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TSUNAMI DESIGN TARGET RELIABILITIES

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Abstract

Many coastal areas in the U.S. are subject to tsunami hazard. Presently, U.S. codes do not include any consideration of tsunami hazard, and important or even hazardous material structures can be built with no planning at all for the consequences of destructive tsunamis. The public safety risk has been partially mitigated through warning and preparedness for evacuation, but community disaster resilience requires that critical and essential facilities provide structural resistance to collapse and the capacity to resume vital services. 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 reliability analysis. The intent of these requirements is to improve on both the siting and design of new Risk Category III and IV buildings and other structures built in U.S. Pacific coast communities. This will result in greater community disaster resilience.

The purpose of this paper is to provide an outline of the analysis of the structural reliability basis for tsunami-resilient design of critical and essential facilities, taller building structures, and tsunami vertical evacuation refuge structures. Probabilistic limit state reliabilities are computed for representative structural components carrying gravity and tsunami loads, utilizing statistical information on the key hydrodynamic loading parameters and resistance models with specified tsunami load combination factors. Through a parametric analysis performed using Monte Carlo simulation, it is shown that anticipated reliabilities for tsunami hydrodynamic loads meet the general intent of the ASCE 7 Standard. Importance factors consistent with the target reliabilities for extraordinary loads (such as seismic events) are determined for tsunami loads. Target structural component reliabilities given that the Maximum Considered Tsunami has occurred are similar to seismic systemic performance reliabilities given that the Maximum Considered Earthquake has occurred.

Keywords: ASCE7-16; Tsunami; Reliability; Resilience; Structural Loads; Seismic Design

1. Introduction

Many coastal areas in the western U.S. are subject to tsunami hazard that is infrequent but potentially extremely destructive. Community disaster resilience would require that critical and essential facilities provide structural resistance to collapse and allow resumption of functionality of those facilities soon after the tsunami to enable quicker recovery. 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 will result in greater community disaster resilience. "Resilience is the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events. Enhanced resilience allows better anticipation of disasters and better planning to reduce disaster losses—rather than waiting for an event to occur and paying for it afterward." [1].

There are many coastal communities in the states of Alaska, Washington, Oregon, California, and Hawaii where there is insufficient time for complete evacuation. When evacuation travel times exceed the available time to tsunami arrival, places of higher elevation and/or taller structures that are tsunami resistant would then provide needed life safety. Multi-story buildings, which are necessary for tsunami safety where evacuation cannot be completely assured, can be designed for life safety or better performance for large tsunamis with local strengthening of relatively few components. Furthermore, ASCE 7-16 provides for the design of Tsunami Vertical Evacuation Refuge Structures, which are a special type of Risk Category IV structure with additional design requirements for very high reliability. This structure serves as a designated point of refuge to which a portion of a community's population can evacuate when higher ground is not reachable in time before tsunami arrival.

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 [2]. The purpose of this paper is to provide a summary of the structural reliability basis of these provisions for tsunami-resilient design of critical and essential facilities, taller building structures, and tsunami vertical evacuation refuge structures [3]. Probabilistic limit state reliabilities are computed for representative structural components carrying gravity and tsunami loads, utilizing statistical information on the key hydrodynamic loading parameters and resistance models with specified tsunami load combination factors. Through a parametric analysis performed using Monte Carlo simulation, it is shown that anticipated reliabilities for tsunami hydrodynamic loads meet the general intent of the ASCE 7 Standard as stated in its Chapter 1 Commentary.

2. Tsunami Hazard Analysis

Engineering design must consider the occurrence of events greater than scenarios in the historical record, based on the underlying seismicity of subduction zones. To achieve a consistent structural performance for community resilience, a probabilistic tsunami inundation geodatabase for design is digitally available with the ASCE tsunami design provisions. The Tsunami Design Zone is the area vulnerable to being inundated by the Maximum Considered Tsunami (MCT) which is taken as having a 2% probability of being exceeded in a 50-year period or a 2475-year mean recurrence interval.

