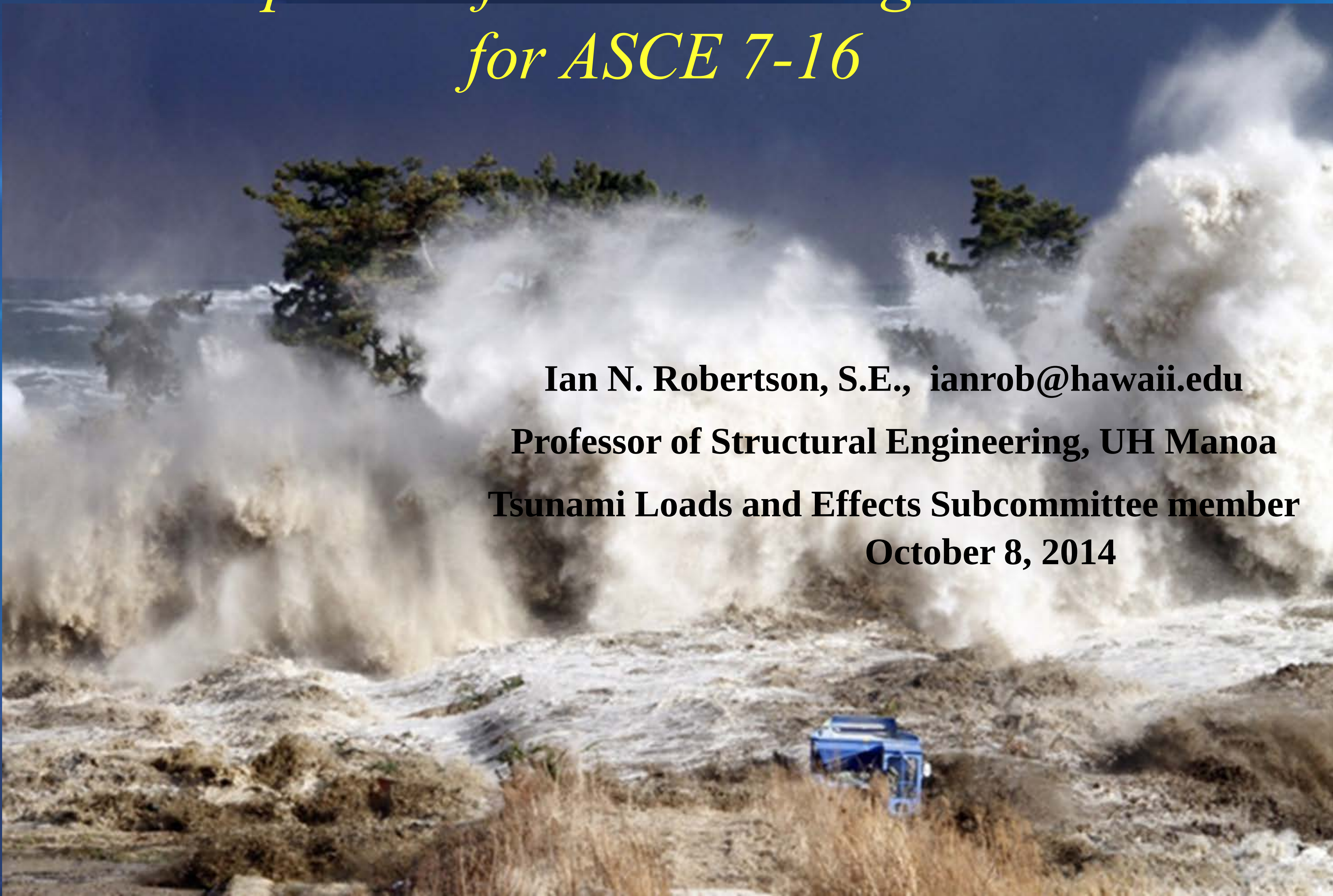
Development of Tsunami Design Provisions for ASCE 7-16



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Professor of Structural Engineering, UH Manoa

Tsunami Loads and Effects Subcommittee member

October 8, 2014

Background Information on the Development of a Tsunami Code

TLESC chair: Gary Chock <gchock@martinchock.com>

- A U.S. national standard for engineering design for tsunami effects does not exist. Tsunami risk to coastal zone construction is not explicitly addressed in design.

- FEMA P646 Guidelines for Vertical Tsunami Evacuation Refuge structures:
  - First Edition in 2008 was very conservative for debris strikes and unconservative for flow depth and velocities and hydrodynamic loadings.
  - Revised in 2012 as Second Edition to improve debris impact loads.
  - Not a consensus-based document, and not written in mandatory language.

Background Information on the Development of a Tsunami Code

- The Tsunami Loads and Effects Subcommittee of the ASCE/SEI 7 Standards Committee was authorized in February 2011 – Chair: Gary Chock
- TLESC has developed a new Chapter 6 - Tsunami Loads and Effects for the ASCE 7-16 Standard, which has passed and is pending approval.
- ASCE 7-16 to be published by March 2016
- Tsunami Provisions would be referenced in IBC 2018
- State Building Codes of AK, WA, OR, CA, & HI ~ 2020
- ASCE will be publishing a design guide in 2015 with design examples.

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 7-10

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ASCE 7-10

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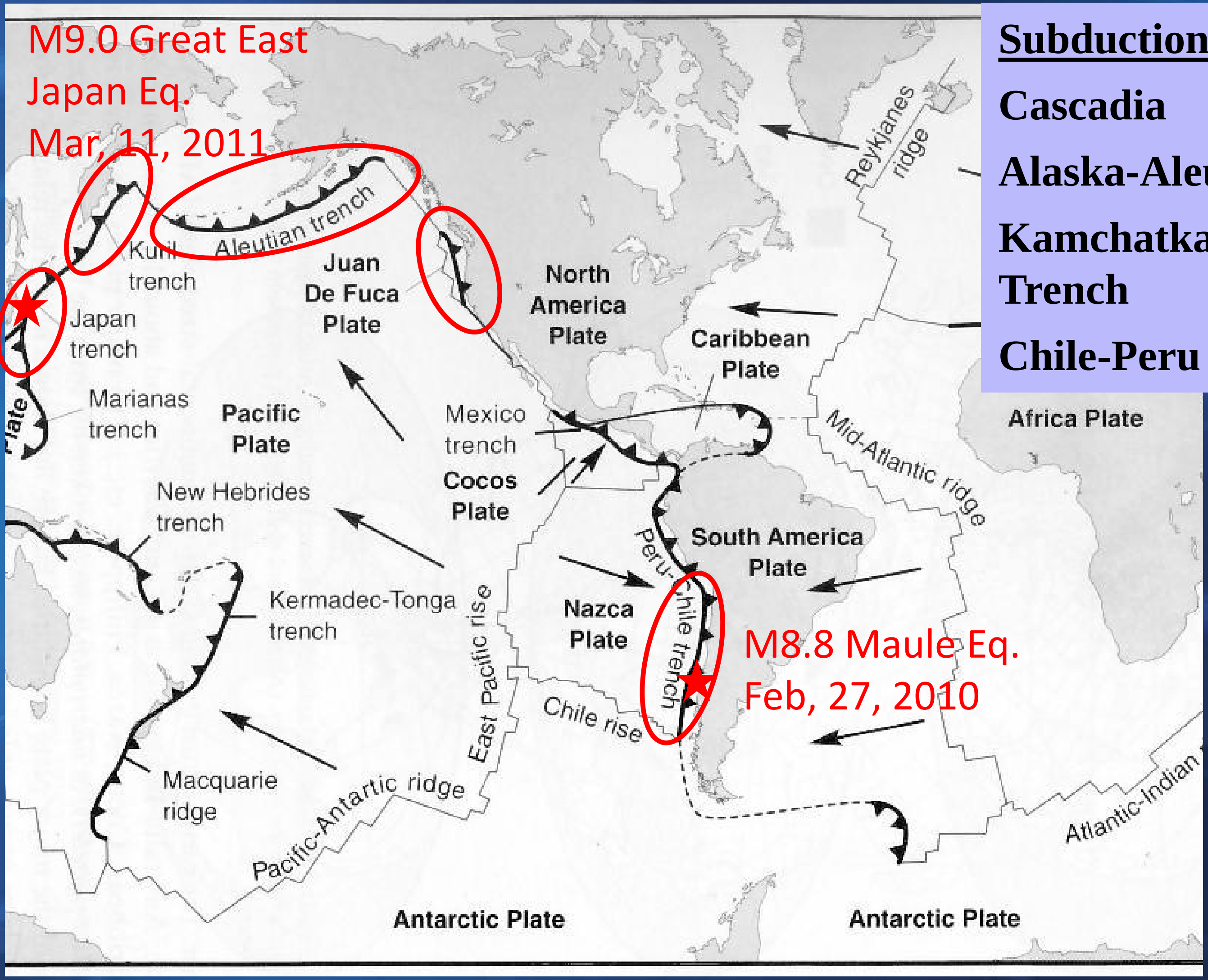
Tsunami-genic Seismic Sources of Principal Relevance to the USA



