Tsunami-Induced Loading on Structures

Beyond Hollywood's Scenarios

By Dan Palermo, Ph.D., P.Eng. and Ioan Nistor, Ph.D., P.Eng.

Made in Hollywood: a 600 foot plunging wave breaking over a frightened couple shivering on a beach! Don't hold your breath: it's basically impossible, according to coastal scientists. A wave propagating towards the shoreline will break at the location where the wave height approximately equals the water depth. Hence, depending on the coastline bathymetry (underwater near-shore topography), such a wave will break, in most instances, well offshore and will continue to advance towards the shoreline as a broken, foamy wall of water. Nevertheless, the impact of a broken tsunami wave on infrastructure located near shoreline can be devastating. The December 26, 2004 Indian Ocean Tsunami is the most recent example of the tremendous forces generated by tsunami waves advancing inland.

The impact of tsunami-generated hydrodynamic forces on coastal protection structures (breakwaters, seawalls, reefs, etc.) is relatively well understood. However, knowledge of the impact on near-shoreline structures such as buildings and bridges is lagging. Further compounding the problem is the lack of guidance from building codes and understanding of tsunami-induced loading. Structural engineers are not aware of the critical conditions in the design of structures located in tsunami-prone coastal areas.

Until recently the position of structural building code officials in North America was that tsunami-induced loading is not critical. Recent events, however, demonstrate the extreme and often catastrophic consequences that arise during a tsunami event in coastal areas. Historical tsunami events of the western North American Seaboard and, to a much lesser extent, the Eastern Seaboard suggests that building codes should consider such effects. *Table 1* is a list of major tsunami events on the Western Seaboard of North America over the past century, highlighting the significant tsunami wave runup, which can be defined as the maximum water elevation occurring along the shoreline after a tsunami.

Date	Location	Maximum Wave Runup (m)
Nov. 4, 1994	Southern Alaska	7.6
Feb. 4, 1965	Western Alaska	10.7
Mar. 28, 1964	Gulf of Alaska	67.1
Mar. 9, 1957	Central Alaska	22.8
June 23, 1946	British Columbia	30
Sept. 10, 1899	Gulf of Alaska	60

Table 1: Recent Tsunamis on the Western Seaboard of North America.

Basic Mechanics of Tsunami Waves

Tsunami waves can be triggered by various geological factors: underwater earthquakes, volcanic eruptions, and submerged or aerial landslides. However, the vast majority of tsunamis are generated by a sudden vertical uplift of the ocean bottom induced by a seismic event. The vertical displacement of such an enormous volume of water generates tsunami waves that propagate at high speed over thousands of kilometres. The velocity of tsunami waves in deep ocean waters can reach several hundreds of kilometres per hour. However, as a tsunami wave advances toward the shoreline and the water depth decreases, it gets "squeezed" by the sloping ocean bottom and hence, its height increases while its speed decreases. Depending on coastal bathymetry, tsunami waves break offshore and further advance inundating low-lying coastal areas in the form of a hydraulic bore, similar to that generated by flood waves occurring in a dam break. The hydraulic bore advancing towards shoreline is similar to a foamy turbulent wall of water advancing towards the beach. In this case, the wave completely looses its shape as a result of breaking. On the other hand, tsunami inundation can also occur as a gradual rise and recession of the sea level for the case of non-breaking tsunami waves, just as a suddenly rising tide. However, this case is rare and only occurs when the near-shore beach slope is vertical, as in the case of coral atolls.

The width of the continental shelf, the initial tsunami wave shape, the beach slope and the tsunami wave length are all parameters which govern the breaking pattern of tsunami waves. A broken tsunami wave travels overland and, depending on the coastal topography, can significantly impact the infrastructure lying in its path. Low-lying coastal communities are particularly vulnerable to tsunami wave attack and subsequent coastal flooding. Moreover, the mechanisms of hydrodynamic impact induced by tsunami waves differ significantly from those generated by storm surges. The increase in water levels during coastal flooding as a result of a storm surge occurs over several hours, as opposed to seconds in the case of tsunami waves.

Tsunami-Induced Forces

Three parameters are essential for defining the magnitude and application of tsunami-induced forces: (1) inundation depth, (2) flow velocity, and (3) flow direction. These parameters mainly depend on: (a) tsunami wave height and wave period; (b) coastal topography; and (c) roughness of the coastal inland. The extent of tsunami-induced coastal flooding, and therefore the inundation depth at a specific location, can be estimated using various tsunami events with various magnitudes and directions, and modeling coastal inundation accordingly. However, the estimation of flow velocity and direction is generally more difficult. Flow velocities can vary in magnitude, while flow direction can also vary due to the local onshore topographic features, as well as soil cover

The reader is referred to the following documents for additional details regarding the force components:

- Federal Emergency Management Agency Coastal Construction Manual (FEMA 55)
- The City and County of Honolulu Building Code (CCH)
- Structural Design Method of Buildings for Tsunami Resistance (SMBTR)
- Development of Guidelines for Structures that Serve as a Tsunami Vertical Evacuation Sites

Severe structural damage.

