Reliability Analysis of Structures Designed in Accordance with ASCE 7, when Subjected to Tsunami and Earthquake Effects

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Tohoku Tsunami photograph at Minami Soma by Sadatsugu Tomizawa

Background Information on the Development of a Tsunami Code

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- A U.S. national standard for engineering design for tsunami effects does not exist. As a result, tsunami risk to coastal zone construction is not explicitly addressed in design.
- The Tsunami Loads and Effects Subcommittee of the ASCE/SEI 7 Standards Committee has developed a new Chapter 6 - Tsunami Loads and Effects for the ASCE 7-16 Standard, which has been passed and is pending approval.
- ASCE 7-16 to be published by March 2016
- Tsunami Provisions would then be referenced in IBC 2018
- State Building Codes of AK, WA, OR, CA, and HI ~ 2020
- ASCE will be publishing a design guide in 2015 with design examples.

ASCE 7 Chapter 6

- 6.1 General Requirements
- 6.2-6.3 Definitions, Symbols and Notation
- 6.4 Tsunami Risk Categories
- 6.5 Analysis of Design Inundation Depth and Velocity
- 6.6 Inundation Depth and Flow Velocity Based on Runup
- 6.7 Inundation Depth and Flow Velocity Based on Site-Specific Probabilistic Tsunami Hazard Analysis
- 6.8 Structural Design Procedures for Tsunami Effects
- 6.9 Hydrostatic Loads
- 6.10 Hydrodynamic Loads
- 6.11 Debris Impact Loads
- 6.12 Foundation Design
- 6.13 Structural Countermeasures for Tsunami Loading
- 6.14 Tsunami Vertical Evacuation Refuge Structures
- 6.15 Designated Nonstructural Systems
- 6.16 Non-Building Structures

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Tsunami Loads and Effects

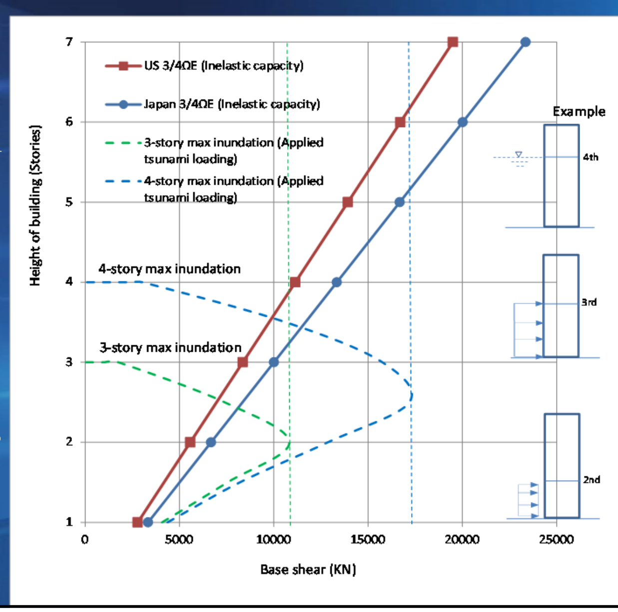
- Hydrostatic Forces (equations of the form $k_s \rho_{sw} gh$)
  - Unbalanced Lateral Forces at initial flooding
  - Buoyant Uplift based on displaced volume
  - Residual Water Surcharge Loads on Elevated Floors
- Hydrodynamic Forces (equations of the form $\frac{1}{2} k_s \rho_{sw} (hu^2)$)
  - ***Drag Forces – per drag coefficient C_d based on size and element***
  - Lateral Impulsive Forces of Tsunami Bores or Broad Walls: Factor of 1.5
  - Hydrodynamic Pressurization by Stagnated Flow – per Benoulli
  - Shock pressure effect of entrapped bore – (this is a special case)
- Waterborne Debris Impact Forces (flow speed and √mass)
  - Poles, passenger vehicles, medium boulders always applied
  - Shipping containers, boats if structure is in proximity to hazard zone
  - Extraordinary impacts of ships only where in proximity to Risk Category III & IV structures
- Scour Effects (mostly prescriptive based on flow depth)

Tsunami design criteria for Resistance R is based on the 2500-year MRI Maximum Considered Tsunami without any load factor.

