GUIDELINES FOR DESIGN OF STRUCTURES FOR VERTICAL EVACUATION FROM TSUNAMIS

J. A. Heintz [1] and M. Mahoney [2]

[1] *Applied Technology Council,Redwood City, California. USA*
[2] *Federal Emergency Management Agency,Washington D.C. USA*
Email: jheintz@ATCouncil.org , Mike.Mahoney@dhs.gov

ABSTRACT:
This work is the result of a three-year effort, known as the ATC-64 Project, funded by the Federal Emergency Management Agency and the National Oceanic and Atmospheric Administration. The purpose of the project is to investigate the feasibility of designing vertical evacuation structures in order to provide refuge from tsunami inundation in communities where there is not enough time to evacuate horizontally out of the inundation zone. This paper summarizes the resulting FEMA P646 Report, *Guidelines for Design of Structures for Vertical Evacuation from Tsunamis*, which provides recommendations on siting concepts, design concepts, performance objectives, design loads, and load combinations that should be considered in locating and designing tsunami vertical evacuation structures.

KEYWORDS:
Tsunamis, vertical evacuation, structure, design, performance

1. INTRODUCTION

In September 2004, the Applied Technology Council (ATC) initiated work on the ATC-64 project, funded by the Federal Emergency Management Agency (FEMA) and the National Oceanic and Atmospheric Administration (NOAA). The objective of this project was to develop technical criteria, design guidance, and recommendations for design and construction of tsunami-resistant structures that would allow for vertical evacuation from tsunami inundation. The results of this project have been published in the FEMA P646 Report, *Guidelines for Design of Structures for Vertical Evacuation from Tsunamis*, in June 2008.

The focus of this document is on structures intended to provide protection during a short-term high-risk tsunami event. Such facilities are generally termed refuges. A *vertical evacuation refuge from tsunamis* is a building or earthen mound that has sufficient height to elevate evacuees above the level of tsunami inundation, and is designed and constructed with the strength and resiliency needed to resist the effects of tsunami waves. In some locations, high ground may not exist, or tsunamis triggered by local events may not allow sufficient warning time for communities to evacuate low-lying areas. Where horizontal evacuation out of the tsunami inundation zone is neither possible nor practical, a potential solution is vertical evacuation into the upper levels of structures designed and detailed to resist the effects of a tsunami.

2. TSUNAMI HAZARD

Tsunami hazard is a measure of the potential for a tsunami to occur at a given site. Tsunami hazard in a particular region is a combination of the presence of a geophysical tsunami source, exposure to tsunamis generated by that source, and the extent of inundation that can be expected as a result of a tsunami reaching a site. Risk is a measure of the consequences given the occurrence of a tsunami, which can be characterized in terms of damage, loss of function, injury and loss of life. Risk depends on many factors including vulnerability and population density. The consequences of tsunami hazard to a coastal community are a function of the time it takes a tsunami to propagate from a source to the site, maximum flood depth, maximum current velocity, integrity of the built environment, and the ability to evacuate to areas of refuge.

The most common triggering events are earthquakes below or near the ocean floor, but a tsunami can also be created by volcanic activity, landslides, undersea slumps, and impacts of extra-terrestrial objects. Tsunamis are categorized by the time it takes a wave to reach a given site. A far-source-generated tsunami is one that originates from a source that is far away from the site of interest, and takes 2 hours or longer to arrive. A near-source-generated tsunami is one that originates from a source that is close to the site of interest, and can arrive in 30 minutes or less. Sites experiencing near-source-generated tsunamis will generally feel the effects of the triggering event (e.g. shaking caused by a near-source earthquake). A mid-source-generated tsunami is one in which the source is somewhat close to the site of interest, but not close enough for the effects of the tsunami generating event to be felt at the site. Mid-source-generated tsunamis would be expected to arrive between 30 minutes and 2 hours after the triggering event.

Given a known or perceived tsunami threat in a region, the first step is to determine the severity of the tsunami hazard. This can include a probabilistic assessment considering all possible tsunami sources, or a deterministic assessment considering the maximum tsunami that can reasonably be expected to affect a site. In this document, the design tsunami event is termed the Maximum Considered Tsunami (MCT). There is, however, no firm policy or methodology for setting a Maximum Considered Tsunami at a specified hazard level. For the design criteria contained within this document, it is anticipated that the hazard level corresponding to the Maximum Considered Tsunami will be consistent with the 2500-year return period associated with the Maximum Considered Earthquake used in seismic design.

