16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 300

Registration Code: S-06109C

Tsunami Design Criteria and Load Cases of the ASCE 7-16 Chapter 6, Tsunami Loads and Effects

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Abstract

The 2016 edition of the ASCE 7 Standard, Minimum Design Loads for Buildings and Other Structures includes a new Chapter 6 – Tsunami Loads and Effects. The ASCE 7-16 Tsunami Loads and Effects chapter has become the first national, consensus-based standard for tsunami resilience for use in the states of Alaska, Washington, Oregon, California, and Hawaii. The intent of these requirements is to improve on both the siting and design of new Risk Category III and IV buildings and nonbuilding structures built in Pacific coast communities. This paper explains the basis of the design flow conditions at a project site and the load cases of various hydrostatic and hydrodynamic loading conditions that must be considered when designing the overall structural system and individual structural members. The principal author is the Chair of the ASCE 7 Tsunami Loads and Effects Subcommittee, and the second author is a member of that subcommittee.

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 1:2475 annual probability of exceedance. The Maximum Considered Tsunami constitutes the design event, consisting of the inundation depths and flow velocities taken at the stages of in-flow and out-flow most critical to the structure. The tsunami design requirements in the ASCE 7 Standard vary by Tsunami Risk Category; tsunami design applies to essential and critical facilities necessary for immediate response and economic / social recovery. It may also be applied to other multi-story buildings where tsunami resilience is desired by a community.

Using the ASCE Tsunami Design Geodatabase to obtain the design level hazard of tsunami Runup, the design flow depth and velocity at the project site location are then determined using the Energy Grade Line Analysis or the Site-Specific Inundation Analysis. 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. The two-dimensional Site-Specific Inundation Analysis utilizes the Offshore Tsunami Amplitude, together with an effective wave period that is considered a conserved constant and other waveform shape parameters specified by the tsunami provisions. This numerical simulation includes a high-resolution digital elevation model of nearshore bathymetry and onshore topography. The flow conditions determined from one of the methods are then used to determine structural loading and scour effects for which the building or structure must be designed.

Keywords: ASCE7-16, Tsunami, Design Criteria, Structural Loads

1. Introduction

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, for use in the states of Alaska, Washington, Oregon, California, and Hawaii. The intent of these requirements is to improve on both the siting and design of new Risk Category III and IV buildings and nonbuilding structures built in Pacific coast communities. This paper explains the basis of the design flow conditions at a project site and the load cases of various hydrostatic and hydrodynamic loading conditions that must be considered when designing the overall structural system and individual structural members. The ASCE 7 Tsunami Loads and Effects chapter is consistent with the principles of probabilistic hazard analysis, tsunami physics, and fluid mechanics, integrated into a comprehensive set of design provisions. The technical basis and methodologies for determination of inundation depth and flow velocity, structural loading, analysis, and tsunami-resilient design can be applied elsewhere, since it utilizes design maps based on probabilistic hazard analysis, loads based on tsunami physics, and a structural ultimate strength basis of design. The units of the ASCE 7 Standard are the Imperial/US customary engineering system of units.

1.1. Terminology and Definitions

Key parameters for tsunami definition are Offshore Tsunami Amplitude, Inundation Depth, Runup elevation, and the (maximum horizontal) Inundation Limit. The ASCE Standard defines the amplitude above the ambient sea level of a probabilistic Maximum Considered Tsunami at a standardized offshore water depth of 100 meters. This is different from the peak to trough tsunami height. 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 1.