Tsunami loads and effects are based on the Maximum Considered Tsunami that is characterized by the inundation depth and flow velocities during the stages of inflow and outflow at the site. There are two procedures for determining the MCT inundation depth and velocities at a site: 1) the Energy Grade Line Analysis (EGLA); and 2) a Site-Specific Inundation Analysis [4] The EGLA is fundamentally a hydraulic analysis along a topographic transect from the shore line to the runup point which takes the runup elevation and inundation limit indicated on the Tsunami Design Zone Map as the given solution point. Site-Specific Inundation Analysis utilizes the Offshore Tsunami Amplitude, the effective wave period that is considered a conserved property, and other specified waveform shape parameters as the input; it is a 2-D numerical simulation based on a higher-resolution digital elevation model of nearshore bathymetry and onshore topography. The Site-Specific

Inundation Analysis is required to be performed for Tsunami Risk Category IV structures unless the Energy Grade Line Analysis shows the inundation depth to be less than 12 feet at the structure. The design of Tsunami Vertical Refuge Structures always utilizes a Site-Specific Inundation Analysis.

For this reliability analysis study, representative vertical load carrying components of prototypical buildings have been evaluated for tsunami load effects. Probabilistic Tsunami Hazard Analysis was performed to obtain prototypical offshore tsunami amplitude hazard curves for California and the associated inland tsunami inundation depth hazard curves for sites located at the shoreline, and a quarter and a half of the inundation distance inland (where $x=0.0X_{R,}$ $x=0.25X_{R,}$ and $x=0.5X_R$; see Figure 1 for $x = 0.0\ X_R$, $0.25X_R$ and $0.5X_R$).

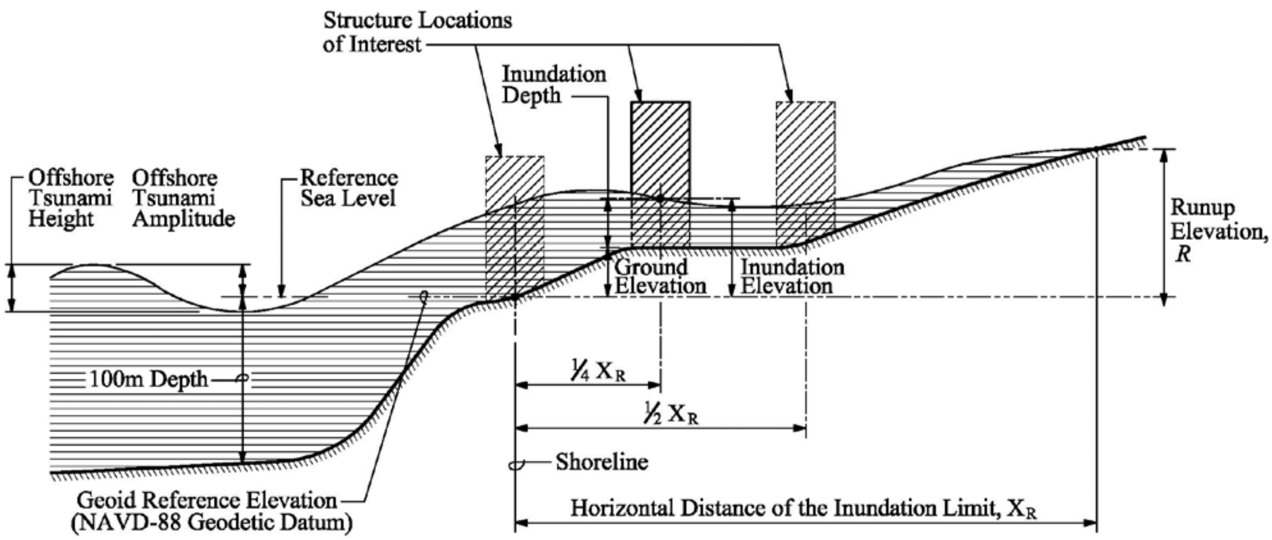

Fig. 1 Locations of three prototypically located sites along a transect in a tsunami design zone [3]

