ASCE 7 AND THE DEVELOPMENT OF A TSUNAMI BUILDING CODE FOR THE U.S.

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Abstract

There is currently no national standard for tsunami design in the US, but that will be changing. The Tsunami Loads and Effects Subcommittee of the ASCE/SEI 7 Standards Committee is developing a proposed new Chapter 6 - Tsunami Loads and Effects for the 2016 edition of the ASCE 7 Standard. These new provisions will include loads for tsunami and its effects, and the design procedure will also incorporate certain aspects of Performance Based Tsunami Engineering. The ASCE 7 Standard classifies facilities in accordance with Risk Categories that recognize the importance or criticality of the facility. The tsunami design requirements in the ASCE 7 Standard vary by Risk Category, so that a higher level of reliability can be achieved as applied to a limited class of essential buildings, critical infrastructure, and taller buildings.

A method of Probabilistic Tsunami Hazard Analysis has been established in the recognized literature that is generally consistent with Probabilistic Seismic Hazard Analysis in the treatment of uncertainty. Structural member acceptability criteria will be based on performance objectives for a 2,500-year Maximum Considered Tsunami. It is presently anticipated that the ASCE 7 Tsunami Loads and Effects Chapter will be applicable only to the states of Alaska, Washington, Oregon, California, Hawaii, and the territories of Guam, American Samoa, and Puerto Rico. Ground shaking effects and subsidence from a preceding local offshore Maximum Considered Earthquake will also need to be considered prior to tsunami arrival for Alaska and states in the Pacific Northwest regions governed by nearby offshore subduction earthquakes.

Introduction

A national standard for engineering design for tsunami effects does not presently exist. Presently, tsunami risk to coastal zone construction is not explicitly and comprehensively addressed in design codes of the United States. Beginning from February, 2011, the Tsunami Loads and Effects Subcommittee of the ASCE/SEI 7 Standards Committee has been developing a proposed new Chapter 6 - Tsunami Loads and Effects, with Commentary for the 2016 edition of the ASCE 7 Standard, *Minimum Design Loads for Buildings and Other Structures*, These new provisions would provide prescriptive loads for tsunami and its effects, and the analysis procedure will also incorporate aspects of Performance Based Tsunami Engineering (Chock, 2011).

The International Building Code (IBC) references design provisions that are given in American Society of Civil Engineers Standard 7. The ASCE 7 Standard becomes part of an enacted building code law through adoption of the model International Building Code by the local authority having jurisdiction (such as a state, county, or city). The IBC will probably incorporate ASCE 7-16 in 2018 or 2021. Therefore, it is anticipated that the first national tsunami design provisions of ASCE 7 would be utilized as a part of mandatory building codes of U.S. jurisdictions after 2020.

In this paper we provide a preview emphasizing the intent of these developing code provisions (subject to final revision) and explain the design methodology.

Overview of the Proposed ASCE-7 Tsunami Loads and Effects Chapter

Organization: The ASCE 7 Tsunami Loads and Effects chapter has been organized into the following sections:

6.1 General Requirements
6.2 Definitions
6.3 Symbols and Notation
6.4 General Tsunami Design Criteria
6.5 Procedures for Tsunami Hazard Assessment
6.6 Procedures for Tsunami Inundation Analysis
6.7 Design Parameters for Tsunami Flow over Land
6.8 Structural Design Procedure for Tsunami Effects
6.9 Hydrostatic Loads
6.10 Hydrodynamic Loads
6.11 Impact Loads
6.12 Foundation Design
6.13 Structural countermeasures for reduced loading on buildings
6.14 Special Occupancy Structures
6.15 Designated Nonstructural Systems (Stairs, Life Safety MEP)
6.16 Non-building critical facility structures

General Requirements and Design Criteria: Mitigation of tsunami risk requires a combination of emergency preparedness for evacuation in addition to providing structural resilience of critical facilities, infrastructure, and key resources necessary for immediate response and economic and social recovery. Critical facilities would include emergency response, medical, tsunami refuges and shelters, ports and harbors, lifelines, transportation, telecommunications, power, financial institutions, and major industrial/commercial facilities. The ASCE 7 Standard (ASCE, 2010) classifies facilities in accordance with Risk Categories that recognize the importance or criticality of the facility (Table 1). In the tsunami chapter, further definitions of Risk Categories for Risk Categories III and IV are given with respect to specific occupancy/functional criteria.

