ONE-STOREY HOUSE DESIGNS FOR TSUNAMI-PRONE AREAS

Panu Promputthangkoon[1,*], Surat Promputthangkoon[2], and Nantachai Choosilp[3]

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Abstract

This study was concerned with the complete collapse of a house constructed on a beach that is prone to a tsunami. During such an incident, huge waves travelling at a very fast speed would hit the house thereby causing it to either partially or completely collapse. A system was first designed and built in order to simulate a tsunami. It comprised a steel chamber housing a model sea and beach and a mass of concrete that can be freely dropped into the sea to generate a tsunami. Two types of model house were built to withstand such waves, with normal and hollow walls. Both had 2 types of front walls, one of which was a plane and the other a curve. In addition, there were 2 levels of slab in the experiment, one on the ground and one 10 cm above the ground. Strain gauges were installed on the front walls to measure the strains induced. A total of 8 different house forms were tested. Overall, it was found that between the normal wall and hollow wall houses, the strain level generated by the latter was much lower. In addition, between the houses having the slab on the ground and 10 m above the ground, it was observed that the latter had a lower strain level, owing to the waves not being able to reach the wall. Of all of the 8 test configurations, it was found that the hollow wall house with curved walls having the slab raised to 10 cm above the ground had the best performance in terms of reducing the wave forces generated by the simulated tsunamis. This result may be employed for future construction of a house to be constructed close to a beach that is very likely to be hit by a tsunami for the purpose of keeping the main structure intact.

[1] *Natural Disaster Prevention and Control for Sustainable Environment, Rajamangala University of Technology Srivijaya, Nakhonsrithammarat, 90000, Thailand. Tel.: + 08- 9502- 4964; E- mail: panu_pptk@hotmail.com*
[2] *Mechanical Engineering Department, Faculty of Engineering, Rajamangala University of Technology Srivijaya, Songkhla, 90000, Thailand.*
[3] *Civil Engineering Department, Faculty of Engineering, Rajamangala University of Technology Srivijaya, Songkhla, 90000, Thailand.*
[*] *Corresponding author*

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Introduction

It may be said that Thailand is one of the most fortunate countries in the world in terms of the frequency of encountering natural disasters, most of which cannot be prevented from occurring. For instance, the country is not situated along the ring of fire on which most major earthquakes constantly occur, as is evident in Figure 1 displaying the boundaries of the tectonic plates (Nelson, 2015). Nonetheless, the Chiangrai earthquake on 5 May, 2014 (InterRisk Thailand Report, 2014) should not be overlooked because it caused so much damage due to shaking that has never been experienced before in the country.

When an earthquake occurs under the ocean, the consequent upward or downward movement of a fault may create a sudden increase or decrease of the sea level. Subsequently, a tsunami is to be expected. According to IOGT (2005), a tsunami is simply a series of waves having very long wave lengths and a period of time between crests. However, the time between the wave crests can vary from a few minutes to an hour. It should be noted that a tsunami is not the same as a tidal wave. Because of the very long wave length, it is very difficult to observe a tsunami with the naked eye. Thus, when a tsunami reaches the beach it would be too late to evacuate. On 26th December, 2004 at 00:58:53 GMT, the Indian Ocean Earthquake struck at a fault off the west coast of northern Sumatra (Fehr, 2006). Approximately 2 h later (9:30 a.m. local time), the first tsunami hit the western shorelines of Thailand, resulting in a total of 5395 deaths and 2822 people reported missing (Thanawood *et al.*, 2006). Across the Indian Ocean, over 200000 people lost their lives. Since then, many projects concerning the warning system to evacuate people in case there is a tsunami have been initiated. Several years later on, at 2:46 p.m. local time on 11th March, 2011, the Tohoku earthquake struck off the Pacific coast of Sanriku, Japan. A total of 15839 people died and 3642 people were missing. Furthermore, 120241 buildings were completely destroyed, 189822 buildings were partially destroyed, and 598587 buildings were partially damaged (Building Research Institute, 2011).

