First European Conference on Earthquake Engineering and Seismology
(a joint event of the 13th ECEE & 30th General Assembly of the ESC)
Geneva, Switzerland, 3-8 September 2006
Paper Number:1526

MODEL TESTING OF TSUNAMI SAFE(R) HOUSE DESIGN

Indrasenan THUSYANTHAN[1] and Gopal MADABHUSHI[2]

SUMMARY

This paper presents the model testing of tsunami safe(r) house designed by Tsunami Design Initiative, a student initiative at Harvard Design School in collaboration with MIT SENSEable City Laboratory. 1/25th scale models of the new house design and a typical coastal house were tested in a tsunami tank. The new house design performed well under tsunami wave loading while the typical coastal house was badly damaged. Digital images obtained during the experiment, by a high speed (500 frames/second) video camera, showed that the tsunami wave passed through the new house design without damaging the house but severely damaging the typical coastal house.

1. INTRODUCTION

Asian tsunami of December 25th 2005 showed us the catastrophic devastation that could be caused by a tsunami on lives, infrastructure and economy (Dias et al. 2006). 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 for us to be better prepared for them so that the damage to the infrastructure can be minimised in the case of such unfortunate events. In order to safe lives, efficient tsunami waning 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.

Tsunami Design Initiative, a student initiative at Harvard Design School, in collaboration with MIT SENSEable City Laboratory developed the Tsunami Safe(r) House design (Chen et al. 2005, TDI 2005). In March 2005, TDI won the Tsunami Challenge Competition hosted by MIT SIGUS group, and presented their ideas at USAID in Washington, D.C. The project is executed by Prajnopaya Foundation and Sri Bodhiraja Foundation in Sri Lanka. The first prototype of the Tsunami Safe(r) House has been completed in September 2005 in Balapitiya in Sri Lanka. Instead of four solid walls, the new house design has four core columns made of concrete reinforced with metal rods about three meters wide. Partition walls of wood or bamboo are built in between the columns. The basic design concept was that these houses would allow the passage of the tsunami wave without attracting too much hydrodynamic loading. While this concept is good, it is still necessary to test and validate the performance of this tsunami safe(r) house design.

This paper presents model testing of the tsunami safe(r) house design in a wave tank. Scale models (1/25th) of the new house design and a typical Sri Lankan coastal house were tested in a wave tank in which the near shore tsunami wave conditions were created. The new design performed well under the tsunami wave loading hence the test results provided validation for the new tsunami safe(r) house design. The video footage of the tests provided insight into the sequence of events that occur as the tsunami wave impacts and destroy typical coastal houses. Other important factors, which are not focused in this paper but are important for tsunami resistant design include debris impact and scouring of foundation (Dias et al. 2005, Myrhauga and Rueb. 2005, Rambabu et al. 2003).

[1] Research Fellow (Churchill College), Department of Engineering, University of Cambridge, Cambridge, CB3 0EL, UK
Email : it206@cam.ac.uk
[2] Senior Lecturer, Department of Engineering, University of Cambridge, Cambridge, CB2 1PZ,UK
Email: mspg1@eng.cam.ac.uk

2. CONSIDERATION OF SIMILARITY

Model testing requires similarity between the model and the prototype. Similarity means that all relevant dimensionless parameters having the same values for the model and the prototype. Similarity generally includes three basic classifications in fluid mechanics: (1) Geometric similarity; (2) Kinematic similarity; (3) Dynamic similarity. Model testing of wave propagation and wave impact is a complex problem as identified and investigated by various researchers (Bullock et al. 2001, Walkden et al. 2001, Hull and Müller, 2002, Martin et al. 1999). A basic dimensional analysis is showed in this paper, detailed analysis will be provided in Thusyanthan and Madabhushi (2006). The relevant parameters for this model testing are given in Table 1.

Table 1: Variables relevant for dimensional analysis

Variable	Symbol	Dimension
Wave loading on the building	F_d	MLT^{-2}
Density of water	ρ	ML^{-3}
Wave velocity	V	ML^{-1}
Building length (length in contact with water)	L	L
Height of the wave	h	L
Frontal area of the house	A	L^2
Gravitational acceleration	g	LT^{-2}
Dynamic viscosity	μ	$ML^{-1}T^{-1}$

The wave loading F_d on the house depends on variables as shown in equation (1).

$$F_d = f(\rho, V, L, h, A, g, \mu) \tag{1}$$

There are 8 variables and 3 dimensions so according to Buckingham's π theorem we expect at least 5 independent non-dimensional groups. The non-dimensional groups can be arranged as shown in equation (2).

