Model Study of Tsunami Wave Loading on Bridges

Indrasenan Thusyanthan & Elena Martinez Engineering Department, University of Cambridge Cambridge, United Kingdom

ABSTRACT

This paper presents the initial results of a series of model tests carried out, as part of an ongoing research project in Cambridge, to understand the maximum impact pressure of a tsunami wave on coastal bridges. The paper also contains a review of literature relevant to this project. A simple pier and deck bridge design was tested at 1:25 scale, using miniature pressure sensors to monitor the impact loads. The effects of foundation depth, pier height, pier width and bridge deck height on the impact pressures have been investigated.

KEY WORDS: tsunami wave, coastal bridges, modelling, wave impact pressure.

INTRODUCTION

Boxing-day 2004 tsunami was a natural disaster that claimed more than 220 000 lives and destroyed infrastructure along the coasts of many counties in the pacific, Indonesia and Sri Lanka being the worst hit. The total economic cost of catastrophe is estimated to be more than 10 billion euros. According to the Red Cross, more than 2.3 million were affected by the disaster. In light of this disaster, early waning system has been put in place for any future tsunamis in the pacific. While early warning systems can be used for evacuating people and saving lives, better designs for coastal structures are required if we are to improve their chances of survival in an event of a tsunami and reduce the economic and financial loss. Bridges are one of the important infrastructures that need to be protected in an event of tsunami. This research aims to better understand the tsunami wave impact loading on bridges.

This paper presents model scale study of tsunami wave loading on bridge structures. Experiments were performed in a 4.5 m length wave tank using model bridge structures (1:25 scale). The tsunami wave was created in the wave tank by releasing a heavy weight (\sim 100 kg) into the water at the deep end of the tank. The sudden displacement of water in the deep end of the tank created a single wave and the wave propagated to the shore where the model bridge was placed. A high speed (1000 frames/s) video camera was used to capture the tsunami wave as it

impacts the structure. The sea bed was instrumented with miniature pore pressure transducers for measuring the excess pore pressures during the passage of tsunami wave, and the model bridge was instrumented with miniature stress transducers to measure the wave loading. A series of experiments were carried out to understand maximum impact wave loading on different bridge configurations.

LITERATURE REVIEW

There is a wide range of literature on the subject of wave loading, with most papers focusing on the effects of individual or continuous waves on vertical walls.

The U.S. Army coastal engineering research centre produces technical notes to aid in the design of walls on the shore. There are two relevant notes (U.S. Army Corps of Engineers, 1990 and 1991), with a distinction made between walls shoreward of the still-water line and those seaward of it.

For walls shoreward of the still-water line, the wave force, F, per unit length of the wall is given by equation (1).

$$F \approx 4.5 \times h^2 \tag{1}$$

where is the specific weight of water, and h is the surge height at the wall.

For walls seaward of the still-water line, the wave force per unit length can be divided into the hydrostatic (R_d) and dynamic components(R_h) as shown below.

$$R_d = \frac{Xd_b h_c}{2} \tag{2}$$

$$R_h = \frac{X \left(d_s + h_c\right)^2}{2} \tag{3}$$

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where h_c is the wave height at the wall, d_c is the water depth at the wall and d_b is the water depth at the point where the wave breaks.

These equations are useful for understanding the problem of loading on the bridge piers. However, all of them assume that the wave collides against an infinitely wide wall, ignoring the three-dimensional nature of the pier of a bridge.

There is a second body of literature that focuses on model scale testing, which is more relevant to the subject of this paper.

Kirkgoz (1992) has performed tests on sloping and vertical walls, using a foreshore slope of 1/10 (which produced maximum impact pressures). The variation of impact pressures with water depth was also investigated. Probability distributions of the results show that the most frequent location for the maximum impact pressure is slightly below the still-water level. For impact pressures at the bottom of the wall, the highest one was found when the wall was completely vertical.

Kato et al. (2005) conducted tests on 1:10 models of a coastal dike installed in Japan to stop or mitigate the effects of tsunamis in coastal areas. The experiments were conducted in a piston-equipped wave tank, on five models with different shore inclinations. The results showed a peak pressure on impact (similar to an impulse, lasting 0.004s), and a sustained but lower pressure for a longer time afterwards.

