Vertical Evacuation Structures
ASCE 7-22 Tsunami Loads and Effects

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Tsunami Loads and Effects Subcommittee member

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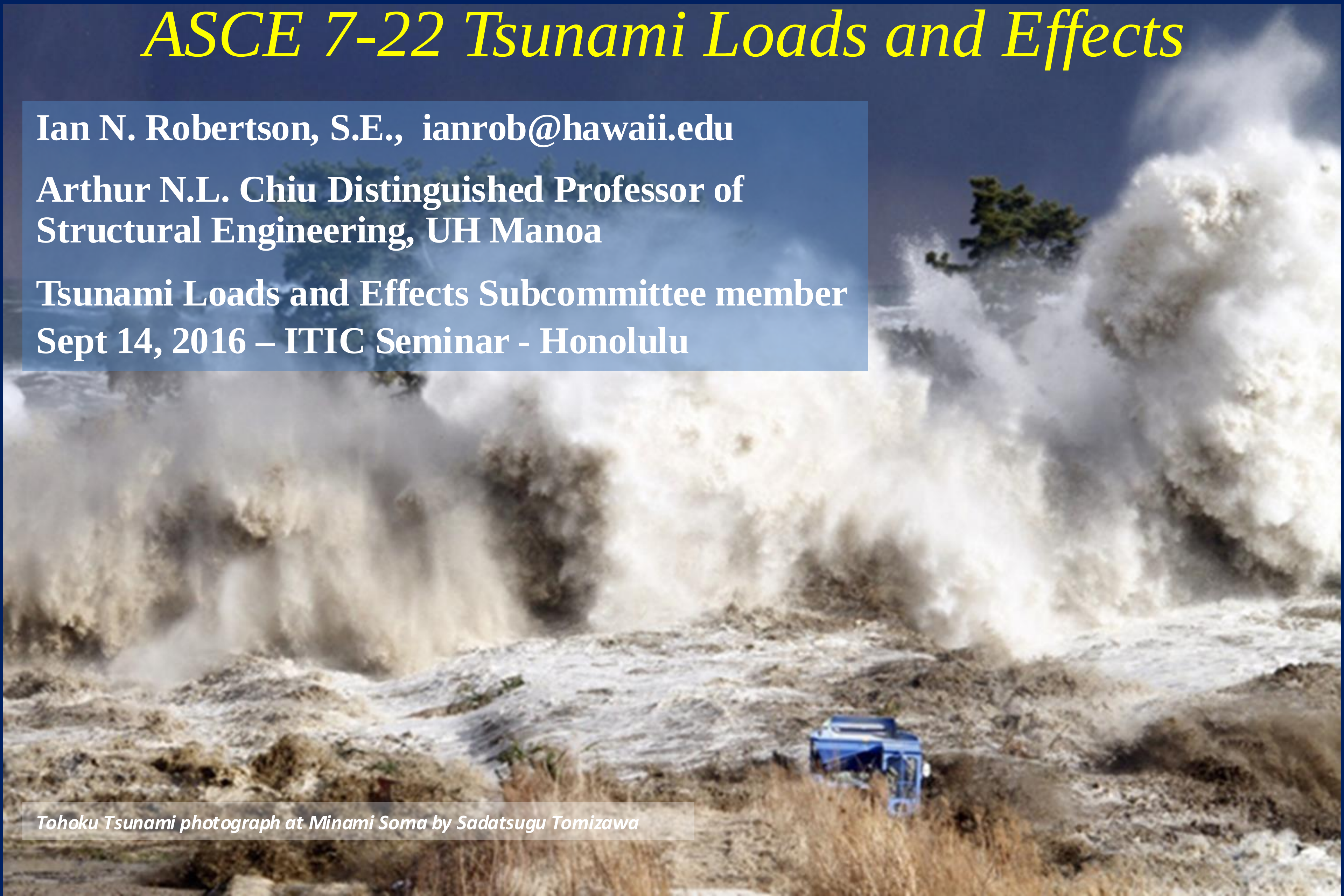

Tohoku Tsunami photograph at Minami Soma by Sadatsugu Tomizawa

Outline

- Need for Vertical Evacuation Refuges
- Performance of Vertical Evacuation Refuges during Tohoku Tsunami
- FEMA P-646 design guidelines
- ASCE-7 Tsunami Loads and Effects chapter
- Vertical Evacuation Refuge designs in US
- Conclusions

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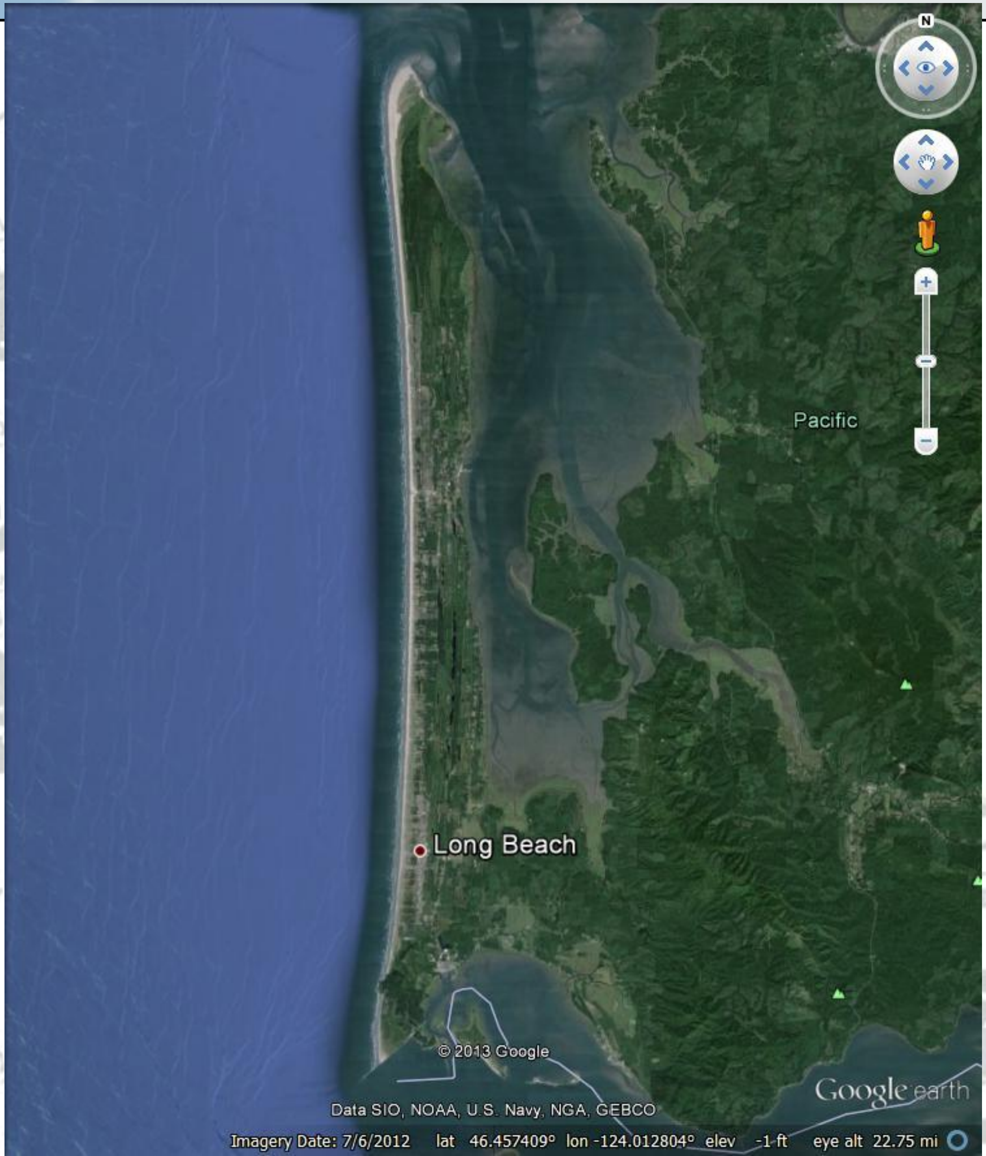
US West Coast Population exposure to tsunami hazard

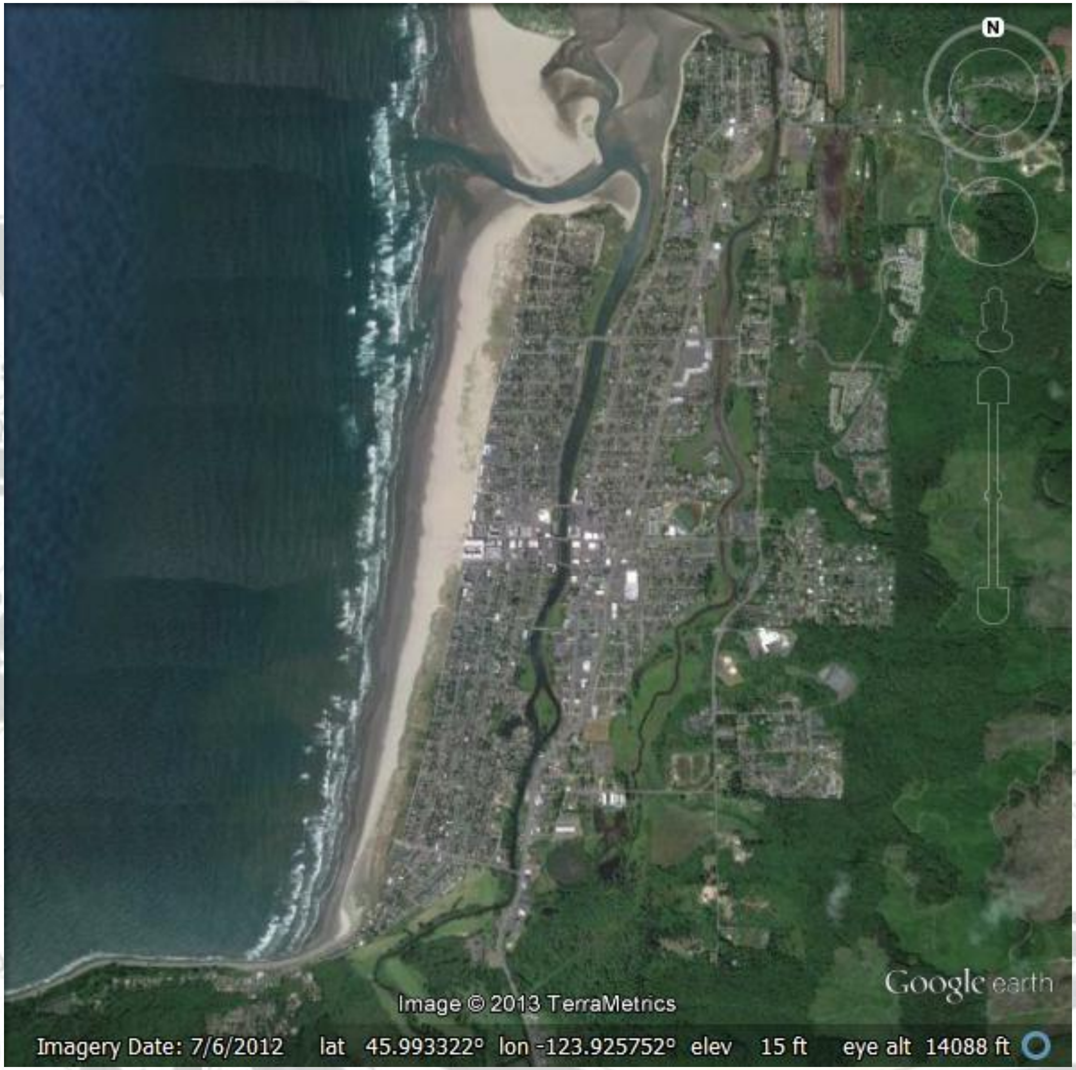
State	Length of Coastline	Population at Risk (in evacuation zone)
California	840 miles	275,000 residents 400,000 to 2,000,000 tourist
Oregon	300 miles	25,000 residents 55,000 tourists
Washington	160 miles	45,000 residents 20,000 tourists
Alaska	6,600 miles	105,000 residents Highly seasonal tourist count
Hawaii	750 miles	200,000 residents 175,000 tourists

Data assembled by Gary Chock, Martin & Chock, Inc.