$$\frac{F_d}{A\frac{1}{2}\rho V^2} = f\left[\frac{\rho VL}{\mu}, \frac{V}{\sqrt{gL}}, \frac{h}{L}, \frac{A}{hL}\right] \tag{2}$$

So $C_D = f$ (Re, Fr, h/L, A/hL) where,

Drag coefficient $C_D = \dfrac{F_d}{A\frac{1}{2}\rho V^2}$, Reynolds number $\mathrm{Re} = \dfrac{\rho VL}{\mu}$, Froude number $Fr = \dfrac{V}{\sqrt{gL}}$

The Reynolds number is the ratio of inertial forces to viscous forces and the Froude number is the ratio of the inertia force on an element of fluid to the weight of the fluid element. If viscous and inertial forces are to be similar the Reynolds number of the model and the prototype must be equal. If the inertial forces and the gravitational forces are to be similar then the Froude number of the model and the prototype must be the same. If water is used in the model testing, it is not possible to keep both the Fr number and Re number same between the model and the prototype. This is because keeping Re same require $(VL)_{model} = (VL)_{prototype}$, but keeping Fr same require $(V/L^{1/2})_{model} = (V/L^{1/2})_{prototype}$. The same problem is faced when ship drag is studied in model testing. In a similar analogy to ship drag, the wave loading on the building can be thought to arise from three sources; the skin-friction drag, wave drag and the pressure drag. Re number determines the skin-friction drag and Fr number determines the wave drag while the pressure drag is reasonably independent of Re and Fr. Since skin-friction drag is thought to be minimum for wave loading on a building, the Re number can be ignored and the scaling can be based on the Fr number as shown in equation (3).

$$\frac{V_m}{\sqrt{gL_m}} = \frac{V_p}{\sqrt{gL_p}} \rightarrow \frac{V_m}{\sqrt{gL_m}} = \frac{V_p}{\sqrt{g25L_m}} \rightarrow V_m = \frac{V_p}{5} \tag{3}$$

Scaling law for the pressure from wave loading on house is given in equation (4)

$$\frac{F_{d\,m}}{A_m \frac{1}{2}\rho V_m^{\ 2}} = \frac{F_{d\,p}}{A_p \frac{1}{2}\rho V_p^{\ 2}} \quad \rightarrow \quad \frac{F_{d\,m}/A_m}{F_{d\,p}/A_p} = \frac{V_m^{\ 2}}{V_p^{\ 2}} = \frac{1}{25} \tag{4}$$

3. EXPERIMENTAL WORK

3.1 Creating a tsunami wave

Tsunamis can be caused by landslides or earthquakes. The origin of a tsunami wave due to an earthquake is a sudden displacement of seabed displacing the water above and causing a pulse of wave. The wave speed is the square root of the product of the gravity constant (g) and water depth. 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 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 Figure 1. The slope angle of the bed was 15°.