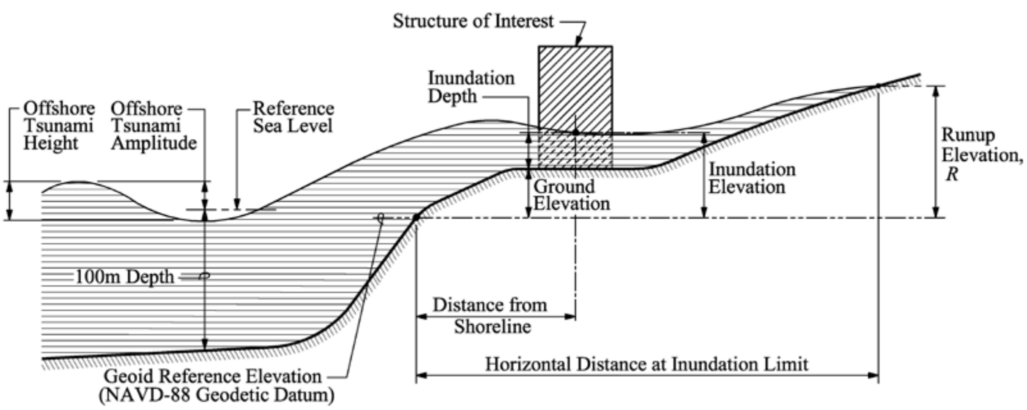

Fig. 1 Illustrated ASCE tsunami terminology [1]

1.2 Symbols and Notation

The following symbols and notation are utilized in this paper and in the ASCE 7-16 Chapter 6 provisions:

E_g	hydraulic head in the Energy Grade Line Analysis
$E_{g,i}$	hydraulic head at point $i = h_i + u_i^2/2g = h_i(1 + 0.5F_{ri}^2)$
E_R	hydraulic head of zero at the point of runup.
F_r	Froude Number = $u/\sqrt{(g\ h)}$
F_{ri}	Froude number at point i
F_{TSU}	tsunami load or effect
g	acceleration due to gravity
h_i	inundation depth at point i
h_0	offshore water depth

L	live load
n	Manning's coefficient
NAVD-88	North American Vertical Datum 1988
s	friction slope of the energy grade line
s_i	friction slope of the energy grade line between points i and i + 1
S	snow load
u	tsunami flow velocity
u_i	maximum flow velocity at point *i*
x	horizontal distance inland from NAVD88 shoreline
x_i	horizontal distance inland from NAVD 88 shoreline at point i
x_R	mapped inundation limit distance inland from NAVD88 shoreline
z	ground elevation above NAVD88 datum
α	Froude number coefficient in the Energy Grade Line Analysis
$\Delta x_i = x_i - x_{i+1}$	increment of horizontal distance, which shall not be coarser than 100 ft (30.5 m) spacing
φ_i	average slope of grade between point i and i-1
Ω_O	Overstrength Factor for the seismic lateral-force-resisting system

2. Analysis of Design Inundation Depth and Flow Velocity

Tsunami inundation analysis procedures for design utilize either, the Offshore Tsunami Amplitude and its effective period from the ASCE 7 Tsunami Design Geodatabase, or the Runup and Inundation Limit from the Tsunami Design Zone Map. There are two procedures available for determining the flow depth and velocities at a site. The Energy Grade Line Analysis (EGLA) 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. The two-dimensional Site-Specific Inundation Analysis utilizes the Offshore Tsunami Amplitude, together with an effective wave period that is considered a conserved constant and other waveform shape parameters specified by the tsunami provisions. This numerical simulation includes a high-resolution digital elevation model of nearshore bathymetry and onshore topography.

2.1 Energy Grade Line Analysis

The EGLA was developed to produce conservative design flow parameters for a given input parameter of the Runup point, and it is always performed for Tsunami Risk Category II, III and IV structures. The tsunami inundation 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, using Manning's coefficient for equivalent terrain macro-roughness per Table 1, to account for the friction slope of the energy grade line per Eq. 1 from ASCE 7-16 Section 6.6.2.

$$E_{g,i} = E_{g,i-1} + (\varphi_i + s_i)\,\Delta x_i \qquad (1)$$

The EGLA determines the variation of inundation depth and associated flow velocity across the inland profile. This equation is applied across the topographic transect from the runup where the hydraulic head at the inundation limit, x_R, is zero, and the water elevation is equal to the runup, R, by calculating the change in hydraulic head at each increment of terrain segment toward the shoreline until the site of interest is reached, as shown in Fig. 2.

