Applied Ocean Research 67 (2017) 188–200

Contents lists available at ScienceDirect

Applied Ocean Research

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

Extreme wave run-up and pressure on a vertical seawall

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ARTICLE INFO

Article history:
Received 4 March 2017
Received in revised form 24 July 2017
Accepted 25 July 2017
Available online 4 August 2017

Keywords:
Extreme sea states
Wave pressure
Wave run-up
Fully nonlinear potential flow theory
Coastal vertical seawall

ABSTRACT

The performance of coastal vertical seawalls in extreme weather events is studied numerically, aiming to provide guidance in designing and reassessing coastal structures with vertical wall. The extreme wave run-up and the pressure on the vertical seawall are investigated extensively. A time-domain higher-order boundary element method (HOBEM) is coupled with a mixed Eulerian-Lagrangian technique as a time marching technique. Focused wave groups are generated by a piston wave-maker in the numerical wave tank using a wave focusing technique for accurately reproducing extreme sea states. An acceleration-potential scheme is used to calculate the transient wave loads. Comparisons with experimental data show that the extended numerical model is able to accurately predict extreme wave run-ups and pressures on a vertical seawall. The effects of the wave spectrum bandwidth, the wall position and the wave nonlinearity on the wave run-up and the maximum wave load on the vertical seawall are investigated by doing parametric studies.

1. Introduction

Extreme waves, which are also known as freak waves, rogue waves or killer waves, are relatively large and rare local water surface elevations that pose potential threats even to navigation vessels and offshore structures. The occurrence of extreme waves has been well documented and is believed to be responsible for many reported accidents. A list of eleven documented catastrophic ship collisions off the Indian Coast of South Africa was reported as a result of freak waves [1]. Lavrenov [2] found that the mechanism of wave concentration due to Agulhas counter-current may explain the formation of these freak waves. Sand et al. [3] identified several freak waves on the Danish Continental Shelf, which were found to be responsible for the platform damage at the Ekofish field in the Norwegian Sector of the North Sea. Observations of freak waves in many areas of the World Ocean suggest that freak waves not only exist in offshore deep water but also occur in coastal zones. Freak wave phenomena on-shore, which result in sudden unexpected flooding of coastal areas and strong impacts on coastal structures, were described in Refs. [4,5]. There were 140 freak wave events being observed in the coastal zone of Taiwan from 1949 to 1999 [6]. It was found that six out of nine freak wave events in 2005 occurred nearshore [7].

Extreme conditions must be considered in the design of coastal structures to ensure safety and stability of these structures, given that over 80% of reported past freak wave events occurred in shallow waters or coastal areas [3,8,9]. Vertical wall-type structures have been widely adopted as the coastal protection structures, with the advantages that they are able to reflect incidental wave energy almost completely and provide a calm zone for safe berthing of vessels. Additionally, it is found that the sloping walls lead to an increase in the run-up by up to 55% [10] and experience larger wave loading and pressures [11] when compared to those for the vertical seawalls. Thus, accurate prediction of the extreme wave loading on vertical seawalls is important and forms a focus of this study.

In the existing design methods, extreme waves are usually simulated by periodic waves with the wave height and the wave period corresponding to identified extreme conditions. Extensive research has been carried out for investigating pressures on vertical walls due to regular waves, such as Refs. [12–14]. The Goda formula [12] is one of the most popular equations for the design of coastal structures, and has been adopted by Japan Standard for estimating wave forces on vertical walls [37]. Lin [15] carried out a series of experiments to measure pressures on vertical breakwaters in the

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http://dx.doi.org/10.1016/j.apor.2017.07.015
0141-1187/

presence of regular waves and found that the pressure distributions on vertical walls are different from those predicted by Goda's theory.

The random and broad-banded nature of ocean waves cannot be taken into account by using regular waves. This often leads to inaccuracy in the estimation of fluid loading for practical applications. The experimental study in Ref. [16] shown that the maximum pressure on the vertical wall due to irregular waves is larger than that in regular waves near the still water level. Chiu et al. [17] found that the use of regular wave leads to an underestimation of wave forces acting on vertical breakwaters by comparing the results of regular waves and irregular waves. They found that the Goda formula [12] would either under-estimate or over-estimate the wave forces on the vertical wall. More studies on random wave impacting on vertical walls can be found in Refs. [18–20].

Random wave simulation is very inefficient due to requirements of very long run-time in order to capture near-extreme events. Wave reflection due to finite sized tanks is another issue in long time-domain simulations. An accurate description of the average shape of an extreme event, in which a single large event formed by focusing all wave components tapers away either side of the large crest, provides a good alternative to random waves. This type of extreme events is commonly referred to as a focused wave group in which both the frequency spectrum and phase of the wave components are carefully controlled so that the constructive interference occurs at one point in space and time. Tromans et al. [21] proposed a design formulation to describe the mean shape of an extreme event, and this formulation has subsequently been validated by comparing with field measurements in Ref. [22]. Baldock et al. [23] presented a series of physical experiments in which a large transient wave group was produced by focusing a large number of wave components. The focused wave group technique has also been used for studying extreme events from a given random sea-state of known spectral content [24–31].