- The Maximum Considered Tsunami (MCT) has 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, characterized by the inundation depths and flow velocities at the stages of in-flow and outflow most critical to the structure.
- The Tsunami Design Zone is the area vulnerable to being flooded or inundated by the Maximum Considered Tsunami. The runup for this hazard probability is used to define a Tsunami Design Zone map.

Comparing Minimal High-Seismic Design of System @ 0.75Ω Overstrength to Maximum Overall Tsunami Loading

- Most buildings subject to these requirements will be designed to Seismic Design Category D or greater.
- Tsunami provisions apply to RCII buildings ≥ 65 ft. tall



PTHA determines the MCT

Probabilistic Seismic Hazard Analysis		Probabilistic Tsunami Hazard Analysis
Moment Magnitude, Source Locations, and Recurrence based on Seismology	SOURCE	Moment Magnitude and Slip, Source Locations, and Recurrence based on Seismology
Ground Motion parameters obtained at site using empirical attenuation from source	PROPAGATION	Propagation per long wave equations in deep ocean to determine amplitude and period at offshore locations
Nonlinear site analysis accounts for local soil conditions, results prescriptively incorporated into response spectrum of design parameters	SITE ANALYSIS of DESIGN PARAMETERS	Inundation limit and Runup determined by nonlinear wave propagation models
Probabilistic Maps of Spectral Accelerations for 50 states	DESIGN MAPS	Probabilistic Maps of Offshore Amplitude, Inundation Limit and Runup for 5 states

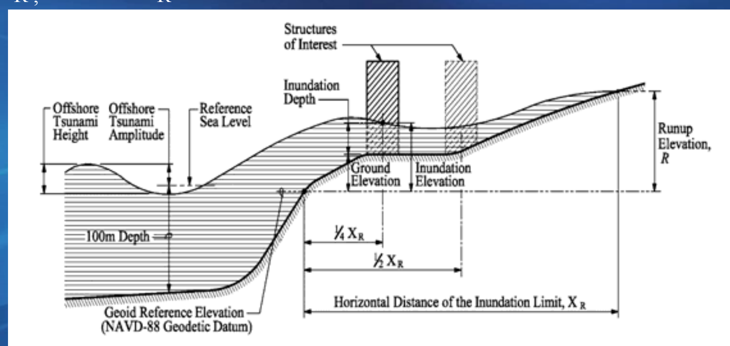
Reliability Analysis of Structures Designed in Accordance with ASCE 7 Tsunami Chapter Hydrodynamic Forces

- Probabilistic limit state reliabilities have been 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) are validated for tsunami loads

Representative Sites

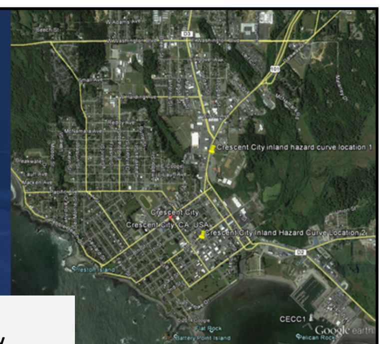
- Sites
- California (Huntington Beach – flatter terrain), where
  - x=0.25 x_R , and 0.5x_R
- b) Pacific Northwest (Crescent City – enhanced runup), where
  - x=0.25 x_R , and 0.5x_R

