Performance of Bridge Girder with Perforations under Tsunami Wave Loading

Sadia Rahman, Shatirah Akib, M. T. R. Khan, R. Triatmadja

***Abstract*—**Tsunami disaster poses a great threat to coastal infrastructures. Bridges without adequate provisions for earthquake and tsunami loading is generally vulnerable to tsunami attack. During the last two disastrous tsunami event (i.e. Indian Ocean and Japan Tsunami) a number of bridges were observed subsequent damages by tsunami waves. In this study, laboratory experiments were conducted to study the effects of perforations in bridge girder in force reduction. Results showed that significant amount of forces were reduced using perforations in girder. Approximately 10% to 18% force reductions were achieved by using about 16% perforations in bridge girder. Subsequent amount of force reductions revealed that perforations in girder are effective in reducing tsunami forces as perforations in girder let water to be passed through. Thus, less bridge damages are expected with the presence of perforations in girder during tsunami period.

***Keywords*—**Bridge, force, girder, perforation, tsunami, wave.

I. Introduction

TSUNAMI is one of the most terrifying and complex natural disaster that may affect coastal area severely. Tsunami waves are long oceanic waves that are mainly caused by earthquake, volcanic eruptions, landslides etc. under the sea bottom. Movement of offshore tectonic plates causes earthquake that led to tsunami in the deep sea. Waves thus created, propagate with considerable speed from the originating sources toward the shore. Their wave lengths decelerate near the shoreline due to compressing effects of up-sloping seabed and due to the reduced water depth. Upon entering the shallower water near the coast, the wave velocity decreases, however, the wave height increases. The devastating power of tsunami forces may ruin infrastructures including bridges, road structures, utilities, wooden and masonry houses.

The destructive effects caused by 2004 Indian Ocean tsunami have demonstrated the demolition power of tsunami that raised the concern about the tsunami impact among people. Although earthquake and tsunami occur simultaneously in a coastal area, in many cases more destruction could be identified to be done by tsunami rather than earthquake. Tsunami has the power to destroy or collapse the infrastructures including bridges in its course. Fig. 1 showed the impact attributed by 2004 tsunami along coastal line in Indonesia. Several structural damages were featured by many researchers during 2004 tsunami [1]-[5]. Therefore, it is evident that the tsunami induced forces should be introduced in the design of coastal structures.

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Fig. 1 Effects of tsunami 2004, along coastal line and bridge structures in Banda Aceh, Indonesia

II. Literature Review

Bridges are the most important lifeline infrastructures that could provide immediate rescue and supportive performance after any disastrous event. During the last two recent tsunamis, extensive bridge damages were observed by tsunami forces. Therefore, it has become imperative to explore bridge performance under tsunami loading and however, adoption of any remedial measure to minimize destruction level is also an important issue. In general, two types of damages are encountered by tsunami waves. That are, damages to bridge sub and superstructures. Damages to substructures are generally caused by scouring of foundation material around bridge pier while damages to super structures were featured by partial transverse deck displacement as well as total or partial wash out of bridge deck (Fig. 2). Bridge failure by excessive scouring of surrounding material is a common phenomenon that occurs frequently all around the world [6]-[9]. Like river flows, tsunami waves also contribute a lot to the extreme removal of foundation material resulting in severe bridge damages. Flow velocities play a crucial role in controlling structural behavior of bridge substructures [10], [11]. Therefore, different loading conditions should be considered to understand the nature of damage pattern. Some of the damaged bridges by tsunami were shown in Figs. 3-5. There are limited research on estimating tsunami forces on bridge girder due to the complex nature and interaction between near shore wave and structures. Most of the researches were concentrated on tsunami force impacts on vertical wall type's structures; however, little attention was given to bridge damages. Post tsunami surveys provided the reported the needs for estimating and evaluating tsunami forces on bridges. This study focused on bridge performances with consideration of perforations in girder during tsunami event.