Table 1. Manning's Roughness, *n*, for Energy Grade Line Analysis [1]

Description of Frictional Surface	***n***
Coastal water nearshore bottom friction	0.025 to 0.03
Open land or field	0.025
All other cases	0.03
Buildings of at least urban density	0.04

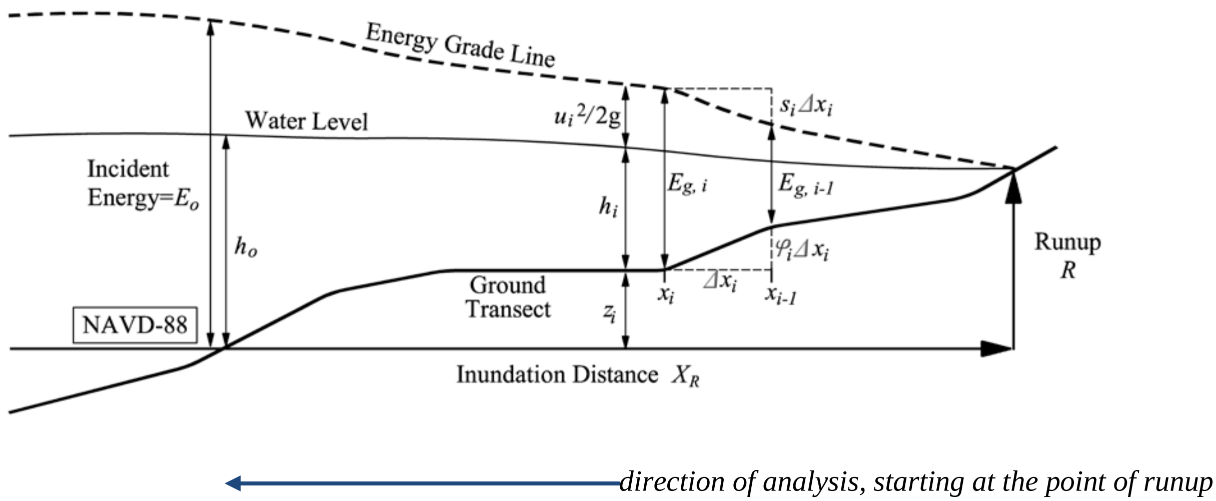

Fig. 2. Illustration of the Principles of the Energy Grade Line Analysis [1]

The EGLA stepwise procedure consists of the following steps:

1. Obtain the runup and inundation limit values from the Tsunami Design Map.
2. Approximate the principal topographic transect by a series of *x*–*z* grid coordinates defining a series of segmented slopes, in which *x* is the distance inland from the shoreline to the point and *z* is the ground elevation of the point. The horizontal spacing of transect points should be less than 100 ft (30.5 m), and the transect elevations should be obtained from a topographic Digital Elevation Model (DEM) of at least 33-ft (10-m) resolution.
3. Compute the topographic slope, s_i, of each segment as the ratio of the increments of elevation and distance from point to point in the direction of the incoming flow.
4. Obtain the Manning's coefficient, *n*, for each segment based on terrain analysis of land cover in accordance with Table 1.
5. Compute the Froude number at each point on the transect using Eq. (2).
6. Start at the point of runup with a boundary condition of $E_R = 0$ at the point of runup.
7. Select a nominally small value of inundation depth [~0.1 ft (0.03 m)] h_r at the point of runup.
8. Calculate the hydraulic friction slope, s_i, using Eq. (3).
9. Compute the hydraulic head, E_i, from Eq. (1) at successive points toward the shoreline.
10. Calculate the inundation depth, h_i, from the hydraulic head, E_i.
11. Using the definition of Froude number, determine the velocity u_i.
12. Repeat through the transect until the *h* and *u* are calculated at the site. These are used as the maximum inundation depth, $h_{\max}$, and the maximum velocity, $u_{\max}$, at the site. However, these two parameters are not coincident in time.

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 ASCE 7-16 Section 6.6.2 per Eq. (2).

$$F_r = \alpha\left(1 - \frac{x}{x_R}\right)^{1/2} \quad (2)$$

The Froude number coefficient, α , in Eq. (2) is 1.0 except where tsunami bores occur, in which case it is increased to a value of 1.3. Where tsunami waves shoal either over long and mild seabed slopes or in river estuaries, or encounter abrupt seabed discontinuities such as fringing reefs, short-period waves called solitons are generated on the front edge of the much larger tsunami waveform, which in the nearshore regime can often lead to the occurrence of tsunami bores where the soliton waves break. These tsunami bores have higher wavespeed and more impulsive impact on structures.