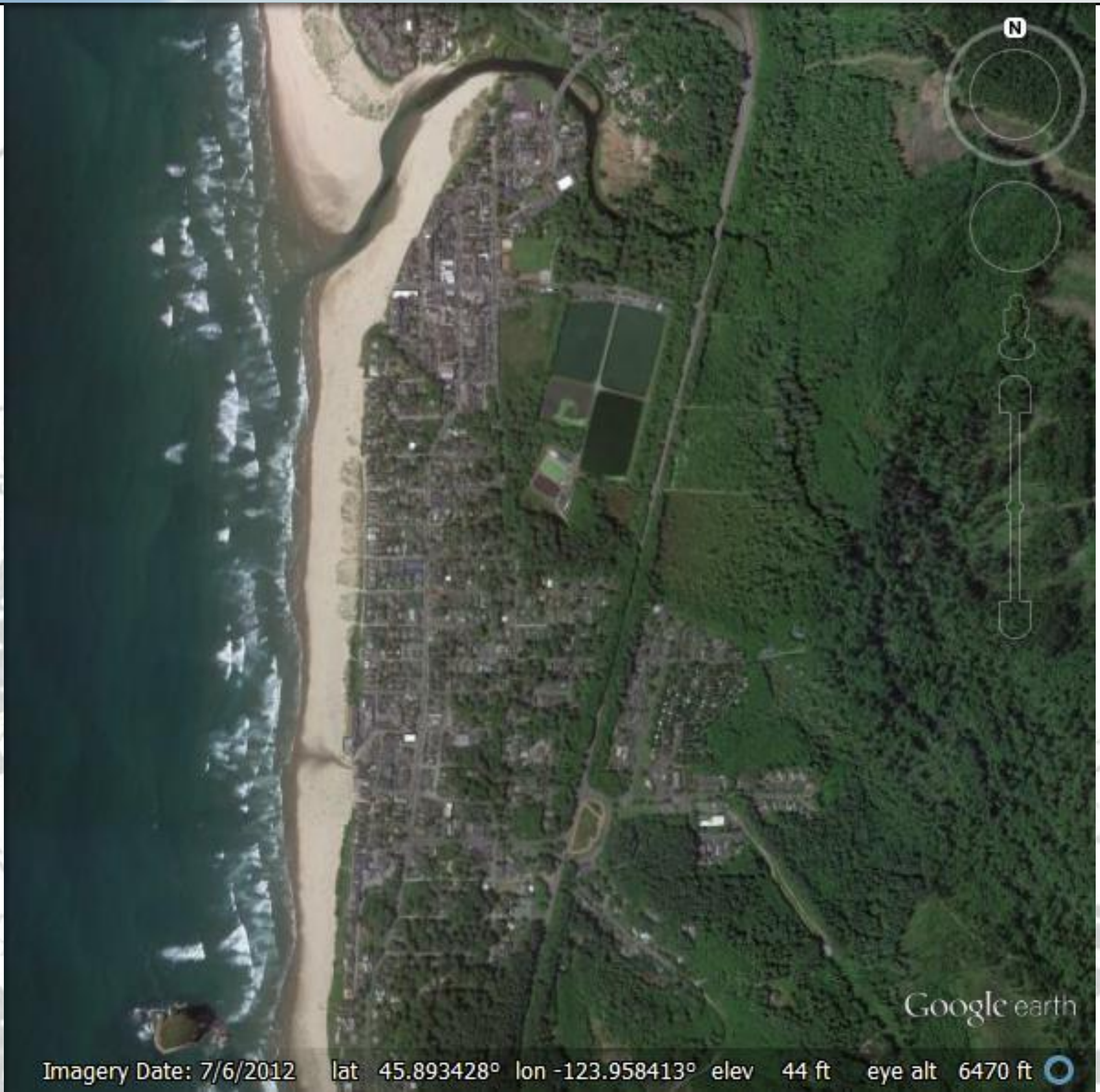
Long Beach, Washington



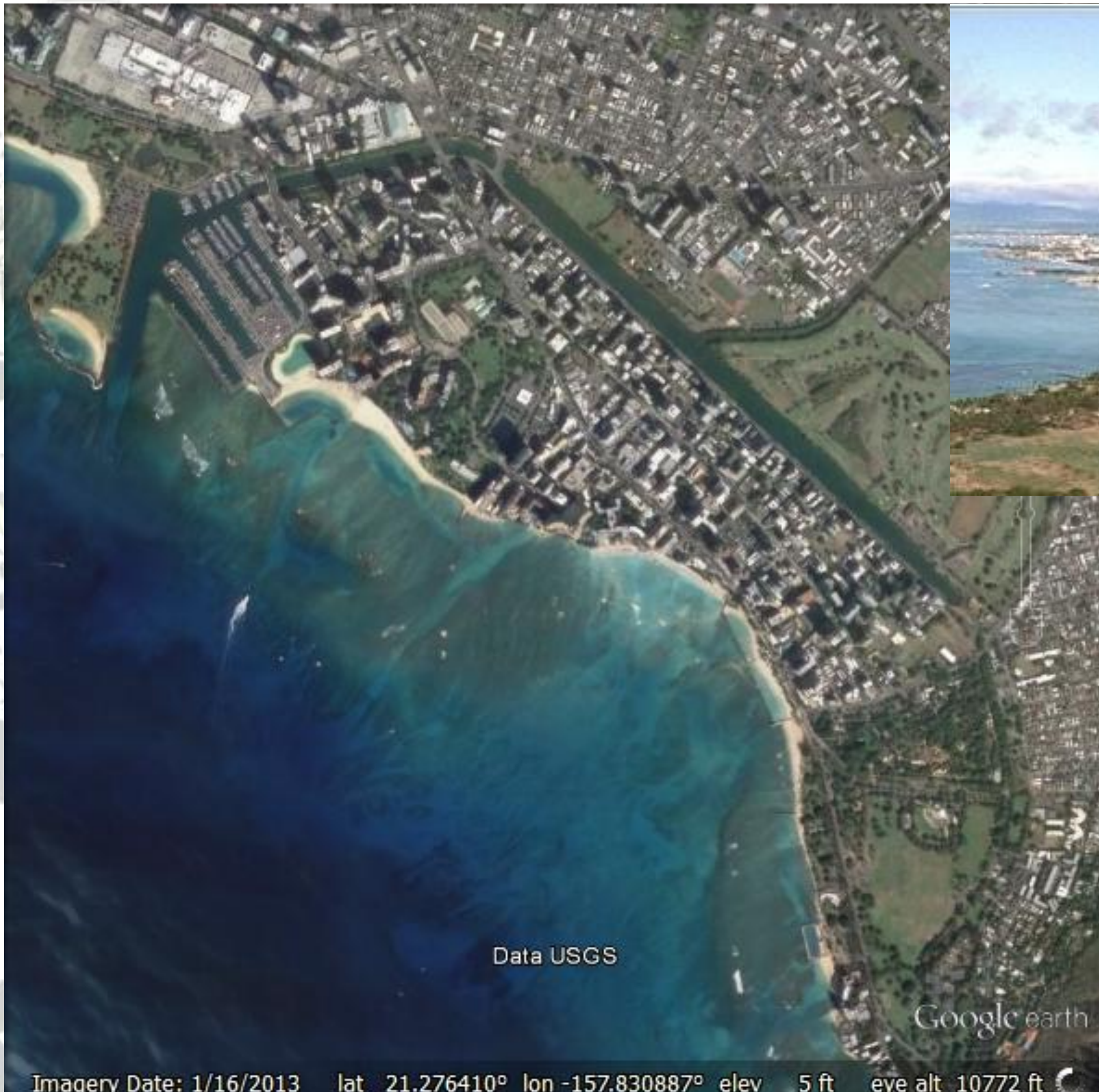
Seaside, Oregon



Cannon Beach, Oregon



Waikiki, Hawaii



<u>Current Evacuation Guidance</u>

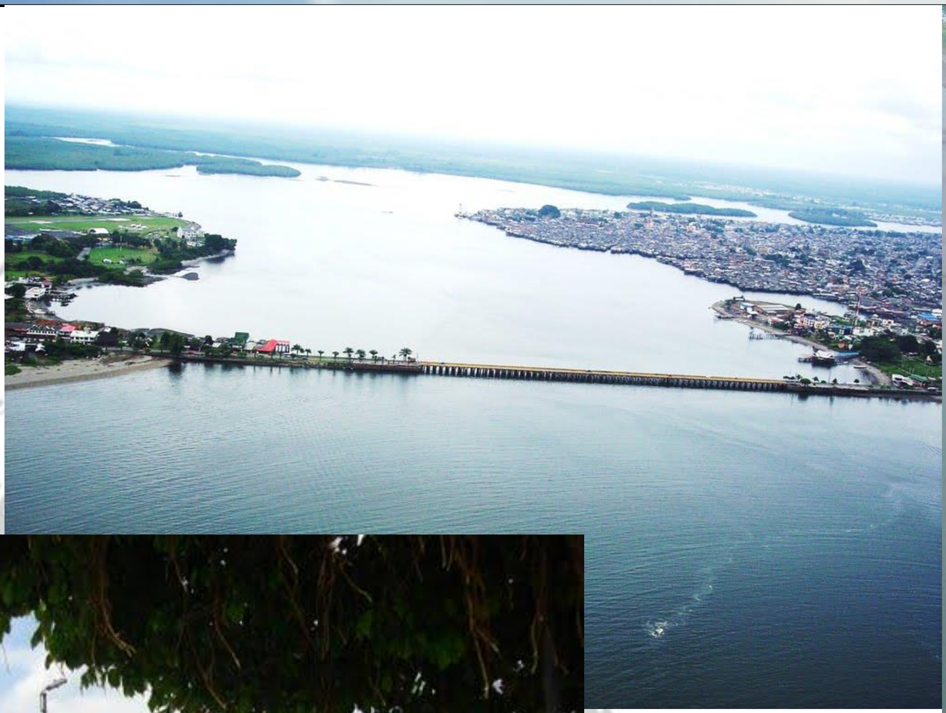
"Structural steel or reinforced concrete buildings of ten or more stories provide increased protection on or above the fourth floor"

Tsunami Hazard in Colombia

- 2:59 AM on Dec. 12, 1979, Tumaco Earthquake
- 8.2 M_w , 33km deep
- Subduction zone between Nazca and South American Plates
- Triggered major tsunami
- First wave reached Tumaco in 3 minutes
- Estimated 600 deaths and 4000 injuries along affected coastline
- Population around 70,000

Tumaco – population 160,000

Bridge to and from Airport



Causeway to and from Airport

Tumaco – Typical Structures

Tumaco – Potential Vertical Evacuation Refuges from Tsunamis

Evacuation sign and taller buildings

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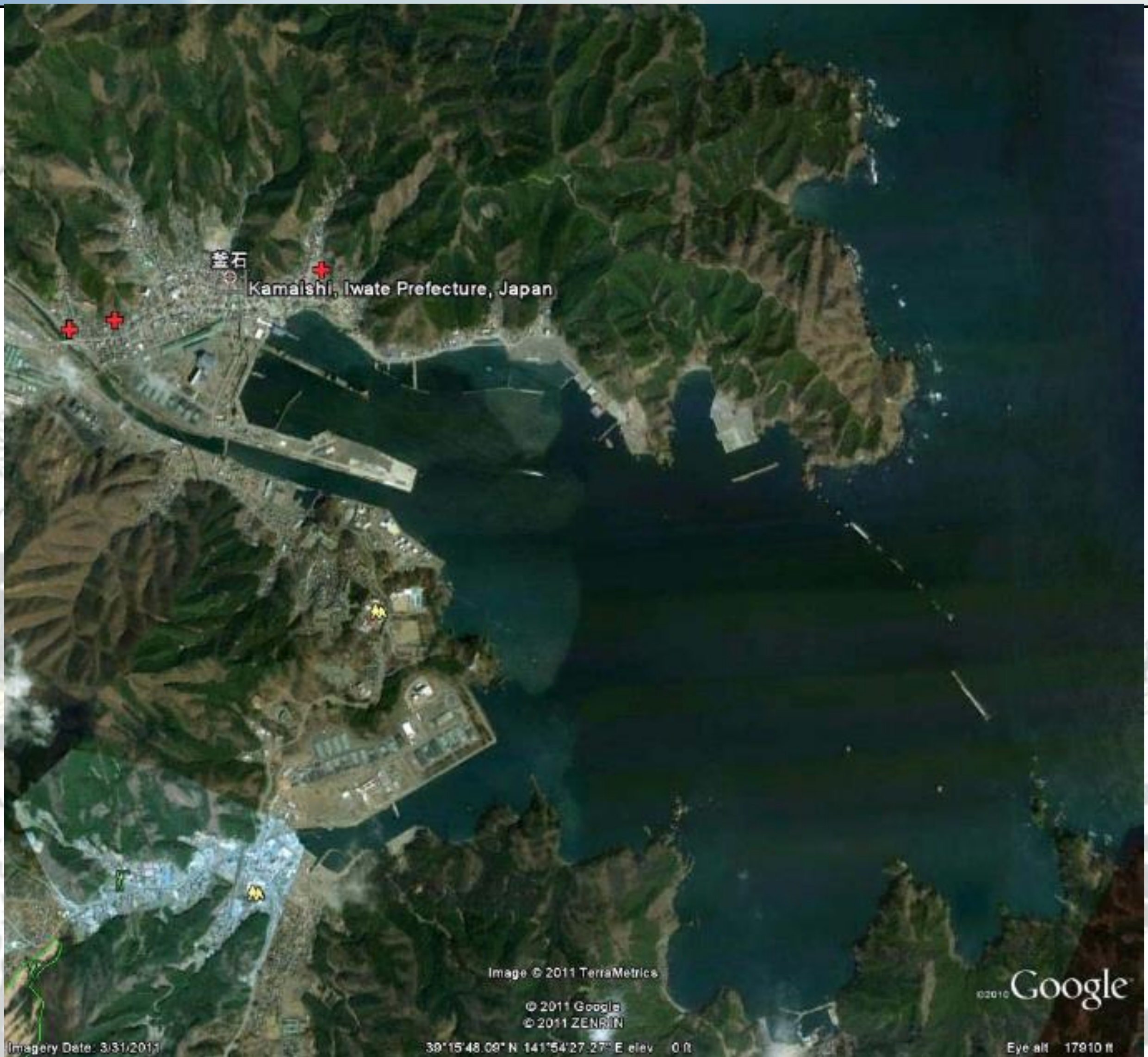
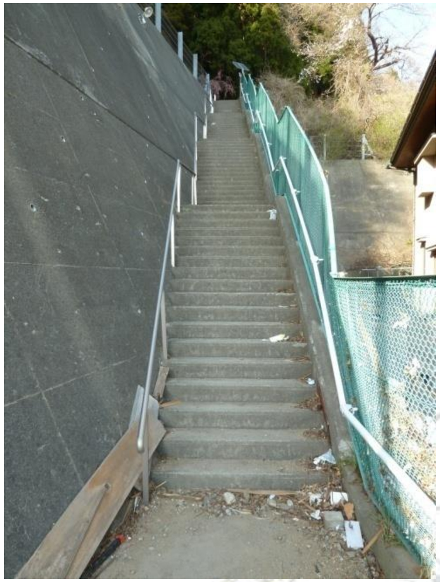
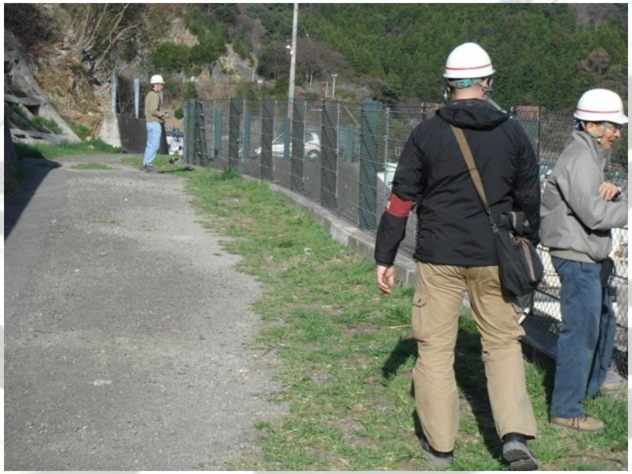
Evacuation to high ground
Kamaishi Example

