Ocean Engineering 159 (2018) 268–279

Contents lists available at ScienceDirect

Ocean Engineering

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

Study on tsunami force mitigation of the rear house protected by the front house

Wanli Yang [a,b], Zhibin Wen [c], Fuhai Li [b,*], Qiao Li [d]

[a] Key Laboratory of High-speed Railway Engineering, Ministry of Education, Chengdu 610031, China
[b] School of Civil Engineering, Southwest Jiaotong University, Chengdu 610031, China
[c] JZFZ Architectural Design Co.Ltd, Chengdu 610023, China
[d] Department of Bridge Engineering, School of Civil Engineering, Southwest Jiaotong University, Chengdu 610031, China

ARTICLE INFO

Keywords:
Tsunami bore force
Mitigation effect
Modeling
Onshore structure
Computational fluid dynamics (CFD)
Residential house

ABSTRACT

The investigation of tsunami bore force mitigation is important to new houses design around already built houses. The tsunami bore is simulated by dam-break wave in the 3D numerical flume built by commercial software ANSYS Fluent, the numerical model is validated by the physical experiment. The tsunami in-line force time history of detached house without protecting barrier is divided into four stages and the characteristics of each stage are analyzed. The influencing parameters of the mitigation effect in the above four stages, including α (the relative clear distance between the front and rear houses) and β (the relative bay width of the front house), are studied elaborately. Further the mechanism of the influence of α and β are explored. Results show the tsunami in-line force on the rear house can be remarkably smaller (even become minus), or slightly larger than the case without front house when α and β changes, characteristics of the reconstruction bore behind the front house, including completeness of bore, bore height, velocity, etc. are responsible for the tsunami force changes on the rear house. At last the chart of mitigation index varies with α and β is presented.

1. Introduction

In the beginning of the 21st century, two devastating tsunamis happened and caused terrific loss of life and serious destructions to the coastal infrastructures. About 200 thousand people were killed and lots of infrastructures were destroyed in the 2004 Indian Ocean Tsunami. And tens of thousands of deaths and missing was reported and many bridges, residential houses and harbors, especially the nuclear power station, were destroyed in the 2011 Japan Tohoku Tsunami. The generation of tsunami could not be controlled by human but researches on how to optimize the structures to increase the resist ability are meaningful and practical.

Many researchers have devoted to the tsunami forces on coastal structures, i.e. the characteristics, influence parameters and calculation methods of tsunami forces have been investigated intensively. Shoji and Hiraki (2011) carried out hydraulic experiments to clarify a tsunami wave load on a bridge deck subjected to different breaker bores. Results show the averaged values of drag coefficient is 1.52 for surging breaker bores, and 1.56 for plunging breaker bores. Hamzah et al. (2001) numerically and experimentally investigated hydrodynamic pressure of a bore on a vertical barrier. The bore impact on the vertical wall is identified and correlated with the incident wave kinematics. The results show two types of pressure peaks: impulsive pressure, and followed by the standing wave pressure. Al-Faesly et al. (2011) conducted physical experiment on a large-scale model of onshore structure to test the pressure distribution around the model and total net forces when the model subjected to tsunami bores. Results show the flume bed conditions (wet or dry), bore water level have influence on time histories of pressure and force. The bore force profile demonstrates the existence of three major components of the hydrodynamic force: impact, runup and quasi-steady hydrodynamic.

And also tsunami forces on coastal houses have been widely studied. Thusyanthan and Madabhushi (2008) studied the tsunami wave loading on coastal house, compared the impact of a tsunami wave on a typical coastal house with that on a new tsunami resistant design. Results reveal how the tsunami wave passed through the new house design without damaging it but severely damaged the typical coastal house. Lindt et al. (2009) studied the tsunami bore forces on a compliant residential building model. The lateral displacement under each wave impact was measured in Oregon State University's tsunami wave basin by using a

---

* Corresponding author.
E-mail addresses: 68360903@qq.com (W. Yang), 475832547@163.com (Z. Wen), 459139277@qq.com (F. Li), ql3721@163.com (Q. Li).

https://doi.org/10.1016/j.oceaneng.2018.04.034
Received 31 October 2017; Received in revised form 9 April 2018; Accepted 10 April 2018

one-sixth scale building model. And an experimental load-deformation relationship was determined for a nominally identical one-sixth scale model in the Colorado State University structure laboratory. Robertson et al. (2013) carried out a series of experiments in the large wave flume at Oregon State University to quantify tsunami bore forces on structures. Results show the bores propagated with a Froude number of approximately 2 and that the forces follow Froude scaling. And a design formula for the maximum impact force is presented. Heintz and Mahoney (2008) investigated the feasibility of designing vertical evacuation structures providing refuge for tsunami inundation area. The FEMA P-646 (2008) introduced the guidelines for design of structures for vertical evacuation from tsunamis, and suggested the recommendations on siting concepts, performance objectives, design loads and load combinations for locating and designing tsunami vertical evacuation structures.

The mitigation effects caused by protecting barriers in front of the coastal structures are seldom investigated. Crespo et al. (2007) reported that the protecting barriers (dikes and seawalls) could mitigate the force and moment exerted on the structures in terms of the dike height and the distance from the dike to the structures. Wei and Dalrymple (2016) used GPUSPH to investigate tsunami forces on bridge superstructures and tsunami mitigation on bridges by employing a service road bridge and an offshore breakwater. It is found that a two-girder service road bridge is effective in reducing tsunami forces on the main bridge. Furthermore, a breakwater can also reduce tsunami force on a bridge and there is an optimal distance (about eight times of the local water depth or 13 times of the incoming tsunami height) between the breakwater and the bridge to achieve the best reduction effect. Wijatmiko and Murakami (2012) used three-dimension numerical simulation based on modified Navier-Stoke equations and VOF model to study the tsunami bore inundation flow around cylindrical structure surrounded by weir. Results indicate that the existence of protective weir significantly reduce wave velocity inside the protective weir.