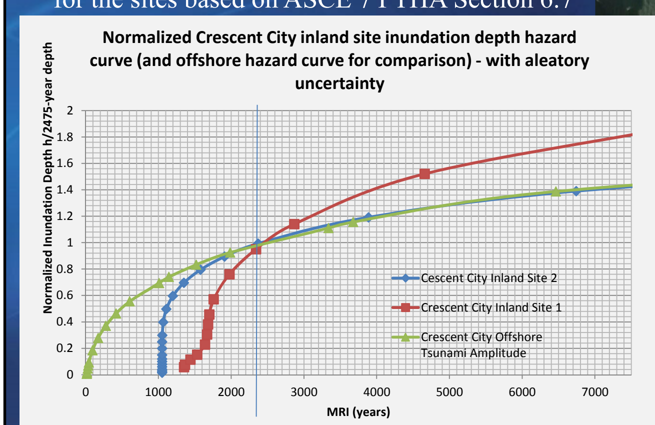
$$F_r = \alpha(1 - \frac{x}{x_R})^{0.5}$$



Crescent City Example of Probabilistic Hazard

- Normalized Inundation Depth
- Hong Kie Thio provided prototypical offshore tsunami amplitude hazard curve and associated onshore tsunami inundation depth hazard curve for the sites based on ASCE 7 PTHA Section 6.7





Representative Buildings

- Tsunami Risk Category:
  - Tsunami Risk Category II building
  - Tsunami Risk Category III and IV buildings
  - Tsunami Vertical Evacuation Refuge Structure, Risk Category IV, with reliability equation adjusted for the prescribed I_{tsu} and 1.3h inundation depth requirements
- Building Structure:
  - 6 to 7-story reinforced concrete
  - Gravity-Load-Carrying Columns
  - Note: tsunami loads are sustained
  - Reliability analysis is for critical gravity-load carrying vertical components whose failure could result in partial collapses

Risk Categories of Buildings and Other Structures per ASCE 7

Not all structures within the TDZ are subject to the provisions

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, the failure of which could pose a substantial risk to human life.** **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** **Buildings and other structures, the failure of which could pose a substantial hazard to the community.**

- **The tsunami provisions target the performance of Risk Category III and IV and taller Risk Category II structures**

Importance Factors I_{TSU}

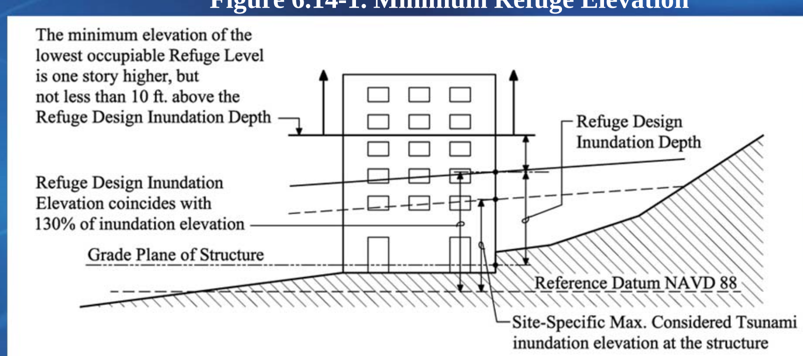
- Takes into account reliability analysis including the requirement to conduct Site-Specific Inundation Analysis for Risk Category IV, Vertical Evacuation Refuges, and Designated Risk Category III Critical Facilities

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

Tsunami Vertical Evacuation Refuge Structures

- Tsunami Vertical Evacuation Refuge Structures - ASCE 7 Chapter 6 is intended to supersede both FEMA P646 structural guidelines and IBC Appendix M – P646 vastly underestimates hydrodynamic forces and vastly overestimates debris impact forces

Figure 6.14-1. Minimum Refuge Elevation



Design Values of Inundation Depth and Flow Velocity *(hu^2)*

- There are two procedures for determining the MCT inundation depth and velocities at a site:
  1. Energy Grade Line (EGL) Analysis
  2. Site-Specific Inundation Analysis
- Energy Grade Line Analysis is fundamentally a hydraulic analysis along the topographic transect from the shore line to the runup point.
- Site-Specific Inundation Analysis utilizes the Offshore Tsunami Amplitude for a numerical simulation that includes a higher-resolution digital elevation model of nearshore bathymetry and onshore topography.
  - Site-Specific Inundation Analysis is required for Risk Category IV structures