3. FEASIBILITY OF TSUNAMI RESISTANT DESIGN

Although there is considerable damage to, and often total destruction of, residential and light-framed buildings during extreme flooding, there are also numerous examples of mid- to high-rise engineered structures that survived tsunami inundation. Structural damage from tsunamis can be attributed to: (1) direct hydrostatic and hydrodynamic forces from water inundation; (2) impact forces from water-borne debris; (3) fire spread by floating debris and combustible liquids; (4) scour and slope/foundation failure; and (5) wind forces induced by wave motion. Studies of damage from historic tsunamis have shown that building survivability varies with construction type and tsunami runup height (Yeh et al., 2005). While observations show that certain types of construction are largely destroyed by high velocity water flow, there is much evidence that appropriately designed structural systems can survive tsunami inundation. This enables consideration of vertical evacuation as a viable alternative when horizontal evacuation out of the inundation zone is not feasible.

4. VERTICAL EVACUATION CONCEPTS

To provide refuge from tsunami inundation, vertical evacuation solutions must have the ability to receive a large number of people in a short time frame and efficiently transport them to areas of refuge that are located above the level of flooding. Potential vertical evacuation solutions can include areas of naturally occurring high ground, areas of artificial high ground created through the use of soil berms, new structures specifically designed to be tsunami-resistant, or existing structures demonstrated to have sufficient strength to resist anticipated tsunami effects. In concept, new or existing structures can serve as vertical evacuation structures, but in general, it will be more difficult to retrofit an existing structure than to build a new structure that is tsunami-resistant.

Vertical evacuation structures can be stand-alone or part of a larger facility. They can be single-purpose refuge-only facilities, or multi-purpose facilities in regular use when not serving as a refuge. Examples are shown in Figures 1 and 2. Nonstructural systems and contents located in the levels below the inundation depth should be assumed to be a total loss if the design tsunami occurs. If the building is required to remain functional in the event of a disaster, the loss of lower level walls, nonstructural systems, and contents should be taken into account in the design of the facility and selection of possible alternative uses.

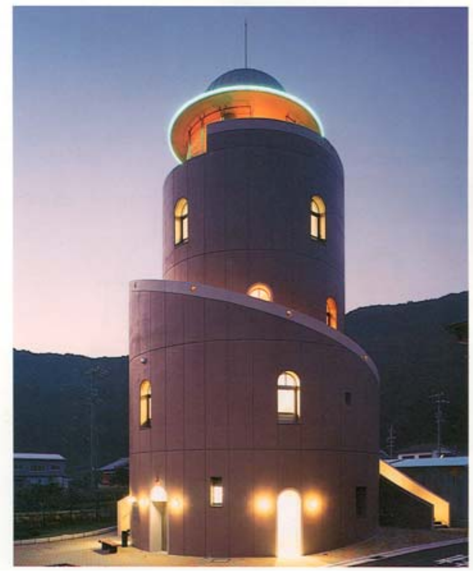

Figure 1. Nishiki Tower, town of Kise, Mie Prefecture, Japan. Designed specifically as a tsunami shelter, but used for other purposes during normal days including public toilets, storage for fire equipment, meeting rooms, and an archival library for natural disasters.

Figure 2. Parking garage concept. Open structural systems allow water to pass through with minimal resistance, and interior ramps allow for easy ingress and vertical circulation.

5. SITING, SPACING, AND SIZING CONSIDERATIONS

Vertical evacuation structures should be located such that all persons designated to take refuge can reach the structure within the time available between tsunami warning and tsunami inundation. Travel time must take into consideration vertical circulation within the structure to levels above the inundation depth.

5.1 Warning, Travel Time, and Spacing

To determine the required number and spacing of tsunami vertical evacuation structures, the critical parameters are warning time and ambulatory capability of the surrounding community. The average, healthy person can walk at approximately 4 mph. Some people in a community, however, may have restricted ambulatory capability due to age, health, or disability. The average pace for mobility-impaired populations can be assumed to be about 2 mph. Assuming the 2-hour warning time associated with far-source-generated tsunamis, vertical evacuation structures should be located a maximum of 4 miles from any given starting point. This would result in a maximum spacing of approximately 8 miles between structures. Assuming the 30 minute warning time associated with near-source-generated tsunamis, vertical evacuation structures should be located a maximum of 1 mile from any given starting point, or 2 miles between structures. Maximum spacing of vertical evacuation structures for mid-source-generated tsunamis would be somewhere between 8 miles and 2 miles. A sample layout of vertical evacuation structures in a hypothetical coastal community is shown in Figure 3.

