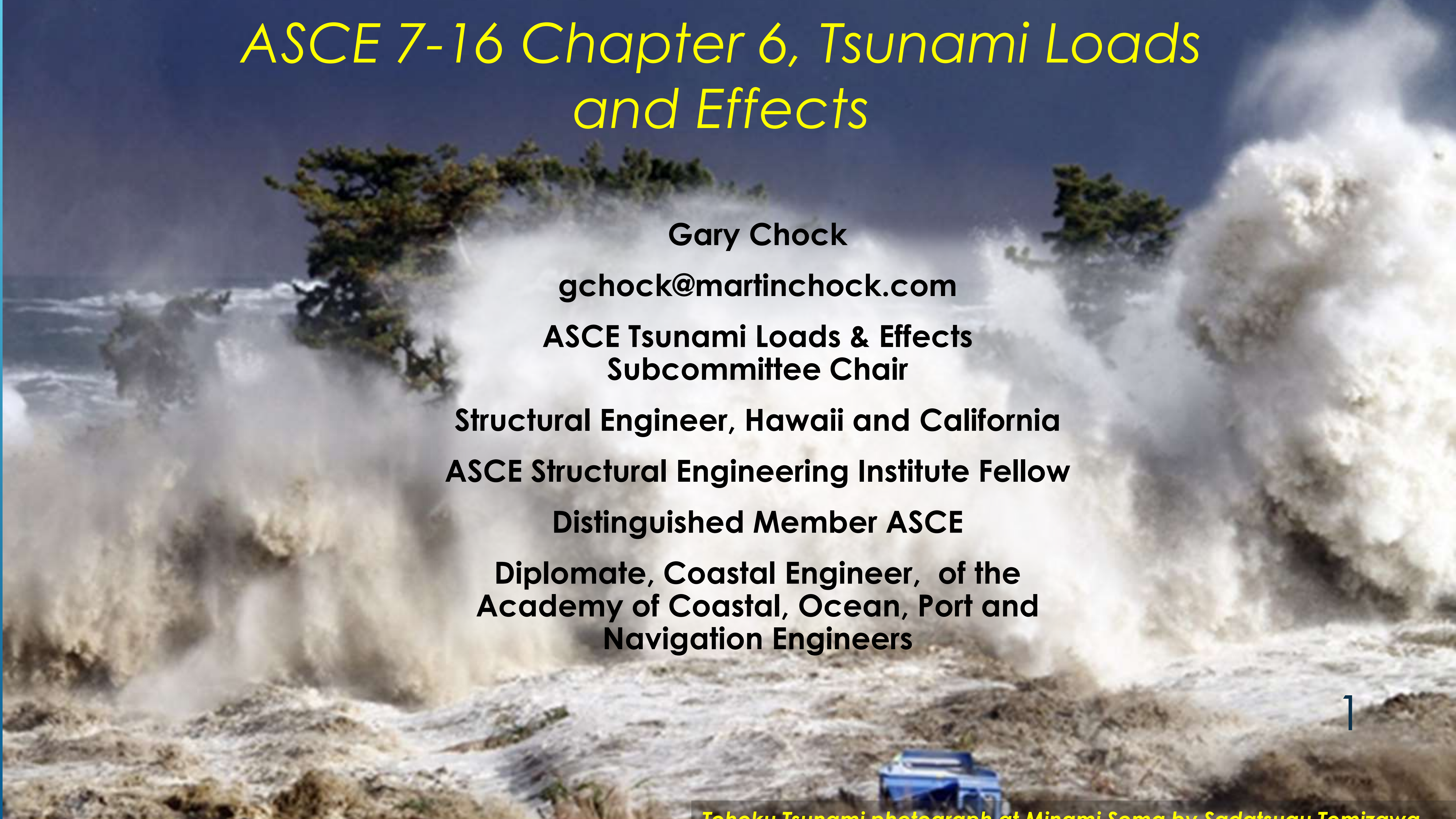
ASCE 7-16 Chapter 6, Tsunami Loads and Effects



Gary Chock

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Structural Engineer, Hawaii and California

ASCE Structural Engineering Institute Fellow

Distinguished Member ASCE

Diplomate, Coastal Engineer, of the Academy of Coastal, Ocean, Port and Navigation Engineers

Tohoku Tsunami photograph at Minami Soma by Sadatsugu Tomizawa

TSUNAMI-RESILIENT DESIGN OF BUILDINGS AND OTHER STRUCTURES

The development of ASCE 7 Chapter 6 – Tsunami Loads & Effects

USA CODES AND STANDARDS

- International Building Code (IBC), which references ASCE 7
- 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 TSUNAMI LOADS AND EFFECTS

THE NEW NATIONAL STANDARD OF PRACTICE FOR PROFESSIONAL ENGINEERS DEVELOPED THROUGH AN ACCREDITED CONSENSUS PROCESS

- **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.**
- **Independently audited process to verify by documentation that every one of the over 1500 comments had been resolved in accordance with its governing rules.**
- **Officially approved as ASCE 7-16 Chapter 6 on March 11, 2016**
- **Approved by ICC voting members for inclusion by reference in IBC 2018 requirements**
- **Adoptions by 5 Western States (AK, WA, OR, CA, and HI) by about 2020 – (adopted 2018 in Hawaii, 2019 in California).**
- **Chapter 6 of ASCE 7-16 is therefore an engineering standard practice for tsunami design of buildings and other structures.**

ASCE 7-16 TSUNAMI LOADS & EFFECTS

ASCE7-16 Chapter 6– Tsunami Loads and Effects is applicable to the five western states of the USA.

Improves resilience of a community for tsunamis in:

- Planning and Siting
- Structural Design for reliability
- 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, with additional factors to account for the approximate nature of tsunami inundation modeling

SCOPE AND GENERAL REQUIREMENTS

Application in accordance with Risk Categories

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.

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

SECTION 6.4 TSUNAMI RISK CATEGORIES

- The following structures need not be included in Tsunami Risk Category IV and state, local, or tribal governments shall be permitted to designate them as Tsunami Risk Category II or III:
  - Fire stations & ambulance facilities, emergency vehicle garages
  - Earthquake or hurricane shelters
  - Emergency aircraft hangars
  - Police stations that do not have holding cells and that are not uniquely required for post-disaster emergency response as a Critical Facility.
- Tsunami Vertical Evacuation Refuge Structures shall be included in Tsunami Risk Category IV.

- Use ASCE 7 Chapter 6 to improve tsunami resilience of a community by:
  - Preventing failures of multistory buildings during tsunamis
  - Creating tsunami refuges
  - Enabling Risk Reduction in Planning and Siting of facilities
  - Designing to Mitigate Damage
  - Designing defense countermeasures for infrastructure
  - Post-disaster reconstruction to Build Back Better

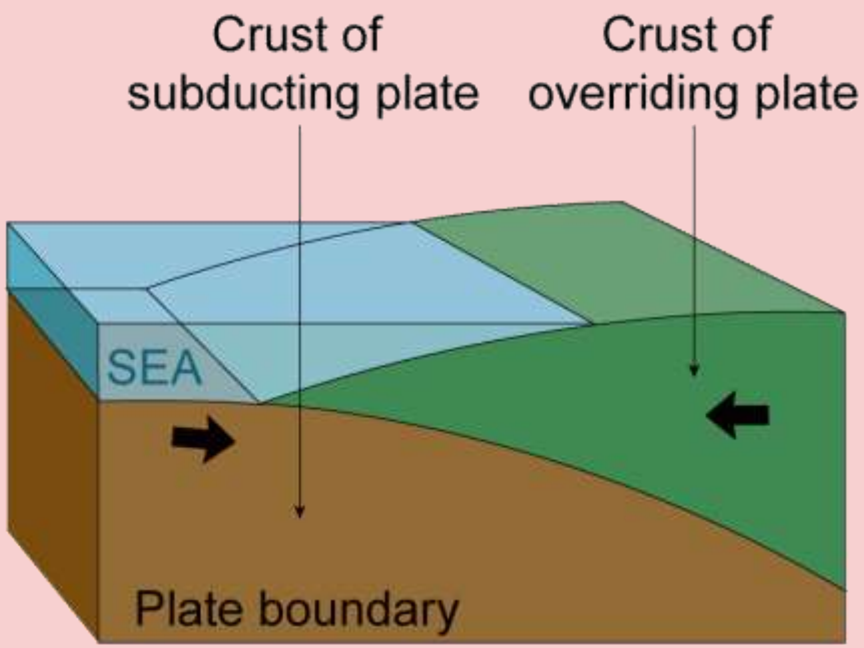
ASCE 7 CHAPTER 6- TSUNAMI LOADS AND EFFECTS

