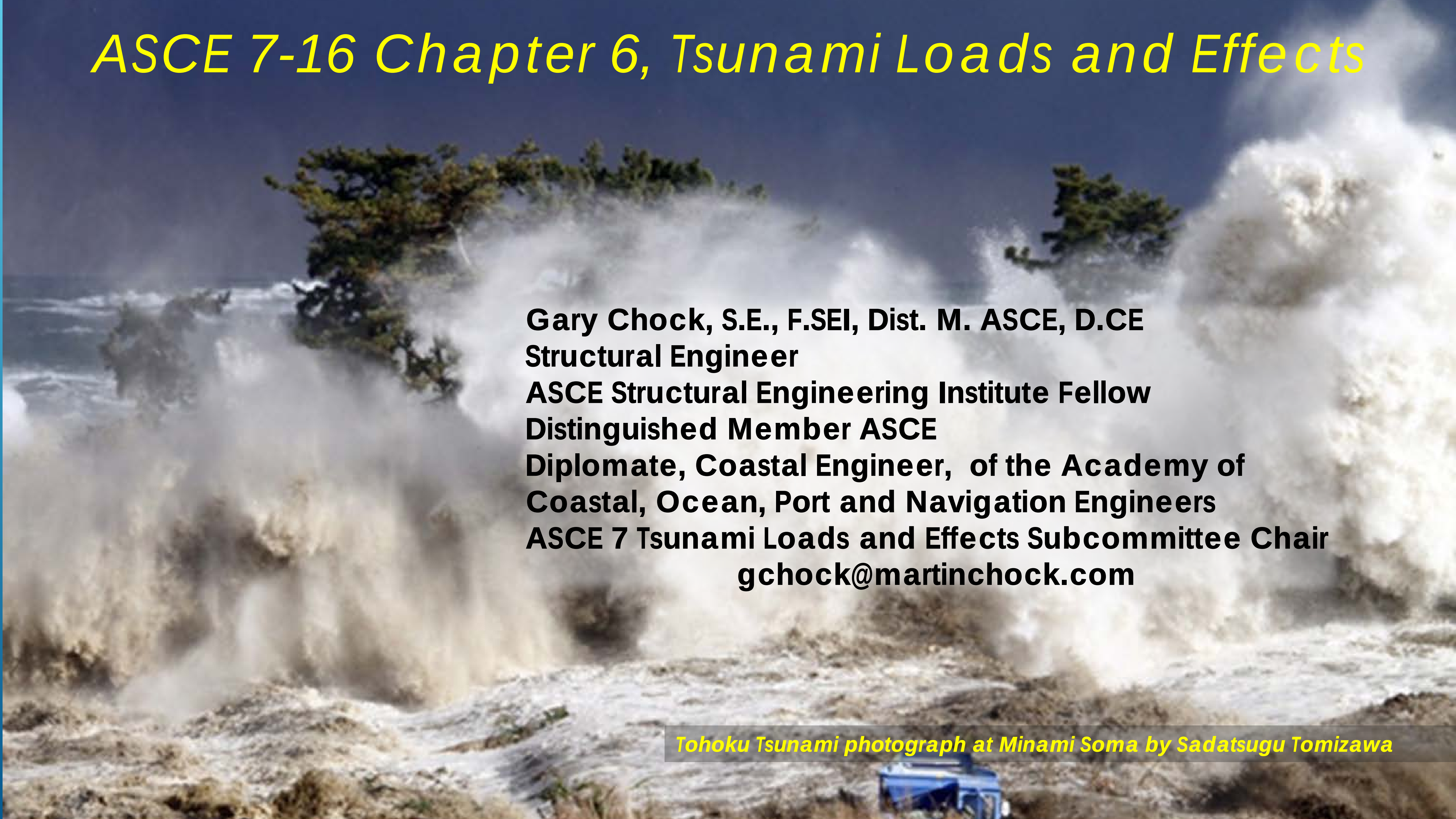
ASCE 7-16 Chapter 6, Tsunami Loads and Effects



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Tohoku Tsunami photograph at Minami Soma by Sadatsugu Tomizawa

THE PURSUIT OF DISASTER RESILIENCE

- **Resilience is *the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events.***
- Address coastal hazards consistently in planning and design
- Provide for a survivable core of critical infrastructure and safe buildings
- Return critical facilities to functional status more quickly
- Enable faster recovery

ELEMENTS FOR CODE DEVELOPMENT

Research & Development

Experience from Design Practice and Post-Disaster Surveys

Codes and Standards

USA CODES AND STANDARDS

- **International Building Code (IBC)**
- **ASCE 7 Minimum Design Loads and Associated Criteria for Buildings and Other Structures (ASCE 7) is developed in an ANSI-accredited consensus process**
  - Other Standards:
    - Material specific design specifications
    - Non-structural installation standards
    - Testing and qualification standards

ASCE 7-16 TSUNAMI LOADS & EFFECTS

The ASCE 7-16 Chapter 6– Tsunami Loads and Effects is applicable to the five western states of the USA. (Alaska, Washington, Oregon, California, Hawaii

It will improve resilience of communities for the tsunamis risk in the areas of:

- **Planning and Siting**
- **Structural Design**
- **Post-disaster reconstruction to Build Back Better**

- **ASCE Tsunami Design Geodatabase**
  - Maps, parameters, and criteria in the ASCE 7 design standard are based on engineering risk analysis and reliability targets, rather than deterministic scenarios.
  - Tsunami Design Zone (TDZ) Maps based on 2500^{+} -yr Maximum Considered Tsunami (MCT) from probabilistically aggregated sources

TSUNAMI-RESILIENT ENGINEERING SUBJECT MATTER INCORPORATED IN ASCE 7

Scope of ASCE 7 Chapter 6

Sources and Frequency — Consensus on Seismic Source Assessment by USGS

Tsunami Generation
Distant and Local Subduction Zones

Open Ocean Propagation

Offshore Tsunami Amplitude

Coastal Inundation and Flow Velocities

Maps based on Probabilistic Tsunami Hazard Analysis (PTHA)

Tsunami inundation Modeling to Define Tsunami Design Zones

Fluid-Structure Interaction

Structural Loading

Structural Response

Scour and Erosion

Loads and Effects incorporating Coastal, Hydraulic, Structural, and Geotechnical Engineering

Performance by Risk Category — Structural Reliability Validated

Consequences
(Life and economic losses)

Warning and Evacuation Capability

Design for Tsunami Resilience

TSUNAMI RESILIENT ENGINEERING BASIS

- The lesson of recent devastating tsunamis is that historical records alone do <u>not</u> provide a sufficient measure of the potential heights of future tsunamis.
- A Probabilistic Tsunami Hazard Analysis methodology was used for the ASCE 7-16 Tsunami Design Geodatabase
- The ASCE 7-16 tsunami design provisions are based on a reliability-based standard of structural performance for disaster resilience of essential facilities and critical infrastructure.

TIMELINE of Development of Tsunami Design in the USA

ASCE 7 TSUNAMI LOADS AND EFFECTS

THE NEW NATIONAL STANDARD OF PRACTICE FOR PROFESSIONAL ENGINEERS

- **Subcommittee of 16 members and 14 associate members formed in February 2011 (Chair: Gary Chock, S.E.)**
- **Met 4-5 times per year for three years to develop draft provisions (26 pages of code; 42 pages of commentary)**
- **Processed 8 consensus ballots through ASCE 7 main committee addressing over 1500 comments**
- **Final version issued for public comment in Fall 2015; Addressed public comments.**
- **Officially approved as ASCE 7-16 Chapter 6 on March 11, 2016**
- **Approved by ICC for inclusion by reference in IBC 2018 requirements**
- **Adoptions by 5 Western States (AK, WA, OR, CA, and HI) about 2020 – (2018 in Hawaii, 2019 in California).**
- **ASCE will be publishing a design guide in 2020 with numerous design examples.**

ASCE 7 CHAPTER 6- TSUNAMI LOADS AND EFFECTS

6.1 General Requirements

6.2-6.3 Definitions, Symbols and Notation

6.4 Tsunami Risk Categories

GENERAL INFORMATION – WHAT BUILDINGS ARE SUBJECT TO CHAPTER 6

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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HAZARD DETERMINATION AT BUILDING SITE (I.E. DEPTH & VELOCITY)

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BUILDING DESIGN FORCES & REQUIREMENTS

ASCE TSUNAMI-RESILIENT DESIGN PROCESS

- Select a site appropriate and necessary for the structure
- Select an appropriate structural system mindful of configuration and perform seismic and wind design first
- Determine the maximum flow depth and velocities at the site based on mapped Runup based on probabilistic tsunami hazard analysis.
- Check robustness of expected strength within the inundation height to resist hydrostatic and hydrodynamic forces
- Check resistance of lower elements for hydrodynamic pressures and debris impacts to avoid progressive collapse
- Design foundations to resist scour and potential uplift
- Elevate critical equipment as necessary

SCOPE AND GENERAL REQUIREMENTS

Application in accordance with Risk Categories

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, 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)***

CONSEQUENCE GUIDANCE ON RISK CATEGORIES OF BUILDINGS PER ASCE 7

Risk Category I	**Up to 2 persons affected** (e.g., agricultural and minor storage facilities, etc.)
Risk Category II (Tsunami Design Optional)	**Approximately 3 to 300 persons affected** (e.g., Office buildings, condominiums, hotels, etc.)
Risk Category III (Tsunami Design Required)	**Approximately 300 to 5,000+ affected** (e.g., Public assembly halls, arenas, high occupancy educational facilities, public utility facilities, etc.)
Risk Category IV (Tsunami Design Required)	**Over 5,000 persons affected** (e.g., hospitals and emergency shelters, emergency operations centers, first responder facilities, air traffic control, toxic material storage, etc.)

SCOPE OF CHAPTER 6

The following buildings and other structures located within the Tsunami Design Zone shall be designed for the effects of Maximum Considered Tsunami .... :

a. **Tsunami Risk Category IV buildings and structures;**

b. **Tsunami Risk Category III buildings and structures with inundation depth at any point greater than 3 feet, and**

c. **Where required by a state or locally adopted building code statute to include design for tsunami effects, Tsunami Risk Category II buildings with mean height above grade plane greater than the height designated in the statute, and having inundation depth at any point greater than 3 feet.**

Exception: Tsunami Risk Category II single-story buildings of any height without mezzanines or any occupiable roof level, and not having any critical equipment or systems need not be designed for the tsunami loads and effects specified in this Chapter.

