Investigation of Tsunami Hydrodynamic Loads Acting on A Slab Bridge

Hartana

Civil Engineering Department, University of Mataram, Mataram - Indonesia
Corresponding author: hartana@unram.ac.id

Abstract. An analytical approach based on numerical simulation is performed to investigate the mechanism of a slab bridge damages caused by tsunami. This slab bridge was constructed in a parallel bridge structure with the adjacent highway bridge. Tohoku earthquake tsunami flooded and washed away this slab bridge. The CADMAS-Surf numerical model was used to determine the dynamic loads acting on the slab bridge subjected to a bore type tsunami. A series of hydraulic experiments were conducted, and the results were compared to the results obtained from numerical simulation. Numerical results showed good agreement with experimental ones in terms of water surface elevation, wave pressure and force. The validated numerical model was applied to the prototype scale of slab bridge that had 3D geometry. Simulation results showed that the tsunami flow fully overtopped the slab. The horizontal force was relatively smaller than the uplift force, however the total uplift force exceeded the dead load of the slab. This result meant that the tsunami flow uplifted the slab and washed the slab downstream. The effect of the existence of adjacent highway bridge on the characteristic of tsunami inundation and forces acting on the slab bridge is also discussed.

Keywords: bore type tsunami, Slab bridge, Tsunami inundation, Force, Mechanism of damage

1. Introduction
Tsunami caused by Tohoku earthquake in 2011, as well as Sumatra in 2004 and others, had brought fatal damages on many infrastructures such as ports, roads, bridges, lifelines and other important structures. Among those damages especially in Tohoku earthquake, we have found many cases of the damage that the tsunami flow washed away the superstructure of bridges [1-3]. After Indonesian tsunami in 2004, many researchers have been investigating the mechanism of damages on bridges caused by tsunami flow. Those studies mainly deal with the response characteristic of bridge against tsunami attack through hydraulic experiments. Interactions between tsunami and bridges include very complex phenomena, and an analytical approach based on numerical simulation has been desired to understand the bridge structural damages caused by tsunami.

This study investigates the tsunami impacts on a slab bridge through numerical simulation and hydraulic experiment. The investigation was focused on the bridge superstructure, so that the pile and abutment were not modelled in this study. The target bridge is a concrete slab bridge as a bicycle path parallel to the adjacent highway bridge. It is located at the estuary of Kujukurihama River, Chiba, Japan. The bridge width is 4.8m, its length is 19.1m, and the height is 0.6m.

The slab bridge was severely damaged and washed away by Tohoku earthquake tsunami, but the adjacent highway bridge was substantially intact. The tsunami loads could prevail over the structural
resistance provided by the self-weight of the slab bridge and its supporting connections. The slab bridge was dislocated from their supporting piers, washed away by the tsunami flow and then laid down on the adjacent highway bridge.

2. Model Setup

2.1. Hydraulic Experiment

The hydraulic experiments were carried out in a 2D open channel flume with 12.0m in length, 0.4m in width and 0.4m in height. The model scale was assumed about 1/40. The schematic of experimental setup is described in Fig.2. The bridge model was installed across the flume and perpendicular to the tsunami flow. A gate was equipped on the upstream of this flume to provide a head between upstream and downstream. The various heights of bore type tsunami were generated with releasing the amount of volume of water from the water tank by lifting up the gate rapidly. The impoundment depths (h1) of 15cm, 20cm, 25cm and 30cm were set in the water tank. The slab clearance is assigned as 2.6cm, and the downstream water depth was set as 5cm.

![Figure 1](image-url) Experimental setup (unit: cm): (a) Plan view, (b) Side view, (c) Bridge models and pressure gauges setup, (d) Strain gauge setup.

Some pressure gauges were attached on the slab model to measure the pressures. P1, P2 and P3 designate the location of pressure gauges at the top side of slab bridge; P4, P5 and P6 are those at the bottom side; P7 at the front face and P8 at the rear face. The water surface elevations were measured at three locations (W1, W2 and W3) by using wave gauges as shown in Figure 1. A strain gauge system was installed to obtain horizontal wave forces and vertical ones.

