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Overview and technical background to development of ASCE 7-16 Chapter 6, Tsunami Loads and Effects

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Abstract

In February 2011, the American Society of Civil Engineers, ASCE, formed a new subcommittee to develop design provisions for Tsunami Loads and Effects (TLE). There is currently no standard in the US for tsunami design, even though five Western states (California, Oregon, Washington, Alaska and Hawaii) are exposed to severe tsunami threats. The TLE subcommittee consists of 16 members and 14 associate members and spent four and a half years developing a new chapter for ASCE 7, Minimum Design Loads and Associated Criteria for Buildings and Other Structures. These design provisions have been approved by the main committee of ASCE 7 for inclusion as Chapter 6, Tsunami Loads and Effects, in the 2016 edition of the ASCE 7 standard. It is also being incorporated by reference in the 2018 International Building Code.

This paper gives a brief history of tsunami design code development in the USA, and an overview of the new Tsunami Loads and Effects chapter of ASCE 7, highlighting how many of the loading expressions were developed based on laboratory experiments and post-tsunami observations. Laboratory experiments performed at the O.H. Hinsdale Wave Research Laboratory at Oregon State University, along with experiments at University of Hawaii at Manoa, Lehigh University, University of Washington, University of Ottawa and other research laboratories contributed to the development of loading expressions for tsunami effects on coastal structures. In addition, valuable information was gained from surveys of buildings and other structures damaged during the 2010 Maule tsunami in Chile and the 2011 Tohoku tsunami in Japan. The authors participated in field surveys after both events and gathered extensive information on structural damage for post-event forensic analysis. The results of these laboratory and field investigations have contributed significantly to the development of the TLE design provisions in ASCE 7-16.

Keywords: ASCE7-16, Tsunami Loading, Structural Design, Building Codes, Overview

1. Introduction

The Maule tsunami of February 27, 2010, and the Tohoku Tsunami of March 11, 2011 caused tremendous damage to many coastal buildings, bridges and port facilities in Chile and Japan, respectively. However, a number of larger concrete and structural steel buildings survived with only non-structural damage, particularly if they had been designed for high seismic conditions. Field surveys following these events and analysis of survivor videos have provided a wealth of information on the tsunami flow characteristics and structural loading that need to be considered in the design of coastal buildings [1, 2].

Since February 2011, the ASCE Tsunami Loads and Effects subcommittee has been working to develop a new chapter for inclusion in the ASCE7-16 Standard, Minimum Design Loads and Associated Criteria for Buildings and Other Structures [3]. This new Chapter 6, Tsunami Loads and Effects, provides comprehensive provisions for design of coastal structures for tsunami loads, scour and related considerations.

Once adopted by the International Code Council, ASCE 7-16, with the new chapter on Tsunami Loads and Effects, will become part of the 2018 version of the International Building Code [4] used throughout the United States of America. The tsunami design provisions will apply to all coastal communities in California, Oregon, Washington State, Alaska and Hawaii. A companion design manual is currently being developed to explain the new provisions and demonstrate their application to prototypical reinforced concrete and structural steel buildings in coastal communities in the Western USA [5].

The ASCE 7-16 Tsunami Loads and Effects chapter will become the first US national, consensus-based standard for tsunami resilience of critical and essential facilities, Tsunami Vertical Evacuation Refuge Structures, and other multi-story building structures. The tsunami design provisions are consistent with the principles of probabilistic hazard analysis, tsunami physics, and fluid mechanics. They can be utilized in any tsunami-prone community once the probabilistic tsunami hazard for that location has been established.

2. History of Tsunami Design Development in the US

Figure 1 shows a timeline of the history of tsunami design code development in the US along with major damaging tsunami events around the world. The first and only jurisdiction in the US to adopt tsunami design provisions was Honolulu City and County on the island of Oahu, Hawaii [6]. This early tsunami code was based on a 1980 study by Dames and Moore [7] of prior laboratory research on tsunami loading. After a number of damaging tsunamis in Japan and SE Asia, the Washington State Emergency Management Division organized a workshop in 2001 bringing together tsunami wave modelers and structural engineers to discuss development of potential tsunami design provisions. This workshop led to funding of a research project by Yeh et al. [8] on the feasibility of designing coastal buildings for tsunami loads. The final report from this study was used as the basis for an Applied Technology Council project (ATC 64) funded by the Federal Emergency Management Agency (FEMA) to develop “FEMA P-646: Guidelines for Design of Structures for Vertical Evacuation from Tsunamis” [9]. These guidelines were not written in mandatory language, and relied on limited laboratory experiments to infer tsunami flow conditions on land and subsequent structural loading.