- 6.1 General Requirements
- 6.2-6.3 Definitions, Symbols and Notation
- 6.4 Tsunami Risk Categories
- 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

TSUNAMI HAZARD AND STRUCTURAL EFFECTS

Fundamentals

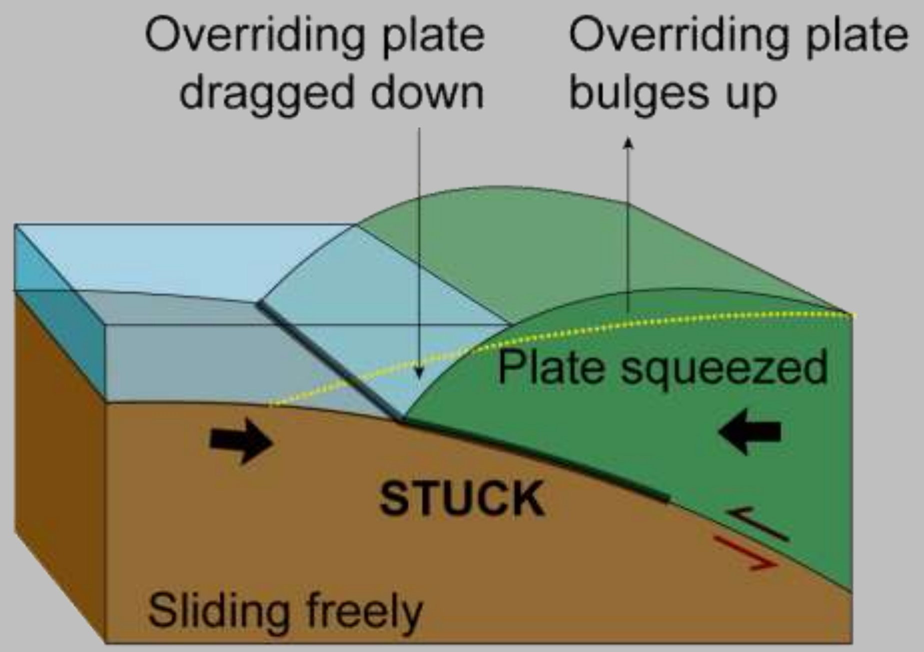
Subduction Zone Tsunami Generation



OVERALL, a tectonic plate descends, or "subducts," beneath an adjoining plate. But it does so in a stick-slip fashion.

After Atwater et al. (2005)

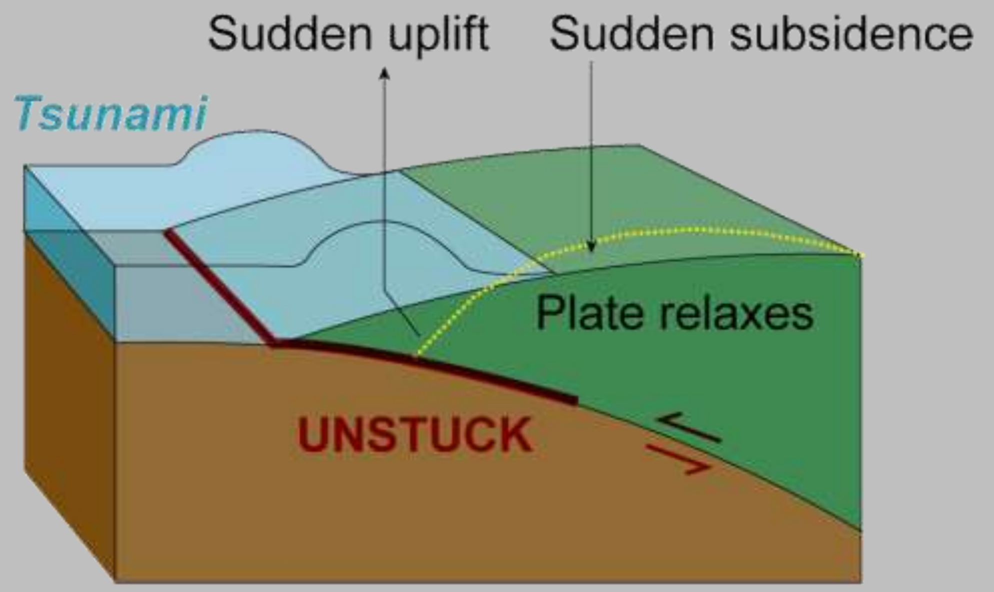
Subduction Zone Tsunami Generation



BETWEEN EARTHQUAKES the plates slide freely at great depth, where hot and ductile. But at shallow depth, where cool and brittle, they stick together. Slowly squeezed, the overriding plate thickens.

After Atwater et al. (2005)