Table 1. Risk Categories of Buildings and Other Structures per ASCE 7

Risk Category I	Buildings and other structures that represent a low risk to humans
Risk Category II	All buildings and other structures except those listed in Risk Categories I, III, IV
Risk Category III	Buildings and other structures with potential to cause a substantial economic impact and/or mass disruption of day-to-day civilian life in the event of failure.
Risk Category IV	Buildings and other structures designated as essential facilities

Tsunami design performance objectives are somewhat similar, but different in certain respects from typical Seismic Performance objectives. What is common in concept is that there are means to generate estimated hazard levels and building performance levels. In Table 2, the key performance levels are shown for two return periods, the 100-year period and a maximum considered 2,500-year event consistent with U.S. seismic provisions.

The proposed tsunami design requirements in the ASCE 7 Standard vary by Risk Category and height. When communities with public awareness are enabled with tsunami warning systems with emergency operations plans for evacuation, Risk Category II and III buildings are not intended to be occupied during a tsunami. For Risk Category IV essential facilities that may necessarily exist within a coastal zone subject to tsunami hazard, an adequate set of design provisions should be capable of addressing the hydrostatic, hydrodynamic, waterborne debris accumulation and impact loads, subsidence, and scour effects generated by the preceding earthquake and the subsequent tsunami flow conditions. The design limit for the 2,500-year event would be based on the inelastic capacity of structural members.

A minimum height would define the range of taller Risk Category II buildings where tsunami design would be required. Based on analysis of reinforced concrete buildings, a threshold of ~20 m (65 ft.) has been recommended as the height sufficient for both reliable life safety and reasonable economics. A Tsunami Vertical Evacuation Refuge is a structure designated to serve as a point of refuge to which a community's population can evacuate above a tsunami when high ground is not available. Shorter Risk Category II buildings would not be subject to tsunami structural design requirements; these low-rise buildings would be at higher risk of being fully inundated, and therefore they should not be considered occupiable during a tsunami.

Table 2. Proposed Tsunami Performance Levels for Various Occupancies

Hazard	**Tsunami Performance Level**			
Tsunami Frequency	**Operational**	**Immediate Occupancy**	**Life Safe**	**Collapse Prevention**
Occasional (100 years)	Risk Category IV	Risk Category II and III		
Maximum Considered (2500 yrs)		Vertical Evacuation Refuge Buildings	Risk Category IV	Risk Category III and > 65-ft.-high Risk Category II

Definitions Key terms for tsunami definition are offshore tsunami height, inundation depth, runup elevation, and maximum (horizontal) inundation limit. Offshore Tsunami Height is measured where the water depth is 100 meters. Inundation Depth is the depth of tsunami water level with respect to the local grade plane. Runup Elevation is the elevation above mean sea level at the tsunami inundation limit. Maximum Inundation Limit is the maximum horizontal extent of the inundation zone relative to the shoreline at Mean Sea Level. There key parameters are illustrated in Figure 1.