Subduction Zones

Cascadia

Alaska-Aleutian

Kamchatka-Kuriles & Japan Trench

Chile-Peru

State	Population at Direct Risk (USGS Lower-bound estimates)	Profile of Economic Assets and Critical Infrastructure
California	275,000 residents plus another 400,000 to 2,000,000 tourists; 840 miles of coastline	>$200 Billion plus 3 major airports (SFO, OAK, SAN) and 1 military port, 5 very large ports, 1 large port, 5 medium ports
	Total resident population of area at immediate risk to post-tsunami impacts: 1,950,000	
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	
Washington	45,000 residents plus another 20,000 tourists; 160 miles of coastline	$4.5 Billion plus essential facilities, 1 military port, 2 very large ports, 1 large port, 3 medium ports
	Total resident population of area at immediate risk to post-tsunami impacts: 900,000	
Hawaii	~200,000 residents plus another 175,000 or more tourists and approximately 1,000 buildings directly relating to the tourism industry; 750 miles of coastline	$40 Billion, plus 3 international airports, and 1 military port, 1 medium port, 4 other container ports, and 1 fuel refinery intake port, 3 regional power plants; 100 government buildings
	Total resident population of area at immediate risk to post-tsunami impacts: 400,000	
Alaska	105,000 residents, plus highly seasonal visitor count; 6,600 miles of coastline	>$10 Billion plus International Airport's fuel depot, 3 medium ports plus 9 other container ports; 55 ports total
	Total resident population of area at immediate risk to post-tsunami impacts: 125,000	

CSZ and Washington, Oregon & N. California

- 30 minutes to first wave arrival
- Some extremely flat coastal topography with long peninsulas; insufficient time for evacuation to high ground

Basic Lessons for Design of Buildings from Past Tsunamis

- While structures of all material types can be subject to general and progressive collapse during tsunami, but it is feasible to design certain buildings to withstand tsunami events
- Mid-rise and larger buildings with robust structural systems survive.
- Seismic design has significant benefits to tsunami resistance of the lateral-force-resisting system.
- Local structural components may need local "enhanced" resistance
- Foundation system should consider uplift and scour effects, particularly at corners.

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
- 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

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.

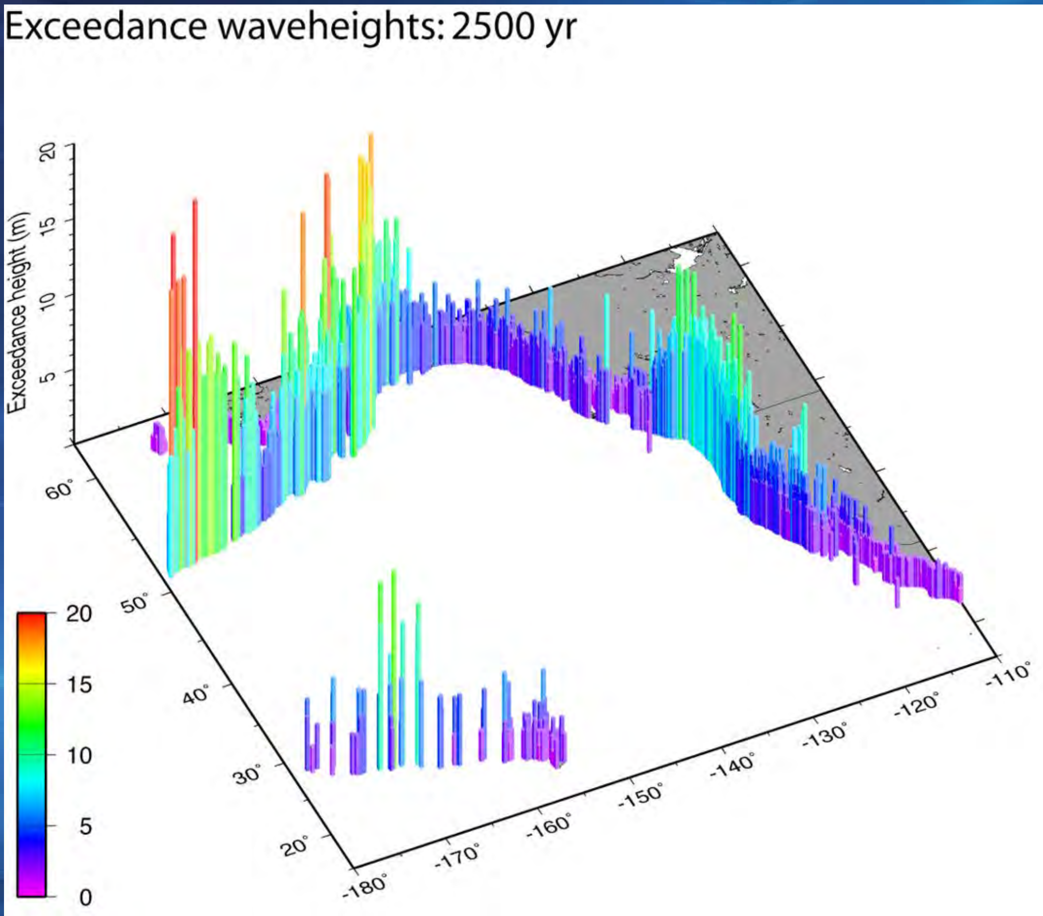
The ASCE 7 Tsunami Loads and Effects Chapter is applicable only to the states of Alaska, Washington, Oregon, California, and Hawaii, which are tsunami-prone regions that have quantifiable hazards.

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.

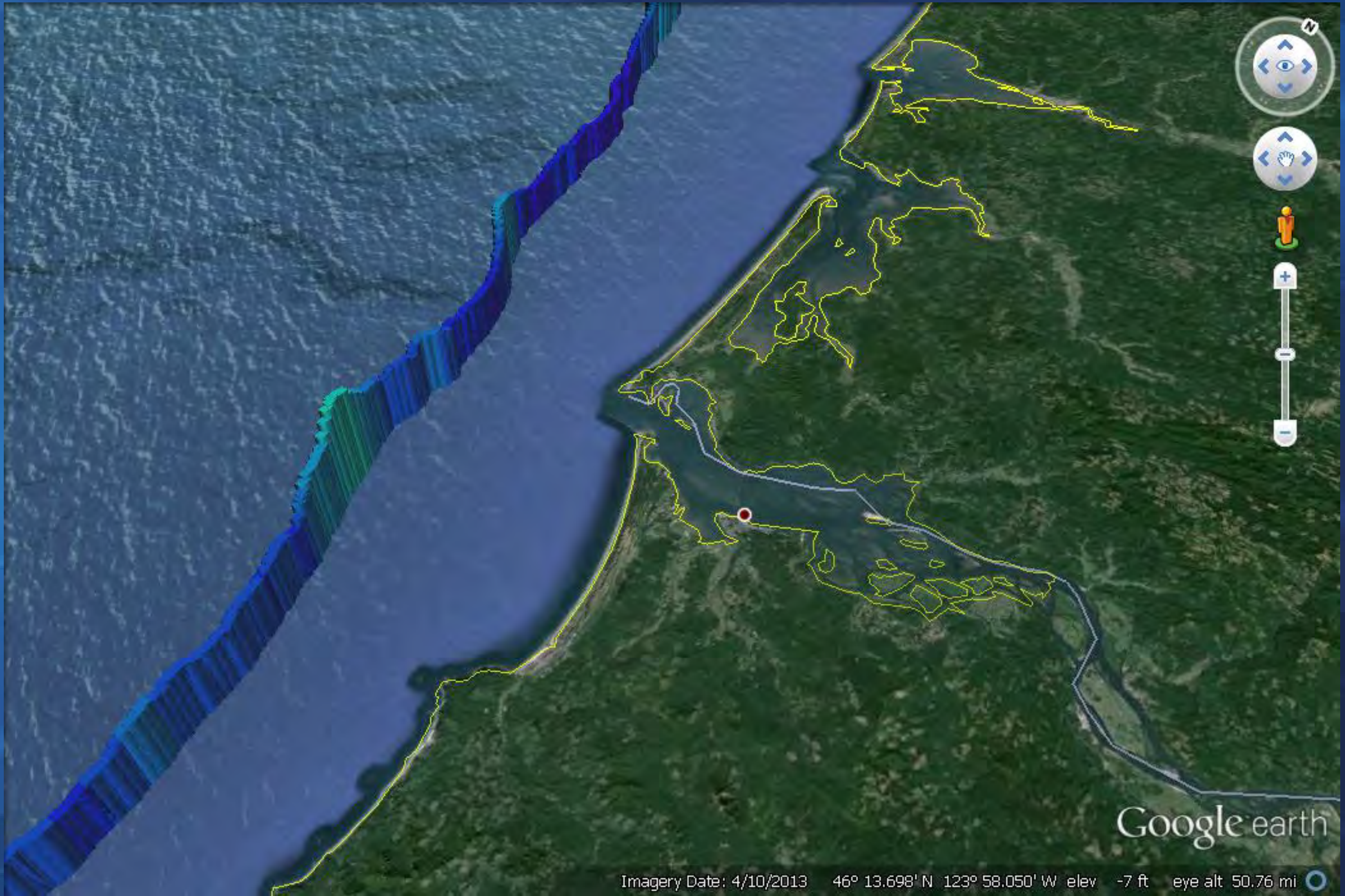
Tsunami Design Zone: Lessons from the Tohoku, Chile, and Sumatra Tsunamis

