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Tests on wave-induced dynamic response and instability of silty clay seabeds around a semi-circular breakwater

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ABSTRACT

Model tests aimed at investigating the wave-induced dynamic response and instability of silty clay seabeds around a semi-circular breakwater were conducted in a large wave flume. The pattern of wave forces was measured and analysed. The seabed responses were presented in terms of pore pressure and vertical stress, which were further characterized in terms of their oscillatory and residual values. The wave-induced settlement and instability of the semi-circular breakwater were studied. Test results reveal that the total horizontal wave force was generally greater than the vertical wave force, and a phase difference existed in the total horizontal and vertical wave force patterns. The trends in the oscillatory pore pressure and vertical stress were very similar: they generally developed rapidly in the seabed on the wave side, tended to be larger in the upper silty clay and smaller in the bottom area and increased with increasing wave height. Furthermore, the oscillatory responses mostly reached stable states but were observed to vibrate with cyclic time in the destroyed silty clay. The residual pore pressure and vertical stress mainly developed in the seabed around the breakwater and could be quite different depending on the location. With the exception of the decrease-increase tendency in some seabed areas, the residual pore pressure generally increased with cyclic time beneath the breakwater. The residual vertical stress generally increased with cyclic time beneath the breakwater, except in some regions beneath the toes of the internal rubble bed. The semi-circular breakwater settled substantially into the silty clay seabed, and the settlement was greater on the wave side. This seabed shear failure is attributed to the strength degradation of the silty clay induced by the development of excess pore pressure and the destruction of the soil fabric.

1. Introduction

A semi-circular breakwater is a type of precast reinforced concrete caisson structure developed for soft subgrades. Such structures were initially built at the Port of Miyazaki, Japan, in the early 1990 s [1] and have seen widespread use in the Port of Tianjin and the Yangtze River estuary in China [2]. The caisson body of a semi-circular breakwater includes two main components: an impermeable or perforated semi-circular arc and a bottom slab [3], which rest on a soft rubble-mound foundation. These unique structural characteristics endow cellular breakwaters with relatively high stability against sliding, zero overturning moment acting on the caisson because the hydrodynamic pressure acting on the structure passes through the centre of the circle, a sufficiently low weight compared with that of gravity vertical caissons, and great ease in construction and removal [4,5].

Because of the abovementioned unique structural characteristics, the wave translations and forces acting on semi-circular breakwaters differ strikingly from those on typical slope rubble mound or vertical caissons, causing the hydrodynamic performance of semi-circular breakwaters to become the main focus of past researchers. For practical design efforts, Tanimoto [1] developed an empirical formula to calculate the wave forces acting on semi-circular breakwaters based on Goda's formula [6] for vertical walls. Because the method of Tanimoto [1] may not be suitable for calculating the wave forces acting on a submerged semi-circular breakwater, Xie [4] developed a test-based formula specifically for submerged conditions. Some parametric experimental studies on the hydrodynamic performance of semi-circular breakwaters were also conducted. Dhinakaran et al. [7–9] examined the effects of perforations and rubble mound height on the wave translations and forces of semi-circular breakwaters. Zhang et al. [2] considered the effect of the incidence angles of obliquely arriving waves on wave forces acting on a semi-circular breakwater. Numerical studies by Cooker et al. [10], Jia et al. [11], Yuan et al. [3] focused on simulating the interactions of waves with a semi-circular caisson based on the boundary element method. Kasem et al. [12] simulated the propagation of water waves over a semi-circular breakwater by solving the

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incompressible Navier–Stokes equations. Very recently, Liu et al. [5] developed a semi-analytical solution for wave interactions with submerged perforated semi-circular breakwaters using the multipole expansion method. These above studies give us a better understanding of the wave-structure interactions for the semi-circular breakwaters.

However, seabed response was not included in the above studies, because wave–structure interactions constituted the key point being addressed. The importance of seabed foundations for a structure's stability should be recognized, since wave-induced instabilities of the seabed foundations have been frequently found to play key roles in accidents involving semi-circular breakwaters [13–17]. For example, during the construction of the middle section of the northern guiding dike in the Yangtze River estuary, some of the semi-circular caissons for the dike structure sank several metres into the soil or slid approximately 20 m from their original locations when a strong storm struck the area [18]. Previously, many analytical works related to seabed responses around breakwaters subjected to cyclic waves have been conducted. Hsu et al. [19], Jeng et al. [20] and Tsai et al. [21,22], when dealing with the responses of interactions between the structure and seabed, simplified the marine structure as a line without width or weight. Numerical modelling is another powerful tool. Ulker et al. [23,24] considered the dynamic response and instability of a sandy seabed around vertical caisson breakwater using finite element method. Jeng et al. [25], Ye et al. [26–28] and Zhao [29,30] used the Biot's dynamic equation (known as "*u-p*") to govern the porous seabed and predicted the wave-seabed-structure interaction of rubble mound or composite breakwaters, in which the vertical wall was a rigid structure, but the rubble mound was a porous structure, the weight of marine structure in the initial consolidation process and the effects of marine structures on wave fields were considered. Zhao [31] also considered the co-existence of wave and current in the fluid-seabed-structure interaction around a submerged rubble mound breakwater using an integrated FVM-FEM scheme, in which the VARANS equation was used to simulate fluid field, while Biot's poroelastic model was used for porous flow in a seabed. By means of an experimental approach, Kudella et al. [32] performed a series of large-scale experiments to study the wave-induced transient and instantaneous pore pressures beneath a vertical caisson breakwater on a loose sand bed with some thin clay layers.

