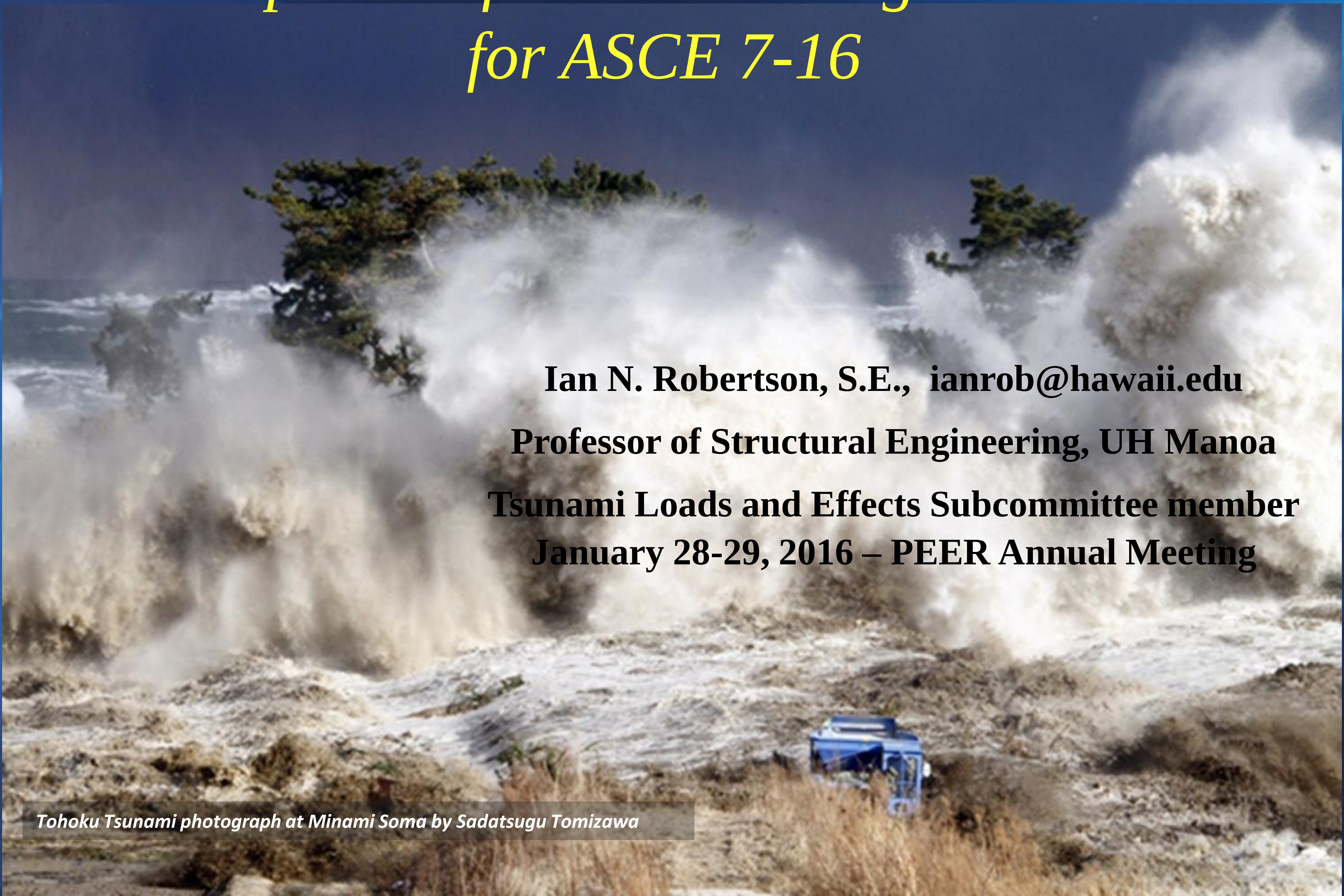
Development of Tsunami Design Provisions for ASCE 7-16



Ian N. Robertson, S.E., ianrob@hawaii.edu

Professor of Structural Engineering, UH Manoa

Tsunami Loads and Effects Subcommittee member

January 28-29, 2016 – PEER Annual Meeting

Tohoku Tsunami photograph at Minami Soma by Sadatsugu Tomizawa

OUTLINE

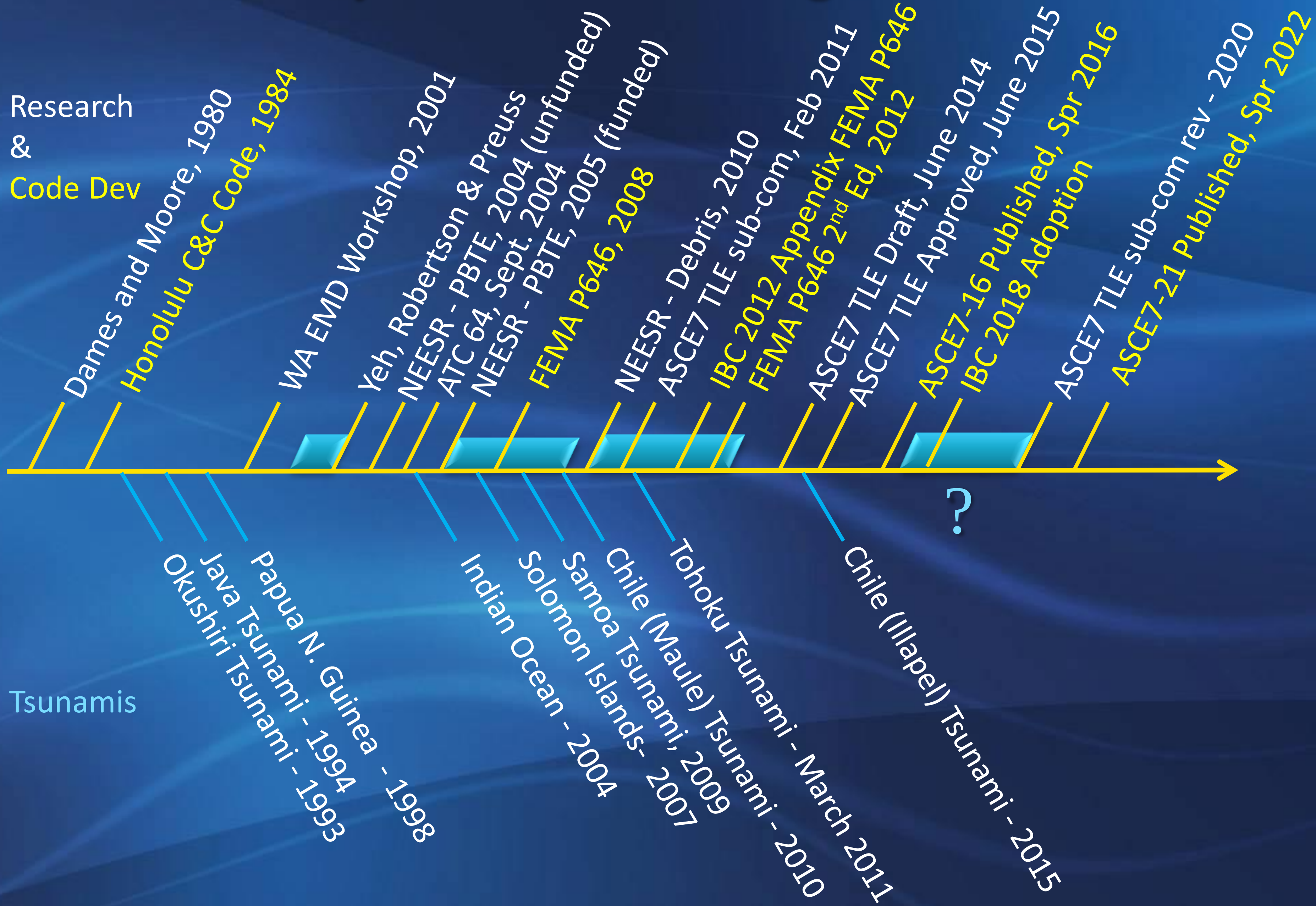
Development of Tsunami Design Provisions in the US

Past

Present

Future

History of Tsunami Design in the US



ASCE 7-10

- Minimum Design Loads for Buildings and Other Structures
- Referenced by IBC and therefore most US jurisdictions

ASCE 7-10

Minimum Design Loads for Buildings and Other Structures

- Chap 1 & 2 – General and load combinations
- Chap 3 - Dead, soil and hydrostatic loads
- Chap 4 - Live loads
- Chap 5 - Flood loads (riverine and storm surge)
- Chap 6 - Vacant
- Chap 7 - Snow loads
- Chap 8 - Rain loads
- Chap 10 - Ice loads
- Chap 11 – 23 - Seismic Design
- Chap 26 – 31 - Wind Loads

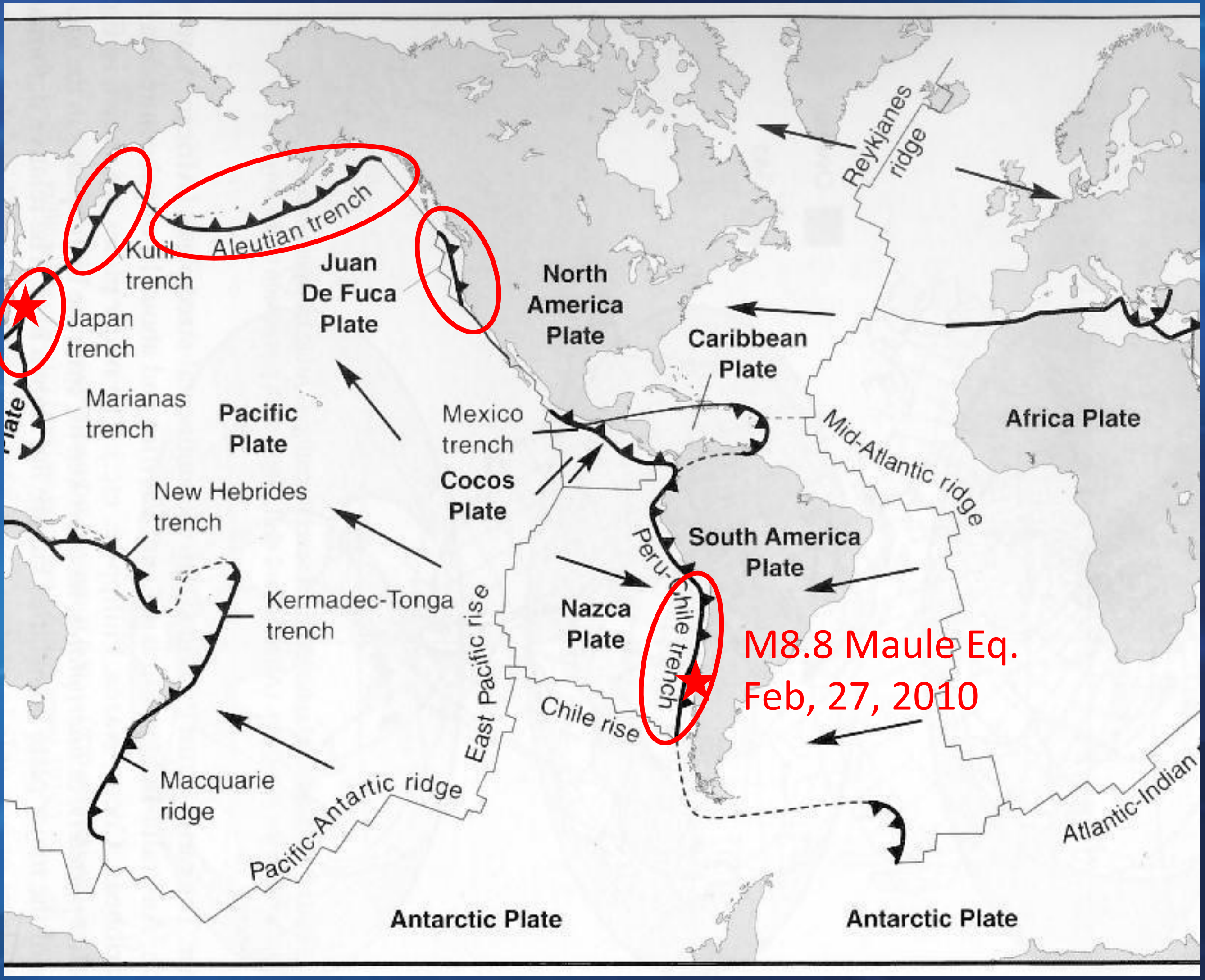
ASCE 7-16

Minimum Design Loads for Buildings and Other Structures

- Chap 1 & 2 – General and load combinations
- Chap 3 - Dead, soil and hydrostatic loads
- Chap 4 - Live loads
- Chap 5 - Flood loads (riverine and storm surge)
- Chap 6 – Tsunami Loads and Effects (42pg + 66 pg C)
- Chap 7 - Snow loads
- Chap 8 - Rain loads
- Chap 10 - Ice loads
- Chap 11 – 23 - Seismic Design
- Chap 26 – 31 - Wind Loads

Tsunami-genic Seismic Sources of Principal Relevance to the USA

M9.0 Great East Japan Eq Mar 11, 2011



Population at Direct Risk to Tsunami Hazard

State	Population at Direct Risk [1]
California	275,000 residents plus another 400,000 to 2,000,000 tourists; 840 miles of coastline
Oregon	25,000 residents plus another 55,000 tourists; 300 miles of coastline
Washington	45,000 residents plus another 20,000 tourists; 160 miles of coastline
Hawaii	~200,000[2] residents plus another 175,000 or more tourists and approximately 1,000 buildings directly relating to the tourism industry; 750 miles of coastline
Alaska	105,000 residents, plus highly seasonal visitor count; 6,600 miles of coastline

[1]USGS Scientific Investigations Reports 2012-5222 (CA),2007-5283 (OR), 2008-5004 (WA), 2007-5208 (HI [2] updated for exposure to great Aleutian tsunamis University of Hawaii and Hawaii State Civil Defense)

OUTLINE

Development of Tsunami Design Provisions in the US

Past

Present

Future

ASCE 7 Proposed Chapter 6 - Outline

- 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
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- 6.15 Designated Nonstructural Systems
- 6.16 Non-Building Structures

Section 6.1 General Requirements

Scope – Chapter 6 is applicable within mapped Tsunami Design Zone

The Tsunami Design Zone is the area vulnerable to being inundated by the Maximum Considered Tsunami, having a 2% probability of being exceeded in a 50-year period, or 1:2500 annual odds of exceedance.

