The ASCE 7 Tsunami Loads and Effects Design Standard for the U.S.

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ABSTRACT: Many coastal areas in the U.S. are subject to tsunami hazard. The public safety risk has been partially mitigated through warning and preparedness of evacuation, but community disaster resilience requires that critical and essential facilities provide structural resistance to collapse. Furthermore, there are coastal communities in the states of Alaska, Washington, Oregon, California, and Hawaii where there is insufficient time for evacuation. Towards the goal of disaster resilience, the American Society of Civil Engineers/Structural Engineering Institute has developed a new chapter on tsunami loads and effects for the 2016 edition of the ASCE/SEI 7 Standard. Chapter 6 of the ASCE 7-16 Standard, Minimum Design Loads for Buildings and Other Structures, provides loads and other requirements for tsunami and its effects. The ASCE 7-16 Tsunami Loads and Effects chapter is applicable for use in the states of Alaska, Washington, Oregon, California, and Hawaii. The new ASCE 7 provisions for Tsunami Loads and Effects implements a unified set of analysis and design methodologies that are consistent with probabilistic hazard analysis, tsunami physics, and structural target reliability analysis. The purpose of this paper is to provide an overview of the technical basis and methodology for tsunami-resilient design of critical and essential facilities, taller building structures, and tsunami evacuation refuge structures.

INTRODUCTION

The recent catastrophic tsunamis in the Indian Ocean (2004), Samoa (2009), Chile (2010) and Japan (2011) indicate that an explicit structural design procedure for risk mitigation of tsunami damage to major structures is much needed. The public safety risk has been partially mitigated through warning and preparedness of evacuation, but community disaster resilience requires that critical and essential facilities provide structural resistance to collapse. Furthermore, there are coastal communities in the states of Alaska, Washington, Oregon, California, and Hawaii where there is insufficient time for evacuation. The 2016 edition of the ASCE 7 Standard, Minimum Design Loads for Buildings and Other Structures, introduces a new Chapter 6 – Tsunami Loads and Effects.
TSUNAMI HAZARD

The lesson of recent catastrophic tsunamis is that historical records alone do not provide a sufficient measure of the potential heights of future tsunamis. Engineering design must consider the occurrence of events greater than scenarios in the historical record, based on the underlying seismicity of subduction zones. For U.S. national tsunami design provisions, Probabilistic Tsunami Hazard Analysis (PTHA) was performed to achieve a consistent reliability standard of structural performance. PTHA generates large probabilistic catalogs of tsunami waveforms directly from the source mechanisms in accordance with logic tree probabilities for each possible subduction source mechanism (e.g., slip distribution and extent of rupture) consistent with their estimated plate convergence rates, and propagates these waveforms to the offshore regimes of the coastlines (Figure 1).

PTHA results are embodied in Offshore Tsunami Amplitude maps. The ASCE Standard defines the Offshore Tsunami Amplitude above the ambient sea level of a probabilistic Maximum Considered Tsunami at a standardized offshore depth of 100 meters. These hazard maps are defined at a bathymetry water depth contour of 100m offshore in order to document the regional probabilistic tsunami hazard. The Tsunami Design 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 2,475 year mean recurrence interval. The Maximum Considered Tsunami events are of comparable probability to the Maximum Considered Earthquake of the ASCE 7seismic design provisions.

FIG. 1 Probabilistic Tsunami Hazard Analysis and Maps

Key parameters controlling tsunami design criteria are Inundation Depth, Runup elevation, and the (maximum horizontal) Inundation Limit. Inundation Depth is the depth of tsunami water level with respect to the local grade plane. Inundation Limit is
the maximum horizontal extent of the inundation zone relative to the shoreline. Runup Elevation is the elevation above reference datum at the tsunami Inundation Limit. These key parameters are illustrated in Figure 2. The runup for the MCT is used to define a Tsunami Design Zone map. Procedures for tsunami inundation analysis are based on using these design map values of Offshore Tsunami Amplitude or the Runup and Inundation Limit from the Tsunami Design Zone Map.

![FIG. 2 Illustrated ASCE tsunami terminology](image)

**PERFORMANCE OBJECTIVES**

Tsunami Risk Category III and Tsunami Risk Category IV buildings and other structures located in the tsunami-prone states of Alaska, Washington, Oregon, California, and Hawaii shall be designed to resist the tsunami loads and effects determined for a Maximum Considered Tsunami. The tsunami design requirements in the ASCE 7 Standard vary by Tsunami Risk Category, so that a higher level of reliability can be achieved when applied to essential buildings, critical infrastructure, and taller buildings. In Table 1, the key performance levels are shown for the Maximum Considered Tsunami. A Tsunami Vertical Evacuation Refuge is a Risk Category IV structure designated to serve as a point of refuge to which a portion of a community’s population can evacuate above a tsunami when high ground is not available in time.