The devastation caused by the Indian Ocean Tsunami of December 2004 led to increased tsunami research and development of warning systems and effective tsunami evacuation strategies. It also provided the impetus for increased laboratory research on tsunami loads and effects, including a major NSF-NEESR project on the Development of Performance Based Tsunami Engineering, PBTE, led by researchers from the University of Hawaii at Manoa [10]. A subsequent NSF-NEESR project to develop loading expressions for floating debris impact was also led by researchers from the University of Hawaii [11].

Based on the information gained from these and other research efforts, Gary Chock of Martin & Chock, Inc., a structural engineering consulting company in Honolulu, Hawaii, and the principal investigators of the NEESR projects assembled a team of 30 experts in tsunami modeling, loading and scour effects, and proposed a new sub-committee be formed under ASCE7 to develop design provisions for Tsunami Loads and Effects. This sub-committee was officially sanctioned by ASCE in February 2011. The next month the Tohoku Tsunami caused significant damage and loss of life along the Northeast coast of Honshu Island, Japan. Members of the newly formed ASCE7 subcommittee on Tsunami Loads and Effects organized an extensive field survey in order to gather information that could be used to validate the recent laboratory experiments at full scale. The results of this field reconnaissance and subsequent failure analyses, and similar field surveys by other members of the TLE subcommittee, were critical to formulating the tsunami design provisions [2].

In 2012, the International Building Code adopted FEMA P646 as an optional Appendix M for application to vertical evacuation structures and other critical buildings in the tsunami inundation zone, even though this document was not written in mandatory code language. In light of lessons from the Tohoku Tsunami, FEMA funded ATC to revise FEMA P646 and published a second edition in 2012 [12].

The ASCE7 TLE subcommittee consisted of 16 full and 14 associate members and met regularly over a three and a half year period to draft the tsunami design provisions. In June 2014 these draft provisions were submitted to ASCE7 main committee for review. After a total of 8 ballots and resolution of over a thousand comments, the provisions were finalized and approved for inclusion as Chapter 6, Tsunami Loads and Effects, in the 2016 edition of ASCE7 [3]. This chapter has now been approved by the ICC Structural subcommittee for inclusion in the IBC 2018 [4], which will then be available for adoption by the five Western US states. It is hoped that this adoption process will occur by 2020.