The ASCE 7 Tsunami Loads and Effects Chapter is applicable only to the states of Alaska, Washington, Oregon, California, and Hawaii, which are tsunami-prone regions that have quantifiable hazards.

Could be adopted by other states and US territories (Guam, Puerto Rico, Samoa, etc.) if desired.

May find substantial international use in lieu of current codes based on FEMA P646 Guidelines.

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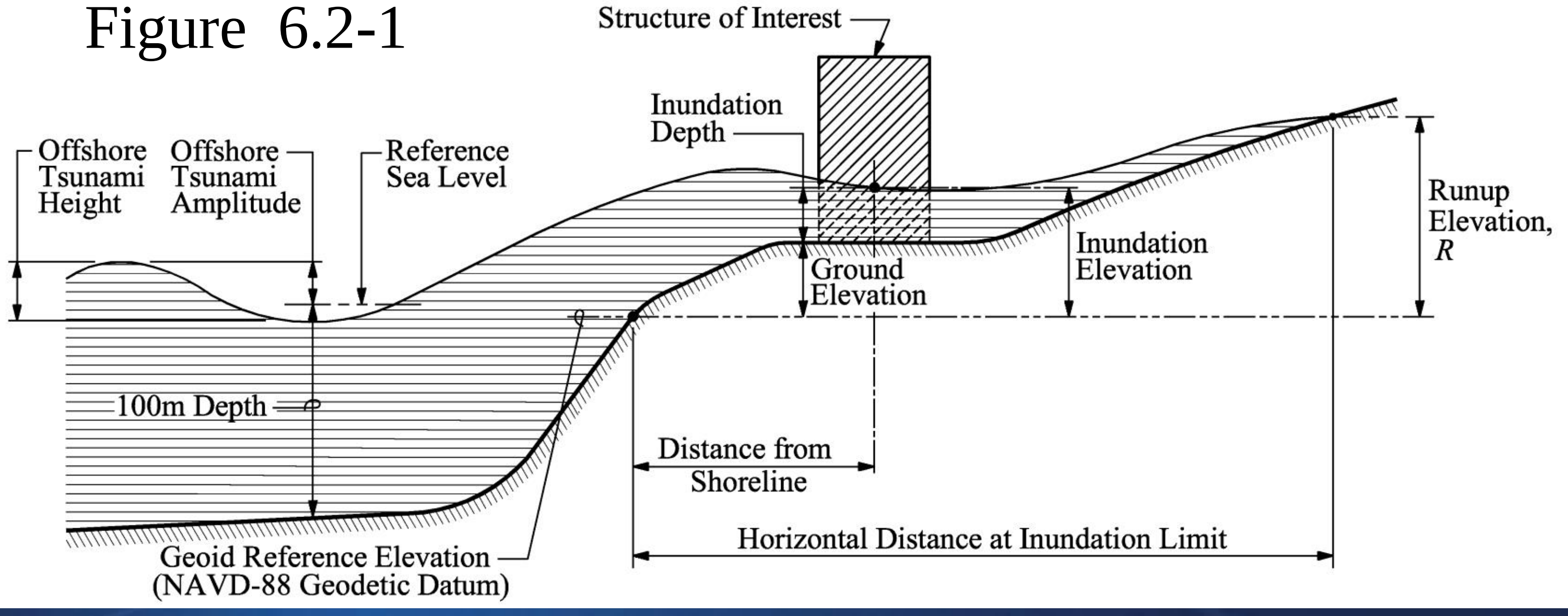
Definitions

- RUNUP ELEVATION: Difference between the elevation of maximum tsunami inundation limit and the (NAVD-88) 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

Figure 6.2-1



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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 with some modifications

Section 6.1

6.1.1 Scope

“The following buildings and other structures located within the Tsunami Design Zone shall be designed for the effects of Maximum Considered Tsunami ….. in accordance with this Chapter”

a. Tsunami Risk Category IV buildings and structures, including Vertical Evacuation Structures.

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

c. If required by the local jurisdiction, Tsunami Risk Category II buildings with mean height above grade plane as specified by the local jurisdiction (eg. greater than 65 ft) and inundation depth at any point greater than 3 feet

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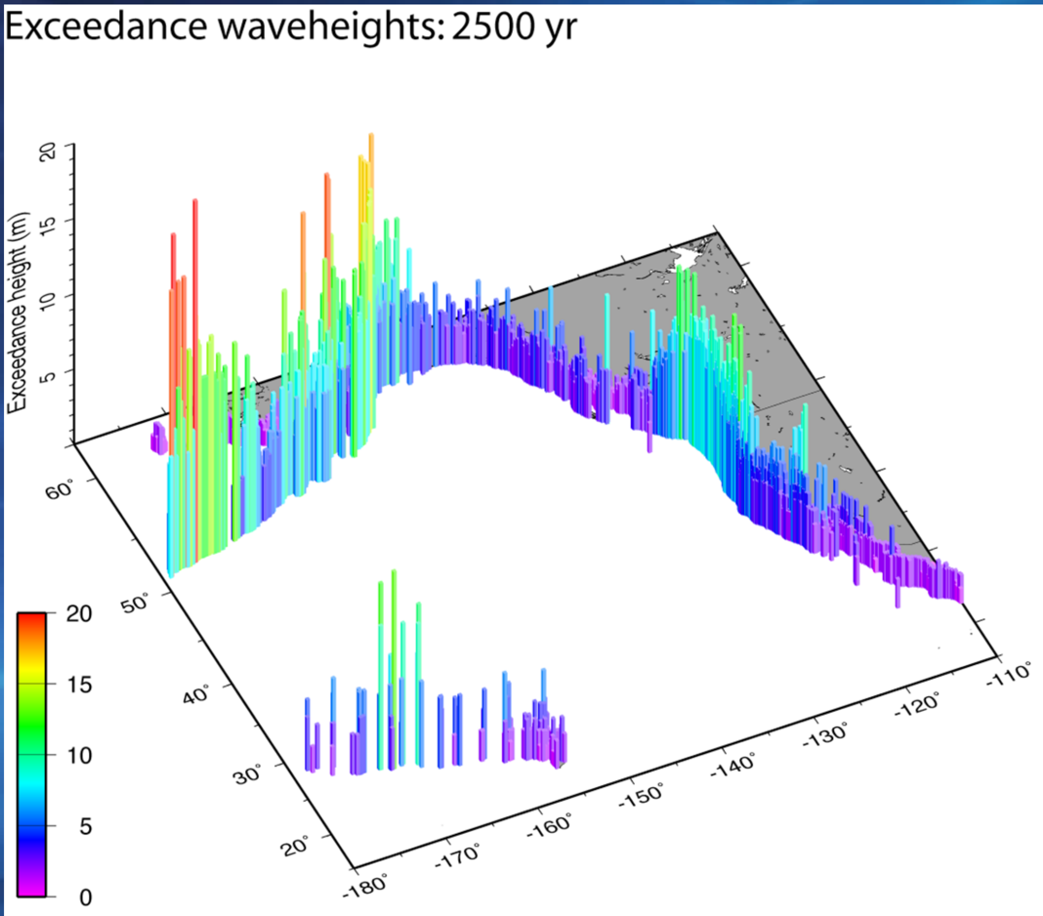
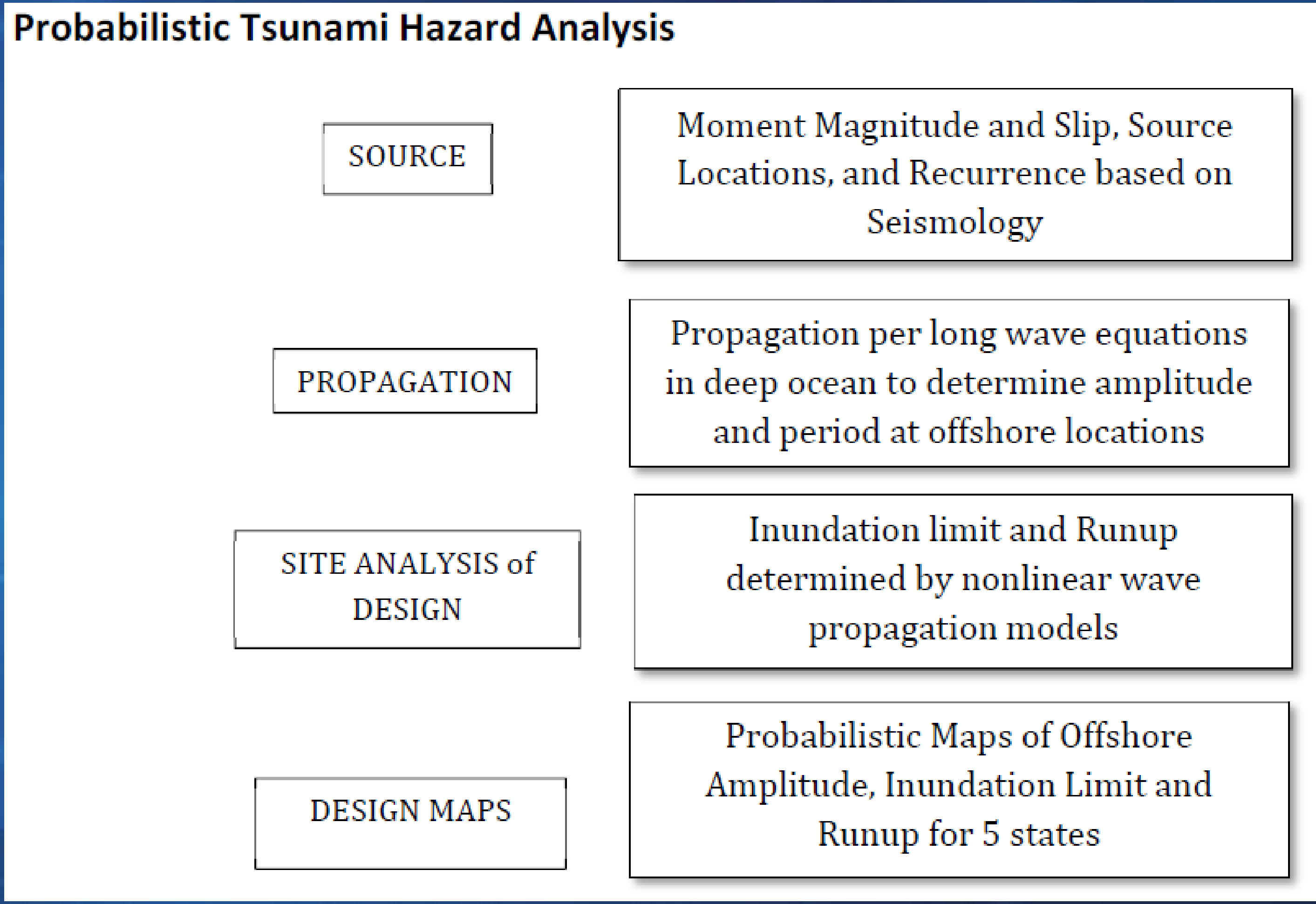
Tsunami Design Zone: Lessons from the Tohoku, Chile, and Sumatra Tsunamis

- Recorded history may not provide a sufficient measure of the potential heights of great tsunamis.
- Design must consider the occurrence of events greater than in the historical record
- Therefore, probabilistic physics-based Tsunami Hazard Analysis should be performed in addition to historical event scenarios
- This is consistent with the probabilistic seismic hazard analysis