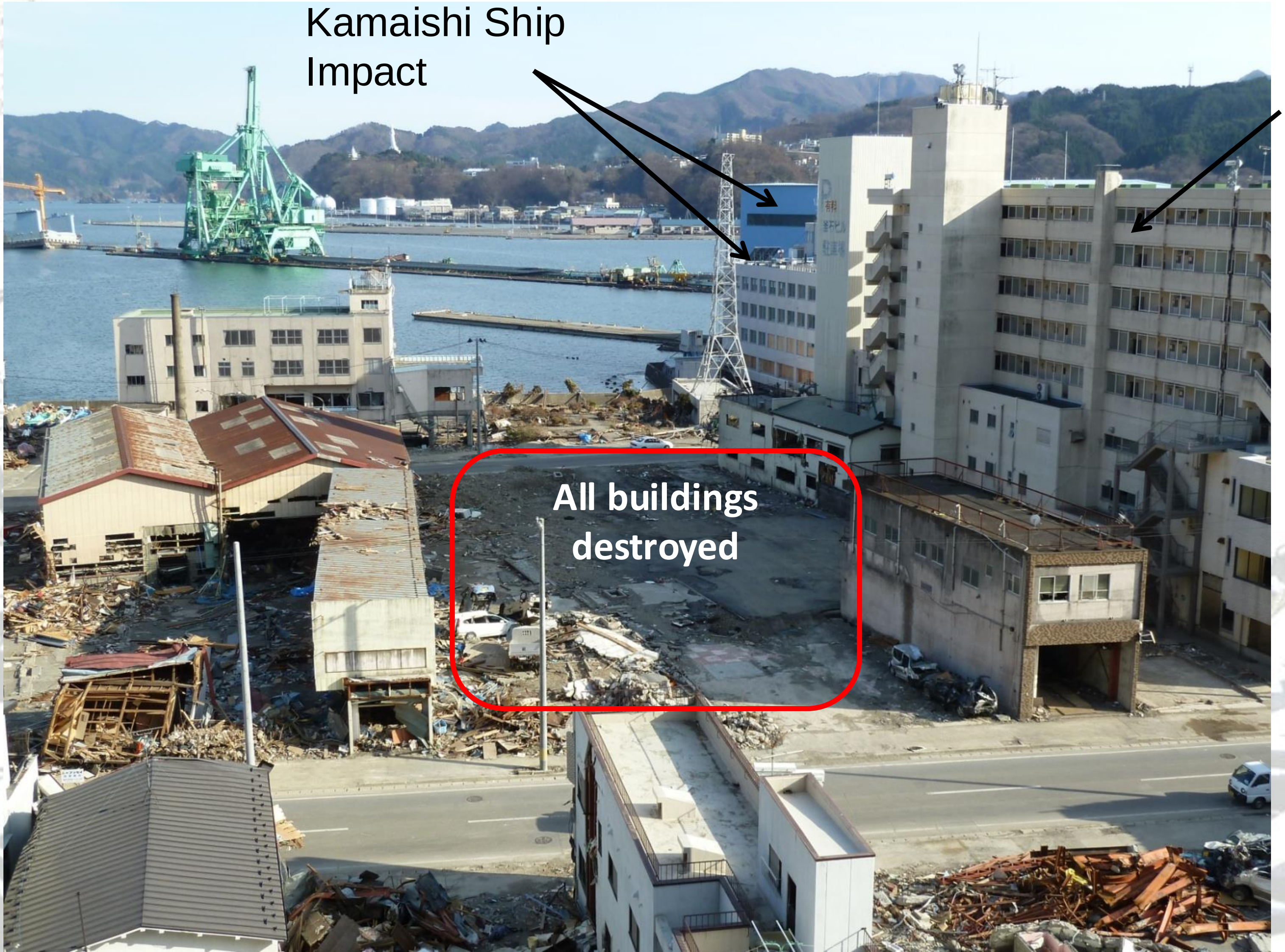


Evacuation to high ground
Kamaishi Example

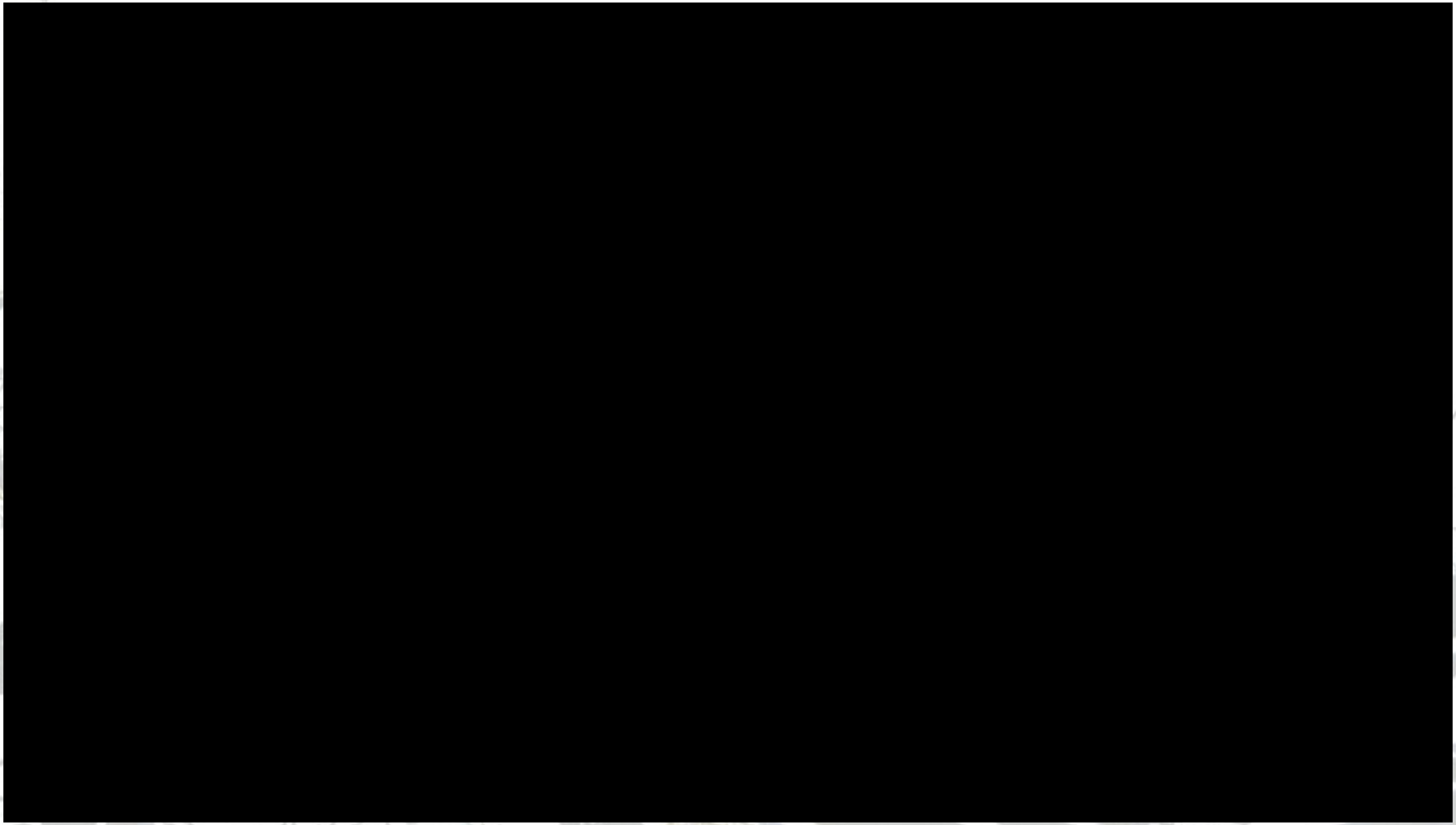




Use of Designated Tsunami Evacuation Buildings

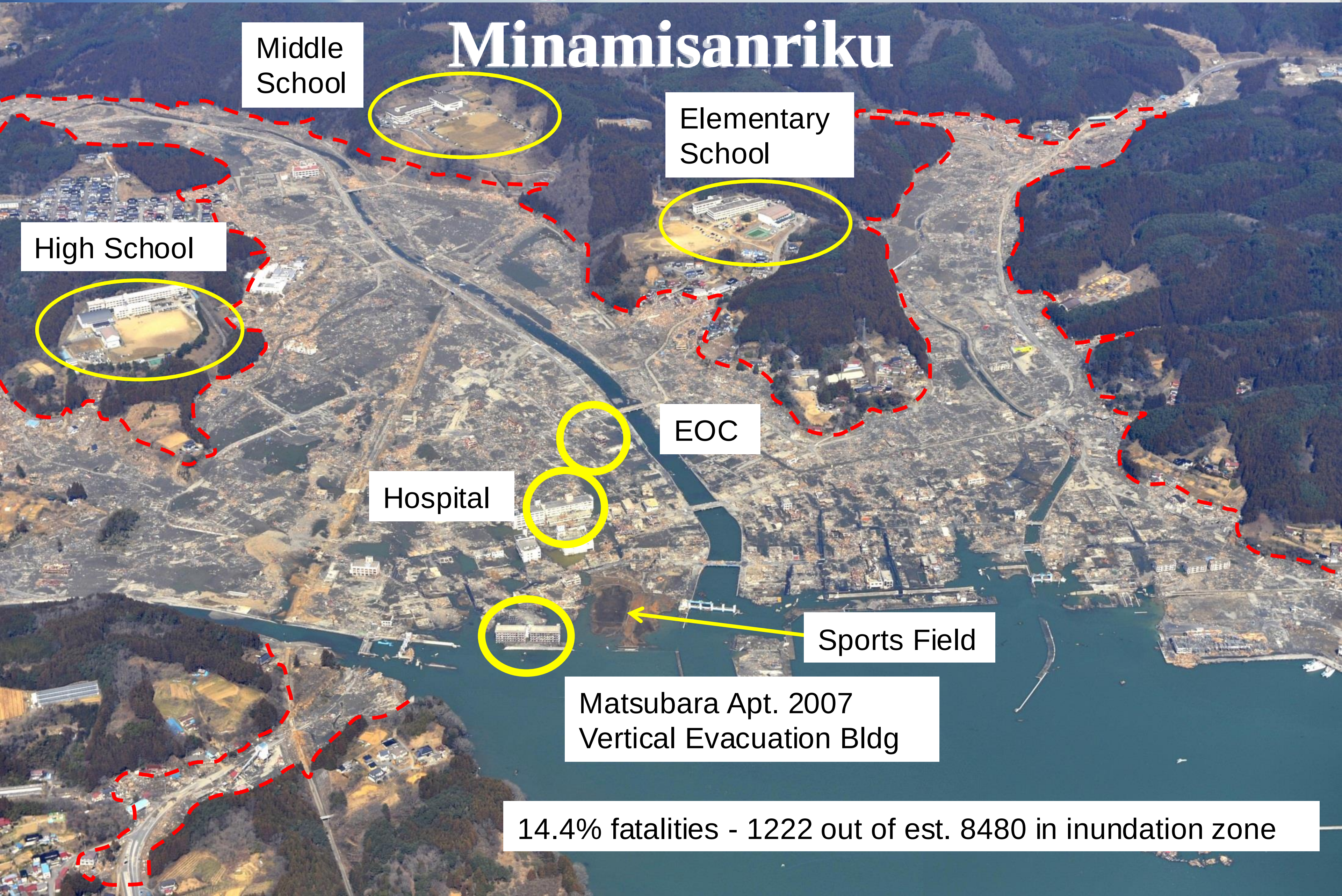


Kamaishi Survivor Video



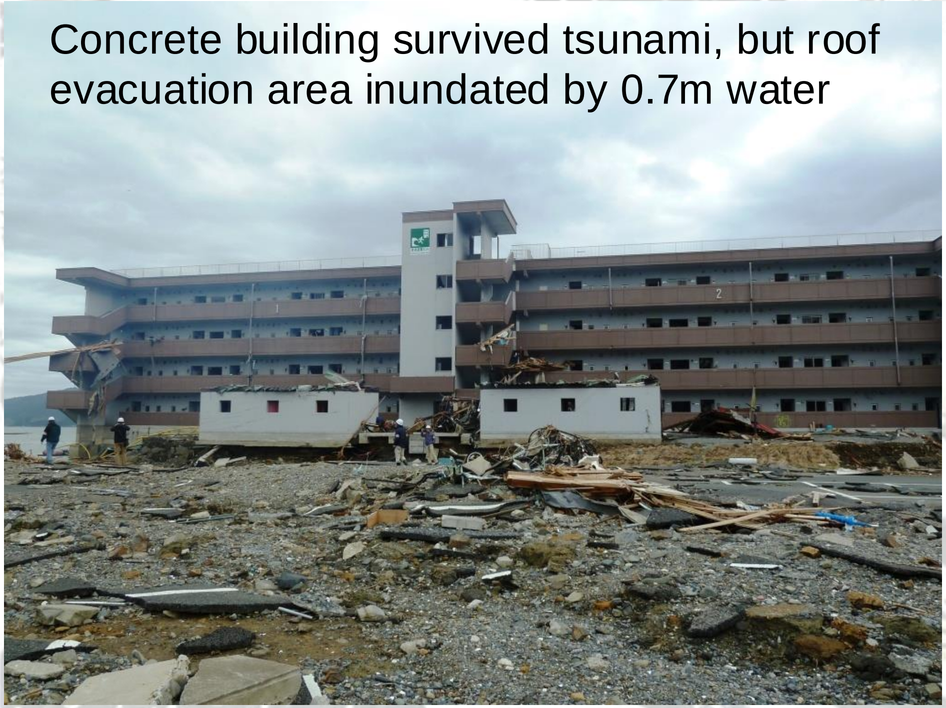
Kamaishi Evacuation Building

Warning and Evacuation



Effective Vertical Evacuation
Matsubara Community Apt. Bldg. - 2007

- **High-rise tsunami evacuation buildings can be effective refuges, but must be high enough!**
- **New 4-story reinforced concrete coastal residential structure with public access roof for tsunami evacuation**



Concrete building survived tsunami, but roof evacuation area inundated by 0.7m water

44 refugees, including several children, survived on roof evacuation area

Effective Vertical Evacuation
Matsubara Community Apt. Bldg. - 2007

- External stair and elevator to roof refuge area
- Large refuge surrounded by secure 6ft fence

Effective Vertical Evacuation
Matsubara Community Apt. Bldg. - 2007

- Significant scour around corners of building
- Collapse prevented by deep foundations





Varied Performance of Reinforced Concrete Buildings

- **Varied performance of neighboring concrete buildings in Minamisanriku**

Essential and Emergency Response Facilities in Harm's Way (over 300 disaster responders killed)

- Minamisanriku Emergency Operations Center
- Mayor Jin Sato, and 29 workers remained at center to provide live warnings during inundation

24 made it to the roof

EOC and Hospital in Background at Minamisanriku

- But only Mayor Sato and 8 others survived by climbing the communication antenna and clinging to the stair guard rail.
- 21 emergency responders died because their vertical evacuation structure was not high enough.

