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MODEL STUDY OF TSUNAMI WAVE LOADING ON COASTAL STRUCTURES

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ABSTRACT: This paper presents a review of literature on tsunami wave loading and some initial results of an ongoing research programme in Cambridge that investigates the tsunami wave loading on coastal structures. Model scale (1/25) experiments were performed on four different structures in a wave tank to understand the initial impact loading of a tsunami wave. Miniature pressure sensors were used to measure the wave pressures on the structures. Results show that the maximum impact pressure depends on the type of the building and can be between 5.5 to 9 times the hydrostatic pressure of inundation height at the scale these tests were carried out. Digital images obtained during the experiment, by a high speed (250 frames/s) video camera, show the flow mechanisms during the initial impact on different coastal structures.

Keywords: Tsunami wave loading, Coastal structures, Modelling, tsunami resistant housing

1. INTRODUCTION

Asian tsunami of 2004 was one of the worst natural disasters in recent times. The tsunami claimed more than 220 000 lives and made almost 800 000 people homeless. The total economic cost of catastrophe is estimated to be more than 10 billion euros. While earthquakes and tsunamis are forces of nature which are going to be inevitable, it is possible to be better prepared for them so that the damage to the infrastructure can be minimised in such unfortunate events. In order to save lives, efficient tsunami warning systems need to be put in place for evacuation of people from coastal areas. The economic and financial loss to the coastal community can be reduced by having tsunami resistant designs for coastal houses.

This paper presents results from on going research that aims to understand the initial loading of the tsunami wave on coastal structures. The results are based on model scale (1/25) testing of coastal structures subjected to tsunami wave loading.

2. REVIEW OF LITERATURE

There is a significant body of research work on the wave impact loading on vertical rigid walls [1-7].

While these give some guidance on the magnitude of tsunami wave loading on coastal houses, three dimensional nature of house structure, the propagation of tsunami wave around and through the house make wave impact on houses different to wave impact on a vertical wall. Asian tsunami of 2004 has shown the damage that tsunami loading can induce on various damage [8,9].

Japanese design method [10] (proposed by Okada et al. 2004) for tsunami wave loading considers both the static and dynamic loads together as an equivalent hydrostatic load with 3 times the inundation depth H, for tsunami wave with no break up (Fig.1). This leads to a resultant force equal to 9 times hydrostatic force of inundation depth H.



Fig. 1. Tsunami wave loading (after Okada et al.2004)

In the case of wave break-up, an additional triangular pressure distribution to a height of 0.8H with base pressure of 2.4ρ gH is superposed. This leads to an equivalent force of ~11 times hydrostatic force of inundation depth H. If the height of the building does not exceed 3H, then the pressure distribution is truncated at the height of the building.

U.S Army coastal engineering research centre technical note [11] also provides guidance on wave force on shoreward vertical wall. This guidance is based on the work of Cross [12] and Camfield [1]. The tsunami wave force F per unit length of the wall is give by Eq. (1).

$$F = \frac{\rho g H^2}{2} + C_F \rho V^2 H \tag{1}$$

where C_F is a coefficient based on the bore gradient and $V = 2(gH)^{0.5}$. It was shown [11] that for most cases the F $\approx 4.5 \rho gH^2$. This is in line with the Japanese design method as it is 9 times hydrostatic force of inundation depth H.

Federal Emergency Management Agency's (FEMA) Coastal Construction Manual [13] provides the total wave load (hydrodynamic and hydrostatic) on vertical wall (height ≥ 2.2 H) of coastal residential building to be about 11 times hydrostatic force with inundation depth H.

Another way to consider the tsunami wave loading is to consider it as consisting of three components; hydrostatic loading, hydrodynamic loading and impact loading. Hydrostatic loading per unit width of the wall can be obtained from Eq. (2).

$$F_s = 0.5\rho g H^2 \tag{2}$$

Total hydrodynamic can be obtained from equation (3).

$$F_d = 0.5 C_D \rho V^2 HA \tag{3}$$

where A is projected area (per unit width) of the house on the plane normal to flow direction, $V = 2(gH)^{0.5}$ [13] and C_D is drag coefficient varying between 1.25 and 2 [14]. If the wave is taken to be normal to the house wall, hence A is equal to height times the width of the house, hydrodynamic loading

per unit length of the wall can be obtained by substituting for V and C_D as in Eq. (4).

$$F_d = 0.5 \times 1.25 \times \rho \times 4gH^2 = 5F_s \tag{4}$$

Impact loading can be deduced from the work of Nakamura [15], Eq. (5)

$$F_i = 0.5 C_t \rho V^2 H \tag{5}$$

where C_t depends on the angle of wave front at impact and its value is typically between 1.7 to 3. If we substitute, $V^2 = 4$ gH and $C_t = 2$ into Eq. (5)

$$F_i = 0.5 \times 2 \times \rho \times 4gH \times H = 8F_s \tag{6}$$

This suggests that the overall loading per unit width can be as high as $14F_s$ (Eq.7), however this is an upper limit and the actual value may be lower.

$$F_{Total} = F_s + F_d + F_i = F_s + 5F_s + 8F_s \approx 14F_s \quad (7)$$

This paper presents experimental results that can be compared with these above mentioned guidelines on tsunami wave loading on structures.