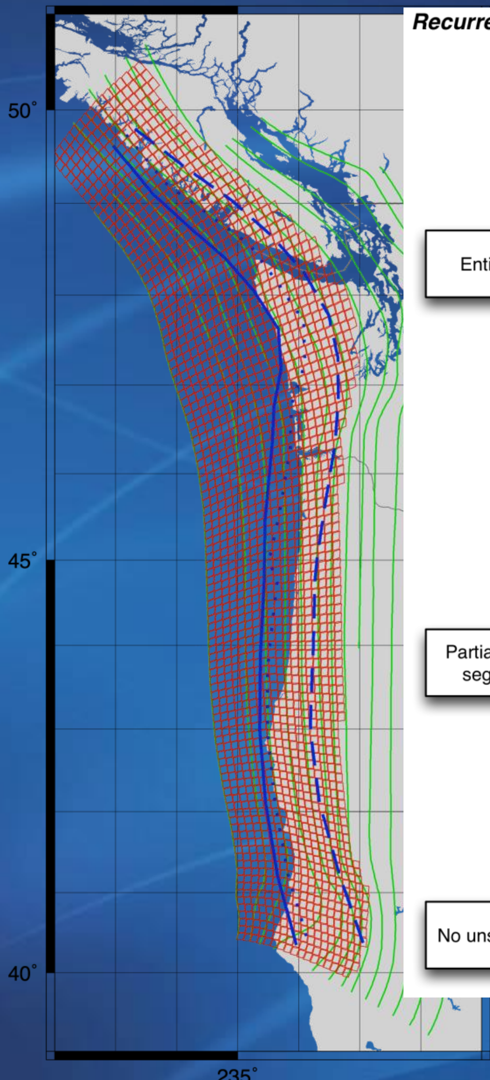


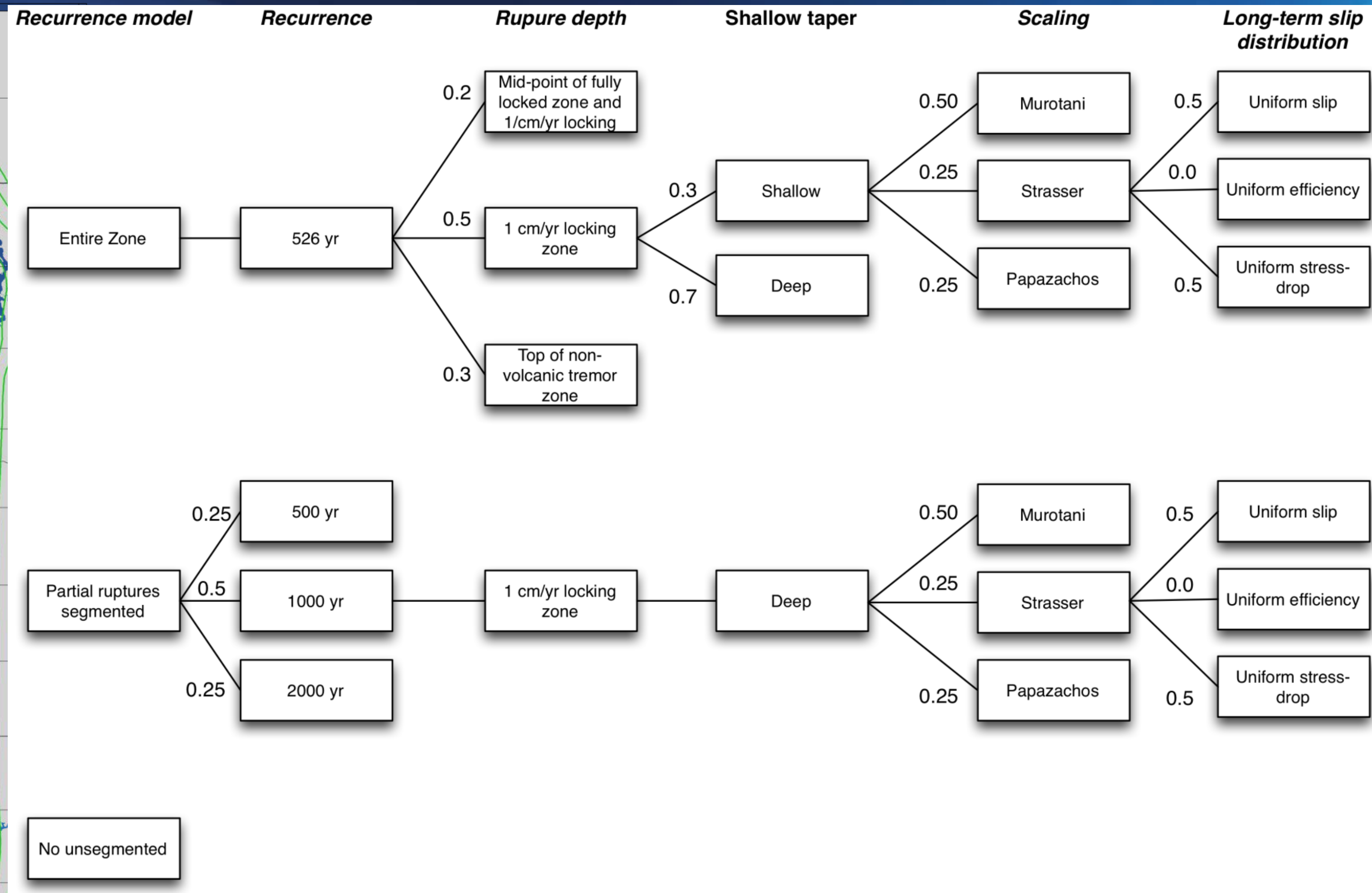
PTHA determines the Max. Considered Tsunami

- 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.



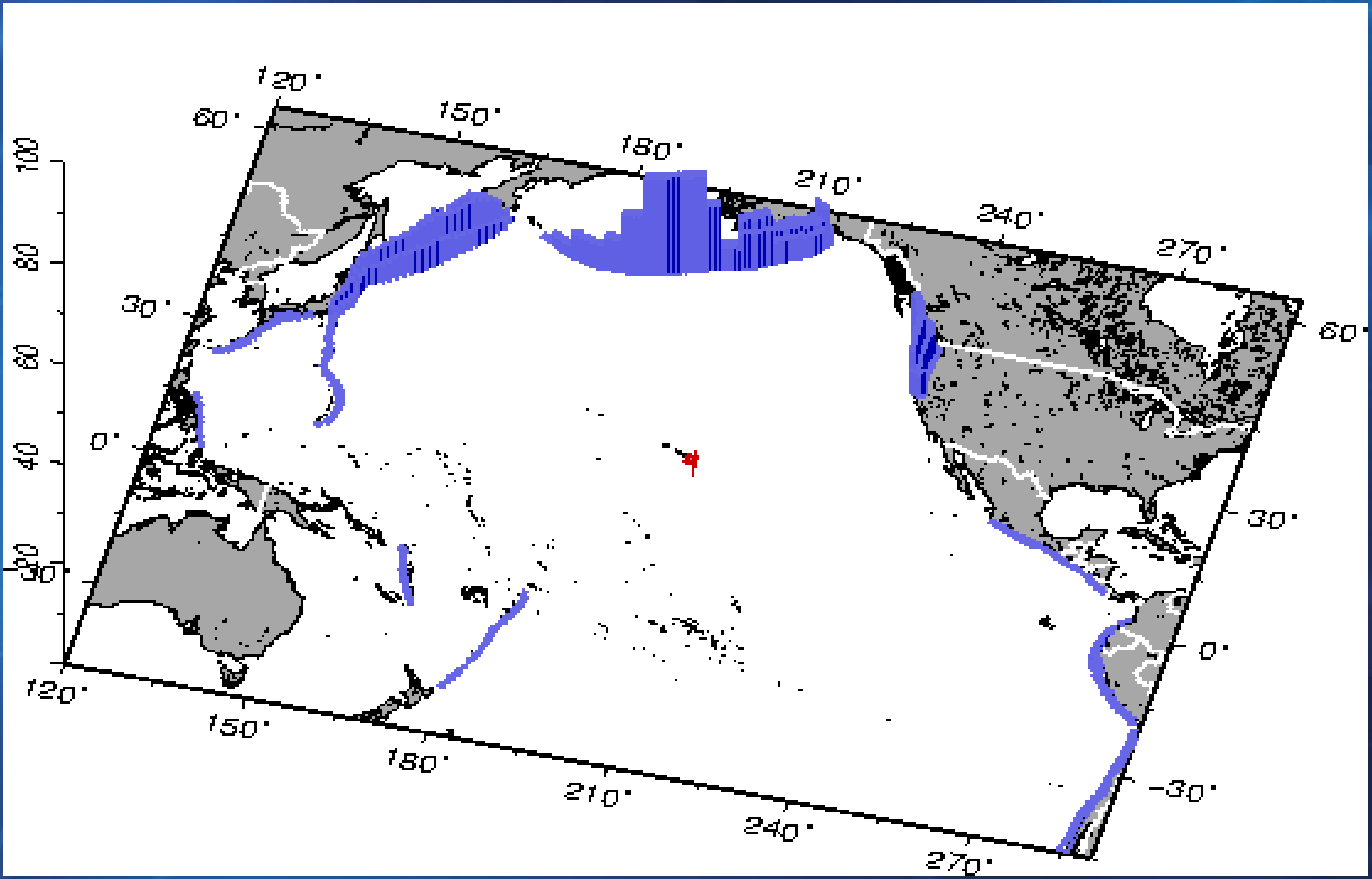
USGS Logic Tree for Cascadia adapted for Tsunamis



