Investigation of Bridge Failure Caused by Tsunami Based on Numerical Method

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1. Introduction

Bridge failure has been a very series issue through the investigation of 2004 Indian Ocean tsunami and 2011 Tohoku tsunami, which shows us that 81 spans were washed out or heavily damaged of 186 spans existed on the route from Banda Aceh to Meulaboh, Sumatra Island, Indonesia [1], and more than 300 bridges were washed out by tsunami in Japan [JSCE 2011]. Superstructures of some bridges were totally washed out by tsunami which was estimated to be several meters over the bridge deck level. Wardhana et al. (2003) analyzed bridge failures in the United States from 1989 to 2000 and found out the most common cause of bridge failure during that time was the flood. In 1993, because of the Mississippi river and Missouri river flood, there were 85 bridges failed in Iowa. Even in 2005, Hurricane Katrina in the United States caused 38 spans lost and 170 bridges shifted on the eastbound lane and 26 spans lost and 303 bridges shifted on the eastbound lane. Evidences showed that bridges were vulnerable when they were facing the flood, which the water surface height was much higher than the normal designed depth. Although many researchers published some papers on this issue, most of those studies mainly represented the wave or fluid force loading on the bridge or the pressure history acting on the bridge. There are a few papers, which focused on the response of the bridge to the tsunami wave force effect. In this paper, using numerical model with a moving structure procedure, the response of bridge under the load of tsunami wave was investigated. The relationship of tsunami wave effect and bridge failure reason is also discussed.

2. Numerical Investigation

The investigation of the bridge-tsunami interaction was carried out based on a one-fluid formulation for incompressible two-dimensional multiphase flows. The different fluids are modeled as a single continuum obeying the same set of governing equations, with the different fluid identified by a volume fraction function governed by a volume convection equation:

$$\frac{\partial v_j}{\partial x_j}=0 \quad (1) \qquad \frac{\partial v_i}{\partial t}+\frac{\partial v_j v_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+g_i+\frac{\partial}{\partial x_j}\left(\upsilon\frac{\partial v_i}{\partial x_j}+\upsilon\frac{\partial v_j}{\partial x_i}\right)+F_{si} \quad (2) \qquad \frac{\partial f}{\partial t}+\frac{\partial v_j f}{\partial x_j}=0 \quad (3)$$

Where v_i is the i-th velocity vector component, ρ denotes density of fluid, ν is the kinematic viscosity coefficient, p is the pressure, F_{si} is the i-th surface tension vector component calculated from the continuum surface force (CSF) model, g_i is the i-th component of the gravitational acceleration vector, f is the volume fraction to track the interface and the density and kinematic viscosity are computed from the linear interpolation of air and water density using volume fraction as a weight factor.

The method of solution used in the present work is a sequential one, where the Navier-Stokes equations and the continuity equation can be solved first by simplified marker and cell (SMAC) method, and then the volume fraction is calculated using multi-interface advection and reconstruction solver (MARS), one of the piecewise linear interface calculation (PLIC) methods. Detail of the procedure can be found in Nakamura and Yim[3].

Tsunami, which is generated with dam breaking, striking the bridge and acting huge force in both vertical and horizontal directions, makes the bridge failure. The process was analyzed with the immersed boundary (IB) method, which is used to track the movement of the bridge deck and calculate the drag and lift forces acting on the bridge. The critical condition of the bridge failure can be found out through a series of tsunamis with various heights. Figure 1 shows the entail computational domain and Figure 2 shows the description of the bridge cross section we used in this analysis. The deck elevation of the bridge is 27 mm above the still water surface and a ranges of the dam height which is 30mm, 40mm, 50mm, 60mm, 70mm, 80mm, 90mm, 100mm above the still water surface are used to generate tsunami. Although some researchers' studies represented that the maximum tsunami wave pressure increased with the decrease in the bridge elevation, we didn't consider this problem here. To estimate the reason and the situation of the bridge failure, two kinds of research are carried out with a moving bridge to find out the critical case where it starts to move and a stable bridge to find out the maximum force loading on bridge, and finally the critical force loading on the bridge that makes it starts to move can be found.