5.2 Consideration of Site Hazards

Due to the limited availability of possible sites, and limitations on travel and mobility of the population in a community, some vertical evacuation structures may need to be located at sites that would be considered less than ideal. Special hazards in the vicinity of each site must be considered in the design of vertical evacuation structures. Potential site hazards include sources for large waterborne debris, and sources of waterborne hazardous materials. Figure 3 illustrates adjacent site hazards that could exist in a typical coastal community. When possible, vertical evacuation structures should be located away from potential hazards that could result in additional damage to the structure and reduced safety for the occupants.

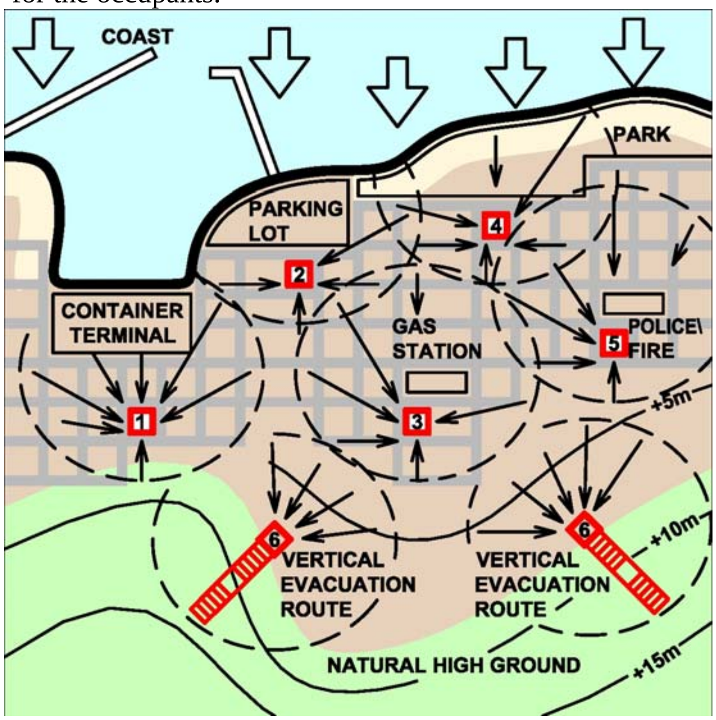

Figure 3. Sample layout of vertical evacuation structures in a hypothetical coastal community, considering travel distance, evacuation behavior, and naturally occurring high ground. Arrows show anticipated vertical evacuation routes.

5.3 Square Footage Recommendations

Sizing of a vertical evacuation structure depends on the intended number of occupants, the type of occupancy, and the duration of occupancy. The number of occupants will depend on the surrounding population and the spacing and number of vertical evacuation structures located in the area. Duration of occupancy will depend on the nature of the hazard and the intended function of the facility. Square footage recommendations vary depending on the anticipated length of stay within the shelter. The longer the anticipated stay in a shelter, the greater the recommended minimum square footage. A refuge for mostly healthy, uninjured people for a short-term event would require the least square footage per occupant. A refuge intended to house sick or injured people, or to provide ongoing medical care, would require more square footage to accommodate beds and supplies.

Based on square footage recommendations employed in the design of shelters for other hazards, the recommended minimum square footage per occupant for a tsunami refuge is 10 ft^2 per person. It is anticipated that this density will allow evacuees room to sit down without feeling overly crowded for a relatively short period of time, but would not be considered appropriate for longer stays that included sleeping arrangements. This number should be adjusted up or down depending on the specific occupancy needs of the refuge under consideration.

5.4 Height Recommendations

In order to serve effectively as a vertical evacuation structure, it is essential that the area of refuge be located well above the maximum tsunami inundation level anticipated at the site. Determination of a suitable elevation for tsunami refuge must take into account the uncertainty inherent in estimation of the tsunami runup elevation, possible splash-up during impact of tsunami waves, and the anxiety level of evacuees seeking refuge in the structure. To account for this uncertainty, the maximum tsunami runup elevation is taken to be 30% higher than values predicted by numerical simulation modeling or obtained from tsunami inundation maps. Because of the high consequence of potential inundation of the tsunami refuge area, it is recommended that an additional allowance for freeboard be provided. The recommended minimum elevation for a tsunami refuge area is, therefore, the maximum tsunami run-up elevation anticipated at the site, plus 30%, plus a freeboard allowance of 10 feet (3 meters).