3. EXPERIMENTAL WORK

3.1. Wave Tank

Tsunamis can be caused by large landslides or earthquakes. The origin of a tsunami wave due to an earthquake is a sudden displacement of seabed due to a thrust fault movement, displacing the water above and causing a pulse of wave. Earthquakes with dip-slip fault results in such seabed displacements.

Creating a tsunami wave under laboratory conditions require alternative methods. In this research, the tsunami wave is created in a large wave tank. A single wave is 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 schematic of the wave tank used in this research is shown in Fig. 2. The slope angle of the bed was 15° . It is recognised that the modelled wave is not representative of tsunami wave as the wave length is only about 2 m. However, the initial wave impact on the house would be similar to that of a tsunami wave impact. Hence, the experiments can be used to understand the impact pressures of a tsunami wave on houses.



Fig. 2. 4.5m long wave tank.



Fig. 3. Schematic diagram of 4.5m long wave tank.

Fig. 3 shows the dimensions of the wave tank and the locations of pore pressure transducers (PPTs) placed in sand.

3.2. Model Structures

Four model scale structures were tested in the wave tank. Table 2 summarises the model structures that were tested in the wave tank.

Control structures 1 and 2 are wooden blocks of height 100 mm and 350 mm respectively. Length and width of both structures are 200 mm \times 200 mm. These control structures have no openings and have well grounded foundations, hence will attract the maximum wave loading from the tsunami wave. The control structure 1 is to be used as control experiment when comparing wave loading on single storey coastal houses and control structure 2 for comparing wave loading on tall structures such as multi-storied buildings.

Structure 3 is a tsunami resistant house design, known as tsunami safe(r) house, designed by Tsunami Design Initiative (TDI). Tsunami Design Initiative was a student initiative at Harvard Design School, in collaboration with MIT SENSEable City Laboratory [16]. The concept of the tsunami safe(r) house design is based on decreasing the wave loading on the structure by allowing part of the wave to pass through the house. Thus the middle section of the house is made of partitions, used as door that can be easily blown away by the wave. The detailed design of the house is given in [16]. A scale model ($1/25^{th}$ scale) of the designed house was built using wood plank for the base and strips for walls (Fig. 5). The foundation of the tsunami safe(r) house design was modelled by attaching bolts to the wooden base. The base of the house is elevated by 2 cm to allow passage of water between the ground and the house.

Structure 4 is a scale model of a typical coastal Sri Lankan house (Fig. 6). This was tested in the wave tank to show the tsunami wave induced damage to such houses. The walls of the model coastal house were built using small model scale bricks and the roof was made of small slates. The model bricks were pasted with mortar. The total weight of the model house was 1.7 kg and the walls cover a base area of 200 mm \times 200 mm. It should be noted that the strength of joints (mortar & glue) in model house were not modelled according to scaling laws. Therefore, the model houses were much stronger for their size and were not expected to fail by shear as real house walls may fail. The main objective of testing the typical Asian coastal house was to obtain the wave loading it attracts in comparison to the tsunami safer houses.

Table 2. Details of structures tested.

Structure	Base floor area	Bearing	
		pressure	
1. Control structure 1	$250 \text{ mm} \times 250 \text{ mm}$	2.50 kPa	
2. Control structure 2	250 mm × 250 mm	1.25 kPa	
3. Tsunami safe(r) house	260 mm × 360 mm	2.20 kPa	
4. Typical coastal house	250 mm × 250 mm	0.26 kPa	

All the model structures were instrumented with miniature pressure sensors (Entran EPN series) in order measure the wave loading. Dimensions of the structures and the locations of the pressure sensors are shown in Fig. 4.

Fig. 5 shows the model tsunami safe(r) house before the attachment of roof and doors. Fig. 6 shows the model scale typical Asian coastal house that was tested under tsunami wave loading.



Tsunami safe(r) house

Typical coastal house

Fig. 4. Dimensions of model structures with instrument locations.







Fig. 6. Model scale (1/25th scale) typical Asian coastal house.