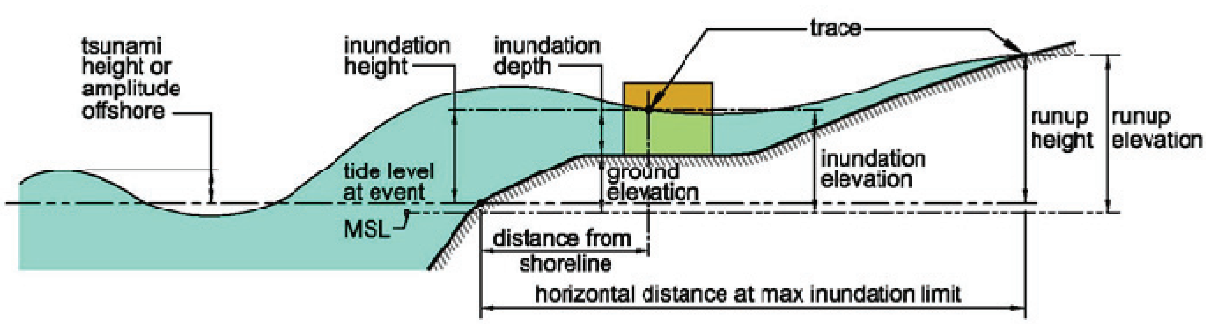

Figure 1. Illustrated tsunami terminology

The Tsunami Hazard Zone is the area vulnerable to being flooded or inundated by the Maximum Considered Tsunami, which is taken as having a 2% probability of being exceeded in a 50-year period, or a 2500 year average return period. The Maximum Considered Tsunami is the design basis event used for design, consisting of the inundation depths and flow velocities at the stages of in-flow and out-flow most critical to the structure.

General Tsunami Design Criteria: As noted above, buildings and structures would have their structural performance objective defined based on height and Risk Category, per one of the following performance level objectives.

> IMMEDIATE OCCUPANCY STRUCTURAL PERFORMANCE: The post-event damage state in which a structure remains safe to occupy
>
> LIFE SAFE STRUCTURAL PERFORMANCE: The post-event damage state is that in which a structure has damaged components but retains a margin against onset of partial or total collapse.
>
> COLLAPSE PREVENTION STRUCTURAL PERFORMANCE: The post-event damage state is which a structure has damaged components and continues to support gravity loads but retains little or no margin against collapse.

It is important to understand that building failure modes differ fundamentally between seismic (high frequency dynamic effects generated on the inertial masses of a structure) and tsunami (externally and internally applied sustained fluid forces varying with stages depth over long period cycles of load reversal). Tsunami forces are not proportional to building mass. Tsunami-induced failure modes of buildings have been examined in several detailed analyses of case studies taken from the Tohoku Tsunami of March 11, 2011 (Chock, et al, 2013). In essence, the building components are subject simultaneously to internal forces generated by the external loading on the lateral-force-resisting system together with high intensity momentum pressure forces exerted on individual members. Because of these differences, prescriptive "R" scalar reduction factors used by historical custom almost exclusively in the U.S. seismic code do not capture the failure modes observed. The tsunami provisions must maintain the physical consistency of tsunami flow conditions with respect to runup, inundation depth and associated current velocities, and use of a single scalar factor applied on depth, current, or force violates fluid mechanics.

It is presently anticipated that the ASCE 7 Tsunami Loads and Effects Chapter will be applicable only to the states of Alaska, Washington, Oregon, California, Hawaii, and the territories of Guam, American Samoa, and Puerto Rico; these regions have quantifiable hazards due to tsunamigenic earthquakes. Regions governed by nearby offshore earthquakes structure will need to resist the design earthquake , prior to the arrival of the design tsunami inundation. For the Pacific Northwest (Geist, 2005) and Alaska, this necessarily includes consideration of ground shaking effects and subsidence from the preceding local offshore subduction earthquake. Tsunami design must also enable a multi-hazard performance-based analysis technique with the ability to evaluate primary members both ductility for initial dynamic earthquake loading and the demand of sustained tsunami hydrodynamic fluid forces on the remaining structural capacities after an near-field subduction earthquake.

To do this analysis of performance, we propose to utilize the Analysis Procedures and Acceptance Criteria of ASCE 41 (ASCE, 2006), *Seismic Rehabilitation of Existing Buildings*. With an adaptation of this method, strength and stability can be checked to determine that the design of the structural components are capable of withstanding the tsunami to achieve the Structural Performance level required. The tsunami adaption allows the techniques of the Linear Static Procedure and the Nonlinear Static Procedure. Lower bound strengths of structural components can then be checked using the ASCE 41 acceptability criteria for actual tsunami loads and depths that are correct from the standpoint of fluid mechanics without load factors. In the case of a preceding local earthquake, the reduction of structural capacity can be conservatively accounted for with this technique. Where tsunami loads or effects exceed acceptability criteria for a structural element, it shall be permitted as an alternative to apply progressive collapse provisions of UFC 4-023-03, Design of Structures to Resist Progressive Collapse, (DoD, 2009). Utilizing the performance-based component acceptability criteria in ASCE/SEI 41-06, , the performance objective for code-defined essential facilities should be at least Immediate Occupancy performance for the Design Basis Earthquake (DBE) and Life Safety performance for the Maximum Considered Earthquake (MCE).