PROBABILISTIC TSUNAMI HAZARD ANALYSIS

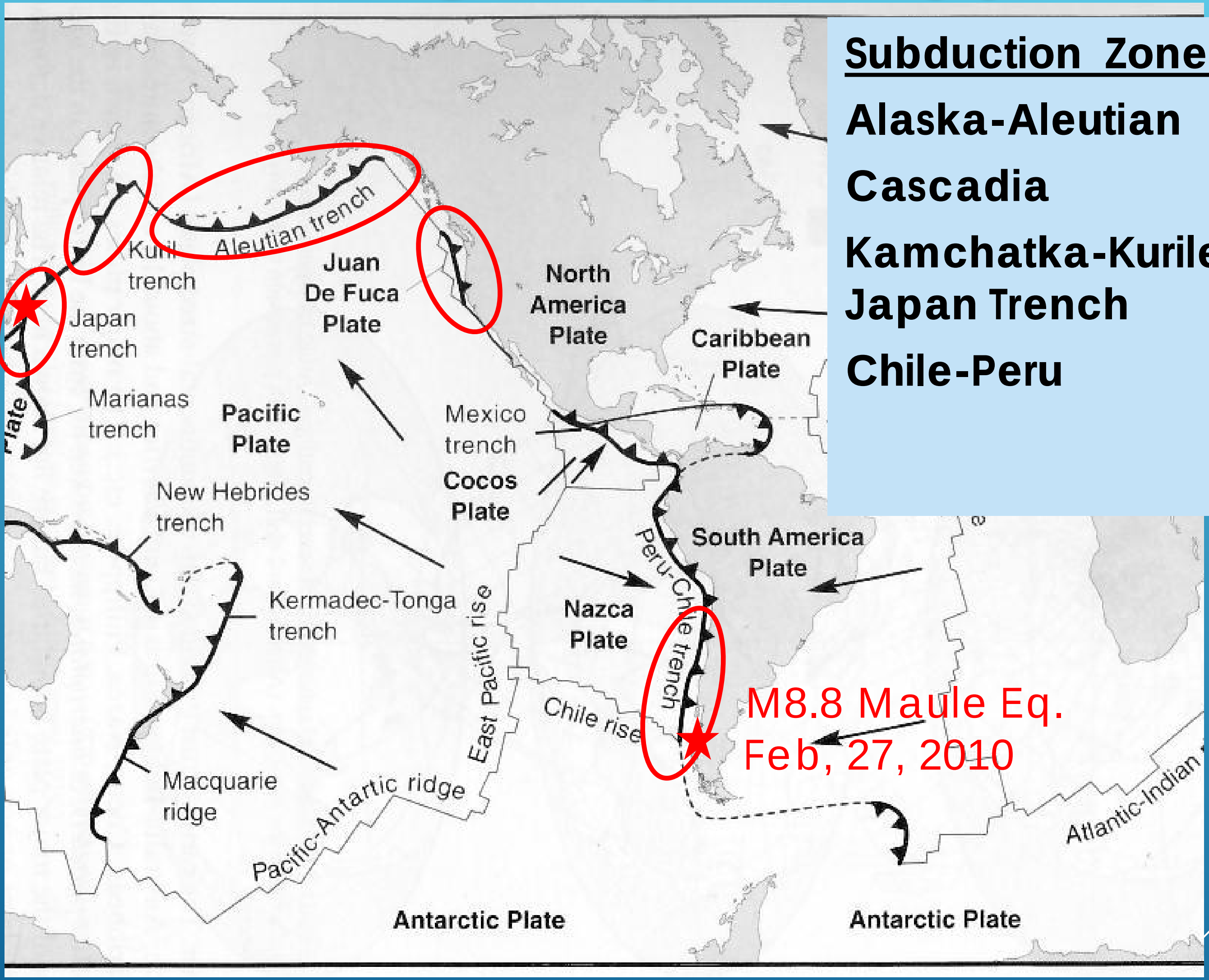
The ASCE Tsunami Design Geodatabase for the Maximum Considered Tsunami

MCT AND TSUNAMI DESIGN ZONE

- 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.

TSUNAMI-GENIC SEISMIC SOURCES OF PRINCIPAL RELEVANCE TO THE USA

M9.0 Great East Japan Eq. Mar, 11, 2011



Subduction Zones

Alaska-Aleutian

Cascadia

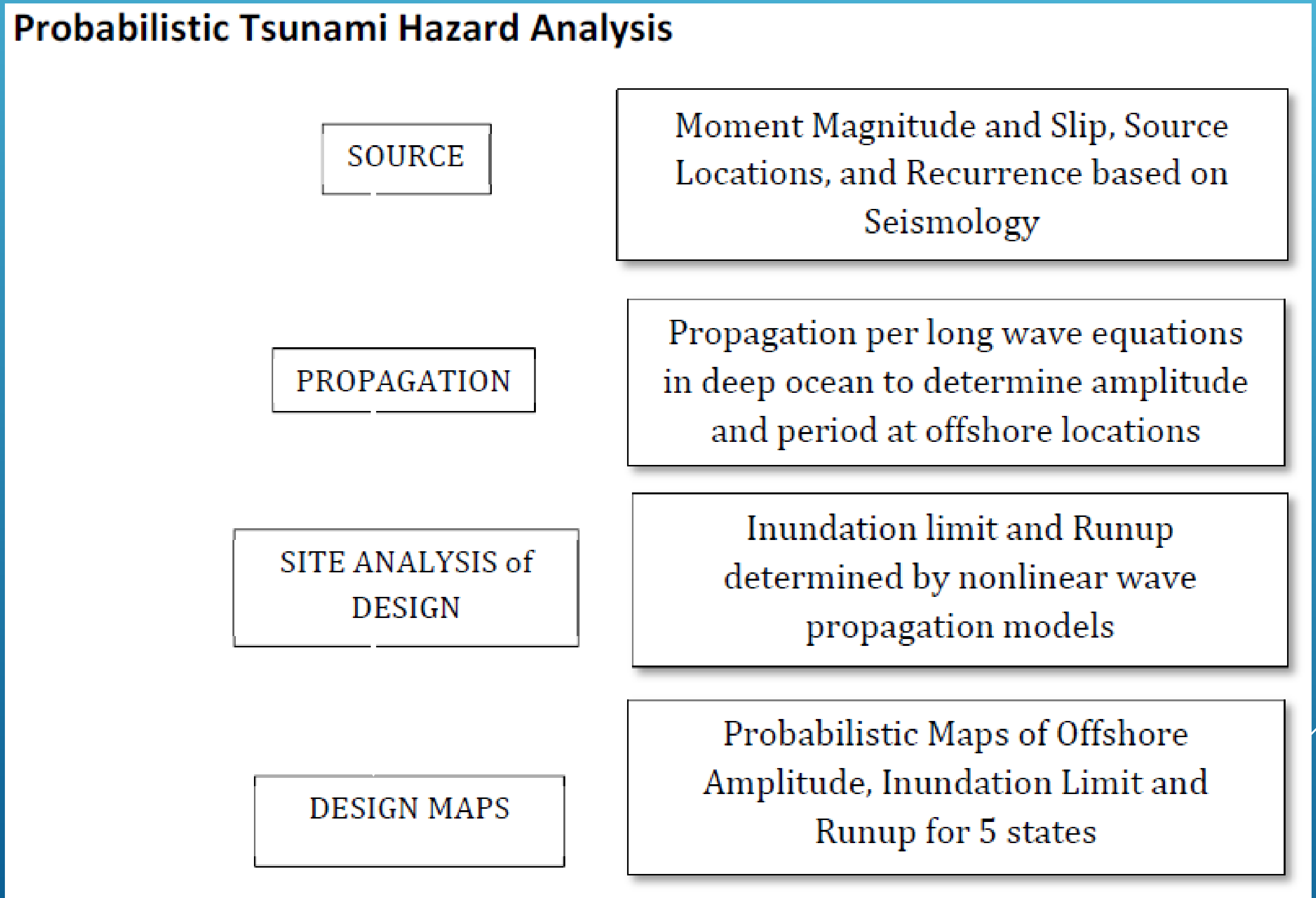
Kamchatka-Kuriles & Japan Trench

Chile-Peru

M8.8 Maule Eq. Feb, 27, 2010

PTHA DERIVED MAX. CONSIDERED TSUNAMI

- The ASCE PTHA procedure was peer reviewed by a broad stakeholder group convened by the NOAA National Tsunami Hazard Mitigation Program, and included independent comparative pilot studies.
- Subduction Zone Earthquake Sources are consistent with USGS Probabilistic Seismic Hazard model.



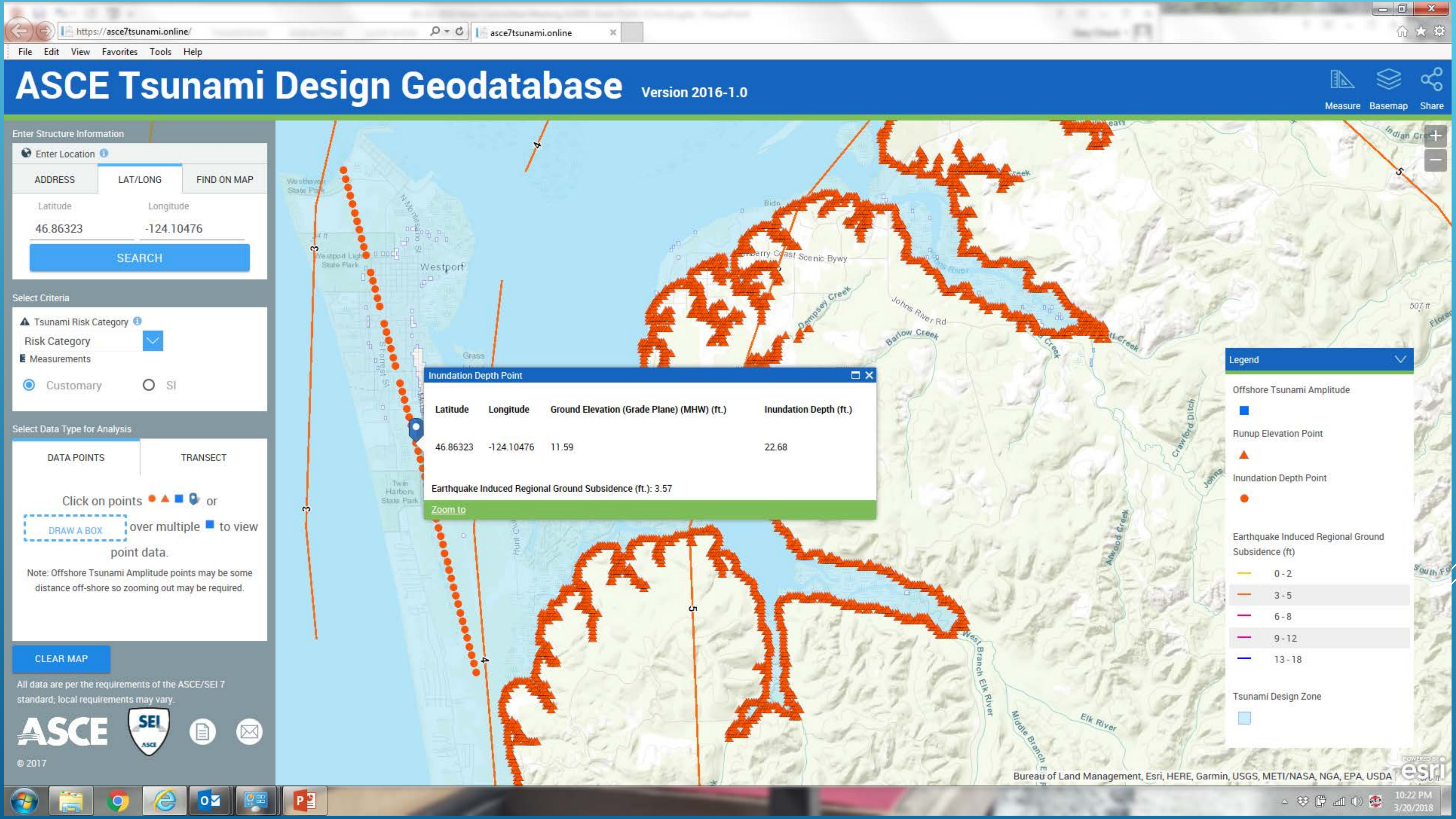
HOW THE PTHA AND TDZ BASIS OF DESIGN ARE INTEGRATED INTO THE ASCE STRUCTURAL DESIGN PROCESS