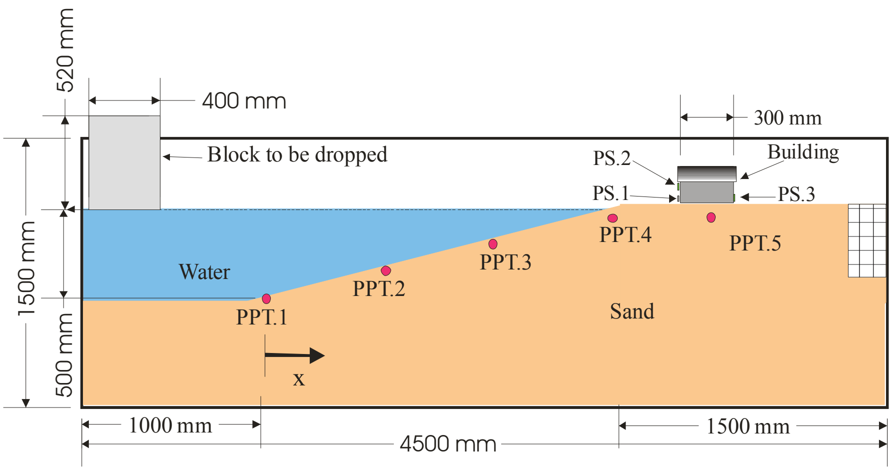


Figure 1: Schematic of the wave tank and location of instruments

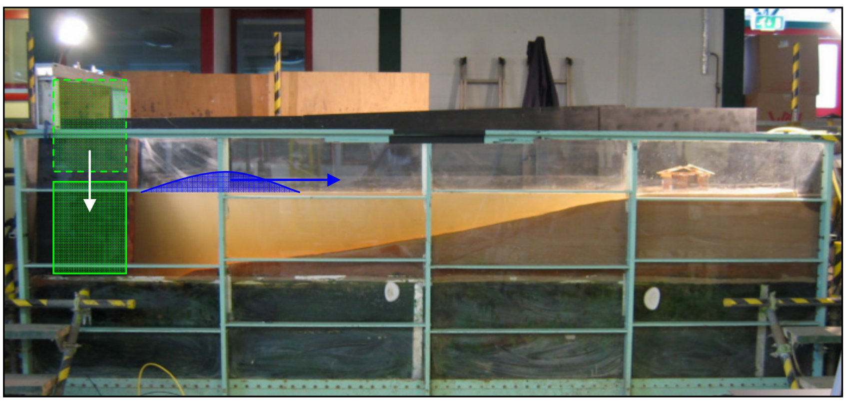


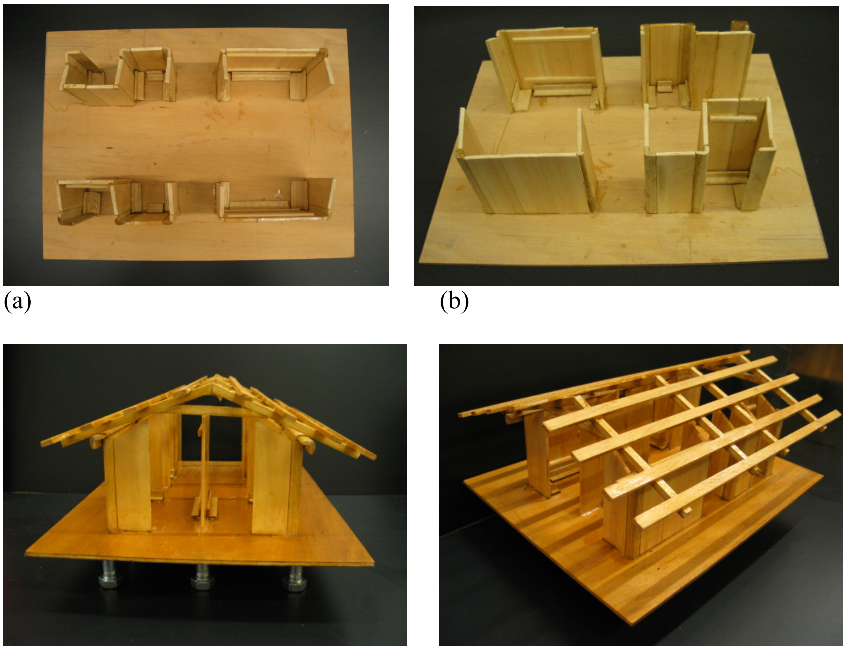
Figure 2: Wave tank with water and model house

3.2 Building model house of tsunami safe(r) house design

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 that can be easily blown away by the passage of water. The detailed design of the house is given in Chen at al. 2005.

A scale model (1/25th scale) of the designed house was built using wood plank for the base and strips for walls. The foundation of the tsunami safe(r) house design was modeled by attaching bolts to the wooden base. The walls of the model house cover a base area of 200 mm × 300 mm. The total weight of the model tsunami safe(r) house was 3.1 kg of which 0.7 kg was the roof structure. The base of the house is elevated by 2 cm to allow passage of water between the ground and the house.

A scale model of a typical coastal Sri Lankan house was also built and 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 × 200 mm. It should be noted that the strength of joints (mortar & glue) in model house were not modeled according to scaling laws. Therefore, the model houses were much stronger for their size and were not expected to fail as real house would fail. The main objective of testing the typical Sri Lankan house was to obtain the wave loading it attracts in comparison to the tsunami safer houses.



(a) (b) (c) (d)

Figure 3: Tsunami safe(r) model house construction

Figure 4: Typical coastal model house

3.3 Testing procedure

The model house, with the pressure sensors attached, was placed on the shore as shown in the Figure 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 traveled towards the shore and impacted the model house. Pore pressure and pressure sensor data were recorded at 1 kHz.