Deformation-Controlled Actions in primary and secondary components shall satisfy Eq. 1

$$mQ_{CE} \geq Q_{UD} \qquad \text{(Eq. 1)}$$

Force-Controlled Actions in primary and secondary components shall satisfy Eq. 2

$$Q_{CL} \geq Q_{UF} \qquad \text{(Eq. 2)}$$

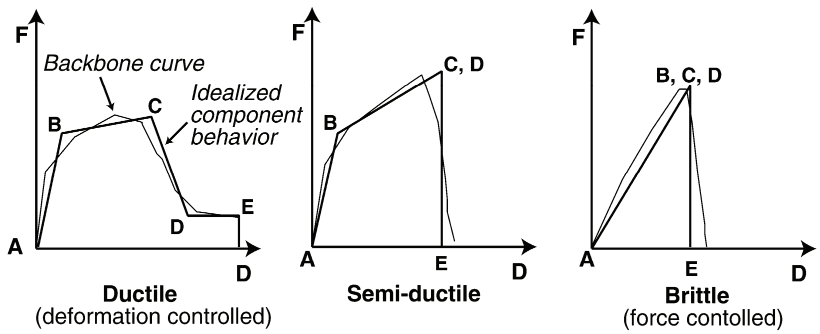

Figure 2. A sample figure of force-displacement capacity boundaries of component behavior.

Loading shall consider a minimum of two tsunami in-flow and out-flow cycles, one of which shall be at the maximum design level. This is required because the condition of the building and its foundation is altered in each load reversal and through each tsunami inflow and out-flow cycle. Building foundation designs shall consider changes in the site surface and the in-situ soil properties during the design seismic event and subsequent design tsunami event. Foundation effects in the geotechnical investigation report shall include consideration of slope instability, liquefaction, total and differential settlement, subsidence, and surface displacement due to faulting or seismically induced lateral spreading or lateral flow.

Procedures for Tsunami Hazard Assessment: Probabilistic Tsunami Hazard Analysis shall be used to determine the offshore tsunami height for the 100-year and Maximum Considered Tsunami. A method of probabilistic tsunami hazard analysis has been established in the recognized literature that is generally consistent with probabilistic seismic hazard analysis in the treatment of uncertainty (Geist and Parsons, 2006). A 2,500-year hazard level Maximum Considered Tsunami is selected for consistency with ASCE 7 seismic hazard criteria with tsunami as a coseismic effect .The runup for this hazard probability is used to define a map the tsunami hazard zone. Another return period of 100-years for the occasional low-level tsunami that aligns better with flood criteria, since there will be a desire to compare the two effects for the elevation of the structure. An example of the probabilistic tsunami hazard analysis technique has been performed for California (Thio, 2010). The basics of Probabilistic Tsunami Hazard Analysis for a region are as follows:

1. Tsunamigenic subduction zones and non-subduction seismic thrust faults are discretized into a compiled system of rectangular subfaults each with corresponding tectonic parameters.
2. Tsunami waveform generation is modeled by deconstructing a tsunami that is generated by an earthquake into a linear combination of individual tsunami waveforms from a set of subfaults that describe the earthquake rupture in location, orientation, and rupture direction and sequence.
3. A statistically weighted logic tree approach is used to account for variations in the model parameters for tsunamigenic earthquake occurrence probabilities from tectonic, geodetic,

historical, and paleo-tsunami data, and estimated plate convergence rates.
4. Propagate tsunamis in deep water using the linear long wave equations to take into account spatial variations in seafloor depth.
5. Determine the highest offshore wave heights at 100m depth, period, and depth-averaged celerity for the design level exceedance rates of the 100-year and the 2,500-year tsunami.
6. Disaggregate the seismic sources and associated moment magnitudes that together contribute at least 90% to the net offshore tsunami hazard at the site under consideration for each design level.

