Experimental Investigation on Tsunami Acting on Bridges

Iman Mazinani, Zubaidah Ismail, Ahmad Mustafa Hashim, Amirreza Saba

Abstract**—**Two tragic tsunamis that devastated the west coast of Sumatra Island, Indonesia in 2004 and North East Japan in 2011 had damaged bridges to various extents. Tsunamis have resulted in the catastrophic deterioration of infrastructures i.e. coastal structures, utilities and transportation facilities. A bridge structure performs vital roles to enable people to perform activities related to their daily needs and for development. A damaged bridge needs to be repaired expeditiously. In order to understand the effects of tsunami forces on bridges, experimental tests are carried out to measure the characteristics of hydrodynamic force at various wave heights. Coastal bridge models designed at a 1:40 scale are used in a 24.0 m long hydraulic flume with a cross section of 1.5 m by 2.0 m. The horizontal forces and uplift forces in all cases show that forces increase nonlinearly with increasing wave amplitude.

Keywords**—**Tsunami, bridge, horizontal force, uplift force.

I. Introduction

THE recent mega-tsunami events of Tohoku-Oki Earthquake (magnitude 9.0; also known as the 2011 Great Eastern Japan Earthquake) on March 11, 2011 and Sumatra Island in Indonesia on December 26, 2004, shocked the whole world, especially South-East Asia.

The enormous loss of human lives in these huge disasters by tsunamis is a wake-up call reminding the international scientific community to recognize and model tsunami generation, propagation and coastal inundation processes. These lead to final operational goals to plan the mitigation of tsunami effects on the coastal communities, to forecast the behavior of structures, and to design structures to the highest possibility of safety. Fig. 1 displays a washed away concrete girder bridge and Fig. 2 shows a washed away steel girder and truss bridge during the Japan Tsunami. Tsunamis are destructive waves which contain a series of long period waves. These waves propagate at very high speed and travel transoceanic distance with very little energy losses.

When tsunamis approach land, their tremendous energy remains nearly unchanged and the high inundation level and the fast moving water of tsunami flow cause loss of human lives and catastrophe to coastal structures including bridges. The extensive bridge damage caused by the recent tsunamis in particular the unprecedented 2004 Indian Ocean tsunami and mega-tsunami of Tohoku-Oki demonstrates an urgent need for an effective method to estimate tsunami forces on bridges. In this tsunami reported that more than 100 bridges had their superstructures washed out or heavily damaged by the Northern Sumatra, Indonesia Tsunami with heights of 5.0 m to over 30.0 m [1].

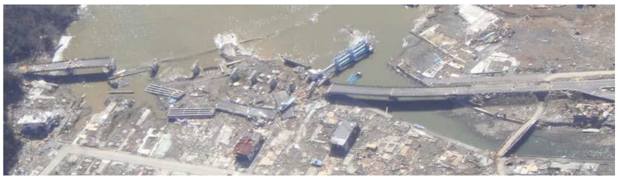

Fig. 1 Washed away concrete girder bridge

Fig. 2 Washed away girder bridge and truss bridge

Although there are some studies on tsunami forces acting on coastal structures by many researchers, however, there are very few researches on the behavior of tsunamis on the superstructures of bridges.

Therefore, further research on tsunami loads on superstructures is required for use by structural designers working according to the limit state philosophy.

In recognition of the requirement for an improved knowledge on tsunami loadings, the hydrodynamic loadings on bridge superstructures and piers are measured using a comprehensive laboratory program for varying ranges of tsunami wave conditions and geometric arrangements likely to be encountered in real life situations.

Because of the complexity of the wave propagation onshore, offshore and wave-structure interaction, a theoretical approach for the determination of tsunami-induced forces cannot be easily applied to a complete bridge structure. Therefore, the first part of this research is carried out to

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experimentally study the flow characteristics of tsunami around complete pier-deck bridges and to estimate tsunami forces on bridges. The second part of this research evaluates the experimental result with the numerical formula by Goring in [2].