- 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



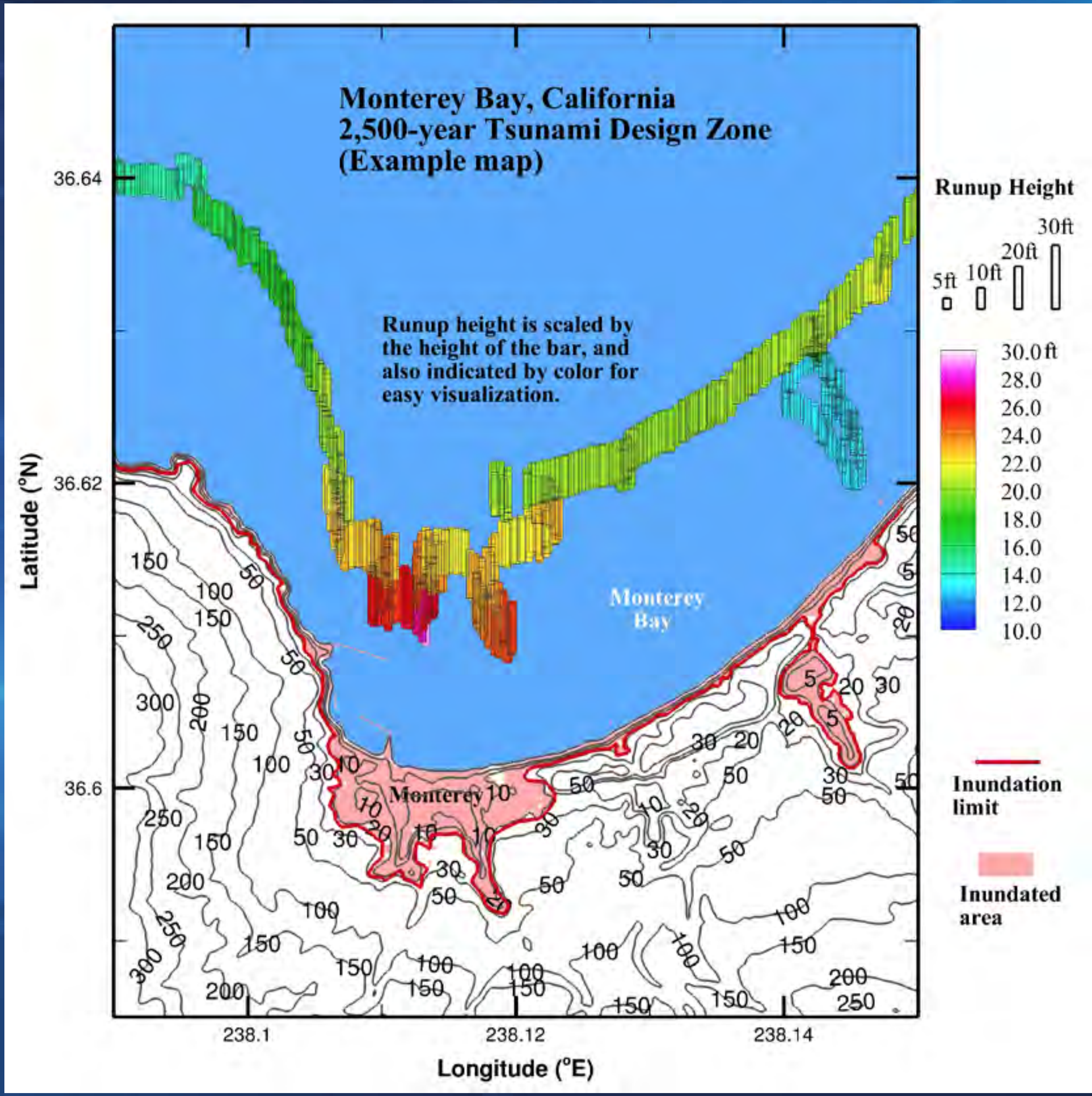
Maximum Considered Tsunami (MCT)

- Probabilistic definition of the 2500-yr return period event – MCT
- Based on probabilistic hazard analysis, the 100-m bathymetric contour offshore amplitude and predominant period of the MCT is defined along the US west coast and Hawaii (KML File)



Tsunami Design Zone

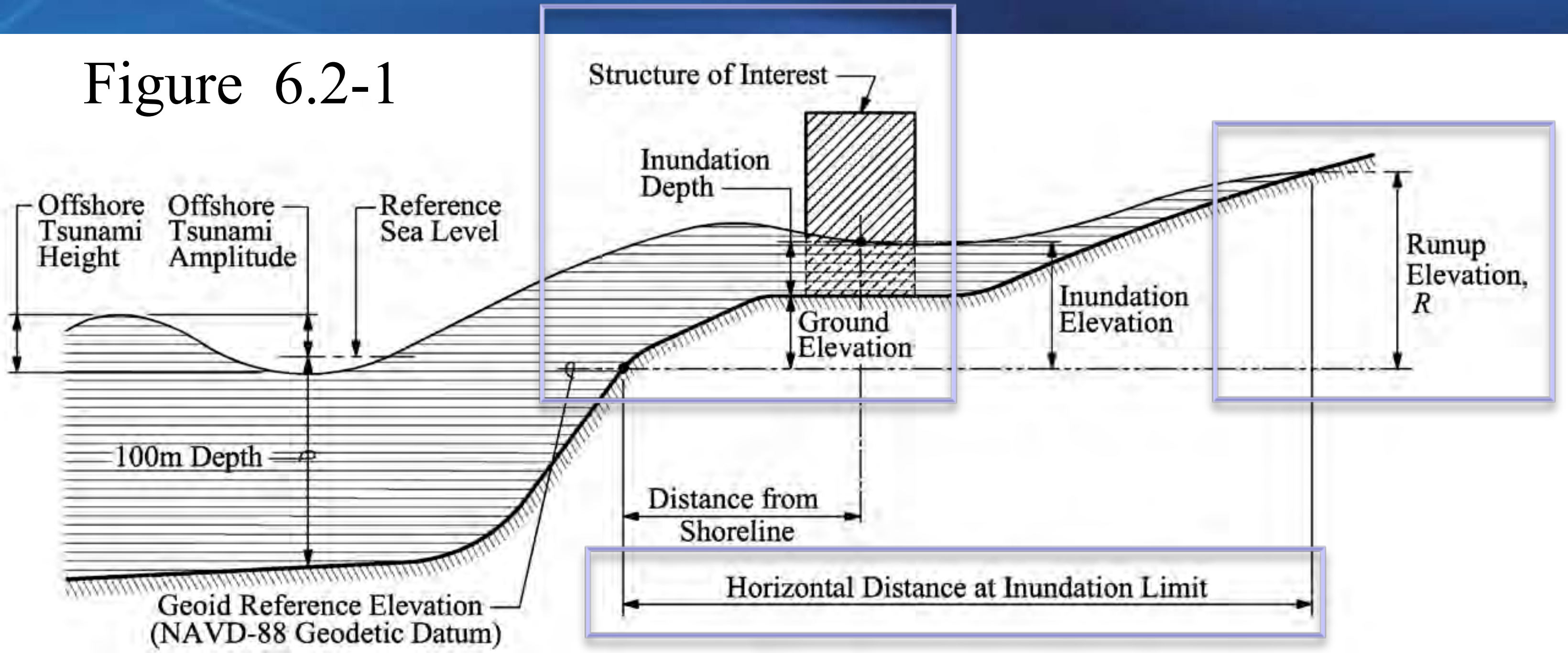
- Inundation from the MCT defines the Tsunami Design Zone (TDZ)
  - Probabilistic inundation is based on the "hazard consistent tsunamis" matching the offshore height and return period
  - Maps will be provided as downloadable KML files for use in Google Earth



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



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. Tsunami Risk Category II buildings with mean height above grade plane greater than 65 ft (19.8m) and inundation depth at any point greater than 3 feet

Exception: Risk Category II single-story buildings of any height without mezzanines or any occupiable roof level, and not having any critical equipment or systems.