Subduction Zone Tsunami Generation

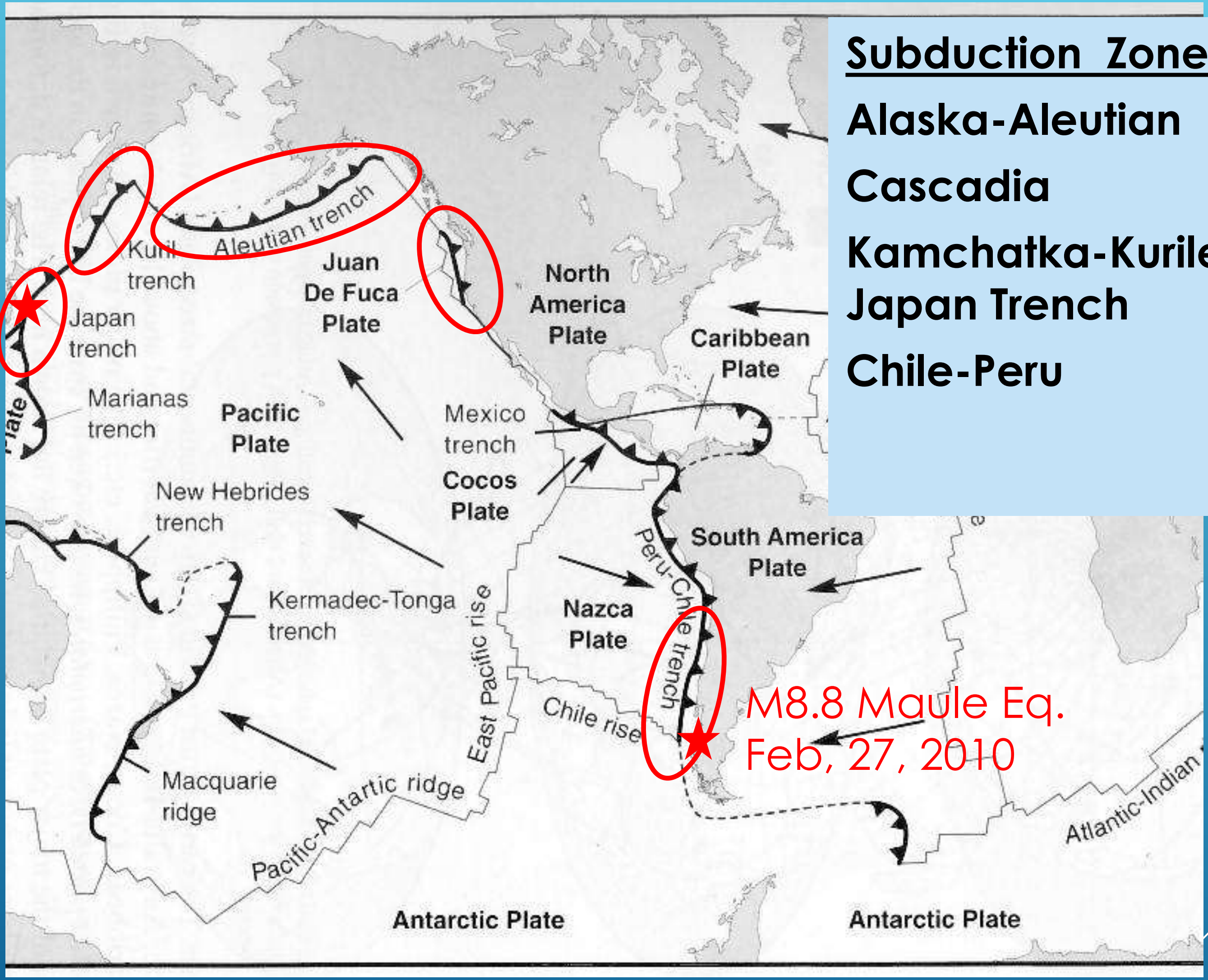


DURING AN EARTHQUAKE the leading edge of the overriding plate breaks free, springing seaward and upward. Behind, the plate stretches; its surface fails. The vertical displacements set off a tsunami.

After Atwater et al. (2005)

TSUNAMI-GENIC SEISMIC SOURCES OF PRINCIPAL RELEVANCE TO THE USA

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



M8.8 Maule Eq. Feb, 27, 2010

Subduction Zones

Alaska-Aleutian

Cascadia

Kamchatka-Kuriles & Japan Trench

Chile-Peru

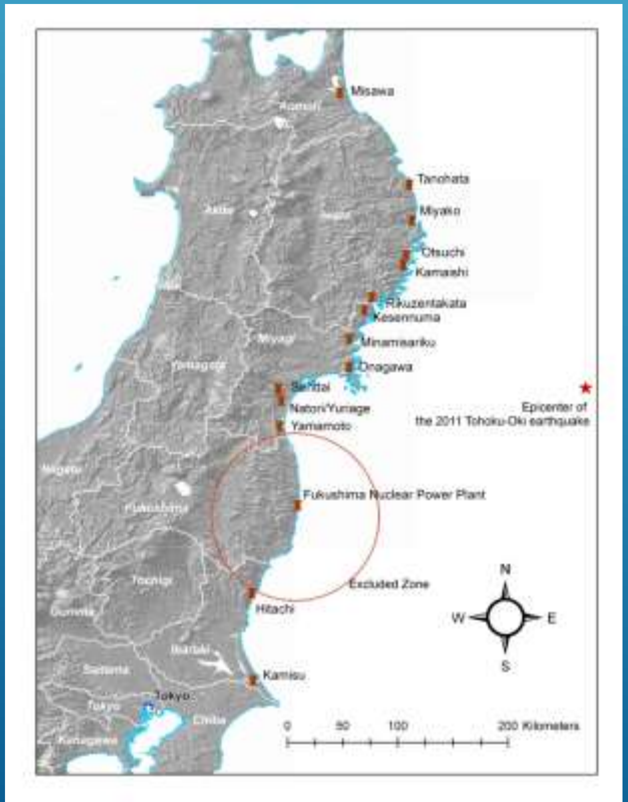
State	Population at Direct Risk (USGS Lower-bound estimates)	Profile of Economic Assets and Critical Infrastructure
Oregon	25,000 residents plus another 55,000 tourists; 300 miles of coastline	$8.5 Billion plus essential facilities, 2 medium ports, 1 fuel depot hub
	Total resident population of area at immediate risk to post-tsunami impacts: 100,000	

BUILDINGS SUBJECTED TO TSUNAMIS

Case Examples and Lessons Learned

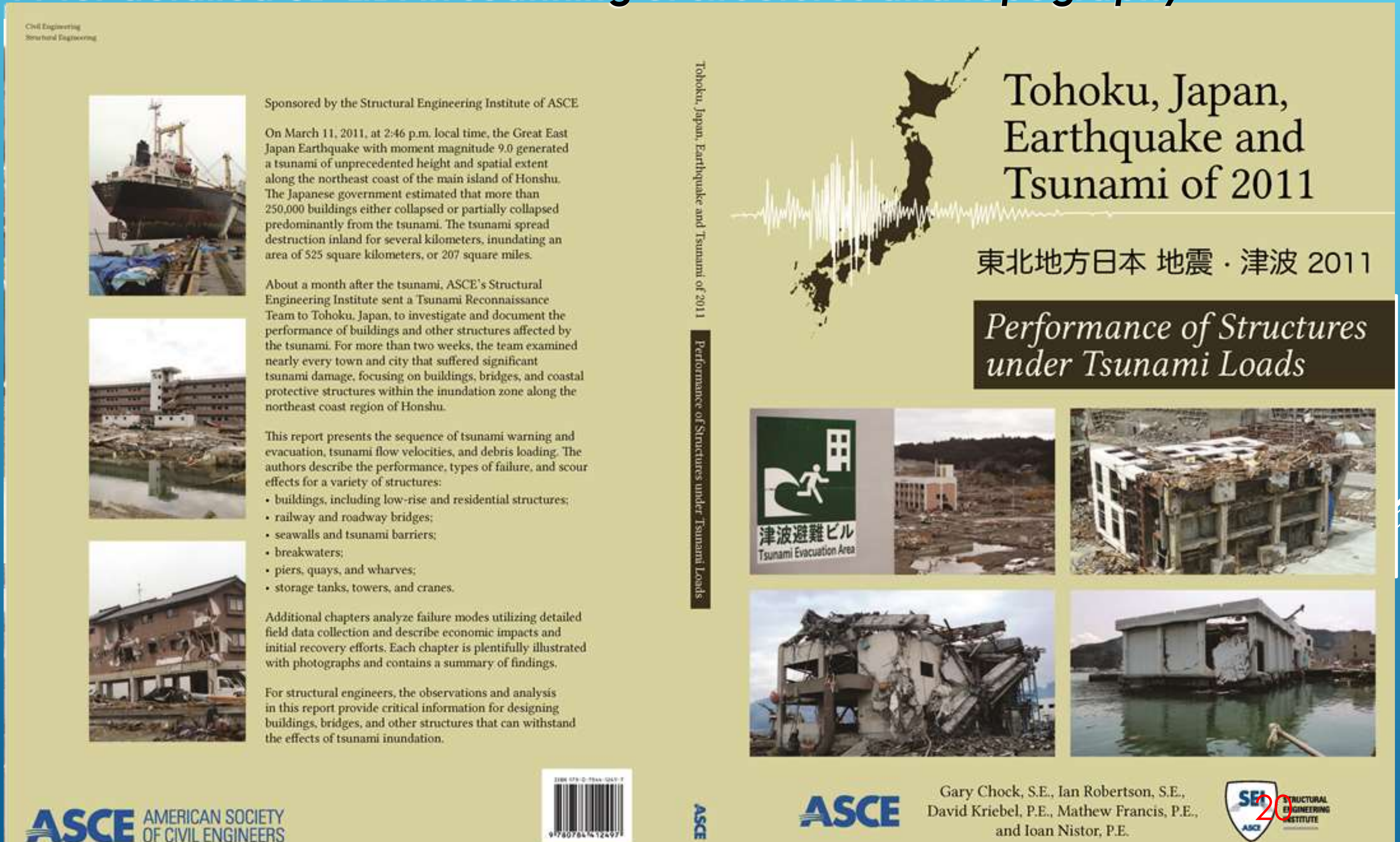
RELEVANCE OF TOHOKU LESSONS TO THE USA

- Cascadia Subduction Zone is larger than the zone that ruptured in Tohoku
- Cascadia Subduction Zone governs both the MCE and MCT for the PNW
- 1700 Cascadia Earthquake M9 is only the most recent occurrence of numerous great earthquakes and tsunamis throughout the past 10,000 years.