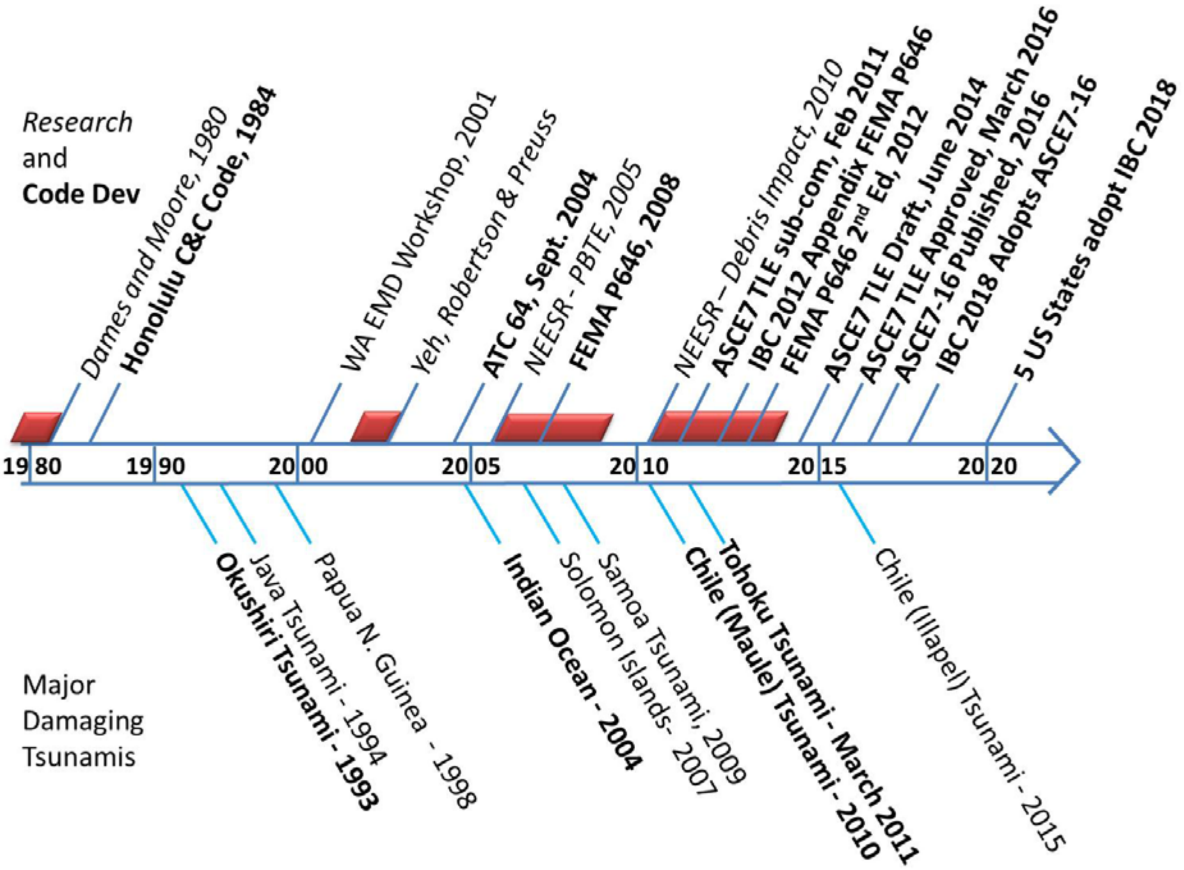

Fig. 1 – History of Tsunami Code Development in the US

3. Tsunami Hazard

3.1 Tsunami Exposure for the USA

Figure 2 shows the locations of four recent subduction zone earthquakes that generated trans-oceanic tsunamis in the Pacific Ocean. In particular, the Tohoku Tsunami off the Northeast coast of Japan caused damage in Hawaii, Oregon and California, along with extensive devastation of the coastal infrastructure along the Tohoku (Northeast) coast of Honshu Island.

The primary subduction zones that threaten tsunami inundation of the US coastline are the Aleutian Subduction Zone off the coast of Alaska and the Aleutian islands, and the Cascadia Subduction Zone off the coast of Washington, Oregon and northern California. These zones are also identified in Figure 2.

In addition, subduction zones around the Pacific basin, including Kamchatka-Kuril, Japan, Mariana trench and Western South America also threaten Hawaii and the US western states with distant source tsunamis.

Because of the high population density along the Pacific coast of the US, particularly in California and Hawaii, there is large life-safety and economic exposure to tsunamis. At any time, over 650,000 residents and as many as 1,000,000 tourists are at risk along the entire coastlines of the five US western states. In addition, economic exposure, particularly of major ports and harbors and associated cities, could mean that a major tsunami will result in significant economic consequences not only for these western states, but for the entire US economy.

Apart from evacuation planning intended to reduce the loss of life during a tsunami, no specific design standards have been available in the US for tsunami design of coastal buildings and other structures. The new chapter 6 of the ASCE7-16 standards fills this gap for future construction.

