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Experimental Investigation on the Stability of Bride Girder against Tsunami Forces

Sadia Rahman[1], Dr. Shatirah Akib[1], M. T. R. Khan[2], Dr. S. M. Shirazi[1]

[1.] Department of Civil Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[2.] Department of Architecture, Faculty of Built Environment, University of Malaya, 50603 Kuala Lumpur, Malaysia
sadia_rahman26@yahoo.com

Abstract: A tsunami is a natural hazard that hits many coastal areas frequently. Bridges are one of the most vulnerable parts of the tsunami disaster. During the latest few tsunami hazards, a number of bridges were affected due to lack of proper provisions of tsunami forces in the design guidelines. In this study, laboratory experiments were carried out to elucidate the damage mechanism of bridge girder by tsunami waves. Results showed that waves with larger wave height reached peak values of forces more rapidly than those of smaller wave heights. Two types of wave forms were considered, broken and unbroken. The forces were larger for broken waves than unbroken waves. It was found that maximum force of broken waves was 4.59 times as large as the hydrostatic pressure. Moreover, the results showed that larger height bridges are more vulnerable to tsunami damages.

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1. Introduction

Tsunamis are series of long oceanic waves generated by rapid displacement of water mainly due to earthquakes, underwater landslide, volcanic eruptions etc. The waves thus created disseminate away from their generating source at significant speed and propagate toward the shore. They are among the most terrifying and complex physical phenomena potentially affecting almost all coastal regions of the Earth. In deep water, the waves remain unnoticeable because of their small amplitude (often less than 1 m) but their wavelengths often approach hundreds of kilometres. As the waves reach the shallow water near the coast, however, their speed and wave lengths reduce while their wave heights increase highly. Upon approaching the shoreline the waves can have tremendous force and height, hitting the coastal area violently, causing tremendous losses to life and property. Infrastructures in coastal areas that are designed without the provisions of tsunami forces and impacts are most vulnerable to tsunami attack.The destructiveness of the tsunami waves are mainly affected by the configuration of the coastline, the shape of the ocean floor, the characteristics of advancing waves and few more parameters.

The catastrophic and alarming impacts of recent Indian Ocean Tsunami in 2004 (Liu et al., 2005) Chile tsunami in 2010 (Michelin et al., 2010) and Tohoku Tsunami in 2011(Mori et al., 2011) increase public awareness significantly. In recent years records of smaller wave fronts by buoys and tide gauges and news from most remote areas of the world are easily accessible to people that led them to think deeply about the consequences of tsunami. (NOAA, 2009; Spiske et al., 2013). A number of post-tsunami reconnaissance surveys were conducted during the last few years that provide crucial insight about dreadful tsunami characteristics as well as associated hydrodynamic conditions during tsunami event (Liu et al., 2005; Synolakis & Okal, 2005; Richmond et al. 2006; Bahlburg & Spiske, 2012; Bahlburg & Weiss, 2007; Fritz et al. 2008;Goto et al., 2012; Richmond et al., 2012).

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. Figure 1 showed the impact attributed by 2004 tsunami along coastal line in Indonesia. Several structural damages were featured by many researchers due to the action of extreme tsunami-induced hydrodynamic forces (Ballantyne, 2006; EEFIT, 2006; Ghobarah et al., 2006; Iemura et al., 2005; IIT, 2011; Kusakabe et al., 2005; Lukkunaprasit & Ruangrassamee, 2008; Maheshwari et al., 2006; Nistor et al., 2005; Saatcioglu et al., 2006; Scawthorn et al., 2006; Sheth et al., 2006; Tobita et al., 2006; Unjoh, 2005; Yim, 2005). Therefore, it is evident that the tsunami induced forces should be introduced in the design of coastal structures.

