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Tsunami wave loading on coastal houses: a model approach

The Asian tsunami of 26 December 2004 killed over 220 000 people and devastated coastal structures, including many thousands of traditional brick-built homes. This paper presents the results of model tests that compare the impact of a tsunami wave on a typical coastal house with that on a new 'tsunami resistant' design developed in the USA and now built in Sri Lanka. Digital images recorded during the test reveal how the tsunami wave passed through the new house design without damaging it, but severely damaged the typical coastal house. Pressure sensor results also provided further insight into tsunami wave loading, indicating that the established Japanese method significantly underestimates maximum impact load.

The Asian tsunami of 26 December 2004 showed the catastrophic devastation that could be caused by a tsunami to human lives, infrastructure and economy.[1–3] The tsunami claimed more than 220 000 lives and made almost 800 000 people homeless. The total economic cost of the catastrophe is estimated to be more than £7·5 billion.

While earthquakes and tsunamis are inevitable forces of nature, it is possible to be better prepared for them so that the damage to infrastructure can be minimised. To save lives, efficient tsunami-warning systems need to be put in place for the evacuation of people from coastal areas. The physical, economic and financial loss to the coastal community can also be reduced by having tsunami-resistant designs for houses and other infrastructure in the region.

Understanding tsunami wave loading on coastal houses is important to improve the design of coastal structures. This paper presents the results of physical model tests of coastal houses subjected to tsunami wave loading in a 4·5 m long wave tank. 1:25 scale models of a typical Sri Lankan coastal house and a new house design were tested in the tank, in which the near-shore tsunami wave conditions were created.

The new house design, named the 'tsunami-resistant house',[4] was designed by a student initiative at Harvard Design School in collaboration with the Massachusetts Institute of Technology (MIT).[5] Instead of four solid walls with small openings for doors and windows used in conventional design, the new design has centrally placed doors facing the sea and the corner walls are made of reinforced concrete. The basic design concept was that these houses would allow the passage of the tsunami wave, through the central part of the house, without attracting too much hydrodynamic loading. While the concept is sound, it was still necessary to test and validate its performance.

Review of the literature

There is a significant body of research work on the wave impact loading on vertical walls. [6–11] While these can give some guidance on the magnitude of tsunami wave loading on coastal houses, the three-dimensional nature of house structures and the propagation of a tsunami wave around and through houses make wave impact very different to that on a vertical wall. The Asian tsunami has shown the severe damage that tsunami loading can inflict on various structures. [12, 13]

A Japanese design method (proposed by Okada *et al.*[14]) for tsunami wave loading considers both the static and dynamic loads together. The force per unit length of the wall is taken as an equivalent hydrostatic load with three times the inundation depth, H, for a tsunami wave with no break-up (Fig. 1(a)). This leads to a resultant force equal to nine times the hydrostatic force of inundation depth H. In the case of wave break-up, an additional triangular pressure distribution to a height of $0{\cdot}8H$ with base pressure of $2{\cdot}4\ \rho\mathbf{g}H$ (where ρ is density of the water and $\mathbf{g}$ is the gravity constant) is superimposed (Fig. 1(b)). This leads to an equivalent force of around 11 times the hydrostatic force of inundation depth H. If the height of the building is less than $3H$, then the pressure distribution is truncated at the height of the building.

The US Army's coastal engineering research centre's technical note[15] also provides guidance on wave force on a shoreward vertical wall. This guidance is based on the work of Cross[16] and Camfield.[17] The tsunami wave force per unit length of the wall is given as a sum of hydrostatic force and dynamic force. It was shown that, for most cases, the tsunami wave force is $4{\cdot}5\ \rho\mathbf{g}H^2$. This is in line with the Japanese design method as it is nine times the hydrostatic force of inundation depth H.

The US Federal Emergency Management Agency's (FEMA) coastal construction manual[18] provides the total wave load (hydrodynamic and hydrostatic) on a vertical wall (height $\geq 2{\cdot}2H$) of a coastal residential building to be about 11 times the hydrostatic force with inundation depth H.

Another way to consider the tsunami wave loading is to consider it as consisting of three components:[13] hydrostatic, hydrodynamic and impact loading. An important part of the hydrodynamic loading depends on the drag coefficient C_D, which varies between 1·25 and 2.[19] FEMA recommends a drag coefficient of 1·25 for width-to-inundation-depth ratios of 1 to 12. If the wave is taken to be normal to the house wall, hydrodynamic loading per unit length of the wall can be shown to be five times that of the hydrostatic force.

Impact loading can be shown to be a function of the impact coefficient C_t. It can be deduced from the work of Nakamura[20] that C_t depends on the angle of wave front at impact, and its value is typically between 1·7 and 3 as bore angles vary from 22·5° to 45°. The impact force based on the above values of C_t can be shown to be 12 times that of the hydrostatic force.

In conclusion, the literature review suggests that the overall loading per unit width can be as high as 18 times the hydrostatic force. However, this is an upper limit and the actual value may be lower. More research is needed to understand the impact loading on houses as the past research has concentrated on vertical walls without openings such as doors or windows.