- PTHA-based design criteria - The method of Probabilistic Tsunami Hazard Analysis is consistent with probabilistic seismic hazard analysis in the treatment of uncertainty.
- Maximum Considered Tsunami – 2500-year MRI
- Probabilistic Offshore Tsunami Amplitude maps and Tsunami Design Zone inundation maps
- Tsunami inundation mapping is based on using these probabilistic values of Offshore Tsunami Amplitude
- Hydraulic analysis or site-specific inundation analysis to determine site design flow conditions
- Physics-based fluid loads, debris loads, foundation demands

TSUNAMI DESIGN GEODATABASE IS HOSTED BY ASCE ON AN ELECTRONIC DATABASE

- Probabilistic Subsidence Maps
- PTHA Offshore Tsunami Amplitude and Predominant Period
- Disaggregated source figures
- Runup, or Inundation depth reference points for overwashed peninsulas and/or islands

ASCE TSUNAMI DESIGN GEODATABASE AS IMPLEMENTED HTTPS://ASCE7TSUNAMI.ONLINE/



CHARACTERIZING THE DESIGN INUNDATION DEPTH AND FLOW VELOCITIES AT A SITE IN THE TDZ

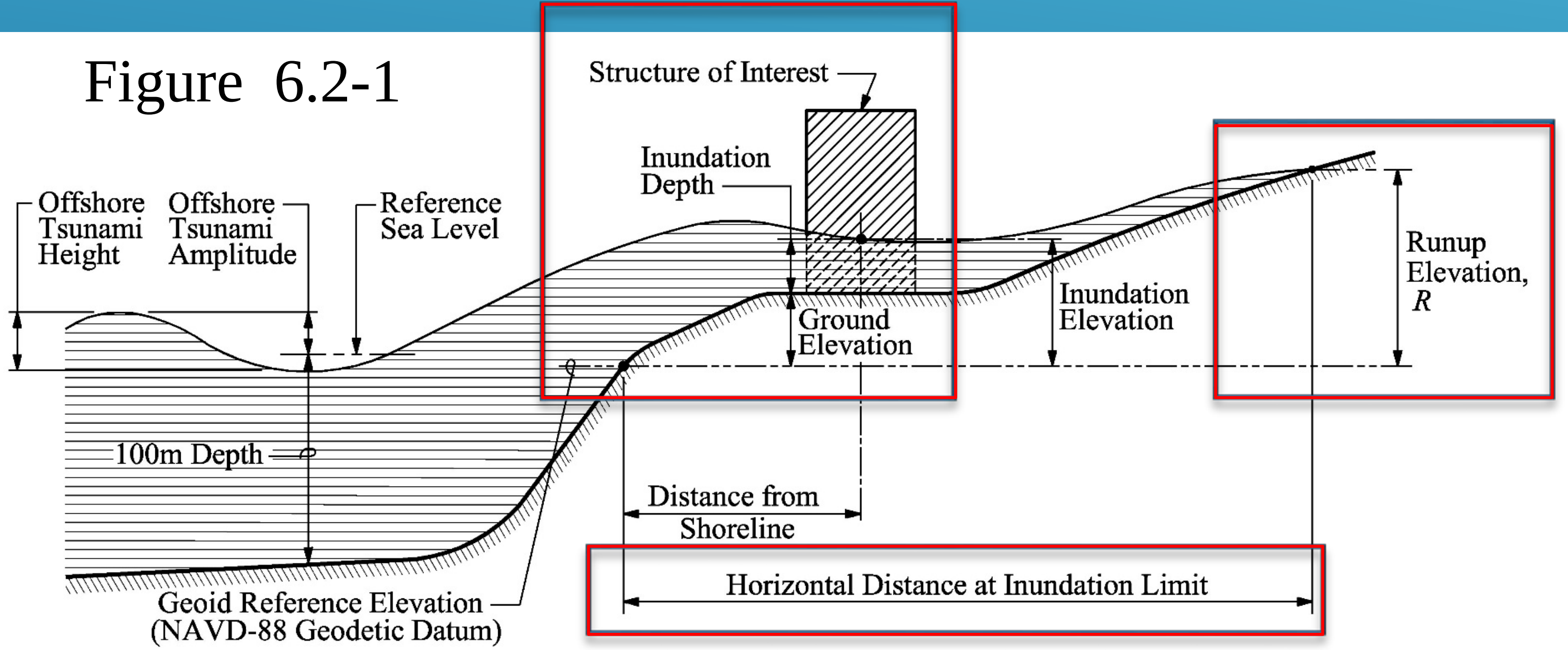
Energy Grade Line Analysis

Site-Specific Tsunami Inundation Analysis

Terminology

- **RUNUP ELEVATION:** Difference between the elevation of maximum tsunami inundation limit and the reference datum
- **INUNDATION DEPTH:** The depth of design tsunami water level with respect to the grade plane at the structure
- **INUNDATION LIMIT**: The horizontal inland distance from the shoreline inundated by the tsunami
- **Froude number:** F_r ; A dimensionless number defined by $u/\sqrt{(gh)}$, where u is the flow velocity and h is the inundation depth

Figure 6.2-1



TSUNAMI FLOW CHARACTERISTICS

Two approaches to determine flow depth and velocity

- **Energy Grade Line Analysis method, EGLA**
  - Developed by members of ASCE 7 Tsunami Loads and Effects Committee
  - Based on pre-calculated runup from the Tsunami Design Zone maps
  - Accumulation of energy lost through friction and altitude gain
  - Biased to provide slightly conservative hydrodynamic forces
- **Site-Specific Probabilistic Hazard Analysis**
  - Required for TRC IV
  - Optional for other TRCs
  - Velocity lower limit of 75-90% EGLA method

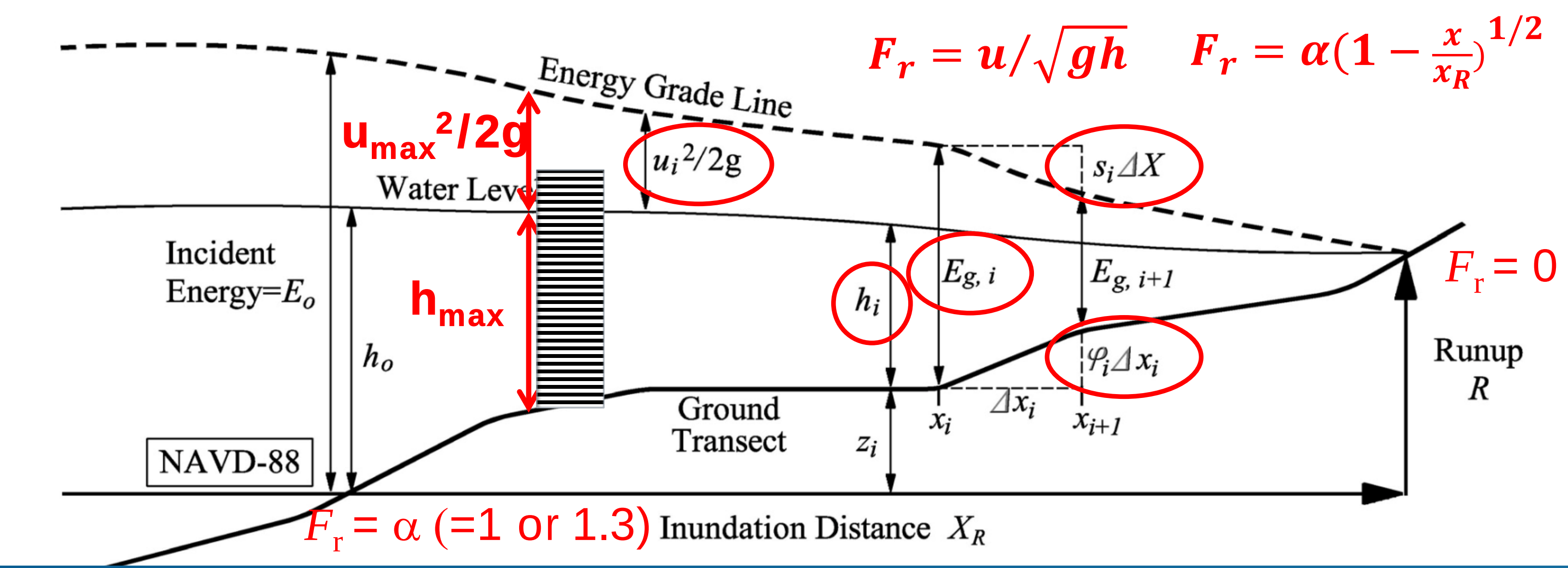
ENERGY GRADE LINE ANALYSIS

- **Re-accumulate the hydraulic head required to reach the inundation limit and runup elevation**
- **Sum the energy lost to altitude ($\varphi_i \Delta X_i$) and friction ($s_i \Delta X_i$) during inflow**

- **Total energy at any location along the transect is then:**

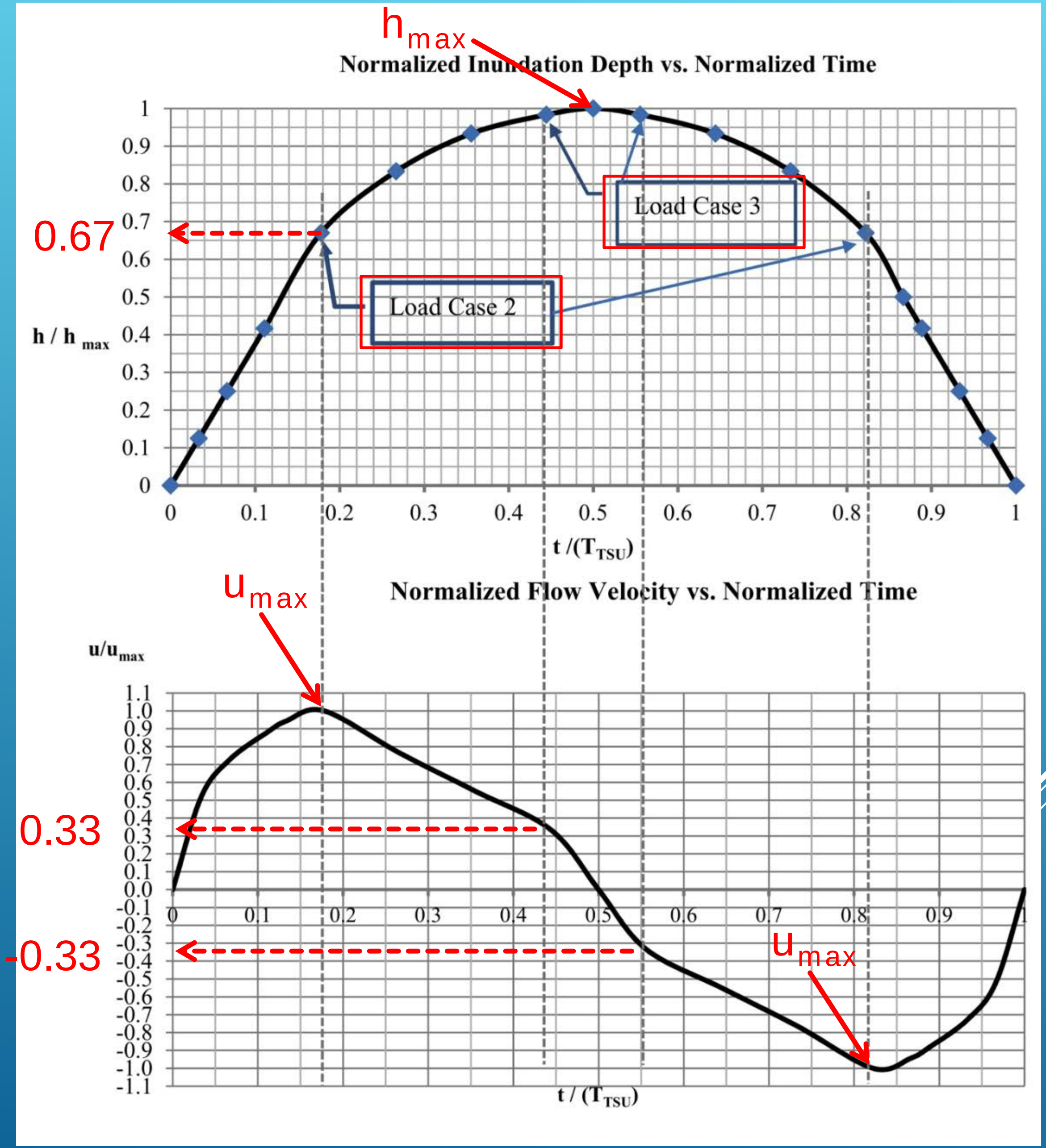
$$E_{g,i} = E_{g,i+1} + (\varphi_i + s_i)\Delta X_i$$