2.2. Numerical Setup

In this study, CADMAS-Surf (Super Roller Flume for Computer Aided Design of Maritime Structure) model is used in numerical simulations. CADMAS-Surf is a CFD package which solves Navier-Stokes equation and continuity one with applying finite difference method. It has been developed by Coastal Development Institute of Technology Japan for advanced maritime structure design [4]. CADMAS-Surf model can solve the fluid motion around a structure with arbitrary cross section. This method employs fractional VOF method to trace the free water surface. The κ–ε turbulence model is used in the numerical model. A structured rectangular grid is assigned for the computational domain. The slab bridge is constructed as an obstacle in the numerical model.

In the numerical simulations, the generation of bore type tsunami requires a time history of water surface elevations and wave velocities. The water surface elevation sat W1 were obtained from the hydraulic experiments and were prescribed as bore tsunami forcing boundary conditions on the face of
input boundary. The quantity of the inflow properties is assumed uniformly distributed on the face of input boundary at each time step. Wave velocity were estimated from the time series water surface elevation by employing an analytical formula proposed by Fukui et al [5].

3. Verification of Simulation Results

3.1. Water Surface Elevation

Figure 2 shows the time history of water surface elevations at W2 located in front of slab bridge. As it can be seen in this figure, the results obtained from numerical model agree well with experimental ones in terms of wave profile and maximum wave surface elevation level for each impoundment height, though the maximum water surface elevations obtained from numerical model are slightly overestimated the measured ones.

![Figure 2. Profiles of water surface elevation at W2 located in front of the slab bridge model](image)

3.2. Pressure Profile

Figure 3 presents the maximum normalized sustain pressure profile acting on slab bridge for all impoundment heights. The normalized pressure was obtained by normalizing the maximum pressure with the hydrostatic pressure based on the bore height at W1. The numerical results correlate well with measured ones, though there are little differences.

![Figure 3. Comparison of normalized initial and sustain pressure acting on slab bridge model: (a) the front and rear face (b) the top and bottom side](image)

3.3. Force Profile

The profile of uplift forces acting on the slab with h1=20cm is presented in Figure 4. The numerical results correlate well with measured ones. The experiments and simulations can observe the initial force when the bore hit the structure. At the moment of the bore hit the bridge, the initial force sharply increases in a short duration. Then the flow consistently inundated the bridge and overtopped the slab.
For vertical force, it leads to generate the downward load that its magnitude is higher than the uplift force and causes the negative values of the sustain forces.

The comparison of maximum initial uplift forces and maximum sustain uplift forces with various bore heights can be seen in Figure 5. In this study, maximum initial forces refer to the maximum positive forces (lifting upward) and maximum sustain forces refer to the maximum negative (pushing downward) forces results obtained from the experiments and numerical simulations. Good agreement can be seen both in maximum initial forces and maximum sustain ones on various bore heights.

Good agreement resulted from the model validation in terms of the water surface elevations, pressures and forces has produced qualitative and quantitive evidences that the numerical model can be used to reproduce the slab bridge prototype. Then, the validated numerical model is implemented for the simulation of the slab bridge prototype that had a 3D geometry.

![Figure 4. Profiles of force with h1=20cm: (a) Horizontal force (b) Vertical force](image)

![Figure 5. Comparison of maximum uplift wave forces: (a) Initial force (b) Sustain force](image)

### 4. Simulation of the Damage of Slab Bridge

#### 4.1. Numerical Simulation Configuration

Figure 6 presents the computational domain of 3D simulation. The computational domain was constructed in an anisotropic mesh. The grid size varied from 1.0m to 0.5m for horizontal axis of x and y; and 0.6m to 0.2m for z vertical axis. The mesh is denser in the vicinity of bridge. As shown in this figure, measurement points of water level elevations (WL1-WL8) were assigned to obtain the wave propagation in the river mouth and tsunami inundation at the land area in the vicinity of observed slab bridge.
In this study, the slab bridge is subjected to the tsunami height of around 2.2m at the field. The slab bridge was about 2.6m above the water level, whereas the water depth in the river is 1.0m. The profiles of water surface elevation and velocity prescribed on the input boundary are presented in Fig. 8. The other numerical input data was set as 1,200 kg/m³ for fluid density. By considering the tsunami water contains entrained sediment, mud and debris; FEMA recommends density of 1,200 kg/m³ (1.2 times the freshwater density 1,000 kg/m³) for sea water in the conservative sensitivity analysis of tsunami forces calculation [6].