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	$ML^{-1}T^{-1}$

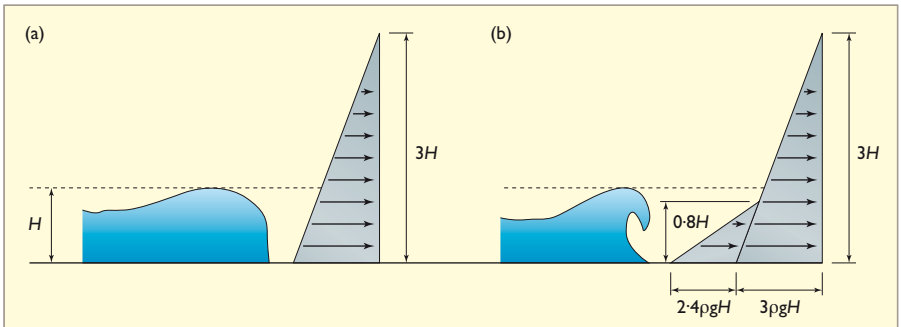

Fig. 1. The Japanese design method assumes tsunami wave pressure is equivalent to three times the hydrostatic pressure for an unbroken wave (a), or around 11 times if the wave breaks (b)[15]

Consideration of similarity

Model testing requires similarity between the model and the prototype. Similarity means that all relevant dimensionless parameters should have the same values for the model and the prototype. Similarity generally includes three basic classifications in fluid mechanics: geometric similarity, kinematic similarity and dynamic similarity. Model testing of wave propagation and wave impact is a complex problem as identified and investigated by various researchers.[21–24] The relevant parameters for the model testing in this paper are given in Table 1.

There are eight variables and three dimensions so, according to Buckingham's π theorem, these give at least five non-dimensional groups such as Reynold's number (Re), Froude number (Fr), drag coefficient and two non-dimensional length parameters.

Re is the ratio of inertial forces to viscous forces; Fr is the ratio of the inertia

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force on an element of fluid to the weight of the fluid element. If viscous and inertial forces are to be similar, Re of the model and the prototype must be equal. If the inertial forces and the gravitational forces are to be similar, then Fr 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 Fr and Re the same between the model and the prototype. This is because keeping Re the same requires $(VL)_{model} = (VL)_{prototype}$, but keeping Fr the same requires $(V/L^{1/2})_{model} = (V/L^{1/2})_{prototype}$.

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 determines the skin-friction drag and Fr determines the wave drag while the pressure drag is reasonably independent. Since skin-friction drag is thought to be minimum for wave loading on a building, Re can be ignored and the scaling can be based on Fr. This suggests that the model velocity must be a fifth of the velocity obtained in the field at full scale. Consequently, the pressure felt by the model structures will be 1/25th of the pressures felt by the structures in the field. These scaling factors will be used while interpreting the experimental results described below.

Experimental work

Creating a tsunami wave in laboratory conditions

Tsunamis are caused by sudden displacement of a large body of water as a result of landslides or earthquakes. The origin of a tsunami wave due to an earthquake is a sudden displacement of the seabed, displacing the water above and causing a wave pulse. The tsunami wave then travels in shallow water with a speed of $\sqrt{\mathbf{g}d}$, where **g** is the gravity constant and d is the water depth.

Creating a tsunami wave under laboratory conditions requires a large wave tank and a sudden displacement of water. Even then, it is difficult to model a tsunami wave accurately under laboratory conditions as a typical tsunami wave has long wavelength and period. The wave tank used in this research was 4·5 m long, 1·5 m deep and 1 m wide (Fig. 2). The base of the tank was filled with sand and profiled with slope angle of 15°. The bed was instrumented with pore-pressure transducers.

The model tsunami wave was created by dropping a rectangular block (mass around 100 kg) into the water at the deepest end of the tank. The sudden displacement of water in the deep end of the tank created a wave that propagated to the shore where the model houses were placed. The wave height was approximately 100 mm and the wave period was 1·5 s. The breaking waves were all 'surging' type breakers.

Building model houses

The concept of the tsunami-resistant 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 displaced by the passage of water. The detailed design of the house is given in Chen *et al.*[4]

A 1:25 scale model of the house was built using a timber plank for the base and glued timber strips for walls.

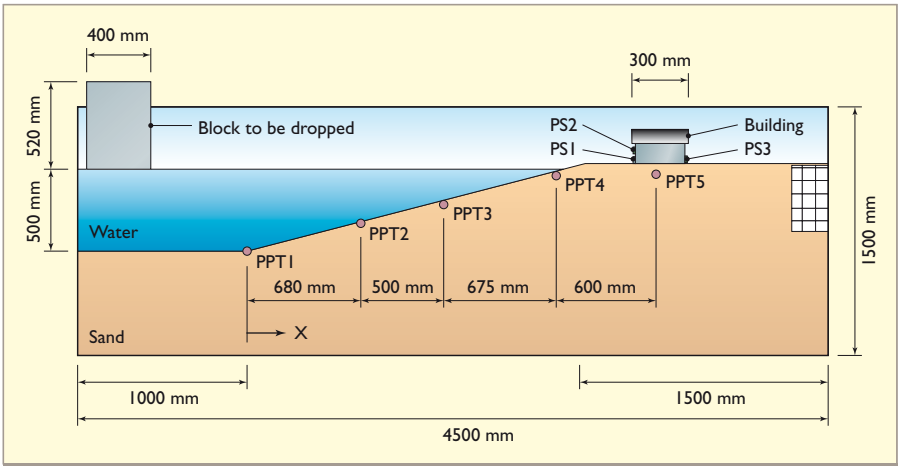

Fig. 2. Layout of the 4·5 m long wave tank, showing location of the five pore-pressure transducers in the bed and three pressure sensors on the model houses

