CURRENT TSUNAMI DESIGN GUIDANCE IN THE UNITED STATES - FEMA P-646

Ian N. Robertson, Ph.D., S.E.
Professor, University of Hawaii at Manoa
Honolulu, Hawaii / USA

Abstract

The use of engineered structures for vertical evacuation from tsunamis has become common place in Japan, and is generating increased interest in other tsunami-threatened coastal communities. During the March 2011 Tohoku Tsunami in Japan, thousands of evacuees survived by seeking refuge in mid- to high-rise buildings, some of which were officially designated for use as tsunami evacuation buildings, but many that were not. A limited number of these buildings were specifically designed for this purpose following Japanese tsunami design provisions. The only tsunami design guidance currently available in the USA is the FEMA P-646 document entitled “Guidelines for Design of Structures for Vertical Evacuation from Tsunamis”. This paper gives an overview of FEMA P-646 and highlights recent revisions made to the second edition published in April 2012.

Because FEMA P-646 is a guideline written in non-mandatory language, it is not suitable for direct adoption into building codes. Nevertheless, the document has been added by reference in an appendix of the International Building Code for use in design of critical facilities and vertical evacuation structures in tsunami inundation zones. It can also form the basis for development of code language in future tsunami design requirements, such as the current effort to develop a chapter of ASCE7 on Tsunami Loads and Effects. Once tsunami design has been incorporated into established building codes, FEMA P-646 may have to be revised to avoid conflicts with the code requirements, but it will continue to provide background information and additional considerations as a complement to the code requirements.

Introduction

In November 2002, a workshop was held in Seattle, Washington, with attendees having expertise in structural, marine, and civil engineering, seismology, geology, and emergency management to assess the feasibility of using vertical evacuation in specially designed buildings in the event of a tsunami (Walsh *et al*, 2002). A two-phase program was recommended. The purpose of Phase I was to extract data from unpublished tsunami surveys to estimate forces from tsunami waves on buildings, to analyze buildings that survived tsunami wave attack, and to test those forces against building code designs. Phase I was funded by the Washington State Military Department, Emergency Management Division, on behalf of the NTHMP and resulted in a final report by Yeh, *et al*. (2005).

Phase II was performed by Applied Technology Council (ATC) of Redwood City, California, as project ATC-64 under contract to the Federal Emergency Management Agency (FEMA). It built on Phase I results to develop guidance on tsunami hazard assessment, design and siting guidelines for vertical evacuation structures and was published as “Guidelines for Design of Structures for Vertical Evacuation from Tsunamis, FEMA P-646” in June 2008 (FEMA, 2008). This document has been used around the world to assist in development of vertical evacuation structures and procedures. For example, it was used as the basis for a conceptual design to replace the City Hall in Cannon Beach, Oregon, with a new City Hall building that could be used for vertical evacuation in the event of a tsunami originating from the Cascadia Fault Zone. These studies identified the need for clarification of certain provisions in FEMA P-646, as well as some needed revisions.

ATC was contracted by FEMA to review the design guidance contained in FEMA P-646, and to consider updates based on new information. These revisions included the clarifications and corrections detected earlier and new lessons learned from the Tohoku Tsunami of March 11, 2011. The second edition of FEMA P-646 was published in April 2012 (FEMA, 2012). This paper provides an overview of FEMA P-646 and highlights some of the modifications made in the second edition.

Vertical Evacuation from Tsunamis

During a tsunami event, the most important procedures for reducing loss of life are an effective warning system and evacuation to high ground outside of the anticipated inundation area. In the event of a tsunami originating from a near-source earthquake, the severe ground-shaking serves as an immediate warning, ideally reinforced by subsequent official warnings. Public education and tsunami exercises are necessary to familiarize the local population with these procedures. However, there are certain communities where evacuation to high ground outside the inundation zone is not possible in the time between the tsunami warning and inundation. This is particularly evident in the northwest USA where numerous coastal communities threatened by the Cascadia Subduction Zone have less than 30 minutes to evacuate. Studies have shown that many lives will be lost if evacuation to natural high ground is the only means of escape.

During past damaging tsunami events, thousands of lives have been saved through people's instinct to seek refuge in the upper floors of buildings and other structures in the inundation area. This was particularly evident in areas in Japan inundated by the Tohoku Tsunami. With as little as 30 minutes between the ground-shaking and tsunami inundation, many evacuees were able to make their way to high ground or into designated vertical evacuation structures. Because of their long history of damaging tsunamis, Japan has built a number of vertical evacuation structures and designated numerous existing buildings as tsunami refuges (Fraser, 2012). In addition, citizens often used any convenient mid- to high-rise building whether or not it was officially designated for tsunami evacuation. In most cases this vertical evacuation saved lives. Unfortunately, there were a number of instances where designated vertical evacuation structures were completely inundated, resulting in loss of life of those seeking refuge. This is one of the major lessons learned from the Tohoku Tsunami regarding design of vertical evacuation structures.