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

2. Behaviors and Characteristics of Tsunamis

Information from historic tsunami events indicates that tsunami behaviors and characteristics are quite distinct from other coastal hazards, and cannot be inferred from common knowledge or intuition. The primary reason for this distinction is the unique timescale associated with tsunami phenomena. Tsunami have wave periods within few minutes to over 1 hour while wind produced waves have periods ranging from 5 to 20 seconds (FEMA, 2005). This timescale is also important because of the potential for wave reflection, amplification, or resonance within coastal features. Table 1 compares various coastal hazard phenomena (FEMA, 2008).

Table 1. Comparison of Relative Time and Loading Scales for Various Coastal Hazard Phenomena

Coastal Hazard Phenomena	Time Scale (Duration of Loading)	Loading scale (Height of water)	Typical Warning Time
Wind generated waves	Tens of seconds	1 to 2 meters typical	Days
Tsunami run up	Tens of minutes to an hour	1 to 10 meters	Several minutes to hours
Hurricane storm surge	Several hours	1 to 10 meters	Several hours to few days
Earthquake shaking	Seconds	N/A	Seconds to none

There is significant uncertainty in the prediction of hydrodynamic characteristics of tsunamis because they are highly influenced by the tsunami waveform and the surrounding topography and bathymetry. Tsunami waves are generally differ from ordinary ocean waves as in case of ocean waves energy is limited to surface only and can be dissipated at a time of breaking. But in case of tsunami, energy does not readily release rather it push up a large volume of water with greater wave length (Figure 2). Tsunami energy propagation has strong directivity. The majority of its energy will be emitted in a direction normal to the major axis of the tsunami source. The more elongated the tsunami source, the stronger the directivity; (Carrier & Yeh, 2005; Okal, 2003). Direction of approach can affect tsunami characteristics at the shoreline, because of the sheltering or amplification effects of other land masses and offshore bathymetry (FEMA, 2005).

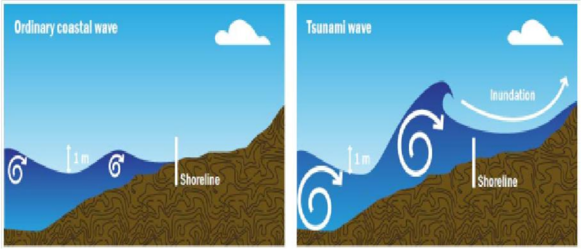

Figure 2. Difference between Tsunami and ordinary coastal waves.

The characteristics of waves near shore and the interaction between wave and structure are so much complex in nature that makes the present established methods inadequate for estimating tsunami forces on bridges. Most of the researches on discovering tsunami impacts were limited to vertical wall type structures, whereas little attention was given on bridge structures that are mostly susceptible to tsunami disaster. Post tsunami surveys on tsunami reported the partial to total collapse of bridges and substantial deck displacement of bridges near coastal areas. Generally approaching waves take different shapes near coastline forming different types of forces that could attack coastal infrastructures. 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 north western coast of Sumatra Island (Unjoh, 2007). In Tohoku tsunami, damage data is more severe, however, at least 200 bridges suffered from serious losses (kosa, 2012). A number of researches were performed to investigate bridge performance and to estimate tsunami induced forces on bridges under tsunami loading through physical simulations (Unjoh, 2005; Sheth et al., 2006; Ballantyne, 2006; Maheshwari et al., 2006; Scawthorn et al. 2006; Lukkunaprasit & Ruangrassamee, 2008). Impacts of tsunami forces were evaluated by placing I-girder bridge deck on the dry land (Kataoka et al., 2006). Results showed that the slowly-varying drag force on the bridge deck which followed the impulsive force, averaged over a 0.5 s duration, could be well predicted with wave height-dependent formula stipulated by the Japan

Port and Harbour Association (1999). Other experiments were performed by placing box type bridge decks with abutments on a wet bed at certain height of still-water (Shoji & Mori, 2006; Iemura, 2007).

Experimental results illustrated that, for the tsunami simulation, maximum forces and maximum velocity were found to occur at the same time (Iemura, 2007). Lukkunaprasit and Lau (2011) identified the impacts of hydrodynamic load on piers with the presence of deck through simulation of pier deck combination. 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 (Matsutomi, 1991; Mizutani & Imamura , 2000; Asakura et al., 2000). Asakura et al. (2000) proposed formula for measuring tsunami fluid forces that attack structures behind the sea wall based on experimental results.