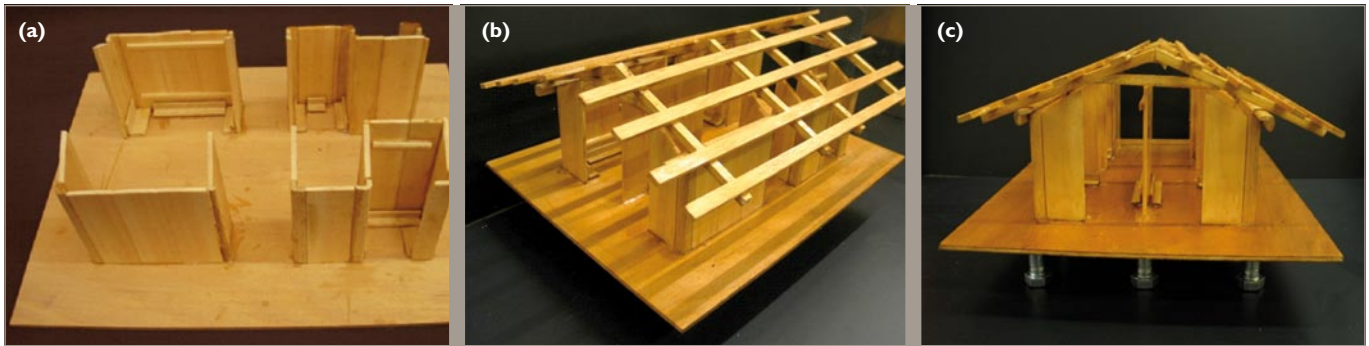

Fig. 3. 1:25 scale model of the tsunami-resistant house design, before (a) and after (b) adding the roof structure (prior to fixing doors and roof cladding), and (c) showing frontal elevation with raised foundations

Fig. 4. 1:25 scale model of a typical Sri Lankan coastal house with brick walls and tiled roof

Fig. 5. View of wave tank with water and model house

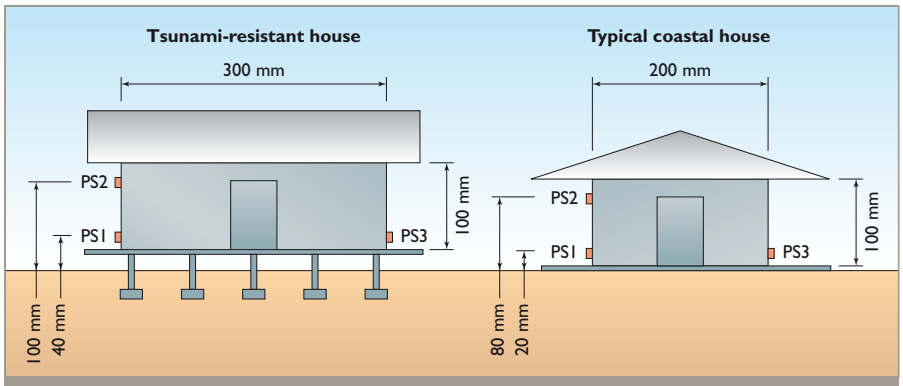

Fig. 6. Dimensions of the model houses, showing the location of pressure sensors

Table 2. Summary of the six model tests

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

Fig. 3 shows the model before and after addition of the roof structure (but prior to fixing doors and roof cladding). The foundations were modelled by attaching bolts to the wooden base. The base area was 200 mm × 300 mm and total weight was 3·1 kg, of which 0·7 kg was in the roof structure. The base of the house was elevated by 20 mm to allow passage of water between the ground and the house.

A scale model of a typical coastal Sri Lankan house was also built (Fig. 4). The walls of the model coastal house were built using model-scale bricks and mortar paste, and the roof was clad with small slates. Total weight was 1·7 kg and the base area was 200 mm × 200 mm.

It should be noted that the joint strength (glue and mortar) in the model houses was not modelled according to scaling laws. As such, the model houses were much stiffer than reality and would therefore attract more wave loading. This was considered acceptable for this study as the main aim was to understand the maximum wave loading on different house designs irrespective of material strengths.

Testing procedure

Pressure sensors were attached to the model houses, which were then placed on the shore in the tank (Fig. 5). The location of the sensors and the dimensions of the houses are shown in Fig. 6. The rectangular block was then dropped into the water, creating a single wave that travelled towards the shore and impacted on the model house. The passage of the wave was captured by a high-speed video camera and pore pressure and pressure sensor data were recorded at 1 kHz.

Table 2 summarises the tests carried out. The first test was carried out without the model house to use as a control experiment. In test 2, the tsunami-resistant house was tested first with the roof off, in order to observe wave reflections from walls and wave passage though the house, and then with the roof on. The typical coastal house was then tested without and then with a proper foundation. The complete tsunami-resistant house was finally tested again.

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Results

Pore-pressure measurements

Pore pressure measurements recorded during test 3 are shown in Fig. 7, which clearly shows the propagation of the tsunami wave. Fig. 8 summarises the excess pore pressures from all the tests. The increase in wave height is manifested as an increase of water pressure at the slope bed. The excess pore pressure experienced along the bed slope increases from about 0·8 kPa in transducer 1 to about 1·1 kPa in transducer 3, corresponding to an increase in wave height from about 80 mm to 110 mm. The excess pore pressure in transducer 4 is slightly reduced to around 1 kPa as the wave breaks onshore. Transducer 5, which is located about 50 mm below the model house, also recorded excess pore pressure in the range of 0·5–0·6 kPa.