Figure 1 shows the Matsubara Community apartment building in Minamisanriku, Japan, built in 2007 as a designated tsunami vertical evacuation building. The open flat roof area, measuring 660 square meters and equipped with a well-braced 2 meter guardrail, was accessible through an external stairway and elevator which could be accessed without entering the rest of the building. Even though this building was overtopped by 0.7 meters, the 44 people who sought refuge on the roof survived the tsunami.

Figure 1: Matsubara Community apartment building at the coastline in Minamisanriku (FEMA, 2012)

Figure 2 shows a designated evacuation building in Rikuzentakata where a number of evacuees sought refuge during the tsunami. Unfortunately the tsunami inundated the second level evacuation area killing most of those inside. Similar tragedies occurred at other evacuation buildings that were not high enough to provide safe refuge.

Figure 2: Rikuzentakata City Hall Community Center and Gymnasium

Honolulu, Hawaii, is the only US community where vertical evacuation from tsunamis is practiced as official policy. In the event of a tsunami warning, residents and visitors in Waikiki are instructed to move to the third level or higher of any reinforced concrete or structural steel building that is taller than 6 stories. This procedure has been used during three recent tsunami warnings, though no inundation occurred in Waikiki during these events. However, the buildings in Waikiki have not been reviewed to determine whether or not they are suitable for use as evacuation buildings. FEMA P-646 provides a means by which these buildings can be evaluated and officially designated for vertical evacuation.

FEMA P-646

Overview

FEMA P-646 provides an introduction to tsunami effects on coastal communities and structures through reference to numerous past tsunami events and storm surge damage during Hurricane Katrina. Important lessons learned from these events relating to the likely performance of vertical evacuation structures during tsunami inundation are highlighted. In the second edition, new lessons learned from the Tohoku Tsunami are emphasized, most notably the need for vertical evacuation buildings to be high enough to ensure safety of the occupants. Past assumptions that reinforced concrete buildings will likely withstand tsunami loads are also debunked based on the numerous concrete structures destroyed by the Tohoku Tsunami, including some that were overturned due to buoyancy or inadequate foundation resistance to overturning.

After an introduction to the concept of vertical evacuation structures, and a review of past tsunami effects, FEMA P-646 provides guidance on: tsunami hazard assessment; vertical evacuation options; siting, spacing, sizing and elevation considerations; tsunami load determination; and structural design considerations. These are covered in more detail in the following sections.

Tsunami Hazard Assessment

In the discussion of tsunami hazard assessment, FEMA P-646 recommends that local jurisdictions take responsibility for specifying the tsunami hazard level to be considered for design of vertical evacuation buildings. However, a 2500 year return period tsunami event is recommended as the maximum considered tsunami (MCT). It is strongly recommended that high resolution tsunami inundation modeling be performed to estimate the likely flow conditions at the location of the vertical refuge. A list of suitable numerical models is provided for this purpose. Because of uncertainty in the precision of these modeling results, it is recommended that they be amplified by a 1.3 factor when estimating the potential inundation depth at the location under consideration.

In the second edition, renewed emphasis is placed on the need to perform inundation modeling rather than relying on analytical estimates of the flow conditions, although the alternative analytical method is retained as a means to evaluate the numerical modeling results.

Vertical Evacuation Options

Preference should always be given to evacuation to naturally occurring high ground wherever possible. This provides the potential for evacuees to proceed to even higher ground if the inundation exceeds prior estimates. FEMA P-646 then recommends artificial high ground in the form of mounds for vertical evacuation. Figure 3 shows a suitable earth mound at the West end of Sendai harbor that could have served as an evacuation site in otherwise flat coastal terrain. It is not known is this site was used by evacuees during the Tohoku Tsunami.

Figure 3: Earth mound suitable for vertical evacuation at Sendai Harbor (FEMA, 2012)

A major advantage of a mound is that it is unlikely to be damaged by the earthquake preceding a local source tsunami. Evacuees will feel more comfortable using a mound as refuge rather than a building which might have suffered superficial non-structural damage during the earthquake. Mounds can also be accessed by ramps for handicapped evacuees, and provide reliable resistance against even the largest of impacts from floating debris such as ships and shipping containers. They can be lined with concrete, as seen on the ocean facing side of the mound in Figure 3 if scour is a concern, however very little scour was evident at this or similar mounds inundated by the Tohoku Tsunami. It must be stressed that an evacuation mound must be high enough to ensure safety of the evacuees since they have no recourse to higher elevations if the mound is overtopped.