**Table 1 Tsunami Performance Levels per Risk Category**

<table>
<thead>
<tr>
<th>Hazard Level</th>
<th>Performance Level Objective</th>
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<tbody>
<tr>
<td>Maximum Considered Tsunami</td>
<td>Immediate Occupancy</td>
</tr>
<tr>
<td>2,475 year mean recurrence interval</td>
<td>Tsunami Vertical Evacuation Refuge Structures</td>
</tr>
<tr>
<td></td>
<td>Damage Control</td>
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<tr>
<td></td>
<td>Risk Category IV and Risk Category III Critical Facilities</td>
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<tr>
<td></td>
<td>Collapse Prevention</td>
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<tr>
<td></td>
<td>Risk Category III (and Taller Risk Category III)</td>
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</tbody>
</table>
Critical Facilities provide services that are designated by federal, state, local, tribal
governments to be essential for the implementation of the response and recovery
management plan or for the continued functioning of a community, such as facilities
for power, fuel, water, communications, public health, major transportation
infrastructure, and essential government operations. Critical facilities comprise all
public and private facilities deemed by a community to be essential for the delivery of
vital services, protection of special populations, and the provision of other services of
importance for that community. Essential Facilities are primarily those facilities
necessary for immediate emergency response and do not include all Critical
Facilities; they are Risk Category IV.

The provisions do not apply to single-family homes and other low-rise Risk Category
II structures. The local government may also decide to enforce tsunami-resilient
design requirements for taller Risk Category II buildings with mean heights above a
specified mean height threshold above grade plane, depending on their community’s
tsunami hazard, tsunami response procedures, disaster resilience goals, and zoning
requirements. Within these circumstances of risk, the availability of taller buildings
that are tsunami resistant is a direct benefit to public safety. An analysis of
prototypical multi-story reinforced concrete and structural steel buildings (Chock, G.
et al. (2013a) demonstrated that 65-ft.-tall buildings subject to the higher Seismic
Design Category D requirements would typically have sufficient systemic strength
for overall lateral tsunami forces without any upgrade, assuming tsunami inundations
commensurate with the Cascadia Subduction Zone of the Pacific northwest. In
California, lesser heights become generally sufficient to achieve parity of the required
tsunami systemic resistance with the systemic strength already provided by the
seismic design, which is an indication of nominal economic costs.

ANALYSIS OF DESIGN INUNDATION DEPTH AND VELOCITY

There are two procedures for determining the flow depth and velocities at a site. The
Energy Grade Line Analysis takes the runup elevation and inundation limit indicated
on the Tsunami Design Zone map as the given solution point of a hydraulic analysis
along the topographic transect from the shoreline to the runup point. Two-
dimensional Site-Specific Inundation Analysis utilizes the Offshore Tsunami
Amplitude, an effective wave period that is considered a conserved property, and
other waveform shape parameters as the input; this is a numerical simulation that
includes a high-resolution digital elevation model of nearshore bathymetry and
onshore topography. The purpose of performing a Site-Specific simulation is to
capture 2-dimensional flow and directionality effects that the linear transect analysis
of the Energy Grade Line Analysis cannot, and so it is particularly useful as an
additional due diligence investigation of flow characteristics for Tsunami Risk
Category IV structures. Because of this, tsunami vertical evacuation refuge structures
shall always utilize the Site-Specific procedure, regardless of the flow depth
calculated by the Energy Grade Line Analysis.
The Energy Grade Line Analysis, which has been developed to produce conservative design flow parameters, is always performed for Tsunami Risk Category II, III and IV structures. The Site-Specific Inundation Analysis may or may not be required, depending on the structure’s Tsunami Risk Category. This procedure is not required for, but may also be used for Tsunami Risk Category II and III structures. It is performed for Tsunami Risk Category IV structures unless the Energy Grade Line Analysis shows the inundation depth to be less than 12 ft. (3.7 m) at the structure.

Where the coastal area terrain can be approximated by the use of one-dimensional linear transects of a composite bathymetric / topographic profile, the design parameters of maximum inundation depth and flow velocity are calculated by the Energy Grade Line Analysis of the terrain idealized as a series of linear sloped segments. The Energy Grade Line Analysis is a procedure based on hydraulic principles applied along a profile comprised of a series of 1-D slopes, using Manning’s coefficient for equivalent terrain macro-roughness to account for the friction slope of the energy grade line (illustrated in Figure 3).