- **The EOC structure has been saved as a memorial to the emergency personnel who perished during the tsunami**

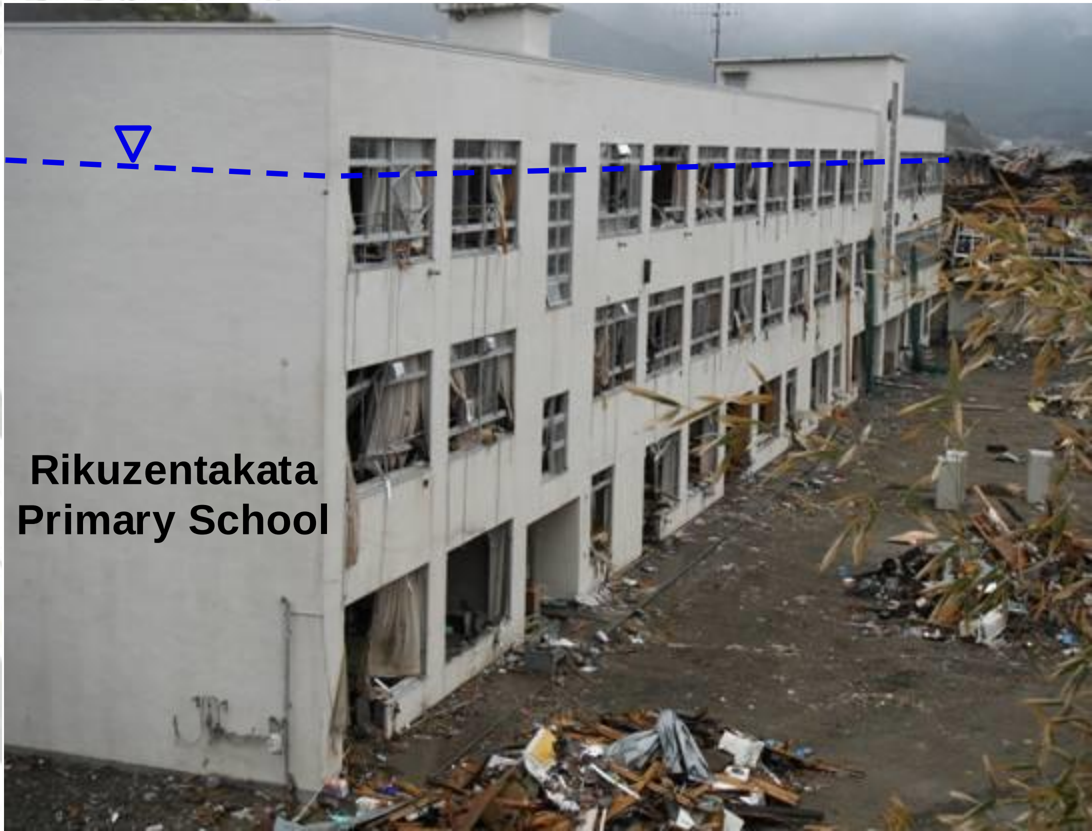
Minamisanriku Hospital
RC building with seismic retrofit

- **Hospital was occupied during the tsunami (320 survived)**
- **Some patients were moved to evacuation zone on roof**
- **Three stories of patient drowning fatalities (71 dead)**

Arahama Elementary School, Sendai

Rikuzentakata School Building Refuge
Reinforced Concrete

Modern mid-rise reinforced concrete buildings with deep pile foundations generally withstood wave loads, even when nearly overtopped



Primary School – designated evacuation center.
Abandoned just in time because notified by disaster officials that seawalls had been overtopped.
No fatalities.

Rikuzentakata School Building Refuge
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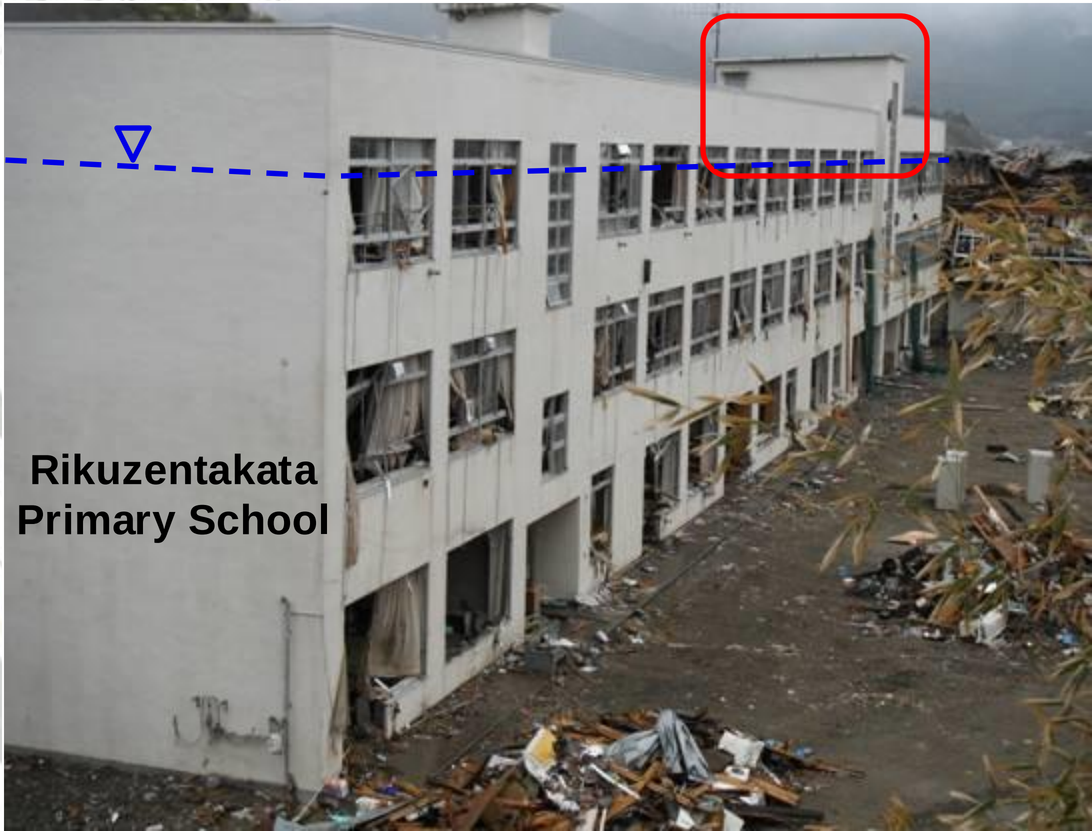


Rikuzentakata Primary School

Many Evacuation Sites Inundated

- **Rikuzentakata City Hall Community Center and Gym that served as an official tsunami evacuation center was completely inundated leading to loss of life of almost all evacuees.**

Cross-walks
Sendai and Rikuzentakata

Sendai Crosswalk
Used as unofficial refuge by 50+

Cross-walks
Sendai and Rikuzentakata

Sendai Crosswalk
Used as unofficial refuge by 50+

Rikuzentakata Crosswalk
Almost completely destroyed – unknown casualties

Report on Performance of Evacuation Structures in Japan

- **By Fraser, Leonard, Matsuo and Murakami**
- **GNS Science Report 2012/17**
- **April 2012**

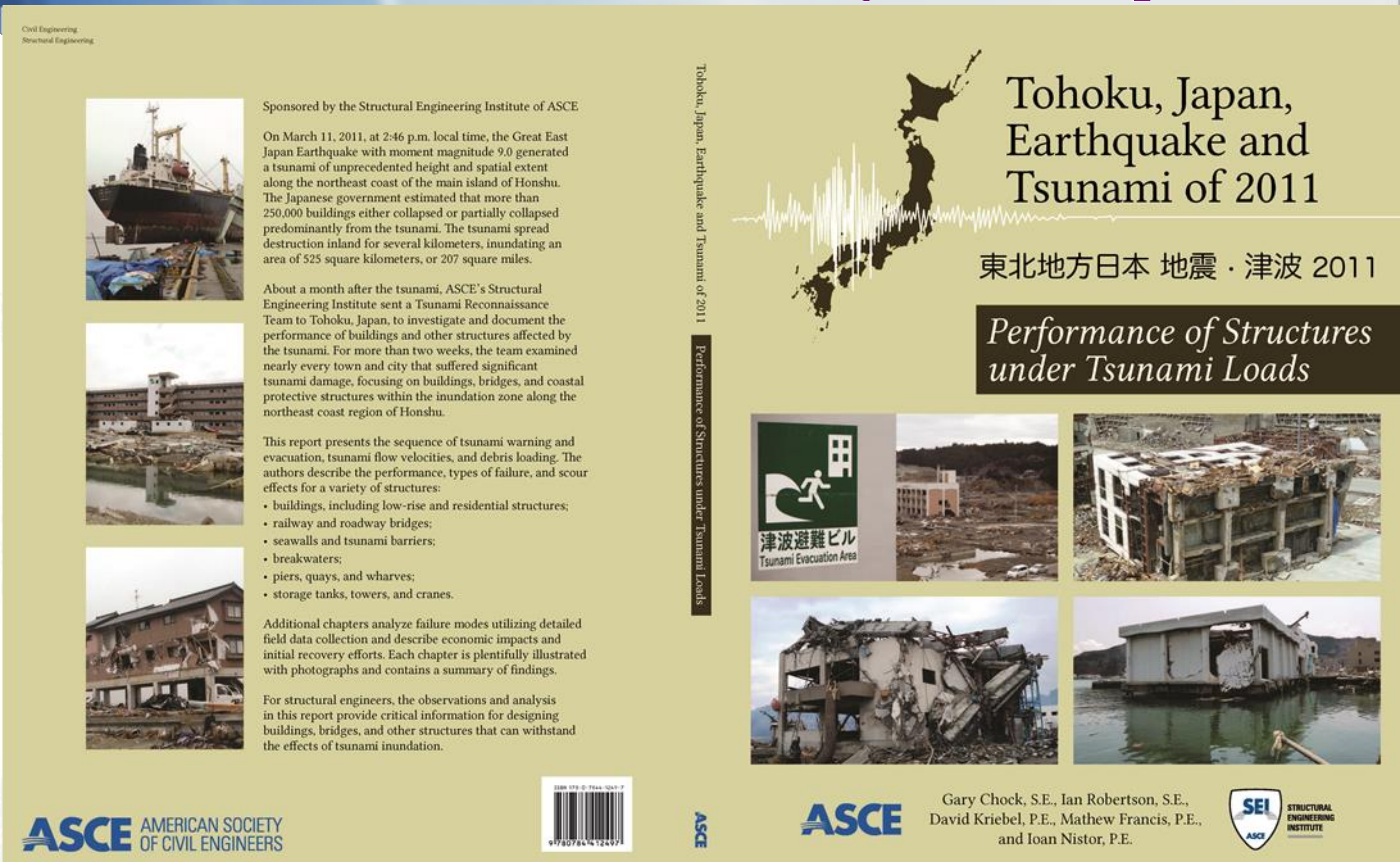
Tsunami evacuation: Lessons from the Great East Japan earthquake and tsunami of March 11th 2011

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

GNS Science Report 2012/17
April 2012

Tohoku Tsunami

ASCE/SEI Tsunami Survey Final Report


Civil Engineering
Structural Engineering

Sponsored by the Structural Engineering Institute of ASCE

On March 11, 2011, at 2:46 p.m. local time, the Great East Japan Earthquake with moment magnitude 9.0 generated a tsunami of unprecedented height and spatial extent along the northeast coast of the main island of Honshu. The Japanese government estimated that more than 250,000 buildings either collapsed or partially collapsed predominantly from the tsunami. The tsunami spread destruction inland for several kilometers, inundating an area of 525 square kilometers, or 207 square miles.

About a month after the tsunami, ASCE's Structural Engineering Institute sent a Tsunami Reconnaissance Team to Tohoku, Japan, to investigate and document the performance of buildings and other structures affected by the tsunami. For more than two weeks, the team examined nearly every town and city that suffered significant tsunami damage, focusing on buildings, bridges, and coastal protective structures within the inundation zone along the northeast coast region of Honshu.

This report presents the sequence of tsunami warning and evacuation, tsunami flow velocities, and debris loading. The authors describe the performance, types of failure, and scour effects for a variety of structures:

- buildings, including low-rise and residential structures;
- railway and roadway bridges;
- seawalls and tsunami barriers;
- breakwaters;
- piers, quays, and wharves;
- storage tanks, towers, and cranes.

Additional chapters analyze failure modes utilizing detailed field data collection and describe economic impacts and initial recovery efforts. Each chapter is plentifully illustrated with photographs and contains a summary of findings.

For structural engineers, the observations and analysis in this report provide critical information for designing buildings, bridges, and other structures that can withstand the effects of tsunami inundation.

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Tohoku, Japan, Earthquake and Tsunami of 2011 Performance of Structures under Tsunami Loads ASCE

Tohoku, Japan, Earthquake and Tsunami of 2011

東北地方日本 地震・津波 2011

Performance of Structures under Tsunami Loads

ASCE

Gary Chock, S.E., Ian Robertson, S.E.,
David Kriebel, P.E., Mathew Francis, P.E.,
and Ioan Nistor, P.E.