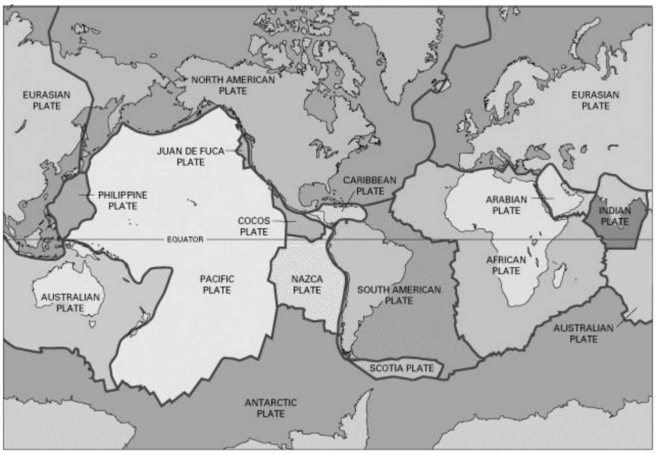

Figure 1. Plate boundaries identified as zones along which earthquakes frequently occur (Nelson, 2015)

From the above examples, it can be clearly seen that even though they do not happen often, particularly in Thailand, when a tsunami strikes a huge amount of damage to the built environment is inevitable. However, it is the loss of human lives that is more important. It should be noted that the damage to buildings induced by tsunamis is because of the force of the waves acting upon structures. This paper proposes alternate designs for a one-storey house in order to reduce the force of the incoming waves. The reduction was achieved by varying wall forms in order to reduce the force of the waves thereby keeping the main structures intact, even though some parts may be destroyed.

Occurrence of Tsunami and Its Consequences

Tsunamis are simply giant waves. Theoretically, anything could initiate waves as big as a tsunami; however, volcanic eruptions and earthquakes are the incidents that most often generate a tsunami. In the case of the former, both under-the-sea volcanic eruptions and normal volcanic eruptions have been observed to initiate tsunamis. It should be noted, however, that it is the undersea activity that is the most disastrous. When an earthquake strikes, the vibrations may be transmitted through the body of ocean water. This may result in giant ocean waves. Sometimes, a fault under the sea that moves rapidly just before the release of the accumulated strain energy also creates a tsunami. The incident would be more severe if the movement is a dip-slip fault, as experienced in the 2004 Indian Ocean tsunami. Figure 2 schematically illustrates the mechanism of a tsunami during the approach to the shore, showing the progressive increase of the waves' height travelling towards the shoreline.

To be able to design a structure to withstand the forces generated by a tsunami, one must comprehend the characteristics of the following forces: hydrostatic forces, buoyant forces, hydrodynamic forces, surge forces, impact forces, and breaking wave forces (Yeh, 2009). Of all of those forces, however, the hydrostatic force is the one most considered when designing a structure likely to be hit by a tsunami, and it may be estimated from the following equation:

$$F_d=\frac{1}{2}\rho C_d A u^2 \quad (1)$$

where F_d is the hydrodynamic force, C_d is the drag coefficient (Table 1), A is the affected area, and u^2 is a parameter.

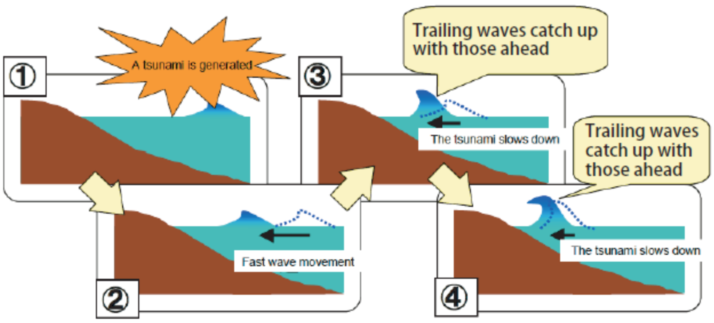

Figure 2. Mechanism of tsunami during the approach to the shore (Japan Meteorological Agency, 2009)

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Alternate Designs for Model One-Storey Houses

There were 2 types of one-storey house in the experiments in this research: (1) with a normal wall and (2) with a hollow wall, as graphically shown in Figures 3 and 4, respectively. They were modelled using a scale of about 1:25. The main material employed for making the houses was balsa wood. Both houses were designed to have a changeable length in the foundation post of 10 cm. In addition, the wall forms for both houses

Table 1. Drag coefficient (Yeh, 2009)