Fig. 2 Bridge damage due to tsunami attack in Banda Aceh (a) Total Wash-Away of Deck [7] (b) Excessive Deck Displacement [12] (c) Damaged steel truss bridge with damaged cement plant in the background in Lhok Nga, Banda Aceh

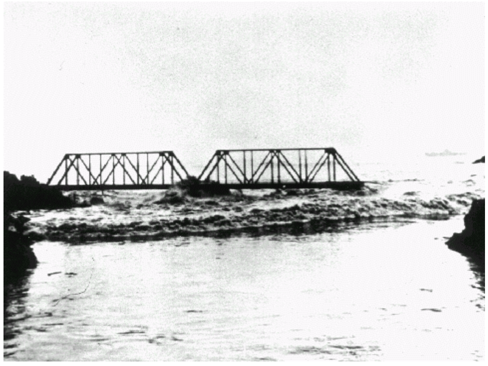

Fig. 3 Tsunami wave destroyed bridges on Wailuku River, HI, 1946

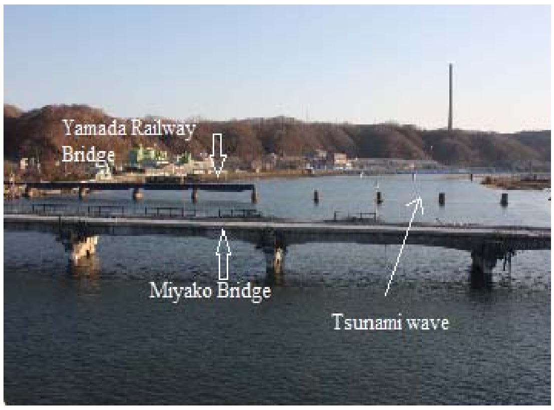

Fig. 4 Damaged Miyako Bridge and Yamada Railway Bridge during Japan Tsunami

Fig. 5 Damaged Numata-Kosen bridge during Tohoku Tsunami

Evidences showed that in Sumatra, 81 bridges out of 168 were washed away by 2004 tsunami waves that occupied 250 km road section on the northwestern coast of Sumatra Island [13]. A number of researches were performed to investigate bridge performance and to estimate tsunami induced forces on bridges under tsunami loading through physical simulations [14]-[19]. Impacts of tsunami forces were evaluated by placing I-girder bridge deck on the dry land [20]. Results showed that the slowly-varying drag force on the bridge deck which followed the impulsive force, averaged over a 0.5s duration, could be well predicted with wave height-dependent formula stipulated by the Japan Port and Harbour Association [21]. Other experiments were performed by placing box type bridge decks with abutments on a wet bed at certain height of still-water [22], [23].

Experimental results illustrated that, for the tsunami simulation, maximum forces and maximum velocity were found to occur at the same time [23]. The impacts of hydrodynamic load on piers with the presence of deck were identified through simulation of pier deck combination [24]. Bridge deck could obstruct the free flowing and topping over the wave before impinging the pier and thus fluid is captured in front of the piers creating larger pressure on them. Experimental results showed that the presence of deck could augment hydrodynamic pressure on pier as much as 50% when compared to only pier model. Some other experiments were performed to measure tsunami forces on the coastal structures [25]-[27]. Based on experimental results, formula was proposed for measuring tsunami fluid forces that attack structures behind the sea wall [27].

III. Experimental Set Up

Physical experiments were conducted in a wave flume of 17.5m long, 0.60m wide and 0.45m high (Figs. 6 and 7). The flume was divided into two sections with the upstream part served as a reservoir for generating tsunami whilst the downstream part was used to simulate tsunami propagation and tsunami force on model structures. A simple quick-release mechanism was used to open the gate with 100-kg weight connected to the gate and a winch with the strings. The sudden release of the gate allowed water to propagate abruptly to simulate tsunami like waves. The experimental setup in this research was similar to physical model used by Triatmadja and Nurhasanah [28] and Arnason et al. [29]. The flume was also equipped with a pump to fill the reservoir and an outlet to drain the downstream part of the flume.