Column failure due to debris impact.

Column failure of a reinforced concrete frame.

Punching failure of infill walls.

Figure 1: Tsunami damage in Thailand and Indonesia (December 2004 Indian Ocean Tsunami).

and obstacles. Forces associated with tsunami bores consist of: (1) hydrostatic force, (2) hydrodynamic (drag) force, (3) buoyant force, (4) surge force and (5) debris impact.

Hydrostatic Force

The hydrostatic force is generated by still or slow-moving water acting perpendicular on planar surfaces. The point of application of the resultant hydrostatic force is located at one third from the base of the triangular hydrostatic pressure distribution. In the case of a broken tsunami wave, the hydrostatic force is significantly smaller than the drag and surge forces. However, the hydrostatic force becomes increasingly important when tsunami-induced coastal flooding is similar to a rapidly-rising tide.

Buoyant Force

The buoyant force is the vertical force acting through the center of mass of a submerged body. Its magnitude is equal to the weight of the volume of water displaced by the submerged body. The effect of buoyant forces generated by tsunami flooding was clearly evident in the areas affected following the December 2004 Indian Ocean Tsunami. Buoyant forces can generate significant damage to structural elements, such as floor slabs.

Hydrodynamic (Drag) Force

Hydrodynamic forces caused by drag occur as tsunami bore moves inland with moderate to high velocity and flows around structures.

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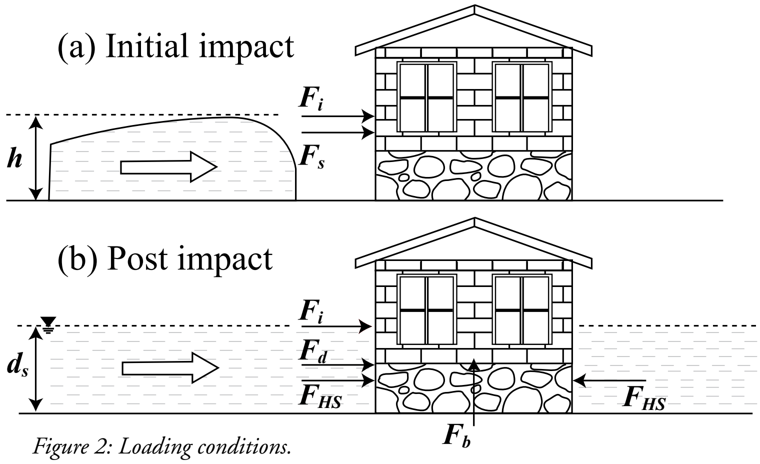

Figure 2: Loading conditions.

The flow is assumed to be uniform, and therefore, the resultant force will act at the centroid of the projected area in the direction of the flow. The hydrodynamic force is a function of the tsunami bore velocity and the drag coefficient, which varies depending on the shape of the structural element around which flow occurs. The formulation used to calculate the drag force is identical for the City and County of Honolulu Building Code (CCH) and FEMA 55; however, differences in the force arise due to the drag coefficient and estimated velocity. For example, drag coefficient values of 1.0 and 1.2 are recommended for circular piles by CCH and FEMA 55, respectively. For the case of rectangular piles, the drag coefficient recommended by FEMA 55 and CCH is 2.0. For walls, CCH suggests a coefficient of 1.5, whereas a range from 1.25 to 2.0, depending on the dimensions of the wall, is suggested by FEMA 55. Regarding the estimated bore velocity, there is significant disagreement. For a inundation depth of 5 meters (16.4 feet), velocities of 14 meters/second (46 ft/s) and 5 meters/second (16.4 ft/s) are assumed by FEMA 55 and CCH, respectively. Essentially, CCH estimates the velocity to be equal in magnitude to the inundation depth, while FEMA 55 estimates the velocity to be, $2\sqrt{gd_s}$, where g is the gravitation constant and d_s is the inundation depth.