  - Validated to be conservative through field data & 36,000 numerical simulations yielding 700,000 data points



PRESCRIPTIVE LOAD CASES FOR DESIGN

- Normalized prototypical time history of depth and flow velocity as a function of the maximum values determined from the Energy Grade Line Analysis
- 3 discrete governing stages of flow
- Load Case 1 is a max. buoyancy check during initial flow
- LC 2 and 3 shown



SITE-SPECIFIC INUNDATION ANALYSIS

- Detailed site-specific inundation analysis is permitted in all cases, and is REQUIRED for RC IV structures and Tsunami Vertical Evacuation Refuge Structures
- Note, EGLA is always required, regardless of whether a detailed site-specific analysis is performed
- In general, site-specific modeling involves the use of a proven tsunami inundation model employed with high-resolution bathymetry and topography (typically 3.0-10.0 m resolution; 3.0 m or less must be used if attempting to resolve individual structures in the grid)
    - Models should include the physical processes relevant to tsunamis [6.7.6.4]
    - Models should include bottom friction / roughness (e.g. Mannings n ~0.025-0.03), unless otherwise justified based on previous validation
    - Models should be validated using historical data and the NOAA Tsunami Benchmarks [6.7.6.7.1, .2]
- Must match the Offshore Tsunami Amplitude specified in the ASCE Geodatabase.

TSUNAMI LOADS

- Hydrostatic Forces
  - Unbalanced Lateral Forces
  - Buoyant Uplift based on displaced volume
  - Residual Water Surcharge Loads on Elevated Floors
- Hydrodynamic Forces
  - Drag Forces – per drag coefficient C_d based on size and element
  - Lateral Impulsive Forces of Tsunami Bores on Broad Walls
  - Hydrodynamic Pressurization by Stagnated Flow
  - Shock pressure effect of entrapped bore
- Waterborne Debris Impact Forces
  - 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

TSUNAMI-SPECIFIC DESIGN CONDITIONS

- **Minimum Fluid Density** – prescribed with 10% increase accounting for debris-laden seawater
- **Directionality of Flow** – variation of flow shall be considered +-22.5 degrees
- **Minimum Closure Ratio** – accounts for the "piling-on" effect of copious tsunami debris to create more obstruction to flow than just the bare structure
- **Tsunami Bores,** criteria based on offshore bathymetry
- **Importance Factor,** based on the Tsunami Risk Category
- **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.

TYPES OF FLOATING DEBRIS
LOGS AND SHIPPING CONTAINERS

Power poles and tree trunks become floating logs

Shipping containers float even when fully loaded

CONDITIONS FOR WHICH DESIGN FOR DEBRIS IMPACT ARE EVALUATED

Debris	Buildings and Other Structures	Threshold Inundation depth
Poles, logs, passenger vehicles	All	3 ft (0.91 m)
Boulders and Concrete Debris	All	6 ft (1.8 m)
Shipping Containers	Where in proximity	3 ft (0.91 m)
Ships and/or barges	Tsunami Risk Category III Critical Facilities and Category IV	12 ft (3.6 m)

ASSESSMENT FOR CONTAINERS AND SHIPS

- Point source of debris
  - Shipping container yards
  - Ports with barges/ships

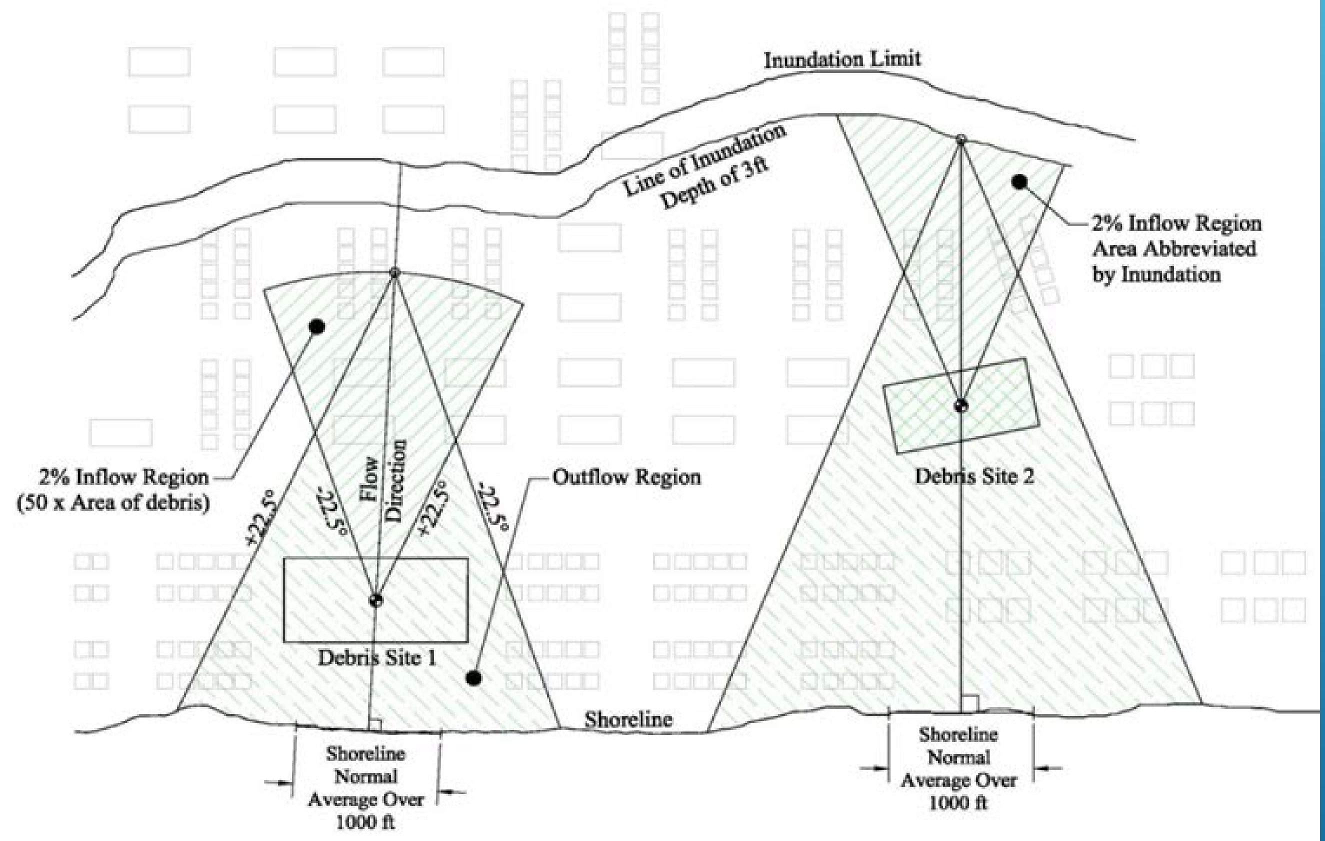


Figure 6.11-1

- Approximate probabilistic site assessment procedure based on proximity and amount of potential floating objects
  - Determine potential debris plan area
    - Number of containers * area of a container
  - 2% concentration defines debris dispersion zone

FOUNDATION DESIGN

- General Site Erosion
- Local Scour
- Plunging Scour (i.e., overtopping a wall)
- Under-seepage Forces
- Loss of Strength due to pore pressure softening during drawdown