3.3. Testing Procedure

The model house, with the pressure sensors attached, was placed on the shore as shown in Fig. 2. The rectangular block was raised just above the water level in the tank and positioned ready to be released by an actuator. The high speed video camera was also positioned to capture the passage of the wave as it impacts the model house. Once the data acquisition system and the high speed video camera were ready to log, the actuator was switched on to release the rectangular block into the water. The sudden displacement of water by the rectangular block created a single wave that travelled towards the shore and impacted the model house. Pore pressure and pressure sensor data were recorded at 1 kHz.

Table 1 summaries all the tests carried out in this study. The wave height was about 10 cm and was same in all the tests. An initial series of tests (series A) was carried out without the model structure to use as a control experiment for measuring wave speeds. In series B and C, control house 1 and 2 were tested. The tsunami safe(r) house was tested in series D and typical coastal house was tested in series E testing.

Three repeated tests were carried out in each of the series, however, only one experiment results from each of the series is presented in this paper.

Test	Description	Maximum wave pressure on the front wall		
Series A	Wave only	-		
Series B	Control structure 1	7.4 kPa		
Series C	Control structure 2	9.0 kPa		
Series D	Tsunami safe design	5.7 kPa		
Series E	Typical coastal house	6.9 kPa		

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4. RESULTS

4.1. Wave Velocity in Experiments

Fig. 7 shows pore pressure measurements recorded by PPTs during a typical test. The figure clearly shows the propagation of a single wave. The average wave velocity was calculated by dividing the horizontal distance between the PPTs by the time lags in excess pore pressures. Fig. 8 shows the wave speeds from a set of tests. The initial wave speeds obtained in the tests are reasonably close to the deep sea theoretical prediction of 2.2 m/s (square root of the product of the acceleration of gravity and the water depth) for a water depth of 0.5 m. As expected, the wave speed decreased as it travelled along the slope while the wave height increased. In all the tests, the wave speed just before reaching the model structure house was about 1 m/s and the wave height was 10 cm.



Fig. 7. Pore pressure measurements during wave propagation.



Fig. 8. Wave speeds calculated from time lags in pore pressure measurements.

4.2. Experiments with Control Structures (Series A and B testing)

Fig. 9 shows the recordings of pressure sensors from control structure 1. Pressure sensors PS.1, PS.2 and PS.3 are all located at the centreline of the front wall of the structure. PS. 4 is located 20 mm from the edge but at the same height as PS.1 and similarly PS. 5 is located 20 mm from the edge but at the same height as PS.3. PS.5 failed to work properly.

It is clear from Fig. 9 that the maximum pressure recorded is by the pressure sensor near the base, PS.3, and is about 7.4 kPa. PS.1 and PS.2 recorded similar maximum pressure of 4.5 kPa. Peak measurement of PS.4 was 3 kPa. Since the inundation height H was 10 cm, the peak wave pressure on control structure 1 is 7.4 times the hydrostatic pressure of inundation height H.

Fig. 10 shows the pressure measurements from control structure 2 for the same wave loading as that applied to control structure 1. The maximum pressure of 9 kPa was recorded by PS. 3 which was 100 mm from the ground level. The lowest pressure sensor PS.4, 20 mm from ground, recorded 5.4 kPa. PS.1 and 2 record about 7 kPa while PS.6, located 330 mm from ground level recorded 2.2 kPa. PS.5 which was located 20 mm from the edge of the structure but at the same elevation as PS. 2 recorded 6.7 kPa as maximum pressure.

The above results show that height of the structure plays a role in the maximum impact pressure exerted by a tsunami wave.

4.3. Experiments with Typical Coastal House and Tsunami Safer House Design

Fig. 11 shows a typical result from series D testing of tsunami safe(r) house. The locations if the pressure sensors are shown in Fig. 4 & 5. The pressure sensors PS.1 and PS.2, which are on the front wall, recorded maximum pressures of 5.7 kPa and 4.5 kPa respectively. The video footage of the test showed that the tsunami wave pushed open the central section of the tsunami safe(r) house and the wave passed through the house.

Fig. 12 shows the results from series E testing of a typical coastal house. The pressure sensors PS.1 and PS.2 recorded maximum pressures of 6.9 kPa and 5.7 kPa respectively. As the tsunami wave impacted the house, the roof of the house was blown away followed by rotation and translation of the house.



Fig. 9. Pressure sensor recording from control structure 1.



Fig.10. Pressure sensor recording from control structure 2.

4.4. Digital Images from the Experiments

A high speed video camera was used to capture the passage of the tsunami wave in all the experiments. A frame rate of 250 per second was used to capture 4 s of video footage starting from just prior to wave reaching the model structures. Fig. 13 & 14 show the clips obtained from tests on control house 1 and 2 respectively. The time lag between the clips is 0.13 s. When the wave impacts the control house 1, the water splash rises to almost three times the house height. In the case of control structure 2, the water splash rises to twice the house height.