SEI STRUCTURAL ENGINEERING INSTITUTE

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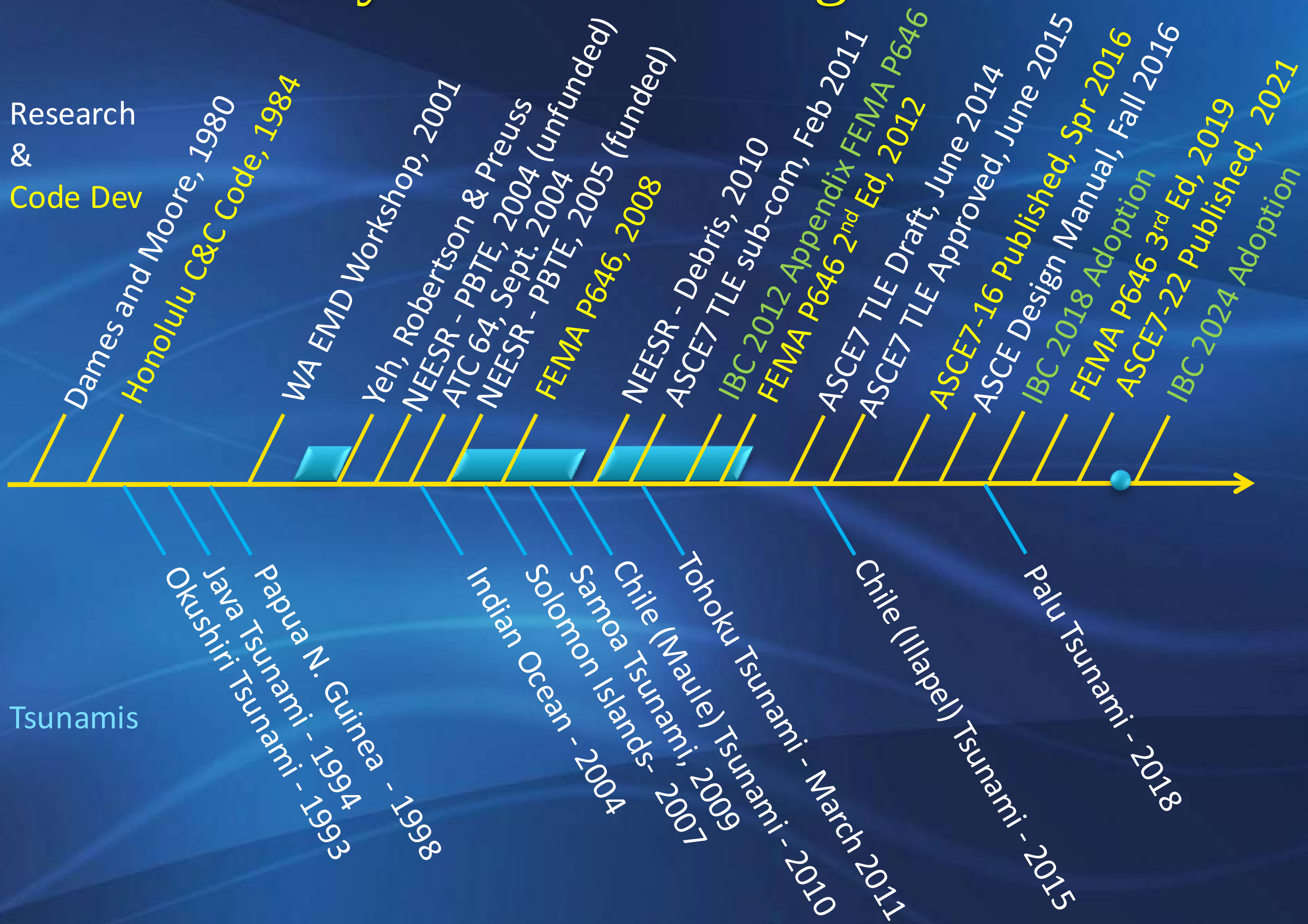
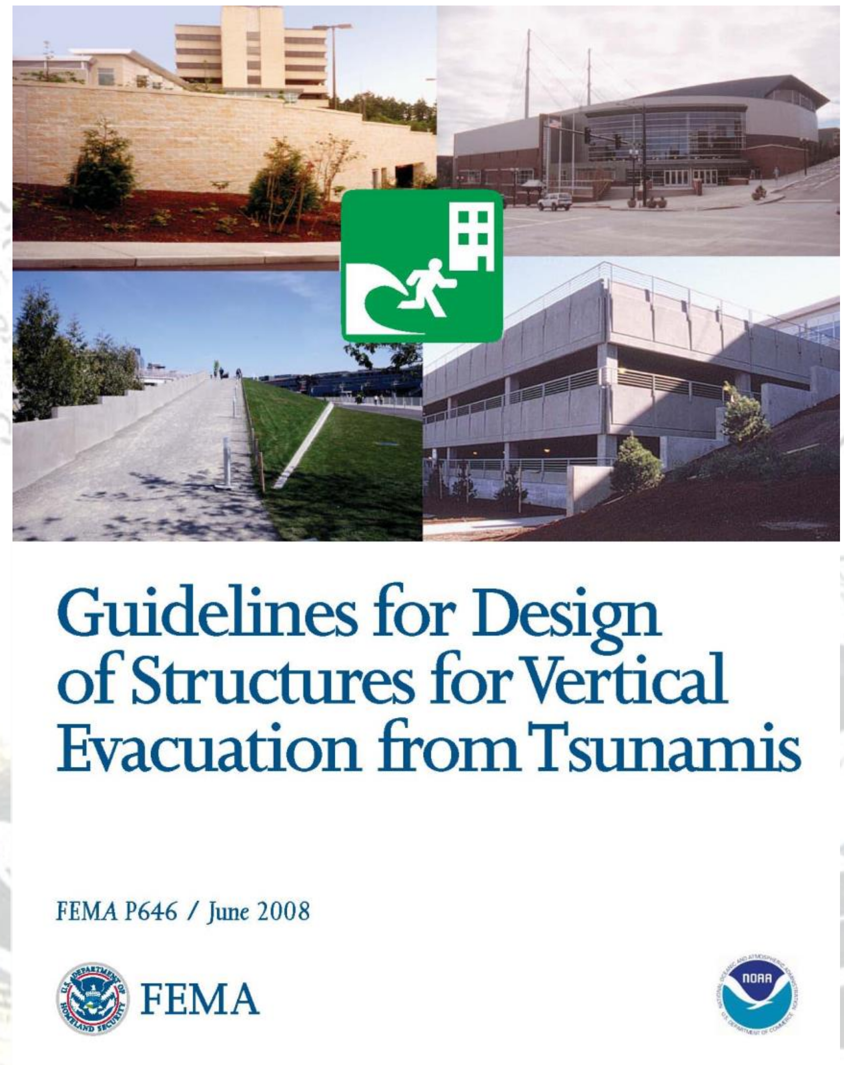
History of Tsunami Design in the US



Guidelines for Design of Structures for Vertical Evacuation from Tsunamis (FEMA P646)

- **Developed by Applied Technology Council as ATC-64**
- **FEMA Funding**
- **First published 2008**
- **FEMA**
  - **Michael Mahoney**
  - **Robert Hanson**
- **ATC Management**
  - **Christopher Rojahn**
  - **Jon Heinz**
  - **William Holmes**



Vertical Evacuation Options

- Preference given to high ground
- Manmade high ground in form of mound
- Building or other structure designed for tsunami loads

Manmade high ground
Sendai Port, Japan

- Earth mounds can act as effective evacuation sites
- Must be high and large enough

Vertical Evacuation Building Designated Refuge

- Port Authority Bldg.
- Kesennuma, Japan
- Designated as tsunami refuge
- Flooded to third level
- Numerous survivors sought refuge on roof

Adjacent Building used as refuge of opportunity

Now designated as tsunami refuge with exterior stair to roof (2013)

Kesennuma Refuge of Opportunity

Vertical Evacuation Building
Parking Garage

- Multi-level Parking structure
- Biloxi, Mississippi
- Hurricane Katrina
- Open to pedestrians 24 hours a day
- Ramps for easy access to roof

Siting and Spacing

- Provide access to high ground
- Guidance on number and location of vertical refuges
- Spacing is based on 2 mph walking speed and expected tsunami warning time

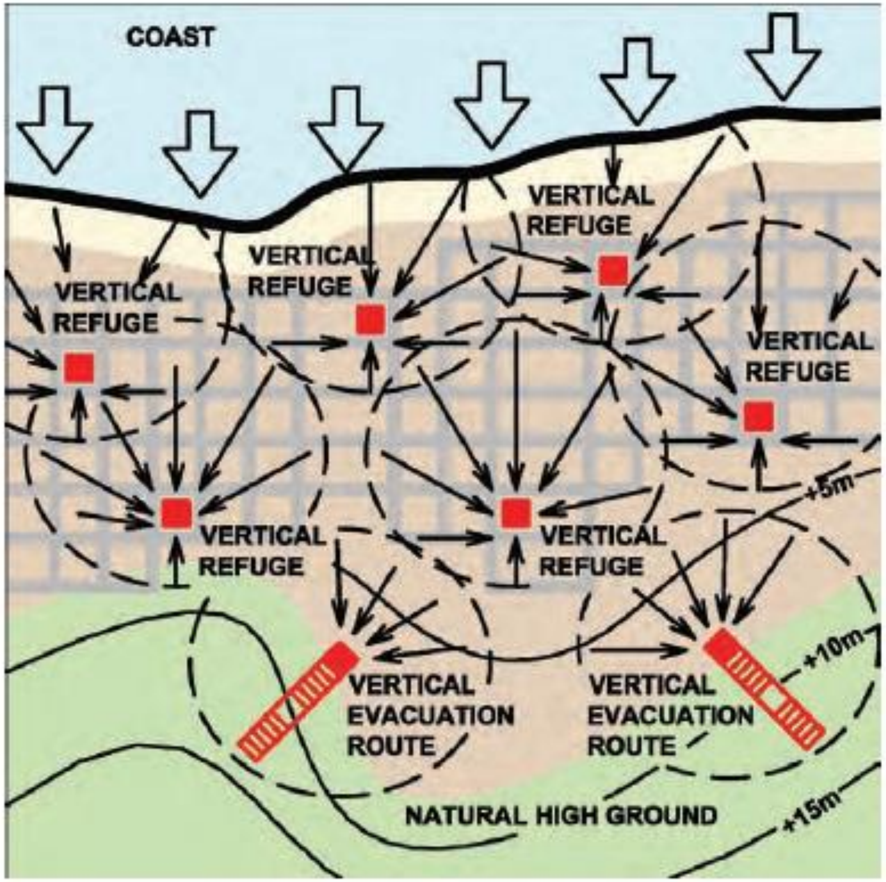


Figure 5-1 Vertical evacuation refuge locations considering travel distance, evacuation behavior, and naturally occurring high ground. Arrows show anticipated vertical evacuation routes.

Siting and Spacing

- Consideration given to proximity of large debris, hazardous or flammable materials
- May require additional precautions

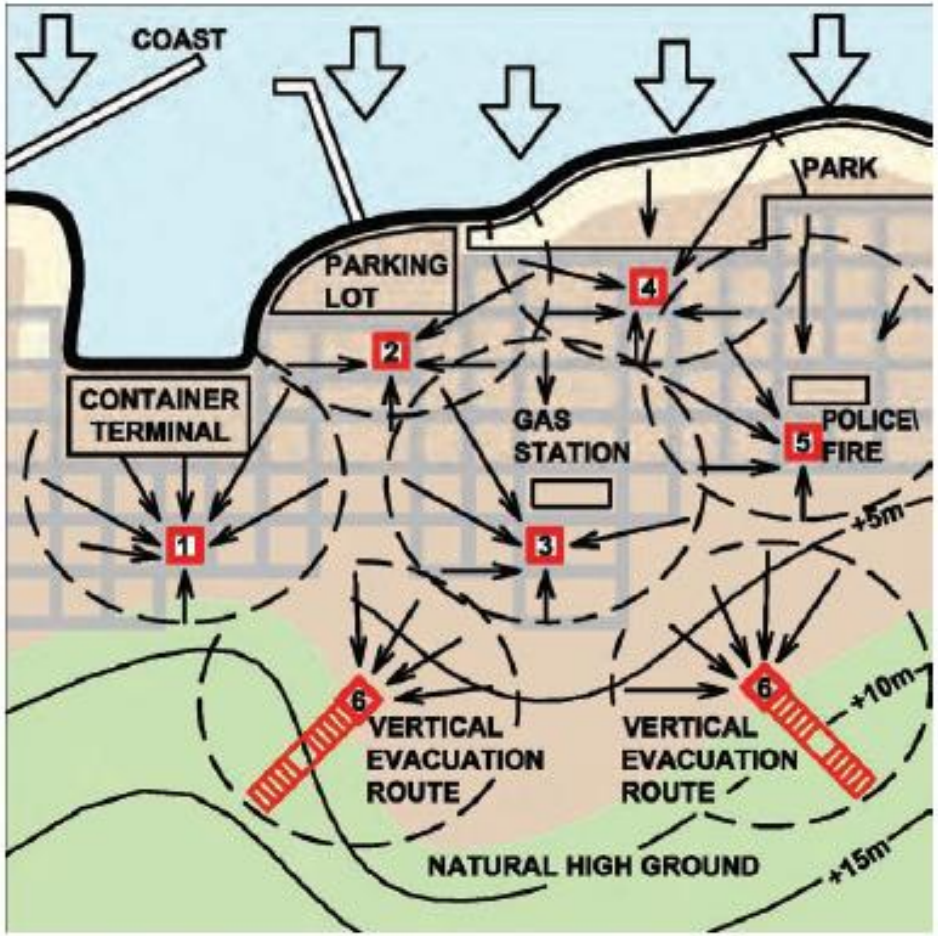


Figure 5-2 Site hazards adjacent to vertical evacuation structures (numbered locations). Arrows show anticipated vertical evacuation routes.

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ASCE 7-10

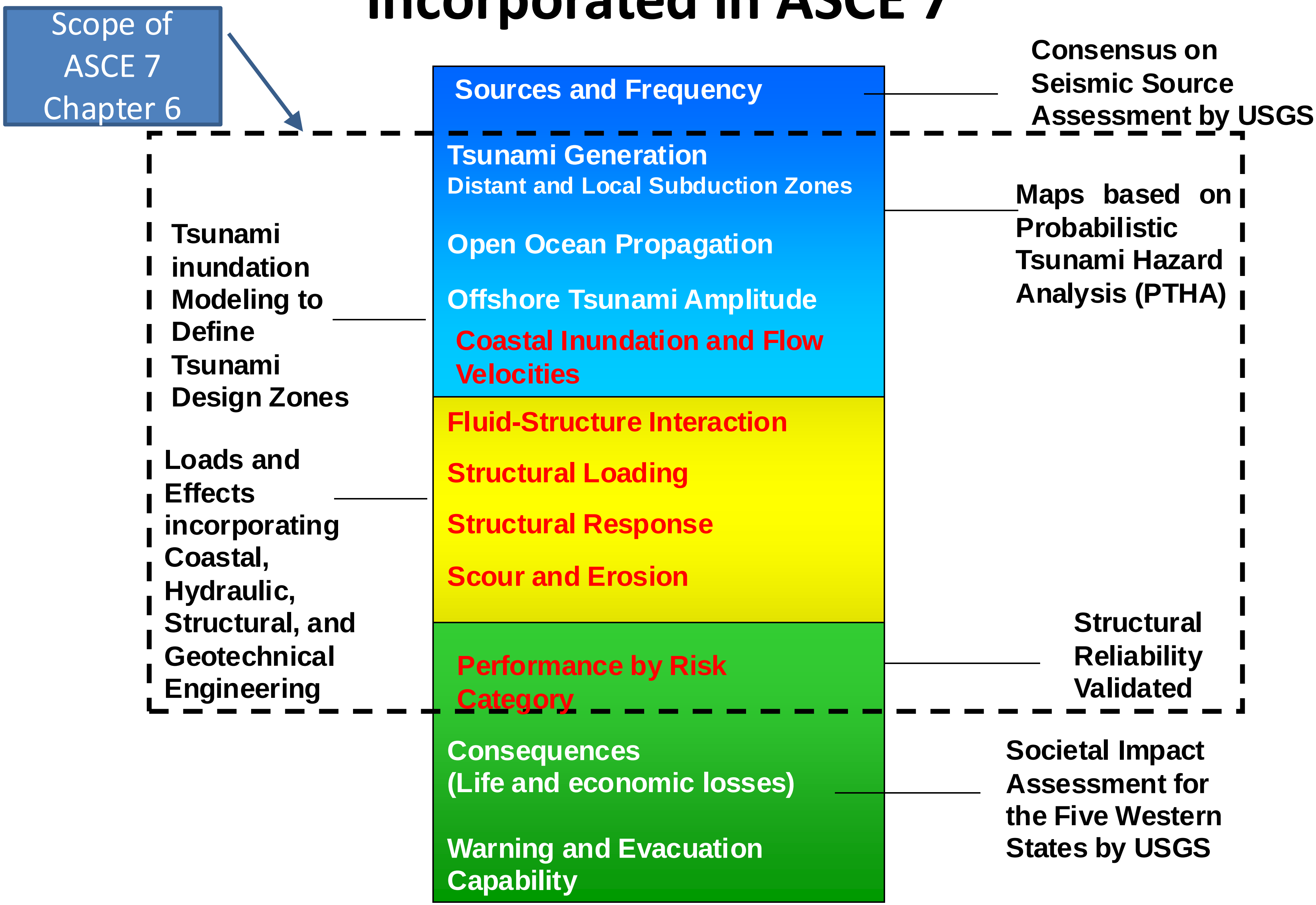
- Minimum Design Loads for Buildings and Other Structures
- Referenced by the International Building Code, IBC, and therefore most US jurisdictions