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



APPLYING THE ASCE PROVISIONS TO CASE STUDY STRUCTURES IN JAPAN (MARCH 11, 2011 TSUNAMI): INUNDATION ZONES, EGL TRANSECTS, AND COASTAL STRUCTURES OF INTEREST AT
A) ONAGAWA,
B) SENDAI,
C) RIKUZENTAKATA
IN ALL CASES STRUCTURAL FAILURE WOULD BE PREVENTED BY ASCE 7

SUMMARY OF FINDINGS FROM AN ANALYSIS OF SURVEYED BUILDINGS

- Using the observed flow characteristics, the ASCE 7 Load equations adequately represent actual tsunami forces
- The Energy Grade Line (EGL) method for calculating flow depth and velocity is generally conservative for design. The method is generally insensitive to the transect chosen, provided the runup elevation at the point of the inundation limit is physically consistent between different possible transects.
- Structural elements in the selected case study buildings would have been conservatively designed using ASCE 7, and the observed failures would have all been precluded.

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

Tsunami Vertical Evacuation Buildings – Lessons for International Preparedness Following the 2011 Great East Japan Tsunami

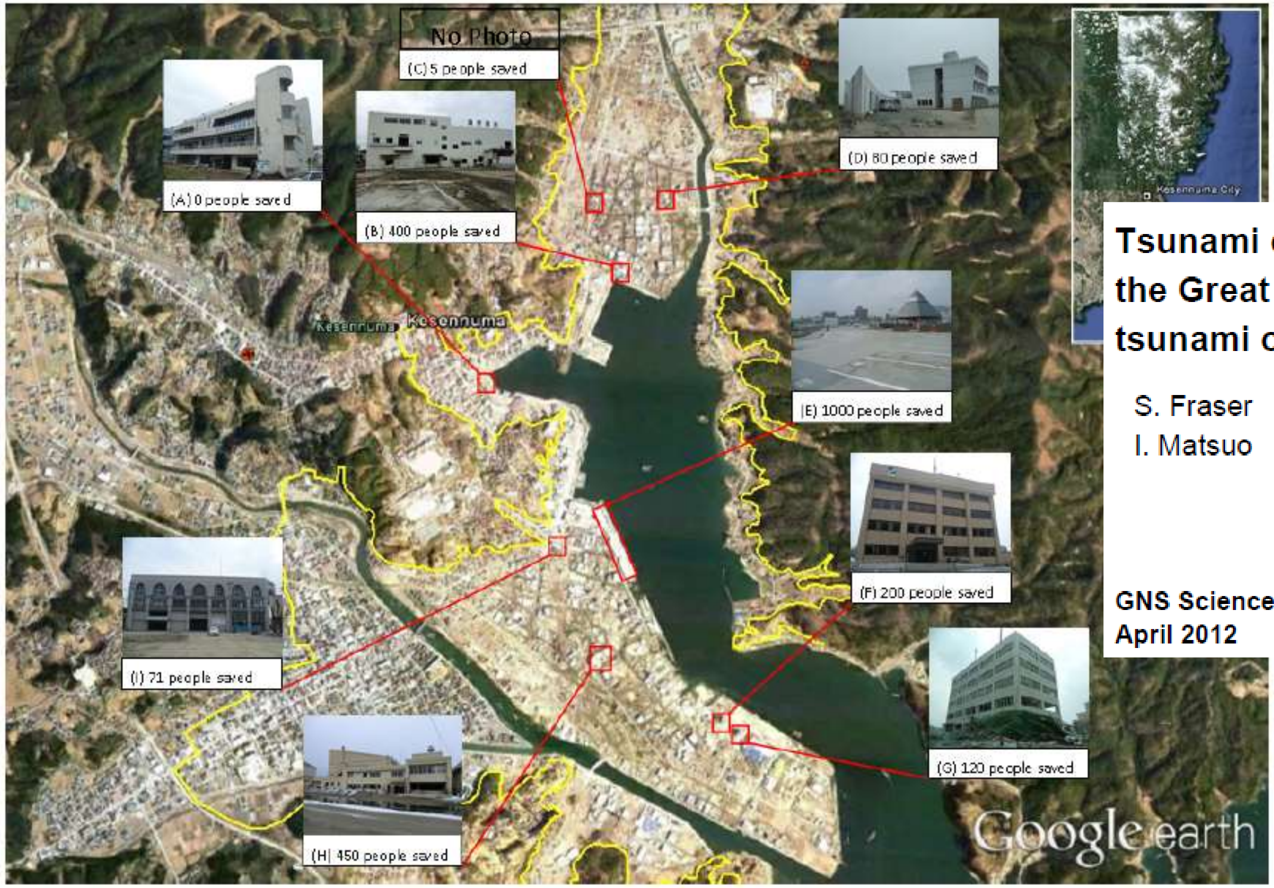
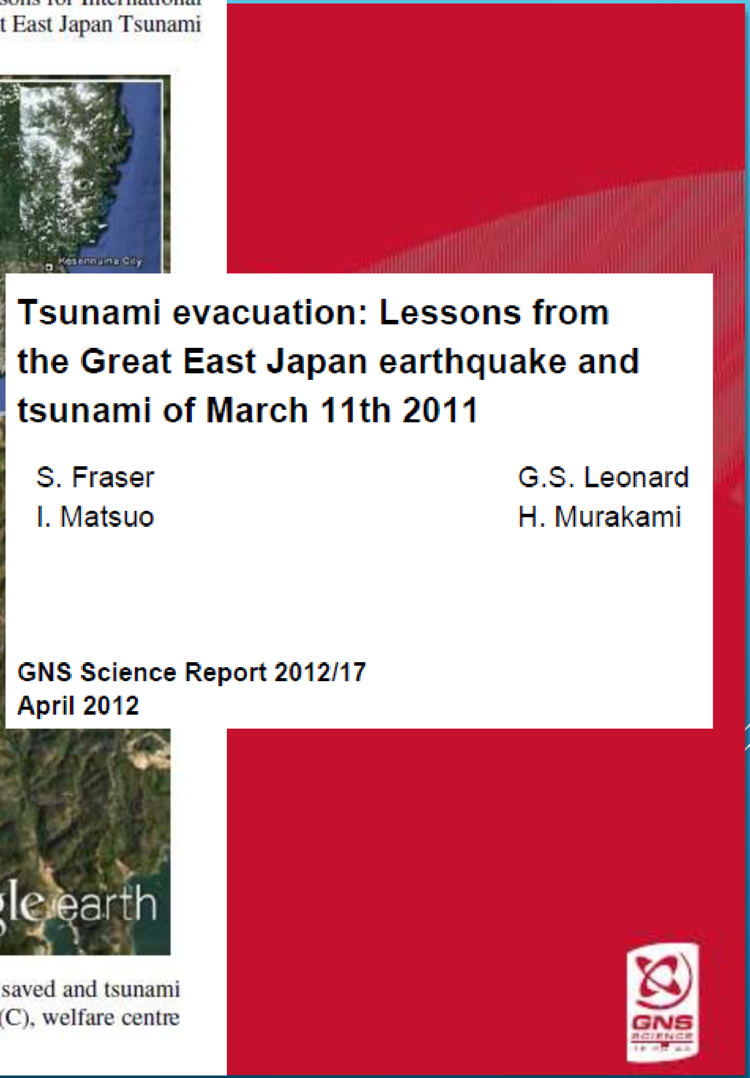