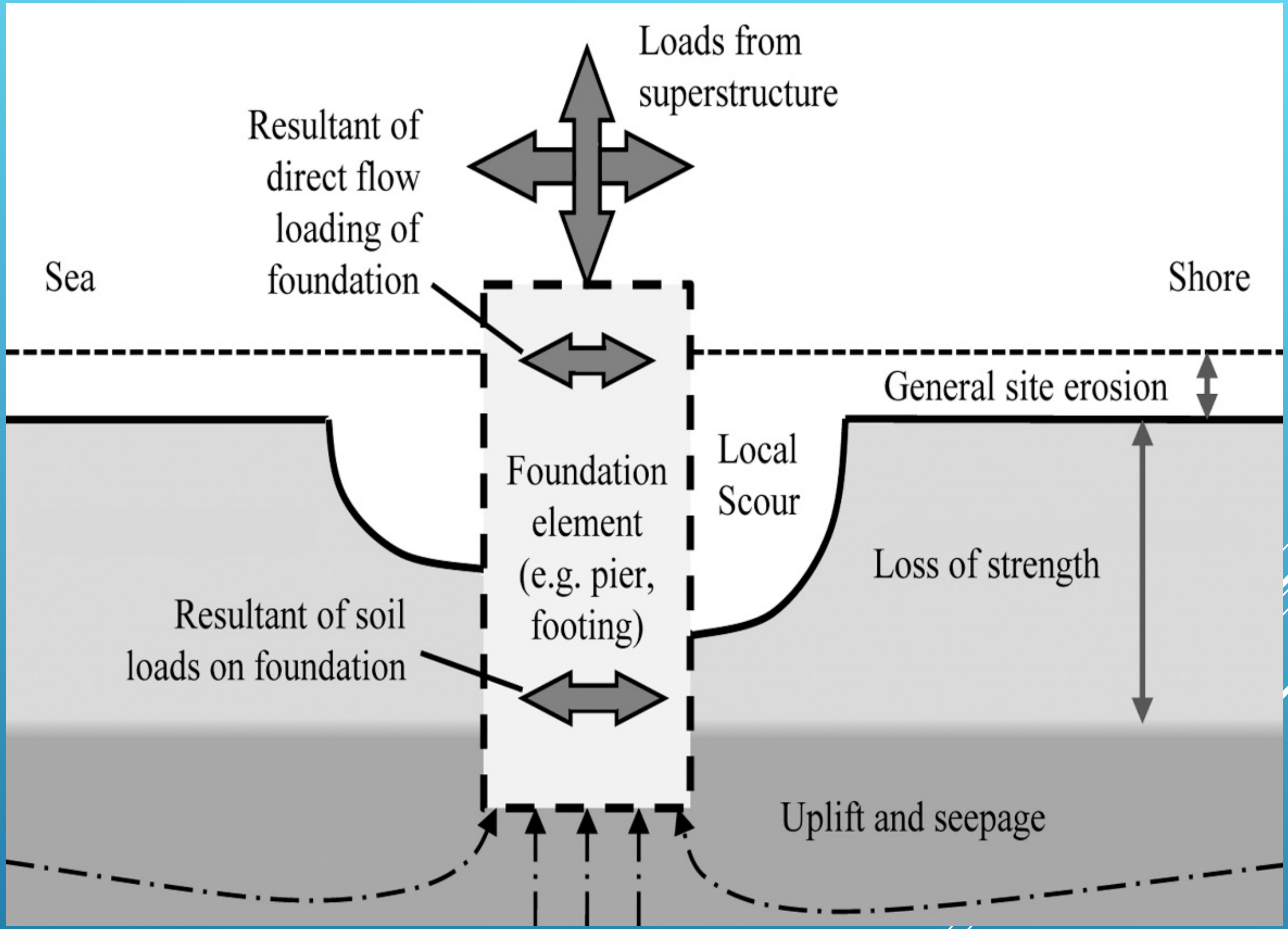


Figure C6.12-1. Schematic of tsunami loading condition for a foundation element

FOUNDATION DESIGN – SCOUR EXAMPLES

8-ft. Scour by inflow at Dormitory Bldg corner

- Scour by return flow around Minamisanriku Vert. Evacuation Apt. building

Onagawa scour during return flow from valleys

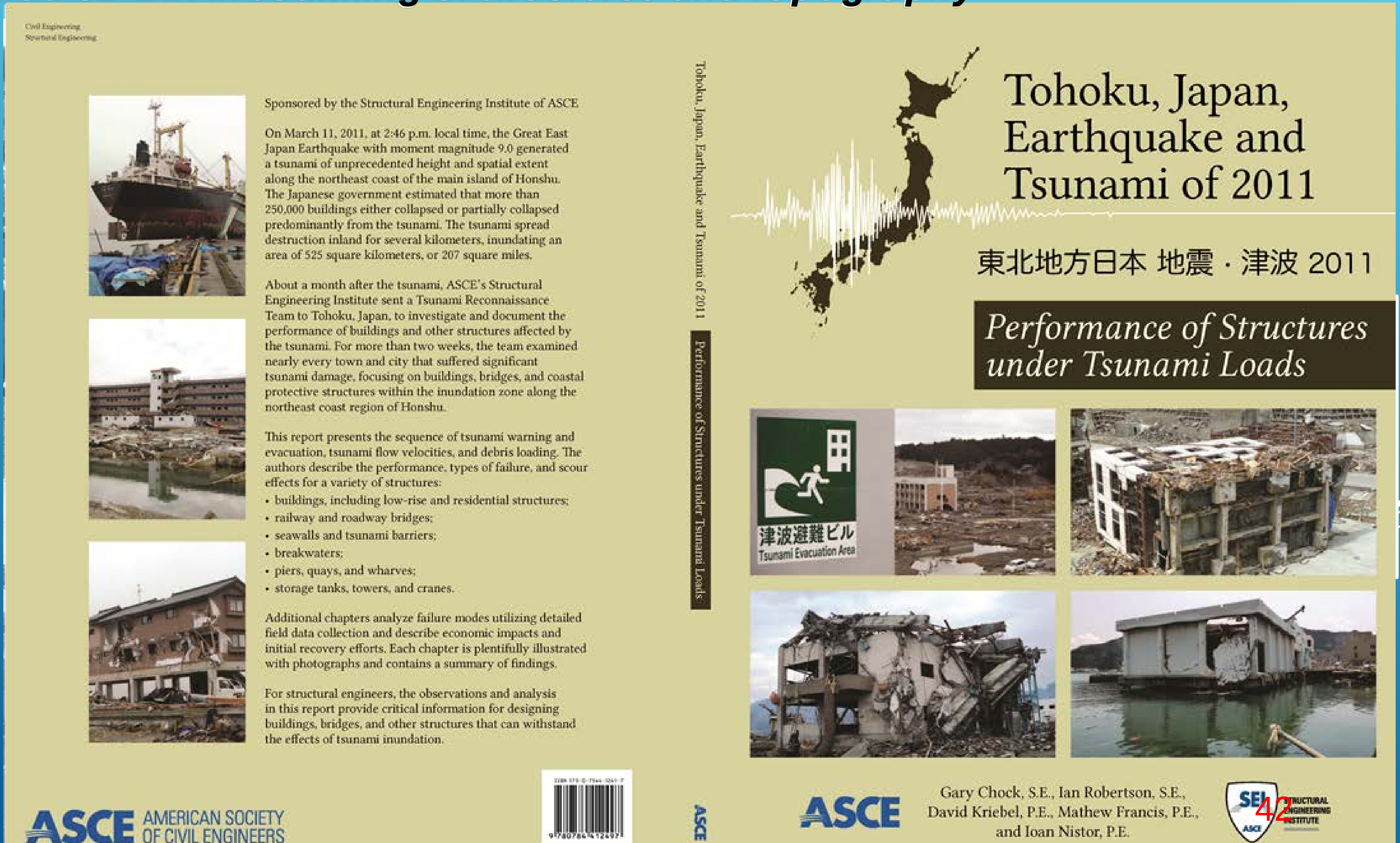
Miyako Bridge Abutment Scour

BUILDINGS SUBJECTED TO TSUNAMIS

Examples (Tohoku Japan)

東北地方津波 TOHOKU REGION TSUNAMI

The ASCE Tsunami Reconnaissance Team was the first independent international team in Japan in early April 2011 and was augmented by a second trip funded by NSF in July 2011 for detailed 3D LiDAR scanning of structures and topography



REPORT ON PERFORMANCE OF TALLER STRUCTURES IN JAPAN USED BY EVACUEES – (WHETHER DESIGNATED OR NOT)

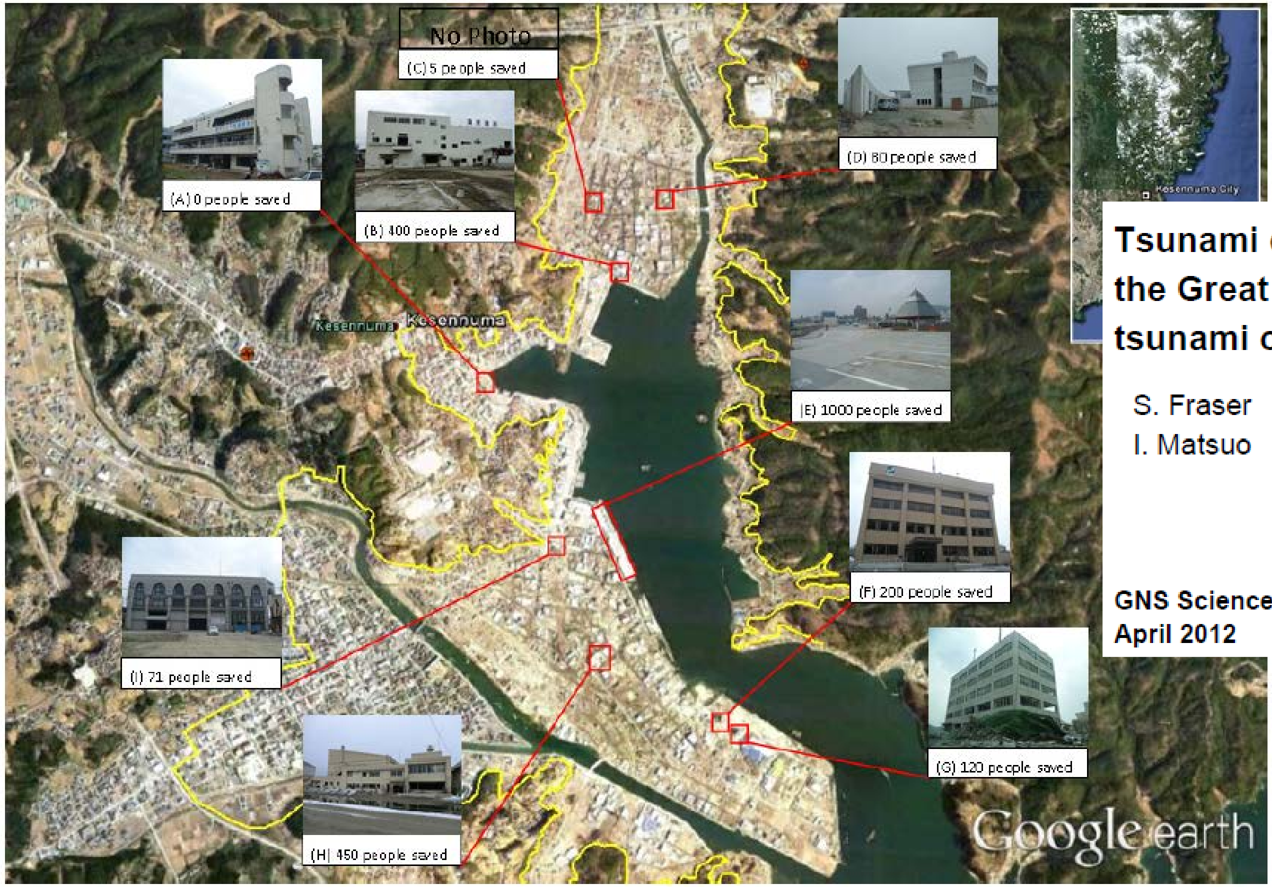


Fig. 2. Map and images of nine vertical evacuation buildings in Kesennuma City, including numbers of people saved and tsunami inundation marked in yellow [29]. These comprise office buildings (A, F, G, I); a cannery (B), a retail building (C), welfare centre (D), a car parking deck (E) and a community centre (H).

Tsunami evacuation: Lessons from the Great East Japan earthquake and tsunami of March 11th 2011

S. Fraser G.S. Leonard
I. Matsuo H. Murakami

GNS Science Report 2012/17
April 2012

GNS SCIENCE

TSUNAMI SAFETY IN MULTI-STORY BUILDINGS

- ***Tsunami Evacuation: Lessons from the Great East Japan Earthquake and Tsunami of March 11th 2011 (State of Washington sponsored investigation)***
- An example from the City of Ishinomaki (low-lying area similar to coastal communities at risk in the US) near Sendai
- "There was widespread use of buildings for informal (unplanned) vertical evacuation in Ishinomaki on March 11th, 2011. In addition to these three designated buildings, almost any building that is higher than a 2-storey residential structure was used for vertical evacuation in this event. **About 260 official and unofficial evacuation places were used in total, providing refuge to around *50,000* people.** These included schools, temples, shopping centres and housing."

