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Sliding and overturning stability of breakwater under combined effect of earthquake and tsunami

Babloo Chaudhary[a,*], Hemanta Hazarika[b], Isao Ishibashi[c], Amizatulhani Abdullah[d]

[a] Division of Environmental Science and Technology, Kyoto University, Kitashirakawa-Oiwake-Cho, Sakyo-Ku, Kyoto 606-8502, Japan
[b] Faculty of Engineering, Department of Civil Engineering, Kyushu University, Fukuoka, Japan
[c] Department of Civil and Environmental Engineering, Old Dominion University, Norfolk, VA, USA
[d] Faculty of Engineering, Department of Civil and Structural Engineering, Kyushu University, Fukuoka, Japan

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ABSTRACT

Powerful tsunami waves were generated by the 2011 off the Pacific Coast of Tohoku Earthquake, and they struck the coast of Japan after few minutes of the main shock. Seismic aftershocks continued for several hours. Many coastal structures such as breakwaters, seawalls were damaged due to the earthquake and tsunami. It may be possible that some coastal structures were hit by the aftershock and the tsunami together. This paper focuses on this fact, and analyzes stability of breakwater under combined effect of earthquake and tsunami. For estimating seismic inertia forces on breakwater, the pseudo-dynamic method was used, which considers seismic waves passing through body of breakwater with respect to depth and time. Stability of breakwater was assessed in terms of factors of safety against sliding and overturning modes of failure. It was found that stability of breakwater reduces drastically under combined effect of earthquake and tsunami as compared to only earthquake and only tsunami. Parameters such as seismic accelerations, height of tsunami wave, seawater level and width of breakwater have significant impacts on stability of breakwater under combined action of earthquake and tsunami. The design charts and tables, presented in this paper, will be helpful for design engineer to design a breakwater under combined effect of earthquake and tsunami in future.

1. Introduction

Large number of coastal structures such as breakwaters, quay walls, jetties, groins were damaged by the past earthquakes (such as 2004 Indian Ocean earthquake and 2011 off the Pacific Coast of Tohoku earthquake) and subsequent tsunamis. The 2011 off the Pacific coast of Tohoku earthquake was the most powerful earthquake ever hit Japan, and the 4th most powerful earthquake in the world since modern record keeping began in 1900. Powerful tsunami waves were generated by the earthquake. Lots of coastal structures were damaged in the affected areas (Takahashi et al., 2011; Hazarika et al., 2012, 2013). Breakwaters at many ports (e.g. Ishinomaki, Souma, Miyako and Ofunato) were heavily damaged due to the earthquake and tsunami. Due to failure of the breakwaters, the tsunami entered into coastal plain areas, and created devastation there. The main shock (M_w=9.0) of the 2011 earthquake was recorded at 14:46 (JST). There were more than 1000 aftershocks, and several of them had magnitude more than M_w=7.0, which were continuing for several hours. For example, aftershock of M_w=7.4 at 15:08 (JST), M_w=7.9 at 15:15 and M_w=7.7 at 15:25 were recorded. The tsunami waves struck different seacoasts of Japan at different times depend on their locations. As per Japan Meteorological Agency (JMA, 2011), the tsunami waves struck Kamaishi port at 15:12, Ofunato (Iwate Prefecture, Japan) at 15:15 and Miyako (Iwate Prefecture, Japan) at 15:21. It may be possible that in a seacoast of Japan, coastal structures were hit by the aftershock and the tsunami simultaneously. In fact, Ofunato was hit by the aftershock (M_w=7.9) and the tsunami together at 15:15. At Ofunato, the first wave of tsunami reached at 14:46, and maximum height of tsunami wave was recorded at 15:18. The height of tsunami wave was 3.2 m at 15:15. It was reported (Sugano et al., 2014) that the caissons of the breakwater (at Ofunato port) shifted before the first peak of the tsunami. However, the exact reasons of failure of breakwater have not been completely revealed. Based on the available data, it can be said that the port was most likely hit by aftershock and tsunami together, and combined action of earthquake (aftershock) and tsunami might be one of the main reasons of the damage of breakwater. The breakwater at Ofunato port was severely damaged (59% - lengthwise) during the earthquake and tsunami. Some other coastal areas (e.g. Soma, Miyako,

* Corresponding author.
E-mail addresses: babloomit@gmail.com (B. Chaudhary), hazarika@civil.kyushu-u.ac.jp (H. Hazarika), iishibas@odu.edu (I. Ishibashi), amihaniabdullah@gmail.com (A. Abdullah).

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Table 1
Time of tsunami (observed) and aftershocks (M_w 7.9).

Port Name	Observed Tsunami (time)		Time of aftershock (M_w 7.9)
	Time of first wave	Time of maximum height of tsunami	
Soma (Fukushima)	14:55 JST	15:51 JST	15:15 JST
Miyako (Iwate)	14:48 JST	15:26 JST	
Ofunato (Iwate)	14:46 JST	15:18 JST	
Ishinomaki (Miyagi)	14:46 JST	15:26 JST	
Kamaishi (Iwate)	14:45 JST	15:21 JST	

Ishinomaki and Kamaishi) were also hit by the aftershock (Mw=7.9) and the tsunami together at 15:15(see Table 1). This paper focuses on this fact, and analyses the stability of breakwater under combined effect of earthquake and tsunami.