Tsunami Flow Characteristics

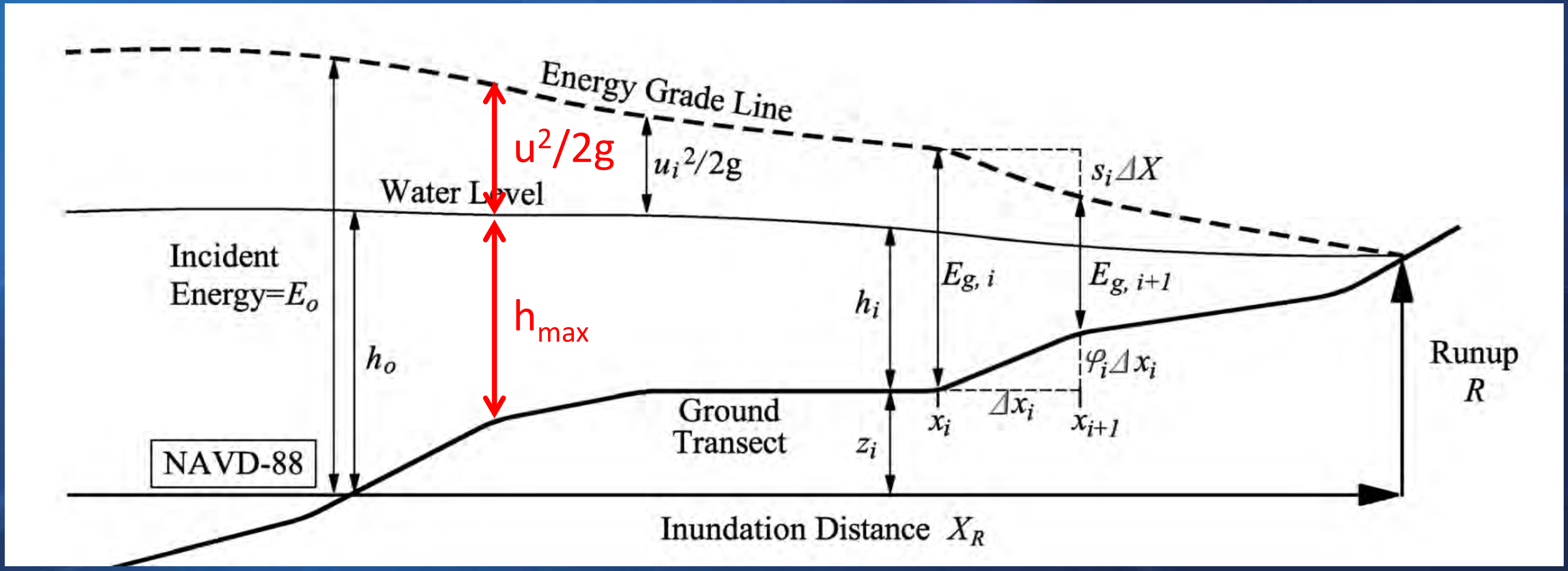
- Near constant velocity over land, top to bottom, with very rapidly rising depth,
- Unlike a storm surge; there is no stillwater
- Wave period ranges between 30 minutes to 1 hour for *each* wave in a series; shoaling leads to nearshore amplitude typically being amplified to several times the offshore amplitude
- Two approaches to determine depth and flow velocity
  - Flow parameters based on pre-calculated runup from the maps (the Energy Grade Line Analysis method)
  - Flow parameters based on a Site-Specific Probabilistic Hazard Analysis (with 75-90% EGL method as "floor velocity value") – Required for TRC IV, optional for others

Inundation Depth and Flow Velocity Based on Runup

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

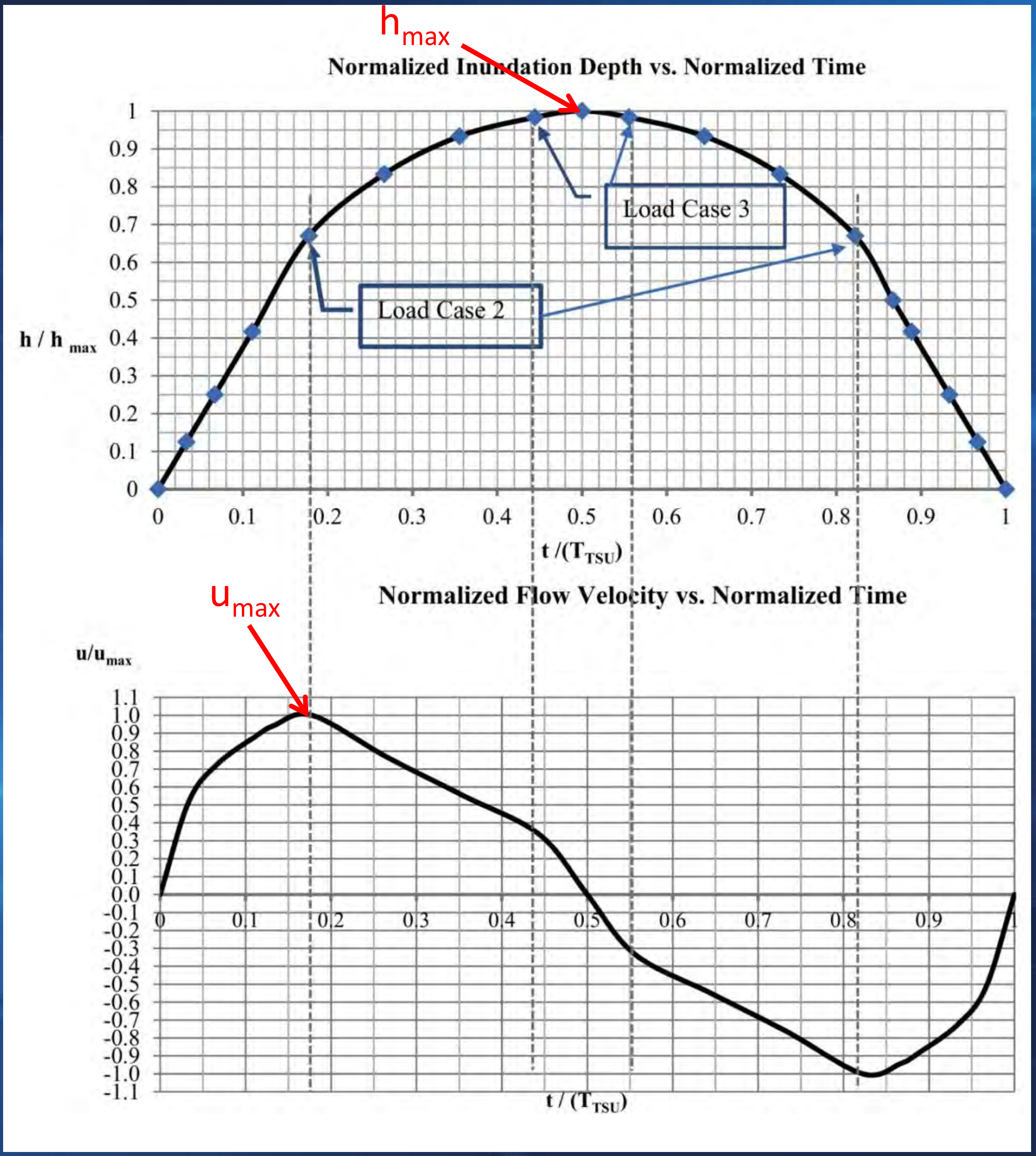
$$E_{g,i+1} = E_{g,i} - \left(\phi_i + s_i\right)\Delta X_i$$

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



Load Cases

- Based on a 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



Inundation Depth and Flow Velocity Based on 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.

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 $\frac{1}{2} k_s \rho_{sw} (h u^2)$)
  - 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)

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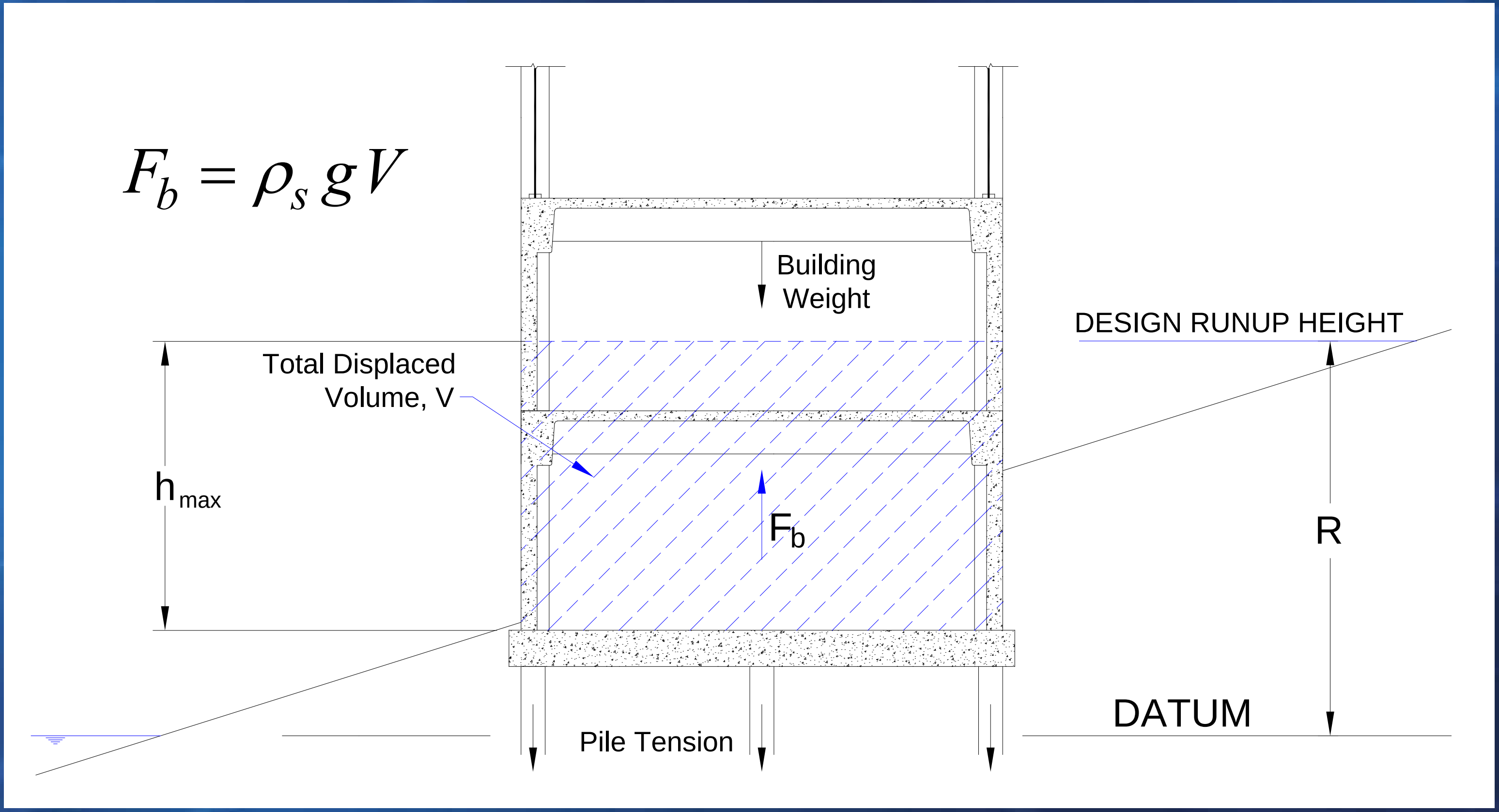
Buoyant uplift