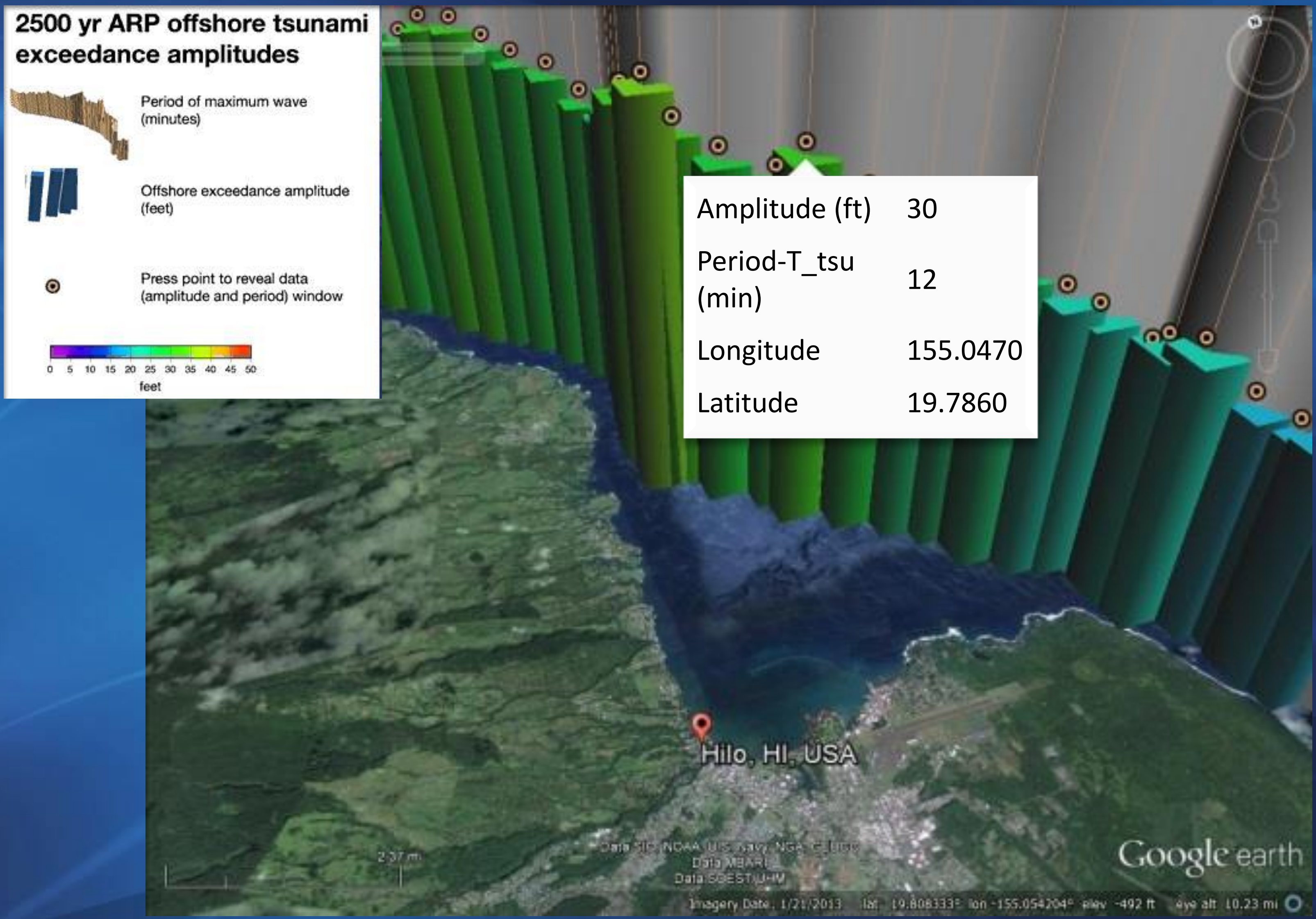


Disaggregated Hazard for Hilo, HI

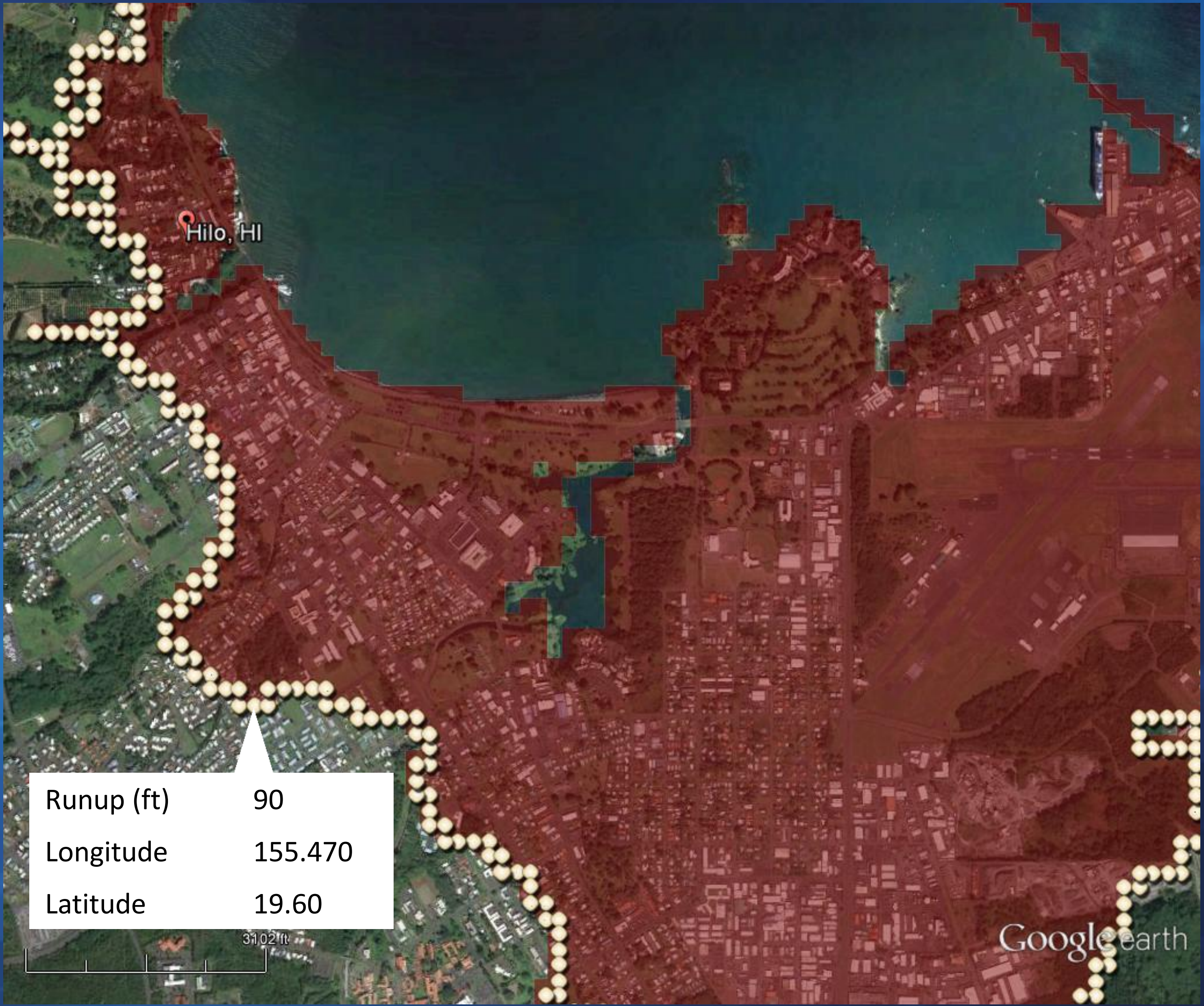
- Sources: Aleutian, Alaska, and Kamchatka-Kurile



Offshore Tsunami Amplitude and Period for the Maximum Considered Tsunami at Hilo Harbor, HI



Tsunami Design Zone - Hilo



Tsunami Flow Characteristics

Two approaches to determine flow depth and velocity

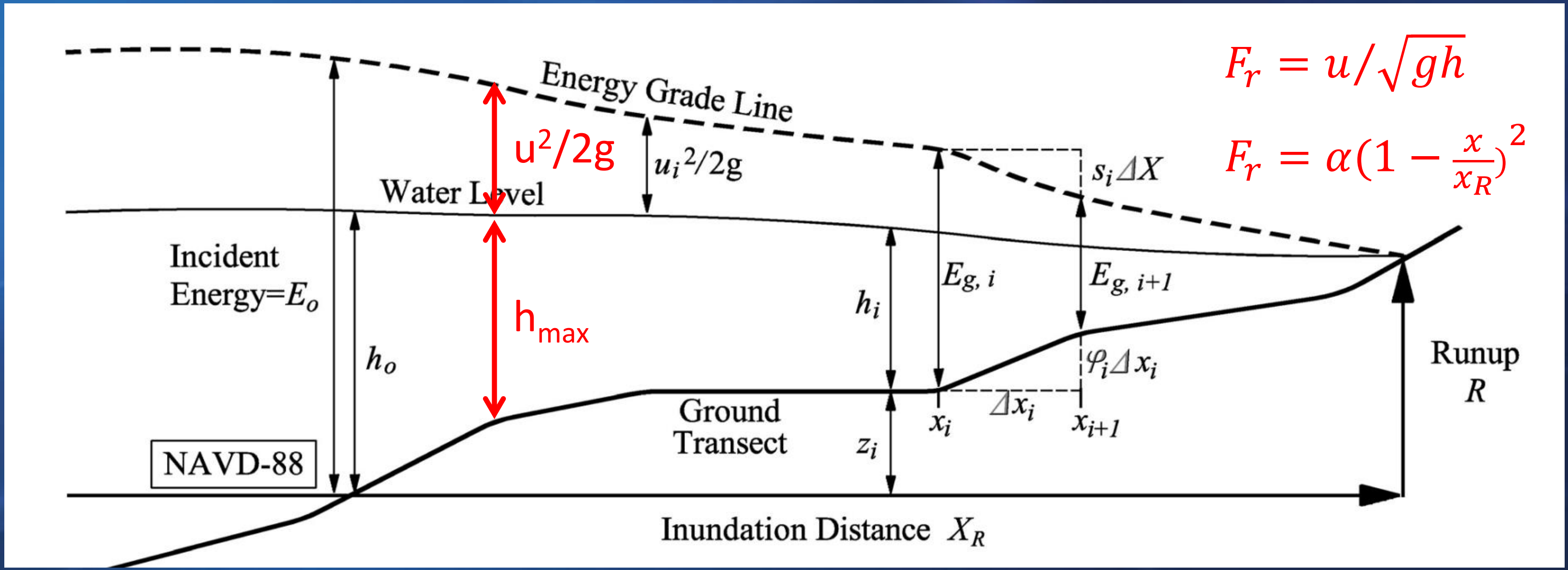
- Energy Grade Line Analysis method based on pre-calculated runup from the Tsunami Design Zone maps
- Site-Specific Probabilistic Hazard Analysis
  - Required for TRC IV
  - Optional for other TRCs
  - Velocity lower limit of 75-90% EGL method

Energy Grade Line Analysis

- Energy Grade Line Analysis
  - Determine hydraulic head at shore required to obtain runup
  - Calculation based on simple hydraulics using Manning's roughness coefficients

$$E_{g,i+1} = E_{g,i} - \left(f_i + s_i\right)\Delta X_i$$

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



Site-Specific Probabilistic Tsunami Hazard Analysis

- Can be run as a nonlinear time history inundation model analysis using Hazard Consistent Tsunami matching the defined probabilistic waveform
  - Offshore Tsunami Amplitude & effective Wave Period Relative amplitudes of crest and trough for each region
- Can be run as a complete probabilistic simulation from the seismic source slip event, calibrated to match the defined probabilistic Offshore Tsunami Amplitude
- In either case, time histories of site-specific flow parameters are generated.

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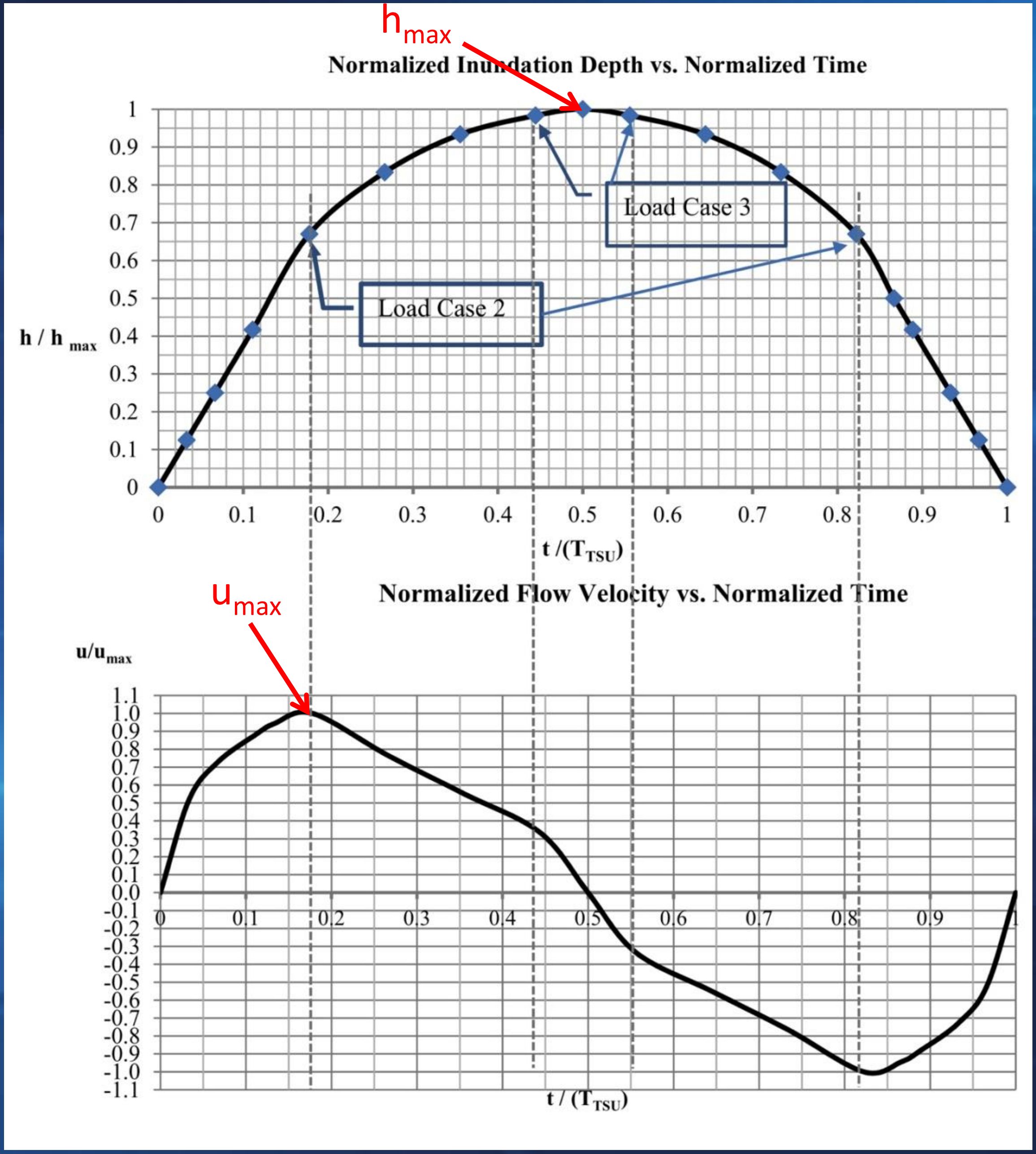
Load Cases

- 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



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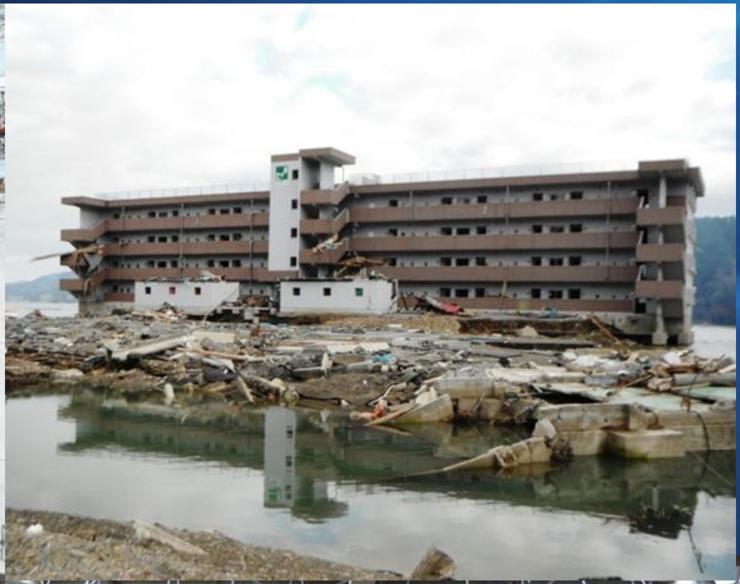
Structural Loads



