Coastal Engineering 117 (2016) 157–165

Contents lists available at ScienceDirect

Coastal Engineering

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

Effect of overflow and seepage coupling on tsunami-induced instability of caisson breakwaters

Shinji Sassa *, Hidenori Takahashi, Yoshiyuki Morikawa, Daiki Takano

Port and Airport Research Institute, National Institute of Maritime, Port and Aviation Technology, National Research and Development Agency, 3-1-1 Nagase, Yokosuka 239-0826, Japan

ARTICLE INFO

Article history:
Received 18 March 2016
Received in revised form 29 July 2016
Accepted 8 August 2016
Available online 23 August 2016

Keywords:
Tsunami
Overflow
Scour
Seepage
Caisson breakwater
Rubble mound

ABSTRACT

In this study, a new tsunami overflow-seepage-coupled centrifuge experimental system was developed and applied to investigate the concurrent processes, and to elucidate the mechanism, of the instability involving the scour of the mound/sandy seabed, bearing capacity failure and flow of the foundation, and the failure of caisson breakwaters, with high-resolution image analysis. A series of experiments were conducted with and without the effects of the seepage by keeping the same overflow conditions (water volume, overflow velocity, fall height and water depth), and with different mound cross-sections. All of the experiments were conducted under 50 gravities and comprised of 3 series. The first series of experiments targeted the instability of the mounds themselves by constraining the caisson movement (sliding and overturning). The second series of experiments then allowed the caisson movement and clarified how the mound scour would affect the overall stability of the caissons. The third series of experiments examined the effect of a countermeasure on the basis of the results from the two series of experiments. The experimental results first demonstrated that the coupled overflow-seepage actions promoted the development of the mound scour significantly. Notably, the scour front developed in the form of progressive slip failure at the vicinity of caissons, regardless of the mound thickness. This stems from the fact that the development of the mound scour shortened the seepage path around the shoulder area of the mound, enhancing the coupling effect of the overflow and seepage. Indeed, the scour stopped far from the caisson toe in the absence of seepage without affecting the stability of the caissons. By contrast, the scour development due to the coupled overflow-seepage approached the caisson toe and brought about bearing capacity failure of the mound, resulting in the total failure of the caisson breakwater, which otherwise remained stable without the coupling effect. The velocity vectors obtained from the high-resolution image analysis illustrated the series of such concurrent scour/bearing-capacity-failure/flow processes leading to the instability of the breakwater. The influence of placing an embankment as a countermeasure was also examined by employing different bank thickness. It is shown that the stability of the breakwaters was significantly improved with decreasing hydraulic gradient that manifested underneath the caissons due to the embankment effect. These findings will facilitate better assessment and improvement of the stability of caisson breakwaters with rubble mound foundations.

1. Introduction

The 2011 Tohoku earthquake tsunami devastated the eastern part of Japan and caused significant damage and destruction of breakwaters. The key factors contributing to the damage have been considered to be closely linked with the scour of the mound in the vicinity of breakwaters due to tsunami-induced overflow above the caissons (Arikawa et al., 2012; Arikawa and Shimosako, 2013). The seepage flow in mounds, stemming from the water level difference between offshore and onshore sides of the caissons, has also been considered to affect the stability of mounds (Takahashi et al., 2014; Sassa, 2014). However, the concrete mechanism at work in the instability of the breakwater foundation under the concurrent actions of the overflow and seepage due to a tsunami still remains unclear.

The role of tsunami-induced overflow in the performance of coastal structures has attracted recent attention in view of the stability of breakwaters, seawalls, tidewalls and dikes (Hsiao and Lin, 2010; Gulera et al., 2015; Kihara et al., 2015; Shimozono and Sato, 2016). The role of seepage in tsunami or wave-induced scour around coastal and marine structures has also been studied recently (Sumer and Fredsøe, 2002; Tonkin et al., 2003; Qi and Gao, 2014; Sumer, 2014). However, the role played by coupling of overflow and seepage in scour and the effect of this coupling on the stability of coastal structures remain poorly understood.

Against this background, the aims of this paper are, first, to clarify the processes involved in and the development of the mound scour due to tsunami-induced seepage and overflow, and secondly to investigate how the coupling actions affect the overall stability of caisson

---

* Corresponding author.
E-mail address: sassa@ipc.pari.go.jp (S. Sassa).

http://dx.doi.org/10.1016/j.coastaleng.2016.08.004

breakwaters. For this purpose, we have developed and applied a new centrifuge experimental system which is capable of controlling the overflow and seepage due to a tsunami. A concise report of preliminary experiment using the system developed was promptly published in Sassa et al. (2014). However, this paper presents and discusses three innovations, namely, (a) by elucidating the effect of overflow and seepage coupling on the development of mound scour as obtained from the experiments with different mound cross-sections and thickness, (b) by clarifying how the overflow and seepage coupling would contribute to the collapse of caisson breakwaters, revealing the mechanism for the concurrent processes of the instability involved, and (c) by examining the influence of a countermeasure in suppressing such an effect of coupled overflow and seepage on stabilization of the caissons. The present study is based on the results of our recent study on the effect of tsunami-induced seepage on the stability of mounds in caisson breakwaters (Takahashi et al., 2014; Sassa, 2014).

2. Tsunami overflow–seepage coupled centrifuge experiment

2.1. Experimental system

It is essential to reproduce a prototype-scale stress field in the mounds that support breakwaters in order to clarify the instability of the breakwater foundations in the presence of a tsunami. A geocentrifuge makes this possible and has proved effective in studying fluid–soil interaction problems (Sassa and Sekiguchi, 1999). Indeed, the role and importance of centrifuge testing in the field of coastal and ocean engineering has recently been emphasized (Sumer and Fredsøe, 2002; Sumer, 2014). In this study, we developed and applied a new centrifuge experimental system that can simulate the combined actions of overflow and seepage due to a tsunami.