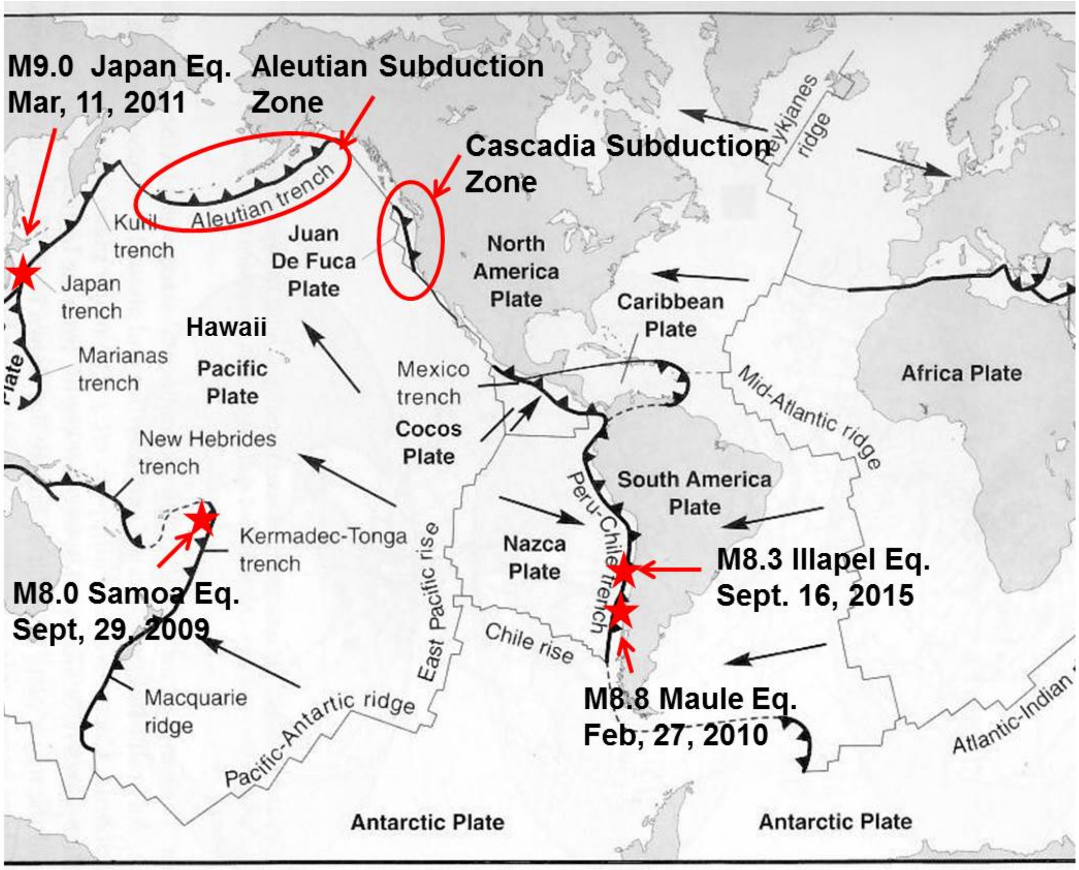

Fig. 2: Recent tsunamis and other tsunamigenic sources around the Pacific Ocean

3.2 Probabilistic Tsunami Hazard Analysis

All of the Pacific basin tsunami sources were considered in development of 2500-year mean reccurrence interval (MRI) probabilistic off-shore tsunami wave conditions for the ASCE 7-16 design standard. Past reliance on historical tsunamis to define the design level have failed, most notably during the Tohoku Tsunami in Japan, so a probabilistic approach is the only defensible methodology to help estimate future potential tsunamis. The anticipated 2500-year offshore wave heights run as high as 30 meters in the Aleutians, 23 meters in Alaska, 11 meters off Washington State and Oregon, but reduce down the West coast of the US. Offshore wave heights are not expected to exceed 12 meters along the coast of Hawaii.

The tsunami sources are fully integrated over seismic sources varying in size and recurrence rate. Uncertainties are included through the use of logic trees and probability distribution functions based on earthquake source predictions by the US Geological Survey, USGS. The results include aleatory uncertainties relating to the lack of understanding about the source mechanism, such as slip distribution and wave generation, and epistemic uncertainties in the tectonic fault maximum magnitude and recurrence and coupling ratio parameters. The resulting probabilistic tsunami hazard is primarily expressed in the offshore tsunami amplitude and characteristic period at 100m bathymetric depth along the entire coastline of Washington, Oregon, California and Hawaii, and the southern coastline of Alaska. During generation of the 2500-year offshore wave properties, source disaggregation was recorded for use in generating scenario tsunamis that represent the 2500-year MRI event. These data are stored in an online ASCE Tsunami Design Geodatabase. They can be viewed using Google Earth, ArcGIS or other geospatial information software. Similar approaches have been used by Australia and New Zealand to represent their offshore tsunami wave conditions. This work was performed primarily by Hong Kie Thio of AECOM with assistance from others in the ASCE7 TLE subcommittee, and is described in more detail in a companion paper [13].