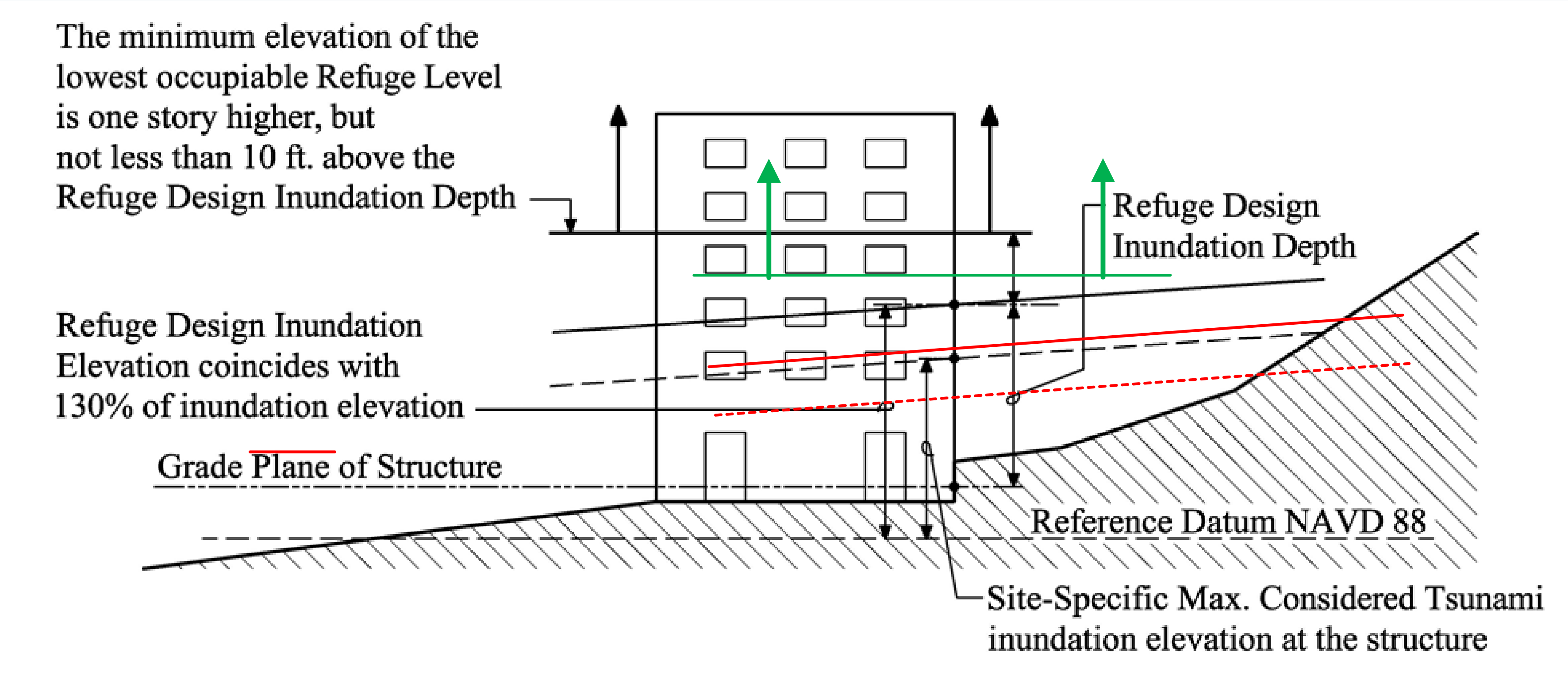
  (emphasis added)

SENDAI SCHOOL ROOFTOP EVACUATION

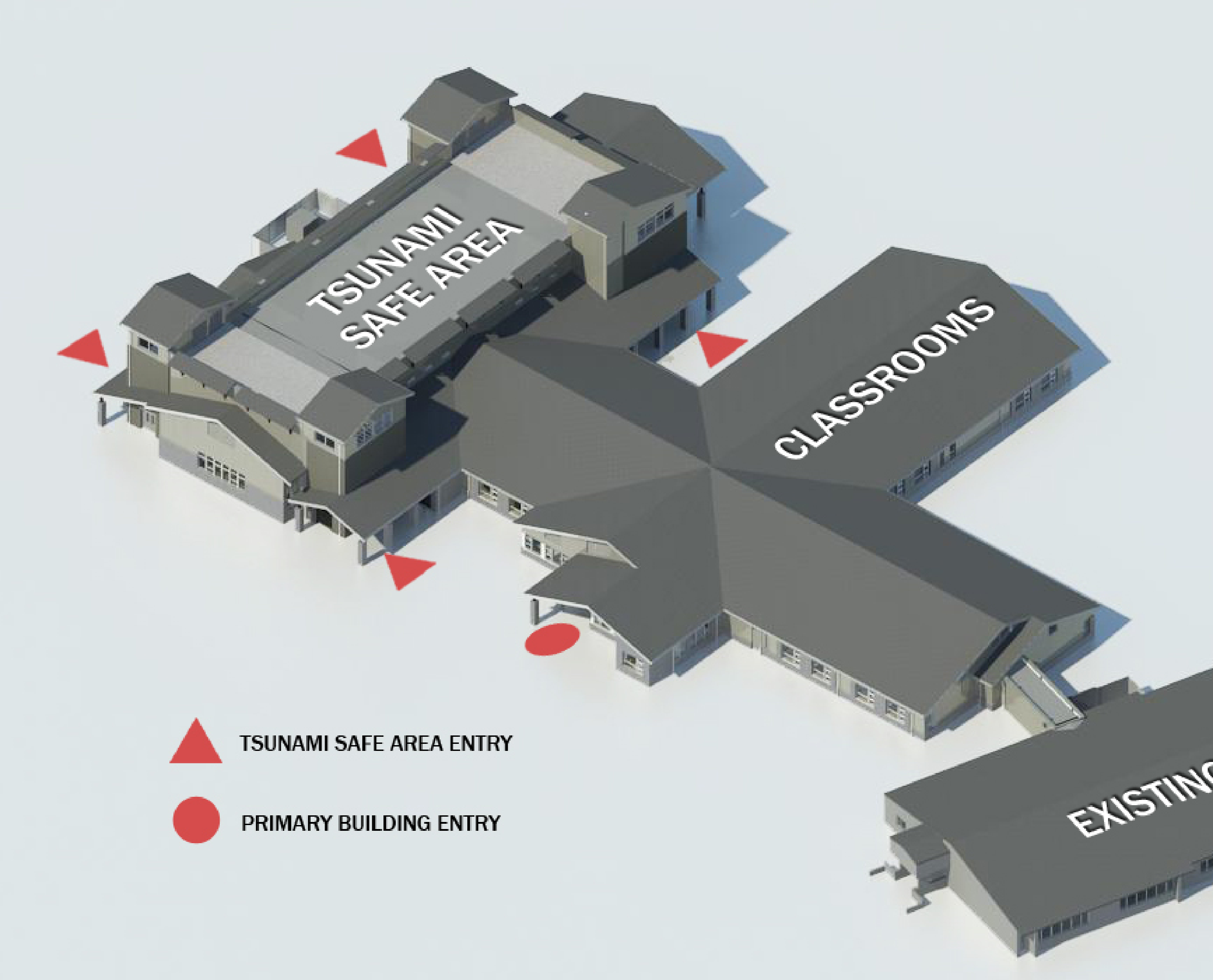
TSUNAMI VERTICAL EVACUATION REFUGE STRUCTURES

- Tsunami Vertical Evacuation Refuge Structures - ASCE 7 Chapter 6
- Additional reliability (99%) is achieved through site-specific inundation analysis and an increase in the design inundation elevation

Figure 6.14-1. Minimum Refuge Elevation

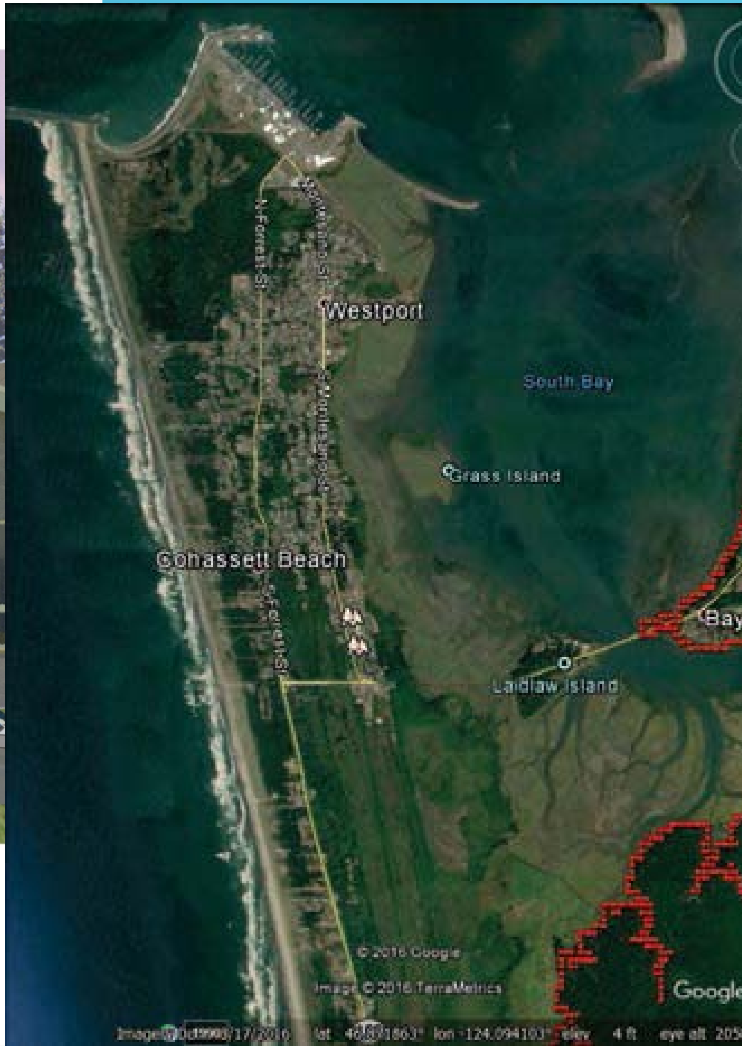


OCOSTA ELEMENTARY SCHOOL
WESTPORT, WASHINGTON
AMERICA'S FIRST TSUNAMI REFUGE



The gym is designed to be 30 feet above grade and 55 feet above sea level following earthquake-induced subsidence, with rooftop capacity for 1000 persons

OCOSTA ELEMENTARY SCHOOL WESTPORT, WASHINGTON



STRUCTURAL RELIABILITY

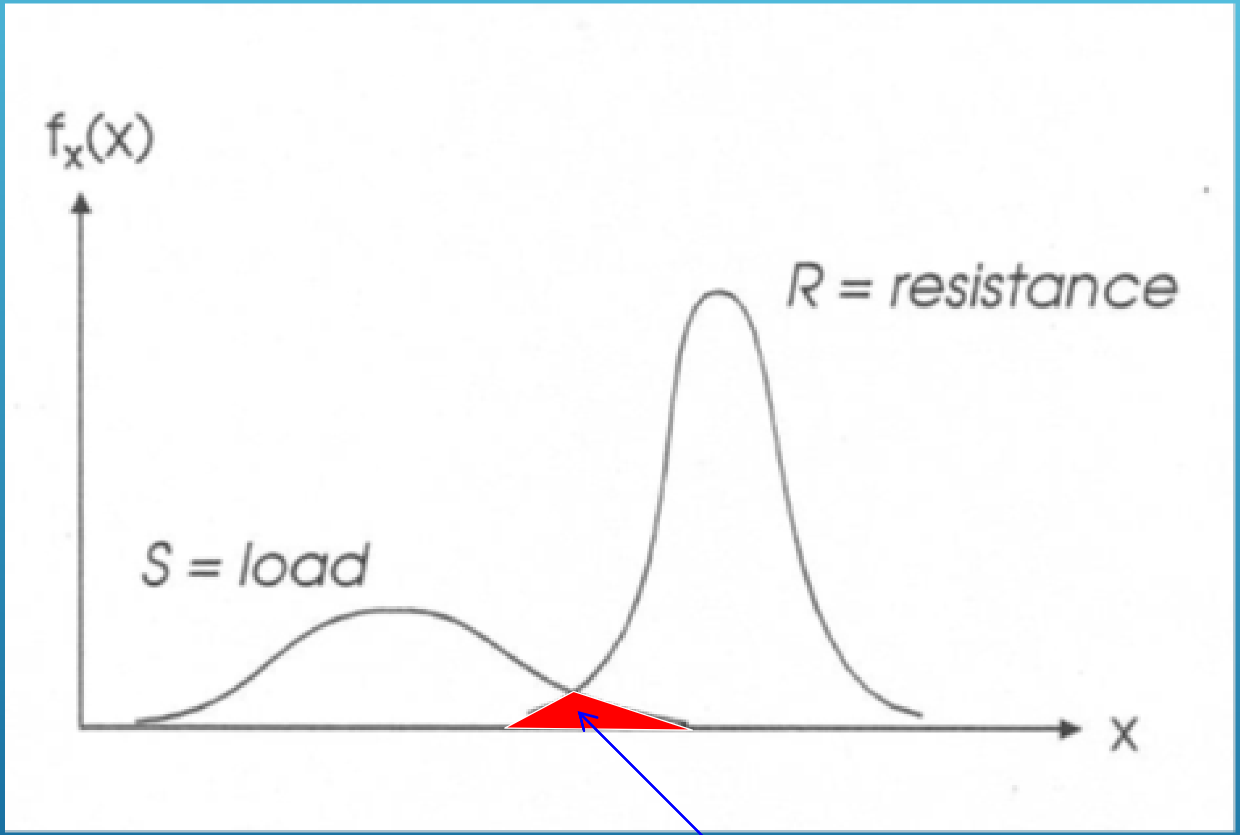
Chock, G., Yu, G., Thio, H.K., Lynett, P. (2016). Target Structural Reliability Analysis for Tsunami Hydrodynamic Loads of the ASCE 7 Standard. Journal of Structural Engineering, ASCE. 10.1061/(ASCE)ST.1943-541X.0001499 , 04016092.