3. Basic Limit State Equation and Tsunami Design Parameters

The following load combinations with tsunami forces as the primary load effect are specified in ASCE 7-16 Section 6.8.3.3 by Eq. (1) and (2):

$$\varphi R_n = 1.2D_n + 1.0\ F_{TSUn} + 0.5L_n \quad (1)$$

$$\varphi R_n = 0.9D_n + 1.0\ F_{TSUn} \quad (2)$$

in which φ = resistance factor, R_n = nominal strength, D_n = nominal dead load, L_n = nominal live load and F_{TSUn} = nominal tsunami effect. The nominal subscript notation refers to the specified loads and resistances, per the convention of engineering reliability analysis.

Lateral hydrodynamic tsunami forces are generally much greater than hydrostatic lateral and buoyant vertical tsunami forces. The primary hydrodynamic load is lateral pressure on vertical elements, so the dead load and live load do not directly counteract the tsunami load for those elements. Tsunami resistant structures will predominately be in the height regime of four or more stories, and the beam-column resistance would also reflect the column design capacity that includes the combination for dead and live load, 1.2D + 1.6L [2]. There is a beneficial effect in flexural capacity of the vertical beam-column under tsunami lateral load component due to the 0.5L axial loading in load combination (1), which results in a capacity bias for beam-columns designed for vertical load.

The general limit state function G(X) = R – S, i.e., the expression for Resistance – Load, can be formulated in Eq. (3) as:

$$G(X) = G(R, \lambda, F_{TSU}) = \lambda R - F_{TSU} \quad (3)$$

in which λ is capacity bias of the beam-column considering effects of axial loading of dead and live loads. Assuming λ_n is the capacity factor of a flexural member to normalize the expression, the limit state function becomes Eq. (4):

$$\frac{1}{\lambda_n \phi R_n} G(X) = \frac{1}{\lambda_n \phi R_n} G(R, \lambda, F_{TSU}) = \frac{\lambda}{\lambda_n} \frac{R}{\phi R_n} - \frac{F_{TSU}}{F_{TSUn}} \tag{4}$$

The lateral hydrodynamic load given in ASCE 7-16 Section 6.10.2.3 by Eq. (5) is assumed to govern when a vertical beam-column is subject to tsunami loading.

$$F_{TSU} = \frac{1}{2} \rho_s C_d b (h_e u^2)\, I_{tsu} \tag{5}$$

in which ρ_s is the minimum fluid mass density, C_d is the drag coefficient for the building component, b is its width perpendicular to the flow, h_e is the inundation depth, u is the flow velocity and I_{tsu} is the Tsunami Importance Factor.

The ASCE 7-16 Standard classifies facilities in accordance with Risk Categories that recognize the importance or criticality of the facility. In the tsunami chapter, Critical Facilities incorporates facilities needed for post-tsunami mission critical functions or facilities that have more critical roles in community recovery and community services. Critical facilities designated by local governments are included in Tsunami Risk Category III. Essential facilities are typically included in Tsunami Risk Category IV. Tsunami Importance Factor, I_{tsu}, is a set of assigned constants, or specified bias factors for each Tsunami Risk Category. These bias factors are included in the reliability analysis for each Tsunami Risk Category. I_{tsu} is given per Table 1 for this reliability analysis.

Table 1. Tsunami Importance Factors for Hydrodynamic and Impact Loads

Tsunami Risk Category	I_{tsu}
II	1.0
III	1.25
Tsunami Risk Category IV, Vertical Evacuation Refuges, and Designated Tsunami Risk Category III Critical Facilities	1.25

To account for assorted debris accumulation, ASCE 7 does not allow the forces to be computed on the bare structure without cladding, interior walls and fixtures, or contents. For buildings initially cladded, the designer can conservatively assume only 30% of this becomes “open” to allow unimpeded flow. Actual accumulation is estimated from field case studies [5]to be in the range of creating a 40% to 60% closure ratio, rather than the prescribed 70% as used for design, so there is some conservative bias in the design provisions that define the minimum value of width b_n to prevent underestimation of loading.