Procedures for Tsunami Inundation Analysis: Analyze each disaggregated tsunami event to determine representative design parameters (max height, depth, velocity, and flux). Regardless of soil type, the Maximum Considered Tsunami inundation shall assume an overall elevation settlement of 3 feet of the inundated region when local subduction thrust faulting is the tsunamigenic mechanism that contributes at least 90% to the net offshore tsunami hazard at the site.

7. Use nonlinear shallow water wave equations to modeling regime from 100m depth towards the shore to transform the probabilistically defined offshore height to maximum inundation. The following effects shall be included as applicable to the bathymetry:
    a. Shoaling to determine peak nearshore tsunami height
    b. Dispersion effects
    c. Resonance waves in bays
    d. Fringing submerged reefs and shelves
    e. Reflected waves
    f. Soliton fission of short period undular waves in gradually sloping offshore bathymetry
    g. Channeling in bays
    h. Shelf and bay resonances
    i. Bore formation and propagation
8. Analyze each tsunami event from the disaggregated sample to determine representative parameters. Manning's coefficient for equivalent terrain macro-roughness is used to account for friction. Maximum. runup, inundation depth, flow velocity, and specific momentum flux is permitted to be evaluated by either of the following techniques:
    a. by taking the weighted average of the scenario runs that bracket the offshore waveheight for the return period,
    b. by developing the probabilistic distributions of flow parameters from the sample of computed tsunamis and construct the statistical distributions of flow parameters for at least four critical stages.
9. From the probabilistic events, capture the design flow parameters of inundation depth, flow velocity, and specific flux at the site of interest.

Design Parameters for Tsunami Flow over Land: Where the coastline can be approximated in behavior by the use of one-dimensional linear transects of a composite bathymetric / topographic profile, in lieu of steps 7, 8, and 9 above, the tsunami inundation design parameters of minimum runup, momentum flux, and range of current are permitted to be estimated by prescriptive analytical formulations for substantially uniform sloped topographic profiles, or by an energy analysis approach for terrain that can be idealized as a series of linear sloped segments. Forces determined with the prescriptive analysis are required to be increased by an Importance Factor depending on the Risk Category. In the energy approach, the potential energy budget of the tsunami is first represented by the theoretical runup at the shoreline on a landward extension of the nearshore bathymetric slope. Then hydraulic analysis using Manning's coefficient for equivalent terrain macro-roughness is used to account for friction along with the profile of a series of 1-D slopes to determine the variation of high velocity-associated inundation depth across the inland profile. Velocity is assumed to be a function of inundation depth, calibrated to the prescribed Froude number.

If only maximum tsunami depth at the site can be estimated, for Risk Category II buildings and structures a conservative simplified pseudo-hydrostatic lateral pressure can be applied to the structure to represent the effect of hydrodynamic flow on the structure. It is determined using the maximum inundation depth with a fluid density of three times that of seawater. This simplified method is similar to the approach taken in Japan using the Structural Design Method of Buildings for Tsunami Resistance (Okada et al, 2004). For the simplified pressure, conventional strength design procedures could be used if only Life Safety Structural Performance is required.

Structural Design Procedure for Tsunami Effects: Four stages of tsunami surge loading defined by inundation depths and their associated velocities are required to be considered. A normalized depth and depth-averaged flow current time-history graph is provided to define these four stages:

1. Near-maximum momentum flux when depth is one-quarter of maximum
2. Two-thirds of maximum inundation depth
3. Maximum water depth when velocity is zero
4. Return flow when depth is one-third of maximum

As an Extraordinary Event, per ASCE 7 Section 2.5 (ASCE, 2010), the appropriate load combinations are shown below.

$$1.2D + - 1.0F_{TSU} + 0.25L + 0.2S$$
$$0.9D + - 1.0F_{TSU}$$

For a distant tsunami, the available strength could be up to the yield point or a post-yield hardening point, depending on the desired performance. When a local subduction zone governs both the design seismic and tsunami events, the acceptable solution point on the force-displacement capacity boundary can only be found to the right of the solution for the preceding earthquake effect 1.0E. The available strength for tsunami resistance would thus account for any strength and stiffness degradation caused by the preceding earthquake. This is conceptually illustrated in Figure 3.