Hydraulic friction slope is given by Eq. (3):

$$\begin{aligned} s_i &= (u_i)^2/((1.49/n)^2 h_i^{4/3}) \quad (3) \\ &= g\, F_{ri}^2/((1.49/n)^2 h_i^{1/3}) \text{ U.S. inch-pound units} \\ &= g\, F_{ri}^2/((1.00/n)^2 h_i^{1/3}) \text{ S.I. units} \end{aligned}$$

Once the maximum inundation depth and flow velocities are determined, normalized depth and depth-averaged flow speed prototypical time-history graphs are provided to define the temporal relationship between depth and velocity during tsunami inflow and outflow, as shown in Figure 3, which is from ASCE 7-16 Section 6.8.3.1, Load Cases.

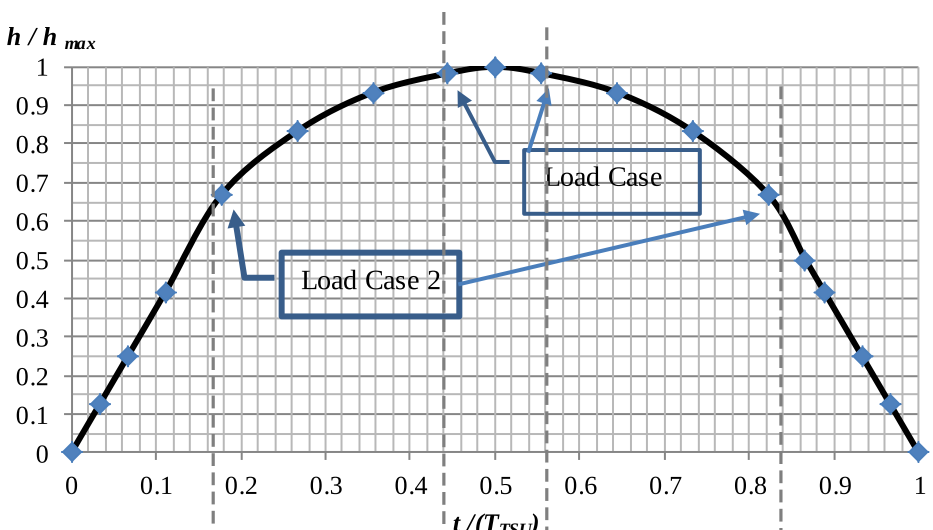

Figure 3(a) Normalized Inundation Depth vs. Normalized Time

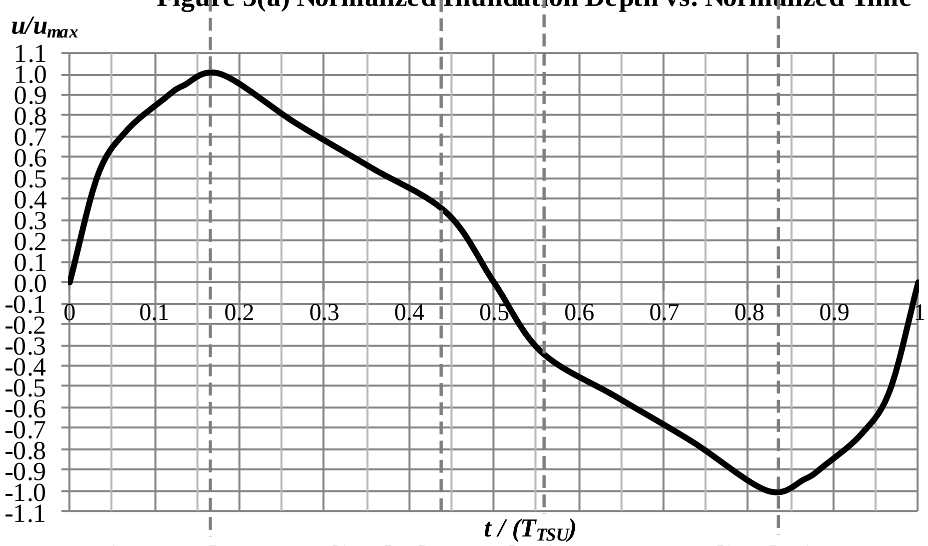

Figure 3(b) Normalized Flow Velocity vs. Normalized Time

At least three cases of tsunami loading defined by inundation depths and their 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 (load case 2 in Figure 3).
3. Maximum water depth when the flow velocity is assumed to be at one-third of maximum, in each direction (load case 3 in Figure 3).