To date, the knowledge on wave pressures due to focused wave groups on vertical seawalls is still rather limited. Improved understanding of spectral and extreme characteristics of wave pressure on a vertical seawall has the potential to lead to better and safe designs of coastal and offshore structures. In this paper, the fully nonlinear numerical model developed to study the evolution of the focused wave group in Ref. [32] is extended in this research. The present work is focused on the assessment of how the extended fully nonlinear numerical model performs when applied to investigate extreme wave loading on a vertical seawall. The model solved the Laplace equation for describing the fluid motion based on the time-domain higher-order boundary element method (HOBEM). A new input boundary condition is proposed to generate focused wave groups by imitating wave paddles in real wave tanks. The numerical results are compared with published experimental data, and favorable agreements are achieved. The variations of wave pressure along the wall height are presented and the effect of wave spectra on the wave pressure distribution is subsequently investigated.

2. Numerical method

The concerned problem can be described as an initial-boundary value problem mathematically and solved by a time-domain higher-order boundary element method (HOBEM) in which a mixed Eulerian-Lagrangian technique and a 4th – order Runge-Kuatta scheme are applied as a time marching technique [32]. The present model is an extension to the model developed in Ref. [32] where a fully nonlinear solution of Laplace equation was obtained with a set of addition constraints for describing the evolution and wave kinematic of focused wave groups. In the present model, new boundary

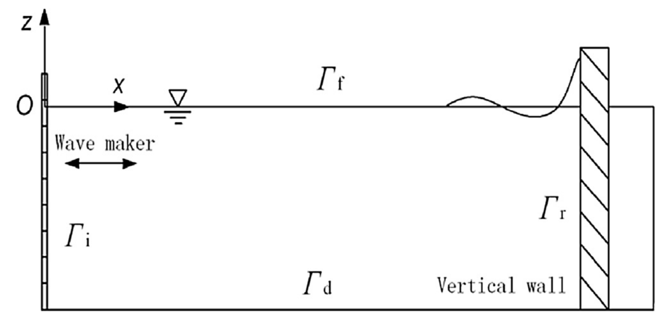

Fig. 1. Definition sketch of the wave flume to give a general idea of the numerical set-up.

conditions are added to extend the capacity of the numerical model in Ref. [32] in simulating the interaction between focused wave groups and vertical seawalls. The underlying equation and algorithm are summarized in this section.

2.1. Governing equation and boundary conditions

The simplified geometry of an extreme wave hitting on a vertical seawall is shown in Fig. 1. A Cartesian coordinate system *Oxz* is introduced such that the origin *O* is in the plane of the undisturbed free surface, $x=0$ at the left end of the domain, z positive upwards. It is assumed that the fluid is incompressible, inviscid and the flow irrotational so that a velocity potential $\phi\,(x, z, t)$ exists and satisfies the Laplace equation inside the fluid domain Ω,

$$\nabla^2\phi = 0, \text{ in}\Omega \tag{1}$$

The fluid domain Ω is bounded by the instantaneous free surface Γ_{f}, the flume bottom Γ_{d} and the vertical end-wall Γ_{r} as well as the input boundary Γ_{I} on which additional constraints are posed to ensure a unique solution. That is, both the fully nonlinear kinematic and dynamic boundary conditions are satisfied on Γ_{f}, and on both Γ_{d} and Γ_{r}, the rigid and impermeable boundary condition is satisfied,

$$\begin{cases} \dfrac{Dx_s}{Dt} = \nabla\phi, \ \dfrac{D\phi}{Dt} = -g\eta + \dfrac{1}{2}\nabla\phi\cdot\nabla\phi, & \text{on } \Gamma_{\mathrm{f}} \\ \dfrac{\partial\phi}{\partial n} = 0, & \text{on } \Gamma_{\mathrm{d}} \text{ and } \Gamma_{\mathrm{r}} \end{cases} \tag{2}$$

where g represents the acceleration due to gravity, x_s denotes the position vector of a fluid particle on the free surface, η is the instantaneous free surface elevation and D/Dt is the material derivative.

Additionally, rather than [32] in which focused wave groups were generated by specifying the velocities on the inlet boundary based on experimental measurements, incident waves here are generated by a piston-type wave-maker in which the motion of the wave-maker S and its velocity u_p are prescribed on Γ_{I}.

$$\begin{cases} S = S_a \ \sin\ \omega t \\ u_p = S_a \ \cos\ \omega t \end{cases}, \quad \begin{cases} S = \displaystyle\sum_{i=1}^{N} S_{a,i} \ \sin\,(k_i x_p + \omega_i(t-t_p)) \\ u_p = \displaystyle\sum_{i=1}^{N} S_{a,i}\omega_i \ \cos\,(k_i x_p + \omega_i(t-t_p)) \end{cases} \quad \text{on } \Gamma_{\mathrm{I}} \tag{3}$$

The first of these expressions is for regular waves, the second is for focused wave groups, where s_a and ω are the stroke and the angular frequency of the wave-maker, respectively. For focused wave groups, N is the total number of wave components, k_i and ω_i are the wave number and the angular frequency of the ith wave component satisfying the dispersion relation ${\omega_i}^2 = gk_i\tanh k_i h$. x_p and t_p denote the focal position and the focal time, respectively.