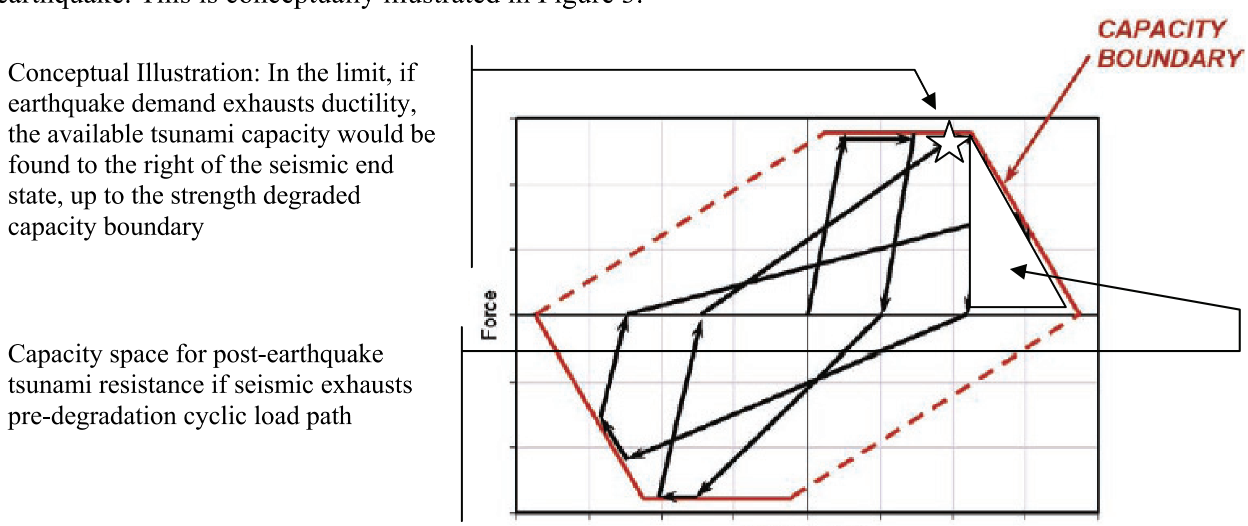

Figure 3 Earthquake load path and force-displacement capacity available for tsunami (adapted from FEMA P440A Figure 2-14)

Structural Loads

The following tsunami load effects should be considered for structural design of buildings and structures:

- hydrostatic forces, buoyant forces, and additional fluid gravity loads from retained water;
- hydrodynamic forces and hydrodynamic uplift forces;
- debris impact forces and debris damming forces
- foundation scour and pore pressure softening effects on the soil

The structural details of numerous damaged buildings in the Tohoku region were documented soon after the March 11, 2011 Tohoku-Oki earthquake and tsunami by a reconnaissance team sponsored by the American Society of Civil Engineers. Tsunami flow depths and velocities were determined based on analysis of video records and the observed effects on simple benchmark structures in the flow. Equations for various conditions of fluid loading were then validated through failure analyses completed for several buildings using finite element modeling and LiDAR scans. These analysis tools were applied full-scale to buildings with clearly identified failure mechanisms to validate the tsunami loading provisions in the ASCE 7 Standard (Chock, 2013).