The average wave velocity was calculated by dividing the horizontal distance between the transducers by the time lags in excess pore pressures. Fig. 9 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 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 house was about 1 m/s.

the main aim was to understand the maximum wave loading on different house designs irrespective of material strengths

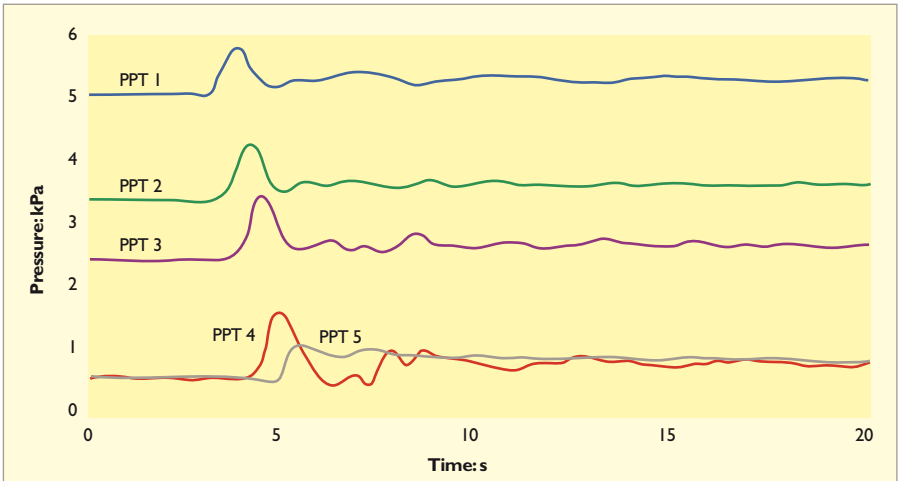


Fig. 7. Typical pore pressure measurements by the five transducers clearly show the propagation of the wave

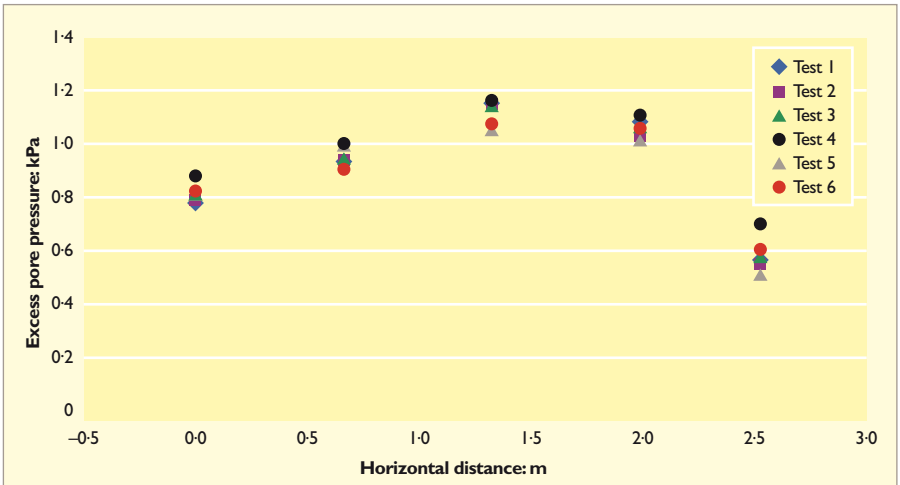


Fig. 8. Summary of excess pore pressures recorded by the five transducers during the six tests—pressure builds as the incoming wave height rises and then falls as it breaks

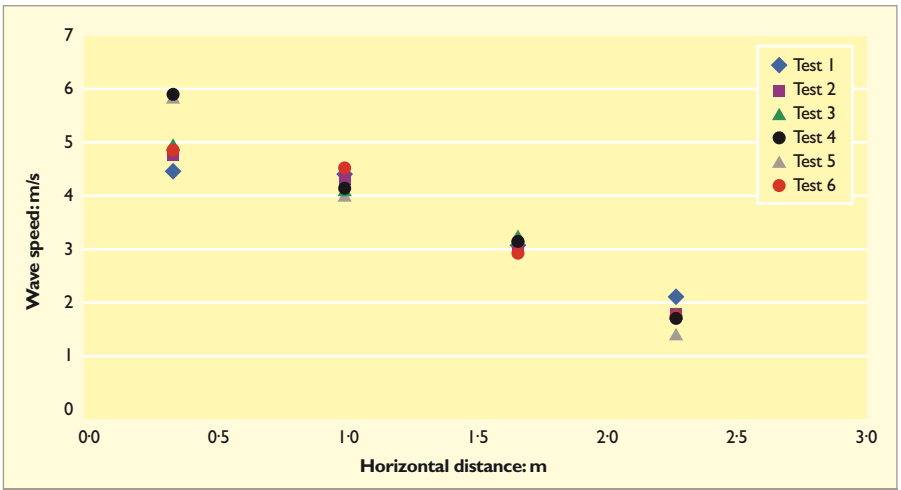


Fig. 9. Summary of wave speeds derived from pressure peaks, show gradual deceleration