Width to depth ratio (w/ds or w/h)	Drag coefficient, C_d
From 1 - 12	1.25
13 - 20	1.30
21 - 32	1.40
33 - 40	1.50
41- 80	1.75
81 - 120	1.80
> 120	2.00

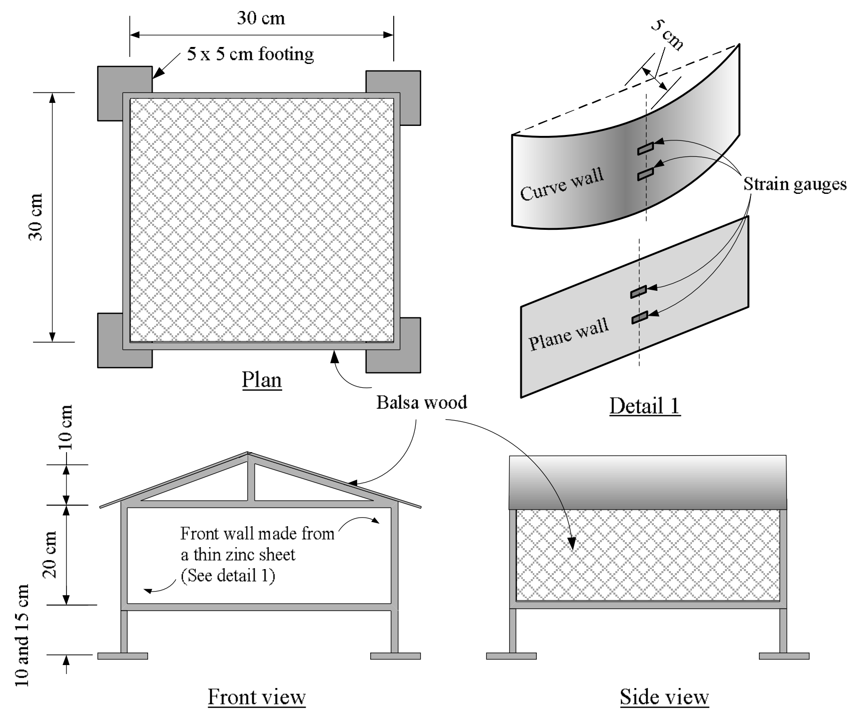

Figure 3. One-storey house with normal walls: plane and curve walls (see Detail 1)

were altered such that they were either a plane or a curve, as depicted in Figures 3 and 4, based on the assumption that the impact on the curved wall would be less than that acting on the plane wall. To prove this assumption, however, 2 strain gauges were installed on each individual wall in order to measure the strain (impact force) during the encounters with the simulated tsunamis.

Tsunami Simulation

In order to house a simulated beach and model house, a steel chamber was designed and built, as shown in Figure 5. The overall

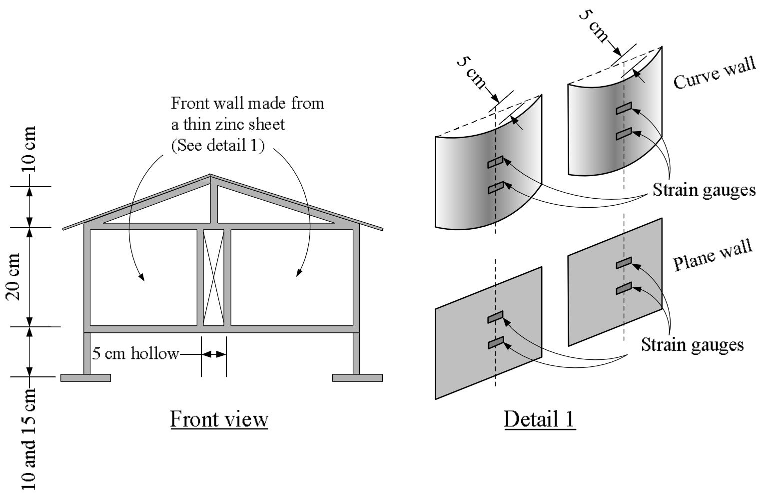

Figure 4. One-storey house with hollow walls: plane and curve walls (see Detail 1)