Normalized Hydrodynamic Load and Resistance

The primary hydrodynamic load is lateral pressure on vertical elements

- Fundamental Limit State Equation

$$\frac{\frac{1}{2}\rho_s C_d b(h_e u^2)}{\frac{1}{2}\rho_{sn} C_{dn} b_n (h_e u^2)_n I_{tsu}} \leq \frac{R}{\emptyset R_n}$$

Parameters

- C_d/C_{dn} is assumed to be constant = 1.0 unbiased
- *Density:* ρ_s/ρ_{sn} is assumed to be with Normal Distribution with mean = 1.0 and a COV = 0.03.
- *Closure Ratio:* b/b_n is also assumed to uniformly distributed. To account for assorted debris accumulation, for buildings initially clad, the designer can conservatively assume only 30% of this becomes "open". Actual accumulation is estimated to be in the range of creating a 40% to 60% closure ratio, rather than the prescribed 70% as used for design
- *Inundation Depth* $\frac{h_e}{h_{en}}$ is sampled from the CDF of maximum inundation depth hazard curve

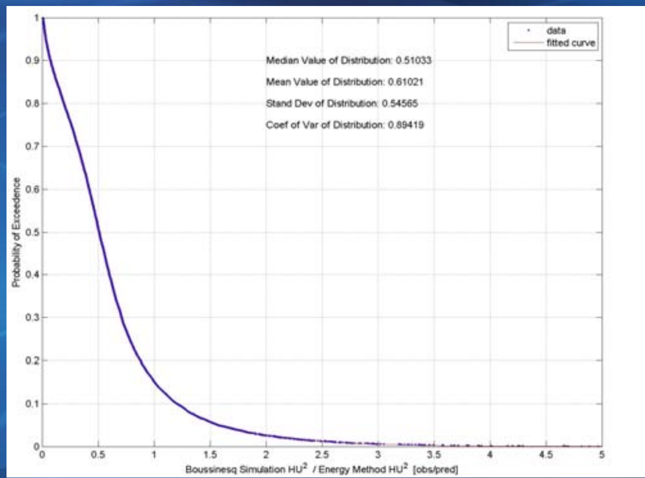
Parameters

$$\frac{\lambda}{\lambda_n}\frac{R}{\phi R_n} = \frac{\rho_s}{\rho_{s\,n}}\frac{C_d}{C_{dn}}\frac{b}{b_n}\psi\varepsilon^2\left(\frac{h}{h_o}\right)^2\frac{1.0}{\mathrm{I}_{\mathrm{tsu}}}$$

- ε accounts for the net aleatory uncertainties in estimated inundation depth (modeled with a lognormal distribution (mean of 1.06 and ζ =0.36 for EGL, 0.30 for Site-Specific)
- ψ is a variable to account for the statistical bias in the nominal solution (i.e., code-specified **Energy Grade Line Analysis**) vs. numerical model (Observed value). it is specified to be a one sigma increase of the mean hazard curve. (Data from 36,000 simulations by Pat Lynett)
- Tsunami Importance Factor I_{tsu} is the specified bias factor that is a constant for each Tsunami Risk Category.