- Applicable to sealed spaces with structural floor
- Buoyancy must be resisted by dead weight of building and tension capacity of piles

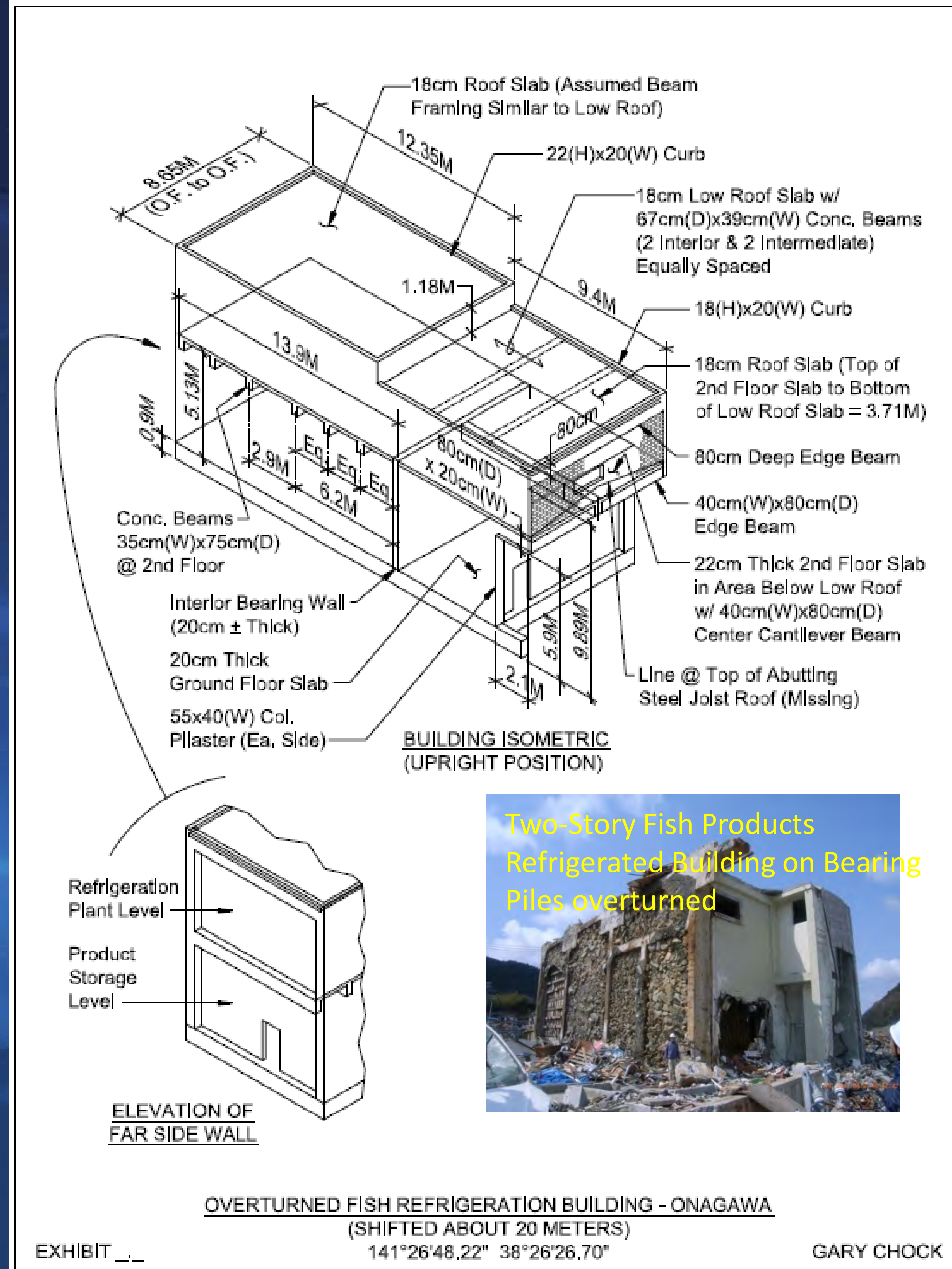


Buoyancy

- Onagawa overturned concrete fish storage building
- Buoyancy and lateral load

Building Performance – Building Overturning

Two-Story Refrigerated Concrete Warehouse (9000 kN deadweight) on Bearing Piles floated at 7 m inundation depth during inflow and then overturned about 20 meters from original position



Types of Floating Debris
Storage Tanks

Storage tankers in Kesennuma

- Storage Tankers will float unless relatively full or well restrained.
- The thin walls rupture easily during impact leading to fuel spills and fires

Storage tankers in Onagawa

Hydrodynamic Loads

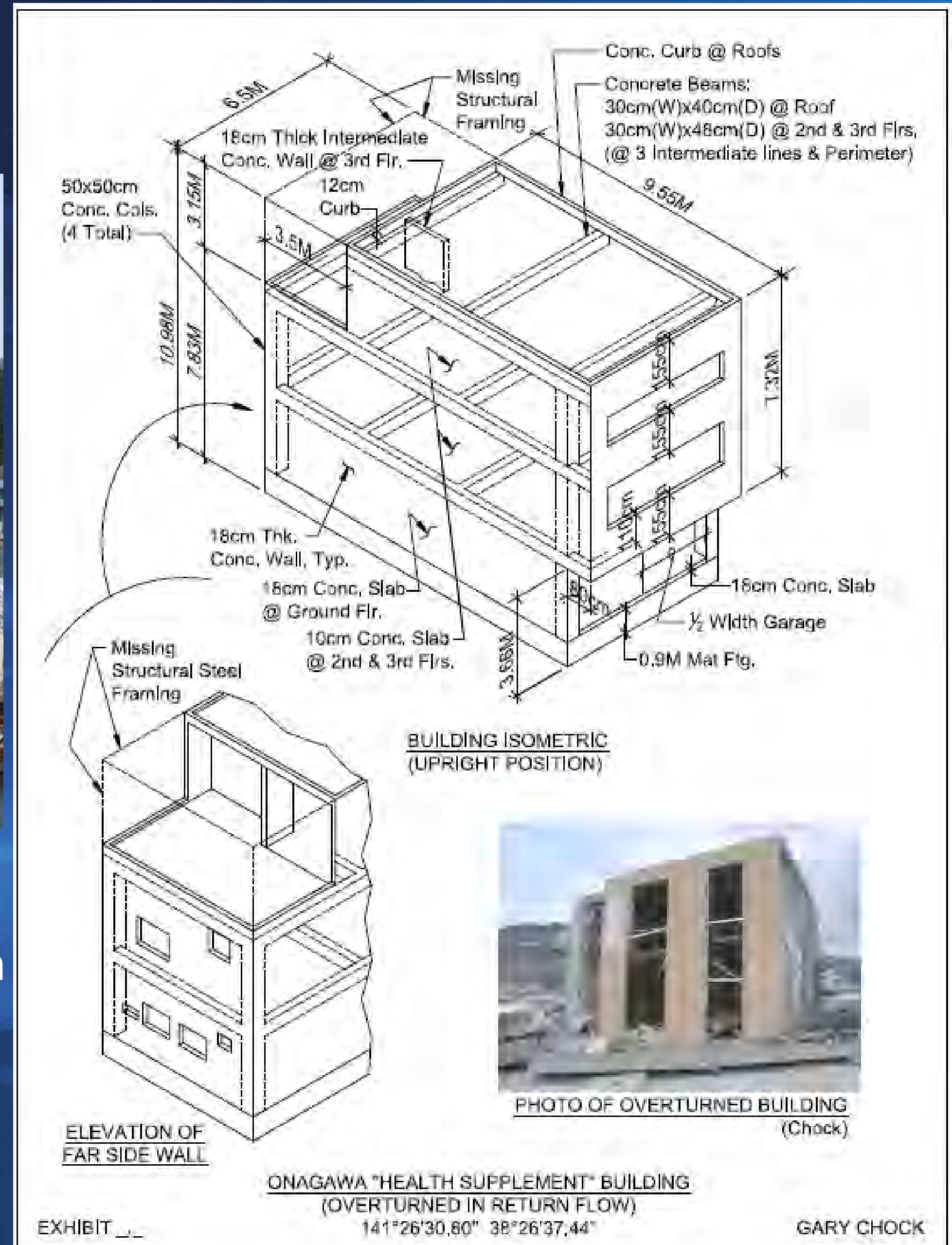
- Formulations for detailed calculations on the building and for loads on components
  - Typically of the standard form drag (h- inundation depth and u – flow velocity for each load case)