Surge Force

The surge force is generated by the impingement of the advancing water front of a tsunami bore on a structure. The magnitude is dependent on the geometry of the structural element subjected to the impingement and the velocity of the tsunami. For example, a wall of significant length and height subjected to the impact of the advancing water front experiences significant surge (build up of water along the height of the member) relative to a column under identical flow conditions. In the case of a wall and for calculation purposes, the surge is assumed to be 9 times the hydrostatic force for the assumed inundation depth. The point of application of the resultant surge force is located at a distance h (inundation depth) above the base of the wall. For a column, the *Structural Design Method of Buildings for Tsunami Resistance* (SMBTR) suggests a reduced surge force, given the potential build up of water in front of the column. The magnitude of this force is 4 times the hydrostatic value and the resultant force is located at ⅔ h above the base of the column.

Debris Impact Force

A high-speed tsunami bore traveling inland carries debris such as floating automobiles, floating pieces of buildings, drift wood, boats and ships. The impact of floating debris can induce significant forces on a building, leading to structural damage or collapse. Currently the impact force is assumed to be a single concentrated load acting horizontally at the flow surface or at any point below it. The magnitude is equal to the force generated by 455 kilograms (1000 pounds) of debris traveling with the bore and acting on a 0.092 square meter (1 ft^2) surface of the structural element (FEMA 55, CCH). The impact force is to be applied to the structural element at its most critical location, as determined by the structural engineer. Relative to the other force components, the impact force is a negligible component when evaluating the global lateral force. However, it is more critical in the design of individual structural members that are subjected to debris impact.

Figure 1 (see page 11) shows structural damage caused by the tsunami-induced loading during the December 2004 Indian Ocean Tsunami.

Loading Combinations for Calculating Tsunami-Induced Forces

Appropriate combinations of tsunami-induced force components (hydrostatic, hydrodynamic, surge, buoyant and debris impact) should be used in calculating the total tsunami force given the location and type of structural elements. Based on current literature, tsunami loading combinations must be significantly improved and incorporated in new design codes. An example of recent improvements in loading combinations is the work of Nouri et al., (2007) as shown in *Figure 2*. The load combinations are separated into two scenarios: (1) Initial Impact and (2) Post Impact. The first combination occurs due to surge and debris impact forces. The second scenario considers the hydrodyamic (drag) and hydrostatic forces, simultaneously with the debris impact force. The buoyant force is omitted for calculation of the global lateral force, but should be considered in the analysis and design of flooring elements.

Figure 3a: Column structural model.

Figure 3b: Wave flume set-up

Figure 3c: Impact.

In *Figure 2*, F_i, F_S, F_d, F_{HS}, and F_b are the debris impact, surge, drag, hydrostatic, and buoyant force components, respectively.

Design Considerations

Tsunami-induced lateral forces can be similar to or exceed seismic forces. Appropriate construction and layout of a structure located in a tsunami-prone region can reduce the hazard associated with a tsunami event. Tsunami forces increase proportionally with exposed area and non-structural elements that remain intact during the impact of the hydraulic bore. Therefore, it is prudent to orient buildings with the shorter side parallel to the shoreline. Further, structural walls should also be oriented to minimize the exposed area. Exterior elements located at lower levels should be designed with a controlled failure mechanism at the instant the tsunami impacts the structure. This concept, known as *breakaway walls*, reduces the amount of lateral load that is transferred to the lateral force resisting system. The use of rigid non-structural exterior components, while providing protection to the buildings from flooding, increases the lateral loading.

Current Research

Currently, the authors are conducting experimental studies on the impact of tsunami-induced forces on structural components. The research consists of imposing a simulated tsunami-induced hydraulic bore on structural models representative of full-size columns. Hydraulic bores, similar to tsunami-induced bores, are simulated in a large-scale wave flume located at the Canadian Hydraulics Centre of the National Research Council, Ottawa, Canada. The flume was modified with a swinging gate mechanism to generate a hydraulic bore. The gate swings open quickly from the base allowing retained water to flow downstream in the form of a hydraulic bore. The bore propagates down the flume and impacts the structural model. The main objective of this study involves evaluating the forces associated with a hydraulic bore, leading to a better understanding of the effects of tsunami-induced loading. *Figure 3a)* is a photo of the structural model, *b)* is a photo of the wave flume, with the installed model and measurement instrumentation, while *c)* shows the impact of the hydraulic bore on the structure.

Conclusions

Tsunami induced forces represent a serious and real threat. In spite of their rare occurrence, tsunami waves represent a significant threat for the western coastline of North America given the major recorded tsunamis in the Pacific Ocean. Considering that major cities are located along this coastline, and the lessons learned following the December 2004 Indian Ocean Tsunami, it is imperative that structural engineers became aware of the possible devastating effects of such natural phenomena on infrastructure located in coastal areas.▪

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