6. PERFORMANCE OBJECTIVES

While specific performance objectives can vary, the notion of acceptable performance generally follows a trend corresponding to: (1) little or no damage for small, frequently occurring events; (2) moderate damage for medium-size, less frequent events; and (3) significant damage for very large, very rare events.

6.1 Tsunami Performance Objective

In general, tsunamis are very large, very rare events. Unfortunately, there are no national maps or firm policy established to define a methodology for setting a Maximum Considered Tsunami (MCT) at a consistent hazard level. Consistent with the general trend of acceptable performance for “Maximum Considered” loadings, the performance of vertical evacuation structures in this event would include the potential for significant damage while maintaining a reliable and stable refuge. Most structures would be expected to be repairable after a large event, although the economics of repair versus replacement will be uncertain.

6.2 Seismic and Wind Performance Objectives

The performance objective for vertical evacuation structures subjected to seismic and wind hazards should be consistent with that of code-defined essential facilities such as hospitals, police and fire stations, and emergency operation centers. In the case of earthquakes, enhanced performance is necessary so that the structure is usable and has sufficient reserve capacity in the event of a tsunami following a local seismic event.

7. TSUNAMI FORCE EFFECTS

A summary of tsunami force effects that should be considered in the design of vertical evacuation structures is included in Table 1. Some of these effects, such as hydrostatic and buoyant forces, are well understood and commonly addressed in structures exposed to water flow. Others, such as hydrodynamic uplift, impulsive (surge), and debris impact forces, require special consideration with respect to tsunamis. There is significant variability in local tsunami runup heights, based on local bathymetry and topographic effects, and uncertainty in numerical simulations of tsunami inundation. Based on empirical judgment from past tsunami survey data, it is recommended that heights used in tsunami force equations be based on 1.3 times the predicted maximum runup elevation, to envelope the potential variability. Readers are referred to the document for more detailed discussion on the development and application of the recommended tsunami force equations.

Table 1. Summary of Tsunami Force Effects

Type of Force	*Tsunami Consideration*	*Equation*
Hydrostatic	Local effect on elements when one side is dry.	$F_h = p_c A_w = \frac{1}{2}\rho_s g b h_{\max}^2$
Bouyant	Controlled by inundation depth and rate of water level increase	$F_b = \rho_s g V$
Hydrodynamic	Drag forces controlled by the product of the inundation depth and the square of flow velocity	$F_d = \frac{1}{2}\rho_s C_d B(hu^2)_{\max}$
Hydrodynamic Uplift	Vertical (upward) forces on the underside of floor structures caused by rapidly rising flood waters; occurs in combination with buoyant forces	$F_u = \frac{1}{2} C_u \rho_s A_f u_v^2$
Impulsive	Impulsive force controlled by the flow velocity of the leading edge of the runup	$F_s = 1.5 F_d$
Debris Impact	Controlled by the maximum flow velocity, debris mass, debris stiffness, and added mass of water behind debris	$F_i = C_m u_{\max} \sqrt{k m}$
Retained Water	Gravity load surcharge controlled by weight of water retained in the structure	$f_r = \rho_s g h_r$
Breaking Wave	Tsunami waves tend to break offshore	Not considered

Notes: ρ_s = fluid density including sediment = 1.2 ρ_{water} (equal to 1,200 kg/m^3 = 2.33 slugs/ft^3)
A_w , A_f = wetted area of the wall or floor
b = width of element
B = breadth of structure in a plane normal to the direction of flow
C_d = drag coefficient = 2.0
C_u = uplift coefficient = 3.0 (recommended)
C_m = added mass coefficient = 2.0 (recommended)
g = gravitational acceleration constant
h_{max} = maximum water height above the base
h_r = maximum potential depth of water retained on an elevated floor
$h\,u^2$ = momentum flux per unit mass
k = effective stiffness of debris
m = mass of debris
$u_{\max}$ = maximum flow velocity
V = volume of water displaced

8. LOAD COMBINATIONS

The tsunami forces described above will not all occur at the same time; and will not necessarily affect a particular structural element simultaneously. In addition, seismic loads are not considered to act simultaneously with tsunami loads. The probability of an aftershock equivalent to a design level earthquake occurring at the same time as the maximum tsunami inundation is considered to be low. Readers are referred to the document for more detailed discussion on the combined application of tsunami forces.