The second term on the right side of the limit state function (Eq. 4) is then expanded to Eq. (6):

$$\frac{F_{TSU}}{F_{TSUn}} = \frac{\rho_s}{\rho_{sn}} \frac{C_d}{C_{dn}} \frac{b}{b_n} \frac{(h_e u^2)}{(h_e u^2)_n} \frac{1.0}{\mathrm{I}_{tsu}} \tag{6}$$

in which ρ_{sn}, C_{dn}, b_n, and $(h_e u^2)_n$ are the nominal design values. The term $(h_e u^2)_n$ refers to the momentum flux calculated in accordance with the EGLA. Introducing $(h_e u)_o$ as the momentum flux obtained by a detailed numerical model for Site-Specific Inundation Analysis, Eq. (6) then can be expressed in the form of Eq. (7):

$$\frac{F_{TSU}}{F_{TSUn}}=\frac{\rho_s}{\rho_{sn}}\frac{C_d}{C_{dn}}\frac{b}{b_n}\frac{(h_e u^2)_o}{(h_e u^2)_n}\frac{(h_e u^2)}{(h_e u^2)_o}\frac{1.0}{\mathrm{I}_{\mathrm{tsu}}} \tag{7}$$

The depth-averaged flow velocity is considered to be a function of inundation depth, as expressed by the Froude number for tsunami flow (the nondimensionalized flow velocity $u/\sqrt{(gh)}$). This leads to the following simplified function (8):

$$\frac{F_{TSU}}{F_{TSUn}}=\frac{\rho_s}{\rho_{sn}}\frac{C_d}{C_{dn}}\frac{b}{b_n}\psi\left(\frac{h_e}{h_{eo}}\right)^2\frac{1.0}{\mathrm{I}_{\mathrm{tsu}}} \tag{8}$$

with ψ being the variable to account for the epistemic uncertainty in the nominal solution of the prescriptive analysis of flow (i.e., imprecisions in the code-specified Energy Grade Line Analysis vs. site-specific numerical model). A robust comparison of the Energy Grade Line Analysis with a detailed inundation model was performed to assess the ability of the EGLA to provide a conservative result for a wide range of possible onshore topographic profiles and wave conditions. The general approach employed was to run a number of simulations using a Boussinesq-type model [6] and compare the inundation properties of the Boussinesq output with the Energy Grade Line Analysis.

$$\psi=\frac{(h_e u^2)_o}{(h_e u^2)_n} \tag{9}$$

In the above equation (8), h_{eo} is the inundation depth with 2475-year return period. Including the effect of aleatory uncertainties, h_e is εh where h is the inundation depth without considering the effect of aleatory uncertainties and ε accounts for the net aleatory uncertainties in estimated inundation depth associated with the modeling of seismic sources and inundation numerical modeling.

Since the terms, $\lambda_n \varphi R_n$ at the left side of Eq. (4) are not random and always greater than 0, the fundamental Limit State equation can thus be further developed to Eq. (10):

$$G(X)=\frac{\lambda}{\lambda_n}\frac{R}{\phi R_n}-\frac{\rho_s}{\rho_{sn}}\frac{C_d}{C_{dn}}\frac{b}{b_n}\psi\varepsilon^2\left(\frac{h}{h_{eo}}\right)^2\frac{1.0}{\mathrm{I}_{\mathrm{tsu}}} \tag{10}$$

in which $G(X) = G(R, \lambda, F_{TSU}) = G(R/R_n, \lambda/\lambda_n, \rho_s/\rho_{sn}, C_d/C_{dn}, b/b_n, \psi, \varepsilon, h_e/h_{eo})$

Lastly, the basic Limit State Function G(R,S) can then be parametrically given in Eq. (11):

$$\boldsymbol{G(R,S)= Z = R - S = (1/\varphi)X_6X_7\,I_{TSU} - X_1X_2X_3^2X_4^2X_5} \tag{11}$$

Where R = Resistance, and
S = Load

The tsunami parameters shown above are summarized in Table 2. Further details on these parameters and their distributions are given in an ASCE *Journal of Structural Engineering* paper [3].