FIG. 3 Illustration of the Energy Grade Line Analysis

The Energy Grade Line determines the variation of inundation depth and associated flow velocity across the inland profile. Velocity is assumed to be a function of inundation depth, calibrated to the Froude number that is prescribed to decay gradually based on distance from the shoreline along the transect, calculated according to Eq. (1).

\[ F_r = \left(1 - \frac{x}{x_R}\right)^{1/2} \]  

(1)

STRUCTURAL DESIGN FOR TSUNAMI EFFECTS

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, 2013b). Building components are simultaneously subjected 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. For structural components along the perimeter of the building, dynamic impacts from debris must also be evaluated.

The following tsunami effects are considered for structural design of structures:
- hydrostatic forces, buoyant forces, and additional fluid gravity loads from retained water
- hydrodynamic forces and hydrodynamic uplift forces
- debris impact forces
- foundation scour and pore pressure softening effects on the soil

The effect of flow laden with small debris is accounted for with an increased effective fluid density. Debris accumulation against the structure is accounted for by a minimum closure (blocking) ratio. Flow directions other than along a principal transect are also considered. Tsunami inflow and outflow cycles are specified to include load reversal as well as scour effects that may occur due to an initial wave prior to a subsequent wave loading. Loading should consider a minimum of two tsunami in-flow and out-flow cycles, the second of which should be at the maximum design level.

Internal actions in structural components of the lateral-load-resisting system that result from the overall tsunami forces applied on the building or structure should be combined with any resultant actions caused by the tsunami pressures that directly act locally on the same individual structural components for that direction of flow. Regardless of whether they are elements of the lateral-force-resisting system, structural components may need local “enhanced resistance”, and shear walls at lower stories may also require localized detailing for out-of-plane hydrodynamic forces or pressurization effects.

The tsunami provisions must maintain the physical consistency of tsunami flow conditions with respect to runup, inundation depth and associated current velocities. A normalized depth and depth-averaged flow speed prototypical time-history graph is provided to define these three load cases, as shown in Figure 4. Three cases of tsunami loading defined by inundation depths and the associated velocities are required to be considered:
1. The minimum condition of combined hydrodynamic force with buoyant force shall be evaluated at an inundation depth not exceeding the maximum inundation depth nor the lesser of one-story or the height of the top of the first story windows.
2. Two-thirds of maximum inundation depth when velocity is near maximum, in each direction
3. Maximum water depth when the flow velocity is assumed to be at one-third of maximum, in each direction
Structures and structural components shall be designed for the Tsunami Forces and Effects, $F_{TSU}$, as specified in the load combinations of Eq. (2) and Eq. (3):

$$0.9D + F_{TSU} + H_{TSU}$$  \hspace{1cm} (2)
$$1.2D + F_{TSU} + 0.5L + 0.2S + H_{TSU}$$  \hspace{1cm} (3)

where,

- $F_{TSU}$ = tsunami load effect for incoming and receding directions of flow
- $D$ = Dead Load;
- $L$ = Live Load;
- $S$ = Snow Load; and
- $H_{TSU}$ = load due to tsunami-induced lateral foundation pressures developed under submerged conditions. Where the net effect of $H_{TSU}$ counteracts the principal load effect, the load factor for $H_{TSU}$ shall be 0.9.
The components of the building must have the necessary design strength for tsunami pressures of ASCE 7 that are calculated at an ultimate load level. The design limit state for the 2,475-year event is based on the design strength capacity of structural members. Material resistance factors, $\phi$, should be used as their values prescribed in the material-specific standards for the component and behavior under consideration.

The main lateral-force-resisting system should also be designed for the overall pressure loading. In high seismic zones where the structure is detailed for ductility and structural integrity of the load path, the overall system capacity will be considered acceptable without additional analysis provided the total tsunami lateral force acting on the structure is less than 75% of the horizontal seismic loads including the system overstrength factor, $\Omega_o$.

**STRUCTURAL LOADS AND EFFECTS**

**Hydrostatic Loads**

Reduced net self-weight due to buoyancy should be evaluated for all inundated structural and non-structural elements of the building. Uplift due to buoyancy should include enclosed spaces without breakaway walls that have opening area less than 25% of the inundated exterior wall area. Buoyancy should 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. All windows, except those designed for large missile wind-borne debris impact or blast loading, shall be permitted to be considered openings when the inundation depth reaches the top of the windows. 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 should be designed to resist an unbalanced hydrostatic lateral force during inflow. All horizontal floors below the maximum inundation depth should be designed for dead load plus a residual water surcharge load to the extent that internal impounded water cannot escape in sufficient time during drawdown outflow.