Tsunami Loads and Effects

- Hydrostatic Forces (equations of the form $k_s \rho_{sw} g h$)
  - 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 on Broad Walls: Factor of 1.5
  - Hydrodynamic Pressurization by Stagnated Flow – per Benoulli
  - Shock pressure effect of entrapped bore
- Waterborne Debris Impact Forces (flow speed and $\sqrt{k\,m}$)
  - 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)

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- Scour Effects (mostly prescriptive based on flow depth)

Hydrodynamic Loads

- Formulations for detailed calculations on the building and for loads on components
  - Typically of the standard form drag (h- inundation depth and u – flow velocity for each load case)

$$f_{dx} = \frac{1}{2} r_s C_d C_{cx} B\left(hu^2\right)$$

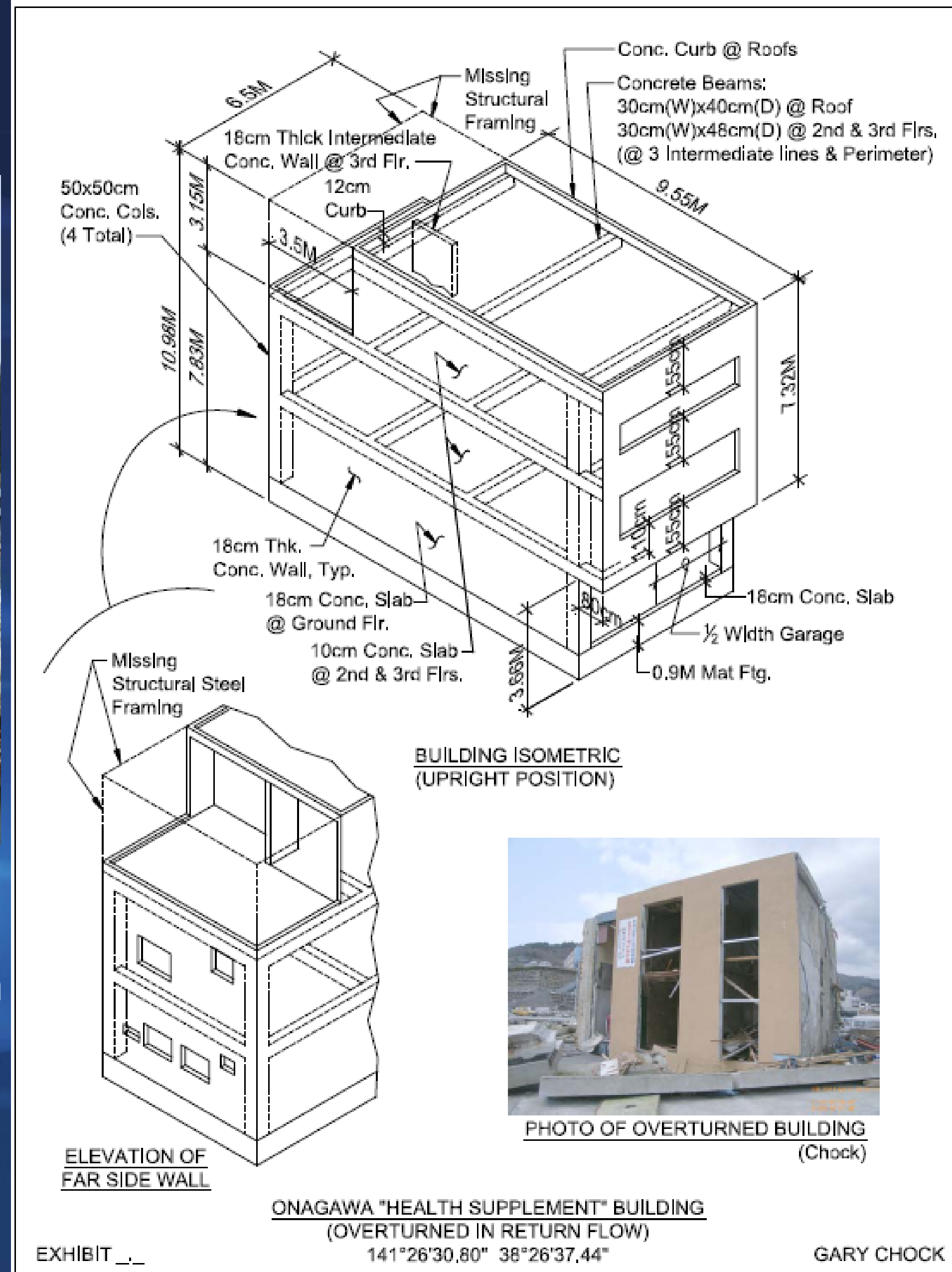
$$C_{cx} = \frac{\sum(A_{col}+A_{wall}) + 1.5A_{beam}}{Bh_{sx}}$$

$$C_{cx} \nless 0.7 \ for \ regular \ structure$$

$$C_{cx} \nless 0.5 \ for \ open \ structure$$

- System Evaluation
  - If $V_{Tsu} \leq 0.75\Omega_o E_h$, then system is adequate
- Component Evaluation
  - Apply drag to individual members, including debris accumulation on exterior of building

Building Performance – Building Overturning



Three-Story Concrete Retail Building (2050 kN deadweight) on mat foundation overturned during return flow when submerged in 8 m/s flow; would have toppled at only 3 m/s

Structural Response
Foundation Failure

Onagawa overturned steel building

Hollow pipe compression piles

Types of Floating Debris
Logs and Shipping Containers

Power poles and tree trunks become floating logs

Shipping containers float even when fully loaded

Types of Rolling Debris
Rocks and Concrete Debris

Medium boulder swept onshore

Large displaced seawall segment

Segment of failed seawall impacted and damaged a concrete column in Tarou

NEESR-CR:Impact Forces from Tsunami-Driven Debris

H.R. Riggs
U. of Hawaii

C.J. Naito
Lehigh U.

D.T. Cox
Oregon State U.

M.H. Kobayashi
U. of Hawaii

P. Piran Aghl (LU)
Lehigh U.

H.T.-S. Ko
Oregon State U.

E. Khowitar
U. of Hawaii

Oregon State University OSU

University of Hawai'i

LEHIGH University

NEES

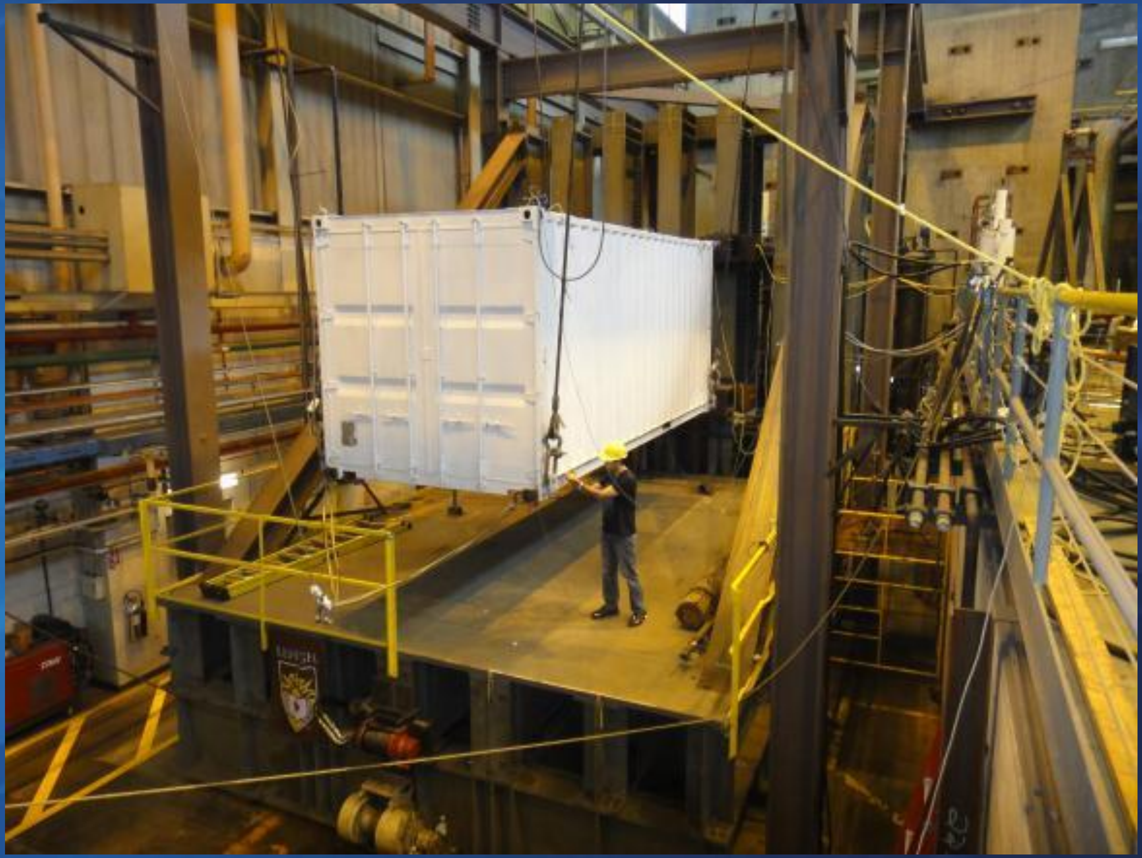
George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES)

NSF

May 16, 2013 https://nees.org/resources/6277/

ISO 20-ft Shipping Container

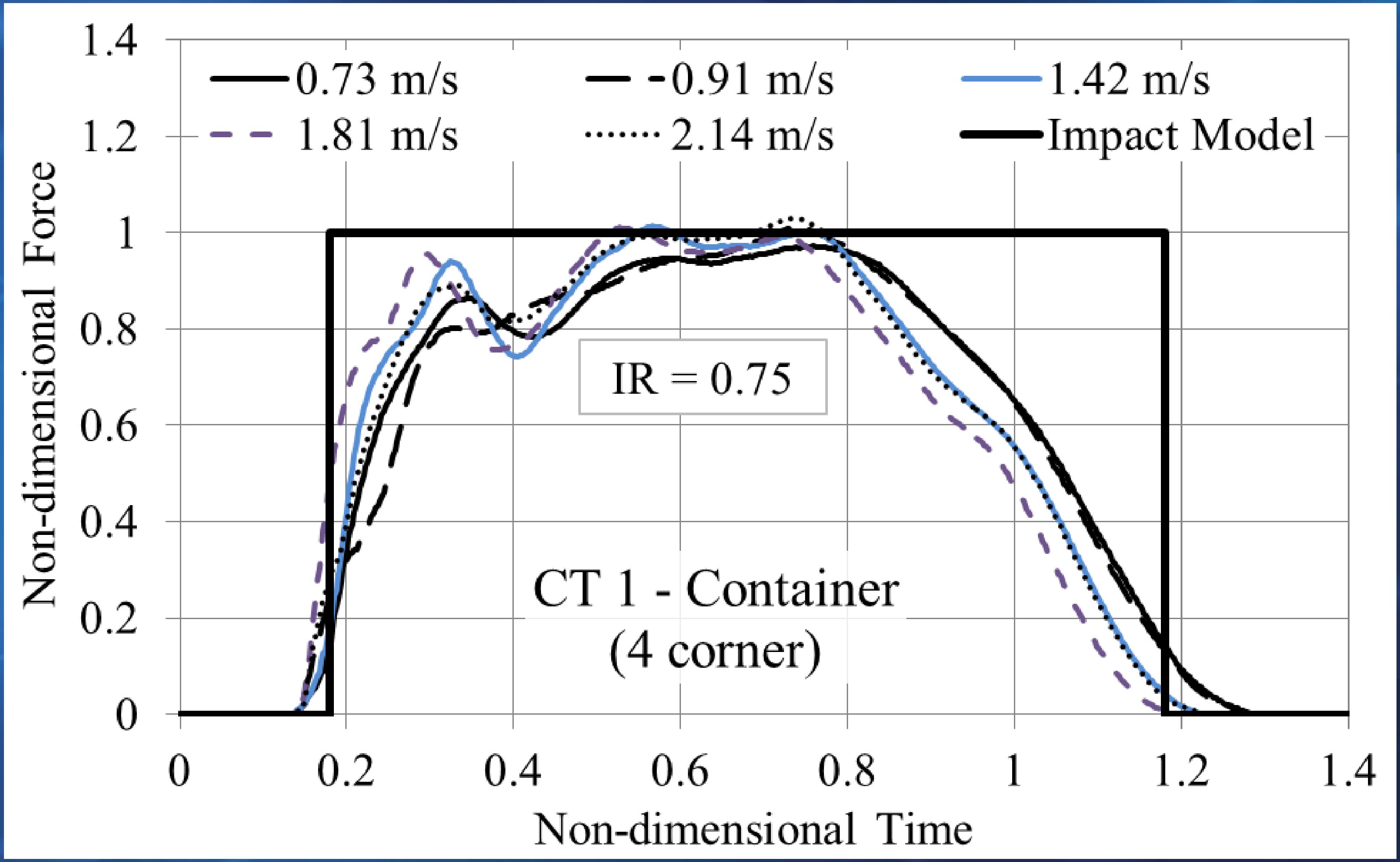
- 6.1 m x 2.4 m x 2.6 m and 2300 kg empty
- Containers have 2 bottom rails and 2 top rails
- Pendulum setup; longitudinal rails strike load cell(s)