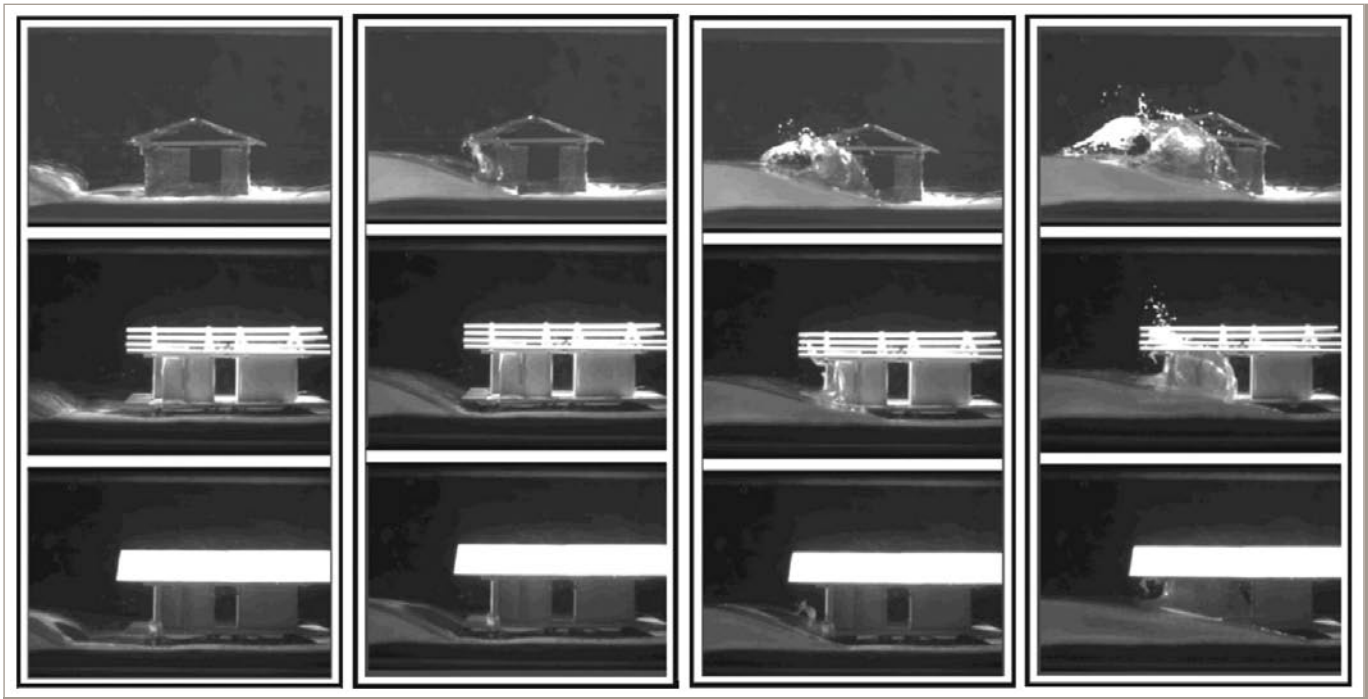


Fig. 10. Clips from the high-speed video camera at 0·12 s intervals, showing the traditional coastal house model being destroyed (test 4, top) while the

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 the wave reaching the model houses. Fig. 10 shows eight clips obtained from video footage of tests 2, 3 and 4. Clips were extracted from the video footage every 60 frames so the time lag between each clips is 0·12 s. The top row shows results from test 4 (typical coastal house without proper foundation), the middle shows test 2 (tsunami-resistant design without roof) and the bottom row shows test 3 (tsunami-resistant design with roof). It is clear from the clips that the breaking waves in these tests were surge breakers.

As the wave impacts on the typical coastal house, water is splashed and curled upwards, as can be seen from Fig. 10. The corresponding clips for the tsunami-resistant 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 was lifted off and carried away in the flow, destroying the roof and its slate cladding.

The water splash from the typical coastal house reached almost twice the height of the building, whereas it is much smaller for the tsunami-resistant house. This alone suggests that the force on the wall of the tsunami-resistant house would be less than that for the model coastal house. This is proved by the readings from pressure sensors 1 and 2 in Fig. 11.