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 – Tsunami Loads and Effects
- Chap 7 - Snow loads
- Chap 8 - Rain loads
- Chap 10 - Ice loads
- Chap 11 – 23 - Seismic Design
- Chap 26 – 31 - Wind Loads

Tsunami-Resilient Engineering Subject Matter Incorporated in ASCE 7



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

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.)**

Risk Category II Buildings – Determined by Local Code Adoption

- The state or local government has the option to determine a threshold height for where tsunami-resilient design requirements for Risk Category II buildings.
- The threshold height would depend on the community's tsunami hazard, tsunami response procedures, and whole community disaster resilience goals.
- When evacuation travel times exceed the available time to tsunami arrival, there is a greater need for vertical evacuation into an ample number of sufficiently tall Category II buildings.

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

NEESR – Development of Performance Based Tsunami Engineering, PBTE

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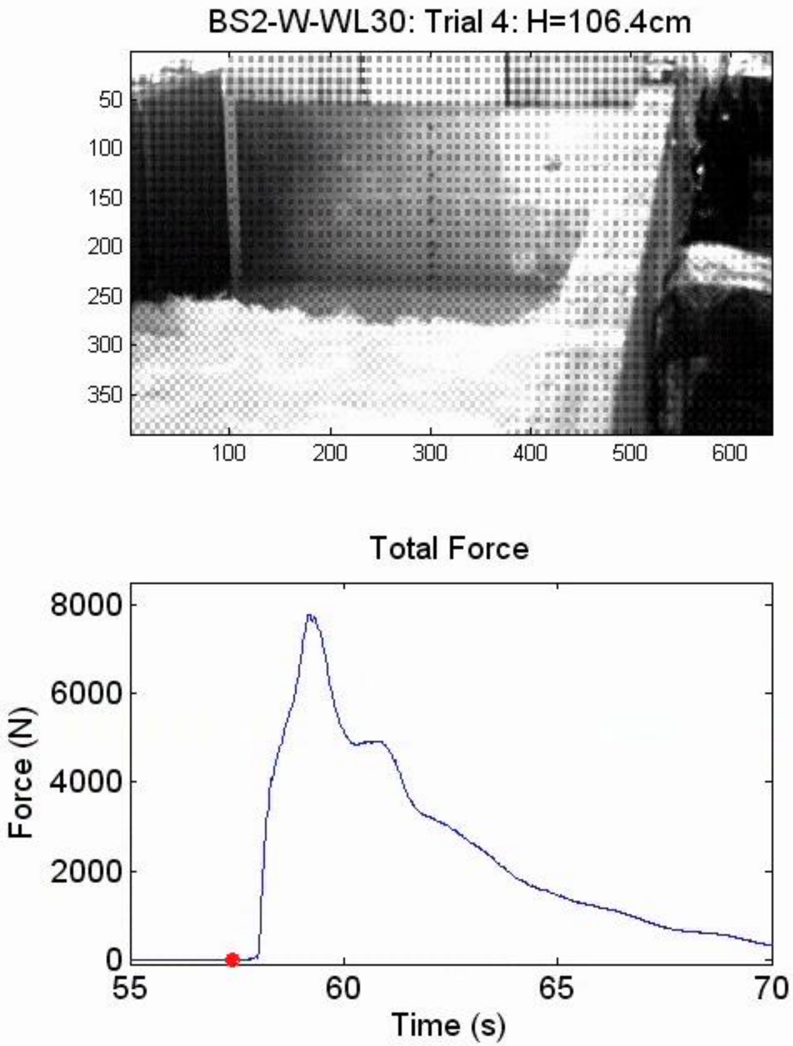
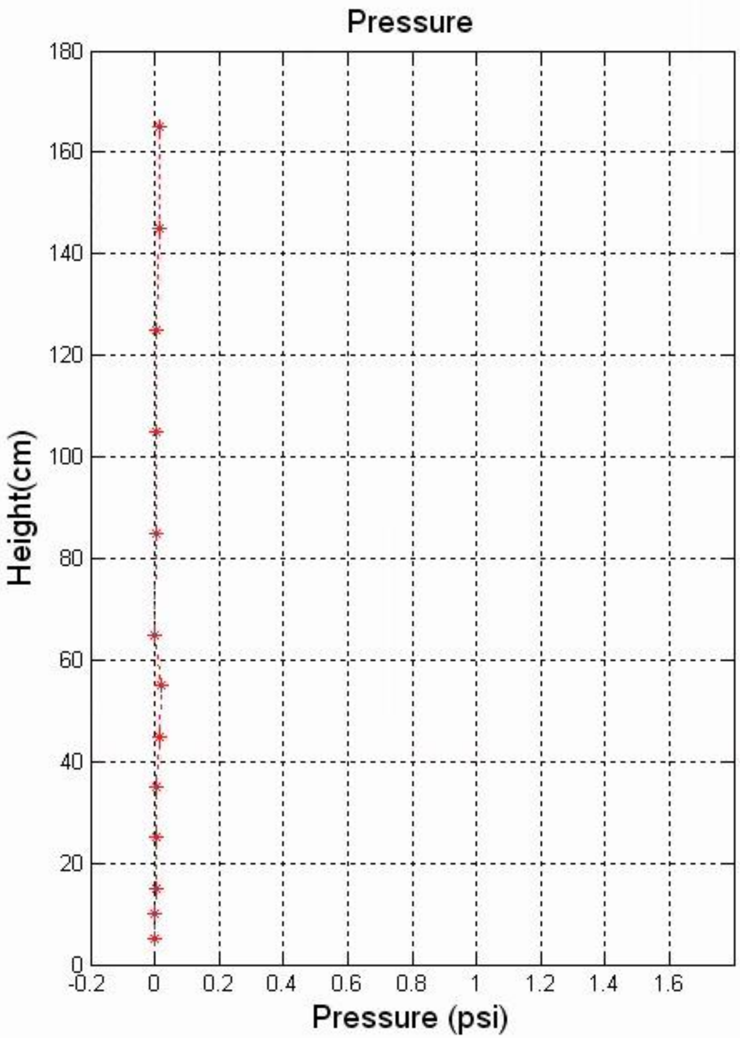
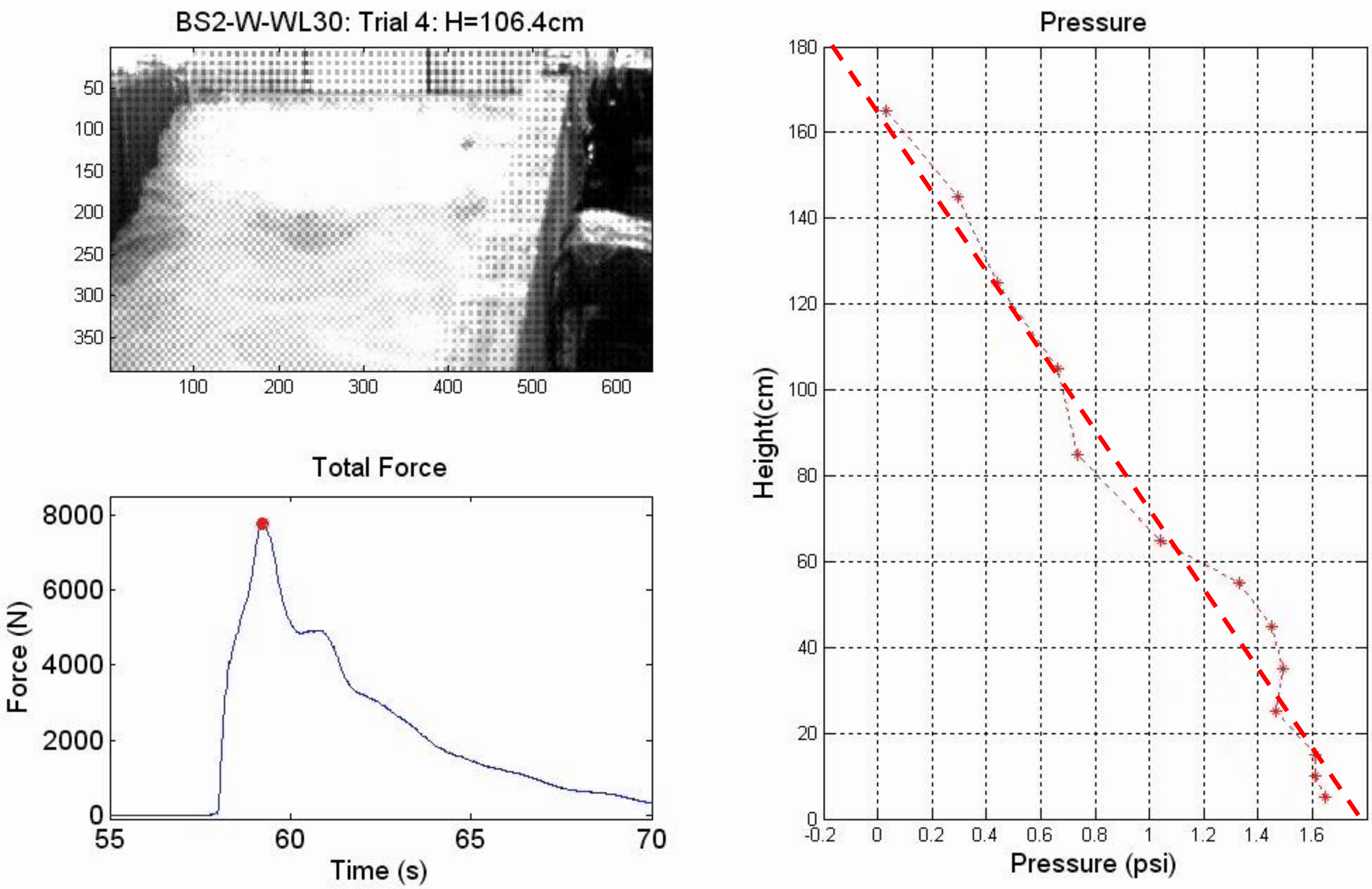




NEESR – Development of Performance Based Tsunami Engineering, PBTE

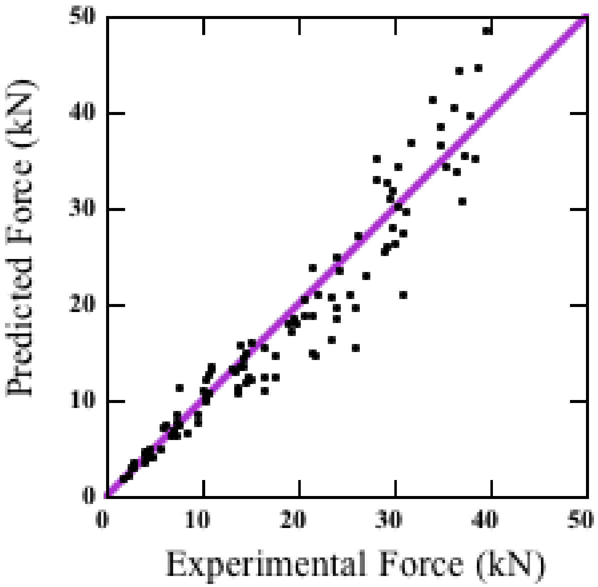
NEESR - Structural Loading
Direct Bore Impact on Solid Wall

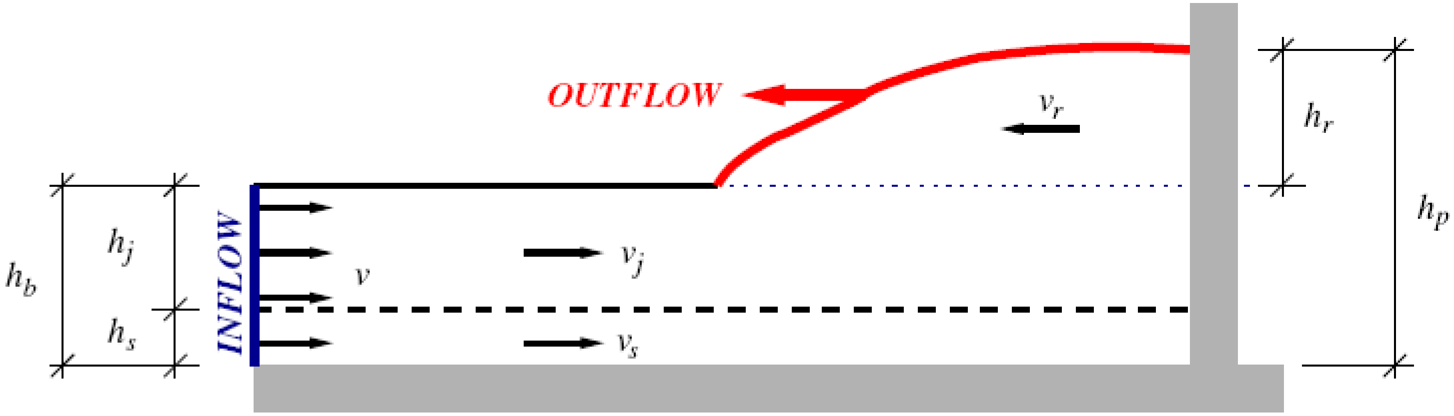


Hydrodynamic Force on Wall due to Bore Impact

- Based on conservation of mass and momentum

$$F_w = \rho_{sw}\left(\frac{1}{2} g h_b^2 + h_j v_j^2 + g^{1/3}(h_j v_j)^{4/3}\right)$$