The use of vertical evacuation buildings is recommended for locations where high ground is not close enough to ensure safe horizontal evacuation. In the second edition of FEMA P-646, a number of successful vertical evacuation buildings in Japan are highlighted as model examples where numerous lives were saved (Figure 4). Parking structures are recommended because they are open to pedestrians 24 hours a day and the vehicle ramps provide easy access to upper levels (Figure 4). Past tsunamis have shown that impact from floating cars is unlikely to cause damage to the structural members in a building of this size.

Figure 4: Examples of suitable vertical evacuation structures from Kessenuma, Japan during the Tohoku Tsunami (left) and Biloxi, Mississippi during Hurricane Katrina (right) (FEMA, 2012).

Siting, Spacing, Sizing and Elevation Considerations

FEMA P-646 provides guidance on how to determine the ideal locations, spacing and sizing of vertical evacuation refuges to accommodate all potential evacuees (Figure 5). Potential secondary hazards such as floating debris, fires, etc. must also be considered when selecting, locating and designing a vertical refuge (Figure 5).

In order to ensure adequate elevation above the anticipated inundation depth, FEMA P-646 recommends that the refuge area be located at least one floor or 3 meters above the predicted inundation depth including the 1.3 uncertainty factor (Figure 6). Prior to the Tohoku Tsunami, this recommendation appeared unnecessarily conservative and was under consideration for revision. However, in light of the experience of refuge overtopping in Japan, this recommendation has been retained and strengthened in the second edition with the added recommendation that “This should be treated as an absolute minimum, with additional conservatism strongly encouraged” (FEMA, 2012, pg. 68).

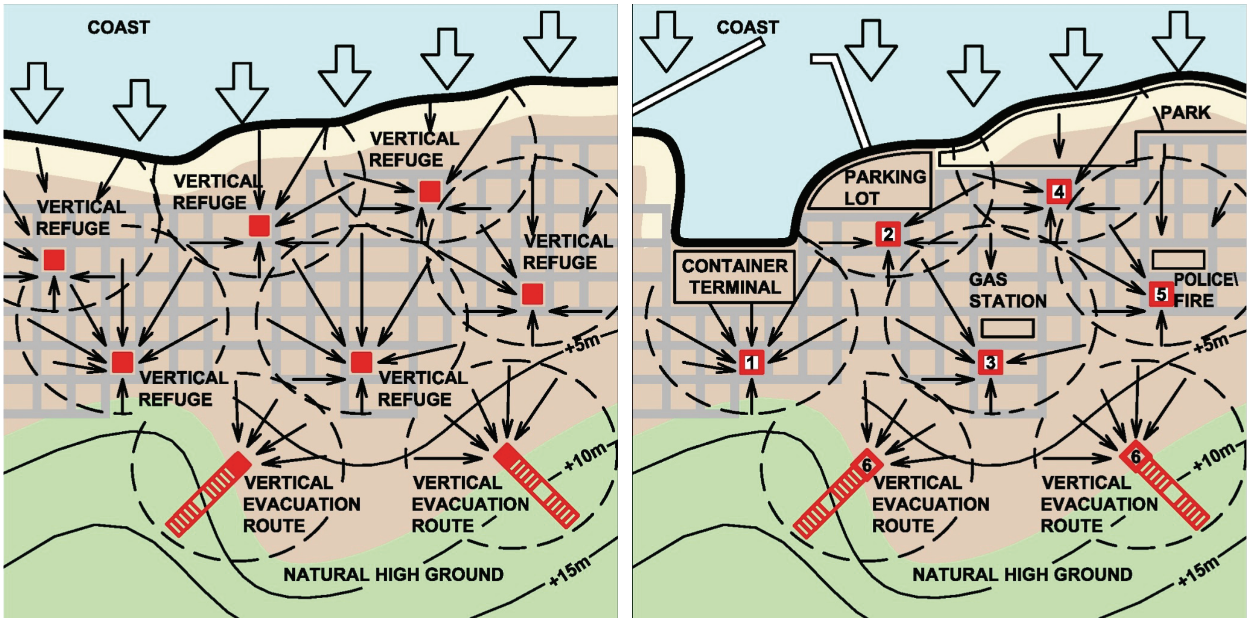


Figure 5: Vertical refuge siting considerations (FEMA 2012)