However, these basic works related to seabed instability around breakwaters (caisson or rubble mound) subject to cyclic waves were largely for slope or vertical walls on sandy seabeds. Considering that the hydrodynamic performance on the semi-circular arc (which can be submerged, alternately submerged, and emerged according to the water level) is different with the highly permeable rubble mound or impermeable vertical walls, the corresponding seabed response could be quite different, and the semi-circular breakwater is a light-gravity type structure that generates a smaller foundation stress than gravity slope or vertical walls. Furthermore, the above studies concerned with sandy seabeds may not be suitable for a silty clay seabed. Normally, silty clay is elastoplastic and has a low relative density and weak bearing capacity. Under long-term wave loading, the soil particles of elastoplastic soils rearrange to reach their optimal potential arrangement, which leads to the compaction of the silty clay, increase in pore pressure and the destruction of soil fabric if the magnitude of the applied force greatly increases, and the consolidation process will have a long duration under static loads, which can be attributed to the poor permeability. In comparison, the physical properties of dense and loose sandy seabeds are demonstrated. Dense sand can be treated as an elastic seabed soil, and there is no unrecoverable deformation under long-term external loading. The soil particles in a loose sandy seabed soil tend to make contact with each other in a dense manner under wave cyclic loading, thereby reaching an optimum state, the relative density and bearing capacity increase due to the pore pressure dissipation, and the consolidation process will be of short duration compared with that for a silty clay seabed.

For the problem under consideration, wave-induced dynamic response and instability of silty clay seabeds around a semi-circular breakwater have not yet been investigated [23]. In this study, a series of large-scale model tests were conducted to gain a full understanding of the wave-structure-seabed behaviour in a large wave flume containing a semi-circular breakwater with a rubble-mound foundation placed on a silty clay seabed. The organization of this paper is as follows. In Section 2, the test procedure and experimental setup are introduced. Wave-pressure sensors were installed on the breakwater, and pore-pressure sensors and earth-pressure cells were embedded in the model seabed to allow for a comprehensive investigation of the wave pressure and dynamic response. Section 3 first shows the test results of the pattern of wave forces and then presents the seabed responses in terms of pore pressure and vertical stress, which are further characterized in terms of oscillatory values that periodically fluctuate around an equilibrium value and residual values that continuously increase (positive) or decrease (negative) with continuous wave loads [33,34]. The distributions of the oscillatory responses with the variations in wave height were specifically investigated, and typical time histories of the pore pressure and vertical stress were analysed. The wave-induced settlement and failure mode of the seabed and breakwater were also studied, and key points are discussed for the purposes of characterizing the mechanism responsible for the instability of a semi-cellular breakwater on a silty clay seabed. Finally, the main conclusions are presented. Through these tests, the following goals were achieved. First, the dynamic responses in the silty clay seabed around semi-circular breakwater can be obtained, which we hoped would clarify the experimental methods and data and to provide the benchmarks for theoretical and numerical analyses. Second, analyses of the results revealed the settlement and instability mechanism of the wave-breakwater-seabed system and thus the results may have practical implications.

2. Test procedure and experimental setup

The tests were conducted in a large wave flume in Tianjin, China. Fig. 1 shows a sketch of the large wave flume, the length, width and depth dimensions of which are 456 m, 5 m and 8–12 m, respectively. Over its length, the flume can be divided into wave making (including wave making equipment shown in Fig. 1(a) and the generating section in Fig. 1(b)), testing and wave absorbing (Fig. 1(e)) areas based on its functions. More details on the configuration of the large wave flume are given by Zhang [35]. The performance of the large wave flume for generating sinusoidal waves was verified by pilot tests, and comparisons between the target and real waveforms indicate that only minor deviations are observed in wave height (represented by *H*) and period (represented by *T*), as shown in Table 1.

Essentially, based on the requirements discussed in the previous section and on considerations of practical feasibility, the test conditions for the model tests are provided in Table 2. A total of seven tests were conducted in this study: Tests H-1, H-2, H-3, H-4, H-5, H-6 and L-1. These tests were divided into two cases. Case 1 (the first six tests: H-1, H-2, H-3, H-4, H-5 and H-6) involved the application of 100 wave loading cycles to obtain the distributions of the oscillatory responses. Case 2 (Test L-1) involved two applications of 1000 cycles of wave loading to obtain the time history of the dynamic responses of the seabed and semi-circular caisson. The interval between the first 1000 cycles and the second 1000 cycles of wave loading was approximately 44 min, which was implemented to guarantee normal equipment operation. The test was designed to satisfy various similarity criteria with regard to the prototype, including criteria of geometric similarity, kinematic similarity and dynamic similarity. The water level and wave height in the model tests were at a 1:5 scale in correspondence with the design conditions; therefore, the water depth was 2.19 m (10.93 m in practical engineering), and the semi-circular breakwater was submerged in this water depth. Sinusoidal waves were utilized in the tests. Wave heights of 0.1 m, 0.2 m, 0.3 m, 0.4 m, 0.5 m and 0.6 m were employed in the first six tests for a parametric study, and a wave height of