Tsunami wave often breaks nearshore, then transforms into a hydraulic bore that has a uniform depth and infinite wavelength with a steep and turbulent bore front. Ordinarily there are two ways to generate tsunami bores in laboratory or in numerical simulation. One is to generate a solitary wave by wave-maker in the wave flume or in the wave basin, and the solitary wave will break and transform into bores at the slope of the flume end because of the shoaling effect. The tsunami bores and the resulting force on structures generated in this way has been employed by Lukkunaprasit et al. (2008), Oshnack et al. (2009), Thomas and Cox (2012), Wang et al. (2014), Ghosh et al. (2016), Pringgana et al. (2016), etc.

Another way is to simulate tsunami bore by using dam-break wave. The water flume with the flat bottom is separated into two parts by a gate, the upstream of the gate acts as a reservoir and the downstream acts as dry bed without initial water or wet bed with a smaller depth of water, representing the structures have already been inundated before the attack by the largest tsunami bore. When the gate is removed away quickly, the water breaks down from the upstream then transform into bores. Chanson (2005, 2006) showed the analogy between a tsunami-induced bore and the dam-break hydraulic bore, and demonstrated the correctness of using dam break bore to quantify the effects of tsunami-induced bores on the structures. Based on these points, many researchers, i.e. Crespo et al. (2007), Douglas and Nistor (2015), Motley et al. (2015), Árnason et al. (2009), Triatmadja and Nurhasanah (2012), Rahman et al. (2014), etc. applied dam break bore to simulate the tsunami induced bore experimentally and numerically. The method of generating tsunami bore by dam break wave is adopted in this study, as the dam break wave is relatively convenient to be generated both in laboratory and in CFD, compared with the generation of the solitary wave. In addition, the wave height, cross-section velocity of tsunami bore could be formulated using downstream initial water depth and upstream water depth, i.e. the formulations presented by Stoker (1957) for wet bed cases and by Chanson (2005) for dry bed cases respectively. Vice versa, by using these formulations, upstream water depth and downstream initial water depth of generating a tsunami bore with designated wave height and cross-section velocity could be estimated, which will greatly facilitate the design of experimental scheme.

Generally, the investigation of tsunami bore force mitigation on the residential houses caused by the front houses has not been reported. The mitigation effect and its influencing factors are important to build new houses around already built houses. This study employs commercial software ANSYS Fluent to investigate tsunami forces mitigation on the rear house protected by the front house, and the influencing factors such as relative clear distance between the front and rear houses, relative bay width of the front house are studied elaborately.

2. Numerical simulation method

2.1. Basic equations

The numerical simulations in this study employ a well-established finite-volume numerical code, called ANSYS Fluent to calculate all the cases. The numerical code Fluent solves the Reynolds Averaged Navier-Stokes (RANS) equations, in which the conservation of mass and the conservation of momentum are, respectively:

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\mu}{\rho}\frac{\partial^2 U_i}{\partial x_j \partial x_j} + \frac{1}{\rho}\frac{\partial\left(-\rho\overline{u_i^{'} u_j^{'}}\right)}{\partial x_j} \tag{2}$$

where U_i is the time-averaged velocity in which the indices i and j represents the directions of the coordinates (x, y, z): note that this index-based notation implies the sum over a repeated index in terms involving multiple indices. The time-averaged velocity can be defined as $U_i = \frac{1}{\Delta t}\int_{t_0}^{t_0+\Delta t} u_i dt$, where the flow velocity can be decomposed to $u_i = U_i + u_i^{'}$, $u_i^{'}$ is the velocity fluctuation, P is the time-average pressure, ρ is the density of water, and μ is the dynamic viscosity. The computational domain consists of water and air, and VOF method is employed to trace the water surface height. As the dam-break bores will deform and break intensively during their generation and advancing process, especially when interacting with structures, so RNG $k-\varepsilon$ turbulent model is chosen. The turbulence kinetic energy k, and its rate of dissipation ε, are calculated from the following equations:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\alpha_k \mu_{eff}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon \tag{3}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho\varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\alpha_k \mu_{eff}\right)\frac{\partial\varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}G_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{4}$$

In which, $G_k = -\rho\overline{u_i^{'} u_j^{'}}\frac{\partial u_j}{\partial x_i}$, $\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$, the constants $C_\mu = 0.0845$, $C_{1\varepsilon} = 1.42$, $C_{2\varepsilon} = 1.68$. In the near-wall region of structure, the solution gradients are much high, so the calculations in the near-wall regions are critical to the precision of simulation. As Reynolds number is large when tsunami bores interact with structures, Scalable Wall Function is chosen to treat the boundary layer. This wall function is able to avoid the deterioration of Standard Wall Function under grid refinement when y^+ is very small. Here $y^+ = \frac{y}{\mu}\sqrt{\rho\tau_w}$, where y is the distance from the wall to the center of the innermost cell and τ_w is the wall shear stress, μ and ρ are dynamic viscosity and density of water respectively. The size of the most inner cell ds is twice of y, and y^+ is set as 60 in this study.

2.2. Validation of the numerical simulation method

In order to validate the numerical simulation method, a numerical testing flume with the same dimensions, say, 16.6 m long, 0.6 m wide and