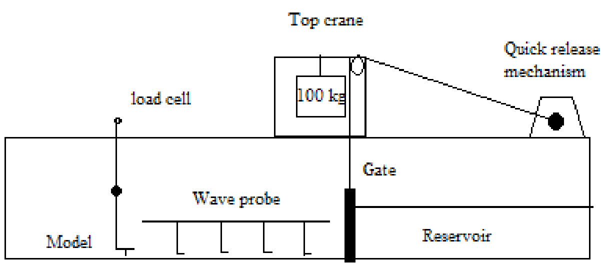

Fig. 6 Experimental Setup

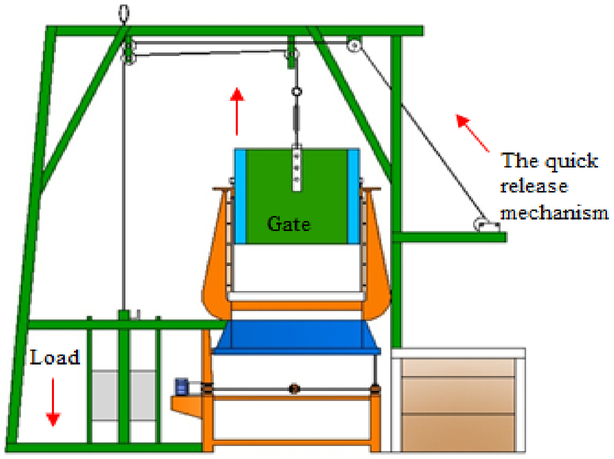

Fig. 7 Quick release mechanism

A 1/100 scale bridge model with three girders was placed inside the wave flume. The bridge model was prepared by Perspex material. Water was reserved in the reservoir and then allowed to flow that could produce several wave heights prior the bridge model. For this investigation three different reservoir depths were chosen based on the maximum flow depth that could occur near the bridge location in the absence of the model. Two bridge configurations were investigated as shown in Fig. 8, viz. the first one was solid girder bridge and the second one was with approximately 16% perforations in its girder. The bridge model was attached to a steel plate that was linked to a vertical rod. This rod could swing freely on a hinge. A small pin was connected to the top of the rod that pressed a load cell when tsunami hit the model. Thus, forces were recorded in the load cell. Recorded values were adjusted by load cell calibration factor and handling factor in order to get the exact forces that was exerted on the bridge model. Water splashing over the bridge girder produced some additional forces on the rod. But, after experiments it was found that this rod assigned only 2~3% forces on the bridge. Fig. 9 is a photograph of the bridge model installed in the wave flume. In order to measure the wave height, a series of wave recorders were installed at selected stations. The distance between the adjacent stations, from Station 1 to Station 4, was 1 m, as depicted in Fig. 6. Table I represents the details of bridge girder.

TABLE I
Details of Bridge Girder

Girder Models	Solid	Perforated
Vertical projection area of each girder (mm2)	3750 mm^2	3750 mm^2
Vertical projection area of the slab	750 mm^2	750 mm^2
Perforation area (percentage) in girders	0 mm^2 (0)	600 mm^2 (16 %)

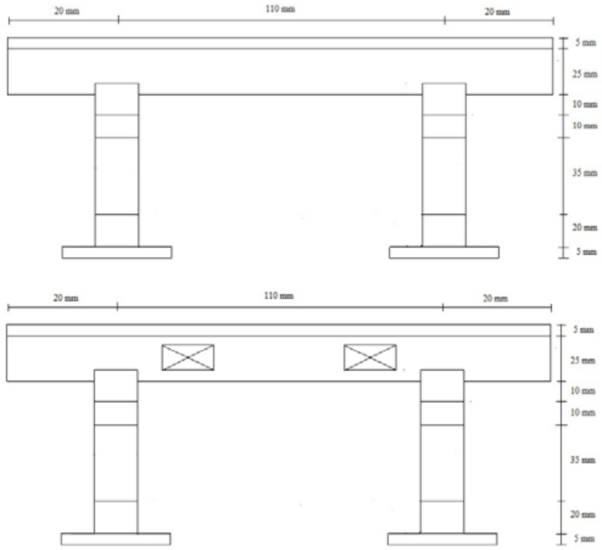

Fig. 8 Bridge model (solid and perforated)