Fig. 2. Map and images of nine vertical evacuation buildings in Kesennuma City, including numbers of people saved and tsunami inundation marked in yellow [29]. These comprise office buildings (A, F, G, I); a cannery (B), a retail building (C), welfare centre (D), a car parking deck (E) and a community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



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

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

GNS Science Report 2012/17
April 2012

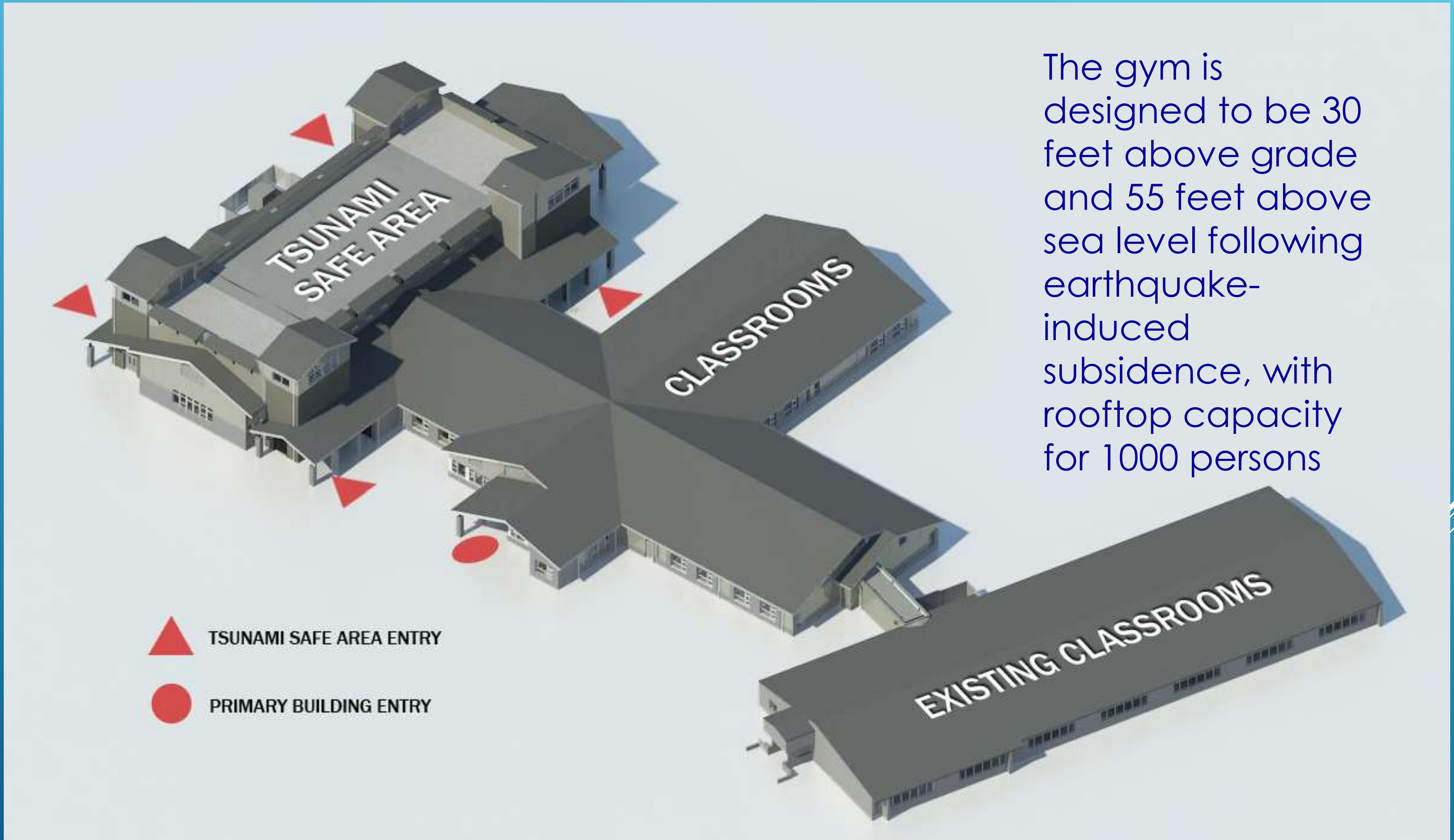
TSUNAMI SAFETY IN MULTI-STORY BUILDINGS

- *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

OCOSTA ELEMENTARY SCHOOL WESTPORT, WASHINGTON
AMERICA'S FIRST TSUNAMI REFUGE FOLLOWS ASCE 7



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

TSUNAMI VERTICAL EVACUATION REFUGE STRUCTURES

- Additional reliability (99%) is achieved through site-specific inundation analysis and an increase in the design inundation elevation