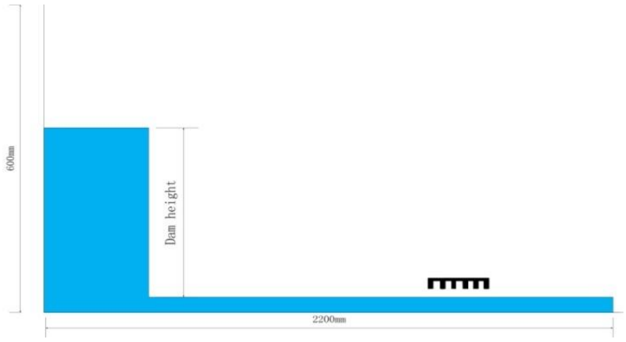

Fig. 1 The computational domain (scale 1/80)

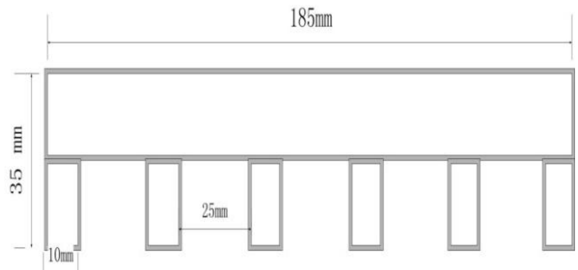

Fig. 2 The cross section of the bridge (scale 1/80)

3. Result and Conclusions

To identify the features of tsunami forces loading on the bridges, we conducted a numerical study with a 1/80 scale model based on the experimental study of Shoji et al [4]. Figure 3 shows the snapshot when the tsunami hits the bridge and makes it failure. The results from the numerical study show that slowly-varying drag force loading on the bridge with long duration caused the failure, which coincides with the investigation of the 2004 Indian Ocean tsunami, in which the main force that washes out the deck was the drag force and bridges with shear keys and connections between superstructure and substructure were rarely damaged in that disaster [1].

For the next step, we will estimate the shear key's effect to a bridge and more results will be discussed in the conference.

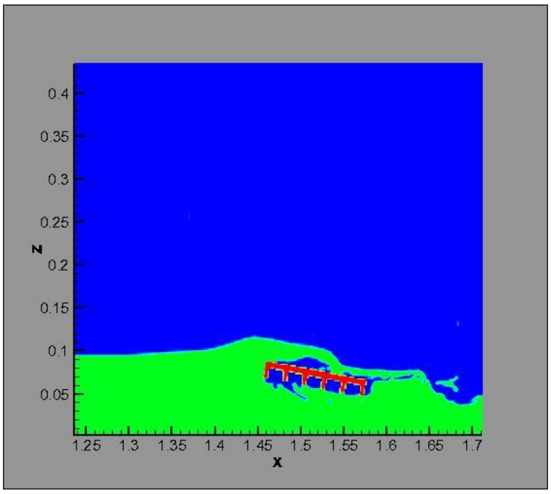

Fig. 3 The free surface when the deck moves

References

[1] S. Unjoh and K. Endoh, 2006, Damage Investigation and the Preliminary Analyses of Bridge Damage Caused by the 2004 Indian Ocean Tsunami, Proceedings of the 38th UJNR Jiont Panel Meeting.

[2] K. Wardhana and F. C. Hadipriono, 2003, Analysis of Recent Bridge Failures in the United States. Journal of Performance of Constructed Facilities, 17 (3), pp.144-150.

[3] T. Nakamura and S. C. Yim, 2011, A Nonlinear Three-Dimensional Coupled Fluid-Sediment Interaction Model for Large Seabed Deformation, Journal of Offshore Mechanics and Arctic Engineering, 133(3), 14p.

[4] G. Shoji, Y. Hiraki, et al., 2010, Experimental Study on Fluid Forces Acting on a Bridge Deck Subjected to Plunging Breakers and Surging Breaker Bores, Journal of Coastal Engineering, Japan Society of Civil Engineering, 56, pp.801-805.