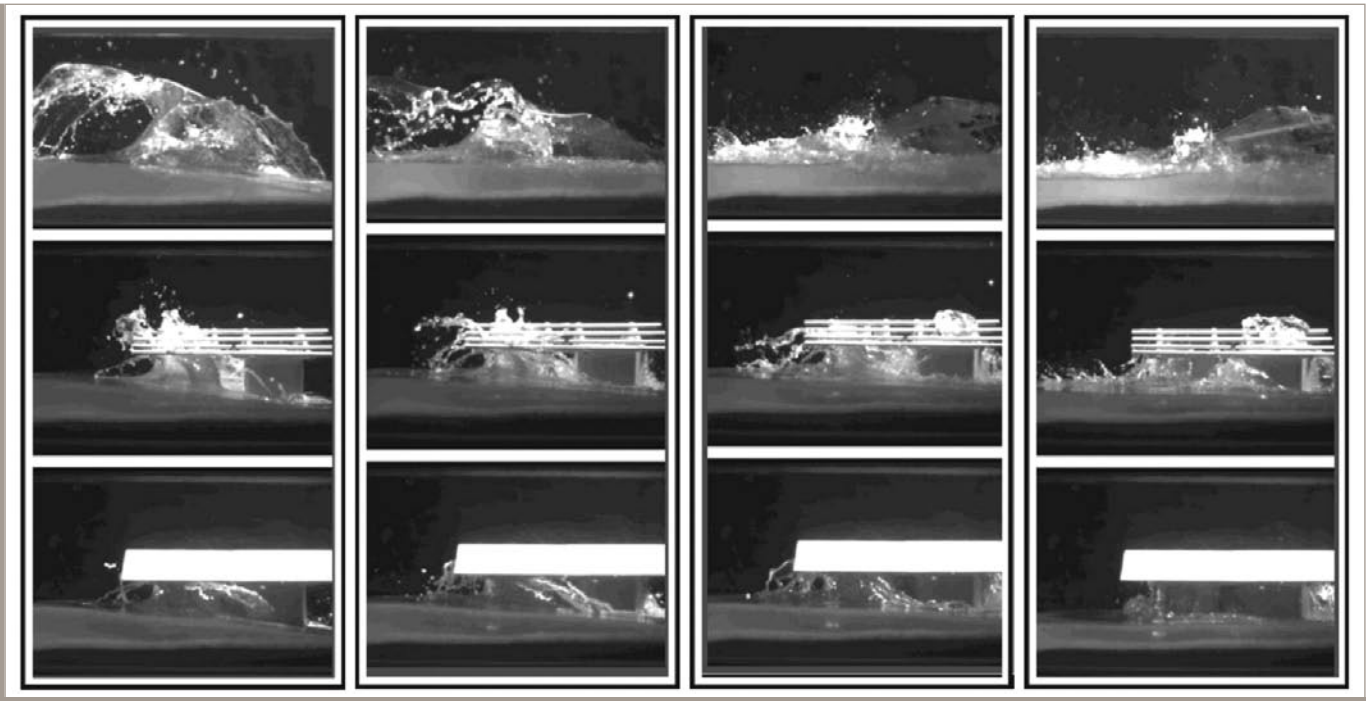
Wave loading on houses

Wave loading on the front and back walls of the model houses was measured by three pressure sensors as shown in Fig. 4. Pressure sensors 1 and 2 were positioned on the front wall about 20 mm and 80 mm from the base of the house, respectively. Sensor 3 was attached to the rear wall at about 20 mm from the base. The prototype interpretation of the wave loading in this paper is based on Froude scaling as discussed previously.

The pressure-sensor readings from the walls of tsunami-resistant house in test 3 are given in Fig. 11(a). Pressure sensors 1 and 2, which were positioned on the front wall, recorded maximum pressures of 5·7 kPa and 4·5 kPa, respectively. The average of peak pressure in sensors 1 and 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 frontal area. Sensor 3, which was on the rear wall, started to record after a time lag of 0·6 s and it showed 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. The pressure record of sensor 3 shows two distinct peaks, the first due to the initial wave and the second 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 Fig. 11(a) that the maximum resultant horizontal force on the house would occur during the initial impact (5–5·6 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—based on Froude scaling—to 127·5 kPa (5·1 × 25) for a full-sized house with a tsunami wave velocity of 5 m/s (1×5).

Figure 11(b) shows the sensor readings from the walls of the typical coastal house in test 4. Sensors 1 and 2 recorded maximum pressures of 6·9 kPa and 5·7 kPa, respectively. Therefore, the aver-



tsunami-resistant house (test 2 middle and test 3 bottom) remained intact, with much lower water splash

age pressure experienced by the front wall is 6·3 kPa, which corresponds to 157·5 kPa (6·3 × 25) for a full-sized house. The pressure experienced by the typical coastal house is slightly higher than that of tsunami-resistant house, even though the waves had the same characteristics, mainly because the latter is located 20 mm above ground due to its elevated foundation. Therefore, the absolute elevation of the pressure sensors in tsunami-resistant house is 20 mm higher than the corresponding sensors in the coastal house. Part of the wave is allowed to travel through the gap between the tsunami-resistant house base and the ground, and 58% of the top part of the wave is also allowed to travel through the house. The tsunami-resistant house thus experiences lesser impact force.

The tsunami-resistant house performed well under the wave loading whereas the coastal house was damaged severely. The roof of the coastal house was forced 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 a proper foundation was assessed in test 5, it performed much better than the house in test 4. Only the roof of the house was damaged by the wave.