Table 2. Reliability analysis parameters

Parameter	Random Variable	Distribution	Mean	Coefficient of Variation (COV)
ρ_s/ρ_{sn} (density)	X_1	Normal	1.0	0.03
C_{d}/C_{dn}	constant	-	1.0	0
b/b_n (closure) – exterior column case	X_2	Uniform	0.71	0.115
h_e/h_{en} (inundation depth)	X_3	Sampled from probabilistic hazard curve		
ε (aleatory uncertainty of hazard analysis)	X_4	Lognormal	1.067	0.283
Ψ (epistemic uncertainty of flow analysis)	X_5	Sampled from a large-scale simulation curve expressing the difference between the EGLA and numerical site-specific analysis		
λ/λ_n (beam-column effect)	X_6	Lognormal	1.15	0.174
R/R_n (Concrete Resistance)	X_7	Normal	1.05	0.11
R/R_n (Steel Resistance)	X_7	Normal	1.07	0.13
I_{tsu} (Tsunami Importance Factor)	assigned scalar factor	In accordance with Tsunami Risk Category (see Table 1)		
φ (strength reduction factor)	assigned constant	0.90 (Under tsunami lateral forces and a 0.5 live load factor, column designs become more flexurally governed)		

4. Reliability Analysis using Monte Carlo Simulation

The reliabilities were calculated using Monte Carlo simulation involving a large number of trial combinations of random variables. The procedure for the Monte Carlo simulation is as follows for the 7 parameters ρ, b, h, ε, ψ, λ, and R:

1. Randomly generate a value for each random variable in the limit state equation. No dependence is assumed between any of the variables. The inundation depth is sampled from its 50-year service life maximum Cumulative Distribution Function (CDF) curve which is derived from the probabilistic tsunami hazard curve for the representative sites.
2. Calculate $Z = R - S$ per Eq. (11). If $G(X) = Z < 0$, then the simulated member fails.
3. Repeat Steps 1 and 2 until a predetermined number of simulations are performed.
4. Calculate the probability of failure as P_f = Number of times that Z < 0 divided by total number of simulations.
5. The reliability index $\beta = \Phi^{-1}(1-P_f)$.

The simulation was software-coded and generally a million simulations were performed for each reliability calculation. The simulation starts at a sample size of a million and increased by an order of magnitude in size, until convergence resulted in acceptable precision, which depended on the reliability target. For Tsunami

Risk Category IV Tsunami Vertical Evacuation Refuge Structures, the sample size was increased up to 250 million, since the probabilities of failure were much less than the other categories.

5. Results of the Reliability Analysis

The reliability indices are calculated for a 50-year service period, while the probabilities of failure have been annualized, except for the failure probabilities conditional on the occurrence of the Maximum Considered Tsunami (MCT). The conditional probability of structural limit state exceedance of a primary beam-column structural component was computed assuming the MCT has occurred, similar to the determination of the ”conditional reliability” of the seismic provisions shown in ASCE 7 Table C.1.3.1b assuming the MCE has occurred. The conditional probabilities are thought to be a better measure of seismic design intent. Table 3 shows the reliabilities and failure probabilities for representative exterior concrete beam-column members when subject to tsunami loading.

Table 3. Reliabilities for Representative Exterior Concrete Beam-Column Members

Site	**Measure of Reliability**	**Tsunami Risk Category II I = 1.0**	**Tsunami Risk Category III I = 1.25**	**Tsunami Risk Category IV I = 1.25**	**Evacuation Refuge I = 1.25 & 1.3h_n**
Average of the Sites	Reliability index, β	2.81	2.93	3.15	3.61
	$P_{f\ annual}$	5.2×10^{-5}	3.4×10^{-5}	2.1×10^{-5}	8.7×10^{-6}
	$P_{f\ 50\text{-year}}$	0.26%	0.17%	0.11%	0.044%
Component Failure conditioned on the occurrence of the MCT	Reliability index, β	1.51	1.75	1.93	2.40
	Maximum probability of failure	6.6%	4.0%	2.7%	0.82%