Hydrostatic Loads: Reduced net self-weight due to buoyancy shall be considered for all inundated structural and non-structural elements of the building. Uplift due to buoyancy shall include enclosed spaces without breakaway walls that have opening area less than 25% of the inundated exterior wall area. Buoyancy shall also include the effect of air trapped below floors, including foundation slabs, and in enclosed spaces where the walls are not designed to break away. Structural walls with openings less than 10% of the wall area and either longer than 30 feet without adjacent breakaway walls or having a two- or three sided structural wall configuration regardless of length shall be designed to resist an unbalanced hydrostatic lateral force during inflow. All horizontal floors below the maximum inundation depth shall be designed for dead load plus a residual water surcharge load to the extent that internal impounded water cannot escape in sufficient time.

Hydrodynamic Lateral Loads: The building lateral framing system shall be designed to resist the overall drag force developed either by in-coming or out-going flow surge. Likewise, the lateral hydrodynamic pressure load shall be applied at the mid-height of the projected area of all structural elements and enclosure component assemblages below the flow depth. Slab hydrodynamic uplift pressure shall be applied to sections where entrapped flow occurs. Where enclosed spaces exist within the building that prevents flow through the section, hydrodynamic flow stagnation internal pressure shall be applied.
For nearshore bathymetric slopes that are shallow, or in the presence of reef discontinuities, tsunami bore solitons shall also be considered superimposed on the hydrodynamic surge. Instantaneous hydrodynamic loads created by bore impact can be severe (Robertson, et al, 2011). At locations specified in accordance with offshore bathymetry, bore impact forces on walls and slabs shall be considered in addition to hydrodynamic drag.

Loads on buildings shall be calculated assuming a minimum closure ratio of 67% of the pressure exposed surface area of the exterior enclosure; this accounts for accumulated waterborne debris as well as trapped against the side of the structure as well any internal blockage caused by building contents that cannot easily flow out of the structure. As a practical matter based on observations of buildings subjected to destructive tsunami, “breakaway” walls cannot be relied upon to relieve structural loading, primarily due to the copious amount of external debris. Also, studs and girts may be capable of entrapping contents within a building, thus generating hydrodynamic drag forces on the internal debris that in turn transfer those loads to the structure.

Impact Loads: Waterborne debris impact is applied to any perimeter structural element of the gravity-load-carrying system within the inundation depth at the site. A 1,000-lb. log impact, a floating passenger vehicle force of 6,000 lbs., and a 2,000-lb. submerged tumbling boulder (or concrete mass debris) impact shall be assumed to impact perimeter vertical structural elements of the gravity-load-carrying system. For buildings and other structures within 1,500 ft. of a shipping port, a shipping container impact on perimeter vertical structural elements of the gravity-load-carrying system shall be assumed to occur. For Risk Category IV buildings and structures adjacent to piers and wharves, an extraordinary mass impact (such as a large ship) on perimeter vertical structural elements of the gravity-load-carrying system shall be assumed to occur.

Foundation Design: Design of structure foundations and tsunami barriers shall consider changes in the site surface and in-situ soil properties during the design tsunami and provide capacity to support the structural loads. Local scour calculations shall evaluate the effects of sustained flow shear, which can be enhanced by pore pressure softening, and both effects can be prescriptively determined using Table 3. For near source tsunami hazards, the in-situ soil and site surface condition at the onset of tsunami loads shall be those determined existing at the end of seismic shaking, including liquefaction, lateral spread and fault rupture. The minimum factor of safety shall be 1.2 for potential failure limits impacting foundations (bearing capacity, uplift, lateral pressure, internal stability, slope stability).

Table 3. Design Local Scour Depth due to Sustained Flow Shear and Pore Pressure Softening

Flow Depth h	Scour Depth D*
< 10 ft.	0.6 × h
10 to 50 ft.	6 ft. + 0.2 × (h – 10 ft.)
> 50 ft.	14 ft.