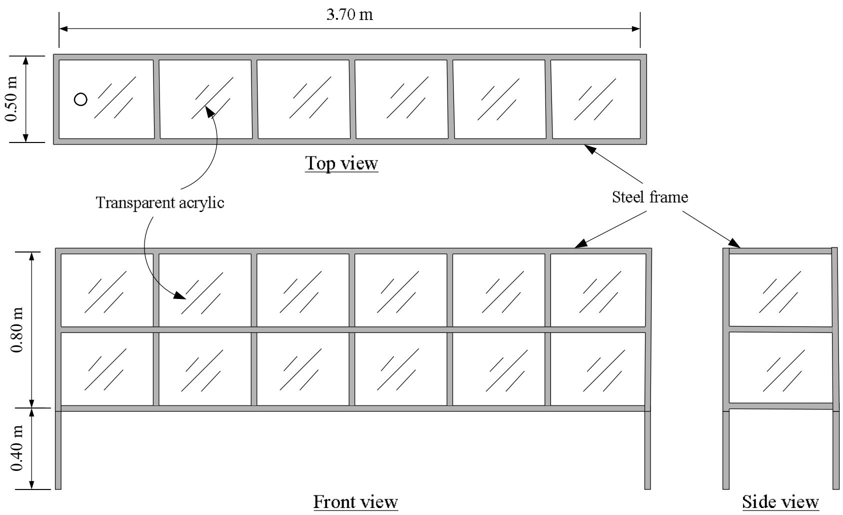

Figure 5. Chamber for housing simulated shore and model houses

dimensions were 3.70 m by 0.50 m. Its height was about 1.20 m. To be able to observe the wave behaviour a transparent acrylic sheet was employed as the walls of the chamber.

One of the most important aspects of this research was a system for generating a tsunami. It should be noted that a tsunami travels very fast compared with other waves such as tidal waves and waves generated by wind. As such, this research designed a weight system that could be instantaneously dropped into the water. This would result in waves that could travel quite fast when flowing towards the shore. The system is illustrated by Figure 6. Basically, it comprised a steel frame connected to a mechanical winch. The weight was simply an in-house cast concrete block having a mass of around 60 kg, as shown in Figure 6. This was experimented many times in order to obtain the right weight for the task.