Similar model testing was performed by Thusyanthan and Madabhushi (2006, 2008) on a 1:25 model of a tsunami safe(r) house. Dimensional analysis showed that the three components of drag need to be considered. The skin-friction drag (associated to Re number), wave drag (Fr number) and pressure drag (reasonably independent of the two) all need to be considered. Since it is impossible to accurately model both the Re and Fr numbers, the scaling was based only on the Fr number (since wave drag was deemed more important than skin-friction drag). The same reasoning has been applied for the testing of bridge structures presented in this paper. Froude numder is a function of wave velocity, V, gravitational acceleration, g, and an associated length, L, as shown below.

$$Fr = \frac{V}{\sqrt{gL}} \tag{4}$$

The main threats to structures from tsunamis have been identified by Dias et al. (2006) as overturning, sliding and scouring. The last two are specially important for bridges, according to a report by Unjoh (2006) in which damage investigations were carried out on the bridges in the Banda Aceh region after the tsunami on December 26th 2004.

Unjoh (2006) found that piers and foundations are specially at risk during tsunamis for two reasons. Firstly, piers are at risk due to debris impact or ship collisions, and hence should be sturdy enough to sustain these loads. In addition scouring, the removal of large volumes of soil from around the foundations, should also be prevented since it decreases the stability of the piers.

Deck sliding was another failure mode considered in both reports. Unjoh (2006) found that large bridges with shear at the joint between the pier and the deck had sustained less damage than the ones without, and had less chances of the deck being washed off. Dias et al. (2006) suggest accepting deck sliding as a 'safe' failure mode, since tying the deck to the piers would increase the load on these.

EXPERIMENT SETUP

Wave Tank

Tsunamis are initiated by large underwater landslides or subsea earthquakes. These result in a sudden displacement of large volume of water. The resulting tsunami wave grows in wave height as it travel towards the shore. These conditions are almost impossible to replicate in a laboratory. In the present study, a single wave is created in a wave tank by displacement of a given volume of water (achieved by dropping a rectangular block into the tank). The wave tank used in this research is 4.5 m long, 1.5 m deep and 1 m wide. The schematic of the wave tank used in this research is shown in Figure 1. The base of the tank was filled with sand and profiled with slope angle of 15°. The bed was instrumented with pore pressure transducers (PPTs) as known intervals. The tsunami wave was created by dropping a rectangular block (mass of ~ 100 kg) into the water at the deepest end of the tank. The sudden displacement of water in the deep end of the tank creates a wave that propagates to the shore where the model house has been placed. The wave height was approximately 10 cm. The breaking waves were all 'surging' type breakers.

The wave generated in the experiment does not exactly model a real tsunami wave, since the wavelength is about two meters, while real tsunamis can have wavelengths of up to 100 m (which would scale to 4 m). Figure 2 shows the differences between the real wave and the one generated under laboratory conditions. It is clear that while the experimental wave does not model the tsunami wave exactly, it models the initial part reasonably well. This is considered sufficient for this study as the aim of this study is to understand the impact pressures of the tsunami wave.



Figure 1. Wave tank used for experiments



(b) Experiment wave impact on bridge

Figure 2. Comparison between ideal wave impact and experimental conditions

Model Bridges and Piers

Two types of structures were tested in the wave tank: piers and model bridges. Table 1 gives a summary of the tests carried out.

Table 1. Summary of Test Series

	Aim of the	Water level*	Variation						
	test series		(mm)						
Series A	Velocity Tests	-	-						
Series B	Variation in	0 mm							
	Pier Height								
Series C	Variation in	10 mm	Pier width						
	Pier Width		50, 100						
Series D	Variation in	0 mm	Foundation Depth						
	Foundation		45, 75, 105, 135						
	Depth								
Series E	Variation in	10 mm	Foundation Depth						
	Foundation		45, 75, 105, 135						
	Depth								
Series F	Variation in	0 mm	Deck Height						
	Deck Height		60, 90, 120, 150						

* Initial water level above ground level

In Series B to E a single pier was placed in the centre of the shore section of the tank. For Series F the whole structure (consisting of two piers and a deck) was assembled as shown in Figure 3, and tested.

Both the deck and the piers were made out of aluminium sections, cut to model a typical coastal bridge at a scale of 1/25. The piers consisted of 100 mm x 50 mm hollow blocks, and the deck was a 750 mm long channel section of dimensions 100 mm x 50 mm. This models a bridge with a span of 18.75 m.

The sections modelling the piers were cut to different lengths so that tests for varying embedment depths and different pier heights could be carried out. Miniature pressure sensors were placed on all the models being tested to measure the impact pressures from the wave. These sensors had a corner frequency of dynamic response of 15 kHz. In addition, an accelerometer and a LVDT were used for some of the tests in order to measure impact and resultant displacements. These were placed at a constant height of 50 mm above the sea bed, attached to the rear of the model structures.