Flow directions other than along a principal transect must be considered. Rather than assume that the flow is uniformly perpendicular to the shoreline, variation by ±22.5 degrees from the perpendicular transect is considered when using the EGLA, in which the center of rotation of the possible transects is located at the site.

2.2 Site-Specific Inundation Analysis

The Site-Specific Inundation Analysis of site inundation depth and flow velocity may be required depending on the structure's Tsunami Risk Category. The procedures for site-specific analysis are mandatory for Tsunami Risk Category IV and Tsunami Vertical Evacuation Refuge Structures. The purpose of performing a Site-Specific Inundation Analysis is to determine the 2-dimensional flow and directionality effects that are not provided by the linear transect analysis of the EGLA. Such simulation modeling is particularly useful to evaluate more detailed flow characteristics for Tsunami Risk Category IV structures.

The input for the Site-Specific Inundation Analysis is one or more surrogate tsunami scenarios generated from the principal disaggregated seismic source regions that replicate the offshore tsunami waveform characteristics for the site of interest, such that the offshore wave amplitudes computed shall not be lower than 80% of the ASCE 7 Offshore Tsunami Amplitudes specified in its Tsunami Design Geodatabase. Utilizing an integrated generation, propagation, and inundation model, the Site-Specific Analysis would be run as a complete simulation from the seismic source slip event, calibrated to match the defined probabilistic Offshore Tsunami Amplitude. Time histories of site-specific flow parameters are generated at the site using numerical inundation simulation software utilizing more detailed spatial bathymetry and topography, previously validated in compliance with the National Oceanic and Atmospheric Administration (NOAA) National Tsunami Hazard Mitigation Program (NTHMP) benchmark test cases [2]

Site-Specific Inundation Analysis is particularly useful in evaluating more complicated bathymetry, and inland flow diversion and amplification around local hills and valley features. Particularly for Tsunami Vertical Evacuation Refuge Structures, these additional bathymetric and topographic effects that may adversely affect the local inundation depth and flow velocities are better captured using the Site-Specific procedure. Although a site-specific inundation analysis is permitted to establish flow vectoring at the site, some uncertainty in the accuracy of this estimation is reflected in a specified ±10 degree variability.

Urban environments may channel and significantly amplify flow velocities. In urban environments with buildings at densities that may reduce tsunami runup, the flow velocities determined by a "bare-earth" Site-Specific Inundation Analysis for a given structure location may not be taken as less than 90% of those determined in accordance with the EGLA method based on urban macro-roughness. For other terrain roughness conditions, the site-specific inundation analysis flow velocities at a given structure location shall not be taken as less than 75% of those determined in accordance with the Energy Grade Line Analysis method. The reason for these safeguard design restrictions is that the tsunami model validation standard, NOAA OAR PMEL-135 [3], presently does not validate flow velocities over land. Moreover, the ASCE 7 tsunami subcommittee's evaluation indicated that in certain case studies of field observations where video analysis of flow was conducted, some numerical inundation models could potentially underestimate flow velocities for flow over land.

3. Structural Design Procedure for Tsunami Effects

The following tsunami effects should be considered for structural design of buildings and structures, of which this paper address the first two types of loading:

- 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

Structures and structural components shall be designed for the Tsunami Forces and Effects, F_{TSU} , as the principal load effect, for incoming and receding directions as specified in the load combinations for strength design per ASCE 7-16 Section 6.8.3.3. using Eq. (4) and Eq. (5):

$$0.9D + F_{TSU} + H_{TSU} \quad (4)$$

$$1.2D + F_{TSU} + 0.5L + 0.2S + H_{TSU} \quad (5)$$

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.

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**.** The lateral-force-resisting system should also be designed for the overall tsunami pressure loading on the entire structure. The design limit state is based on the design strength capacity of structural members. Material resistance factors, ϕ, should be used per the prescribed values provided by the material-specific standards for the component and structural behavior under consideration.

