Tsunami research at Oregon State University

Professor Harry Yeh and Professor Solomon C. Yim, Oregon State University, Edited by Alan C. Burr, corresponding member of the Research Panel

The Great Indian Ocean Tsunami on 26 December 2004, took almost 300 000 lives in Indonesia, Thailand, Malaysia, Myanmar, Bangladesh, India, Sri Lanka, Maldives, and neighboring African counties. This mega tsunami was generated by a subduction-type fault of nearly 1000km (United States Geological Survey, 2005). It was an extremely low-probability-high-consequence event. In fact, this was the first time in recorded history that the North-East Indian Ocean was struck with this magnitude of tsunami; the most significant prior tsunamis in this region were the 1881 Bay of Bengal and the 1883 Krakatoa eruption tsunamis.

There is the potential that a similar disaster could strike the Pacific Northwest by rupturing the 800km long Cascadia subduction that runs from Northern California, USA to British Columbia, Canada. Because such mega tsunamis are rare and their forewarning is possible (although the lead time can be very short), the primary mitigation tactic is evacuation. Hence most of the efforts to prevent loss of life have focused on the development of an effective warning system, inundation mapping, and tsunami awareness.

However, an understanding of effects of tsunamis on buildings is also important because the provision of safe havens in the form of tsunami shelters could significantly reduce the loss of life in communities at risk where residents may have insufficient time to evacuate to higher ground prior to the tsunami.

Vertical evacuation shelters

This condition would exist, for example, where people live on a wide coastal plain, a long narrow spit, or areas bounded by rivers or canals. The concept of 'vertical-evacuation' shelters is not new; there are many cyclone shelters in Bangladesh and India. In Japan, there are already shelters specifically designed for tsunamis, see Fig 1. On the other hand, the shelters could be nothing more than sturdy public buildings such as schools, fire stations, and city halls.

It is also quite possible that such shelters in vulnerable coastal zones could have served as an evacuation option and could have saved many lives from the storm surges and flooding during the recent Hurricane Katrina.

A group of researchers at Oregon State University is currently conducting research for the development of a rational and comprehensive design guideline for tsunami and hurricane shelters using both numerical and experimental approaches.

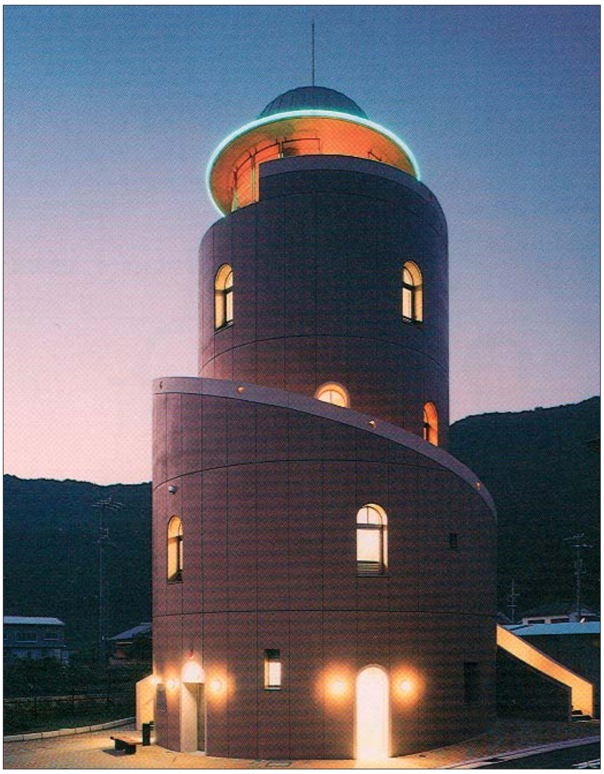

Fig 1. Tsunami shelters – Nishiki Tower – in Nishiki, Japan. This reinforced concrete structure has a spiral staircase winding up the outside and offers almost 3500ft^2 of refuge floor space on the upper two floors

Fig 2. Demonstration of tsunami structure interaction in Tsunami Wave Basin at O.H. Hinsdale Wave Research Laboratory, Oregon State University.