II. Literature Review

Many valuable experimental studies of tsunami forces on bridges have been conducted after the huge disaster of the 2004 Indian Ocean tsunami and 2011 Tohoku-Oki events by some researchers. Nistro and Yeh, Robertson in [3], [4] presented clear examples of damage as a result of both scour and fluid loadings from the tsunamis. In [5], [6] and later research in [7] investigated the wave action on an I-girder bridge deck which was located on a dry bed while the others modelled box type bridge decks which were placed on a wet bed at certain heights of still-water. The research in [6], located the bridge deck on abutments whereas [5], [7] simplified the models by neglecting the bridge piers (personal communication with the authors). No pressure or force measurements were recorded in [6]. However, in [5] found that the slowly-varying drag force on the bridge deck which followed the impulsive force, averaged over a 0.5s duration, can be well predicted with wave height-dependent formula stipulated by the Japan Port and Harbour Association. On the other hand, drag force with a drag coefficient of 1.1 is proposed for estimating tsunami forces on the bridge deck in [7] which the maximum forces and maximum flow velocities were found to practically occur at the same time. In addition, [8], [9] carried out experimental studies on fluid force acting on a bridge deck subject to tsunami waves breaking on a bridge deck. A computational simulation method in order to investigate the damage on bridges due to tsunami action carried out in [10]. The numerical method consists of a hydraulic analysis and a structural analysis. The proposed method was applied to the damaged bridge whose superstructure was flooded away by the Tohoku earthquake tsunami. In [11], experimental and numerical modelling of tsunami force on bridge deck. They categorized tsunami forces on a bridge deck into four types i.e. impulsive, slowly-varying, uplift and additional gravity force. The outcomes of the above researches do not determine tsunami forces on bridges.

Furthermore, in [5], [7] researches, for simplicity, the piers were as thin as they can be in the experiments. In [8]-[10] researches omit the piers or use un-proportionally small dimensions in their prototype models. They basically neglect the impact of the flow condition on the piers and deck. Actually, the interactions between tsunami and bridge are very complex phenomena and an analytical approach based on numerical simulation is necessary to understand the mechanism of structural damage. Also, there is little research of the effects on the bridge cross section due to tsunami loadings.

The outcomes of this experimental and numerical study evaluate tsunami wave forces on coastal bridges over sea or river. These experiments assess tsunami wave forces on the complete pier and deck of a coastal bridge where the bridge crosses sea or river. The experiment and numerical tests are carried out on a 1:40 scale model of the approach bridge to the second Penang Bridge. An indepth study using analytical and numerical models is used to evaluate the effects of tsunami bore at various wave heights and water depths on a simplified bridge model which is constructed with actual material and weight.

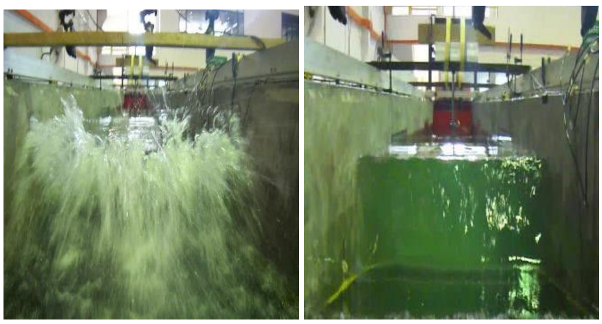
III. Methodology

This study includes an experimental study in the Coastal & Offshore Laboratory of University Technology Petronas (UTP) and the Hydraulic Laboratory of University of Malaya with computational and numerical modelling to validate and have a better understanding of the experimental study.

A. Experimental Study

The purpose of the experimental study is to simulate the tsunami bore of the proposed bridge at a reduced scale. A wave flume experiment will be conducted to obtain the time histories of pressures and forces on the bridge models subjected to tsunami loadings. The experimental study will be carried out in the Coastal & Offshore Laboratory of University Technology Petronas and the Hydraulic Laboratory of University of Malaya. A long tank, 24.0 m long, 1.5 m wide, and 2.0 m deep will be used for the experimental study. To enable observations from the sides, the side walls of the tank are made up of transparent glass. Fig. 3 illustrates the entire structure of the wave tank in UTP laboratory.