Thus considering shocking powers of tsunami, it is evident that failure of bridges by tsunami forces should be encountered in the design provision and effective remedial measures should be considered to withstand against these devastating forces. The present study investigated the tsunami forces for four different wave heights with various static water depths. Forces were evaluated based on both wave heights and static water depths.

3. Bridge Vulnerabilities to Tsunami Hazards

Bridges are the important lifeline infrastructures to cover immediate rescue activities during tsunami disastrous event. During reconstruction and rehabilitation period, bridges prove their upmost necessities not only for evacuating people but also for transferring first aid to wounded people and for providing emergency relief to the affected areas. Hence, Bridges should be designed with adequate capacity to withstand tsunami hazards. During the last few cases of tsunami attacks, a number of bridges were suffered severely from tsunami flows. Damages to bridges by tsunami are identified into two categories. These are i.e. damage to substructure and superstructure. Bridge substructures are affected by removal of sediment material from foundation and excessive settlement of the embankment where superstructures are affected by horizontal and uplift forces resulting in displacement or washing out of deck or total collapse of structures (Figure 3). Some of the damaged bridges by tsunami were shown in Figure 4, Figure 5 and Figure 6.

Figure 3. Bridge damage due to tsunami attack in Banda Aceh

(a) Total Wash-Away of Deck [9] (b) Excessive Deck Displacement [25] (c) Damaged steel truss bridge with damaged cement plant in the background in Lhok Nga, Banda Aceh.

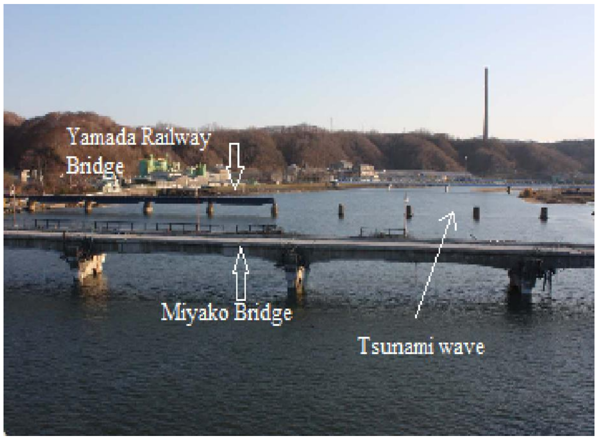

Figure 4. Damaged Miyako bridge and Yamada railway bridge during Japan Tsunami

Figure 5. Damaged Numata-kosen bridge during Tohoku Tsunami

Figure 6. Utatsu bridge, the middle part was washed away

Current theoretical approaches for tsunami force estimation for bridges are proved to be inadequate due to complex wave formation and propagation and complicated relation between wave and structure. Therefore, both physical and numerical approaches have to be developed to evaluate tsunami fluid forces acting on bridges. The nature and impact of tsunami force on bridge structures are quite different from other coastal and harbour structures, such as breakwaters and seawalls because of the presence of obstacles between structures and still water level (Araki et al., 2010).

4. Experimental Set up

Physical experiments were carried out to produce tsunamis following dam break model in a 17.5m long, 0.45m high, and 0.6m wide wave tank (Figure 7 and Figure 8). The tank was divided into two parts in which the upstream part was served as reservoir for generating tsunami whilst the downstream part was used to simulate tsunami propagation and tsunami force on bridge structures. There was a sluice gate in between upstream and downstream part. A simple quick-release mechanism was used to open the gate with 100-kg weight connected to the gate and a winch with strings. The sudden release of the gate allowed water to propagate abruptly to simulate tsunami like waves. The gate was completely opened (above the water level of the reservoir) within 0.2 ~ 0.3secs or less depending on the impoundment depth (the water depth of the reservoir when the gate is closed). This type of simulation method followed the methods proposed by Arnason et al. (2009). The flume was also equipped with a pump to fill the reservoir and an outlet to drain the downstream part of the flume.