Shipping Container Impact

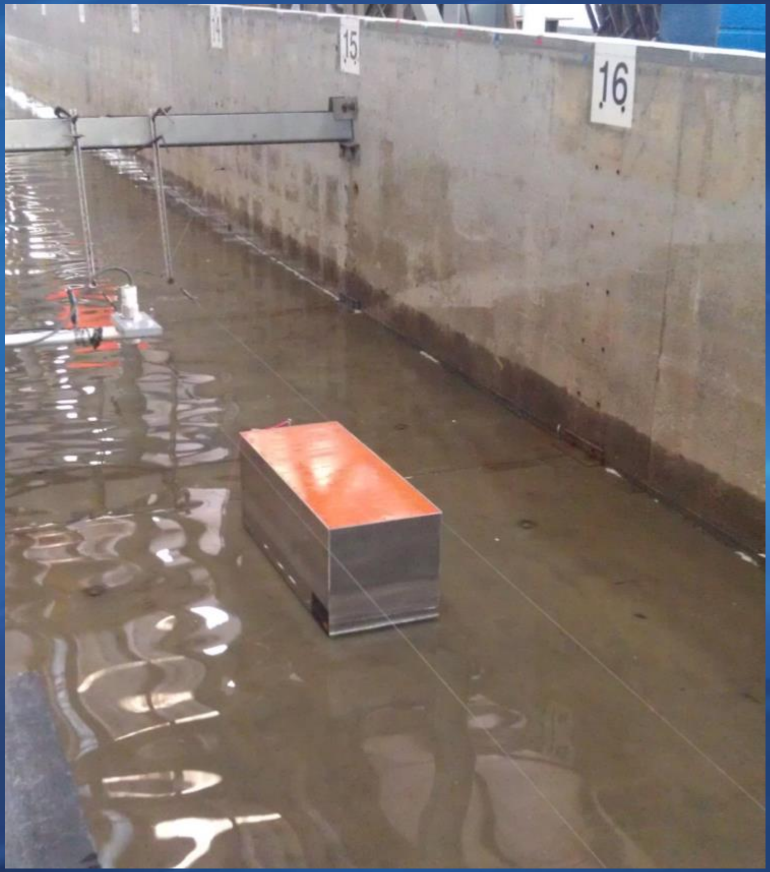
Video

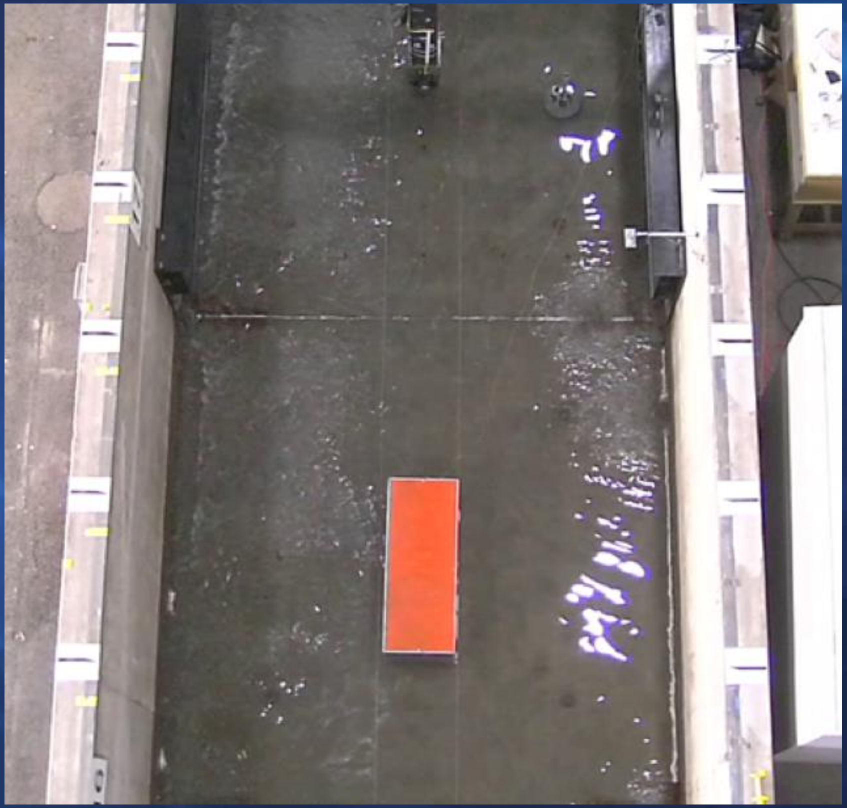
Impact Force Time History



Aluminum and Acrylic Containers

- 1/5 scale model containers of aluminum and acrylic
- Guide wires controlled the trajectory
- Container hits underwater load cell to measure the force



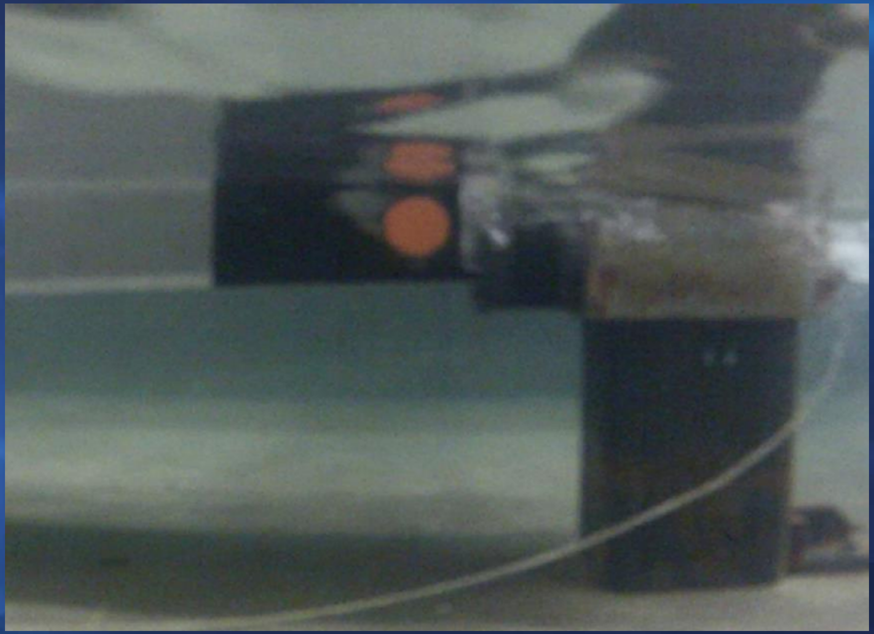


Column and load cell at top of photo

Impact with Load Cell

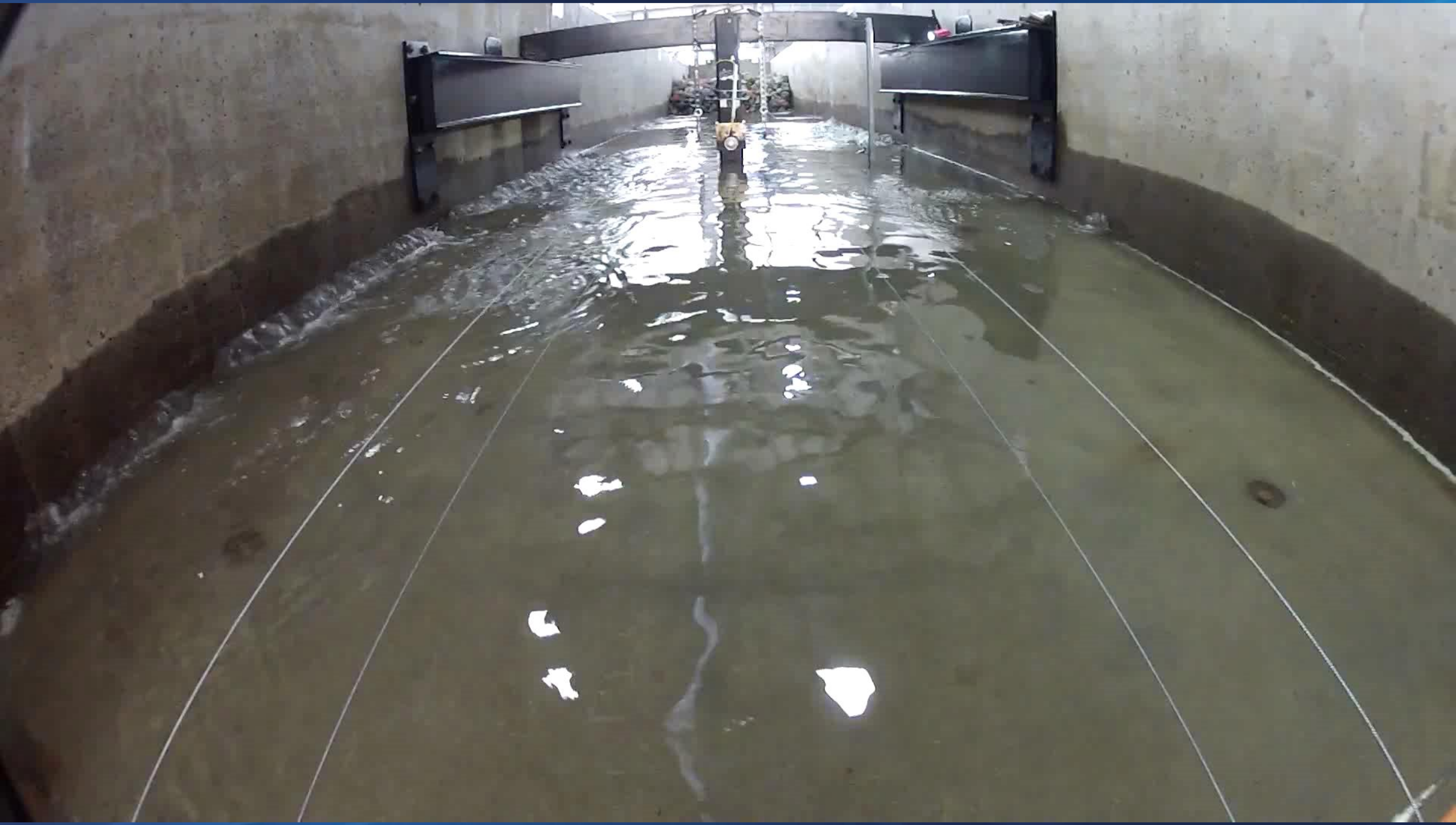
- In-air tests carried out with pendulum set-up for baseline
- In-water impact filmed by submersible camera
- Impact was on bottom plate to approximate longitudinal rail impact

In-air impact



In-water impact

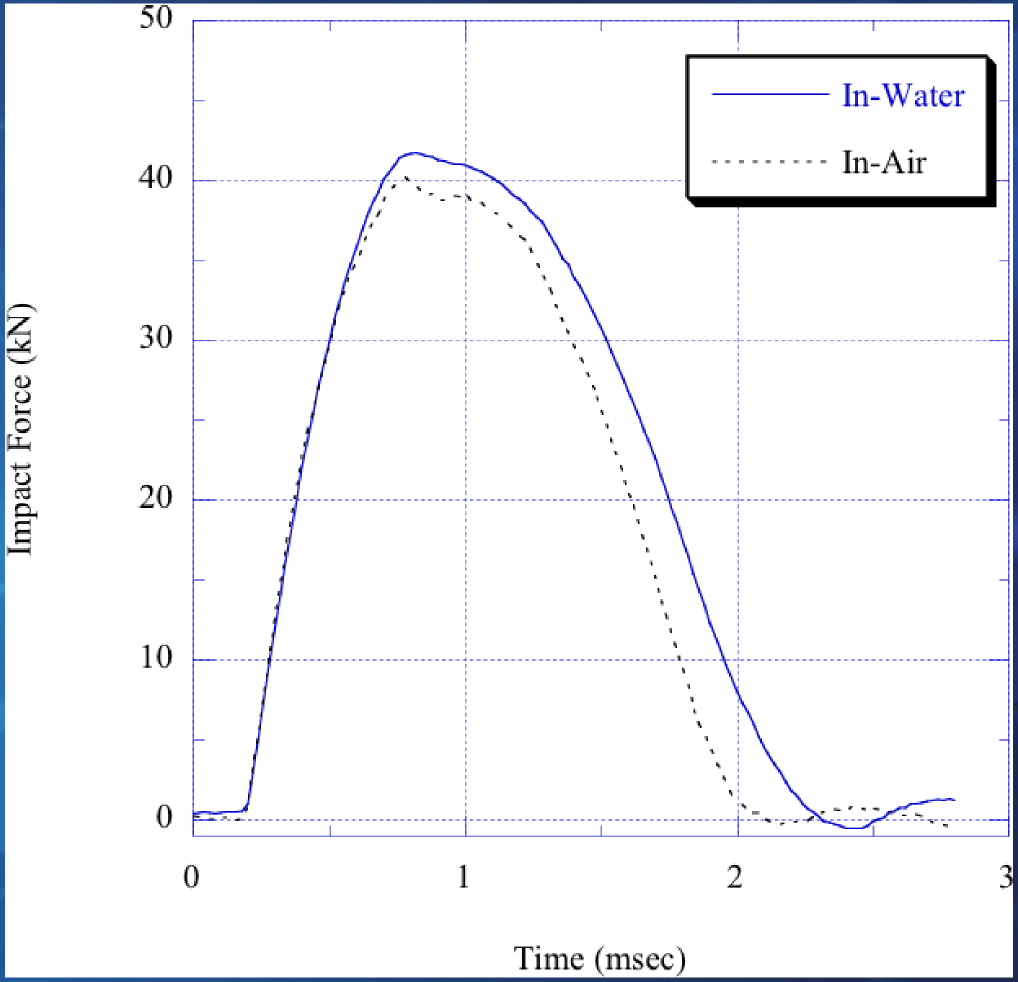
Container Impact



Side View

Force Time-History

- In-water impact and in-air impact very similar
  - Less difference between in-air and in-water compared to scatter between different in-water trials