**Hydrodynamic Loads**

Hydrodynamic loads develop when fluid flows around objects in the flow field. The building lateral framing system should be designed to resist the overall drag force developed either by in-coming or out-going flow. Likewise, lateral hydrodynamic pressure load should be applied on the projected area of all structural components and enclosure component assemblages below the inundation flow depth. Slab hydrodynamic uplift pressure should 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 should be applied.
For nearshore bathymetric slopes that are shallow, or in the presence of reef discontinuities, tsunami bore solitons should also be considered superimposed on the hydrodynamic surge. Instantaneous hydrodynamic loads created by bore impact can be severe. At locations specified in accordance with offshore bathymetry, bore impact forces on walls and slabs should be considered as an amplified force equivalent to 150% of the hydrodynamic drag.

Loads on initially (i.e., prior to the tsunami arrival) enclosed buildings should be calculated assuming a minimum closure ratio of 70% 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.

For open structures having not greater than a 20% closure ratio, it is observed in post-tsunami surveys that debris may still accumulate against structural framing components. For this reason, a minimum closure ratio of 50% represents that additional debris accumulation, in which hydrodynamic drag of the entrapped debris is transmitted to the structure. The cumulative sum of hydrodynamic forces on individual column and wall piers in an open structure can also reach the equivalent of the hydrostatic force on the overall structure that is 50% closed.

**Debris Impacts**

Tsunamis can transport a large volume of debris. The impacts of a 1,000-lb. (452kg) log, a floating passenger vehicle, and a submerged tumbling boulder or concrete mass debris (weighing 5,000-lb., or 2267 kg) are assumed to impact perimeter vertical structural components. The most severe effect of impact loads within the inundation depth should be applied to the perimeter gravity-load-carrying structural components located on the principal structural axes perpendicular to the inflow or outflow directions.

Other debris impact forces are applicable depending on the location of the structure and potential debris in the surrounding area that would be expected to reach the site during the tsunami. To determine the extent of the debris impact hazard region around a port, harbor, or shipping container yard, an empirical approach is based on the amount of available debris and the flow depth in the vicinity, along with other significant structures that may be between the origin of debris and the structure being designed. In this bi-directional sectored region, there is a greater probability of receiving a colliding impact (illustrated in Figure 5).
FIG. 5 Illustration of Determination of Floating Debris Impact Hazard Region

For buildings and other structures within the debris impact hazard region of a shipping port, a shipping container impact on perimeter vertical structural components of the gravity-load-carrying system should be assumed to occur. For Risk Category III and IV buildings and structures adjacent to piers and wharves, an extraordinary mass impact (such as a large ship) on perimeter vertical structural components of the gravity-load-carrying system should be evaluated.

FOUNDATION DESIGN

Design of structure foundations and tsunami barriers should consider changes in the site surface and in-situ soil properties during the design tsunami. Tsunami flow around structures can cause local scour around foundation elements, and sustained flow can also result in general erosion at a site. Foundations are designed to maintain support of superimposed loading of the superstructure under these conditions, and accordingly foundations should be designed to resist vertical and lateral tsunami loads during and after any applicable general site erosion and scour. Foundation embedment depth and the capacity of exposed piles to resist structural loads, should take into account the cumulative effects of general erosion due to flooding and pore-pressure softening, as well as local scour.

Tsunami inflow and outflow cycles are specified to include load reversal as well as scour effects that may occur due to an initial wave prior to a subsequent wave loading. 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. Figure 6 presents a schematic representation of the applicable loading on a foundation
element for the design condition after local scour and general erosion have occurred and pore pressure and seepage effects are present.

FIG. 6 Schematic of tsunami loading condition for a foundation element

TSUNAMI VERTICAL EVACUATION REFUGEE STRUCTURES

Vertical Evacuation Refuge Structures are 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. 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. The minimum elevation for a tsunami refuge area is, therefore, the Maximum Considered Tsunami runup elevation anticipated at the site, increased by 30%, plus 10 feet (3 meters), as illustrated in Figure 7.

FIG. 7 Minimum Refuge Elevation and Design Inundation
CONCLUSIONS

The American Society of Civil Engineers/Structural Engineering Institute has developed a new chapter on tsunami loads and effects for the 2016 edition of the ASCE/SEI 7 Standard. This method is consistent with probabilistic seismic hazard analysis in the treatment of uncertainty. The tsunami design provisions utilize probabilistic Offshore Tsunami Amplitude maps and Tsunami Design Zone inundation maps. Procedures for tsunami inundation analysis are based on using design map values of Offshore Tsunami Amplitude or the Runup and Inundation Limit from the Tsunami Design Zone Map. The new ASCE 7 provisions for Tsunami Loads and Effects enables a set of analysis and design methodologies that are consistent with tsunami physics and hydraulic engineering principles. Further details on the design procedures described here will be found in ASCE 7-16, along with an extensive commentary.

REFERENCES