3.3 Tsunami Design Zone Maps

In order to determine the extent of tsunami inundation along the exposed coastlines, the offshore wave heights are used to generate onshore inundation modeling to determine the Tsunami Design Zone (TDZ) and runup elevation. The disaggregated sources were used to generate scenario tsunamis which were propagated towards the coastline of interest. The resulting offshore wave at 100m bathymetric depth must not be less than 80% of the PTHA 2500-year wave amplitudes. The tsunami is then propagated onland using a 60m horizontal grid resolution Digital Elevation Model (DEM) to determine the inundation limit. All land seaward of the inundation limit is in the TDZ. This work was performed by researchers at the NOAA Pacific Marine Environmental Laboratory, PMEL, in Seattle, Washington, and is described in more detail in a companion paper [14]. It is proposed that the five individual US states use higher resolution DEM’s to generate more accurate TDZ data for highly populated regions, but the ASCE database will at least contain the TDZ data that have already been generated.

4. Tsunami flow characteristics

In order to design structures for tsunami loading, it is necessary to determine the flow depth and velocity at the project site during the 2500-year Maximum Considered Tsunami (MCT). These flow characteristics can be determined either by site specific tsunami inundation modeling, or by use of the Energy Grade Line Analysis, developed specifically for the ASCE7 tsunami design provisions [15].

4.1 Site Specific Tsunami Inundation Modeling

ASCE7-16 provides procedures that must be followed if one selects to perform a site specific tsunami inundation analysis to determine flow conditions at the site of interest. This method has the advantage that it is likely to be more precise than the EGL analysis, and it provides a full time history of both incoming and outgoing flow conditions for all waves making up the tsunami event. The procedures are similar to those used to generate the TDZ, described above, but require the use of higher resolution bathymetry and topography. The results of the site specific analysis are also restricted to a certain percentage of the EGL analysis results for the same site in order to avoid unconservative estimates of flow velocity from the choice of tsunami model.

Site specific inundation analysis is required for all Tsunami Risk Category IV structures, such as hospitals, emergency response centers and tsunami vertical evacuation refuge structures. It can also be used for other risk category structures if desired.

4.2 Energy Grade Line Analysis

The Energy Grade Line analysis method is based on a step-wise calculation of the energy in the tsunami flow, starting at the runup point and progressing towards the shoreline. One need only complete the calculation to the site of interest, but it is often helpful to visualize the full energy profile to the shoreline. The energy is accumulated based on the topographic slope, and the equivalent slope due to surface friction. At any location along the EGL, the total energy is a combination of potential energy and kinetic energy. Because there is only one energy equation but two unknowns, depth h, and velocity, u, it is necessary to use a relationship between these two to solve the problem. This relationship is the Froude number, $F_r = u/\sqrt{gh}$, which decreases from the shoreline to zero at the runup location.

The EGL has been calibrated against a numerical inundation model over 36,000 randomly generated topographical profiles, yielding 700,000 points for comparison between EGL and numerical model. The EGL analysis was intentionally biased upwards by one standard deviation to ensure conservative results for the majority of analyses [15]. Further information on the EGL is provided in a companion paper [16].

5. Structural design provisions

5.1 Tsunami Risk Categories

Just as for other loading conditions in ASCE 7, four Tsunami Risk Categories (TRC) are defined. TRC IV includes all essential and critical buildings, including those that pose a substantial hazard to the community. TRC III includes large occupancy buildings where there is substantial risk to human life if the building fails. TRC I includes buildings that are generally not occupied continuously, and represent little risk to humans. TRC II includes all other buildings, which is the vast majority, including all residential, office, storage buildings, etc. All TRC IV and TRC III buildings and structures, located within the TDZ, must consider the effects of tsunami loading in their design. The local jurisdiction is encouraged to require tsunami design for TRC II buildings with sufficient height to provide emergency refuge for people stranded within the TDZ. This will also enhance the resilience of the community since these buildings are likely to be structurally sound after the tsunami, requiring only replacement of non-structural elements below the maximum tsunami flow elevation for them to resume their pre-tsunami function.

All smaller TRC II buildings such as light-framed single and multiple family residences and low-rise office buildings, and those that are only single story (like warehouses and airplane hangers) are not required to be designed for tsunami loading. The economic cost of hardening these buildings for tsunami loads is not justified considering the low probability of tsunami inundation at any specific site, and the inability of these low-rise or single-story structures to provide safe refuge for people stranded in the tsunami zone.