Debris Impact Force

- Nominal maximum impact force

$$F_{ni} = u_{\max}\sqrt{km_d}$$

- Factored design force based on importance factor

$$F_i = I_{TSU} F_{ni}$$

- Impact duration

$$t_d = \frac{2 m_d u_{\max}}{F_{ni}}$$

- Force capped based on strength of debris
- Contents increase impact duration but not force

Assessment for Shipping Containers and Ships

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

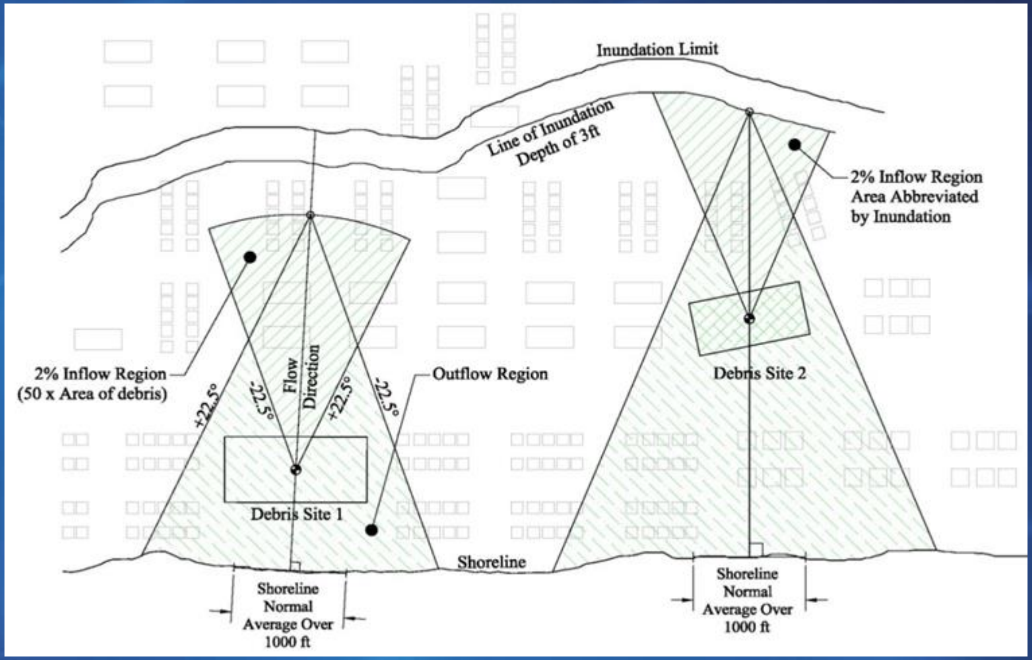
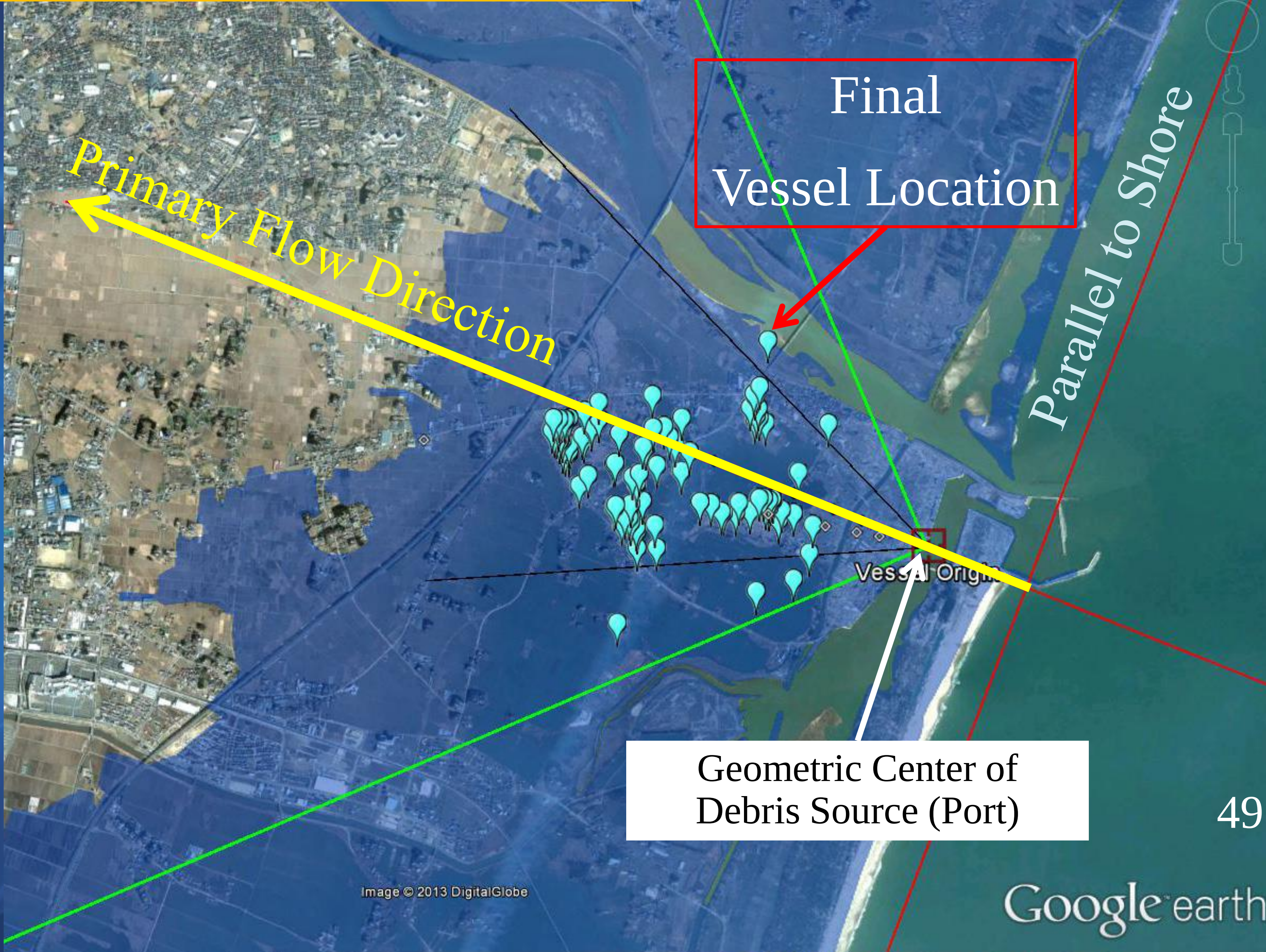


Figure 6.11-1

- 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

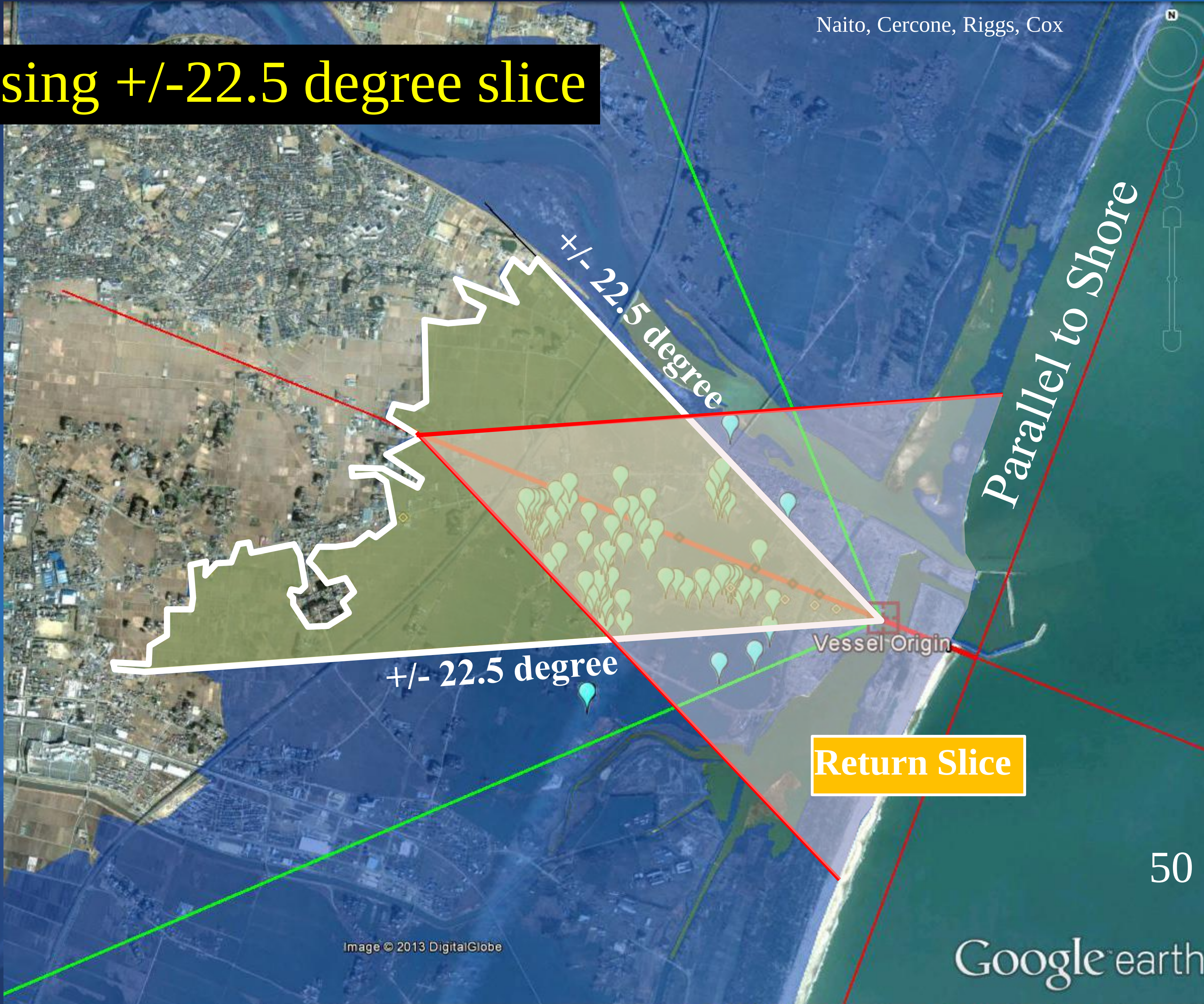
Natori, Japan (Vessels)