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

  - Adjustments for perforated and angled walls

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

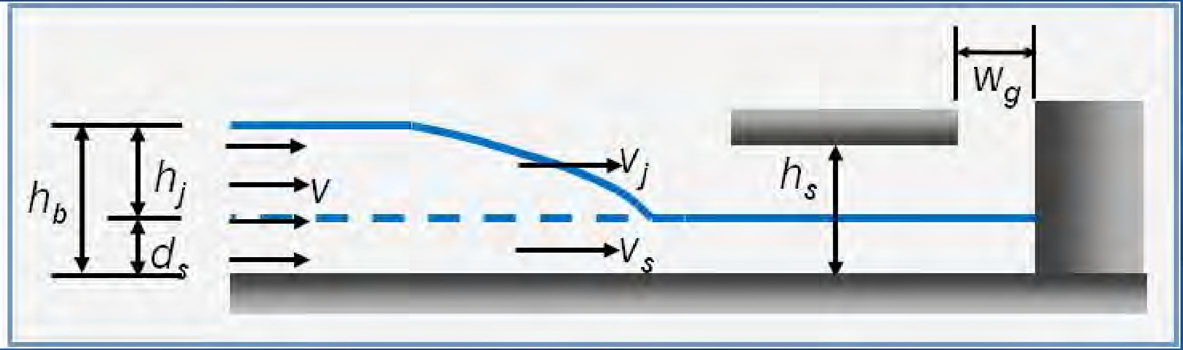
Onagawa overturned steel building

Hollow pipe compression piles

Performance of Concrete Piers and Wharfs

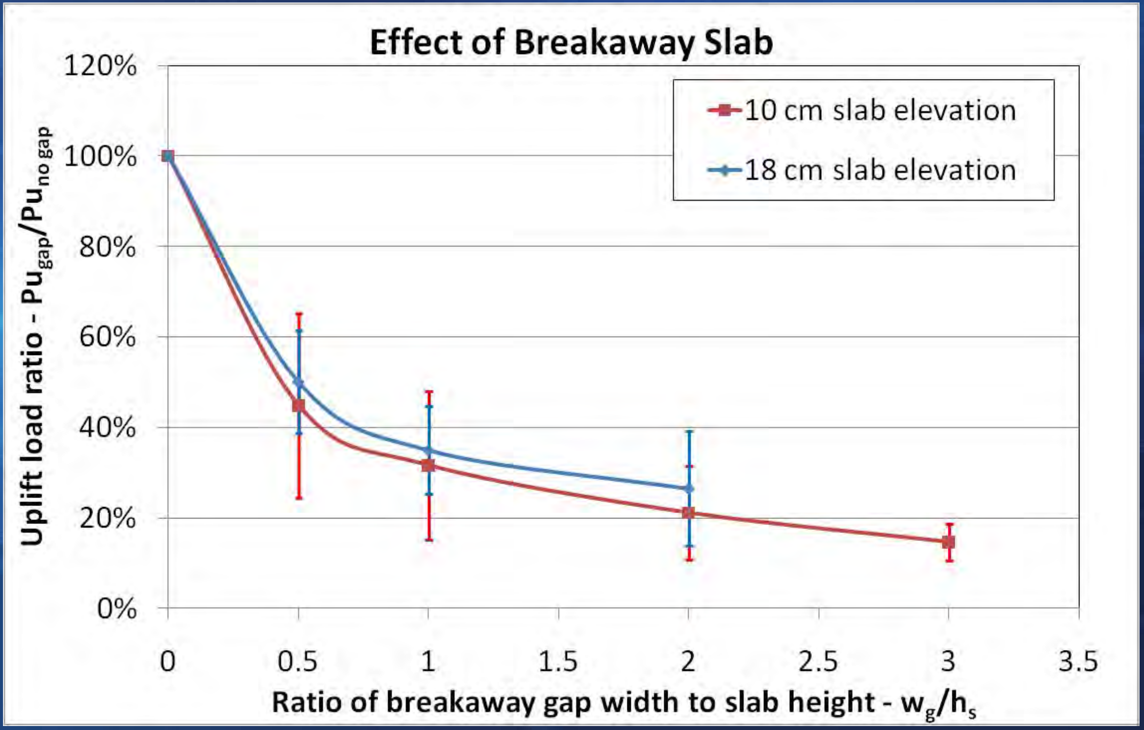
- Pressure relief grating and/or breakaway panels between pile-supported pier and wharf sections can lessen damage to both

Vertical Hydrodynamic Uplift on Floors and Wharves due to Entrapped Bore



Gap created by "breakaway" slab

- Uplift force on deck decreases if a "breakaway" or "gap" slab is provided in front of the wharf



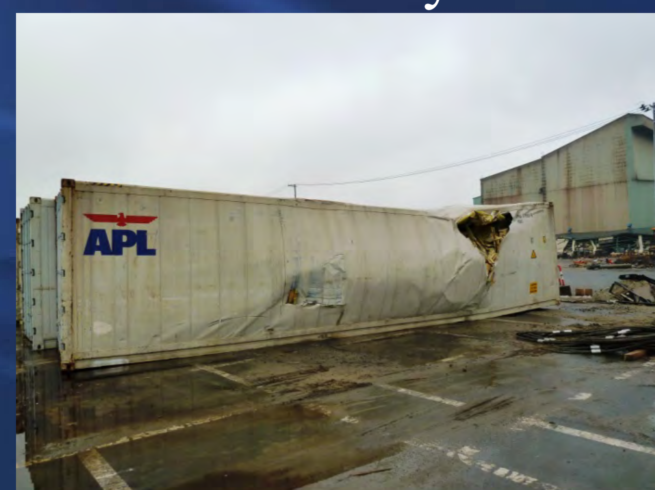
Debris Impact Loads

- Waterborne Debris Loads
  - Utility poles/logs
  - Passenger vehicles
  - Tumbling boulders and concrete masses
  - Shipping containers only where near ports and harbors
  - Large vessels considered for Critical Facilities and Risk Category IV only where near such ports and harbors