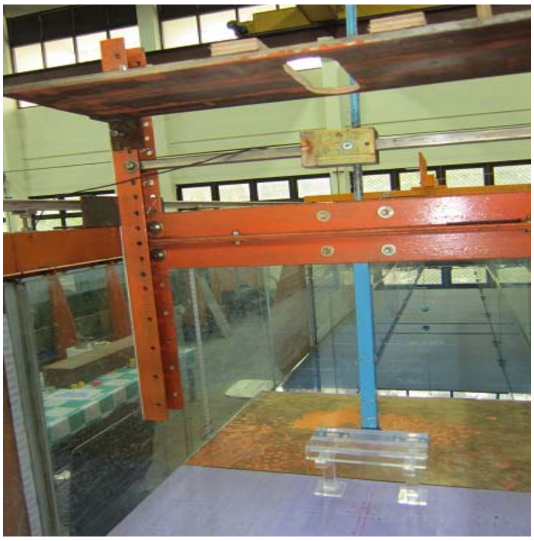

Fig. 9 Photo of the bridge model installed inside the flume

IV. Experimental Results

The present investigation includes the experimental modeling of wave forces acts on a bridge girder struck by a tsunami. It includes the advantages in introducing perforations in bridge girder in assessing tsunami forces that attacks the bridge structures. Three different reservoir depths were considered that produced three different wave heights adjacent to the bridge model. Waves were propagated from right to left side of the model bridge. Fig. 10 showed the sequential attack of tsunami waves to the bridge model.

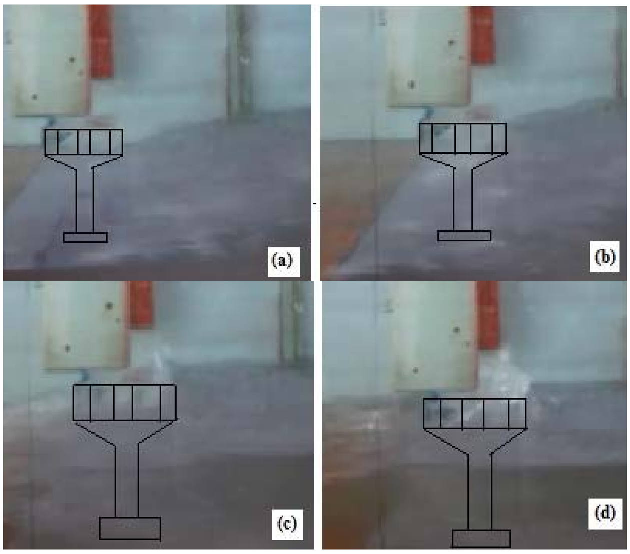

Fig. 10 Snapshots were taken during the wave attacking bridge model

The time history of wave heights and the total forces for the three different wave heights were depicted in the Fig.11 and Fig. 12, respectively. The front of the coming waves had smaller height that attacked the base of the bridge pier with maximum velocity. With time, velocity decreased and wave height increased and hit the bridge girder. While hitting the girder, waves splashed strongly and then overtopped the girder. Recorded wave heights during overtopping were almost twice as the real wave height that might occur near the bridge location inside the flume without the present of model.