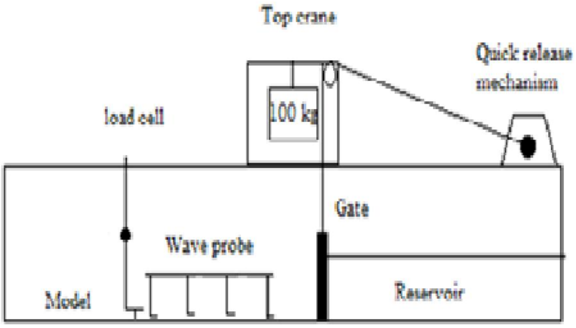

Figure 7. Experimental Set up

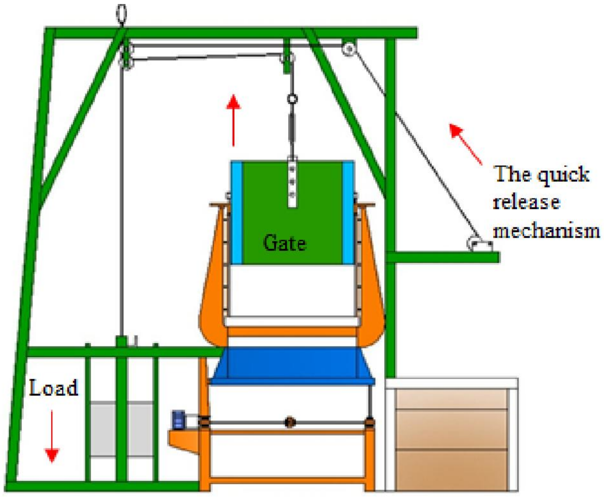

Figure 8. Quick Release Mechanism

A 1/100 scale bridge model with three girders was placed inside the wave tank. The bridge model was prepared by Perspex material (Figure 9). Water was reserved in storage basin and then allowed to flow that could produce several wave heights prior the model bridges. For this investigation, different wave heights were chosen based on the maximum flow depth that could occur near the bridge location in the absence of the model. 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 hits 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 model bridge. 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. Figure 10 is a photograph of the model bridge 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 Figure 7.

The experimental parameters were the types of waves, static water depth (length between the bottom of seabed to the static water level and the girder height (the distance between static water level and girder lower panel). Here, both broken and unbroken waves were considered and forces exerted by these two forms of waves were investigated. Table 2 shows the different static water depth and the selected tsunami wave height. Each case was executed two times to have accuracy in result.

Table 2. Static water depth (h) with different wave height (a)

Impoundment depth (cm)	Wave height, a (cm)	Static water depth, h (cm)
30	7.5	3, 4, 5.5,7
25	6.25	3, 4, 5.5, 7
20	5	3, 4, 5.5, 7
15	3.75	3, 4, 5.5, 7

Figure 9. Bridge Model

Figure 10. Photo of the bridge model installed inside the flume.

5. Experimental Results and Discussions

The present investigation includes the experimental modelling of wave forces acts on a bridge girder struck by a tsunami. Four different wave heights were considered that propagate from right to left side of the model bridge. Both broken and unbroken waves were considered for analysis purposes. Types of wave forms were selected very carefully considering tsunami wave height in cooperation with static water depth conditions.

The time histories of wave heights for the three different wave heights were depicted in the Figure 11. The front of the wave, having smaller wave height attacks the model at the base of the pier with maximum flow velocity. The simulated waves reached the girder site very speedily and hit the girder with tremendous forces, then splashed upward and collapsed at the girder site. Finally, these waves overtopped the girder. The wave heights that were recorded during overtopping the girder were almost two times the real wave height that was anticipated near the bridge model during simulation period for the three different wave forms.