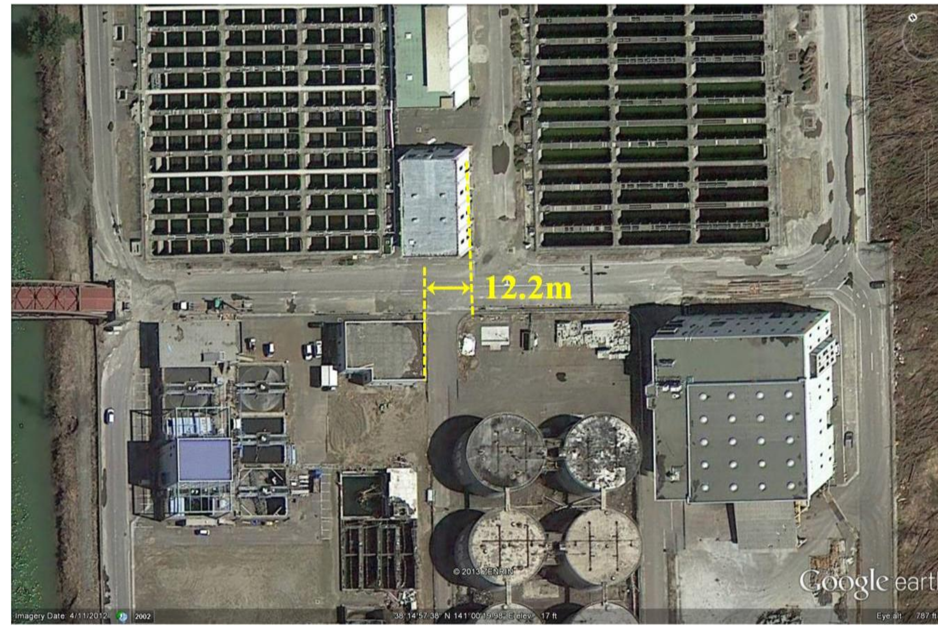
Sendai
Bore Strike on R/C Structure

Sendai
Bore Strike on R/C Structure

Velocity Analysis

Frame 260 – First Building Impact

Frame 316 – Second Building Impact



Video rate of 30 fps
Time from Frame 260 to 316 = 1.87 sec.
Distance between buildings = 12.2 m
Bore velocity = 12.2/1.87 = 6.5 m/s
Jump height approx. 5.5m over approx. 0.5m standing water

Bore Strike on R/C Structure

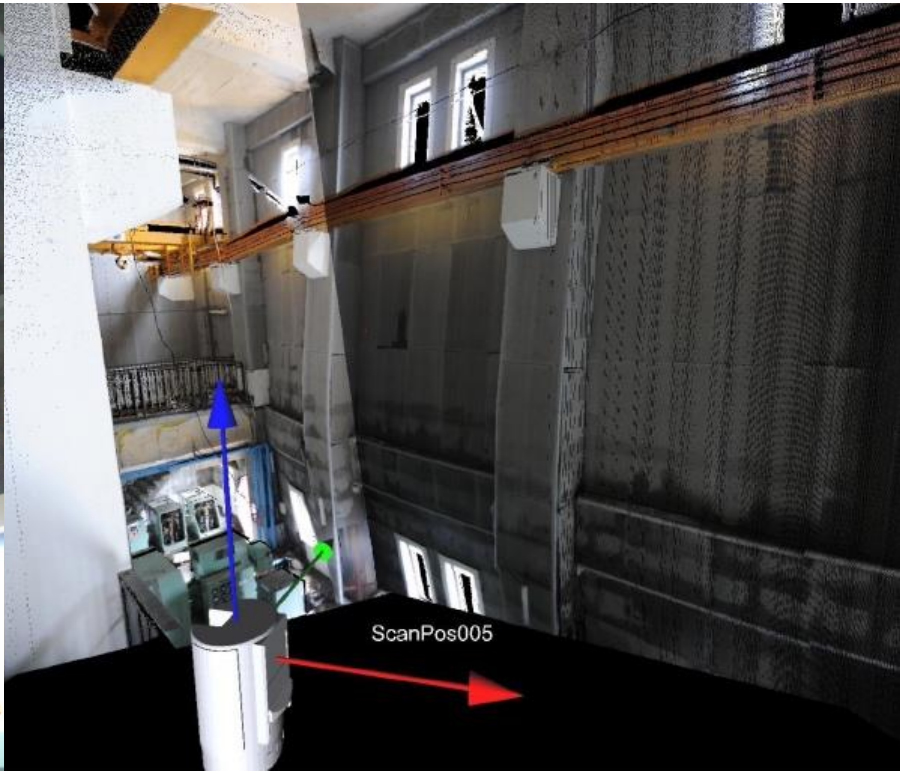
Minami Gamou Wastewater Treatment Plant - subjected to direct bore impact

Lidar Scan of deformed shape

Structural drawings obtained from the Wastewater Treatment Plant

Bore Strike on R/C Structure

Interior view of 2-story wall

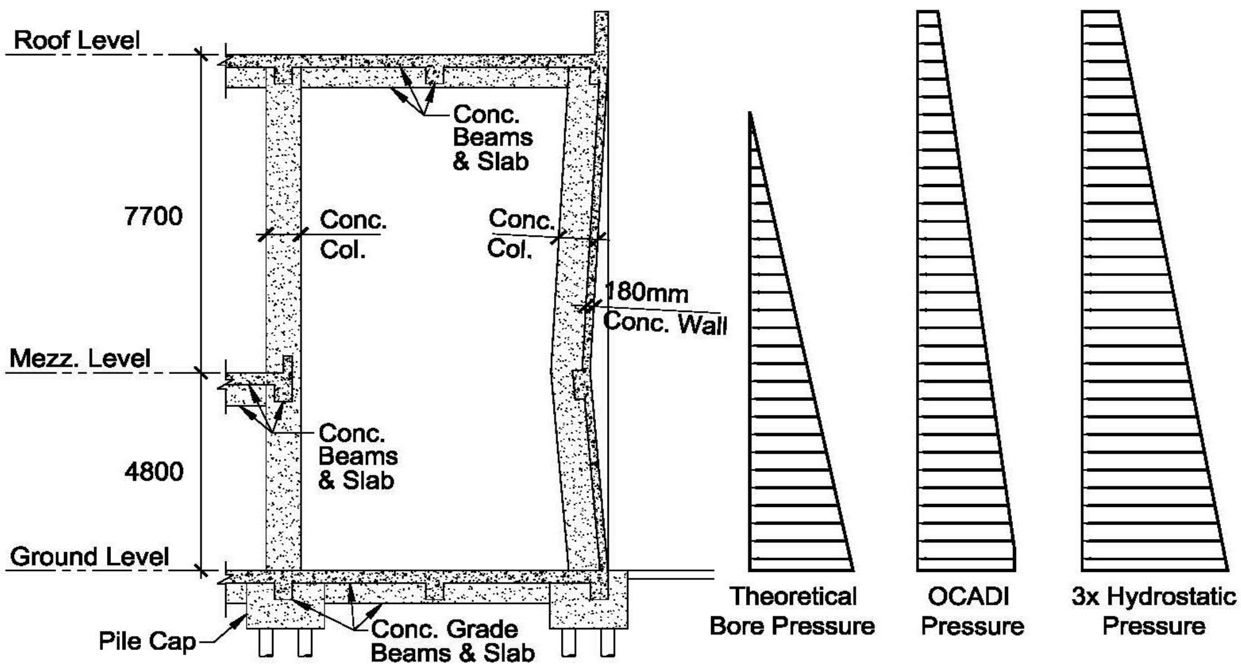


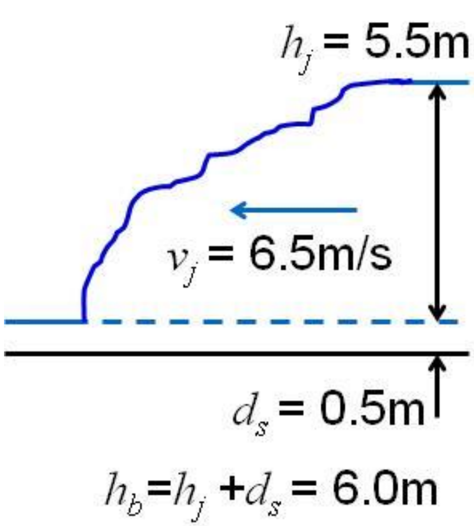
Lidar scan of 2-story wall

Minami Gamou Wastewater Treatment Plant

Bore Impact Forces
Minami Gamou Treatment Plant

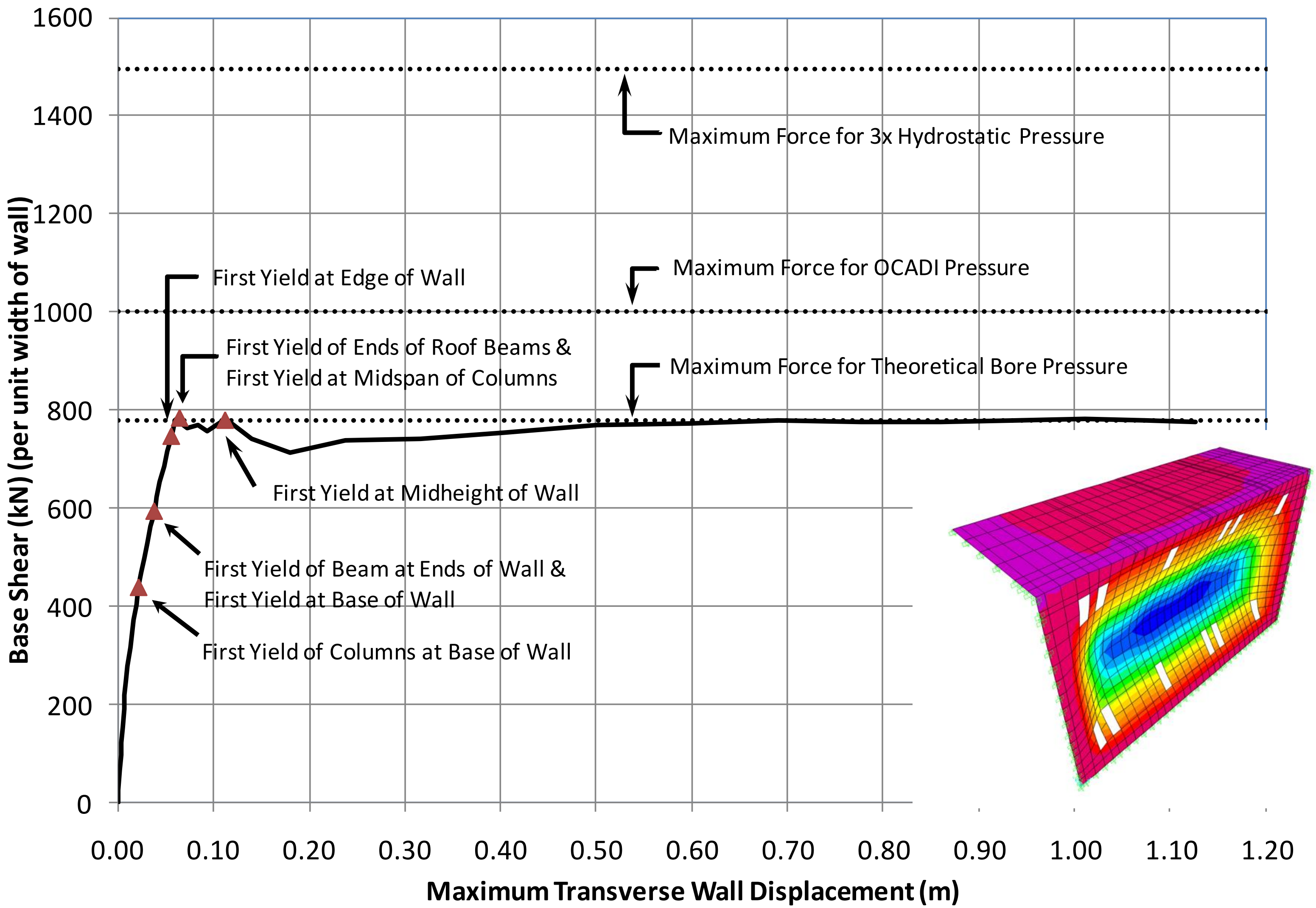
- Comparison with Different Bore Pressures used in Japan Tsunami Standards





$$F_w = \rho_{sw}\left(\frac{1}{2} g h_b^2 + h_j v_j^2 + g^{1/3}(h_j v_j)^{4/3}\right)$$

Bore Impact Forces
Non-linear Finite Element Analysis



Types of Floating Debris

Logs and Shipping Containers

Shipping Container Debris

Talcahuano harbor area four days after the Feb 27 2010 Chile tsunami

Shipping Containers

(Japan)

(Samoa)