5.2 Tsunami Load Cases

Three tsunami load cases must be considered. Load Case 1 is a buoyancy check to ensure that the initial tsunami flow does not lift the building off its foundations. Load Case 2 represents the maximum flow velocity, assumed to occur simultaneously with a flow depth of 2/3 of the maximum flow depth. This load case was based on analysis of tsunami video evidence recovered from past tsunamis, most notably the Tohoku Tsunami [17]. Load Case 3 is assumed to occur at the maximum inundation depth, but with only 1/3 of the maximum flow velocity. Normalized time histories of flow depth and velocity are provided to determine conditions other than these load cases which may need to be considered. Design is required for both incoming and outgoing flow. Observations after the Tohoku Tsunami indicated that drawdown velocities were sometimes higher than the original inflow, resulting in buildings failing towards the ocean. More details on loading criteria are provided in a companion paper [16].

5.3 Hydrostatic Forces

Hydrostatic forces that must be considered in the structural design include buoyancy, unbalanced lateral forces when fluid loads are applied to only one side of a structural element such as a wall, and residual water surcharge loads that can apply to elevated floors during drawdown. Design equations are provided for each of these loading conditions.

5.4 Hydrodynamic Forces

Hydrodynamic loads include traditional drag forces on both the overall structure and on individual structural elements, lateral impulsive forces due to the initial impact from a tsunami bore on structural walls or other broad structural elements, pressurization of enclosed spaces due to flow stagnation, and shock pressure effects below piers and elevated floors due to entrapped bore conditions. Design equations and procedures are given for each of these conditions. In addition, a simplified design formula is available that provides a conservative check that the overall structure is able to resist the combined hydrodynamic and hydrostatic lateral load effects. If the structure passes this simplified check, it is still necessary to evaluate individual structural elements below the maximum flow level for their capacity to resist the appropriate hydrodynamic and hydrostatic loading conditions.

When considering hydrodynamic drag conditions for both the overall structure and individual exterior structural elements, it is necessary to consider the additional drag generated by the accumulation of debris against the structure. Based on observations and analysis of damaged structures during the Tohoku Tsunami [2], it was determined that the minimum percentage closure of the exposed face of a structure should be 70% for typical buildings and 50% for “open” buildings with specifically designed “tsunami breakaway walls” below the tsunami inundation level. More information is provided in a companion paper [16].

The resulting tsunami base shear on the entire structure is compared with the seismic base shear for which the lateral framing system was designed. If the tsunami base shear is less than 75% of the seismic base shear, including overstrength factor, then the system is deemed adequate to resist the tsunami loads. If the tsunami base shear exceeds this limit, then the lateral framing system will need to be enhanced to resist the tsunami loads. For most mid- to high-rise buildings in the five US western states, the high seismic design requirements are expected to provide adequate lateral load resistance for the anticipated tsunami loading [18]. However, individual structural members below the inundation level may require enhancement to resist localized tsunami load effects. A companion paper in this session provides more information on the application of the ASCE7-16 tsunami design provisions to buildings damaged by the Tohoku tsunami [19].

In order to evaluate the reliability of the ASCE7-16 tsunami design provisions, the probability of failure of an exterior load-bearing column due to hydrodynamic loading was evaluated by Chock, et al. [20]. A summary of this study is presented in a companion paper in this session [21].

5.5 Waterborne Debris Impact Forces

Tsunamis can generate a large quantity of debris, some of which can cause substantial forces when impacting a structural member. The prototypical debris that the ASCE7-16 provisions consider are utility poles/logs, shipping containers, passenger vehicles, tumbling boulders/concrete debris, and ships. Impact force equations for all of these conditions, except ships, are specified in the provisions. The impact loading expressions for logs and shipping containers are based on research performed at the University of Hawaii, Lehigh University and Oregon State University [11]. Full scale in-air impact tests at Lehigh University were shown to agree well with theoretical impact load expressions developed at the University of Hawaii [22]. The effect of water on the impact load was studied in the Large Wave Flume at Oregon State University using 1/5th scale model containers. The results show that for a longitudinal strike (which is the critical design condition), the added mass due to the surrounding water is negligible [23].

For TRC IV structures located close to a port, impact from ships must be considered. If it is unrealistic to design the structural members for impact by a ship, then it can be assumed that these members will fail. The structure must then be designed for progressive collapse prevention following the appropriate design standard.

