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EDUCATIONAL PAPER

Tsunami-proof design

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Abstract

Buildings constructed according to local seismic codes have shown excellent seismic-proof characteristics; however, tsunami-proof design codes and concepts are not yet systematic. Scientists and engineers around the world have performed extensive research and experiments in the field (especially following the devastating tsunami that occurred in the Indian Ocean on Dec 26 2004). Japan, which is located in a high-risk zone of seismic and tsunami activity, has taken considerable measures and incurred high costs to ensure that the nation's ports are tsunami-proof and that the people living near the sea are protected by appropriate constructions and a tsunami alert system. These measures performed well in the March 11th tsunami; yet, the casualties and structural damage were still significant. Tsunami mechanical analyses (load models and structure response models) must be quantified and codified in the design of coastal homes near tsunami and seismic zones to save lives and avoid severe structural damage. Extensive seismic design experience is critical. The paper discusses possible rules of tsunami-resistant design concepts by analyzing homes damaged by tsunamis, experiments undertaken by well-known civil engineering groups, and current structural design codes.

Keywords

tsunami-proof · wave velocity · tsunami load

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1 Introduction

On March 11, 2011, an 8.9-magnitude earthquake and a subsequent tsunami struck Japan. Japanese buildings exhibited a very strong seismic resistance, and very few people were hurt during the earthquake. Unfortunately, most coastal seismically sound buildings failed to survive the tsunami that followed the huge earthquake, which caused a large number of casualties.

Strict seismic design codes and concepts are well-rounded and have proven to be resistant to earthquakes all around the world; some examples include the zero casualty 7.2-magnitude earthquake in New Zealand on Sep 4, 2010 and the 8.9-magnitude earthquake in Japan on March 11, 2011. Buildings constructed according to local seismic codes have shown excellent seismic-proof characteristics; however, tsunami design codes and concepts are not yet systematic. Scientists and engineers around the world have performed extensive research and experiments in the field (especially following the devastating tsunami that occurred in the Indian Ocean on Dec 26, 2004). Japan, which is located in a high-risk zone of seismic and tsunami activity, has made massive efforts and incurred high costs to ensure that the nation's ports are tsunami-proof and that the people living near the sea are protected by appropriate constructions and a tsunami alert system. These measures performed well in the March 11th tsunami; yet, the casualties and structural damage were still significant. Tsunami mechanical analyses (load models and structure response models) must be quantified and codified in the design of coastal homes near tsunami and seismic zones to save lives and avoid severe structural damage. Extensive seismic design experience is critical. The paper discusses possible rules of tsunami-resistant design concepts by analyzing homes damaged by tsunamis, experiments undertaken by well-known civil engineering groups, and current structural design codes.

2 Tsunami design target

A tsunami wave can be 10∼30 m high at the shore. Therefore, houses located within the coastal V zone (defined in ASCE 5.2 as a high flood hazard area) and less than 10 m from the shore cannot with certainty protect their inhabitants during a tsunami.

Tsunami design targets should aim to prevent homes from collapsing and minimize the damage.

The buildings located within the coastal zone A could be considered tsunami-safe homes if they are of a certain height (such as higher than the one-hundred-year local wave height). design target could also be to reduce the allowable drift.

3 Tsunami design load

Consider the 2011 Japanese tsunami as an example for defining the loads acting on buildings during a tsunami. Fig. 1 shows that light wall panels were totally damaged and that the steel frame without panels survived and protected people on top of the buildings.

Fig. 1. Home damaged during the 2011 Japanese tsunami.

Japanese houses stood unscathed during the 8.9-magnitude earthquake, contrasting sharply to the debris and fragments floating on top of tsunami wave surfaces. These houses were primarily light frame structures, which can effectively dissipate the seismic load. We can see how this occurs by examining the formulas shown below.

The lateral seismic load acting on each floor is distributed from the seismic base shear V. In a given direction, V shall be determined in accordance with the following equation [3]:

$$V = C_s \cdot W,$$

where

C_s is the seismic response coefficient (which is related to the seismic magnitude according to the local ground acceleration data captured during an earthquake)

W is the effective seismic weight of a structure (which includes the total dead load and other loads acting on the building and is related to the weight of the building).

When the building is lighter, the seismic force V is smaller, which is why these light houses perform well during an earthquake. However, tsunami loads, as we can conclude from the equations listed below, are determined primarily by wave velocity and height, and light materials cannot resist buoyant forces like heavy materials can. Obviously, the joints and strength of these light materials were not designed to bear the severe perpendicular pressures exerted by 10-m tsunami waves, as shown in Fig. 1.