RELIABILITY ANALYSIS OF STRUCTURES DESIGNED IN ACCORDANCE WITH ASCE 7 HYDRODYNAMIC TSUNAMI FORCES

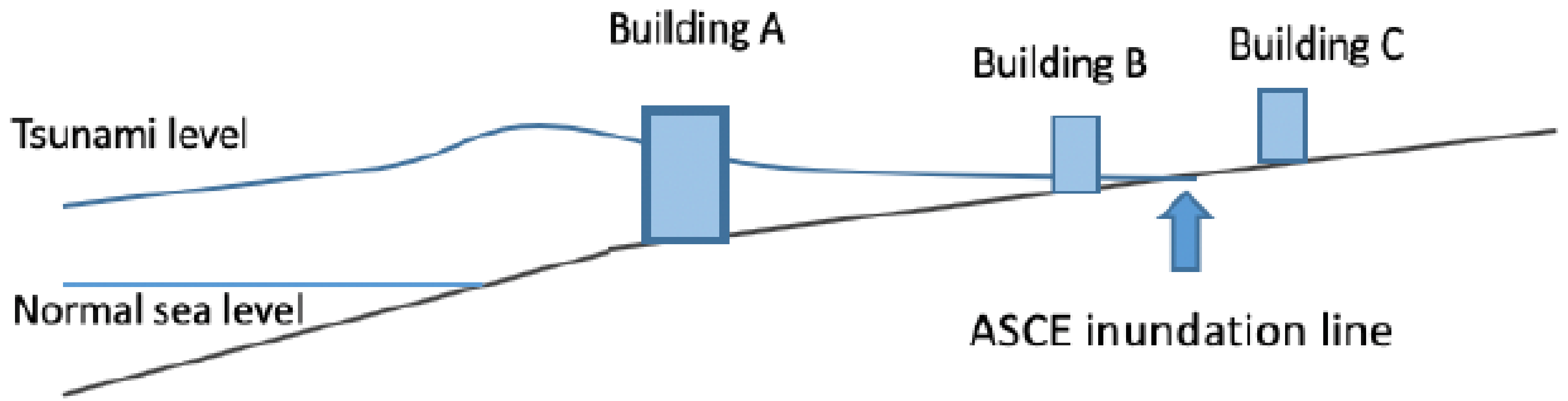
- Probabilistic limit state reliabilities have been computed for representative structural components carrying gravity and tsunami loads,
- Utilized statistical information on the key hydrodynamic loading parameters and resistance models with specified tsunami load combination factors.
- Through a parametric analysis performed using Monte Carlo simulation, it was shown that anticipated reliabilities for tsunami hydrodynamic loads meet the intent of the ASCE 7 Standard.

BASICS OF RELIABILITY ANALYSIS

- **Limit State (LS) equation for $Z = R - S < 0$**



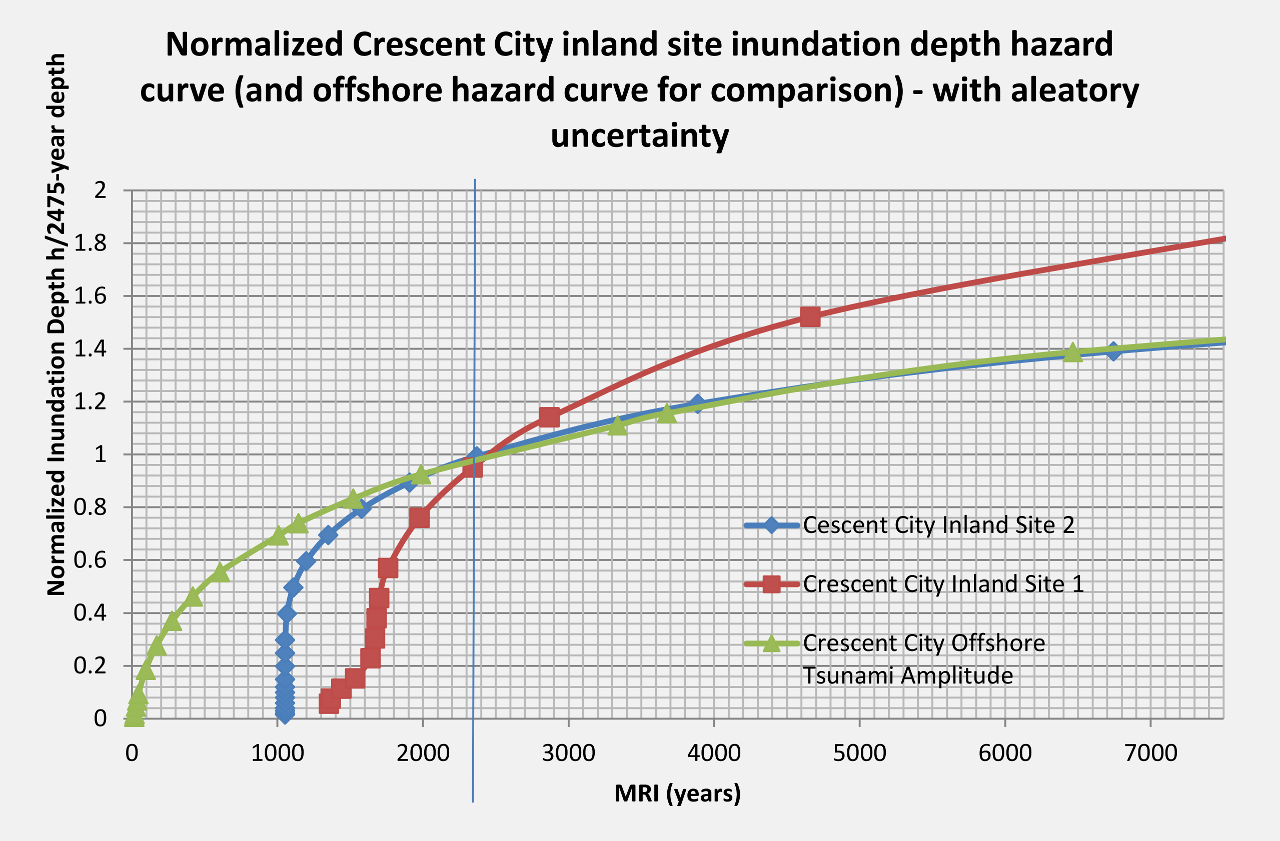
GOAL: LIMIT THE OVERLAP, I.E., PROBABLITY OF FAILURE



TSUNAMI INUNDATION DEPTH WILL VARY WITHIN THE TSUNAMI DESIGN ZONE

PROBABILISTIC HAZARD CURVES - CRESCENT CITY EXAMPLE

- Normalized Inundation Depth
- Prototypical offshore tsunami amplitude hazard curve and associated onshore tsunami inundation depth hazard curve for the sites



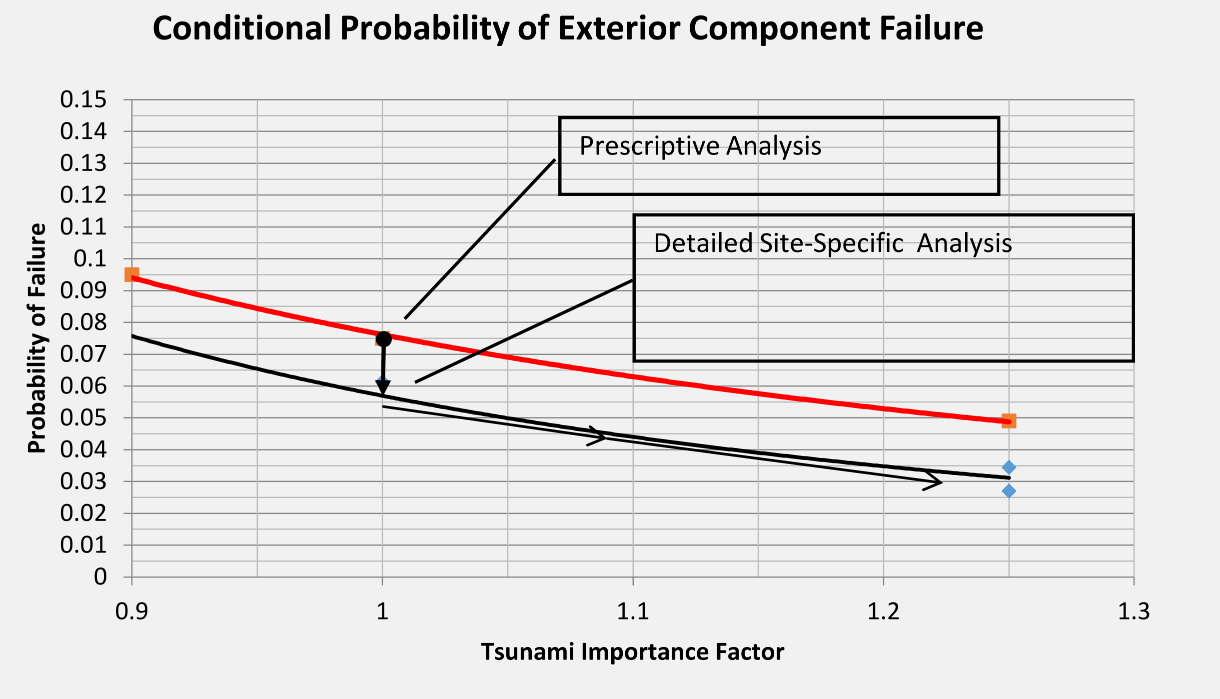
IMPORTANCE FACTORS I_{TSU}

- The reliability analysis also accounts for the requirement to conduct Site-Specific Inundation Analysis for Risk Category IV, Vertical Evacuation Refuges, and Designated Risk Category III Critical Facilities

Tsunami Risk Category	I_{tsu}
II	1.0
III, Tsunami Risk Category IV, Vertical Evacuation Refuges, and Tsunami Risk Category III Critical Facilities	1.25
<u>Tsunami Risk Category IV where the inundation depth is less than 12 ft (3.66m) and a site-specific Probabilistic Tsunami Hazard Analysis is not performed, per the exception to Section 6.5.2</u>	<u>1.5</u>