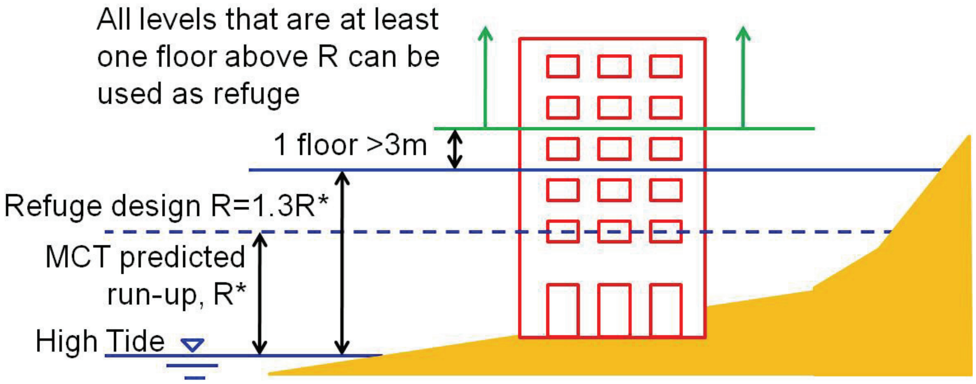
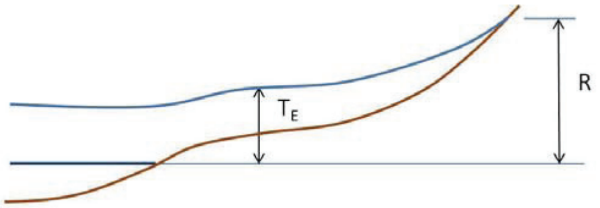


Figure 6: Graphical illustration of FEMA P-646 refuge elevation guideline

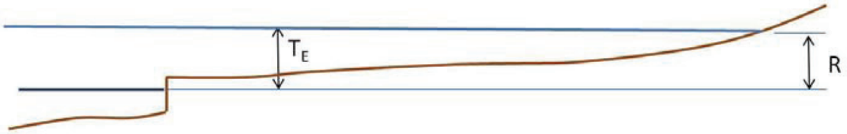
Tsunami Load Determination

In order for a tsunami refuge to serve its purpose in locations threatened by near-source tsunamis, it must first survive the large magnitude earthquake responsible for the tsunami. FEMA P-646 recommends that the refuge be designed for seismic performance consistent with that of code-defined essential facilities. To obtain a higher level of confidence that enhanced seismic performance is achieved, the design can be evaluated using performance-based seismic design techniques such as ASCE/SEI 41-06. FEMA P-646 recommends that the performance objectives should be at least Immediate Occupancy performance for the Design Basis Earthquake (DBE) and Life Safety performance for the Maximum Considered Earthquake (MCE). The structure must then be designed for all likely tsunami loads and effects. Under these design conditions, it is anticipated that the refuge structure will survive the earthquake with limited structural and non-structural damage, and have sufficient remaining strength to resist all tsunami induced loads and foundation scour without collapse.

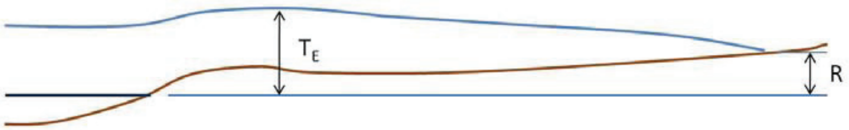
Tsunami loading provisions in FEMA P-646 are based on a number of general assumptions. Given the density of seawater and the potential for sediment transported within the tsunami flow, the water density is taken as 1.1 times that of freshwater. Tsunami flow depths vary significantly depending on the complexity of bathymetry and topography at the location under consideration. In the second edition of FEMA P-646 Figure 7 was added to illustrate potential tsunami inundation depending on local topography. FEMA P-646 assumes the condition shown in Figure 7b unless high resolution tsunami inundation modeling is performed for the specific location under consideration.



a) Steep coastal topography (eg. Coastal cliffs, Tohoku, Japan)



b) Gradual topography inland from port or harbor (eg. Onagawa, Japan)



a) Flat topography inland from coastal dune (eg. Sendai Plains, Japan)

Figure 7: Topographical effect on coastal inundation such that the tsunami elevation (T_E) at a site of interest could be less than, equal to, or greater than the ultimate inland runup elevation (R) (FEMA, 2012)

Tsunami loading expressions are provided in FEMA P-646 for the following conditions:

- Hydrostatic Forces
- Buoyant Forces
- Hydrodynamic Forces
- Impulsive Forces
- Debris Impact Forces
- Damming of Waterborne Debris
- Uplift on Elevated Floors, and
- Additional Gravity Loads on Elevated Floors

For example, the hydrodynamic force acting on a structural element is given by:

$$F_d = \tfrac{1}{2}\rho_s C_d B(hu^2)_{\max} \tag{1}$$

Where: $\rho_s = 1.1 \times$ density of water = 1,100 kg/m^3,

$C_d = 2.0$ is the recommended drag coefficient,

B is the width of the structural element, and

$(hu^2)_{\max}$ is the maximum specific momentum flux based on flow depth, h, and corresponding velocity, u.