Yeh and Robertson (2005) presented the code defining the tsunami load that is shown below [5].

3.1 Hydrostatic forces

Hydrostatic forces occur when standing or slowly moving water encounters a building or a building component:

$$F_h = 1/2 \cdot \rho \cdot g \cdot (h + u_p^2/2g)^2,$$

where

F_h is the hydrostatic force on a wall per unit width of wall,
$up$is the velocity component normal to the wall,
h is the height of the wall,
ρ is the density of the water.

3.2 Buoyant force

All codes provided the same expression for the buoyant force:

$$Fb \geq g \cdot V,$$

where

$V$is the volume of water displaced by the building.

3.3 Design flood velocity

The FEMA CCM (Federal Emergency Management Agency Coastal Construction Manual) and the CCH (City and County of Honolulu Building Code) provide the following estimate of flood velocity (u) Dames & Moore (1980):

$$u = 2(g \cdot h)^{1/2},$$

where

h surge depth.

3.4 Hydrodynamic force

When water flows around a building (or a structural element or other object), hydrodynamic loads are exerted on the building. Both the CCH and the FEMA CCM provide the following expression for the hydrodynamic force (F_d :drag force):

$$F_d = 1/2 \cdot \rho \cdot C_d \cdot A \cdot u^2,$$

where

C_d is the drag coefficient (1.0∼2.0),
A is the projected area of the body on the plane normal to the flow direction.

3.5 Surge force

Surge forces are caused by the leading edge of a surge of water impinging on a structure. The surge force is computed as the force per unit width on a vertical wall subjected to a surge from the leading edge of a tsunami. The CCH adopted the following equation (Dames & Moore, 1980) for the surge force F_s:

$$F_s = 4.5 \cdot \rho \cdot g \cdot h^2,$$

where

$h$is the surge height.

The resultant force acts at a distance approximately h above the base of the wall. This equation is applicable for walls with heights equal to or greater than $3h$. Walls whose heights are less than $3h$ require surge forces to be calculated using an appropriate combination of hydrostatic and hydrodynamic force equations.

3.6 Impact force

Impact loads are those that result from debris such as driftwood, small boats, portions of houses, etc., which is hard to predict during tsunami house design, and comparing to the weight of the whole water wave during the tsunami, the wood or boats could be a supplementary consideration.

Judging from the definition, hydrodynamic and hydrostatic forces would occur after a tsunami surge, which is much less then the surge force according to experiments and the equation expression; therefore, the surge force can be regarded as a control force when designing a house for tsunami resistance. However, the surge force equation has limits and for walls less than 3h high the hydrostatic and hydrodynamic force equations have to be combined. Let's see whether we can make it easier for designers to determine the relevant forces.

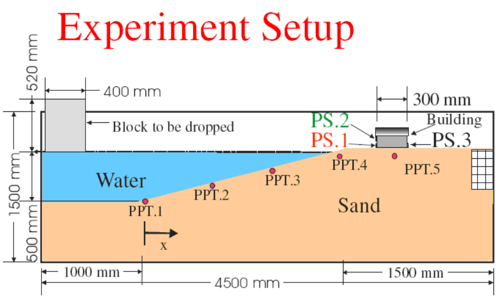

Fig. 2. Cross-section of the experimental model.

Figs. 2 and 3 were retrieved from the tsunami-safe home experimental diagrams of Indrasenan Thusyanthan and Gopal Madabhushi [3]. They show that the peak pressure on the building occurs when the wave first impinges it. The impinging time to the peak pressure is quite short, and we assume that the wave surge contacts the wall uniformly, at the same time, and at the same speed,

$$u = 2(g \cdot h)^{1/2},$$

where

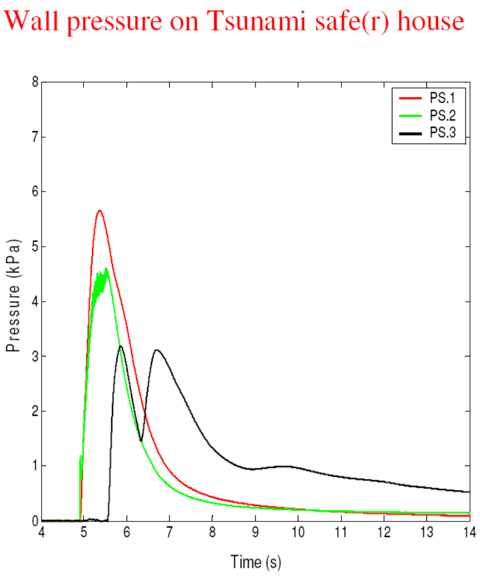

Fig. 3. Pressure/time at the wall.

h is the surge height.