4.2. Tsunami inundation
Figure 8 presents the result of tsunami wave propagation obtained from numerical simulation. The bore wave hit the slab bridge at around t=10sec, and the tsunami continued to flow over the bridge. Even though the incoming bore height is 2.2m and the elevation of the top side of slab bridge is 3.2m above the water level, it can be shown that the tsunami flow was able to submerge the slab bridge. Tsunami wave height increased due to the morphology of the river mouth which its width is gradually narrower to the landward side, as shown in Fig. 7.
Figure 8. Tsunami wave propagation and the inundation over the bridge

The time history of water surface elevation development on 4 measurement points (WL1, WL2, WL3 and WL4 as shown in Figure 6) is presented in Figure 9(a). At WL3 located in front the slab bridge, water level elevation reached up to the elevation of 6.27m and almost twice the height of the slab bridge elevation (3.2m). Figure 9(b) shows the inundation at land area in the vicinity of bridge. It is apparent that maximum inundation at the land area around the bridge is about 2.47m at WL7. At the land area, the inundation depth not only was resulted from tsunami flow, but also was raised by the additional volume of water from the river.

![Graph showing wave pressure and time history](image)

Figure 9. Development of water surface elevation: (a) at the river mouth (b) at land area

4.3. Wave Pressure

Figure 10 present the time history of computed wave pressures resulted from the CADMAS-SURF simulations on the centre of all slab bridge sides. Both initial impact pressures and sustain ones could be simulated well on all sides. The pressure records the peak value at about t=10sec. It can be shown that the values of both initial pressure and sustain ones acting on the front side of slab bridge were higher in comparison with those acting on the other sides, because the front side directly faces the incident wave. Moreover, the sustain pressure acting on the top side is slightly higher than that acting on the bottom side, and this leads to the higher downward pressure acting on the slab bridge.
4.4. Mechanism of damage

In this section, the structural analysis was conducted to investigate the slab bridge failure during tsunami action. The resistance force due to the dead load of slab bridge is compared to the uplift force acting on it. The analysis is based on unit length of the bridge. By ignoring the supporting bolts fixed at the piers, the critical force for the stability of bridge is assumed that the uplift force exceeds the dead load of the slab, or in another word, the slab bridge did not have adequate resistance to prevent the impacts of tsunami loads.

During the submergence of tsunami flow, the slab bridge suffered hydrodynamic uplift force due to the vertical wave impact and hydrostatic uplift force due to the buoyancy. Figure 11 shows the time series of horizontal force and vertical uplift one acting on the slab bridge. The positive magnitudes of initial and sustain horizontal force denotes force in line with flow direction. Whereas the positive magnitude and negative one of vertical forces refer to the lifting upward and pushing downward, respectively. At about $t=10$ sec, the bore wave hit the seaward side of the slab bridge, the initial uplift force sharply increases in a short duration. Then the flow consistently inundated the slab bridge and overtopped the slab. In comparison with the uplift force, the horizontal force (the peak magnitude is 42.69kN) was relatively smaller than the uplift one (274.95kN). It is due to the narrower surface area on which the acting horizontal force acted, even though the front side of slab bridge suffered the highest pressures as shown in Figure 10(c).

**Figure 10.** Time history of pressure acting on the slab bridge
The slab bridge’s weight was determined based on standard density for concrete, i.e. 2,600kg/m³. The slab bridge has a cross-sectional area of 2.88m² (4.8m x 0.6m) and 19.1m in length, resulting the self-weight of slab bridge is 1,500kN, and the self-weight of slab bridge per unit length is 78.5kN.