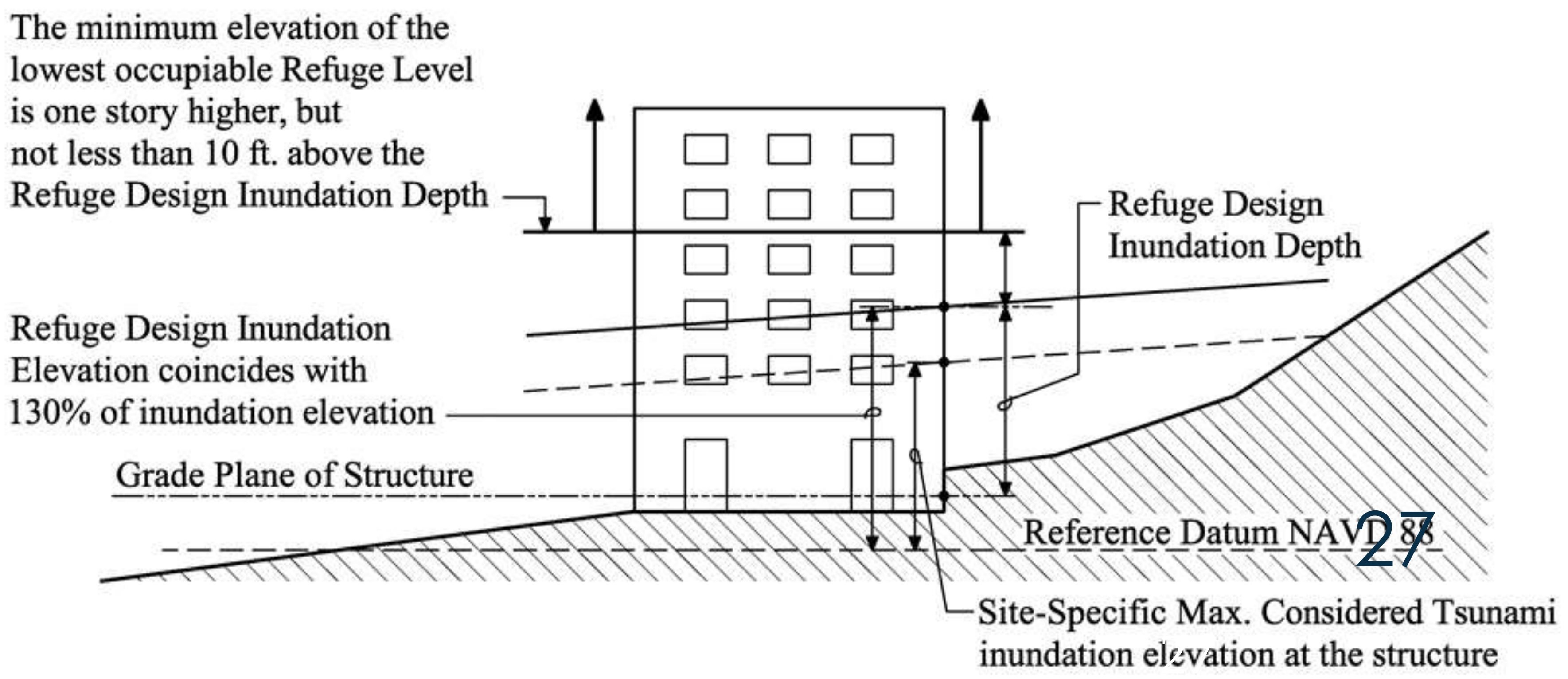


Figure 6.14-1. Minimum Refuge Elevation

OCOSTA ELEMENTARY SCHOOL GYM WESTPORT, WASHINGTON

PROBABILISTIC TSUNAMI HAZARD ANALYSIS

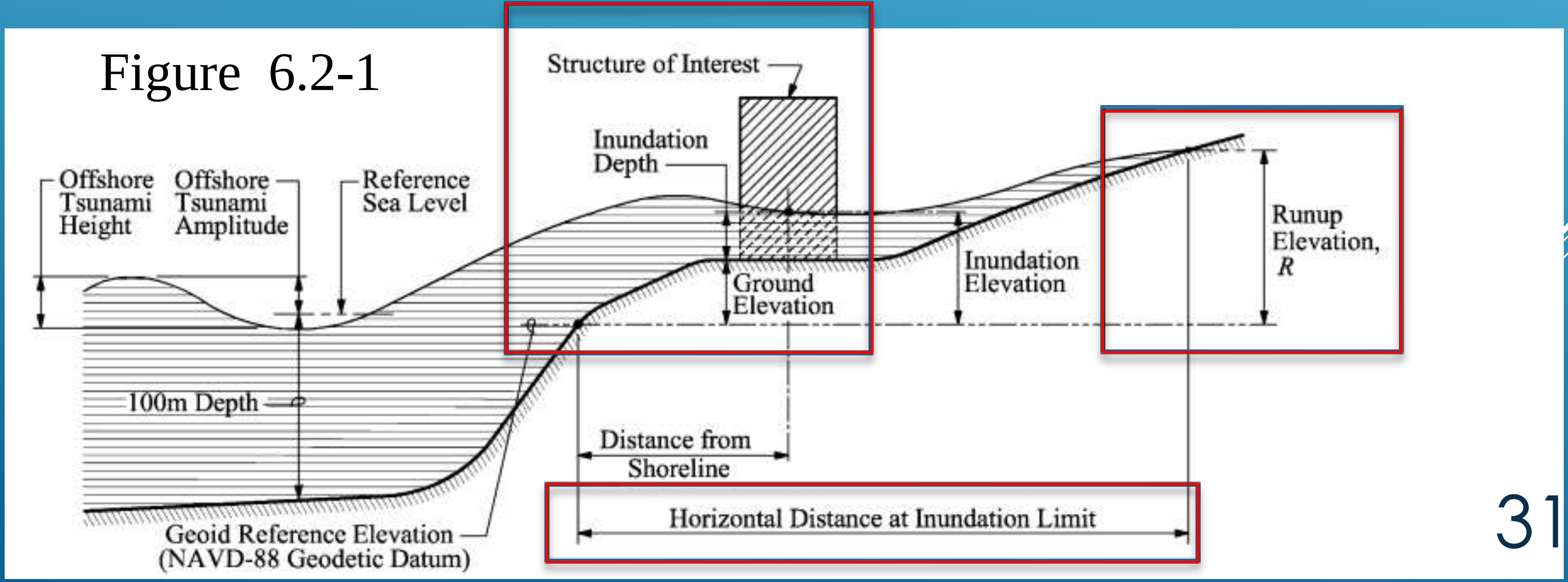
The ASCE Tsunami Design Geodatabase for the Maximum Considered Tsunami

MCT AND TSUNAMI DESIGN ZONE BASED ON PROBABILISTIC ANALYSIS

- The Maximum Considered Tsunami (MCT) has a 2% probability of being exceeded in a 50-year period, or a ~2500 year average return period, with an additional statistical allowance for modeling uncertainty. The runups for this hazard probability is used to define a Tsunami Design Zone in the ASCE Tsunami Design Geodatabase.
- The Tsunami Design Zone is the area vulnerable to being flooded or inundated by the Maximum Considered Tsunami
- The Maximum Considered Tsunami specifies the design basis inundation depths and flow velocities at stages of in-flow and outflow most critical to the structure.