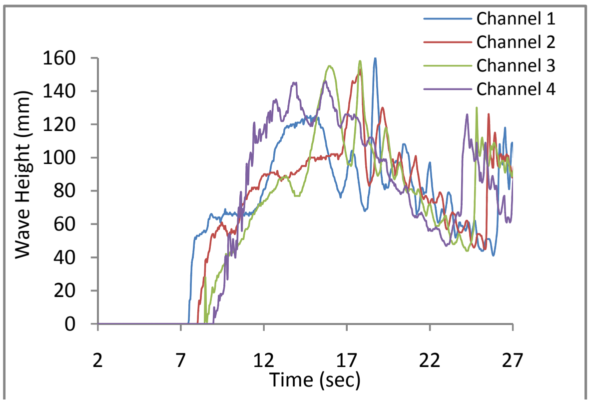

Fig. 11 Measured time histories of tsunami wave height

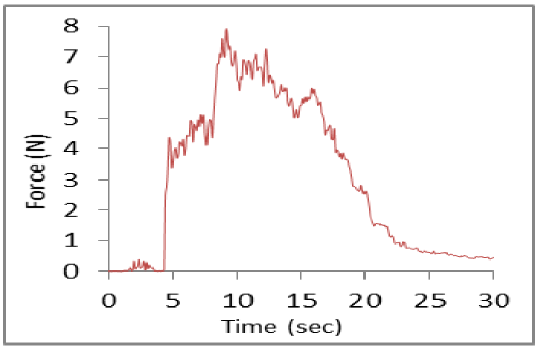

Fig. 12 Time histories of measured forces for reservoir depth 25cm

The main findings of this paper rest on ensuring the performance of perforated girder bridge against tsunami forces. In order to do this, approximately 16% perforations were considered within girder. The time history of forces for both solid and perforated girder bridge was presented in Fig. 13. The peak forces were taken as the maximum forces from the force time history. From Fig. 13, it has been found that substantial amount of force reduction were observed due to the use of perforations in girder. This force reduction was experienced not only in peak force but also throughout the whole time history. Table II showed the results obtained from using solid and perforated bridge girder. Another finding was that, time to attain peak forces were less for perforated girder bridge than that of solid girder bridge (Table III).

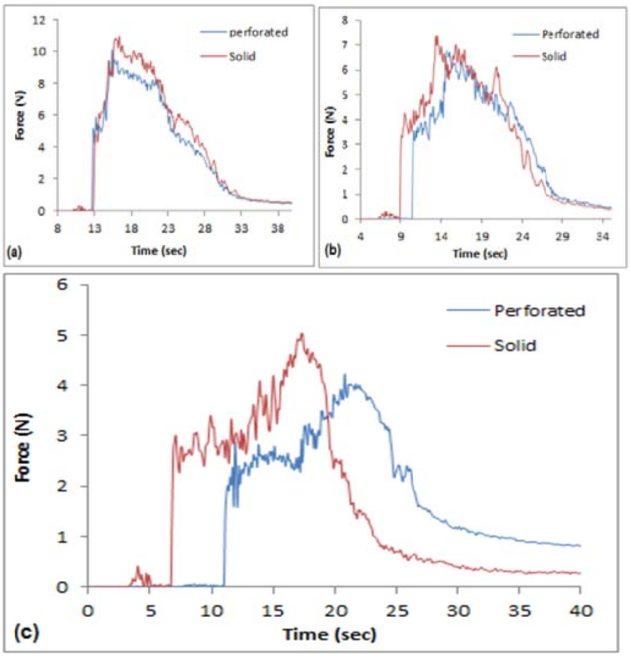

Fig. 13 Force time history for both solid and perforated girder for different reservoir depths

TABLE II
FORCE REDUCTIONS BY PERFORATIONS IN GIRDER

Reservoir Depth (cm)	Peak forces in Solid Girder Bridge (N)	Peak forces in Perforated Girder bridge (N)	Reductions in forces
30	11.075	9.97	10%
25	7.9	6.464	13%
20	4.67	3.8	18%

TABLE III
TIME TO REACH PEAK VALUE

	Time to attain peak force (sec)	
Wave height (cm)	Solid girder bridge	Perforated girder bridge
7.5	3.6	2.3
6.25	4.5	4.2
5	11.1	7.4

Tested were performed with perforations in the girder to observe the bridge performance under tsunami attack. For all of the selected wave heights, substantial reductions were observed due to the presence of perforations in the girder. These reductions were attributed not only at the peak value but also throughout the whole time history. The reductions in total forces due to the presence of perforations were given in Table II. For 20cm reservoir depth, the percentage of reduction was higher compared to reduction during 30cm and 25cm reservoir depth. It has been found from summary Table II that the peak forces reductions were 10%, 13% and 18% for reservoir depth 30cm, 25cm, and 20cm, respectively. The reduction of the wave attacked area in the girder was mainly responsible for the reductions in forces in the girders. Perforations in girder allow some amount of flowing water to pass through the perforations, thus contributing in force reduction. Moreover, with decreasing reservoir depth declinations of forces were increasing. This indicated that reduction in forces were more apparent for smaller wave heights. Table III demonstrated that lesser time were required for perforated girder bridge to reach the peak value than that of solid girder bridge.

V. CONCLUSION

Tsunami is a type of natural disaster that couldn’t be avoided. Bridges without adequate seismic loading provisions could be easily damaged by tsunami waves. This paper tries to find out the effectiveness of using perforations in girders. Several tests were performed with different reservoir depths. Subsequent reductions of forces were found by using perforated girder compared to solid girder. Force reductions were observed not only in peak but also throughout the whole force time history. These reductions were more apparent for smaller wave heights. Another, finding was that, for perforated girder bridge, lesser time was required to attain the peak value than that of solid girder bridge.

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