Coastal Engineering 104 (2015) 43–53

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Performance of rubble mound breakwaters under tsunami attack, a case study: Haydarpasa Port, Istanbul, Turkey

Hasan Gokhan Guler [a],*, Taro Arikawa [b], Takayuki Oei [b], Ahmet Cevdet Yalciner [a]

[a] Department of Civil Engineering, Ocean Engineering Research Center, Middle East Technical University, Ankara, Turkey
[b] Port and Airport Research Institute (PARI), Yokosuka, Kanagawa, Japan

ARTICLE INFO

Article history:
Received 7 September 2014
Received in revised form 17 June 2015
Accepted 18 July 2015
Available online 15 August 2015

Keywords:
Rubble mound breakwaters
Tsunami attack
Solitary wave
Tsunami overflow experiments

ABSTRACT

Ports are one of the most vulnerable coastal utilities in case of marine natural hazards such as tsunamis and need to be protected against their devastating effects. Thus, studying the effects of tsunamis on protective structures such as breakwaters is critical. The Sea of Marmara is a part of an active earthquake zone that has generated tsunamis in the history. In terms of population density, coastal utilization, and economic potential, Marmara coastline seems most vulnerable to marine hazards. The availability of natural stones allows for wide use of rubble mound breakwaters as coastal protective structures in Turkey. The stability of these types of structures under the attack of storm waves has already been studied. However, their stability and performance under the effect of long waves and tsunami attacks have not yet been studied experimentally. The present study is a case study focusing on Haydarpasa Port, located at the southern entrance of Istanbul Bosphorus Strait (North coast of the Sea of Marmara). It aims to investigate the performance level of the port in case of tsunami attack.

Physical model experiments were conducted in the 105-m long wave flume in the Port and Airport Research Institute (PARI), Japan, with a Froude-type length scale of 1/30. The experiments conducted to test the stability of rubble mound breakwater were twofold: (i) solitary wave experiments and (ii) tsunami overflow experiments. The heights of incoming tsunami waves were selected from results of simulations were conducted in the same region (Oyo Int. Co., 2007; Ayca, 2012; Yalciner et al., 2014; Guler et al., 2014; Aytore, 2015). First, the incoming solitary wave heights were selected as 5, 7.5, and 10 cm. Using the overflow heights obtained from solitary wave experiments, i.e., wave height at the top of crown wall when the solitary waves are overtopping the crown wall, tsunami overflow experiments were conducted ranging from an overflow height of 1.1 cm to 4.6 cm. Results of these experiments showed that Haydarpasa Breakwater, especially the crown wall of the breakwater, is not stable under a moderate tsunami attack. Therefore, an improved cross section was also tested under the same conditions, and the improvement proved successful.

1. Introduction

Ports are the main infrastructures that should continue to function properly after any disasters. Because of their economic and social importance, the performance of the ports must be assessed under the effect of natural hazards. The Marmara sea coastline is the most vulnerable region in Turkey, considering its population density and economical potential. It is located at the western part of the North Anatolian Fault (NAF) zone in Turkey, which has experienced so many earthquakes and tsunamis throughout the history. Studies concluded that 35 tsunamis have occurred in this region in the past two millenniums, not only generated by earthquakes but also generated by landslides (Altinok et al., 2011; Yalciner et al., 2002).

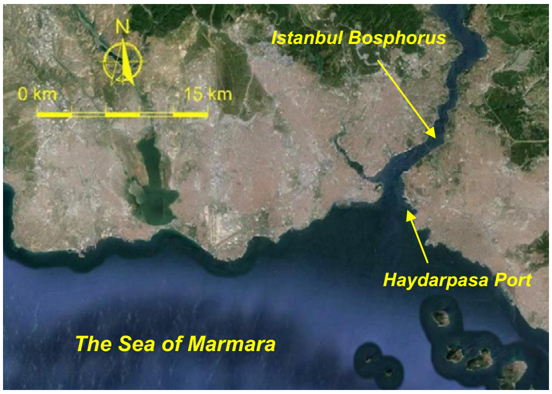
Haydarpasa Port located in the southern entrance of the Istanbul Bosphorus Strait in the Sea of Marmara (Fig. 1) was selected as the subject of the case study, which intends to investigate its performance under tsunami attack. This port is one of the most important ports in Turkey, serving both public and commercial activities of millions of people for passenger transfer between Europe and Asia and also carrying out cargo handling operations for megacity Istanbul. It has critical components such as the main railway station at the Asian Side of Istanbul, passenger terminals, cargo and container stock areas, and ro-ro handling operations. The railway station itself is a historical building which has architectural importance.

In this study, performance of the breakwaters of Haydarpasa Port – hereafter Haydarpasa Breakwaters – were tested by physical model experiments. Haydarpasa Breakwaters are off-shore rubble mound breakwaters, including crown wall units, and have a length of approximately 3000 m in total. The longer off-shore rubble mound breakwater, i.e., the breakwater at the western side in Fig. 1b, was selected for the physical model experiments. Tests were conducted in two parts: (i) solitary wave experiments and (ii) tsunami overflow tests, in Port and Airport Research Institute (PARI), Japan. Solitary wave experiments