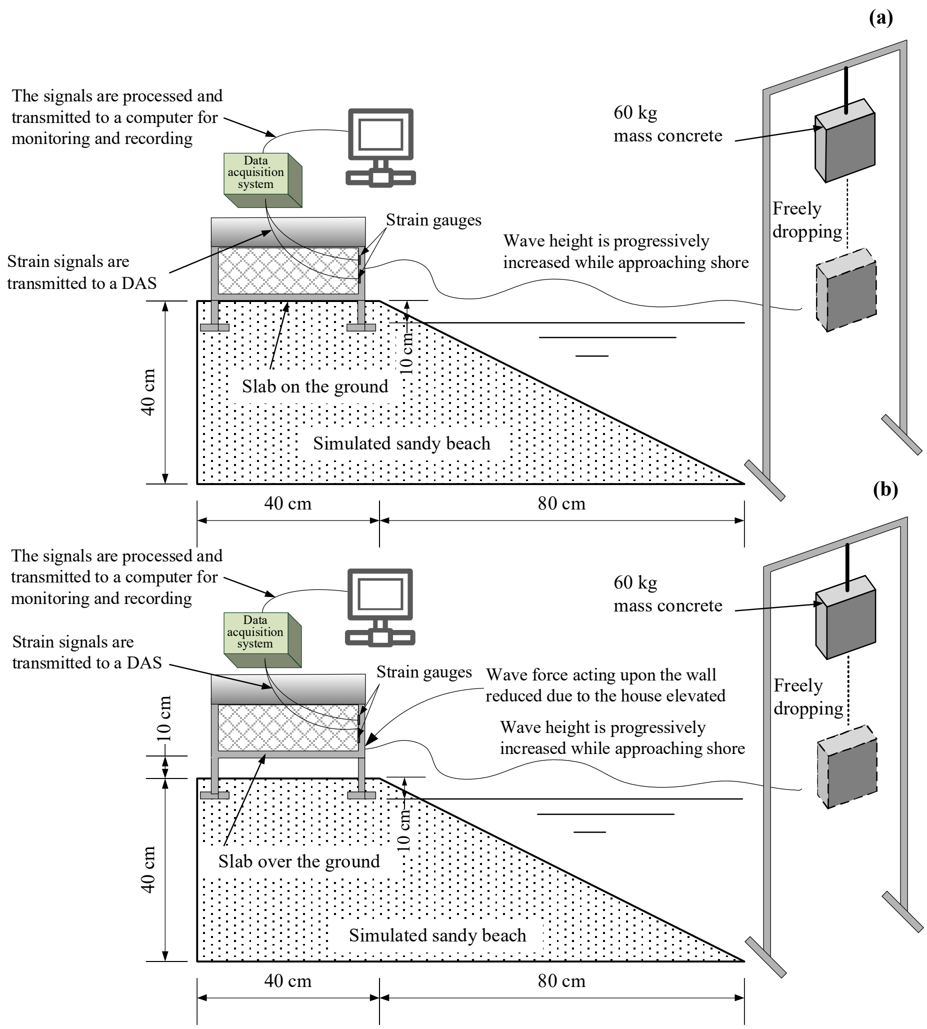

Figure 6. Test set-up for the model house with the slab on the ground (a) and with the slab 10 cm above the ground (b)

For instance, if it was too light the waves would be small and travel at speeds lower than required. In contrast, if the weight was too heavy, during the drop the chamber might be damaged. It should also be noted that there are several systems that could generate the tsunami, depending on the objectives and budget for a project. In addition, the system was similar to that of the study carried out by Thusyanthan and Madabuhushi (2008).

Testing Procedures

Strain gauges were chosen to measure the strain induced by the simulated tsunamis in this study. To obtain such a quantity of information, however, a data acquisition system is required. The NI 9235 measurement system (National Instruments Corp., Austin, TX, USA) was employed to gather the strain signals. It was connected to the NI cDAQ 9174 USB chassis that processed the signals. The data were transmitted to a computer via a USB cable, as illustrated in Figure 6.

For each test configuration, the test was carried out by first lifting the 60 kg mass of concrete to 10 cm above the water level; then, it was instantaneously freely dropped into the water to generate simulated tsunamis. When the wave was calm another drop was activated. During testing, a video was also taken in order to further analyse the behaviour of the waves while in the sea and after being on shore. Figure 7 shows the steps taken for the strain gauge installation, strain gauge wiring with the data acquisition system, and test set-up. A total of 8 test configurations were carried out, as shown in Table 2, to investigate whether different wall forms could alter the wave forces.

Results and Discussion

Figure 8(a-d) displays the strain records for the test configurations of N-GL-PW, N-GL-CW, N-OG-PW, and N_OG-CW, respectively. They

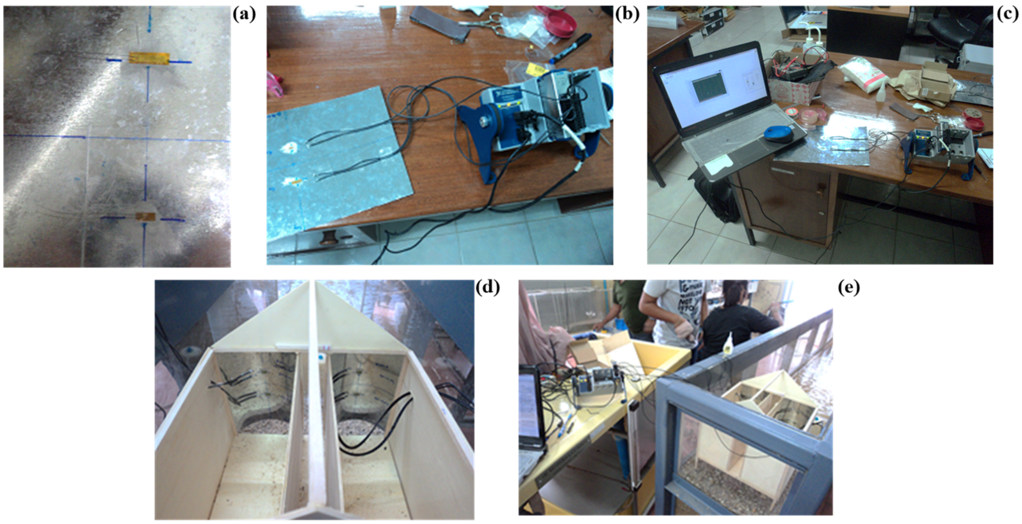

Figure 7. Strain gauges attached to the wall made from a zinc sheet (a), the strain gauges wired and connected to a data acquisition system (b), the strain gauges being tested to observe the signals (c), curve walls with the strain gauges attached being installed for testing (d), and test set-up for one-storey house to be hit by simulated tsunami (e)

