that for a quarter-circular breakwater. The dimensionless peak wave force for irregular waves is less than that for regular waves. The performance of our theoretical wave load model is improved significantly by incorporating the effect of wave transmission and flow separation. A RANS-VOF model was used to investigate the effect of local hydrodynamic disturbances by submerged breakwaters on the pressure distribution around the breakwater and total wave load. The numerical results reveal that wave-induced vortices at the structure have a substantial influence on the wave loading on the submerged quarter-circular breakwater but not on the semicircular breakwater. A parametric analysis is required to further improve the relationship between wave loads and the vortices.

1. Introduction

Breakwaters play an important role in mitigating wave damage and protecting shorelines from erosion. Traditionally, emerged breakwaters have been used for this purpose. However, designing emerged breakwaters has become increasingly difficult since the construction often takes place in a severe environment caused by fierce waves and a poor seabed [1, 2]. According to Rambabu and Mani [3], submerged breakwaters have recently gained popularity in order to reduce pressures on the sheltered structures and retain sediments in the sheltered harbor through premature wave breaking [4]. In addition, submerged breakwaters provide more aesthetically pleasing view of the sea and better water quality in a harbor than emerged breakwaters [5,6].

Various types of submerged breakwaters have been employed in engineering practice, such as vertical, rubble mound, and circular-front breakwaters. They have different hydrodynamic performances due to the variation of wave reflection, dissipation, and transmission in response to the structure geometry. Young and Testik [7] reported that semicircular breakwaters reflect less and transmit more energy than vertical breakwaters at the same relative submergence depth. Reduced wave reflection minimizes the seaside scour at the structure and benefits the navigation of vessels near the structure but greater wave transmission may deteriorate harbor tranquility and encourage beach erosion behind the structure. However, the submerged semicircular breakwaters with perforated walls may work well resulting in a smaller transmission coefficient because of additional energy dissipation by the turbulence inside the hollow chamber [8, 9] . Regarding wave loading, extensive studies on vertical breakwaters have been carried out in the past decades. Examples include the effect of wave breaker on dynamic pressures by Kirkgöz [10, 11], Ergin and Abdalla [12], Hattori et al. [13], Cooker and Peregrine [14], Prabhakar and Sundar [15], the influence of aeration and scale on wave impacts by Blackmore and Hewson [16], Bullock et al. [17,18], and dynamic response under wave attack by Oumeraci [19], Franco [20], Goda and Takagi [21], Takahashi et al [22], Li et al. [23], Cuomo et al. [24]. In comparison with vertical breakwaters, the pressure on a circular wall acts towards the center of the circle and therefore circular breakwaters generally have smaller horizontal force, overturning moment and soil subgrade reaction [25] that results in better stability and lower engineering cost [26] (see Fig. 1).

This study focuses on the characteristics of wave loads on the circular-front breakwaters due to irregular waves. Two types of circular-front breakwaters have been used in coastal protection, i.e.

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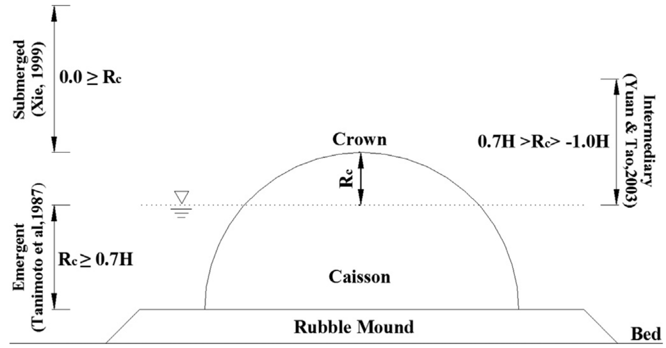

Fig. 1. The valid range of freeboard of the empirical wave load models for semicircular breakwaters. R_c is crest freeboard height.

quarter-circular breakwaters (QCB) and semicircular breakwaters (SCB). They consist of a curved concrete caisson founded on a rubble mound (see Fig. 2). At low water levels, circular breakwaters act as a rubble mound breakwater while serve as a composite breakwater at high water levels.

Since the first SCB was constructed at Miyazaki Port in Japan in 1993, efforts have been dedicated to characterize the dynamic pressure on SCBs. In summary, three wave load models for SCBs have been proposed. First in Tanimoto et al. [27], Goda's formulation for vertical breakwaters was modified by incorporating the phase and center angle difference to calculate the pressures on semicircular breakwaters. More wave energy will pass over submerged structures than emerged structures and therefore generate substantial surface fluctuation on the leeside, which can significantly alter the total wave loads. Yu et al. [28] indicated that irregular wave forces on submerged SCBs exhibit very different behaviors from those on emerged SCBs. Xie [29] concluded that submerged semicircular structures may be at risk if Tanimoto's formula was used in design. Instead, he proposed the second wave load model by including a pressure distribution on the inside circumference of the rear wall and introducing a new phase modification coefficient in Tanimoto's model. Yuan and Tao [30] presented the third wave load model to predict the total wave forces on submerged, alternately submerged, and emerged SCBs based on a potential flow model. Fig. 1 shows the freeboard ranges that the aforementioned three models can be applied [31]. More discussions about the dynamic pressure on SCBs exposed to normally incident and oblique waves can be found in Sundar and Ragu [32, 33], Zhang et al. [34], and Liu and Li [35], respectively.