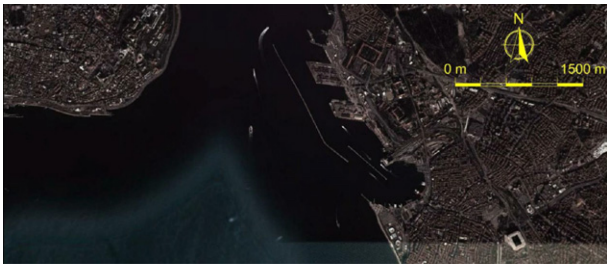
---

* Corresponding author.
E-mail address: goguler@metu.edu.tr (H.G. Guler).

http://dx.doi.org/10.1016/j.coastaleng.2015.07.007



(a) General View of The Sea of Marmara



(b) Haydarpasa Port

Fig. 1. The location of the Haydarpasa Port.

were performed to understand the effect of the tsunami-like waves and to find the related tsunami overflow heights. It was concluded by Madsen et al. (2008) that the solitary waves are not capable of expressing the impact of tsunami attacks. As stated in Arikawa et al. (2012), the stability of breakwaters depends on the period of time elapsed during tsunami overflow, due to water level difference between the sea side and the harbor side of breakwaters. For this reason, a continuous flow over the cross section is used to effectively understand effect of elapsed duration during tsunami attack referred as tsunami overflow experiments in this study in addition to the solitary wave experiments to understand the acting mechanism of the tsunamis on the selected coastal structure.

Physical model experiments showed that the current cross section of the Haydarpasa Breakwater is not stable under a possible tsunami attack in the Sea of Marmara. Therefore, a countermeasure cross section was proposed and tested. It was shown by physical experiments that the Haydarpasa Breakwater will be stable if its armor layer width at the harbor side of the breakwater is doubled.

2. Experimental setup

2.1. Scaling of breakwater cross section

In this study, Froude Law is used as the scaling law since inertial and gravitational forces are dominant in wave motion and in wave effects on coastal structures. The stability of armor units can be modeled correctly if the stability numbers given in Eq. (1) in both prototype and the model are the same (Hydralab, 2007). This condition can be satisfied when the weight scale (λ_W) is computed using Eq. (2).

$$N_s = \frac{H_s}{\Delta D_{n50}} \tag{1}$$

$$\lambda_W = \left(\lambda_L^3\right) \frac{(\gamma_r)_m}{(\gamma_r)_p} \left[\frac{(\gamma_r)_p/(\gamma_w)_p - 1}{(\gamma_r)_m/(\gamma_w)_m - 1}\right]^3 \tag{2}$$

In Eq. (1), H_s is defined as the significant wave height (m), Δ is the relative mass density, and D_{n50} is the nominal diameter of armor stone units. Following Eq. (1), $(\gamma_r)_m$ and $(\gamma_r)_p$ are unit weights of stones that are used in model and prototype, which are taken as 2.65 t/m^3 and 2.7 t/m^3, respectively, in Eq. (2). Furthermore, $(\gamma_w)_m$ is the unit weight of water that is used in the model, and $(\gamma_w)_p$ is the unit weight of sea water in the prototype. In the experiments, the unit weight of water was taken as 1.0 t/m^3, whereas the unit weight sea water was assumed as 1.025 t/m^3.

The length scale of the physical model was selected as 1:30 due to the limitations in wave channel dimensions and wave generator. Length, time, pressure, and weight scales are given in Table 1.

The original cross section of Haydarpasa Breakwater (Fig. 2) was scaled (Fig. 3) according to the model scales. Scaled stone weights are presented in Table 2. Note that the filter and the core layers of the breakwater were also scaled using the same weight scale obtained for the armor layers.

2.2. Overview of the wave channel and experimental setup

Physical model experiments were conducted in 105 m Wave Channel of PARI. Channel dimensions are 105 m × 3.0 m × 2.5 m with a smaller channel divided along this channel with dimensions 105 m × 0.78 m × 2.5 m. Tests were conducted in the smaller channel. There are two sloped parts in this smaller channel where the slopes are 1/100 and 1/10. Furthermore, there is a flat part following the sloped parts, where the cross section was built. In the experiments, nine water level (wave) gauges (WG1 to WG9) and four velocity meters (V1 to V4) were used, and experiments were recorded with three cameras. Experimental setup and measurement devices are given in Fig. 4a and b.

Crown wall units of Haydarpasa Breakwater were constructed in four pieces, and nine pressure gauges are placed on one of the pieces of crown wall units in the middle as shown in Fig. 5. Pressure gauges are denoted as UG1 to UG9.

2.3. Solitary wave generation for stability experiments and pumping system for tsunami overflow experiments

In the first stage of the experiments, the solitary waves were generated by piston-type wave generator. Different heights of solitary waves were generated in the experiments. Tsunami overflow caused damage due to the difference in acting forces originating from water level differences between the harbor and the sea sides of the breakwater. In order to generate constant level overflow on the breakwater, a pump was used to increase water level up to a constant height at the sea side of the breakwater. This overflow height was kept constant during the experiments by the use of the circulating pump at the harbor side. The experiment continued until the damage occurs at the cross section, which also reveals duration of tsunami overflow (with respect to the tsunami period) necessary for the damage to occur.

3. Physical model experiments

Previous stability experiments on rubble mound breakwaters show that there are different damage and failure modes of rubble mound structures. Armor layers of rubble mound structures consisting of large rocks are usually designed to resist extreme storm conditions

Table 1
Model scales.

Length	$\lambda_L = 1:30$
Time	$\lambda_t = 1:5.477$
Pressure	$\lambda_p = 1:30.75$
Weight	$\lambda_w = 3.53 * 10^{-5}$