RELIABILITY BENEFIT WITH INCREASING ACCURACY OF INUNDATION ANALYSIS

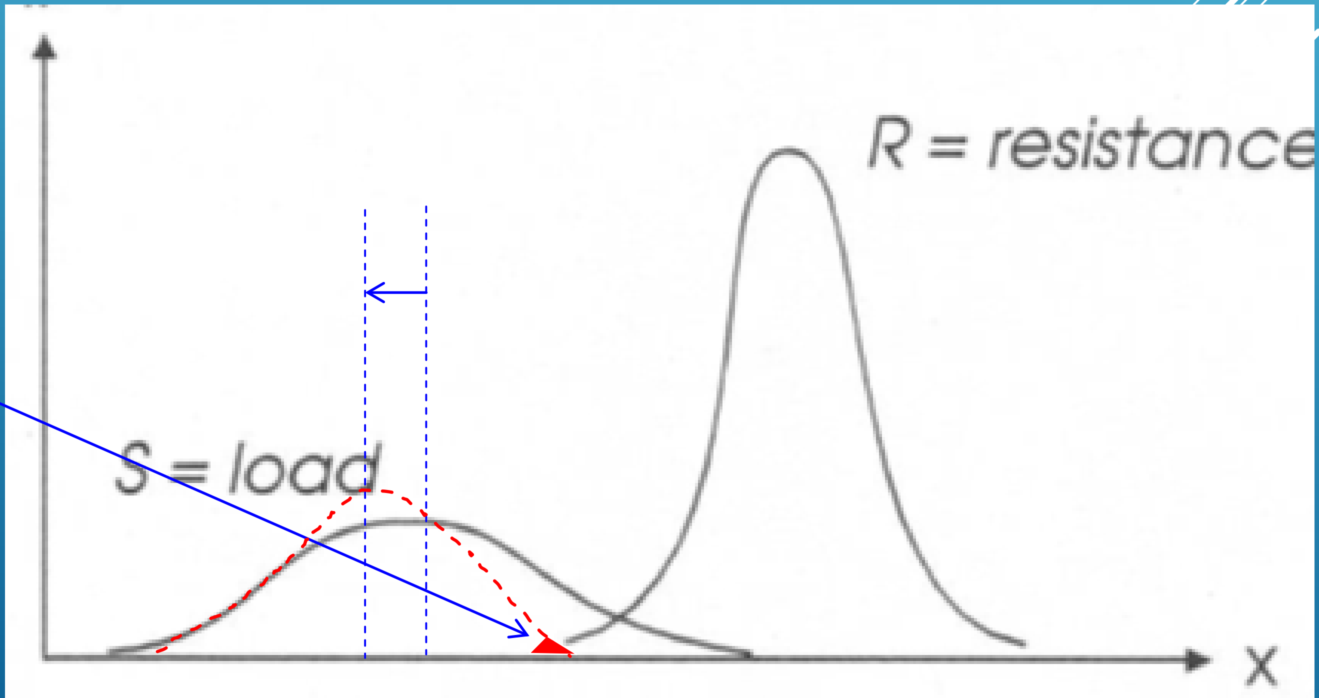
- By reducing uncertainty in the site inundation analysis method, greater structural reliability is obtained without a further increase in the I_{TSU} scalar beyond 1.25.



SECTION 6.14 – TSUNAMI VERTICAL EVACUATION

- Additional reliability (99%) is achieved through site-specific inundation analysis and an increase in the design inundation elevation
  - Site specific modeling required (less uncertainty)
  - 30% + 10ft increase in flow depth
  - RC IV – so loads multiplied by I = 1.25

REDUCED PROBABLITY OF FAILURE
BY ADDITIONAL REQUIREMENTS



BASICS OF RELIABILITY ANALYSIS

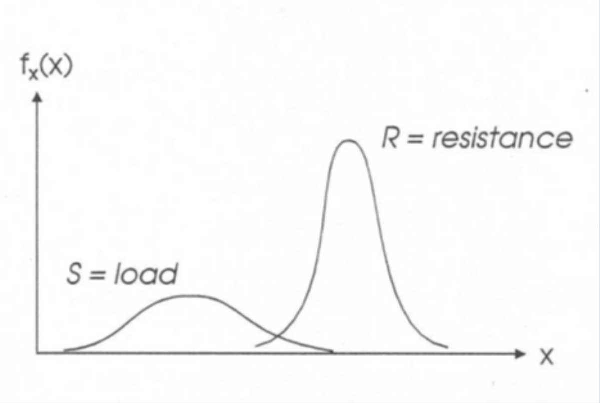
Load Combination including Tsunami $\varphi R_n = 0.9D_n + 1.0\, F_{TSUn}$

φ = resistance factor, R_n = nominal strength, D_n = nominal dead load, and F_{TSUn} = nominal tsunami effect. Subscript n refers to the nominal design resistance and specified loads

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

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.

- Dead load is not counteracting the F_{tsu} lateral hydrodynamic force
- **General Limit State function for G(X) = R – S < 0**
- Resistance (design requirements)-S (load)
- $G(X) = G(R, \lambda, F_{TSU}) = \lambda R - F_{TSU}$
- λ is capacity bias of the beam-column component



ψ

FUNDAMENTAL LIMIT STATE EQUATION

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

Ψ is the variable to account for the epistemic uncertainty in the nominal solution of the prescriptive EGL analysis of flow vs. numerical model

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.

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

The basic Limit State Function G(R,S) can then be parametrically given by

$$\boldsymbol{G(R,S) = Z = R - S = (1/\varphi)X_6 X_7 I_{TSU} - X_1 X_2 X_3^2 X_4^2 X_5}$$

Where R = Resistance, and S = Load

7 STATISTICAL PARAMETERS & 3 SCALARS - SUMMARY

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)		

MONTE CARLO SIMULATION (7 DOF)

- Reliabilities were calculated using Monte Carlo simulation involving trial combinations of random variables independently occurring in proportion to their statistical distributions
- 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 $\beta = \varphi^{-1}(1-P_f)$.

ANTICIPATED RELIABILITIES (MAX. PROBABILITY OF A 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%
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%

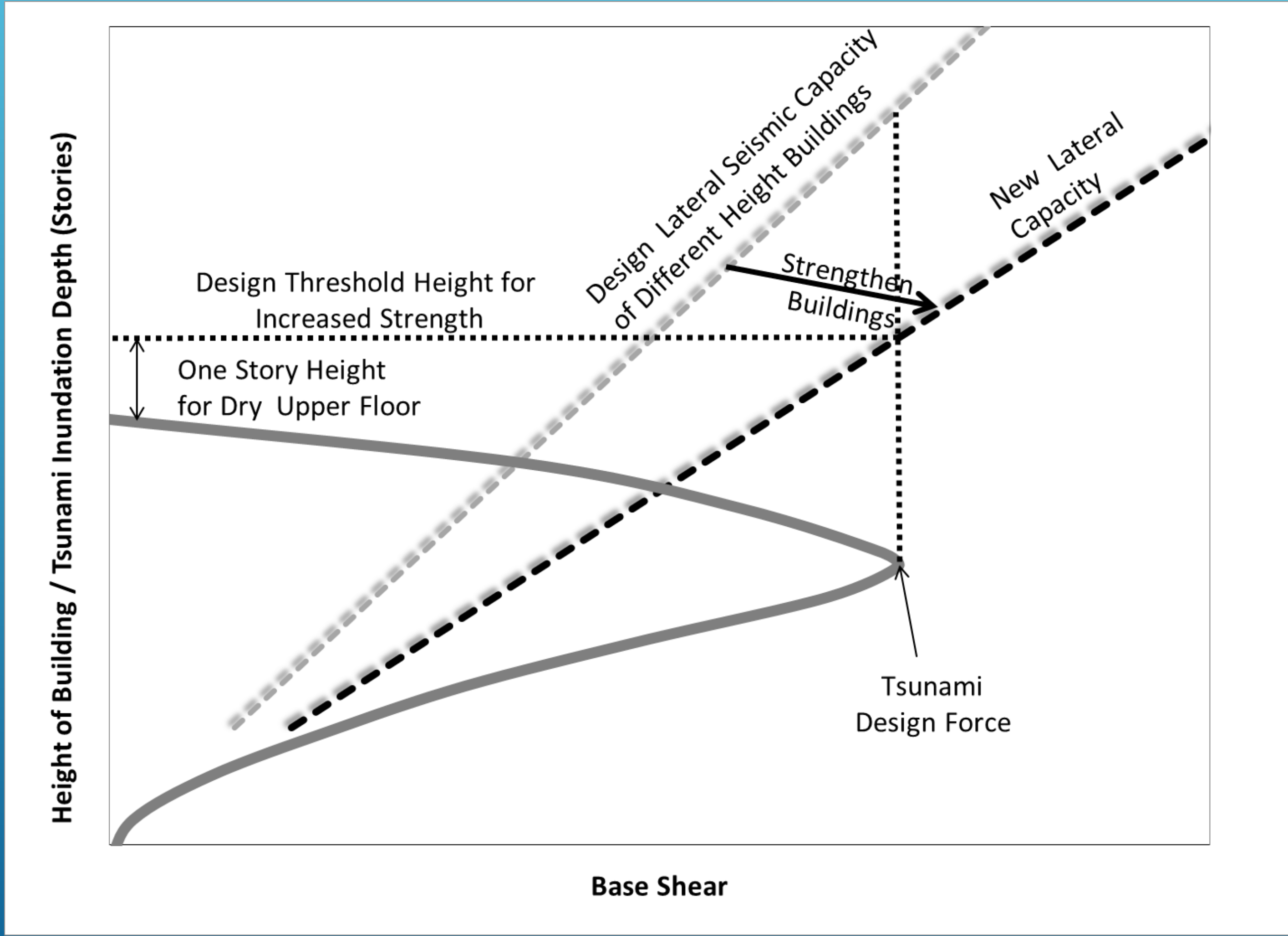
* Tsunami probabilities are based on exceeding an exterior structural component's capacity that does not necessarily lead to widespread progression of damage, but the seismic probabilities are for the more severe occurrence of partial or total systemic collapse.

.COMMUNITY PLANNING

- Chock, G., Carden, L., Robertson, I.N., Wei, Y., Wilson, R., Hooper, J. (2018). Tsunami Resilient Building Design Considerations for Coastal Communities of Washington, Oregon, and California, Journal of Structural Engineering, DOI: 10.1061/(ASCE)ST.1943-541X.0002068

COMMUNITY PLANNING– TSUNAMI RESILIENCE BASED ON CRITERIA OF HAZARD, BUILDING HEIGHT THRESHOLD, AND OCCUPANCY TYPE

- Establish a threshold height of applicability for tsunami design, with at least one story floor level above maximum inundation depth, with specified types of occupancy.
- Economic impact to the structural system is still relatively nominal in seismic zones
- Locally strengthen components of the building for tsunami loads and impact forces
- This policy would benefit communities with high tsunami hazard, especially where evacuation is difficult



SUMMARY

- The ASCE 7 provisions constitute a comprehensive method for reliable tsunami structural resilience, making tsunamis a required consideration in planning, siting, and design of coastal structures in the five western states of the USA.
- Probabilistic Tsunami Hazard Analysis is the basis for the 2475-yr MRI Tsunami Design Zone maps.
- Specified design procedures are provided for all possible loading conditions to achieve target reliabilities based on Risk Categories.
- Coastal communities and cities are also encouraged to require tsunami design for taller Risk Category II buildings, in order to provide a greater number of taller buildings that will be life-safe and disaster-resilient, especially where horizontal egress inland to safe ground takes longer than the travel time of the tsunami.

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