Table 2. List of one-storey house forms with different wall configurations

No.	Wall form	Floor level	Wall shape	Symbol
1	Normal wall	On ground	Plane	N-GL-PW
2			Curve	N-GL-CW
3		10 cm above the ground	Plane	N-OG-PW
4			Curve	N-OG-CW
5	Hollow wall	On ground	Plane	H-GL-PW
6			Curve	H-GL-CW
7		10 cm above the ground	Plane	H-OG-PW
8			Curve	H-OG-CW

Table 3. Maximum measured strains for each house form during being hit by tsunami

No.	Symbol	Maximum measure strain	Note
1	N-GL-PW	0.118	Maximum capacity of the gauge
2	N-GL-CW	0.118	Maximum capacity of the gauge
3	N-OG-PW	0.070	
4	N-OG-CW	0.000	
5	H-GL-PW	0.060	
6	H-GL-CW	0.000	
7	H-OG-PW	0.080	
8	H-OG-CW	0.000	

show the measured strain versus time while the walls were encountering the simulated tsunamis. For the hollow walls, including the test configurations of H-GL-PW, H-GL-CW, H-OG-PW, and H-OG-CW, the strain records were plotted and are shown in Figure 9(a-d), respectively. The maximum strains for each test are summarised and shown in Table 3.

Overall, it can be clearly seen that the strain generated on the hollow house walls (Figure 9) is much lower than that of the normal house walls (Figure 8). This may be because the former has a lower wall area thereby receiving less of the wave forces. Another possible reason is that the former has a hollow that let some waves flow through the house which would also result in a decrease of the wave forces. The maximum strain of 0.118 was observed for both N-GL-PW and N-GL-CW. It should be noted herein that 0.118 is the maximum capacity of the strain gauge that was employed. Thus, in reality, the actual strain for N-GL-PW should be greater than that of N-GL-CW. This is because, during testing, it was observed that the wall of N-GL-PW crumpled, while the wall of N-GL-CW was still intact. This observation suggests that a curve wall could somewhat reduce the impact generated by wave forces.

Comparing all 4 configurations for the normal house, it was found that the strain for the test N-OG-CW is zero. This does not mean that no waves made an impact on the wall, but rather that the combination of curved wall design and the elevated floor dramatically reduced the wave forces. When considering all the tests, 3 of them had zero strains, including N-OG-CW, H-GL-CW, and H-OG-CW. These