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

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

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

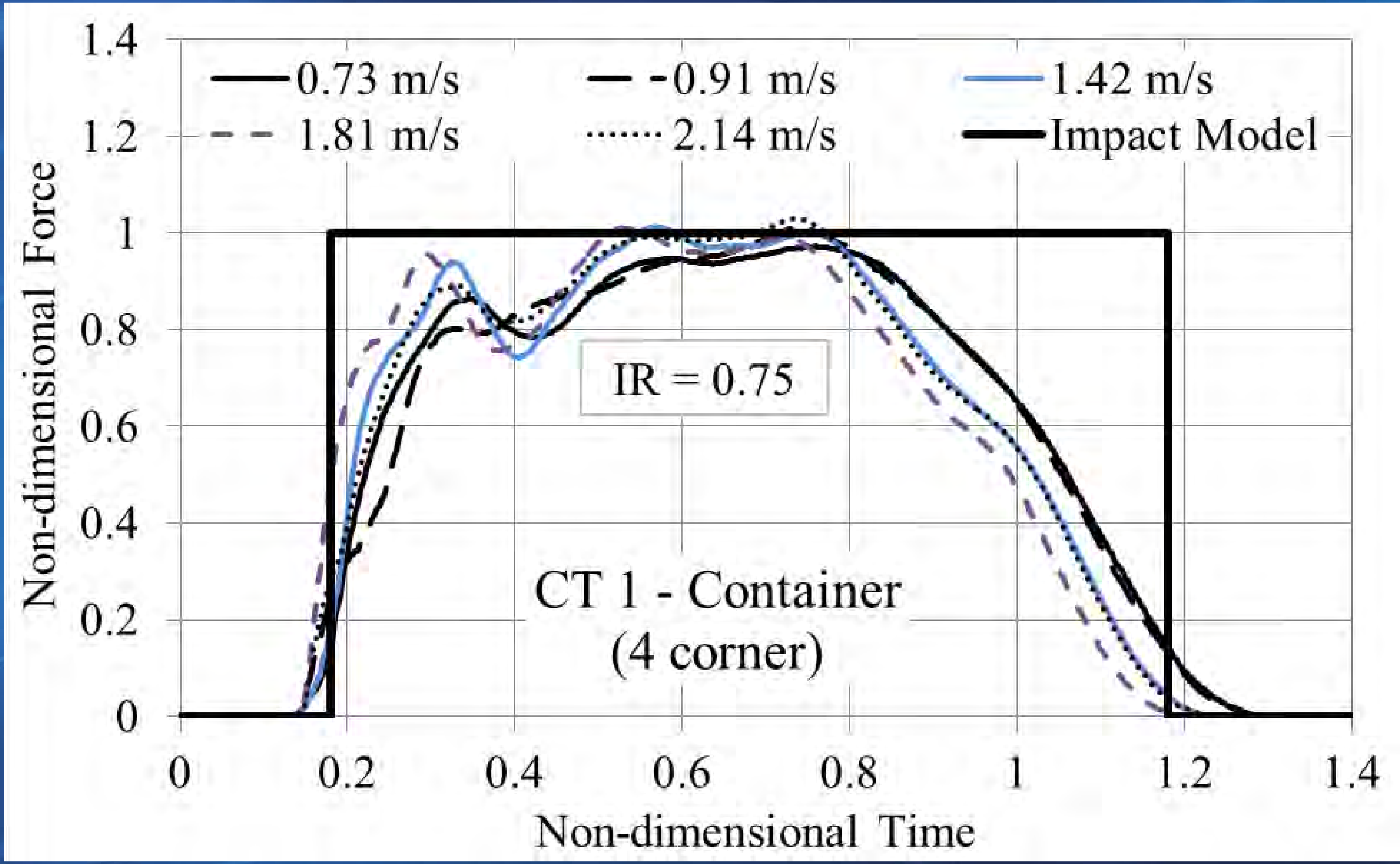
ISO 20-ft Shipping Container

- 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

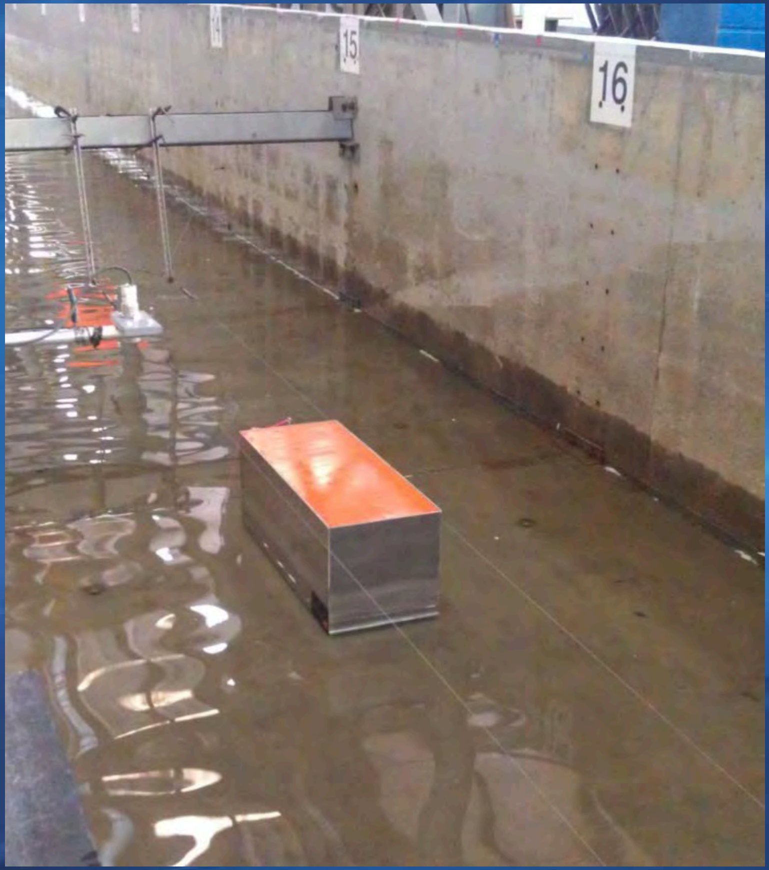
Video

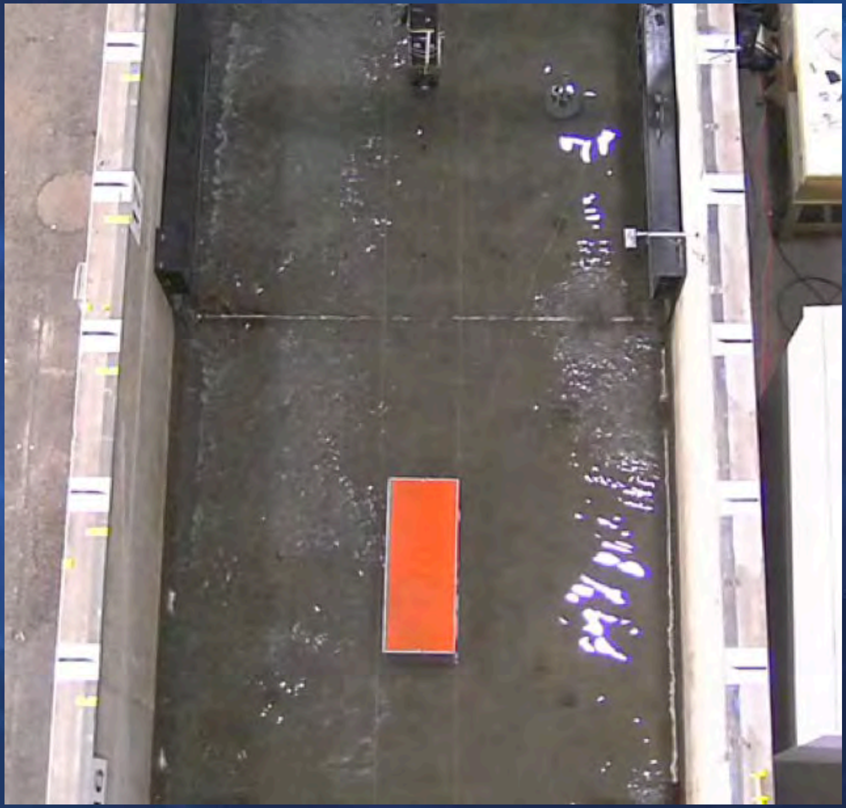
Impact Force Time History



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



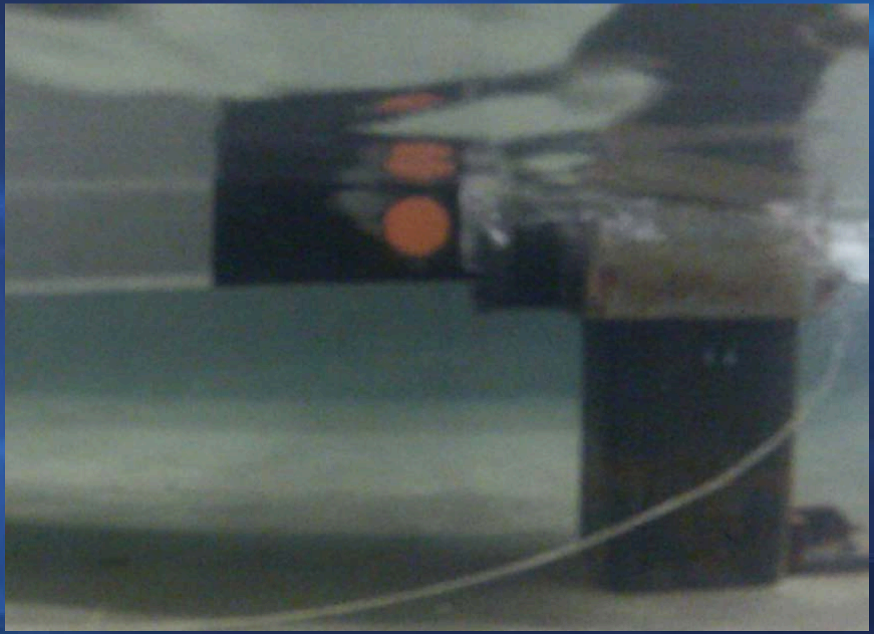


Column and load cell at top of photo

Impact with Load Cell

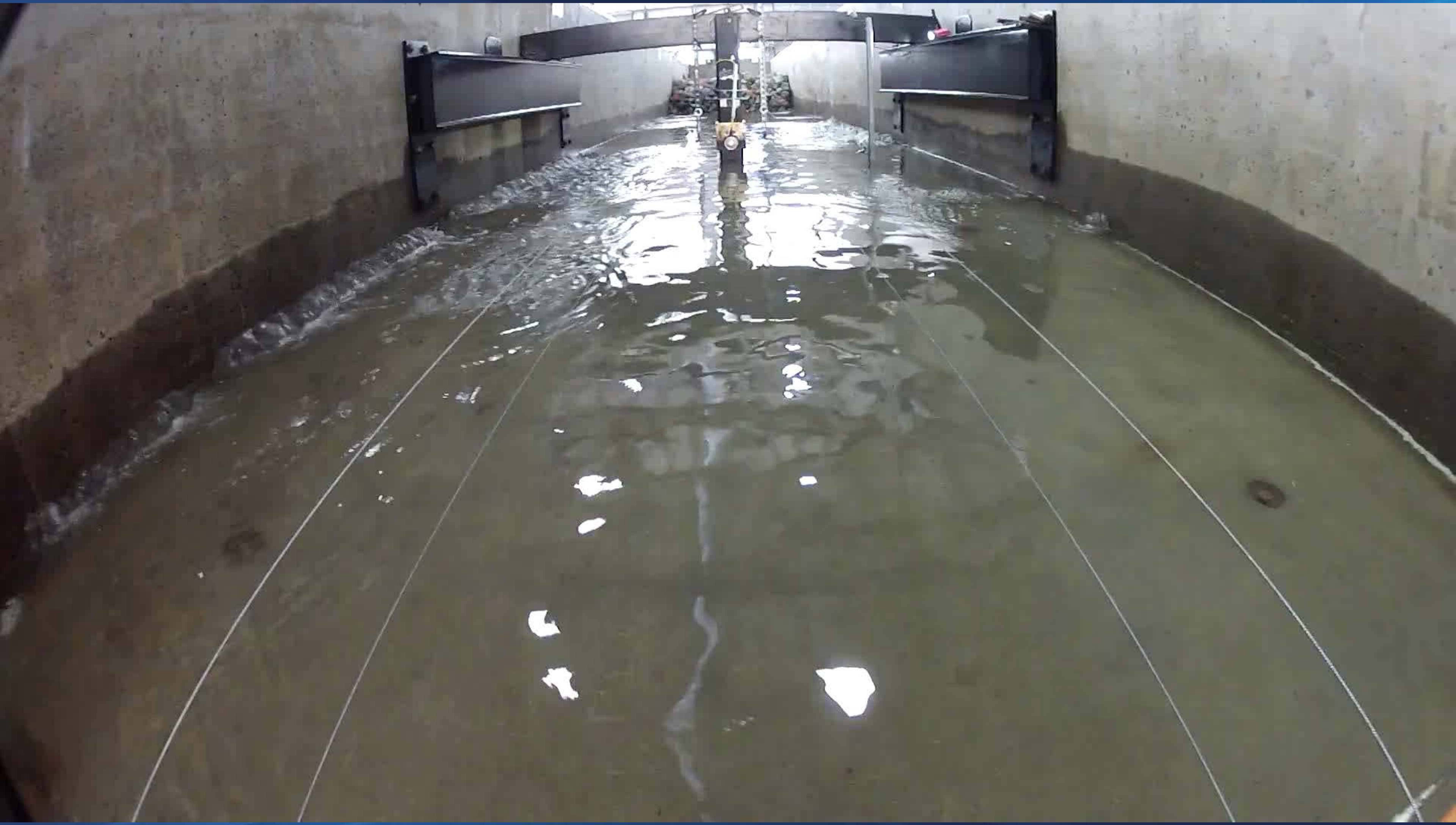
- In-air tests carried out with pendulum set-up for baseline
- In-water impact filmed by submersible camera
- Impact was on bottom plate to approximate longitudinal rail impact