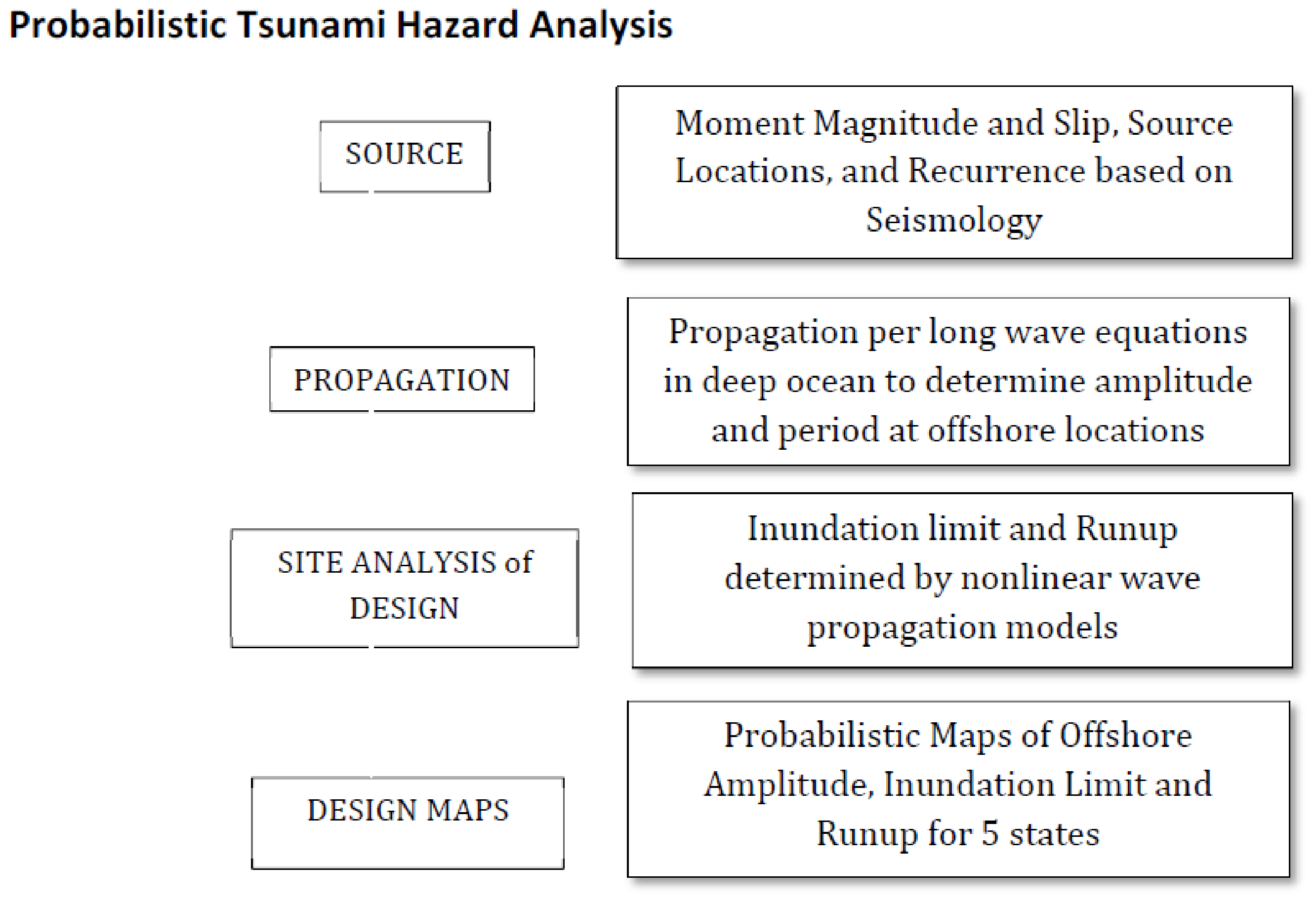
Terminology

- 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



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.**



SUMMARY OF PROBABILISTIC TSUNAMI SOURCES

Provide fit of all PTHA offshore amplitudes within an error range of 5 - 15%

Estimates of the 2,475-year probabilistic tsunami sources

	Dominant Source Region	Mw	Length (km)	Avg. Slip (m)
Alaska	Alaska - Aleutian Subduction Zone (Local)	9.0 – 9.5	300 -1000	32 - 59
Cascadia	Cascadia Subduction Zone (Local)	8.7 – 9.0	300 - 500	17 - 40
California	Alaska Subduction Zone (Distant)	9.2 – 9.6	700 – 1,600	31 - 60
Hawaii	Aleutian or Kuril-Kamchatka Subduction Zone (Distant)	9.2 – 9.6	1,000 – 1,500	20 - 51

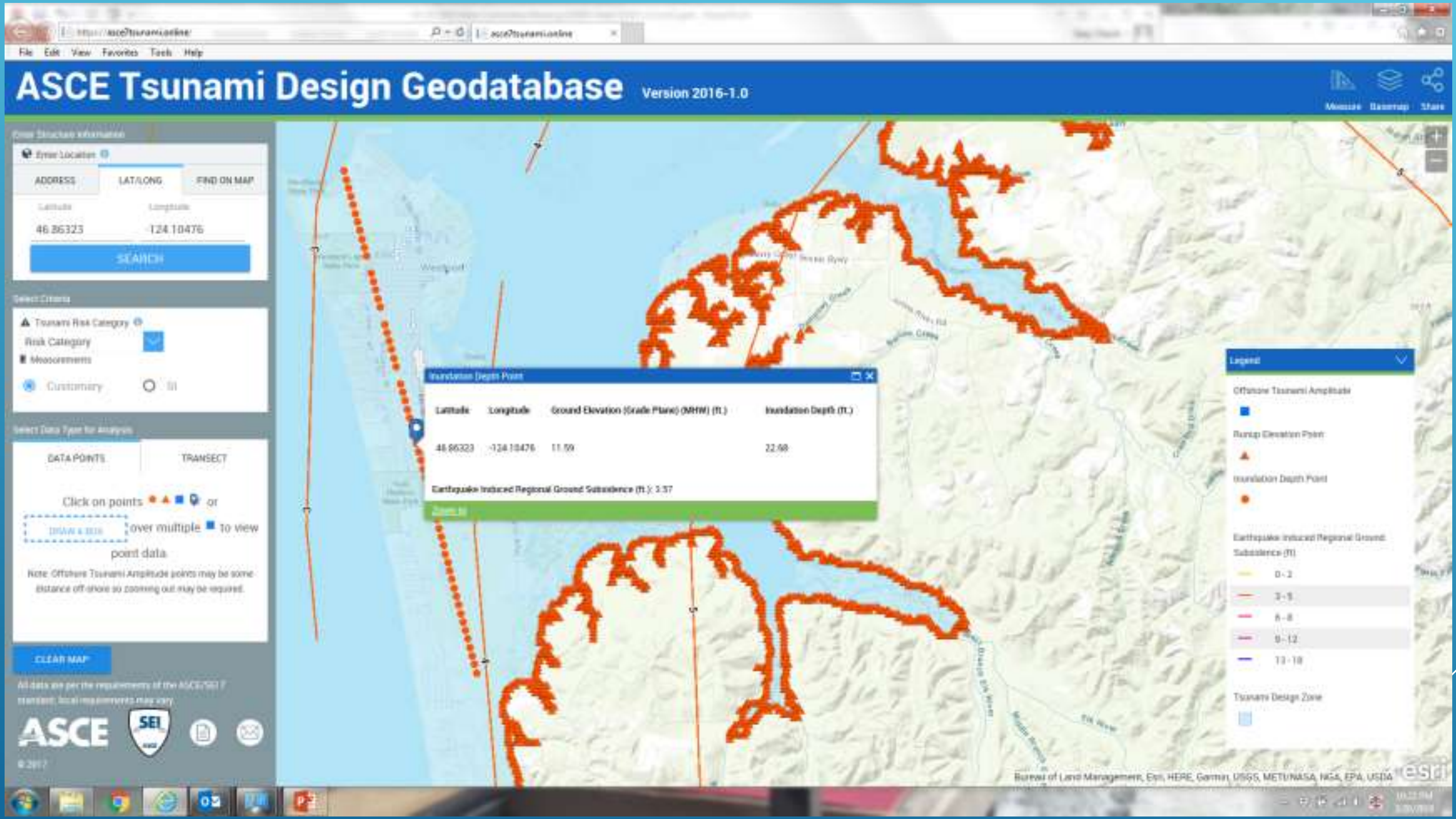
HOW THE PTHA AND TDZ BASIS OF DESIGN INTEGRATE INTO THE ASCE STRUCTURAL DESIGN PROCESS

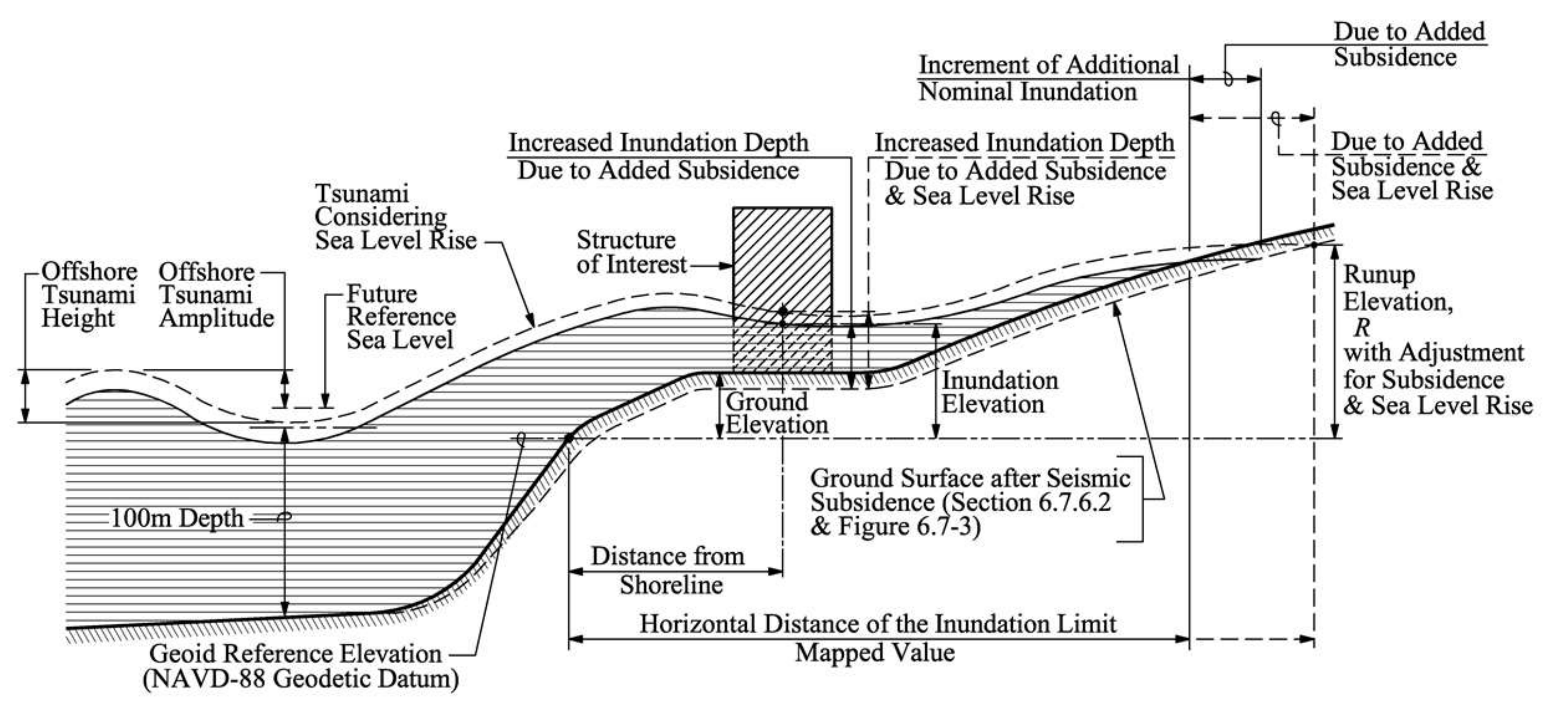
- **PTHA-based design criteria - The method of Probabilistic Tsunami Hazard Analysis is consistent with probabilistic seismic hazard analysis in the treatment of uncertainty.**
- **Maximum Considered Tsunami is a 2500+ year MRI**
- **The MCT has Probabilistic Offshore Tsunami Amplitudes**
- **The Tsunami Design Zone results from the inundation limits resulting from the probabilistic values of Offshore Tsunami Amplitude**
- **Hydraulic analysis or site-specific inundation analysis to determine site design flow conditions**
- **ASCE 7 uses physics-based fluid loads, debris loads, and foundation effects**