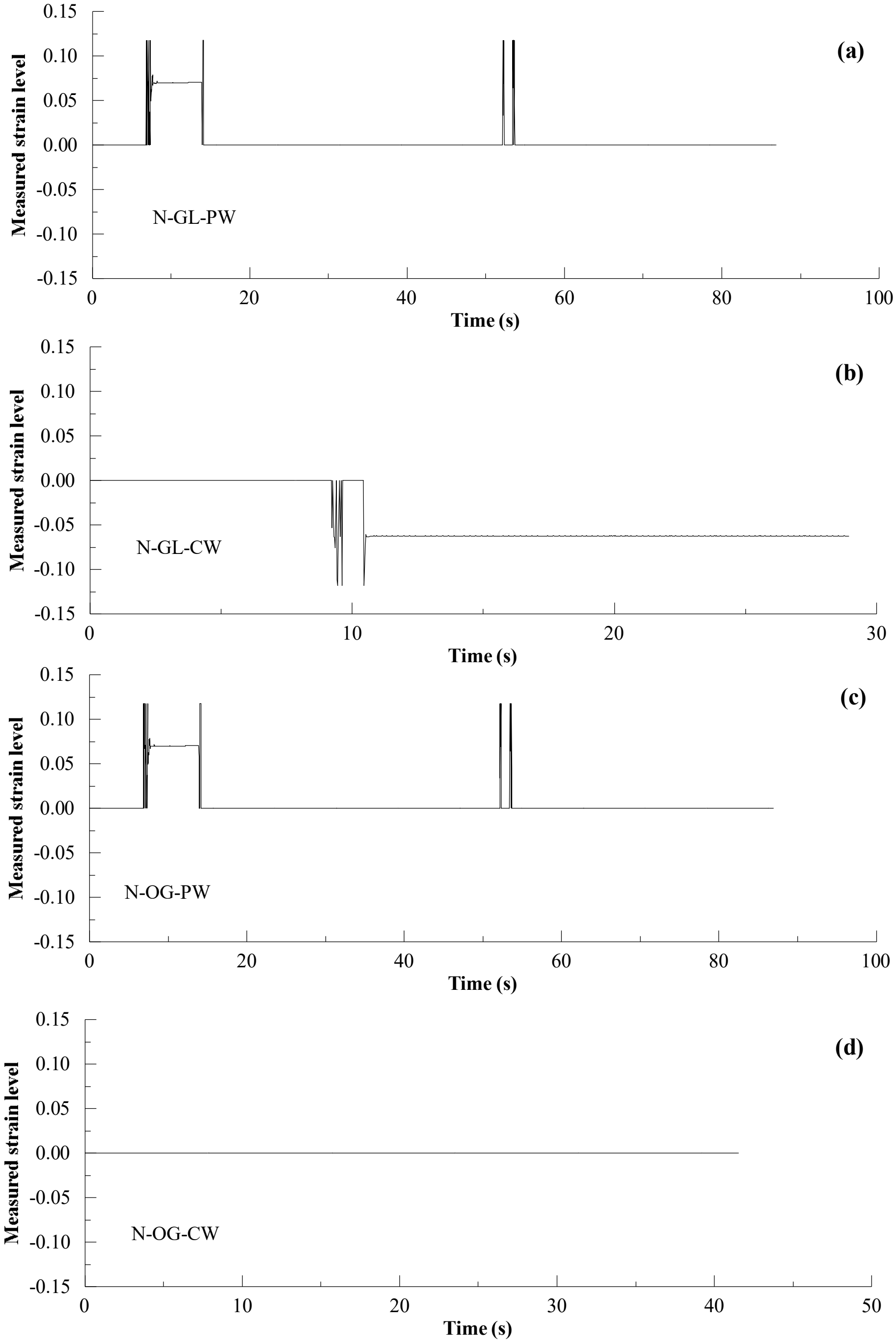

Figure 8. Strain records for N-GL-PW (a), N-GL-CW (b), N-OG-PW (c), and N-OG-CW (d)