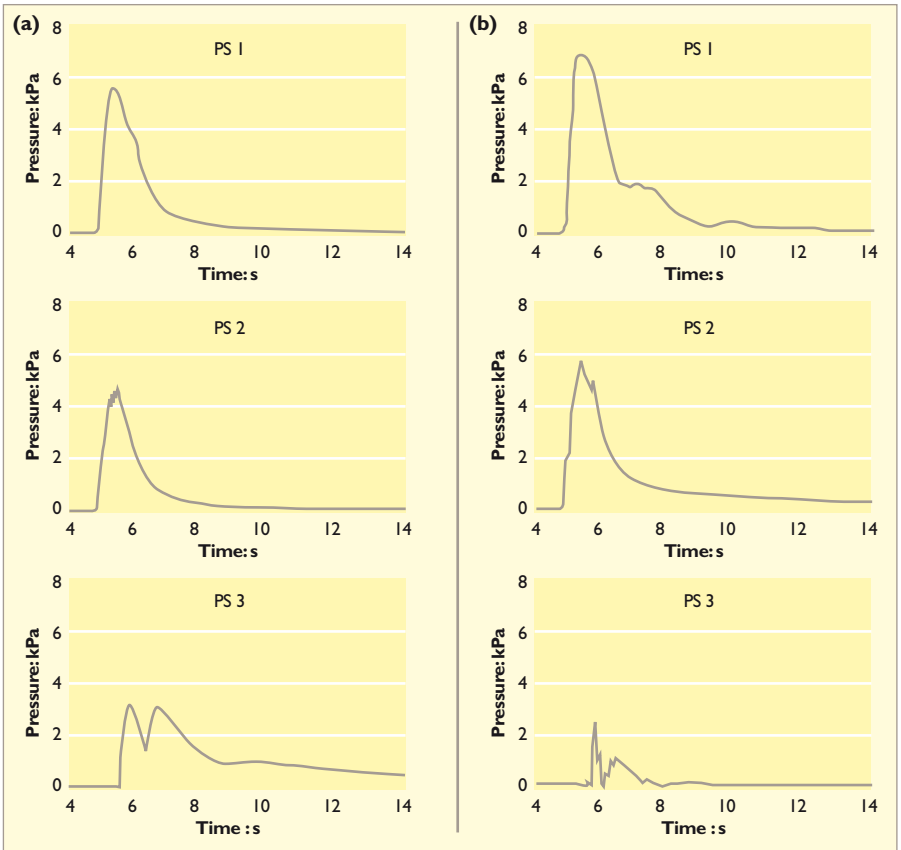


Fig. 11. Pressure sensor readings on the front of the tsunami-resistant house (a) were lower than on the typical coastal house (b) due to lower water splash

Figures 12(a) and 13(a) show the pressure readings from sensors 1 and 2 during the initial impact of the wave in tests 3 and 4, respectively. Figs 12(b) and 13(b) show corresponding pressure distributions on the house walls increases every 0·1 s as the wave impacts.

From Figs 12(b) and 13(b), the maximum force acting on the model house can be estimated as $0{\cdot}5w_1$ kN for the tsunami-resistant model house and $0{\cdot}6w_2$ kN for the typical coastal model house (where w_1 and w_2 are the corresponding effective width of the front walls). Since the area of the tsunami-resistant house's front wall is only 42% of that of the typical coastal house, the maximum force on tsunami resistant house wall is $0{\cdot}21w_2$, almost three times smaller than the force ($0{\cdot}6w_2$ kN) on a typical coastal house wall. For comparison, the hydrostatic force on a wall (with width w) is $0{\cdot}05w$ kN.

The tests show that the maximum wave loading on the wall at impact is about 10–12 times the hydrostatic force, which is closer to the upper estimate of 18 times the hydrostatic force. If the Japanese method is applied with the pressure distribution truncated at height H, the force for no-wave-break and break-up cases are $0{\cdot}25w$ kN and $0{\cdot}33w$ kN, respectively. This suggests that the methods of guidance in the literature underestimate the initial impact loading. More research is required in this area to understand the impact loading on houses more fully.

Discussion on tsunami wave loading

The peak impact pressures measured in this study agree well with data from other researchers. Chan[9] reported the mean peak pressure on a vertical wall by wave impacts as 9 ρc^2, where ρ is water density and c is wave speed. For a wave height of 130 mm and wave velocity of 1·7 m/s, the measure maximum pressure on a vertical wall was measured as 29 kPa.

Hull and Müller[21] studied wave-impact pressures on vertical walls in a wave

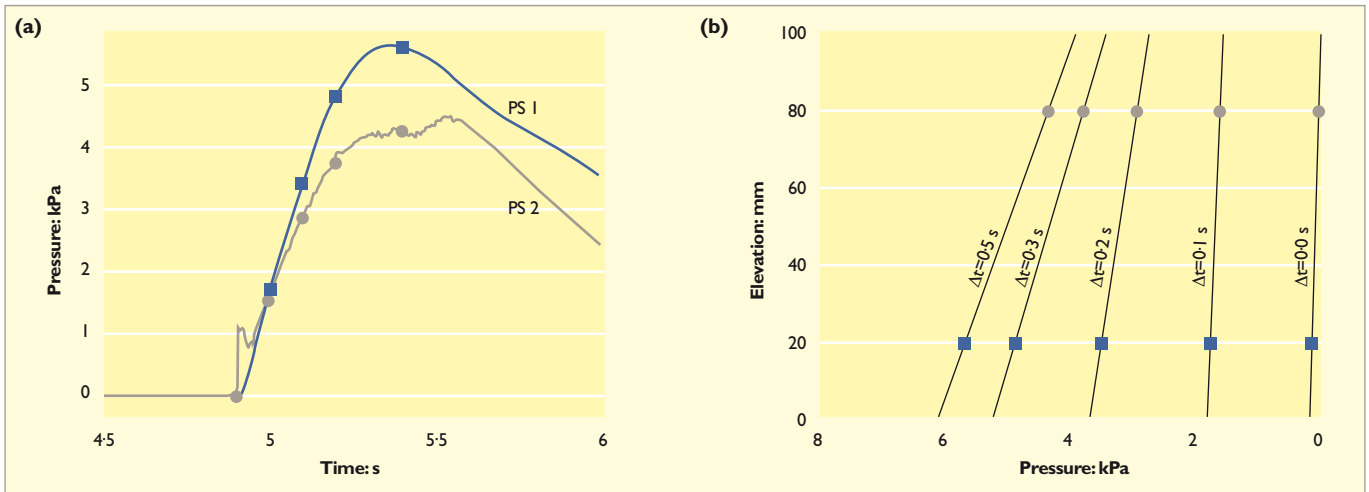


Fig. 12. Combined sensor 1 and 2 readings from test 3 on the tsunami-resistant house (a) and corresponding pressure distribution on the front wall shown in 0·1 s intervals from the time of impact (b)