Table 2 summaries all the tests carried out in this study. The tests were done in two phases. Tests 1 to 4 were carried out in phase one and test 4 and 5 were done in phase 2. Initial test (Test 1) was carried out without the model house to use as a control experiment. In test 2, the tsunami safe(r) house was tested without the roof to observe the wave reflections from the walls and wave passage though the house. The complete tsunami safe(r) house was tested in test 3. The typical coastal house without proper foundation was tested in test 4. In test 5, the typical coastal house was tested with proper foundation. In test 6, the tsunami safe(r) house was tested again.

Table 2: Summary of the tests

Test number	Description	Outcome
Test 1	Wave only	Control experiment
Test 2	Tsunami safe design without roof	House performed well
Test 3	Tsunami safe design with roof	House and roof performed well
Test 4	Typical coastal house without proper foundation	Roof was destroyed and the house displaced and tilted
Test 5	Typical coastal house with proper foundation	Roof was destroyed but the house was intact
Test 6	Tsunami safe design with roof	House and roof performed well

4. RESULTS

4.1 Pore pressure measurements

Pore pressure measurements recorded by PPTs during test 3 are shown in Figure 5. The figure clearly shows the propagation of the tsunami wave. Figure 6 summarises the excess pore pressures from all the tests. The excess pore pressure experienced along the bed slope increases from about 0.8 kPa in PPT.1 to about 1.1 kPa in PPT.3. This increase in pore pressure corresponds to the increase in the tsunami wave height as it travels alone shallower depths towards the shore. The corresponding tsunami wave height is about 8 cm to 11 cm from PPT.1 to PPT.3 location. The excess pore pressure in PPT.4 is slightly reduced to around 1 kPa as the wave breaks onshore. The PPT.5, which is located about 5 cm below the model house recorded, also recorded excess pore pressure in the range of 0.5 kPa to 0.6 kPa.

The average wave velocity was calculated by dividing the horizontal distance between the PPTs by the time lags in excess pore pressures. Figure 7 shows the wave speeds from all the tests. The initial wave speeds obtained in the tests are reasonably close to the 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 traveled along the slope while the wave height increased. In all the tests, the wave speed just before reaching the model house was about 1 m/s. The increase in wave height is manifested as an increase of water pressure at the slope bed as seen in Figure 6.