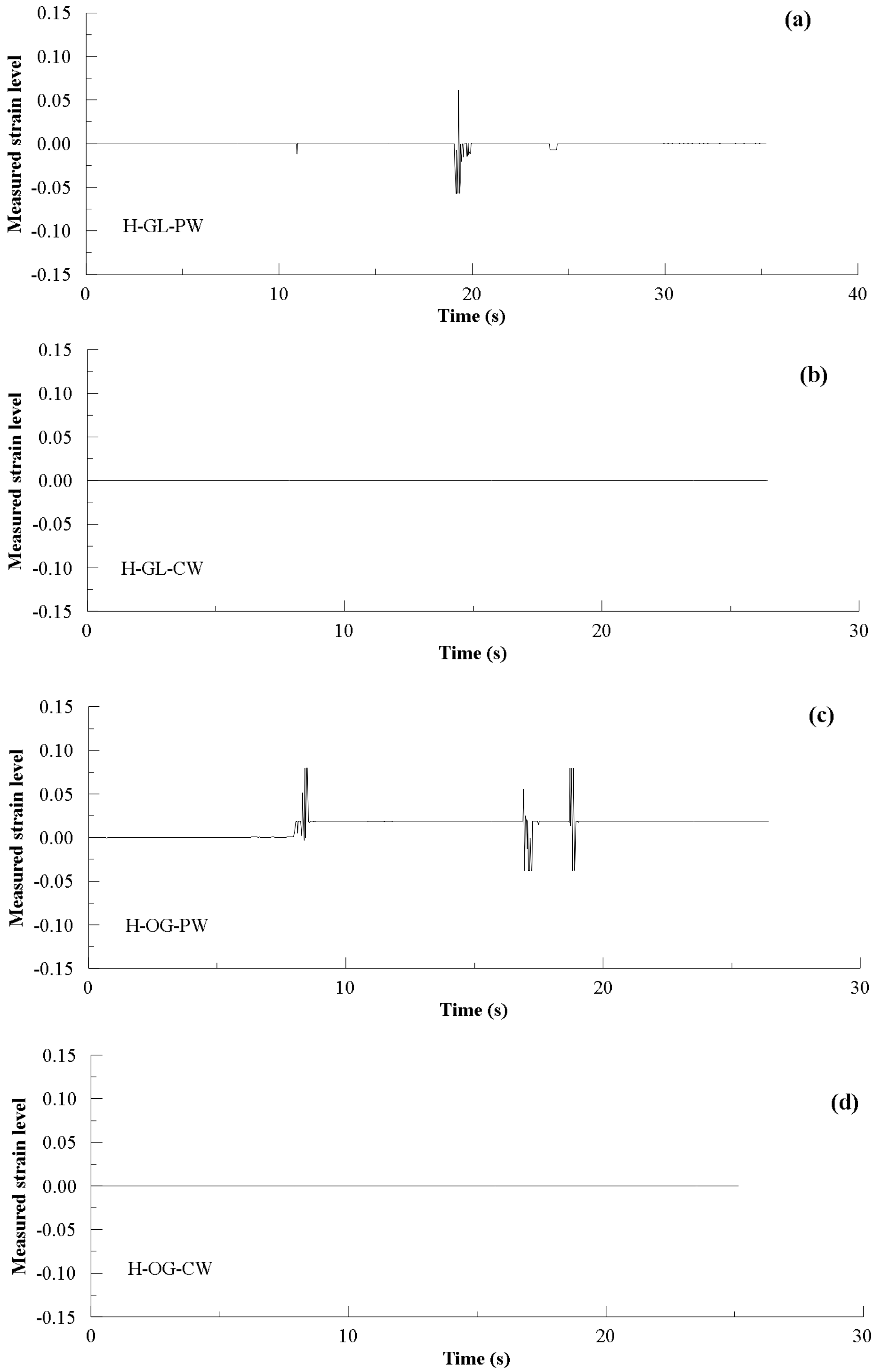

Figure 9. Strain records for H-GL-PW (a), H-GL-CW (b), H-OG-PW (c), and H-OG-CW (d)

a curved wall with elevated floor in terms of reducing wave forces. It is more obvious when considering all tests for the hollow wall house. For instance, all curved wall configurations (H-GL-CW and H-OG-CW) had zero strain, while all plane walls (H-GL-PW and H-OG-PW) had some values of strain.

From these results, even though it is not a very accurate experiment, it can be seen that altering the wall form from simply a plane to a slight curve could somewhat reduce the impact generated by wave forces. Accordingly, a further enhancement which includes a hollow at the middle of the house also decreases the wall area to be hit by wave forces thereby further reducing the impact.

Conclusions

A system was designed and built to simulate tsunamis that hit model houses having different forms of wall and slab elevations. Strain gauges were installed on the front walls in order to measure and record the strains generated by the wave forces. The results were analysed and compared to obtain a house form that is the best in terms of reducing the wave forces. Based on reviewing the literature indirectly or directly related to this research and the test results, the following conclusions have been drawn:

(1) The highest strain level was observed on the normal house having plane walls and being on the ground.

(2) When the house has a hollow in the middle, with the slab being raised to 10 cm above the ground and having curved walls, it was found that the strain is zero. This may owing to 2 facts: i) the slab was elevated so the waves could not reach the wall, and ii) even though some waves reached the walls, the impact was minimal so there was not enough energy to bend the wall.

(3) Compared with the same house forms, the one that had curved walls generated less strain than those of the house that had plane walls.

(4) In a comparison between the normal and hollow houses, it was found that the latter generates much lower strain levels.

(5) In a comparison between the same house forms, it was found that the one that has its slab raised to 10 cm above the ground generates less strain.

(6) Overall, the best performance in terms of reducing the force of the waves was the hollow wall house with curved walls and with its slab raised to 10 cm above the ground. From this conclusion, its form may be employed for future construction of a house to be constructed on a beach that is prone to tsunamis.

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