Fig. 3 Wave tank in the UTP laboratory



(a) (b)

Fig. 4 Solitary tsunami wave in the flume, (a) Tsunami wave in the UTP flume 0.4 second before breaking up, (b) Broken tsunami wave (tsunami bore)

The wave-making device on the right side of the tank is a slide type board controlled by a computer. When the required wave height and initial water depth are inputted, the computer will automatically perform calculations and determine the necessary force to push the wave-making board. A wave generator as shown in Fig. 4 generates a tsunami-like solitary wave in the flume.

The experimental tests are carried out at four wave heights i.e. 36 cm, 32 cm, 28 cm and 24 cm. The setup is illustrated in the Fig. 5.

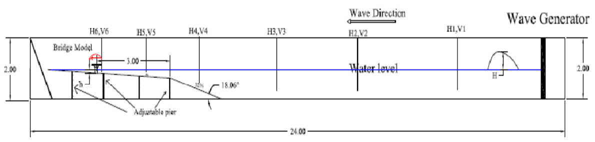


Fig. 5 Experimental setup

B. Scale Model

The prototype model is a 1:40 scaled complete pier and deck of the approach bridge of the Second Penang Bridge (refer to Fig. 6). This bridge is of the box girder type.

Fig. 6 Second Penang Bridge

The deck and box girder of the bridge model is constructed from reinforced concrete. The span is l_s= 1.375 m, the deck width is 0.36 m and total height is 0.273 m. Fig. 7 illustrates the scaled model.

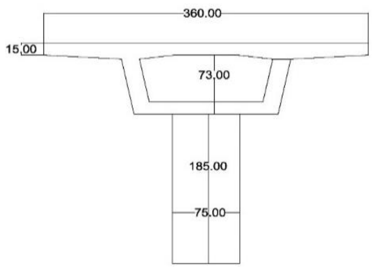


Fig. 7 Model dimensions

C. Instrumentation

The high frequency load cell bolted to the pier is used to record the total horizontal wave forces acting on the complete pier-deck bridge model. The load cell location is shown in Fig. 8.

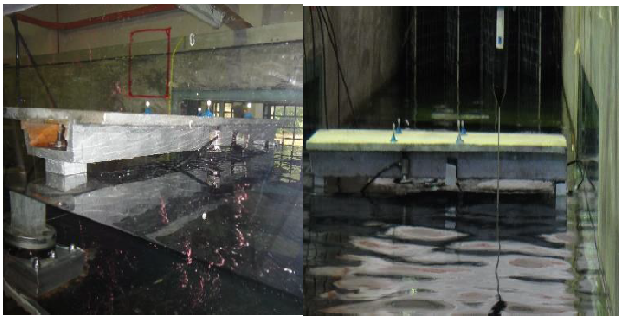


Fig. 8 Experimental model in the flume

Capacitance type wave gauges are used to measure the wave profiles at six different locations as illustrated in Fig. 5. The first is at H1, after the wave generator, until H6, after the bridge model's location. The velocities of the flow in the flume for various wave heights are recorded by propeller type current meters from V1 until V6.

IV. Experimental and Numerical Results

Goring in [2] stated that a solitary wave includes an individual hump of water completely above the still water level with a very long wavelength. In [12] utilizes a piston-type wave generator to generate the solitary wave for the first time. In this experiment the solitary wave is generated with piston type generator produced by Edinburgh design. They stated that the surface elevation of a solitary wave may be achieved from below equation.

$$\eta = Hsech^2\left[\sqrt{\frac{3H}{4d^3}}(x-ct)\right]$$

where η is the surface wave elevation, H is the wave height, c is wave celerity that c=√gd(1+H⁄(2d),) d is water depth, t is time, g is the gravitational acceleration.

Fig. 9 shows a comparison between the time series results in surface elevation of the experiment and Goring's method in [2] at the water depth of 1.0 m and wave height of 0.36 m. According to the results, the experimental measurements for surface elevation and wave height performed are in agreement.