Intentional Statistical Bias in the EGL momentum flux

- The estimate of the COV of the EGL data from the simulations for a given nominal numerical momentum flux, are:
- Observed/nominal mean value: 0.61021 Coefficient of Variation: 0.8942



Monte Carlo Simulation (7 DOF)

$$\frac{\lambda}{\lambda_n}\frac{R}{\phi R_n} > \frac{\rho_s}{\rho_{s\,n}}\frac{C_d}{C_{dn}}\frac{b}{b_n}\psi\varepsilon^2\left(\frac{h}{h_o}\right)^2\frac{1.0}{\mathrm{I_{tsu}}}$$

- Reliabilities were calculated using Monte Carlo simulation involving a million to 50 million trial combinations of random variables independently occurring in proportion to their statistical distributions of 7 parameters ρ, b, h, ε, ψ, and λ, R

1. Randomly generate a value for each random variable in the limit state equation. The inundation depth is sampled from its CDF curve which is derived from the probabilistic tsunami hazard curve for the representative sites.
2. Calculate Z = R – S. If Z < 0, then the simulated member fails.
3. Repeat Steps 1 and 2 until a predetermined number of simulation is 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 $\beta = \varphi^{-1}(1-P_f)$.

7 Statistical Parameters & 3 scalars - Summary

Parameter	Mean	COV (sigma/mean)	Distribution
ρ/ρn (density)	1.0	0.03	Normal
b/b_n (closure)	0.714	0.124	Uniform
ε (aleatory uncertainty of hazard analysis)	1.06 (Median 1.0)	sigma =0.36 COV= 0.34 (EGL)	Lognormal
ψ (epistemic uncertainty of EGL momentum flux)	0.610	0.894	Empirical curve derived from 36,000 numerical simulations
$\frac{h_e}{h_{en}}$ (inundation depth)	PTHA Hazard Curve		
R/R_n (Resistance)	1.05	0.11	Normal
Resistance factor	0.9		Scalar
λ/λ_n (beam-column effect)	1.15	COV = 0.17	Lognormal
I (Importance Factor)	Constant in accordance with Tsunami Risk Category		
Vertical Evacuation Structure	h_{en} increased by 1.3		Scalar

Reliabilities

Site		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**	**2.74**	**2.87**	**3.03**	**3.68**
	$P_{f\ annual}$	$6.1x10^{-5}$	$4.1x10^{-5}$	$2.6x10^{-5}$	$9.2x10^{-6}$
	$P_{f\ 50\text{-}year}$	**0.31%**	**0.21%**	**0.13%**	**0.05%**
Failure conditioned on the occurrence of the MCT	**Reliability index**	1.44	1.66	1.93	2.40
	Maximum probability of failure	**7.5%**	**4.9%**	**2.7%**	**0.82%**

Anticipated reliability (maximum probability of systemic failure) for earthquake

Risk Category	Probability of failure in 50-years	Failure probability conditioned on Maximum Considered Earthquake shaking
II (Total or partial structural collapse)	1%	10%
III (Total or partial structural collapse)	0.5%	5-6%
IV (Total or partial structural collapse)	0.3%	2.5-3%

Component Reliabilities for Tsunami Vertical Gravity-Load Carrying Members (MCT) vs. System Pushover Reliabilities for Seismic (MCE)

- Conditional Probabilities of limit state exceedance
  - II: 7.5% $_{(MCT)}$ vs 10% $_{(MCE)}$,
  - III: 4.9% $_{(MCT)}$ vs. 5% $_{(MCE)}$, and
  - IV: 2.7% $_{(MCT)}$ vs. 2.5% $_{(MCE)}$
  - Tsunami Vertical Evacuation Refuge Structure <1% $_{(MCT)}$
- The 50-year exceedance of limit state probabilities are:
  - , II: 0.3% $_{(MCT)}$ vs 1% $_{(MCE)}$,
  - III: 0.2% $_{(MCT)}$ vs. 0.5% $_{(MCE)}$, and
  - IV: 0.13% $_{(MCT)}$ vs. 0.3% $_{(MCE)}$.

Conclusions

- PTHA-based design criteria - The method of Probabilistic Tsunami Hazard Analysis is consistent with probabilistic seismic hazard analysis in the treatment of uncertainty.
- **The conditional vertical load-carrying component reliabilities for the Maximum Considered Tsunami (MCT) are nearly equivalent to those expected for seismic systemic pushover (MCE) effects.**