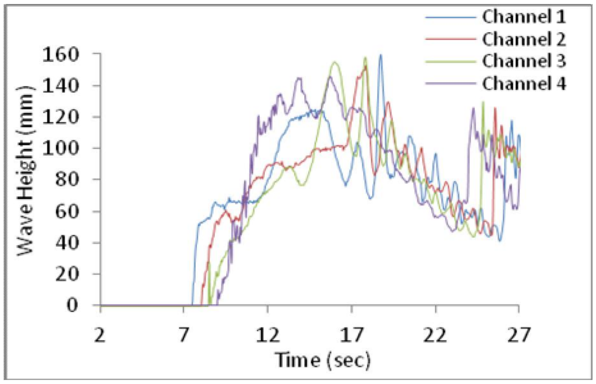

Figure 11 Measured time histories of tsunami wave height

The time histories of forces for different wave height were portrayed in Figure 12 (a, b). The pick forces were recorded as the maximum forces that were taken from the force time history (Fig. 11). The wave force at 7.50 cm wave height reached the peak value more rapidly than those at 6.25 cm, 5cm and 3.75 cm wave height. This indicated that the time required to attain peak value is smaller for larger wave heights.

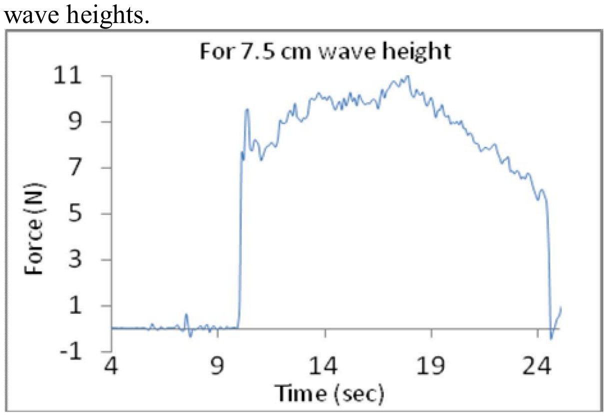

Figure 12 (a) Time histories of measured forces for wave height 7.5 cm

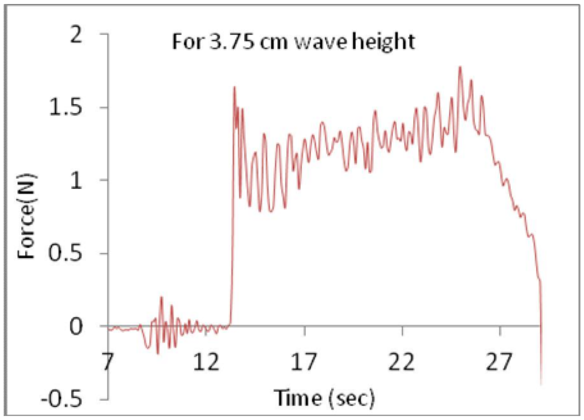

Figure 12 (b). Time histories of measured forces for wave height 3.75 cm.

Figure 13 (a, b) shows typical examples of time histories of the tsunami horizontal forces acting on the model bridge. In Figure 13 (a), broken waves hit the model girder while unbroken waves hit the model bridge in Figure 13 (b). The tsunami heights in Figure 13 (a) and 13 (b) were a = 7.5 cm and 3.75 cm, respectively. The static depth at the model bridge was h = 4.0 cm in both cases. The impact force was measured when tsunami hits the model bridge. However, duration of impact was very short for broken waves, but the magnitude of the force was large. In case of broken waves, waves got broken before struck the model and proceeded on the girder from the lower side. In this case, with increasing wave height, more water splashed against the girder. For unbroken waves, waves did not break before colliding with bridge model. In the time history of the horizontal forces for broken waves shown in Figure 13 (a), two peaks were measured where as just one pick was observed from the time history of forces for unbroken waves Figure 13 (b). In the case of broken waves, the horizontal wave forces had reached a peak before the wave height became higher. On the other hand, for unbroken waves, peak forces attained after the wave height got higher value. In the case of broken waves, as waves were broken before hitting the model, wave height was measured in an uneven condition. Among all the combinations of wave height and static water depth, the forces observed during the experiment with wave height=7.5 cm and static water depth = 4 cm was maximum in magnitude. At this moment, the wave was breaking with a higher impulsive force having shorter duration.