5. Comparison of the Tsunami Reliability Analysis with Seismic Reliabilities

The component reliabilities for the Maximum Considered Tsunami (MCT) rounded-off from the values of Table 3 for exterior beam-columns are compared to the systemic reliabilities given for seismic Maximum Considered Earthquake (MCE) effects (Table 4). The 50-year service life anticipated reliabilities listed in Table 4 are based on average results of the integration of the conditional (on MCE) reliabilities with seismic hazard curves from the USGS [7] The MCT reliabilities for Tsunami Risk Categories II and III are for the primary vertical load-carrying beam columns subjected to lateral tsunami loading, and not for the systemic (seismic) collapse mechanisms. Tsunami probabilities are based on exceeding an exterior structural component’s capacity that does not necessarily lead to widespread progression of damage, but the seismic probabilities are for the more severe occurrence of partial or total systemic collapse. The 50-year service life probabilities of tsunami component failure of the exterior elements along the building perimeter are less than the 1%, 0.5%, and 0.3% systemic collapse probability in 50 years for Risk Category II, III, and IV structures, respectively, that are the basis of the present-day Risk-Targeted Maximum Considered Earthquake Ground Motion maps and Seismic Importance Factors (See [2]). Target structural component reliabilities given the Maximum Considered Tsunami (MCT) has occurred are similar to seismic systemic performance reliabilities given the Maximum Considered Earthquake (MCE) has occurred. This analysis indicates that the new ASCE 7 tsunami design provisions will result in a design with a level of reliability for structural components generally equivalent to or exceeding the targeted reliabilities for other types of extraordinary loadings such as Maximum Considered Earthquake events.

Table 4. Anticipated reliabilities (maximum probability of failure) for earthquake and tsunami

Risk Category	Probability of failure* in 50-yrs		Failure* probability conditioned on Maximum Considered event	
	Earthquake	**Tsunami**	**Earthquake (MCE)**	**Tsunami (MCT)**
II	1%	0.3%	10%	7.5%
III	0.5%	0.2%	5-6%	4-5%
IV	0.3%	0.1%	2.5-3%	2.5-3%
Vertical Evacuation Refuge Structures.	0.3%	<0.1%	2.5-3%	0.5 - 1%

6. Conclusions

The values of target structural reliabilities were calculated using Monte Carlo simulation involving a large number of trial combinations of random variables independently occurring in proportion to their statistical distributions for the demand parameters of fluid density, closure ratio, Energy Grade Line momentum flux, inundation depth hazard, and the aleatory uncertainty of inundation depth. Failures of exterior columns are more commonly observed in post-tsunami investigations, and this is considered the more practical case of application of the reliability analysis. These reliability estimates are predicated on the assumption that the load combinations with tsunami as the primary load effect would govern the design of the members. In ASCE 7-16, it is stated that structural components designed with performance-based procedures shall be demonstrated using an analysis to provide a reliability not less than the target reliabilities. Therefore, the recommended tsunami target structural reliability values are given in the last row of Table 5, for use in performance-based engineering of structural components designed to meet the intent of ASCE 7-16, Chapter 6 - Tsunami Loads and Effects.

Table 5. Summary of Target Reliabilities of the ASCE 7 Tsunami Design Provisions

Basis	**Measure of Reliability**	**Tsunami Risk Category II I = 1.0**	**Tsunami Risk Category III I = 1.25**	**Tsunami Risk Category IV I = 1.25**	**Tsunami Vertical Evacuation Refuge RC IV I = 1.25 & 1.3h_n**
Average Reliabilities	Reliability index, β	2.74	2.87	3.03	3.68
	$P_{f\ 50\text{-year}}$	0.31%	0.21%	0.13%	0.05%
Component Failure conditioned on the occurrence of the MCT	Reliability index, β	1.44	1.65	1.92	2.43
	Probability of component failure	**7.5%**	**5%**	**3%**	**<1%**

4. Acknowledgements

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