The Tsunami Wave Basin (TWB) at O. H. Hinsdale Wave Research Laboratory, Oregon State University is 48.8m long, 26.5m wide, and 2m deep (see Figs 2 & 3). The directional wave generator is composed of 29 segments (with 30 independent actuators), each 0.91m wide and 2m high, moving as a piston capable of a maximum 2.07m displacement with a maximum velocity of 1.87ms^{-1}.

A typical tsunami often contains several waves, each separated by several minutes. The characteristic of the wave form as it approaches a coastal area depends on the local bathymetry of the surrounding region. To model tsunami features, large amplitude, near-breaking solitary waves and various non-linear long waves can be generated. The basin makes it possible to conduct experiments at a size large enough to minimise the effects of scale.

Using ordinary small laboratory apparatus, it would be impossible to obtain quantitative data for tsunami problems, owing to grossly enhanced scale effects. The large-scale TWB is close enough to full-scale to provide quantitative measurements and to minimise scale effects. Froude's law is used to scale the results from the experiments, which are approximately equivalent to a $^{1}/_{20}$ scale model. In additional a Large Wave Flume (LWF) is used for part of the testing programme.

The large scale TWB and LWF enable a wide range of laboratory experimentation to address the needs for understanding long-wave phenomena and well as providing adequate data for model validation in areas such as the following:

Fig 3. The Tsunami Wave Basin at O.H. Hinsdale Wave Research Laboratory, Oregon State University

- quantitative evaluation of scale effects:
- wave breaking and turbulence;
- wave–structure interaction;
- precise measurements of run-up and velocity in a highly three-dimensional flow domain;
- tsunami generation and propagation behavior caused by subaqueous landslides.

The numerical approach is currently made with the use of a commercial software package, LS-DYNA, which is an explicit finite element program for the analysis of the non-linear dynamic response of three-dimensional structures. The program is owned and developed by Livermore Software Technology Corporation (LSTC) based in Livermore, California. The program has been found to be versatile and most capable for modeling tsunami effects as it contains modules for very large strain deformations, non-linear materials, fracture, shearing detachment, contact and impact. Figure 4 represents an example of wave–structure and structure–structure impact. Researchers at Oregon State University are conducting joint research with LSTC staff to further develop LS-DYNA's capabilities to model tsunami wave properties and exact boundary condition representation for a coupled fluid-structure interaction, particular to tsunami situations.

Although there is no well-established design criterion for tsunami resilient buildings, the criteria for structures vulnerable to hurricane surges are relatively defined and extensively documented in publications such as the *Coastal Construction Manual* (CCM) (Federal Emergency Management Agency, 2000). The guidelines are based on considerations of:

- hydrostatic forces;
- buoyant or vertical hydrostatic forces;
- hydrodynamic forces from drag forces in a steady flow;
- surge forces from impingement of the leading edge of a surge;
- impact forces resulting from debris;
- breaking wave forces.

A review by Yeh and Robertson[1] suggests that among these components, hydrostatic and buoyant forces can be computed accurately for a given inundation depth. The fluid force exerted on a structure by steady flow can be evaluated with hydrodynamic force (drag force) F_D:

$$F_D = {}^1/_2\, \rho C_D A u_p^2 \qquad \text{(Eq 1)}$$

where C_D is the drag coefficient, and A is the projected area of the body on the plane normal to the flow direction. According to CCM, the drag coefficient C_D for larger obstructions ranges from 1.2 to 2.0 depending on the width-to-depth ratio. The recent laboratory experiments by Arnason[2] also show $C_D \approx 2$ for a square shaped column, confirming the range of C_D given by CCM.

Surge force is caused by the leading edge of a surge of water impinging on a structure, namely, slamming force. Ramsden[3] performed comprehensive experiments on the surging force on a vertical wall in a narrow wave flume. His data clearly indicates no slamming force for the case of a dry-bed surge, i.e. the hydrodynamic force (Eq 1) dominates. The lack of overshoot may be attributed to the relatively mild front profile of the (dry-bed) surge: the momentum increases gradually.

It is very difficult to accurately estimate breaking wave forces. Considering a probable location of a tsunami shelter being sufficiently away from the shoreline, it is unlikely that an incident tsunami would break directly onto the building; therefore a tsunami attack on an inshore building should be in the form of surging.