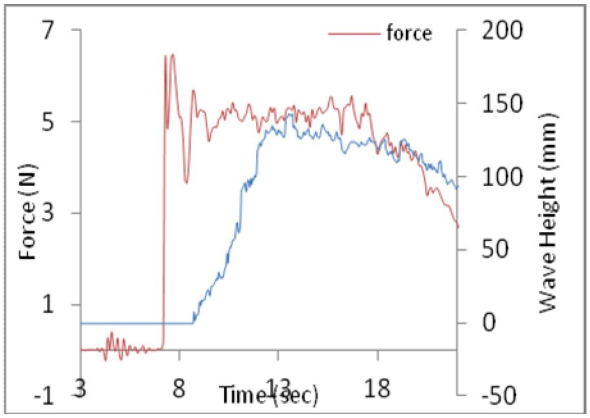

Figure 13 (a). Time histories of forces of broken waves and wave height

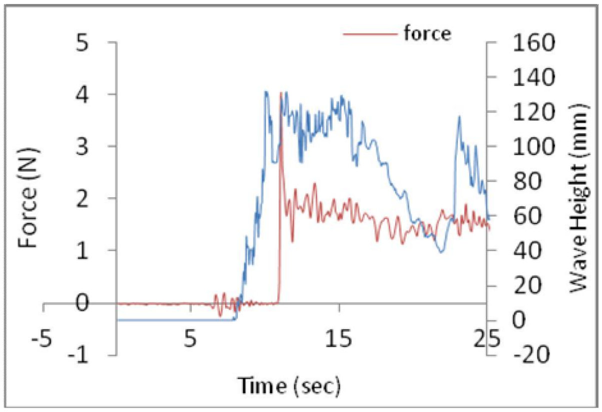

Figure 13 (b). Time histories of forces of unbroken waves and wave height

Figure 14 shows the maximum value of horizontal force obtained from different experimental cases. The vertical axis represented the dimensionless ratio of the girder height to the tsunami wave height that was represented by δ.

$$\delta = Z/a \quad (1)$$

Z = girder height (distance between the static water level and girder lower panel),

a = wave height.

Forces were evaluated through this ratio. In this experiment girder height was controlled by changing static water depth. It is seen that the maximum value of forces were obtained for higher girder height (lower static water level). Forces were increasing significantly with increasing wave height at lower static water depth. From this figure it was also found that horizontal forces are larger for broken waves than unbroken waves. In the case of larger girder height, as the upper part of tsunami waves struck the girder, the increase of forces were significant with increasing wave height than that in the case of lower girder height. From these results, it could be said that, larger height bridges are more vulnerable to tsunami destruction.

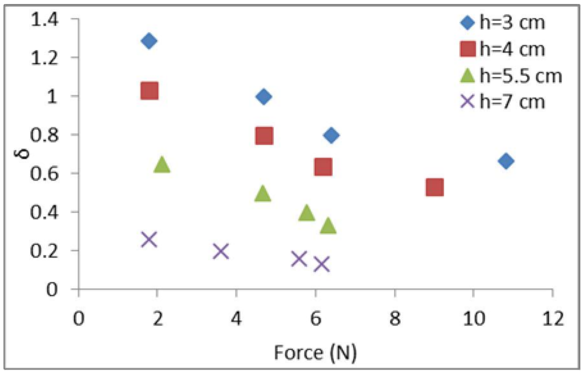

Figure 14. Relation between δ and measured forces

Another parameter was defined by κ which was obtained by dividing the maximum measured forces by possible area of wave attack on the girder's side plan and static water pressure against the tsunami height.