TSUNAMI DESIGN GEODATABASE IS HOSTED BY ASCE ON AN ELECTRONIC DATABASE

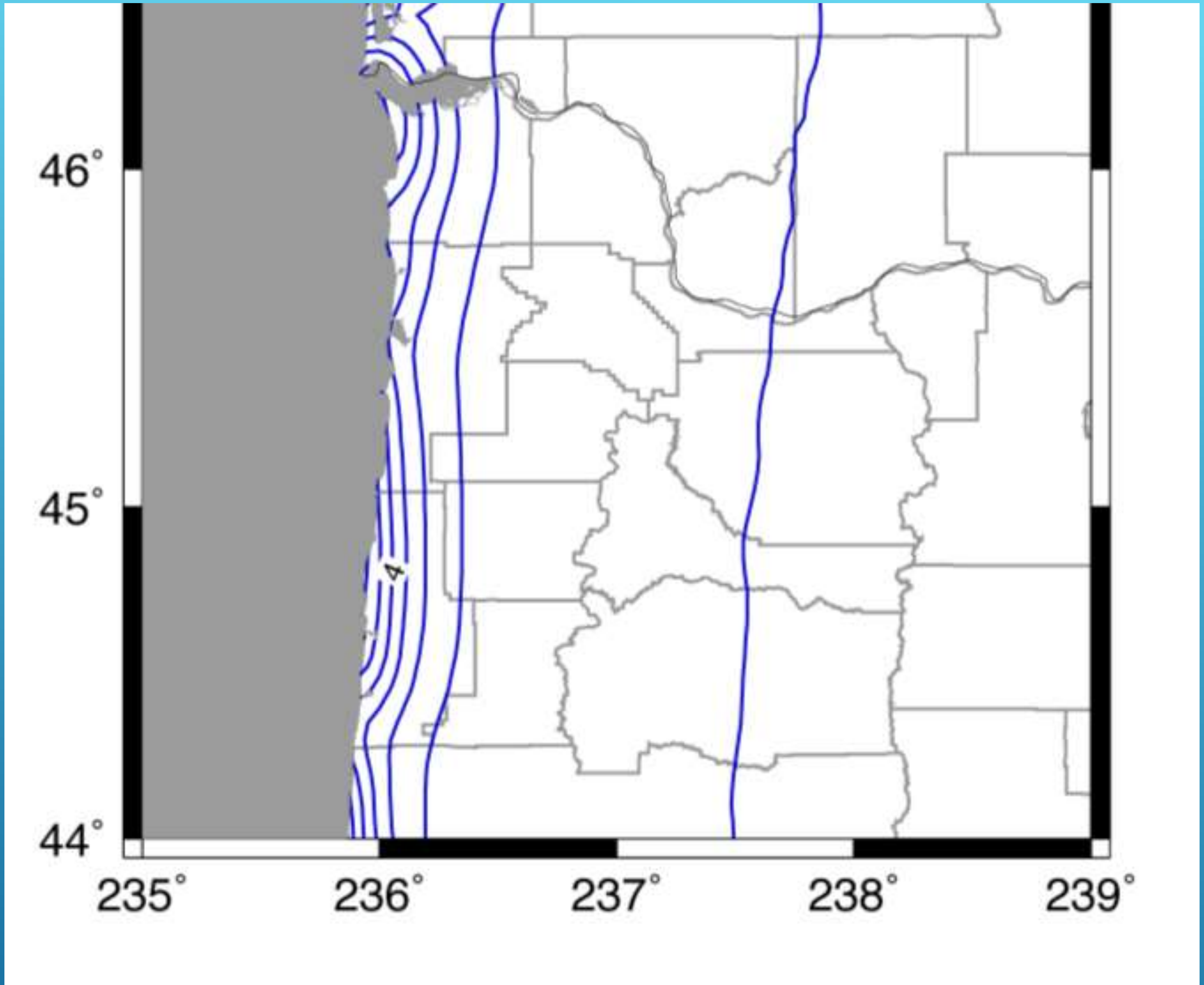
- PTHA Offshore Tsunami Amplitude and Predominant Period
- Disaggregated source figures showing the influence of various faults on the likelihood
- Runup, or Inundation depth reference points for overwashed peninsulas and/or islands
- Probabilistic Subsidence Maps

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





REGIONAL SEISMIC SUBSIDENCE IS DETERMINED BY LIKELIHOOD



PROBABILISTIC MAP OF SEISMIC SUBSIDENCE (FT)

ENGINEERING BASIS OF DESIGN

Tsunami Design Parameters

TSUNAMI RESILIENT ENGINEERING PHILOSOPHY

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

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

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,
- 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.

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.

DETERMINING THE INUNDATION DEPTH AND FLOW VELOCITIES AT A SITE IN THE TDZ

Energy Grade Line Analysis

Site-Specific Tsunami Inundation Analysis

TSUNAMI FLOW CHARACTERISTICS

Two approaches to determine flow depth and velocity

- **Energy Grade Line Analysis method** based on pre-calculated runup from the Tsunami Design Zone maps
- **Site-Specific Probabilistic Hazard Analysis**
  - Required for TRC IV
  - Optional for other TRCs
  - Velocity lower limit of 75-90% EGLA method

PHYSICS-BASED TSUNAMI LOADS

- Hydrostatic Forces
  - Unbalanced Lateral Forces
  - Buoyant Uplift based on displaced volume
  - Residual Water Surcharge Loads on Elevated Floors
- Hydrodynamic Forces
  - Drag Forces
  - 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

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 development of 2500 + yr MRI Tsunami Design Zone maps.
- Specified design procedures are provided for all possible loading conditions
- 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.

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 inundation Modeling to Define Tsunami Design Zones:

- 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)

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

- Fluid-Structure Interaction
- Structural Loading
- Structural Response
- Scour and Erosion

Performance by Risk Category — Structural Reliability Validated

Consequences (Life and economic losses) — Design for Tsunami Resilience

Warning and Evacuation Capability

THANK-YOU

Questions?