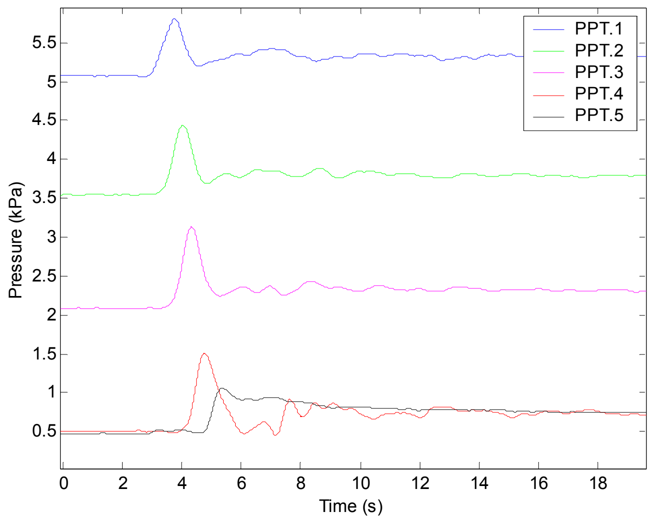


Figure 5: Pore pressure readings during Test 3

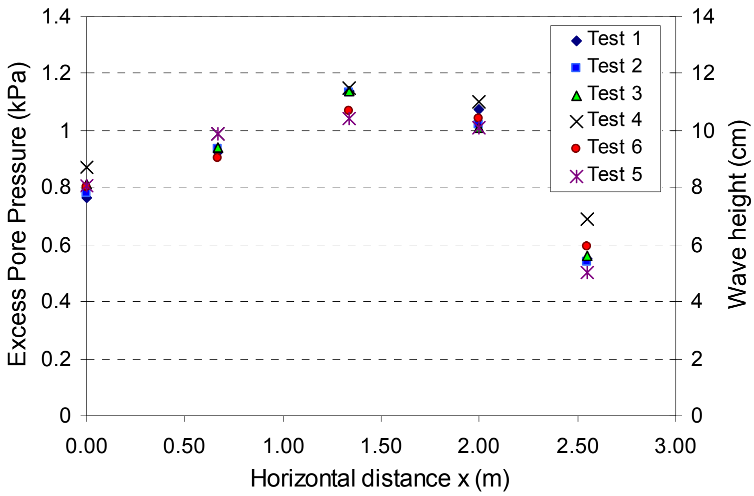


Figure 6: Excess pore pressures recorded in all the tests

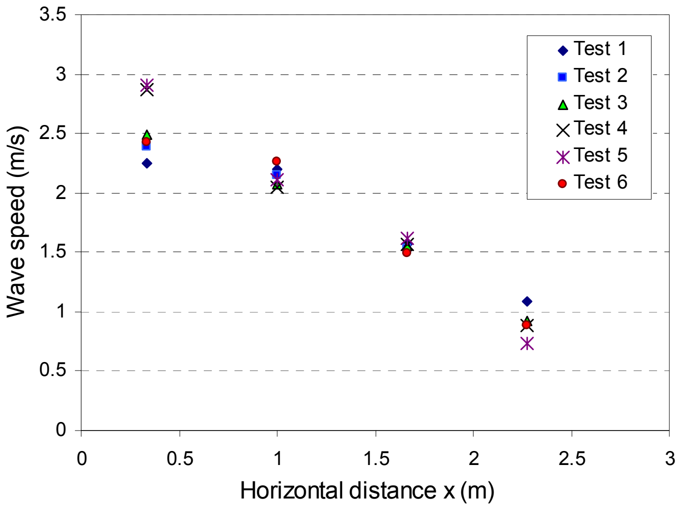


Figure 7: Wave speed

4.2 Wave loading on the house

The doors occupy 58% for the frontal area of the tsunami safe(r) house, thus the wave loading on the tsunami safe(r) house can be expected to be 58% less than that of the typical coastal house for the same house dimension and wave pressures. Wave loading on the front and back walls of the model houses were measured by 3 pressure sensors as shown in Figure 1. Pressure sensors PS. 1 and PS. 2 were positioned on the front wall about 20 mm and 80 mm from the base of the house respectively. PS. 3 was attached to the rear wall at about 20 mm from the base.

The pressure sensor readings from the walls of tsunami safe(r) house in test 3 are given in Figure 8. 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 average of peak pressure in PS.1 and PS.2 can be taken as the peak pressure on the front wall, 5.1 kPa. Thus the horizontal force on the front wall can be calculated by multiplying this pressure by the frontal area. The pressure sensor PS.3 which was on the rear wall started to record after a time lag of 0.6 s and it recorded a maximum pressure of 3 kPa. This is expected, as the wave needs to travel the length of the house before applying pressure on the back wall. Reading of PS.3 show two distinct peaks, first one due to the initial wave and the second one possibly due to the reflecting wave from the wave tank.

As a first estimate, ignoring the frictional forces on the side-walls of the house by the wave, the resultant horizontal force on the house at any instant can be obtained by subtracting the force on the rear wall from the force on the front wall. It is clear from Figure 8 that the maximum resultant horizontal force on the house would occur during the initial impact (5 s to 5.6 s) as there is no pressure on the rear walls during this time. The maximum pressure on the front wall of the house is 5.1 kPa. This corresponds to 127.5 kPa (5.1 × 25) for a prototype house and the prototype wave velocity is 5 m/s (1×5). Figure 9 shows the pressure sensor readings from the walls of typical coastal house in test 4. The pressure sensors PS.1 and PS.2 recorded maximum pressures of 6.9 kPa and 5.7 kPa respectively. Therefore, the average pressure experienced by the front wall is 6.3 kPa, which corresponds to 157.5 kPa (6.3 × 25) for a prototype house. The pressure experienced by the typical coastal house is slightly higher than that of tsunami safe(r) house even though the tsunami waves have the same characteristics. This is mainly because the tsunami safe (r) house is located 20 mm above ground due to its elevated foundation. Therefore, the absolute elevation of the pressure sensors in tsunami safe(r) house is 20 mm higher than the corresponding sensors in the coastal house. In the tsunami safe(r) house bottom part of the wave is allowed to travel through the gap between the house base and the ground, and the 58% of the top part of the wave is also allowed to travel through the house. Therefore, the tsunami safe(r) house experiences lesser drag force. The tsunami safe(r) house performed well under the wave loading whereas the coastal house was damaged severely. The roof of the coastal house was blown off by splashing water from the wave and the house as a whole was translated and tilted by the wave force.

When a coastal house with proper foundation was tested in test 5, it performed much better than the house in test 4. Only the roof of the house was damaged by the wave. Further details and analysis of the test results will be provided in Thusyanthan and Madabhushi (2006).

The peak impact pressures measured in this study agrees well with data from other researchers. Hull and Müller (2002) 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 in the range 5 cm to 8 cm. Hattori et al. (1994) 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) 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.