Figure 3. Pier and deck setup

Testing Method

The model to be tested, once fully instrumented, was placed on the horizontal section of the beach profile, at the far side of the tank. The

miniature pressure sensors, LVDT and accelerometer were connected to a junction box and to a computer with data-logging software, which recorded at a frequency of 200 Hz. Digital cameras were positioned so that the general arrangement of the model, the tilt and the scour could be photographed before and after the test. In some of the tests a high speed video camera was also used to record the shape of the wave and its impact on the structure.

A rectangular block on the other side of the tank was raised using a winch, and placed on an actuator. Once the system was logging and the cameras recording, the actuator was released, and the block fell. The sudden displacement of water created a wave that travelled along the length of the tank and finally collided with the structure. The typical wave height was 10 cm (scaling to 2.5m in real life). Care was taken to ensure the profile was smooth so that the wave did not break before reaching the structure. Six series of tests were carried out, as shown in Table 1. Several drops were conducted for each individual test in order to achieve good results and ascertain repeatability, but only one drop per test is shown in this paper.

RESULTS

Velocity Tests (Series A)

No model structures were placed in the wave tank in series A tests, since the main aim was only to measure the velocity of propagation for a typical wave. PPTs had been placed at known intervals on the sandy slope of the tank. As shown in Figure 4, the sensors record a peak in their pressure as the wave propagates, corresponding to the additional height of water above them. Wave velocity was calculated using PPT the horizontal distance between the PPTs and the time elapse in the pressure response peaks. The summary of this analysis is given in Figure 5.



Figure 5. Variation in wave speed with distance along the tank

Variation in Pier Height (Series B)

In this series of tests, a bridge pier alone was used to investigate wave impact pressures for different pier heights (60 mm, 90 mm, 120 mm and 150 mm). The width of the pier was 50 mm and the foundation depth was kept at 75 mm throughout. Figure 6 shows the positioning of the pressure sensors for each of the different pier heights. Figure 10 shows images from the high speed video camera, which was used to record the wave shape before its collision with the pier, and the actual impact. Results for the 60 mm and 120 mm pier heights are shown in Figure 7 and Figure 8. As expected, the lowest sensor registers the highest pressure, which then decreases as we move up the structure. Using this data we can construct a pressure profile for both pier heights, shown in Figure 9.



Figure 6. Position of pressure sensors relative to ground level



Figure 7. Results for a 60 mm pier height, 75 mm embedment



Figure 8. Results for a 120 mm pier height, 75 mm embedment



Figure 9. Peak impact pressure profile for 60 mm and 120 mm high piers



Figure 10. Still frames from high speed video camera showing wave impact against a 60 mm high pier (75 mm foundation depth).

Variation in Pier Width (Series C)

A pier with a 90 mm height and a 135 mm deep foundation was used to test whether variations in pier width affect the wave impact pressures. Two different pier widths 50 mm and 100 were tested. The water was 10 mm above ground level before the start of both tests.

The results (Figure 11 and Figure 12) show that the peak impact pressure at the base of 100 mm wide pier was approximately 25% more than that of 50 mm wide pier. This is due to water having to curve a greater distance to get around the wider pier.





Variations in Foundation Depth (Series D and E)

The stability of any structure is controlled by a series of factors. Foundation depth is one of them, specially important in the case of bridges and tsunami loading for two reasons. Firstly, the deeper the foundation the stiffer the response of the structure. This leads to high impact pressures, which might not be desirable. Foundation depth is also important in bridges since initial tsunami wave action can remove large volumes of sand from the pier footings, making the actual embedment depth much less than the one designed for when a second wave impacts.

Four tests were conducted with foundation depths of 45 mm, 75 mm, 105 mm and 135 mm, and a constant pier height of 90 mm. In series D the tests were conducted with no water at the pier base before the tsunami wave (dry condition). Series E tests were carried out with shallow layer of water (10 mm above the ground level at the base of the pier –wet condition). Results for the series D (Figure 13) show the maximum impact pressures occurring near the base for dry condition and slight above the water level for wet case (Figure 14).

Figure 15 show the results obtained with an initial water level of 10 mm and pier embedment of 105 mm. The maximum pressure occurred at PS3 (55 mm above the base and 45 mm above the original water

level). The maximum pressure (6.5 kPa in PS3) obtained when the embedment was 105 mm was almost 3 times higher than that obtained when the embedment was 45 mm. This shows that as the foundation depth increases the resulting maximum impact pressures increase. This is because as the foundation depth increases the stiffness of the foundation increases and results in higher wave loading on the pier.