An analytical expression is given for estimating the maximum specific momentum flux, but the user is cautioned that this expression is based on laboratory experiments on a frictionless constant slope beach. This expression is not suitable to represent the potentially complex three-dimensional bathymetry and topography at the site under consideration. It is strongly recommended that high resolution numerical inundation modeling be used to determine the maximum specific momentum flux at the refuge location.

At the leading edge of a tsunami surge or bore, there is potential for a short duration load that exceeds the steady state hydrodynamic drag force given by Equation 1. For conservatism FEMA P-646 recommends that an impulsive load be considered at the leading edge of the tsunami flow equal to 1.5 times the hydrodynamic force. The second edition clarifies that this impulsive force is most appropriate when the flow impacts a wide object such as a wall, but is unlikely to apply to narrow columns.

In order to design for potential impact from floating debris, FEMA P-646 considers wood logs and shipping containers as the most prevalent large debris objects. In the first edition of P-646, the impact force was given by:

$$F_i = C_m u_{\max} \sqrt{km} \tag{2}$$

Where: C_m is the added mass coefficient, taken equal to 2.0
$u_{\max}$ is the maximum flow velocity when flow depth is sufficient to float the debris
k is the effective stiffness at impact, and
m is the debris mass.

A table was provided with values for *k* and *m* for wood logs, and empty 20-ft and 40-ft shipping containers. On subsequent review, the values of effective stiffness, *k*, provided in this table for shipping containers were determined to be unrealistically high.

For the second edition of FEMA P-646, the expression for debris impact has been modified to:

$$F_i = 1.3 u_{\max} \sqrt{k m_d (1 + c)} \tag{3}$$

where *c* is the hydrodynamic mass coefficient. A table is provided with revised values for *k* and values for *c* depending on orientation of the impact strike.

Structural Design Considerations

FEMA P-646 provides recommendations on how the various tsunami load conditions should be considered, including combinations with live and dead loads. Guidance is also given as to the design of breakaway walls at the lower levels of the building in order to reduce the potential tsunami loads. In order to protect against progressive collapse caused by large floating object impact or other loads exceeding those considered in the design, FEMA P-646 recommends that the vertical evacuation building be designed for progressive collapse prevention. This will provide the building with increased resistance against collapse even if individual columns or walls are damaged. References are provided to current US Department of Defense guidelines for progressive collapse prevention design.

Summary and Conclusions

FEMA P-646 is the first comprehensive tsunami design guidance developed in the USA. It provides recommendations for planning and design of refuges for vertical evacuation from tsunamis. It has been used around the world as a resource for coastal communities threatened by tsunami inundation. A second edition of P-646 was published in April 2012 to include clarifications and revisions made following review of the design provisions. The second edition was also able to incorporate important lessons learned from the Tohoku Tsunami of March 11, 2011.

Although not written in mandatory code-style language, P-646 is referenced in the International Building Code (ICC, 2012) for design of critical facilities and vertical evacuation structures in tsunami inundation zones. The document also provides a foundation for development of more specific code language for incorporation of tsunami design into future building codes.

References

Yeh, H., Robertson, I.N., and Preuss, J., 2005, "Development of Design Guidelines for Structures that Serve as Tsunami Vertical Evacuation Sites," *Open File Report 2005*-4, Washington Division of Geology and Earth Resources, Olympia, Washington, 40 pages.

FEMA, 2008, "Guidelines for Design of Structures for Vertical Evacuation from Tsunamis," *FEMA P-646*, Federal Emergency Management Agency, Washington, DC, 175 pages.

FEMA, 2012, "Guidelines for Design of Structures for Vertical Evacuation from Tsunamis," *FEMA P-646, Second Edition*, Federal Emergency Management Agency, Washington, DC, 180 pages.

Fraser, S., Leonard, G.S., Matsuo, I., and Murakami, H., 2012, "Tsunami Evacuation: Lessons from the Great East Japan earthquake and tsunami of March 11th 2011," *GNS Science Report 2012/17*, Institute of Geological and Nuclear Sciences, Wellington, New Zealand, 89 pages.

ICC, 2012, "International Building Code," International Code Council, Inc., Country Club Hills, Illinois.