In Fig. 15 (a) to (h), the top, middle and the bottom rows show clips of typical coastal house, tsunami safe(r) house without roof and tsunami safe(r) house respectively. It is clear from all the clips that the breaking waves in all these tests are surge breakers. The water splash from the model coastal house reached almost twice the height of the model house (Fig.15(e)) where as it is almost non-existent for the



Fig. 11. Pressure sensor recording from tsunami safe(r) house.



Fig. 12. Pressure sensor recording from typical coastal house.

tsunami safe(r) house. The roof the typical coastal house was completely uplifted by the wave, and the rest of the house was titled and translated with the passage of the wave. The tsunami safe(r) house performed well under the wave loading. Since the doors of the house are centrally located, the water wave was able to open up a clear path through the central region of the house. This allows part of the wave to pass through the house, hence causing less uplift splash and lower impact pressures on the walls.

5. DISCUSSION

The peak impact pressures measured in this study agrees well with data from other researchers. Hull and Müller (2002) [17] studied wave impact pressures on vertical walls in a wave tank and they reported peak pressures in the range of 5 kPa to 10 kPa for wave velocity of 1.5 m/s with wave heights



(a)



(b)



(c)



(d)



(e) Fig. 13. Images of Control structure 1, Δt~0.13s



(a)









(e) Fig. 14. Images of Control structure 2, $\Delta t \sim 0.13$ s.



(e)(f)(g)Fig. 16. Images of tests showing typical coastal house being
destroyed and tsunami safe(r) house with standing the wave
load, Δt~0.12s.

(h)

in the range 5 cm to 8 cm. Hattori et al. (1994) [6] had also performed similar experiments and reported peak pressures around 5 kPa for wave heights of 7 cm and wave velocity of 2 m/s. Chan (1994) [5] reported the peak pressure on vertical wall by wave impacts as $9\rho c^2$ where ρ is water density and c is wave speed. For a wave height of 13 cm and wave velocity of 1.7 m/s the measure maximum pressure on vertical wall was 29 kPa.

Fig. 18(a) and (b) summarises the peak impact pressures experienced by the front walls of the control structure 1 and 2 respectively. The points on the plot are the values from the pressure sensors (Fig.9,10) when PS.3 was at its peak. The shaded areas can be used to estimate the peak force on the wall. From Fig.18, the peak force on control structure 1 can be estimated as 10 times the hydrostatic force from 10 cm water (wave height). For control structure 2, the peak force can be estimated as 40 times the hydrostatic force from 10 cm water (wave height). It should be noted that this peak force is impact force and not continuous and these results are based on small scale (1/25) testing and should not be interpreted to prototype scale until further research is carried out to confirm the findings. Scaling laws for prototype interpretation are explained in [18,19].



Fig. 18. Tsunami Safe(r) house construction in Sri Lanka

The pressure values obtained from Froude law scaling of small-scale fresh water models tends to overestimate the magnitude of impact pressures likely to occur in the field [21,22]. Two main reasons for this discrepancy are the aeration level in water and air entrapment. The aeration levels are higher in sea water than in fresh water. Consequently, impact pressures by seawater are lesser than by fresh water. Bullock et al. (2001)[21] has shown, using wave tank tests with wave height of 267 mm, the difference is about 10%. Impact pressure is also governed by the air entrapment. Hattori et al. (1994) [6] has shown that a small amount of air entrapped between the breaking wave and the wall increases the impact pressure considerably. Therefore, more research is required

before impact pressures on houses obtained from model tests can be confidently interpreted to prototype scale.

Fig. 19 shows the tsunami safe(r) house being constructed in Sri Lanka. It should be noted that practical implications and society views mean that the final built-house has few features different to that of original design.



Fig. 19. Tsunami Safe(r) house construction in Sri Lanka

6. CONCLUSIONS

Model study of tsunami wave loading on coastal structures has produced valuable understanding on the magnitude of wave loadings on structures and identified mechanisms of wave propagation around structures.

For a given tsunami wave velocity and height, the maximum pressure distribution on a coastal structure depends highly on whether there is openings for the passage of water and the height of the structure. Results from control structures showed that maximum impact force on a single storey house, with a tsunami wave velocity of 1 m/s (5 m/s prototype) and 10 cm (2.5m prototype) wave height (same as house height), can be estimated as 10 times the hydrostatic force. For the same tsunami wave loading, the maximum impact force on a taller structure can be as high as 40 times the hydrostatic force.

Tsunami safe(r) house design performed well in the test while typical coastal structure failed by roof lift off. More research is needed before the results based on model scale tests can be confidently interpreted to field situations.

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