In-air impact



In-water impact

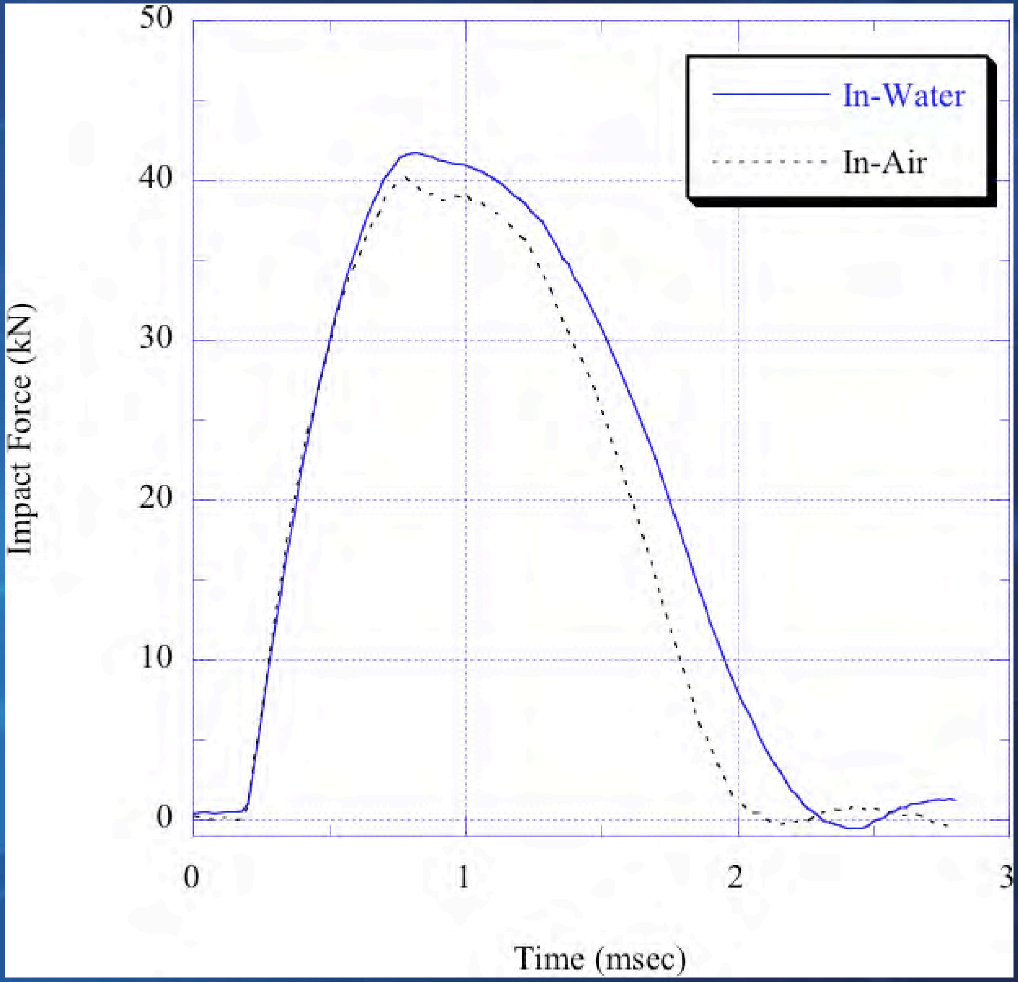
Container Impact



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

$$F_{ni} = u_{\max} \sqrt{k m_d}$$

- Factored design force based on importance factor

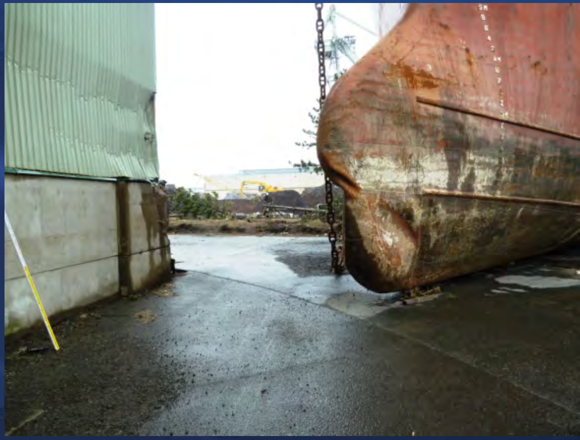
$$F_i = I_{TSU} F_{ni}$$

- Impact duration

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

- Force capped based on strength of debris

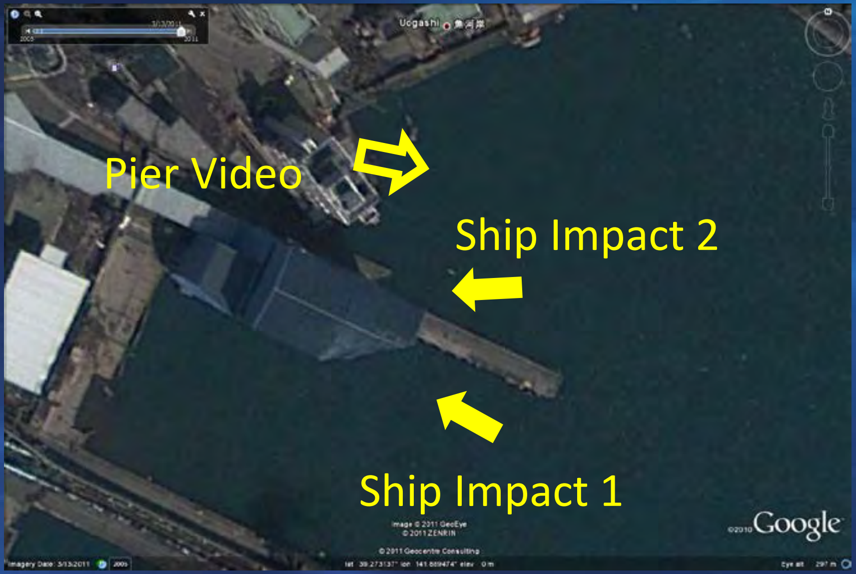
Ship Impact – Sendai Port



Ship Impact damage - Kamaishi

Damage to pier and warehouse due to multiple impacts from single loose ship

Kamaishi Ship Impact



- Two survivor videos show evidence of ship impact on blue warehouse

Kamaishi Ship Impact

Ship Velocity

$$\Delta t = \frac{(1805 - 1666)}{30\,fps} = 4.63s$$

$$\therefore v = \frac{33m}{4.63s} = 7.13m/s = 13.9knots$$

Ship Impact in Kamaishi Port

Plan for Ship Evacuation

Design for Progressive Collapse Prevention

MOTEMS - Tsunami Guidelines

- Section 3103F.5.7 – Tsunamis
- Limited information, but references other documents
- Tsunamis can be generated by earthquake or landslide
- May be distant or near source
- Warns that “large wave or surge and the excessive currents are potentially damaging, especially if there is a tank vessel moored alongside the MOT wharf.”
- Requires each MOT to have a “tsunami plan” in the event of distant tsunami

- Computational tsunami models should be used to determine likely currents, including effects of resonance

MOTEMS - Tsunami Guidelines

- Reference California study for near field tsunamis with 5,000 to 10,000 year return periods
- Also reference a study by Synolakis et al. with run-up estimates as follows:
  - Port of Los Angeles and Long Beach = 8 ft.
  - Port Hueneme = 11 ft.

MOTEMS - Tsunami Guidelines

- Also reference a study for San Francisco Bay

S.F. Bay MOT Locale	Maximum Water Levels (ft)	Current Velocity (ft/sec)
Richmond, outer	7.5	4.9
Richmond, inner	7.9	8.9
Martinez	2.3	1.3
Selby	2.6	1.6
Rodeo	2.6	2.0
Benicia	2.0	1.0

* Golden Gate Tidal Current Velocity – up to 3.6 knots (6 ft/sec)

- ASCE 2500 year tsunami maps may be useful for offshore wave height predictions

MOTEMS - Tsunami Guidelines

- Largest estimated wave height should be added to mean high tide
- Reference provided where loads can be calculated for various structural configurations
- Other structural considerations include uplift and debris impact

- ASCE loading expressions may be useful, particularly debris impact provisions

The ASCE Tsunami Loads and Effects Subcommittee

Comments to: Gary Chock, Chair gchock@martinchock.com
Ian Robertson, ianrob@hawaii.edu