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 (Bullock et al. 2001, Bird et al. 1998). 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) 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) 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.

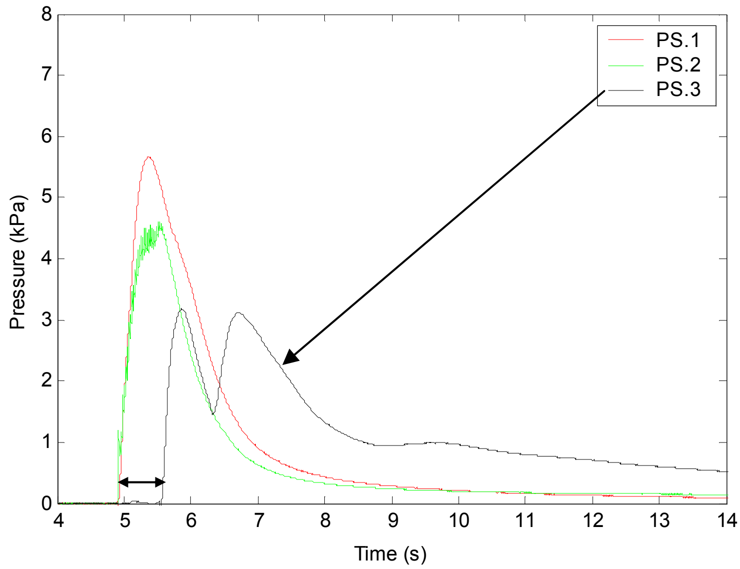


Figure 8: Pressure sensor measurements from Test 3

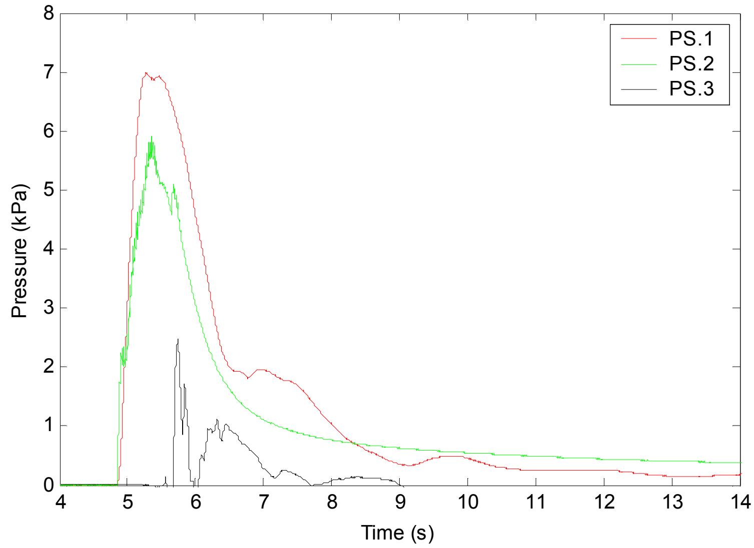


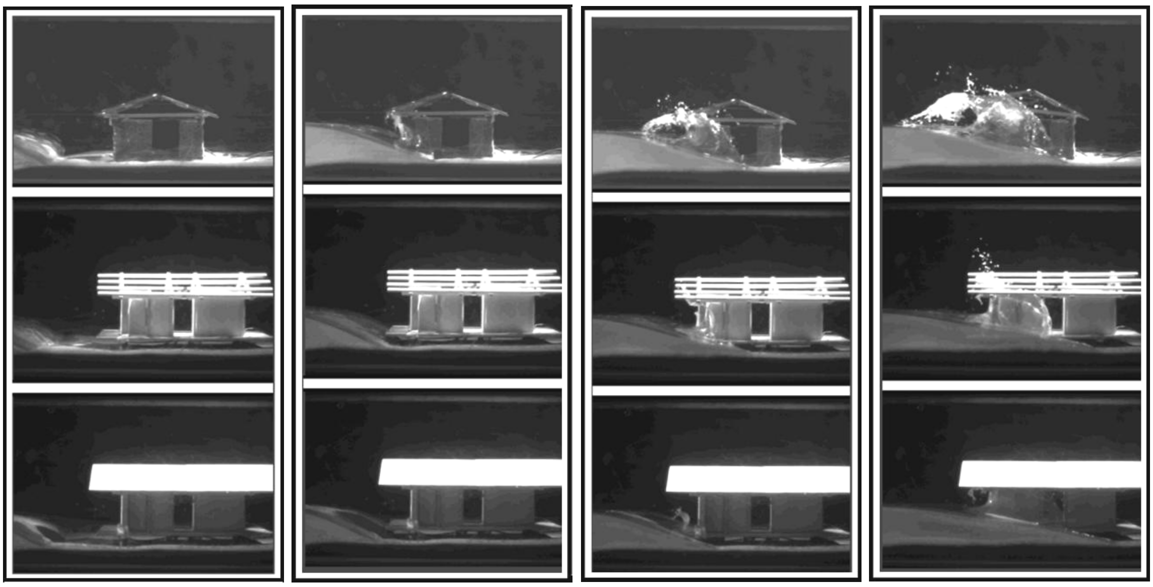
Figure 9: Pressure sensor measurements from Test 4

