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Journal of Hydro-environment Research 9 (2015) 582–591

Journal of Hydro-environment Research

www.elsevier.com/locate/jher

Research papers

Laboratory experiments on run-up and force of solitary waves

Sejong Han [a,1], Taemin Ha [b,2], Yong-Sik Cho [a,*]

[a] Department of Civil and Environmental Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 133-791, Republic of Korea

[b] Department of Civil Engineering, Kangwon National University, 346 Joongang-ro, Samcheok, Kangwon Province 245-711, Republic of Korea

Received 6 August 2014; revised 28 May 2015; accepted 29 May 2015

Available online 9 June 2015

Abstract

In this study, a series of laboratory experiments were conducted to measure the run-up heights on plane slopes and wave pressures on vertical structures resulting from solitary waves, which represent the characteristics of tsunamis well. The measured run-up heights were compared with predictions of available run-up formulas. Pressure transducers were used to measure time histories of wave pressure according to wave height and thus to record pressure distributions in laboratory experiments. The force of each incident solitary wave was estimated by integrating pressure distributions, for both square and cylindrical columns. Experimental measurements agreed well with the predictions of existing empirical formulas frequently used in design of coastal structures.

Keywords: Tsunami; Laboratory experiment; Wave pressure; Run-up; Solitary wave

1. Introduction

The recent 2011 Tohoku earthquake and resulting tsunami have attracted the attention of researchers and engineers on the need for risk assessment of potential tsunami damage. In particular, research that estimates tsunami forces acting on structures in coastal regions has the potential to prevent great losses by predicting the destruction of structures, thereby enabling the preparation of appropriate countermeasures in the design of structures for vertical evacuations (FEMA, 2008). A tsunami run-up is an important parameter in prediction of tsunami damage, and many studies have investigated run-up process. A tsunami can propagate over a long distance without transformation of its wave form. For this reason, solitary waves are often utilized and evaluated to investigate the characteristics of tsunami behaviors (Cho, 1995; Fernando et al., 2008; Huang and Yuan, 2010). To predict an inundation area, tsunami run-up is widely employed to predict structural damage, based on inundation depths and velocities. However, using only flow depth and velocity limits the accuracy of such predictions, because a tsunami behavior is also affected by beach slope conditions and the shapes of structures (Yeh, 1991). It is necessary for researchers to suggest obvious relations between tsunami-like wave force and the shapes of structures.

Cooker et al. (1997) investigated part of the motion near a vertical wall when it comes into contact with a large-amplitude solitary wave. Liu and Al-Banaa (2004) investigated the interaction between a solitary wave and a thin vertical barrier using a numerical method based on Reynolds-averaged Navier–Stokes (RANS) equations and laboratory experiments for measuring the velocity field by particle image velocimetry (PIV). Liu and Al-Banaa (2004) suggested equations for the relationship between maximum wave force, solitary wave height, and run-up, based on experimental data and a numerical method. Their empirical equations represented with Cooker et al. (1997) when the vertical barrier was completely down as vertical wall. In order to apply practical use, the researches which considered on-shore structure and protection structure in a coastal area have represented tsunami force on coastal structures.

* Corresponding author. Tel.: +82 2 2220 0393; fax: +82 2 2220 1945.
E-mail addresses: sjhan19@hanyang.ac.kr (S. Han), tmha@kangwon.ac.kr (T. Ha), ysc59@hanyang.ac.kr (Y.-S. Cho).
[1] Tel.: +82 2 2220 0318; fax: +82 2 2220 1945.
[2] Tel.: +82 33 570 6514; fax: +82 33 570 6517.

http://dx.doi.org/10.1016/j.jher.2015.05.002

Mo and Liu (2009)validated their dimensional numerical simulation model, based on Navier–Stokes equations, for determining the wave pressure distribution of the solitary wave acting on a group of cylindrical structures. They also conducted laboratory experiments to confirm the accuracy of the numerical simulations, finding slight differences between the experimental and numerical results for hydrodynamic pressure. Bisgard (2005) used solitary waves to model wave pressure on beach slopes that represented real areas, including measurement of spatial pressure around cylindrical structures. Fujima et al. (2009) conducted experiments for estimating the force acting on rectangular on-shore structures, using an integrated maximum pressure distribution and comparing this technique with available empirical formulas. Recently, Goseberg et al. (2013) improved a technique of generating tsunami and long waves using a high-capacity pipe pump. Their research tried to generate 4 types of waves characterized as tsunami. However, the laboratory experiments are not applicable to the real-scale tsunami. The researches about tsunami have used a solitary wave as the tsunami-like wave (Riggs et al., 2008; Lukkunaprasit et al., 2009).

