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Numerical assessment of tsunami attack on a rubble mound breakwater using OpenFOAM®

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ABSTRACT

A numerical assessment study of tsunami attack on the rubble mound breakwater of Haydarpasa Port, located at the southern entrance of the Istanbul Bosphorus Strait in the Sea of Marmara, Turkey, is carried out in this study using a Volume-Averaged Reynolds-Averaged Navier-Stokes solver, IHFOAM, developed in OpenFOAM® environment. The numerical model is calibrated with and validated against the data from solitary wave and tsunami overflow experiments representing tsunami attack. Furthermore, attack of a potential tsunami near Haydarpasa Port is simulated to investigate effects of a more realistic tsunami that cannot be generated in a wave flume with the present state of the art technology. Discussions on practical engineering applications of this type of numerical modeling studies are given focusing on pressure distributions around the crown-wall of the rubble mound breakwater, and the forces acting on the single stone located behind the crown-wall at the rear side of the breakwater. Numerical modeling of stability/failure mechanism of the overall cross-section is studied throughout the paper.

The present study shows that hydrodynamics along the wave flume and over the breakwater can be simulated properly for both solitary wave and tsunami overflow experiments. Stability of the overall cross-section can only be simulated qualitatively for solitary wave cases; on the other hand, the effect of the time elapsed during tsunami overflow cannot be reflected in the simulations using the present numerical tool. However, the stability of the overall cross-section under tsunami overflow is assessed by evaluating forces acting on the rear side armor unit supporting the crown-wall of the rubble mound breakwater as a practical engineering application in the present paper. Furthermore, two non-dimensional parameters are derived to discuss the stability of this armor unit; and thus, the stability condition of the overall cross-section. Approximate threshold values for these non-dimensional parameters are presented comparing experimental and numerical results as a starting point for engineers in practice. Finally, investigations on the solitary wave and tsunami overflow experiments/simulations are extended to the potential tsunami simulation in the scope of both representation of a realistic tsunami in a wave flume and stability of the rubble mound breakwater.

1. Introduction

After the Great East Japan Tsunami in 2011, small-scale computational fluid dynamics (CFD) simulations became necessary as the tsunami destroyed many bridges, breakwaters, and other coastal infrastructures in an unexpected manner [1]. Although there are various studies focusing assessment of tsunami impact on seawalls, composite breakwaters, and bridges, there is a limited number of studies investigating the effect of tsunamis on rubble mound breakwaters considering both physical and numerical modeling studies. Esteban et al. [2] studied the stability of armor units of rubble mound breakwaters against tsunami attacks by physical model experiments. Guler et al. [3], the reference paper for the present study, studied the performance of a selected rubble mound breakwater under the attack of tsunamis as a case study. Furthermore, Harbitz et al. [4] tested a similar cross-section to the one used in Guler et al. [3] considering similar wave conditions. On the other hand, Sakakiyama [5] presented both physical and numerical experiments investigating flow fields of tsunamis passing over

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a rubble mound breakwater. In the numerical part of Sakakiyama [5], a numerical model solving Reynolds Averaged Navier-Stokes (RANS) equations and using Volume of Fluid (VOF) method for free-surface tracking [6] used.

In this study, tsunami attack on a rubble mound breakwater is assessed numerically using a Volume-Averaged Reynolds-Averaged Navier-Stokes (VARANS) solver called IHFOAM [7–11] developed in OpenFOAM® environment [12]. Numerical results are compared with the physical model experiments of Guler et al. [3]. The physical model experiments focused on rubble mound breakwater of Haydarpasa Port (Haydarpasa Breakwater, hereafter), located at the southern entrance of Istanbul Bosphorus Strait in the Sea of Marmara, Turkey. Several studies concluded that 35 tsunamis have occurred in the Sea of Marmara [13,14] including the recent 1999 Marmara Event [15–17]. The physical model experiments [3] conducted in 105 m long wave flume of Port and Airport Research Institute (PARI) consist of both solitary wave and tsunami overflow experiments. Solitary wave experiments aimed to understand the effect of the tsunami-like long waves and to find the related tsunami overflow heights. However, Madsen et al. [18] concluded that solitary waves could not adequately represent the effect of tsunamis. Arikawa et al. [19] revealed that stability of breakwaters depends on the duration of the overflow, due to water level difference between the seaside and the harbor side of breakwaters. Therefore, Guler et al. [3] used tsunami overflow experiments in addition to solitary wave experiments to understand the effect of the duration of the overflow during tsunami attack and the tsunamis' action mechanism on the selected coastal structure.