4.3 High speed video capture

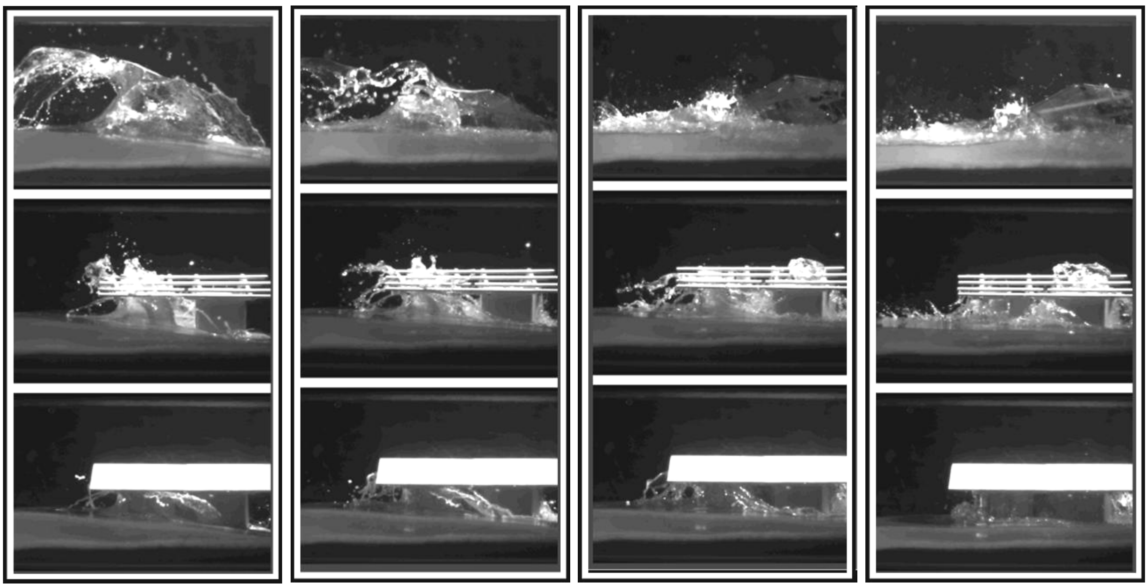
A high speed video camera was used to capture the passage of the tsunami wave in the experiments. A frame rate of 500/s was used to capture 2 s of video footage starting from just prior to wave reaching the model house. Figure 10 (a) to (h) shows the clips obtained from video footage of tests 2, 3 and 4. The clips were extracted from the video footage every 60 frames so the time lag between the clips is 0.12 s. In Figure 10 (a) to (h), the top, middle and the bottom rows show clips from test 4 (typical coastal model house without foundation), test 2 (tsunami safe design without roof) and test 3 (tsunami safe design with roof) respectively. It is clear from clips in Figure 10 that the breaking waves in these tests are surge breakers.

As the wave impacts the typical coastal model house, water is splashed and curled upwards as can be seen from Figure 10(c) and (d). The corresponding clips for the tsunami safer house show minimum water splash as water passes through the house and below the base of the house. The roof of the model coastal house lifted off due to the uplift force of the water splash and was thrown way into flow, destroying the roof and the slates (Figure 10(f)..(h)).

The water splash from the model coastal house reached almost twice the height of the model house (Figure 10(e)) where as it is much smaller for the tsunami safer house. This alone suggests that the force of the wall of tsunami safer house would be less than that for the model coastal house. This is proved correct by the pressure sensor readings (from PS.1 and PS.2) shown in Figure 8 and Figure 9 and the fact that the frontal area of the tsunami safe(r) house is 58% lesser than that of coastal house. While the roof of the coastal house was completed removed from the house by the tsunami wave, the rest of the house was tilted and translated with the passage of the wave.