Many researches have been conducted related to tsunami force. However, the behavior of tsunami force varies according to a bottom topography and shapes of structures. In this study, a series of laboratory experiments were carried out to measure solitary wave force on vertical structures. The solitary wave force was estimated by integrating the pressure distribution envelopes. This study focused on estimating the relationship between solitary wave height and wave pressure on square and cylindrical piles. We proposed the coefficients estimating a tsunami-like wave force by using the hydrostatic force and compared them with the results of the Goda pressure formula (a well-known formula used in the design of coastal vertical structures).

2. Experimental setup and procedure

2.1. Experimental setup

A series of laboratory experiments were performed to investigate the solitary wave pressure on vertical structures in a wave tank as shown in Fig. 1. We conducted experiments in a wave tank 32.5 m long, 0.6 m wide, and 1.1 m deep, fixed with glass walls. The wave tank was equipped with a piston-type wave generator and wave absorbers. The wave generator is consisted of a servo-piston with the maximum operating range of ±0.75 m; this was able to generate solitary waves up (H) to 0.06 m high, provided that the undisturbed water depth (h) in the wave tank was 0.25 m deep. The water surface elevations were measured by capacitance-type wave gages distributed at three stations along the tank. The wave gages (WGs) measured the incident wave amplitudes, allowing analysis of the relation between solitary wave height and the resulting wave pressure. Generally, a tsunami can propagate over a long distance without breaking. To ensure non-breaking conditions, the relative wave height (H/h) was set to range between 0.1 and 0.3. The still-water depth was kept constant at 0.25 m for considering the heights of structures. To analyze the characteristics of incident waves, WG 2 was installed at an appropriate distance from the test structure. The theoretical wavelength of a solitary wave is infinity. The measurement of solitary wave pressure was measured by 4 pressure transducers, which has high response time, 120 kHz, for abnormal pressure and impact pressure. Wave pressures were measured at 0.02, 0.05, 0.9, 0.12, 0.16 m and 0.19, 0.23, 0.26 m in twice under same wave height conditions. In this study, we focused on measuring the maximum pressure (P) and calculating the horizontal force (F_s) on the front faces of structures. It is generally accepted that the relations of structures width (B) and wave flume width (W) should be between 0.1 and 0.15 to avoid lateral wall effects. For the tsunami-like waves, Nouri et al. (2010) identified that a blockage ratio under 0.4 shows stable results according to their experiments which were changed to structure width and measured velocities around structures. We set up structures of both width (B) and diameter (D) equal to 0.2 m, for which the blockage ratio (B/W) was determined to be 0.33.

2.2. Incident wave height

Fig. 2 shows that wave profiles of solitary waves were compared at WG 1, 2 and 3. In the figure, t is measurement time, t^* is arrival time of wave crest. In this research, we considered a delicate difference that the wave height measured at WG 1 was higher than those measured at WG 2 and WG 3, which can be attributed to bottom friction. We need to find out an accurate incident wave height affected for relations of pressures. Goring (1978)proposed equations to calculate the wavelength of the solitary wave; based on this information, the wave gage can be installed at a suitable distance from structure. After calculating the wavelength of the solitary waves, the WG 2 was installed 0.9 m upstream of the structure to monitor the incident wave

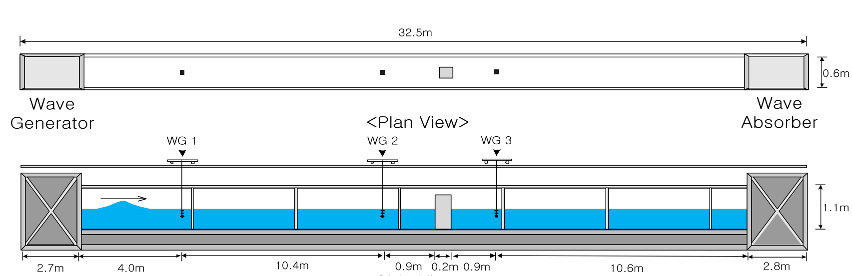

Fig. 1. Schematic layout of wave tank and wave generator.