* Not applicable to scour of sites with intact rock strata

Special Occupancy Structures: Vertical Evacuation Refuge Structures are a special classification of buildings and structures within the tsunami evacuation zone designated as a means of alternative evacuation in communities where sufficiently high ground does not exist or where the time available after the tsunami warning is not deemed to be adequate for full evacuation prior to tsunami arrival. Such a building or structure must have the strength and resiliency needed to resist all effects of the maximum considered tsunami. Despite the devastation of the March 11, 2011 Tohoku Tsunami along the northeast coastline of Honshu island of Japan, there were many tsunami evacuation buildings that provided safe refuge for thousands of survivors (Fraser, et al, 2012). In the U.S., FEMA P646 (Applied Technology Council, 2012) exists as a set of guidelines but is not written in mandatory language necessary for building code and design standards. Therefore, the ASCE 7 Standard would incorporate the technical requirements for such structures, utilizing P646 as a pre-standard reference. A particularly important consideration is the elevation and height of the refuge, since it must provide structural life safety for the occupants within a portion of the refuge that is not inundated. Therefore, additional conservatism is necessary in the estimation of inundation height. The recommended minimum elevation for a tsunami refuge area is, therefore, the maximum considered tsunami runup elevation anticipated at the site, plus 30%, plus 10 feet (3 meters), as illustrated in Figure 3.

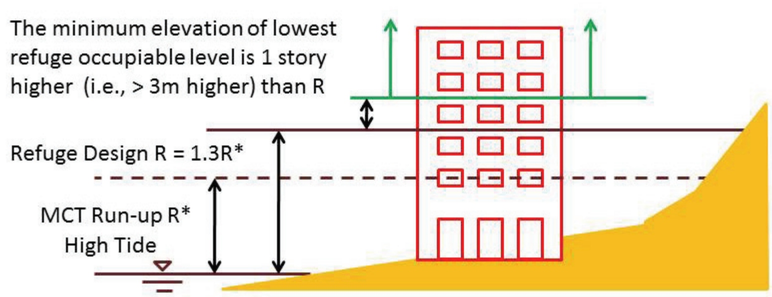

Figure 3. Minimum Refuge Elevation

For the Pacific Northwest and Alaska, design necessarily includes consideration of ground shaking effects and subsidence from a preceding local offshore subduction earthquake, prior to the arrival of the design tsunami inundation. To help ensure adequate strength and ductility in the structure for resisting tsunami load effects, Seismic Design Category D, as defined in ASCE/SEI 7-10, should be assigned to the structure, as a minimum. The tsunami evacuation refuge should have a post-earthquake seismic performance objective of Immediate Occupancy prior to the tsunami arrival in order to receive evacuees and to have sufficient margin remaining to resist sustained tsunami loads. The overall capacity of the lateral-load-resisting system can be checked using its overstrength factor, Ω. In multi-story buildings greater than about four stories tall, once the Immediate Occupancy seismic design objective is utilized at the Maximum Considered Earthquake hazard level, most of the overall systemic lateral strength necessary will have been provided for tsunami resistance to the Maximum Considered Tsunami resulting from that event. However, structural components may need local "enhanced resistance" and ground level shear walls may also require localized detailing for out-of-plane hydrodynamic forces or pressurization effects. (Chock, et al, 2012). Because the tsunami evacuation refuge is assumed to be occupied at the designated levels during the event, load combinations for refuge structures are modified to the following:

- Load Combination 1: $1.2D + - 1.0F_{TSU} + 1.0L_{Refuge} + 0.25L_{Non\text{-}refuge} + 0.2S$
- Load Combination 2: $0.9D + - 1.0F_{TSU}$

Conclusions

- A method of probabilistic tsunami hazard analysis has been established in the recognized literature that is generally consistent with probabilistic seismic hazard analysis in the treatment of uncertainty.
- Methodologies for 2D tsunami inundation modeling have been further developed and utilized for various designated communities and regions.
- Structural loading and analysis techniques for determining building performance have been developed. Experimental and field validation studies of these techniques have been performed.
- Measures of seismic performance in the inelastic range have been developed that appear to have relevant application for tsunami performance metrics.
- Analysis procedures for regions governed by local subduction earthquakes involves a multi-hazard performance-based approach to provide both ductility for dynamic earthquake loading and remaining strength for sustained hydrodynamic fluid forces
- The proposed ASCE 7 provisions for Tsunami Loads and Effects enables a set of analysis and design methodologies that are consistent with tsunami physics and performance based engineering.

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