Tsunami forces that will act on the entire structure and on individual structural members should be calculated, and the resulting member forces should then be combined with gravity load effects using the following Strength Design Load Combinations (LRFD):

Load Combination 1: $1.2D + 1.0T_s + 1.0L_{REF} + 0.25L$ (1)
Load Combination 2: $0.9D + 1.0T_s$ (2)

where D is the dead load effect, T_s is the tsunami load effect, L_{REF} is the live load effect in refuge area (assembly loading), and L is the live load effect outside of the refuge area.

A load factor of 1.0 is used in conjunction with tsunami forces calculated in accordance with this document for the following reasons: (1) it is anticipated that the tsunami hazard level corresponding to the Maximum Considered Tsunami will be consistent with the 2500-year return period associated with the Maximum Considered Earthquake used in seismic design; (2) potential variability in tsunami runup elevations is explicitly considered by applying a 30% increase to runup elevations used in tsunami force calculations; (3) and design for tsunami forces considers only the elastic response of components, without consideration of inelastic response and corresponding force-reduction factors (as is used in seismic design).

9. DESIGN PROCEDURES

Model building code provisions and engineering standards for Strength Design or Load and Resistance Factored Design (LRFD) currently available in the United States provide material-specific member capacity calculations and strength reduction factors for various forces acting on different structural components. Until further research shows otherwise, it is recommended that these capacity calculations and strength reduction factors be applied to design for tsunami loading in the same way they are currently applied to design for earthquake and wind loading.
In addition, because of uncertainties in tsunami force calculations (debris impact, in particular), explicit investigation of the potential for disproportionate (i.e., progressive) collapse due to the loss of one or more structural elements is recommended. In the United States, primary design approaches for progressive collapse include the “tie force” strategy (DOD, 2005) and the “missing column” strategy (GSA, 2003).

10. COST CONSIDERATIONS

Design of vertical evacuation structures for tsunami load effects will require more strength, ductility, and robustness than is necessary for normal-use structures. As recommended in this document, this can include the use of seismic detailing provisions, progressive collapse preventative measures, customized breakaway wall details, and deeper foundation systems. As such, it is expected that structural construction costs will be higher for vertical evacuation structures than for other structures. Structural costs, however, are only a fraction of total construction costs for a building. While there are no direct comparisons between the cost of a conventional structure versus the cost of a tsunami-resistant structure, order of magnitude information on potential cost impacts can be obtained from anecdotal evidence on cost premiums associated with seismic design requirements for essential facilities and studies on cost premiums associated with progressive collapse-resistant design.

Considering the relative magnitude of structural costs versus total building costs, it is reasonable to expect that a tsunami-resistant structure, including both seismic-resistant and progressive collapse-resistant design features, would experience about a 10% to 20% order-of-magnitude increase in total construction costs over that required for normal-use buildings. While each project will be unique, and relative costs will depend on the specific tsunami hazard and site conditions, it should not be assumed that incorporation of tsunami-resistant design features in a vertical evacuation structure will be cost prohibitive.

11. CONCLUSIONS

While observations from past tsunami events show that certain types of construction are largely destroyed by high velocity water flow, there is much evidence that appropriately designed structural systems can survive tsunami inundation. This enables consideration of vertical evacuation as a viable alternative when horizontal evacuation out of the inundation zone is not feasible.

Many common structural systems can be engineered to resist tsunami load effects. Structural attributes that have demonstrated good behavior in past tsunamis include: (1) strong systems with reserve capacity to resist extreme forces; (2) open systems that allow water to flow through with minimal resistance; (3) ductile systems that resist extreme forces without failure; and (4) redundant systems that can experience partial failure without progressive collapse. Systems exhibiting these attributes include reinforced concrete and steel moment frame systems, and reinforced concrete shear wall systems. The use of deep foundations for resistance to scour and breakaway wall systems to minimize hydrodynamic forces should be considered. Recommendations in the FEMA 646 Report, *Guidelines for Design of Structures for Vertical Evacuation from Tsunamis*, will provide engineers and emergency planners with the information needed to design new and assess existing structures for possible use as vertical evacuation facilities.

12. ACKNOWLEDGEMENTS

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