Xie et al. [36] introduced the concept of QCBs based on SCBs in order to cut the construction cost since the bulk volume of QCBs is smaller than SCBs at a given crest height. Literature on wave loads exerted on QCBs is rare. Xie et al. [36] estimated the regular wave loads on QCBs by adding an amplification factor to Tanimoto's model for SCBs. Liu et al. [37] discussed the effects of wave steepness, relative wave height, and water depth on the regular wave forces acting on QCBs. However, the irregular wave loads on QCBs have not been investigated previously.

Shi et al. [38] found that with the same curved front wall, emerged QCBs and SCBs have the same hydrodynamic performance and wave loading. However, when a coastal structure is submerged, the presence of the structure changes the flow field adjacent to the structure, for example, the generation and shedding of vortices around the structure [39]. These vortices are expected to cause the oscillation of forces on

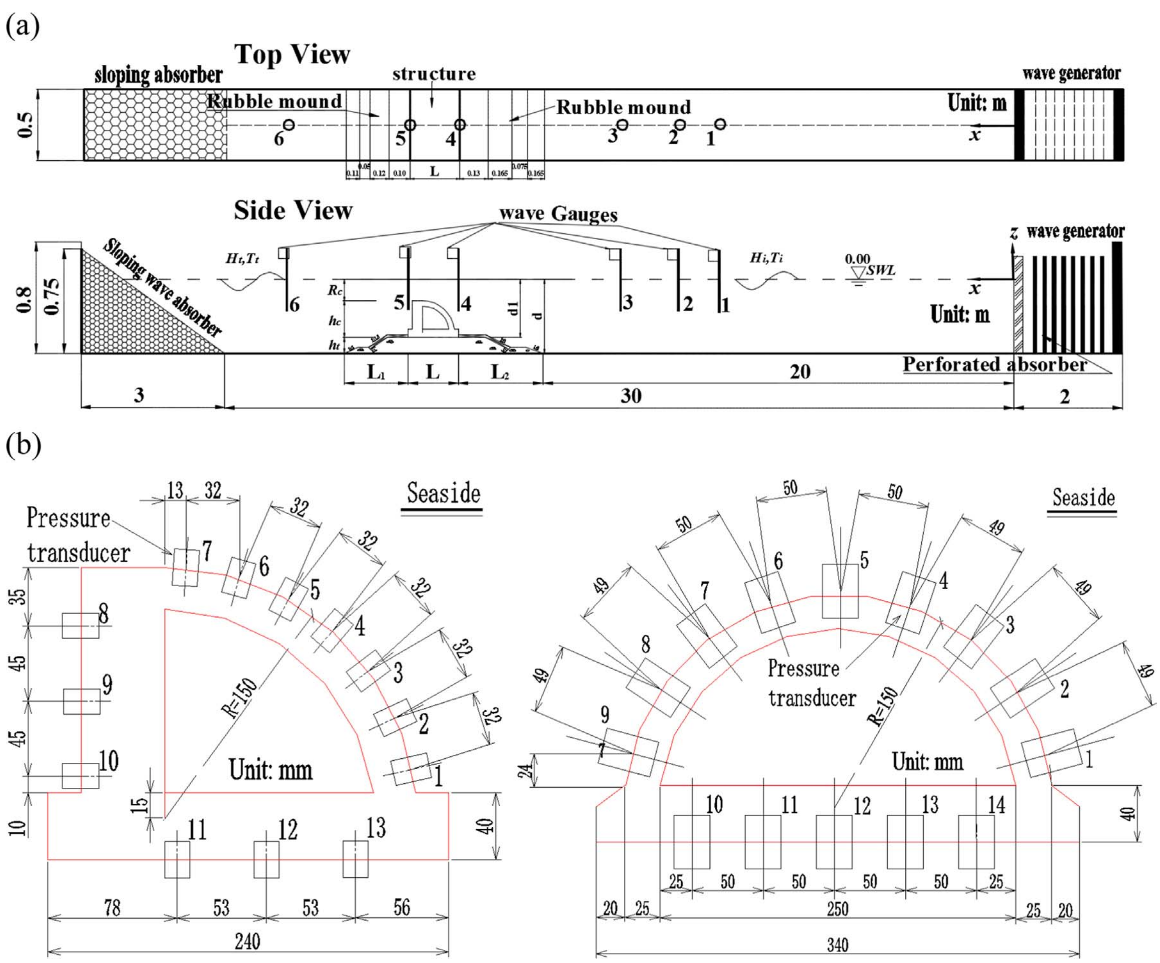

Fig. 2. (a) Diagram of the experiment setup in the wave flume; (b) Pressure transducers on caissons.