$$\kappa = (F/A)/\rho g a \quad (2)$$

A=possible area of wave attack on girder's side plan

a=tsunami wave height

ρ= Density of water

g= Gravitational acceleration

A relationship was developed between, δ and κ in Figure 15. The vertical axis shows the ratio of the girder height to the tsunami wave height, δ and the horizontal axis shows the maximum measured forces normalized by possible area of wave attack on the girder's side plan and static water pressure against the tsunami height, which was identified as κ. The increase of κ was slower with decrease of δ due to the increase of wave height, as the lower part of tsunami waves hits the girder in the case of higher static water depth (lower girder height). In the case of lower static depth, the increase of κ value was significant with decrease of δ due to increase in wave height, since upper part of waves act on the girder. Wave pressure could be evaluated through parameter κ.

$$q = \kappa * \rho g a \quad (3)$$

Based on this result, approximate linear line was drawn for 3 cm static water depth. From this linear line horizontal wave pressure (q) was evaluated. The linear equation can be written as:

$$\delta = -0.732\kappa + 3.36 \quad (4)$$

$$\frac{Z}{a} = -0.732\,\frac{q}{\rho g a} + 3.36$$

After simplification, it becomes

$$q = \rho g\left(4.49\,a - \frac{1}{0.73}\,Z\right) \quad (5)$$

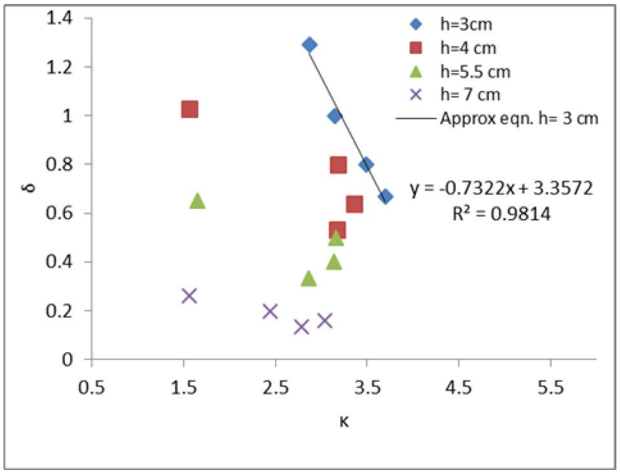

Figure 14 Relation between δ and κ

7. Future Recommendations

Recent tsunami events showed that bridges are critically sensitive to tsunami induced forces. However, robust experimentation and analysis should have to be done for clear understanding of the relationship among the multiple variables controlling tsunami effects on bridge structures. Following future works can be done towards improving existing understanding of these phenomena.

- Quantitative analysis and estimation of tensile and uplift effects of tsunamis on bridge components.
- Numerical analysis should be done and results should be compared with physical experimental dataset.
- Laboratory experimental data could be validated with large scale bridge model. Model should be constructed behind any irrigation or hydro-electric dam where a large volume of water could be released in a very short period of time to simulate tsunami type's waves.
- Further study could focus on measuring scour around bridge pier created by tsunami waves. Development of new guidelines for the estimation of the hydrodynamic impact forces on specific structures.
- Development and verification of coupled hydraulic-structural numerical models capable of real-time analysis of structural response to hydrodynamic forces.
- Investigation of the applicability of the surge force component in the calculation of the tsunami load.

6. Conclusions

Tsunami is a type of natural disaster that couldn't be avoided. In order to evaluate proper mitigation measures to control damage pattern, it is imperative to know the damage mechanism of bridge girders under tsunami loading. This paper tries to assess the stability of bridge girder with different tsunami wave height. In this experiment, it was found that for selected larger wave height, waves got broken prior to bridge structures. But, with smaller wave height, waves struck the bridges with its full form. Waves reached to peak value more rapidly for larger wave heights than those of smaller wave heights. Measured forces for broken waves were larger than unbroken waves. Again, bridges with higher girder height are more vulnerable to tsunami attack.

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Corresponding Author:

Sadia Rahman
Department of Civil Engineering
Faculty of Engineering
University of Malaya
50603, Kuala Lumpur
Malaysia
E-mail: sadia_rahman26@yahoo.com

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