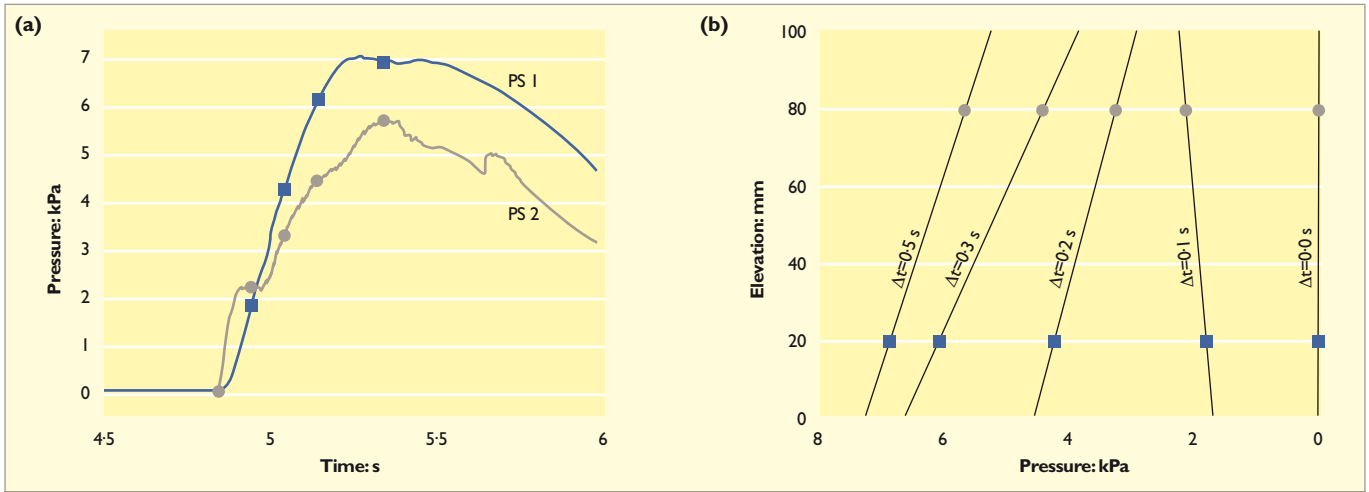


Fig. 13. Combined sensor 1 and 2 readings from test 4 on the typical coastal house (a) and corresponding pressure distribution on the front wall shown in 0·1 s intervals from the time of impact (b)

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tank and they reported peak pressures in the range 5–10 kPa for wave velocity of 1·5 m/s with wave heights in the range 50–80 mm. Hattori *et al.*[10] also performed similar experiments and reported peak pressures around 5 kPa for wave height of 70 mm with wave velocity of 2 m/s.

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 field cases with sea water.[22,25] Two main reasons for this discrepancy are the aeration level in water and air entrapment. [26-29]

Aeration levels are higher in sea water than in fresh water, so impact pressures from sea water are less. Bullock *et al.*[27] have 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.*[10] and Wood *et al.*[30] have 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. Nevertheless, the prototype interpretation of the present study indicates that a tsunami wave with velocity of 5 m/s (1 × 5) can induce a maximum loading of 375w kN (0·6 × 25 × 25) on a typical coastal house with frontal wall height 2·5 m and width w.

Other factors, which are not focused on in this paper but are important for tsunami-resistant design, include debris impact and scouring of foundation.[12, 31, 32]

Conclusions

Model testing of a new tsunami-resistant 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 coastal houses. The new design performed well under the tsunami wave loading while the typical coastal house was destroyed.

The first prototype of the tsunami-resistant house was completed in September 2005 in Balapitiya in Sri Lanka (Fig. 14). The project was executed by the Prajnopaya Foundation and Sri Bodhiraja Foundation in Sri Lanka. It should be noted that practical implications and society views mean that the final as-built house has a few features different to that of original design.

The video footage of the model tests provided a useful insight into the sequence of events that occur as the tsunami wave impacts a house wall, applying uplift force to the roof structure and destroying a typical coastal house design.

The following facts were observed in the tests.

- House roofs experience uplift forces due splashing water that curls upwards after impacting on the wall.
- Houses can slide or overturn if the foundations are not properly designed to account for tsunami wave loading.
- The maximum wave loading on house walls at wave impact was about 10–12 times the hydrostatic force.

Further study is currently under way to investigate the detailed loadings on houses, excess pore pressures beneath the foundations, scouring effects, scaling effects of model studies and the effectiveness of various other tsunami-resistant designs. Some further details of this research can be obtained from Thusyanthan *et al.*[33]

The new design performed well under the tsunami wave loading while the typical coastal house was destroyed.

Fig. 14. Prototype tsunami-resistant house built in Sri Lanka—but more research is necessary to understand more fully the effects of tsunami waves on houses

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