The effect of ships and shipping containers need only be considered if the building is located in a port influence area as determined by a graphical tool provided in the standard. This tool was developed by observing the location of floating containers and boats after the Tohoku Tsunami [24].

5.6 Scour Effects

Sediment transport and scour around building foundations can result in localized and overall structural failure. Estimation of scour based on sediment transport modeling is not yet at a level where it can be recommended for design of structures. The ASCE7-16 provisions are therefore based on an empirical expression derived from field observations after numerous past tsunamis. The foundation design is required to consider at least two tsunami waves. After the first wave, the predicted scour must be assumed to have occurred around the perimeter of the building foundation. During the second wave, the structural system, including scoured foundations, must be able to resist all tsunami loads described earlier.

The ASCE7-16 Tsunami Loads and Effects provisions also provide requirements for the design of countermeasures to reduce the potential for geotechnical failures. A companion paper provides more detailed information about the design requirements for scour and sediment transport, as well as soil remediation measures to limit the scour potential [25].

6. Additional design requirements

6.1 Tsunami Vertical Evacuation Refuge Structures

The design of structures that are specifically designated as tsunami vertical evacuation refuge structures must, of necessity, be more conservative than typical construction. This is particularly important when considering the height of the refuge levels so as to minimize the potential for overtopping during an extreme event. The ASCE7-16 provisions require that a site specific tsunami inundation analysis be performed in addition to the Energy Grade Line analysis. The results of this inundation study must then be increased by 30% to cover potential uncertainties in the modeling, and an additional 3 meters (or one floor) added to this conservative height, to define the elevation required for the evacuation site. Floors and roof levels above this elevation can be used as refuge during the tsunami (see Figure 3).

All structural elements must be designed for the specified tsunami loads, considering the 30% increased flow depth, with an importance factor of 1.25 corresponding to TRC IV structures.

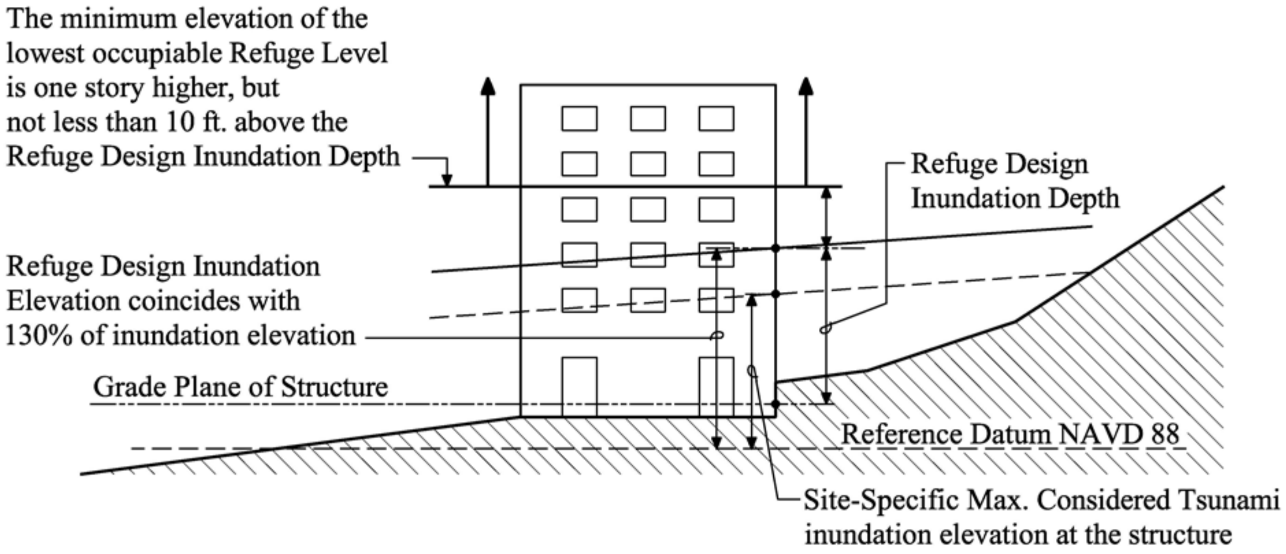

Figure 3: Elevation requirements for designated Tsunami Vertical Evacuation Refuge Structures (ASCE)

6.2 Designated Nonstructural Systems

The ASCE7-16 tsunami provisions list requirements for protection of all critical nonstructural systems within essential facilities. Alternatively, these systems can be elevated above the anticipated maximum tsunami inundation level.