The pressure P at a certain point Z on the wall is a function of the wave velocity P_u and depth pressure P_d. P_u is the same at every point on the wall that is contacted by the same wave, and P_d can be determined using the distance from point Z to the surge surface $(h - h_1)$. Fig. 4 displays a diagram of the surge force.

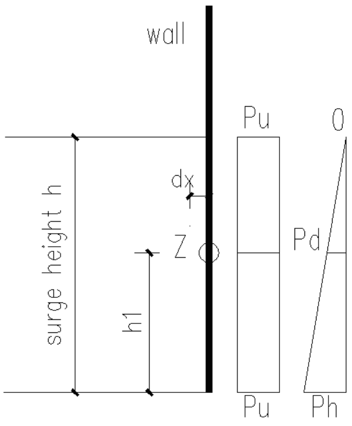

Fig. 4. Illustration of the surge pressure.

Consider a volumetric water element dv that contacts point Z:

$$dv = dx \cdot dA,$$

where dA is the area of point Z.

When the water dv contacts the wall, its speed decreases to 0:

$$F \cdot \Delta t = m \cdot u$$

$$F = P_u \cdot dA$$

$$m = \rho dx \cdot dA.$$

When dx is small enough, $\Delta t \approx dx/u$, therefore

$$P_u \cdot dA \cdot dx/u = \rho \cdot dx - dA - u,$$

$$P_u = \rho u^2 = 4\rho g h,$$

$$P_h = \rho g h, P_d = g(h - h_1),$$

and

$$P = P_u + P_h = 4\rho g h + \rho g(h - h_1), \quad (1)$$

where h_1 varies from 0 to h and P varies from 5 to $4gh$.

A modification factor can be added to Eq. (1) according to the experimental result.

In all of these load equations, the tsunami wave height is a criterion for determining the design load, which can be determined by analyzing the local tsunami history data base.

The surge load acts as a lateral load on the structure, and the numerical mechanical model is similar to the seismic and wind models; story drift and elemental strains can be analyzed to meet standards that are similar to seismic standards. Two additional important calculations must also be considered for structures bearing tsunami loads: one is the building's resistance to capsizing, and the second is that the vertical wall panel and joints must be designed to bear perpendicular tsunami loads to ensure that the wall panel will not fail or drift by the force of the tsunami wave.

4 Possible design concept for a tsunami-proof home

The surge load pressure P may reach up to 500 kN/m^2; thus, solid walls that face the surge should have a minimal area to minimize the force acting on it. To allow water to pass through the building as quickly as possible, openings in the walls should be as large as possible; alternatively, weak panels may be utilized at certain locations on solid walls because they can be easily destroyed by the wave, which will alleviate the pressure on the main structure. The design of a weak wall is addressed by ASCE 7-05, clause 5.3.3 (load on breakaway walls) [1]. Fig. 1 is an extreme example of what occurs when no wall is present: the tsunami loads do not harm the slim steel frame.

The resistance moment of the wall must also be increased to reduce the strains that are caused by severe tsunami loads. Indrasenan Thusyanthan and Gopal Madabhushi used "[" and "S"-shaped wood walls in tsunami-safe home experiments, which proved to be successful [3].

5 Other solutions for reducing tsunami loads

5.1 Mangrove coast

Analytical models show that 30 trees per 100 m^2 may reduce tsunami flow rates by as much as 90%. Studies performed in Vietnam also demonstrated the usefulness of mangrove forests in coastal protection[2]. The factor by which tsunami loads are reduced in the mangrove coastal area can be determined from experiments and existing empirical data.

5.2 Reinforced concrete sea wall

A sea wall is a form of coastal defence constructed where the sea impacts directly upon the landforms of the coast. It can slow or deflect the tsunami waves but cannot be expected to stop huge waves, as we can see from the 2011 Sendai tsunami, which spilled over the seawall into the town of Miyako, Japan, and struck costal buildings. According to experiments and existing empirical data, a reduced tsunami load factor can also be taken into account where there is a sea wall along the coast.

6 Conclusions

As Robert A. Dalrymple and David L. Kriebel said six years ago, "the design of civil engineering structures in tsunami-prone areas can be critical." [4] The development of tsunami-proof home designs is still critical and requires continued efforts until attainable regulations for tsunami-proof home designs become available to designers and until they have been proven in the field to be effective in protecting structures and saving lives. Perhaps when there's a standard in coastal design and be recommended, propagated by the government to save people and minimize losses along high hazard coastal area, tragedies might not occur again.

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