Breakwater is very important coastal structure for protection of lives and structures near to coastline. Stability of breakwater may be affected significantly subjected to earthquake and tsunami together. In the case of combined effect of earthquake and tsunami, a number of forces such as (1) seismic forces (Q_H and Q_v), (2) tsunami forces (P_{th} and P_{ts}), (3) hydrodynamic forces (P_{dyns} and P_{dynh}), (4) hydrostatic forces (P_{sts} and P_{sth}) and (5) buoyancy force (U) need to be considered together for designing a breakwater. Due to combined effect of these forces, design of breakwater becomes more complicated. Available literatures suggest that this area of study has not been thoroughly researched, and whatever has previously been done in this area is generally confined to consideration of either only one force or combination of few of these forces at a time (e.g. only earthquake or only tsunami or earthquake and hydrodynamic force). Combined effect of earthquake and tsunami has not been considered. For example, many researchers discussed the effect of only seismic forces. Cuomo et al. (2011) discussed dynamic response of a composite breakwater, and developed a method to predict sliding distance considering non-linear wave structure soil interaction. Ozaki and Nagano (2004) described stability of caisson type breakwater under seismic forces. Ye and Jeng (2013) discussed three dimensional dynamic transient responses of a poro-elastic unsaturated seabed and a rubble mound breakwater due to seismic loading using finite difference method. It was found that the porous seabed foundation amplified the seismic waves from bottom to surface. However, these researchers considered only seismic forces, but they did not consider hydrodynamic and tsunami forces. Chakrabarti et al. (1978) took into account both seismic force and hydrodynamic force generated due to shaking of water for a cofferdam. Ebeling and Morrison (1992) and Nozu et al. (2004) also studied the effect of hydrodynamic pressure on coastal structures in addition to seismic forces. Chen and Huang (2002) investigated dynamic response of breakwater during earthquake, and determined hydrodynamic pressures on the breakwater as well as pore water pressures in seabed. Again, these researchers considered seismic and hydrodynamic forces, but did not consider tsunami force.

Goda (1974) and Yeh (2007) proposed a formula of tsunami wave force on breakwaters. Asakura et al. (2000) performed an experiment to determine wave force acting on on-shore structures due to over-flowing tsunamis. Tanimoto (1983) and Tanimoto et al. (1983, 1984) performed large-scale experiments using sine waves, and proposed formulas to estimate tsunami wave force on breakwater. Later, Ikeno et al. (2001, 2003) conducted model experiments for offshore and onshore structures, and modified the formulas proposed by Tanimoto (1983) and Tanimoto et al. (1983, 1984). Mizutani et al. (2000, 2002) carried out a hydraulic model experiment for a dike, and proposed a formula to calculate maximum tsunami wave pressure behind the dike. Here again, these researchers dealt with only tsunami forces, and seismic forces were not considered. Recently, combined effect of earthquake and tsunami was discussed in few research works (Choudhury and Ahmad, 2007; Ahmad and Choudhury, 2008; Kang et al., 2014, Chakraborty, 2014), but these were subjected to retaining walls or quay walls. Breakwater, as offshore structure, is different from onshore structure (e.g. quay wall). Especially, under action of earthquake and tsunami the behavior of breakwater is very different from quay wall. Presence of seawater on both the sides of breakwater makes its stability critical. Under combined action of earthquake and tsunami, effects and mechanisms of all these forces (acting together) for breakwater are quite different from quay wall.

In spite of being an important coastal structure, perhaps no study is available for breakwater subjected to combined effect of earthquake and tsunami. After the 2011 earthquake and subsequent tsunami, it becomes very important to develop a method to analyze the stability of a breakwater for combined effect of earthquake and tsunami. This study presents a simplified method to analyze the stability of breakwater subjected to combined effect of earthquake and tsunami in terms of factor of safety against sliding and overturning modes of failure.

2. Method of analysis

Breakwater of height H, width B and weight W was considered in this study, and is shown in Fig. 1. Height of seawater level was h_w from base of the breakwater. During tsunami, there was a rise in the seawater level by h_t above the seawater level. Due to earthquake, seismic inertia forces $Q_h(t)$ and $Q_v(t)$ act on the breakwater in horizontal and vertical direction respectively. Hydrodynamic force (P_{dyn}) was generated due to shaking of seawater during earthquake. Tsunami forces acting on the breakwater on seaside and harbor side are P_{ts} and P_{th} respectively. Different forces on the breakwater during earthquake and tsunami, and their respective points of application are shown in Fig. 1. It was assumed that the breakwater rests on rubble mound. Possibility of any failure other than sliding and overturning mode of failures was kept beyond scope of the present study. During tsunami, scouring and seepage may occur around breakwater, and may affect its stability. But, to simplify the analysis, these were not included in the paper. However, experiments are ongoing for stability of breakwater (including scouring and seepage) subjected to earthquake and tsunami, and it may be addressed in a paper in the future.

2.1. Seismic inertia forces on the breakwater

It was assumed that the breakwater tended to move towards harbor side under combined effect of earthquake and tsunami. Directions of the forces were chosen in such a way that combination of these forces provides a critical condition for stability of the breakwater. The seismic forces were generated due to inertia of the breakwater during earthquake, and are called seismic inertia forces, which act at center of gravity of the breakwater. The pseudo-dynamic method was used to

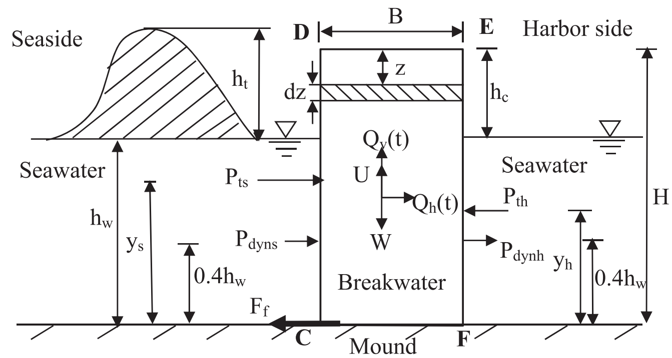

Fig. 1. Breakwater subjected to different forces during earthquake and tsunami.