The impact force of a water-borne missile (washed-away automobiles, drift wood, lumber, boats etc.) could be the dominant cause for destruction of onshore structures but it is difficult to estimate the force accurately. The recommended equation in the present design guideline is based on the concept of impulse–momentum approach: the impulse of the resultant force acting for an infinitesimal time is equal to the change in linear momentum. For the actual computation, a small-but-finite time Δt and the averaged change in momentum are used as the approximation. The drawback of this approach is the uncertainty involved in evaluating the duration of impact, Δt. According to recent reports from the aftermath of Hurricane Katrina, many buildings were severely damaged by floating casinos and other craft which broke their moorings and became floating battering rams.

It is well known that ductile structures are capable of surviving applied forces that are much larger than their design resistance if the duration of the force is sufficiently short and the resistance of the structure is sufficiently large. Ductile design requirements have been the focus of seismic design for building structures. Tsunami forces may be very large, and surge, missile impact, and breaking wave forces may be of relatively short duration. Nevertheless, there is a fundamental difference between the dynamic pressures caused by water waves and earthquake loading. The intent of this research at Oregon State University is to provide tools for the engineer to predict and design for the effects of giant waves and flooding due to tsunamis and extreme hurricanes.

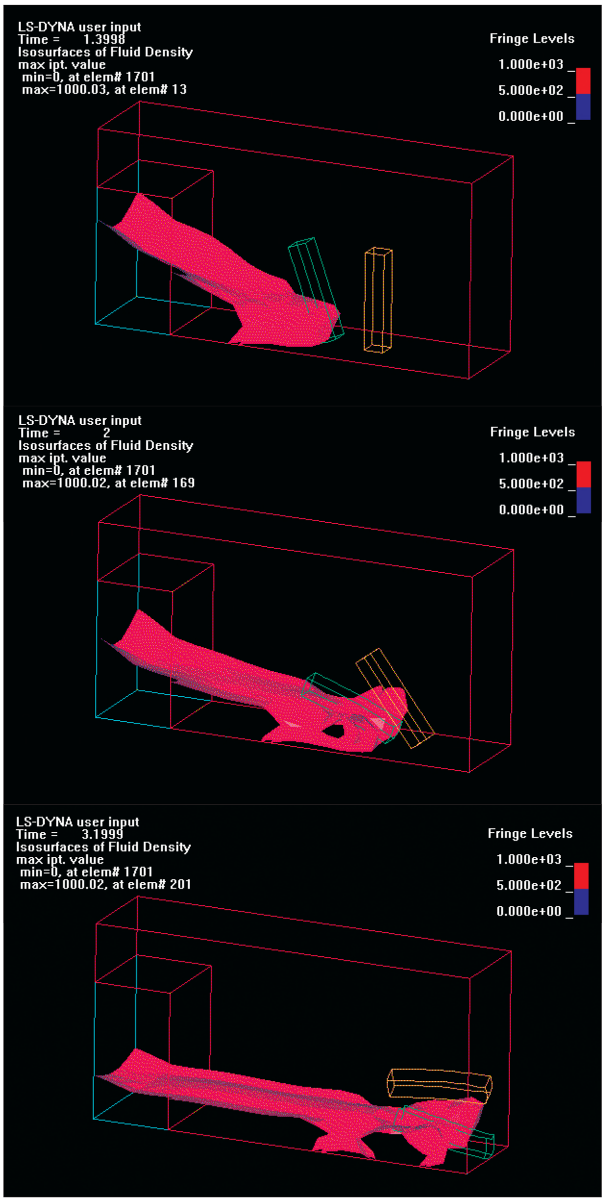

Fig 4. LS-DYNA fluid-structure interaction with fluid-structure and structure-structure impact

- Further information: (email Prof. Harry Yeh: (harry@engr.orst.edu).

REFERENCES

1. Yeh, H., Robertson, I., and Preuss, J.: *Development of design guideline for structures that serve as tsunami vertical evacuation sites,* Report No 2005-4, Washington Dept of Natural Resources, Div. Geology & Earth Resources
2. Arnason, H.: 'Interactions between and incident bore and a free-standing coastal structure', *PhD Thesis,* 2005, University of Washington, Seattle, 172pp
3. Ramsden, J. D.: *Tsunamis: Forces on a vertical wall caused by long waves, bores, and surges on a dry bed,* Report No. KH-R-54, W. M. Keck Laboratory, California Inst. Technology, Pasadena, Calif., 1993