3.1 Hydrostatic Loads

Reduced net self-weight due to buoyancy should be evaluated for all inundated structural and non-structural elements of the building. That full hydrostatic pressure develops below the grade level of the building is a conservative assumption based on permeable foundation soils such as silts, sands and gravels, but may be too conservative for cohesive soils such as clay and clayey silt. Soil permeability should be evaluated in the context of the duration and pressure head of the tsunami inundation depth at the site. Consideration of 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 integrated structural 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. Buoyant uplift may be avoided by preventing the build-up of hydrostatic pressure beneath structural slabs, allowing the interior space to become flooded or designing for pressure relief or structural yielding relief of the hydrostatic head pressure, sufficient deadweight, anchorage, or a combination of the above design considerations.

Structural walls with openings less than 10% of the wall area and either longer than ~10m (30 ft.) 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.

3.2 Hydrodynamic Loads

Hydrodynamic loads develop when fluid flows around objects in the flow path. 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 inflow and outflow cycles, the second of which should 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 outflow cycle.

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.

The lateral hydrodynamic load given by Eq. 6 is the hydrodynamic drag for tsunami loading per ASCE 7-16 Section 6.10.2.

$$F_{TSU} = \frac{1}{2}\rho_s C_d b(h_e u^2)\, I_{tsu} \tag{6}$$

in which ρ_s = the minimum fluid mass density= $k_s\ \rho_{sw}$, the fluid density factor (k_s = 1.1) multiplied by the mass density of seawater, C_d = the drag coefficient for the building or component, b = the width perpendicular to the flow, h_e = the inundation depth, u = the flow velocity and I_{tsu} = tsunami importance factor.

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. Based on post-tsunami observations, it is extremely unlikely and unconservative to assume that all walls and internal contents would breakaway, but yet no debris from other sources becomes entrapped against the structure being designed. Therefore, enclosed buildings should be calculated assuming a minimum closure ratio of 70% of the pressure exposed surface area of the exterior enclosure, and initially open structures should be calculated assuming a minimum closure ratio of 50%, accounting for entrapped debris. Also, the cumulative sum of hydrodynamic forces on the 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.

Tsunami inundation may take the form of a rapidly rising surge, or a broken bore. 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.

Hydrodynamic (and impact forces) are required to be increased by an Importance Factor, I_{tsu}, based on the Tsunami Risk Category. I_{tsu} is given as 1.0 for Tsunami Risk Category II and 1.25 for Tsunami Risk Category III and IV. I_{tsu} is also 1.25 for Tsunami Vertical Evacuation Refuge Structures, which have an additional requirement of a 1.3 factor applied to increase the site-specific inundation elevation.

Conditions of hydrodynamic flow in ASCE 7-16 include:

- Overall drag forces on buildings and structures
- Drag forces on components
- Tsunami loads on vertical structural components, perforated walls, and walls angled to the flow
- Hydrodynamic pressures on slabs due to flow stagnation, surge uplift, and pressures caused by bores entrapped in wall-slab recesses

4. Summary and Conclusions

The new Chapter 6 – Tsunami Loads and Effects, in the 2016 edition of ASCE 7 provides the first comprehensive tsunami design provisions for use in the US. Although the current application is intended only for the five Western States, namely Alaska, Washington, Oregon, California and Hawaii, these provisions can be used for other US and International territories with an established probabilistic tsunami hazard. In addition, many of the provisions in this chapter may also find application to non-building structures in the tsunami inundation zone. Although intended specifically for application to new construction, the provisions in this standard could also be applied, in conjunction with ASCE-41, to the assessment of existing coastal structures for tsunami resistance.

4. Acknowledgements

The support of the American Society of Civil Engineers, Structural Engineering Institute and the Coasts, Oceans, Ports, and Rivers Institute, towards the development of the tsunami design provisions in ASCE 7-16 by the Tsunami Loads and Effects Subcommittee is gratefully acknowledged. This paper is based on a more general discussion of the ASCE 7-16 tsunami chapter published in the ASCE Journal of Structural Engineering [4].

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