Tsunami model experiments usually model tsunami as solitary waves and thus cannot distinguish the effects of the overflow on and seepage in the mounds due to a tsunami. By contrast, in this study we constructed a system that can independently control the tsunami-induced overflow volume/rate and the water level differences causing the seepage, as shown in Fig. 1. The figure shows the system before being mounted on a centrifuge at the Port and Airport Research Institute. The mariotte water supply tank utilizes the principle of a "mariotte bottle" which enables a constant rate of flow at a constant pressure by setting the air-open interface in the tank at a prescribed location. The principle is schematically shown in Fig. 1, where the pressure at the bottom of the inlet tube is equal to atmospheric pressure, and as long as the level of water inside the tank is above the bottom of the inlet tube, the pressure at the exit hole remains constant at ρ*gh*, realizing a constant rate of flowage. The overflow–seepage division unit controls and divides the outflow for seepage and overflow. The tank has a vertical partition that contains several drainage holes at given heights by which to set the water level difference between the inside and outside of the caisson in the range 0–200 mm in the model, corresponding to 0–10 m under fifty gravities (50 G) on the prototype scale.

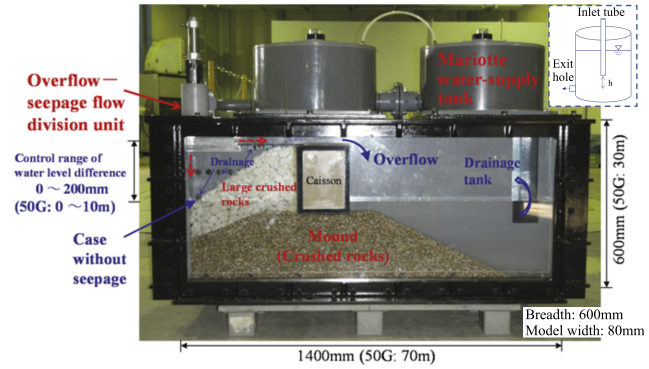

Fig. 1. Developed tsunami overflow-seepage-coupled centrifuge experimental system: The panel schematically shows the principle of the mariotte water-supply tank. Set-up for Series 1 is shown.

In selecting the mound material, a similitude of the seepage flow in the mound was considered together with the mechanical similarity between the model and the prototype. Specifically, the seepage flow in the mound becomes turbulent due to the high permeability of the mound (crushed rock). In this respect, a series of modeling tests were conducted, showing that one can satisfy the similitudes concerning the stress state and the turbulent seepage flow by using $1/N$-th diameter stone as a mound material under an N-g centrifugal field in a $1/N$-th scale model in light of a prototype in the field (Takahashi et al., 2014). In the present experiments, the mound materials had a mean grain diameter of 5 mm and the underlying sand layer had a median grain diameter of 0.18 mm. The theoretical background and the similitudes for the overflow–seepage coupled centrifuge experiment are summarized in Appendix A.

The overflow control capacity of the tank is shown in Fig. 2. Here, the overflow velocity was identified through image analysis, and the number in the parenthesis shows that on the prototype scale. This figure shows that a constant rate of overflow was maintained for a given water volume in the tank, and the duration of the constant flow rate increased with increasing water volume in the tank. Accordingly, the system realized a constant-flow-rate duration of about 10 min. on the prototype scale with an overflow speed equal to 4 m/s, which corresponds to a typical overflow state as observed during the 2011 off the Pacific coast of Tohoku Earthquake Tsunami (Arikawa et al., 2012).

2.2. Experimental design

A series of the overflow–seepage coupled centrifuge experiments using the newly developed system described above were conducted, first to investigate the stability of the mounds, and second to clarify how it would affect the overall stability of the caisson breakwaters. The centrifugal acceleration was set at 50 G. Three series of experiments were performed. In the first series (Series 1, see Fig. 1), in order to elucidate the effect of the seepage on the overflow scour, the overflow conditions, including the overflow volume, velocity, falling height from the caisson and the water depth above the mound, were all kept constant, and then the results with and without the seepage were compared. In the cases without the seepage, the water level difference between inside and outside of the caisson was set at zero, with reference to Fig. 1. In the cases with the seepage, a water level difference equal to a maximum of 8 m on the prototype scale was imposed. This maximum state means that it required some time to set-up the targeted water level difference during the experiment. The development of the mound scour was examined for two different sets of the mound width and slope, specifically 5 m and 3.5 m widths and 1:2 and 1:1.5 slopes, along with a caisson width of 10 m on the prototype scale. On the basis of these results, Series 2 examined the influence of the mound thickness on the stability of the mounds. All of the experiments in Series

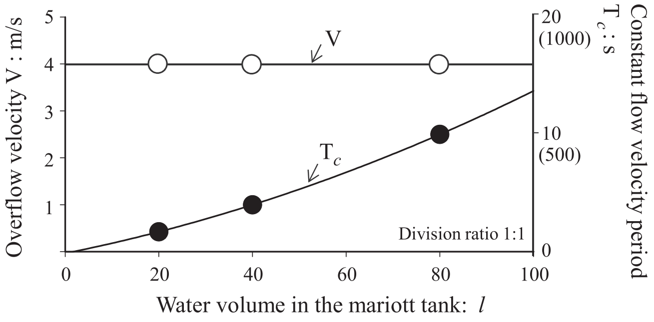

Fig. 2. Control capacity of the overflow in the tank. The values in parentheses represent those on the prototype scale. T_c represents a period where a constant flow velocity ensued.