The uplift forces obtained from the numerical result is 274.95kN, exceeded the mass of the bridge deck (78.5kN). This magnitude is about 3.5 times the dead load of slab bridge. It can be shown that the high magnitude of uplift force was large enough to lift the slab bridge’s weight and then displaced laterally to downstream by the sustain hydrodynamic forces.

4.5. Effect of adjacent highway bridge existence

In order to understand the effect of the adjacent highway bridge on tsunami inundation and wave impact, simulation on two cases of slab bridge of with and no adjacent bridge were carried out. The case of no adjacent bridge was set by removing it from the parallel bridge structure. Figure 12(a) presents the comparison of water surface profile at W2 located in front of the slab bridge between in case of no adjacent highway bridge and with adjacent highway bridge. The existence of adjacent bridge slightly increased the water surface elevation. It is because the adjacent bridge acted as a horizontal obstacle behind the slab bridge while the incoming sustain wave continuously flowed over the bridge. After passing the slab bridge, the existence of adjacent bridge begins to produce slightly higher water surface elevation compare to the case of no adjacent bridge.

The effect of adjacent bridge on the force acting on the slab bridge can be seen in Figure 13(b). The adjacent bridge tended to slightly reduce the sustain force. It can be explained that the higher overtopping wave over the bridge due to the existence of adjacent bridge increased the downward sustain force acting on the slab bridge. However, it can be shown that there is no significant difference of the magnitude of initial uplift force between in case of with and no adjacent bridge highway bridge.
5. Conclusions

CADMAS-Surf numerical model based on Navier-Stokes equations and VOF method has been used to simulate the tsunami dynamic loads acting on a slab bridge model similar to the slab bridge structure which was constructed in a parallel bridge structure with the adjacent highway bridge. This slab bridge was severely damaged by Tohoku tsunami. The numerical results were validated by comparing to the hydraulic experiment results. Numerical results showed good agreement with experimental ones in terms of water surface elevation, wave pressure and force.

The numerical model was applied to the prototype scale that had 3D geometry, and the model investigated the tsunami inundation and dynamic loads on the slab bridge. Simulation results showed that the tsunami flow fully overtopped the slab. The slab suffered the hydrodynamic uplift force due to vertical tsunami action and hydrostatic uplift due to buoyancy. The horizontal force was relatively smaller than the uplift force, and the total uplift force exceeded the dead load of the slab. This result meant that the tsunami flow uplifted the slab and washed the slab downstream. Furthermore, the existence of adjacent highway bridge tended to slightly increase the sustain force acting on the slab bridge.

6. References

[1] Unjoh S 2008 *Damage to Transportation Facilities, The Damage Induced by Sumatra Earthquake and Associated Tsunami of December 26 2004* A Report of the Reconnaissance Team of Japan Society of Civil Engineers pp. 66-76

[2] Lekkas E, Andreadakis E, Alexoudi V, Kapourani E, and Kostaki I 2012 The Mw=9.0 Tohoku Japan Earthquake (March 11, 2011) Tsunami Impact on Structures and Infrastructure, *Proc. of the 15th World Conference in Earthquake Engineering* Lisbon Portugal.

[3] Kawashima K, and Matsuzaki H 2012 Damage of Road Bridges by 2011 Great East Japan (Tohoku) Earthquake *Proceeding of the 15th World Conference in Earthquake Engineering* Lisbon Portugal

[4] CADMAS-SURF 2010 The Study Group for the Development of *CADMAS-SURF/3D User's manual* in Japanese

[5] Fukui Y, Hidehiko S, Nakamura M, and Sasaki Y, 1962 Study of tsunami -Investigation of wave velocities in case of bore type tsunami *Annual Journal of Coastal Engineering in Japan* 9 44-49

[6] Applied Technology Council 2008 *Guidelines for Design of Structures for Vertical Evacuation from Tsunamis* Report FEMA P646 of the Federal Emergency Management Administration