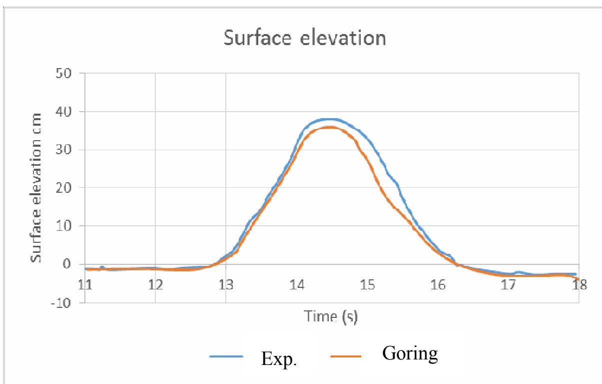


Fig. 9 Comparisons between experimental result and theoretical result of solitary wave elevation

Fig. 10 shows the horizontal force obtained from the contact of an initial solitary wave with the bridge. Four wave heights are applied in this research i.e. 36 cm, 32 cm, 28 cm and 24 cm. The maximum force occurred at the highest wave height. The maximum horizontal force of 87.34 N occurred at 36 cm wave height with the lower value of maximum horizontal force of 42.44 N at a lower solitary wave height. The results illustrate that the horizontal force shows an increase with increasing wave height.

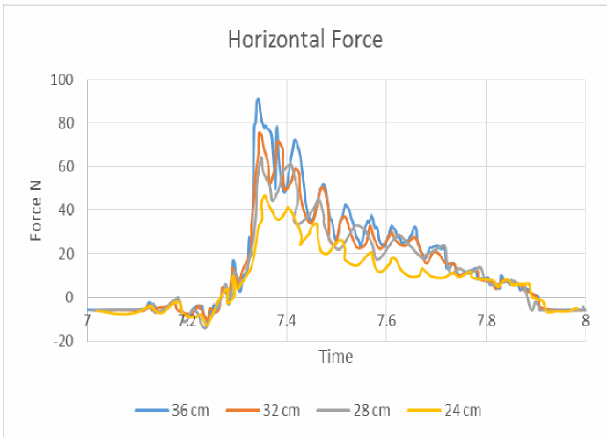


Fig. 10 Horizontal bore force

The result from the uplift forces is as indicated in Fig. 11. The experiment result illustrates that wave interaction with the bridge model contributes significantly to horizontal forces. Although both horizontal and uplift forces increase with increased wave heights, we cannot determine that this as a linear relationship. However, horizontal forces and uplift forces in all cases show that forces increase nonlinearly with increasing wave amplitude.

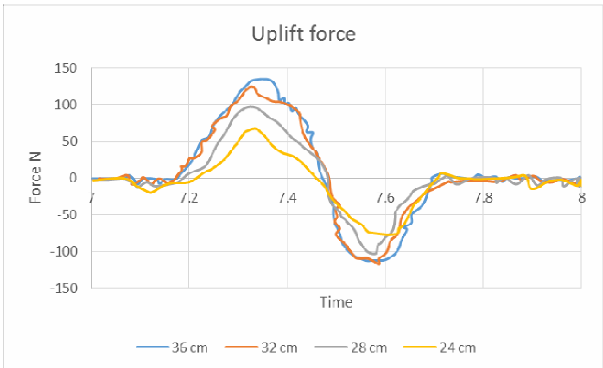


Fig. 11 Uplift bore force

V. Conclusion

The results from this series of experiments cover the effects of tsunami bore and solitary waves propagating over a bridge. The result shows that there is overall good agreement between the experimental measurements for surface elevation and theoretical prediction by Goring in [2]. In the tsunami bore, the horizontal force and vertical force increase as the solitary wave increases. Further detailed experiments are required to fully evaluate the results presented in this paper. Uplift force presents a higher value than horizontal force. This experimental work is currently ongoing in the University of Malaya and University Technology Petronas.

Acknowledgment

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