Naito, Cercone, Riggs, Cox, 2013



Using +/-22.5 degree slice

Naito, Cercone, Riggs, Cox



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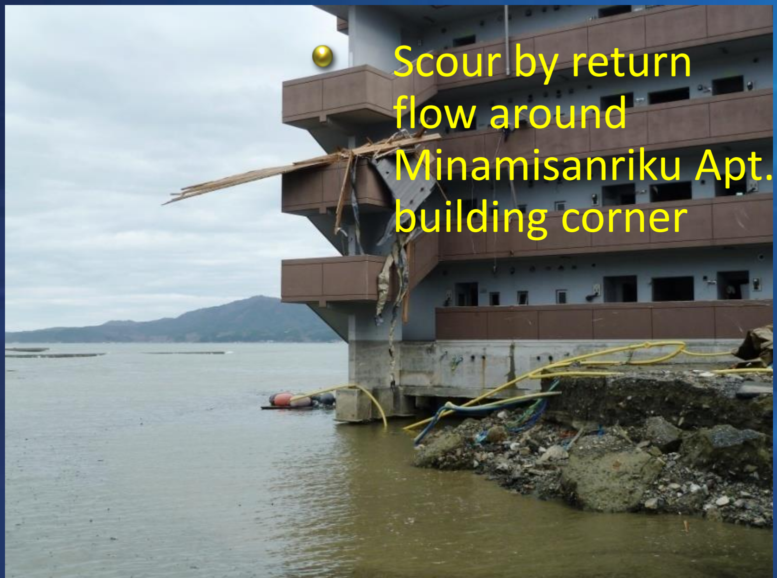
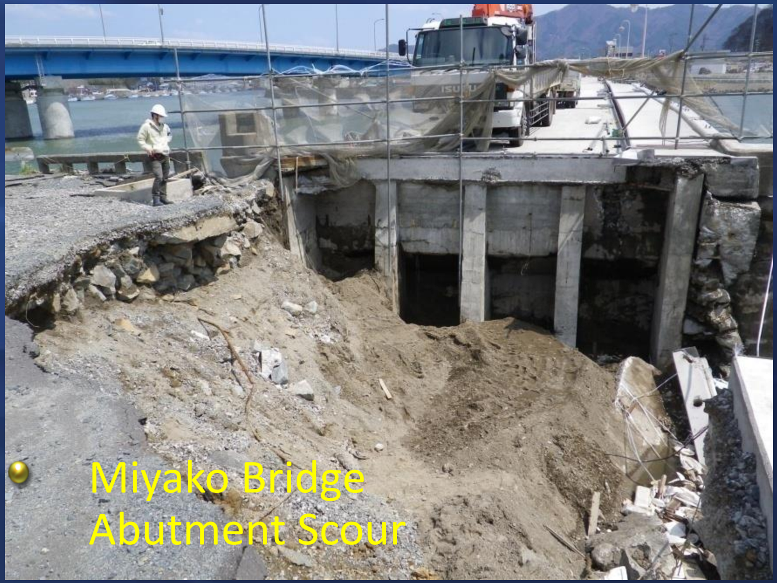
Foundation Design – Scour Examples





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

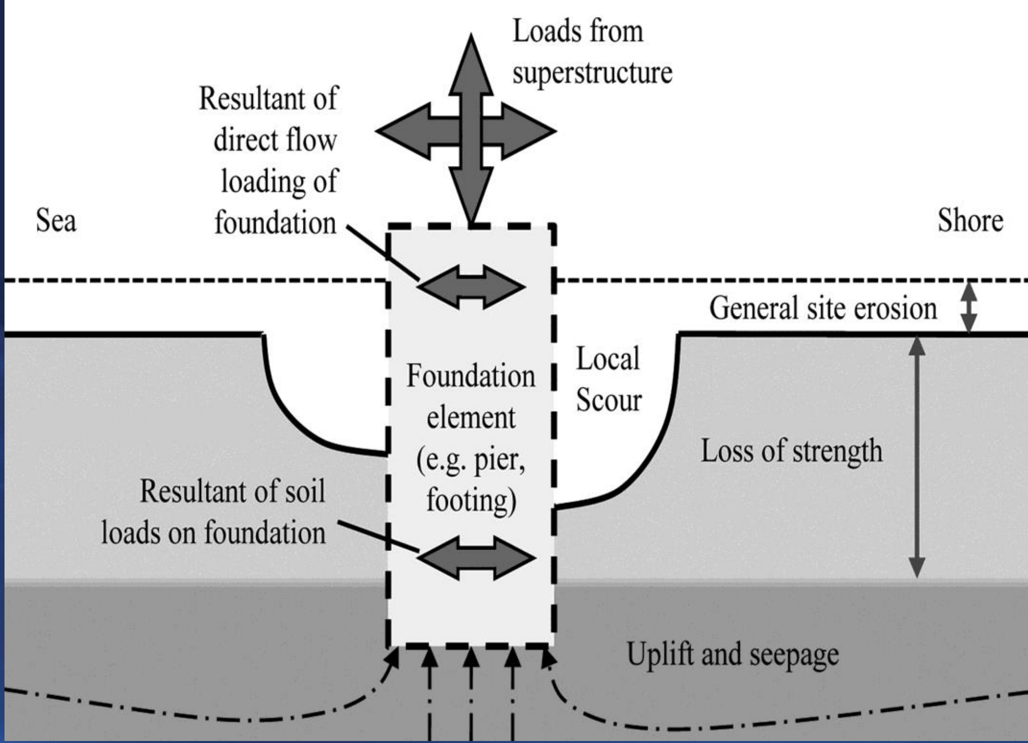


Figure C6.12-1. Schematic of tsunami loading condition for a foundation element

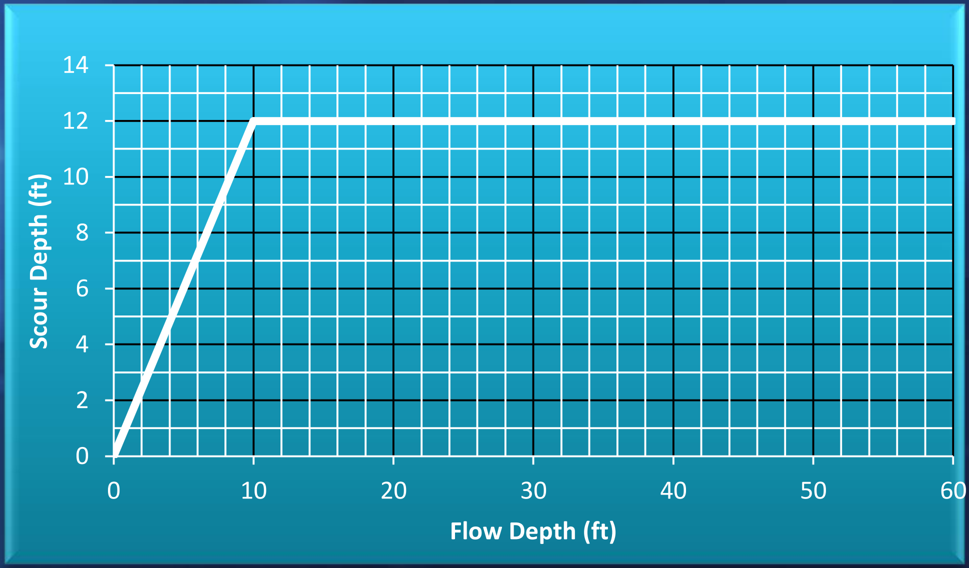


Figure 6.12-1 Local Scour Depth due to Sustained Flow and Pore Pressure Softening

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- 6.4 Tsunami Risk Categories
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- 6.6 Inundation Depth and Flow Velocity Based on Runup
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- 6.8 Structural Design Procedures for Tsunami Effects
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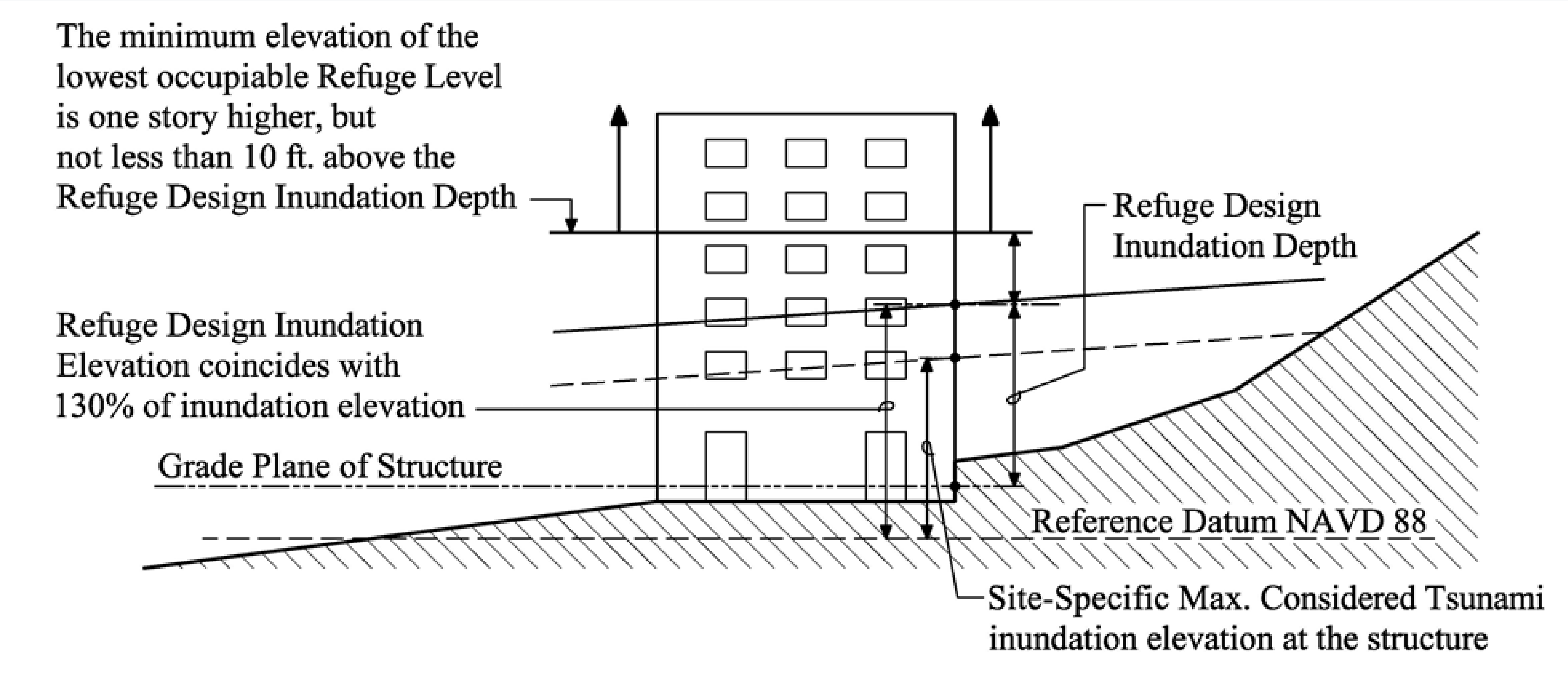
- 6.14 Tsunami Vertical Evacuation Refuge Structures
- 6.15 Designated Nonstructural Systems
- 6.16 Non-Building Structures

Tsunami Vertical Evacuation Refuge Structures



ASCE 7 Proposed Chapter 6 - Outline

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Anticipated Reliabilities for Tsunami and Earthquake

Risk Category	Column Failure* probability conditioned on occurrence of MCT	Systemic Failure probability conditioned on occurrence of MCE
II	7.5%	10%
III	4.9%	5-6%
IV	2.7%	2.5-3%
Tsunami Vertical Evacuation Refuge	< 1%	NA

Chock et al. 2016 — FEMA P-695 and Luco (2007)

* Based on hydrodynamic drag including debris accumulation, but not debris impact

OUTLINE

Development of Tsunami Design Provisions in the US

Past

Present

Future

Future Tsunami Research Needs

- Improved Probabilistic Analysis
  - Seismic Source Mechanism (PEER NGA-Sub)
  - Tsunami Generation Modeling (Slip distribution)
  - Paleotsunami validation of magnitude and return periods
- Improved Inundation Modeling
  - Bore formation
  - Flow velocity validation
  - Higher resolution modeling in built environment
  - Structural loading directly from fluid model
- Energy Grade Line Analysis
  - Field validation – Past and Future

Future Tsunami Research Needs

- Community Resilience
  - Life safety primarily depends on evacuation planning and public education
  - Evacuation Modeling, Planning and Exercise
  - Performance Based Design
  - Loss Estimation Modeling (HAZUS MH, others)
  - Development of Fragility Curves
  - Lifeline Redundancy/Resilience
  - Tsunami Cognizant Town Planning

Future Tsunami Research Needs

- Improved Structural Loading Expressions
  - Field validation based on observed damage
  - Fluid density including suspended solids ($\rho_s = 1.1\rho_{sw}$)
  - Debris accumulation estimate ($C_{cx} = 0.5, 0.7, ?$)
  - Scour estimates and modeling
  - Fluid loading and design of coastal infrastructure
    - Bridges (PEER DOT Pooled Funds project)
    - Wharves and Piers
    - Breakwaters and Levees

Application Timeframe for ASCE 7-16 Tsunami in the Five Western States

- ASCE 7-16 with Chapter 6, Tsunami Loads and Effects
  - Public Comment period just ended
  - Will be published in Spring 2016
- ASCE 7-16 will be referenced by IBC 2018
- State Building Codes of AK, WA, OR, CA, & HI ~ 2020

Educational activities

- ASCE Publications
  - *Tsunami Loads and Effects: Guide to the Tsunami Design Provisions of ASCE 7-16* ,with worked examples (Robertson)
  - Volume II with additional design examples emphasizing RC III, RC IV, and nonbuilding critical facility structures (Thomas)
- ASCE Webinars and Seminars
  - Panel Discussion at SEI/GEO Congress, Feb. 2016
  - Webinar Aug. 22, 2016
  - Future Seminars to be planned
- Journal and conference papers
  - Special Session at 16th WCEE, Santiago, Jan. 2017

The ASCE Tsunami Loads and Effects Subcommittee

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Any Questions?