Figure 13. Results in the dry condition, 45 mm embedment



Figure 14. Results in the wet condition, 45 mm embedment



Figure 15. Results in the wet condition, 105 mm embedment

Variation in Deck Height (Series F)

An aluminium channel section was placed on top of two piers in order to model a bridge deck (as shown in Figure 3). No adhesive was used, so the deck was free to slide on the top surface of the pier structures. The pressures were monitored by placing miniature pressure sensors in the positions shown in Figure 16. Table 2 summarises location of all the stress sensors for each of the tests. Deck height given as the height above the ground level.



Figure 16 Distribution of pressure sensors on pier and deck

Table 2. Positions of stress sensors for each test								
Deck	Α	В	С	D				
Height								

Height					
60 mm	5 mm	45 mm	85 mm	70 mm	95 mm
90 mm	5 mm	50 mm	115 mm	100 mm	125 mm
120 mm	5 mm	60 mm	145 mm	130 mm	155 mm
150 mm	5 mm	80 mm	175 mm	160 mm	185 mm

Е

Tests were carried out with different sizes of piers (60 mm, 90 mm, 120 mm and 150 mm) to monitor the response of the impact pressures to a variation in the pier height. The foundation depth was 45mm and remained unchanged throughout.

Results are shown in Figure 17 to Figure 20. Tests for the 150 mm, 120 mm and 90 mm heights only show a marked increase in pressure for positions PS1 and PS2, this is to be expected since the wave height is about 10 cm, and hence would not have impacted fully on the deck. These graphs show a gradual decrease in pressure from PS1 to PS3, as would be expected, since the greater impact pressures would occur at the base of the pier.

In Figure 20 we can clearly identify impact on the pier and deck. Firstly, PS 1 & PS 2 responds followed by PS 3. After a very small time, the crest of the wave impacts the deck of the model resulting in higher impact pressures for PS4 and PS5. Hence we could state that in the case of a bridge deck being low enough to receive the impact of a tsunami wave, the deck will experience the highest impact pressure.



Figure 17. Results for deck at 150 mm



Figure 18. Results for deck at 120 mm



Figure 19. Results for deck at 90 mm



Figure 20. Results for deck at 60 mm

DISCUSSION

The first set of experiments show how variations in pier height, pier width and foundation depth affect impact pressures on a bridge pier. This provides an understanding of the factors that affect pier performance during tsunami wave loading. The experiments confirm that foundation depth affects the stiffness (resulting in higher pressures for a deep foundation), and that wide piers experience higher pressures than narrow ones. The tests with different pier heights provided a way to develop a pressure profile for a single pier when the stiffness was kept constant.

Similarly, a pressure profile can be computed for the tests conducted with the whole model structure (piers and deck). Figure 21 shows the peak pressure profile on pier and deck for the experiment with the deck height 60 mm from ground surface. Experiment peak pressures are shown as red points. This figure is useful to be able to understand the location of maximum impact pressures on a bridge.

The tests were conducted at a scale of 1:25. Using the scaling law in which the Froude number is kept constant, the prototype pressures can be estimated by multiplying the measured pressures by 25.



Figure 21. Pressure profile on bridge deck and pier (only half the bridge is shown). Foundation depth was 45mm and deck height 60 mm from ground surface.

Taking the 60 mm test in Series F as an example, we can calculate the maximum impact pressures on a full scale bridge deck (1.5 m above ground level, 60 mm \times 25) and pier would experience under a tsunami wave load. The peak pressure for the deck would be 72.13 kPa (2.885 kPa \times 25), and 54.28 kPa for the pier (2.171 kPa \times 25). These initial experimental values need to be validated with further experimental and numerical work.

Pressures found in these tests are much smaller than those in the literature. This could be due to the fact that the bridge piers and deck were only 50 mm wide, while most model tests are usually conducted on long, continuous walls, which would give higher pressures (as demonstrated by the variation in pier width tests). Hence, more investigation is needed before these values can be confirmed.

CONCLUSIONS

Impact of a tsunami wave on a structure can be modelled in laboratory using a wave tank and models provided the scaling laws are observed. Tests carried out on model bridge piers show that the highest impact pressures due to a tsunami wave will occur at the base of the pier in the dry condition, and slightly above the water level for the wet condition (10 mm water leve). Impact pressures on the pier depend on the wide of the pier as well.

Model bridges were also tested, consisting of two piers and a deck. The pressure distribution in the piers was similar to the one described above. Pressures in the deck peaked with a slight time delay, but their magnitude was as high as the impact pressures at the base of the pier.

Further detailed experiments are required to fully validate the results presented in this paper. This experimental work currently is on going in Cambridge.

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