6.3 Non-building Structures

The ASCE7-16 tsunami provisions also provide requirements for the design of critical non-building structures such as fuel storage facilities, industrial plants, etc. that are located within the tsunami design zone.

7. Design examples

In order to assess the economic consequences of adding tsunami design to the requirements for coastal construction, a number of mid-rise prototypical reinforced concrete and structural steel buildings were designed for various wind and seismic loading conditions, and then subjected to tsunami loading corresponding to selected locations in Hawaii and the US west coast [26, 27, 28]. More information on these and other example tsunami designs is contained in a companion paper [29].

7.2 Prototypical Reinforced Concrete Buildings

The first reinforced concrete prototypical building consisted of a 6-story office building with a Moment Resisting Frame lateral system around the exterior of the building, and interior gravity load columns supporting flat slab floors. The second reinforced concrete building was a 7-story residential structure consisting of shear walls to provide the lateral load resistance, and gravity columns supporting flat slab floors.

When designed for high seismic conditions, as are typical of all five US western states, these buildings performed very well during tsunami loading. For example, the MRF buildings required no structural enhancement when located in Monterey, California, and required only minor upgrades if located in Hilo, Hawaii. The shear wall buildings were adequate for overall lateral loading considerations, but required upgrading of the exterior gravity load columns to resist the effects of enhanced hydrodynamic drag due to debris damming. The exterior columns and any structural walls located on the exterior of the building would also require upgrading if the building was located within close proximity to a shipping container handling or storage facility due to increased floating debris impact forces.

7.3 Prototypical Structural Steel Buildings

The first structural steel prototypical building consisted of a 6-story office building with a Moment Resisting Frame lateral system around the exterior of the building, and interior gravity load columns supporting girders, joists and a composite concrete-slab-on-metal-deck floor system at each level. The second structural steel building was a 6-story residential building consisting of eccentric braced frames to provide the lateral load resistance, and gravity columns supporting composite concrete-slab-on-metal-deck floors.

When designed for high seismic conditions these buildings performed well during tsunami loading. For example, the MRF buildings required no structural enhancement when located in Monterey, California, and required only minor upgrades to the lateral framing system if located in Hilo, Hawaii. The eccentric braced frame buildings also required some upgrading of the lateral framing system, and upgrading of the exterior columns to resist the effects of enhanced hydrodynamic drag due to debris damming and impact loading. This was particularly critical if the building was located within close proximity to a shipping container handling or storage facility.

7.4 Economic Consequences of Tsunami Design

Based on the material and labor required to meet the tsunami loading requirements, the additional cost for the multi-story prototypical building designs is estimated to result in an increase of between 5 and 15 percent of the structural system construction cost. Given that the structural system is generally on the order of 25 to 30 percent of the total cost of a building, this implies only a 1 to 5 percent increase in overall building construction cost to incorporate tsunami design. It should be noted that this economic analysis assumed that the buildings were already constructed on robust deep foundations, which did not require upgrading. If the wind and seismic design were such that only shallow footings were required, then additional expense would be incurred in upgrading these foundations for tsunami scour effects. It would also be expected that taller buildings would require less upgrading for tsunami design, while lower rise buildings would require more expensive upgrades.

Although intended for use when designing new construction, the ASCE7-16 Tsunami Loads and Effects provisions could also be used to evaluate existing buildings for tsunami resistance. It would be anticipated that if retrofits are required to meet the ASCE7-16 tsunami design provisions, the costs would be greater than if tsunami design is incorporated into new construction.

8. Conclusions

In spite of considerable exposure to the damaging effects of tsunamis in the Pacific Ocean, the five US western states have not included rigorous tsunami design in any of their coastal construction. Thanks to funding from ASCE and considerable volunteer effort from dedicated members of the ASCE sub-committee on Tsunami Loads and Effects, a new chapter has been added to the ASCE7-16 Standard. This chapter provides comprehensive provisions for the design of buildings and other structures for all loading conditions anticipated during tsunami inundation. Application of these tsunami design provisions to prototypical mid-rise reinforced concrete and structural steel buildings shows that the effect on construction costs is relatively small, particularly if the structural system was already designed for high seismic conditions, as is typical for most construction around the Pacific Rim.

9. Acknowledgements

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