(a) (b) (c) (d)



(e) (f) (g) (h)

Figure 10: clips from high speed video camera (time lag ∆t between the clips is ~ 0.12 s)

5. CONCLUSION

Model testing of a tsunami safe(r) house design and a typical Sri Lankan coastal house was carried out in a wave tank to study the effectiveness of the new design and to understand the wave loading on the house. The new tsunami safe(r) house performed well under the tsunami wave loading while the typical coastal house was destroyed by the tsunami wave. Miniature instruments were used to measure water pressures at the seabed and hydrodynamic pressures on the model houses. The video clips of the tests showed details of how the tsunami wave impacts the house wall and applies uplift force to the roof structure.

The following facts were observed in the tests.

- The roof of the house experiences uplift forces due the splashing water that curls upwards after impacting the wall.
- The walls of the house tend to shear off the foundation if the shear strength of the wall-foundation connection is not sufficient.
- The house can slide or overturn if the foundations are not properly designed to account for tsunami wave loading.

Further study is required to investigate the detailed loadings on the house, excess pores pressures near the house foundation and the effectiveness of various other tsunami resistant designs.

6. ACKNOWLEDGEMENT

The authors would like to thank all staff at the Schofield Centre for their help in carrying out the testing. Advice and guidance of Domenico del Re of Buro Happold, London, has been valuable and is acknowledged with thanks. The first author would like to thank the Churchill College for its financial support.

7. REFERENCES

Bird, P. A. D., Craford, A. R., Hewson, P. J. and Bullock, G. N. (1998), An instrument for the field measurement of wave impact pressures ans seawater aeration, Coastal Engineering, no. 35, 103-122.

Bullock, G. N., Crawford, A. R., Hewson, P. J., Walkden, M. J. A. and Bird, P.A.D. (2001), The influence of air and scale on wave impact pressures, Coastal Engineering, no. 42, 291-312.

Chan, E. S. (1994), Mechanics of deep water plunging-wave impacts on vertical structures, Coastal Engineering, no. 22, 115-133.

Chanson, H. and Maruyama, M. (2003), An experimental study of tsunami run-up on dry and wet horizontal coastlines, Science of Tsunami Hazards, Volume 20, no. 5, 278-293.

Chen, E., Ho, E. Jallad, N., Lam, R., Lee, J. Zhou, Y., Domenico Del Re, Berrios, L., Nicolino, W. and Ratti, C. (2005), Resettlement or Resilience? The Tsunami Safe(r) project, International Symposium - Disaster Reduction on Coasts Scientific-Sustainable-Holistic-Accessible, Monash University, Melbourne, Australia.

Dias, P., Dissanayake, R. and Chandratilake, R. (2006), Lessons learned from tsunami damage in Sri Lanka, Proceedings of ICE Civil Engineering, paper 14199, 74–81.

Dias, P., Fernando, L., Wathurapatha, S. and Yenuka de Silva (2005), Structural resistance against sliding, overturning and scouring caused by tsunamis, International Symposium - Disaster Reduction on Coasts Scientific-Sustainable-Holistic-Accessible, Monash University, Melbourne, Australia.

Hattori, M.m Arami, A. and Yui, T. (1994), Wave impact pressures on vertical walls under breaking waves of various types, Coastal Engineering, no. 22, 79-114.

Hull, P. and Müller, G. (2002), An investigation of breaker heights, shapes and pressures, Ocean Engineering, Vol 29, 59-79.

Kirkgöz, M. S. (1995), Breaking wave impact on vertical and sloping coastal structures, Ocean Engineering, Vol 22, no. 1, 35-48.

Martin, F. L., Losada, M. A. and Medina, R. (1999), Wave loads on rubble mound breakwater crown walls, Coastal Engineering, no. 37, 149-174.

Myrhauga, D. and Rueb, H. (2005), Scour around group of slender vertical piles in random waves, Technical note, Applied Ocean Research, 27, 56–63.

Rambabu, M. Narasimha Rao, S., Sundar, V. (2003), Current-induced scour around a vertical pile in cohesive soil, Ocean Engineering, 30, 893–920.

TDI design (2005), Tsunami safer house design for the Prajnopaya Foundation, http://senseable.mit.edu/tsunami-prajnopaya/

Thusyanthan, N.I. and Madabhushi, S.P.G. (2006), Tsunami wave loading on structures, in preparation.

Walkden, M. J., Wood, D. J., Bruce, T. and Peregrine, H. D. (2001), Impulsive seaward loads induced by wave overtopping on caisson breakwaters, Coastal Engineering, no. 42, 257-276.