Selected solitary wave and tsunami overflow experiments are simulated for calibration and validation of the numerical solver. Comparisons of numerical and experimental results are performed for water surface elevations and velocity measurements along the wave flume, and time variation of safety factors against sliding and overturning are calculated evaluating stability condition of the crown-wall of the breakwater. In addition to simulations of solitary wave and tsunami overflow experiments, a simulation with a potential tsunami in Haydarpasa Region is presented based on the data of a numerical tsunami assessment study by Aytore et al. [20]. The potential tsunami simulation aims to extend understanding of tsunami attack on a rubble mound breakwater by numerical simulations, as it is not possible to generate a "real" tsunami in a wave flume with the present state of the art technology.

Numerical assessment studies show that hydrodynamics along the wave flume and over the breakwater can be simulated accurately. On the other hand, stability conditions in the solitary wave cases can be qualitatively assessed as the pressure forces around the crown-wall of the breakwater governed the sliding of the crown-wall and failure of the overall cross-section. Furthermore, the effect of the duration of the flow during tsunami overflow cannot be simulated with the present numerical tool since it is not capable of directly evaluating forces acting on the structural units of the rubble mound breakwater; and thus, the motion of them as a function of time. However, it is still possible to discuss the stability of the overall cross-section under tsunami overflow by evaluating forces acting on the single stone behind the crown-wall at the rear side of the breakwater as presented in the present paper as an engineering application.

This paper is structured as follows: After this brief introduction, an overview of the experiments, and selected experimental cases for numerical simulations are given in Section 2. Next, the numerical model, computational domain, model parameters, and boundary conditions are described in Section 3. Section 4 presents the results of numerical simulations, and Section 5 discusses the possible engineering applications of this type of numerical studies. Finally, conclusions are presented in Section 6.

2. Overview of physical model experiments

Guler et al. [3] used both solitary waves and tsunami overflow tests to represent the effect of tsunamis more relevantly; and thus, to understand the failure mechanism of the breakwater under tsunami attack. In these experiments, solitary waves are generated by piston-type wavemaker, and constant flow over the crown-wall of the breakwater, i.e., tsunami overflow, is achieved by the inflow from a pump at the inlet and outflow by another pump at the outlet. It is seen that tsunami overflow can be more destructive than solitary waves due to the time elapsed during tsunami overflow.

These physical model experiments were conducted in 105 m channel of Port and Airport Research Institute (PARI) in Japan using a Froude type model scale of 1:30. In the experiments, water surface elevations and the flow velocities were measured by eight wave gauges (WGs) and three acoustic Doppler velocimeters (ADVs), respectively. Dimensions of the channel, locations of wave gauges and ADVs are shown in Fig. 1, and a closer side view of the rubble mound breakwater is given in Fig. 2 indicating WGs and ADVs on the cross-section.

Three experiments of Guler et al. [3] are selected for calibration and validation of the numerical model. Solitary wave tests with the wave heights of H = 7.5 cm and H = 10 cm are selected for calibration and validation of the numerical model, respectively. In the reference experimental study [3] and in the present study, these experiments are named according to the resulting solitary wave heights at WG6 before construction of the cross-section during the wave calibration stage of the physical model experiments. However, we calibrate and validate the numerical model using the measured experimental data after the construction of the cross-section during the actual experimental stage. As the solitary waves are extremely long waves compared to wind waves, the wave heights of solitary waves increase when there is such an obstacle at the end of the cross-section. Therefore, the reader might observe much higher solitary wave heights than the name of the experiments in the figures comparing the physical model experiments and numerical simulations in the further sections. Water surface elevation time-series data without the rubble mound breakwater

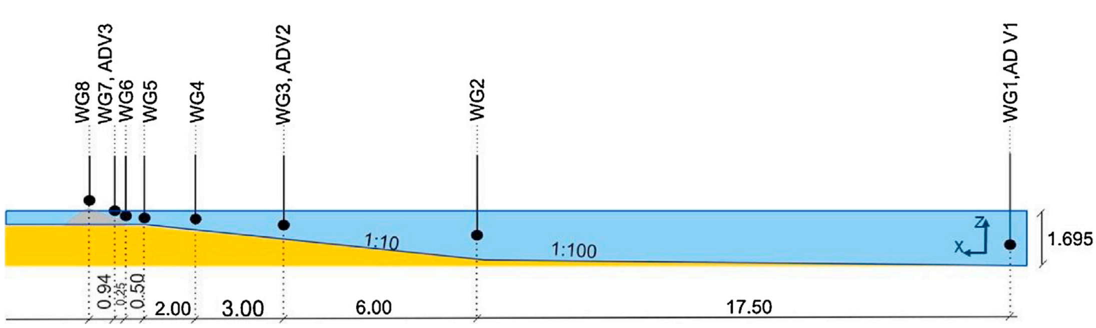

Fig. 1. Cross-Sectional View of Wave Flume (Dimensions are given in meters.).