Types of Rolling Debris

Rocks and Concrete Debris

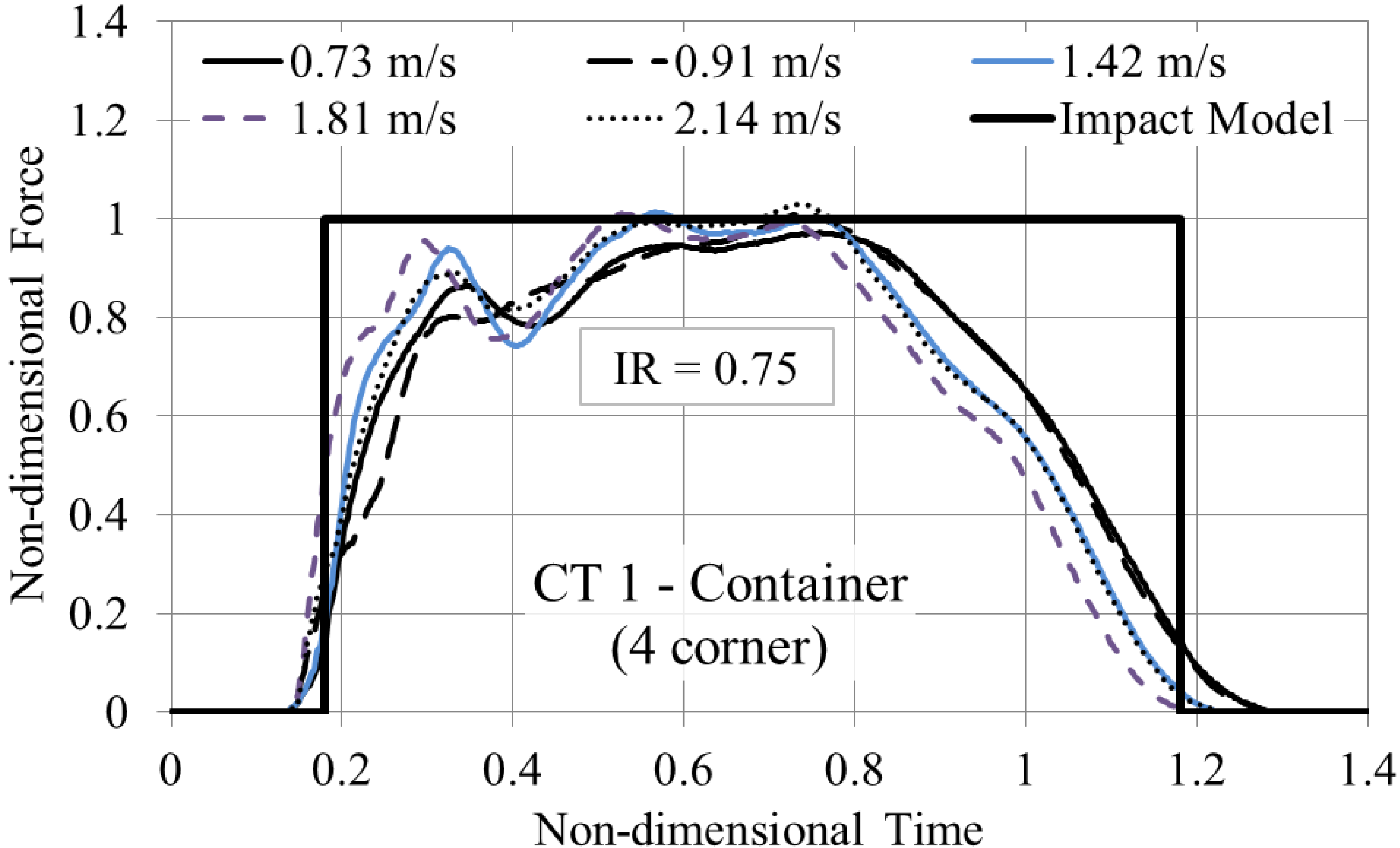
ISO 20-ft Shipping Container

- 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

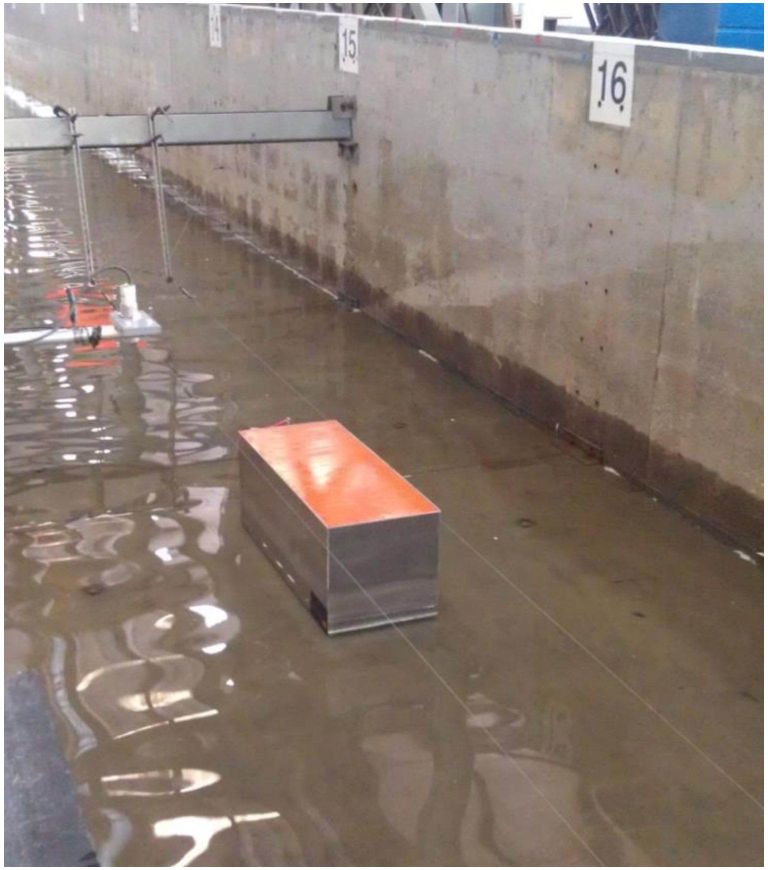
Video

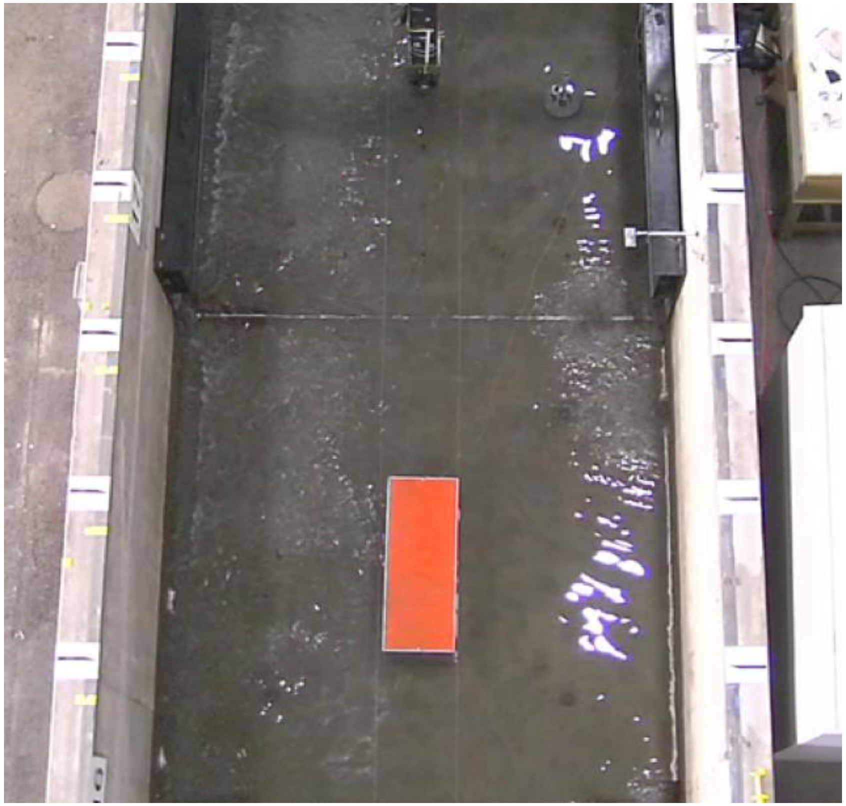
Impact Force Time History



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



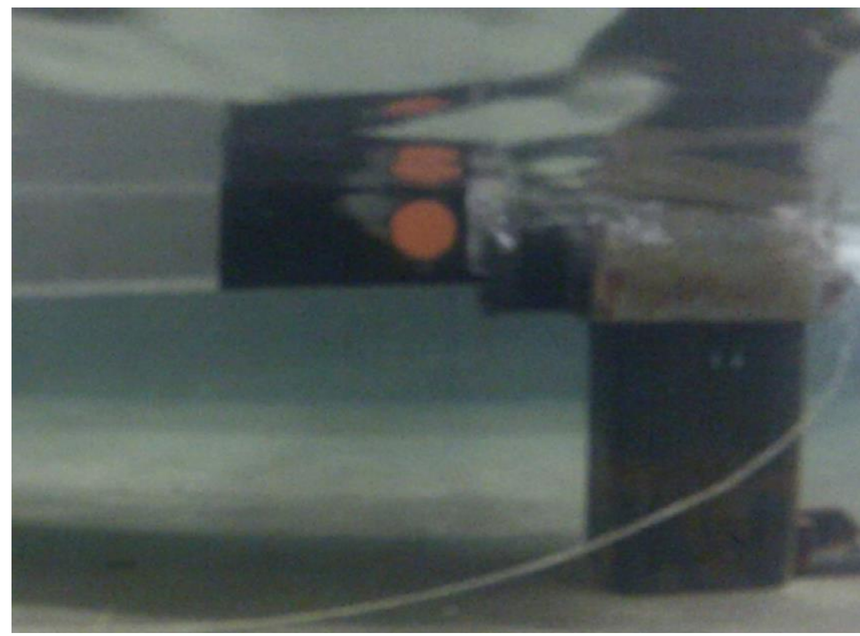


Column and load cell at top of photo

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

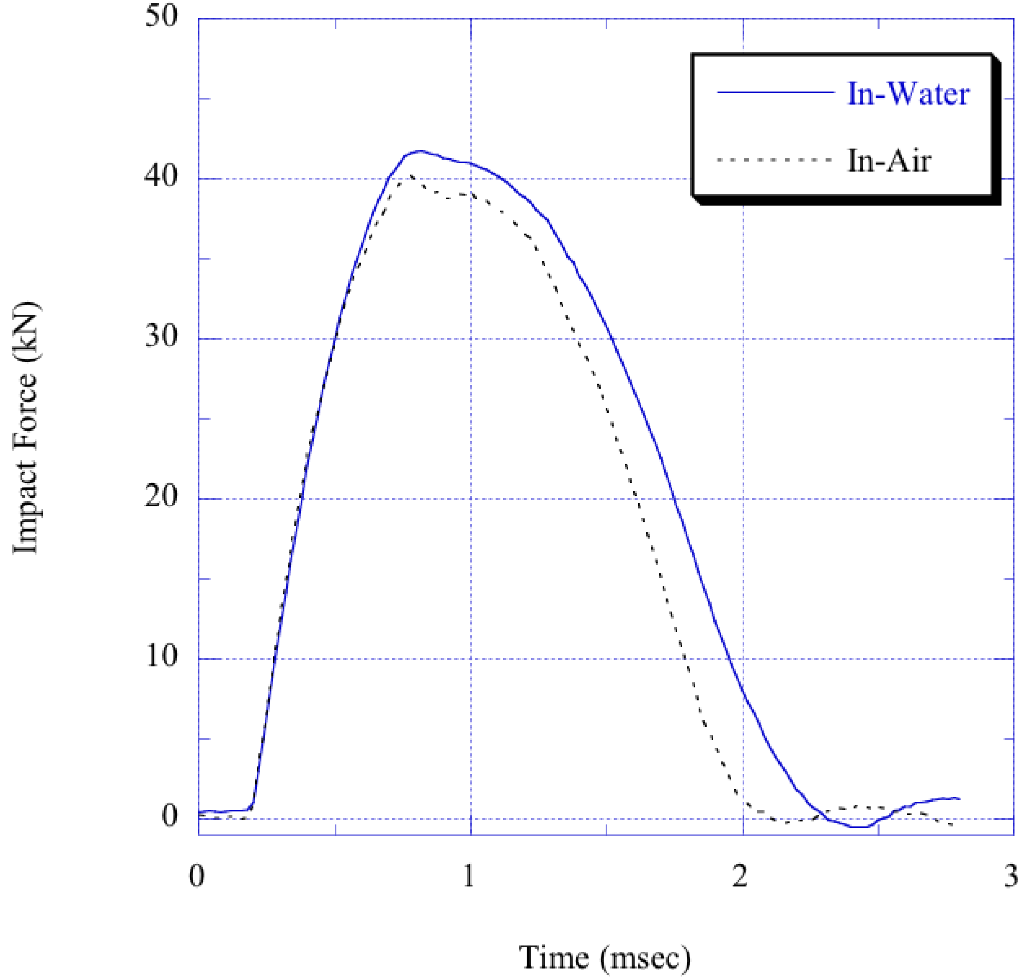
In-air impact



In-water impact

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

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

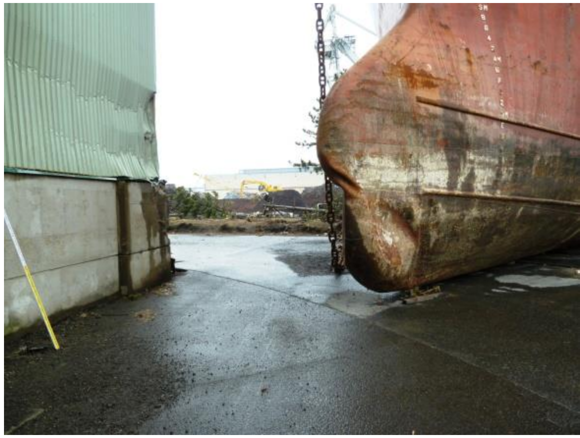
- Impact duration

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

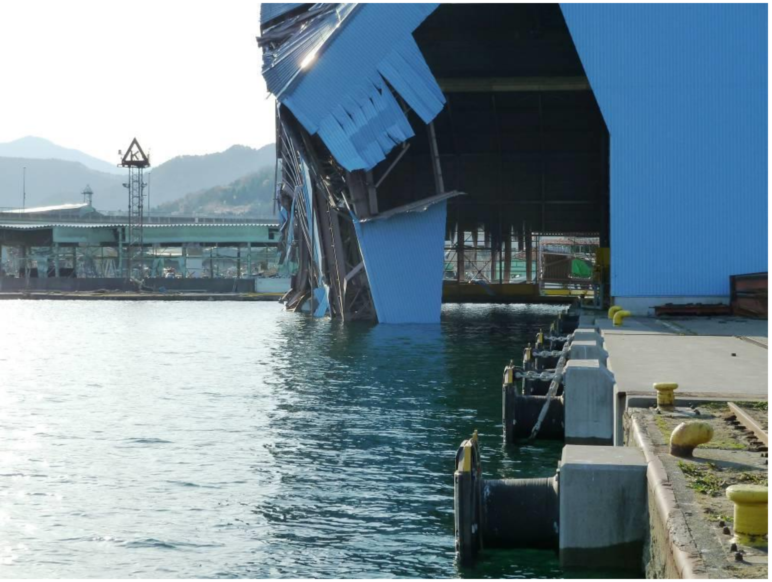
- Force capped based on strength of debris
  - Shipping Container: $F_i = 330C_oI_{TSU}$
  - Wooden Log: $F_i = 165C_oI_{TSU}$
  - Where: C_o=0.65, Impact orientation factor
- Contents increase impact duration but not force

Impact induced Progressive Collapse

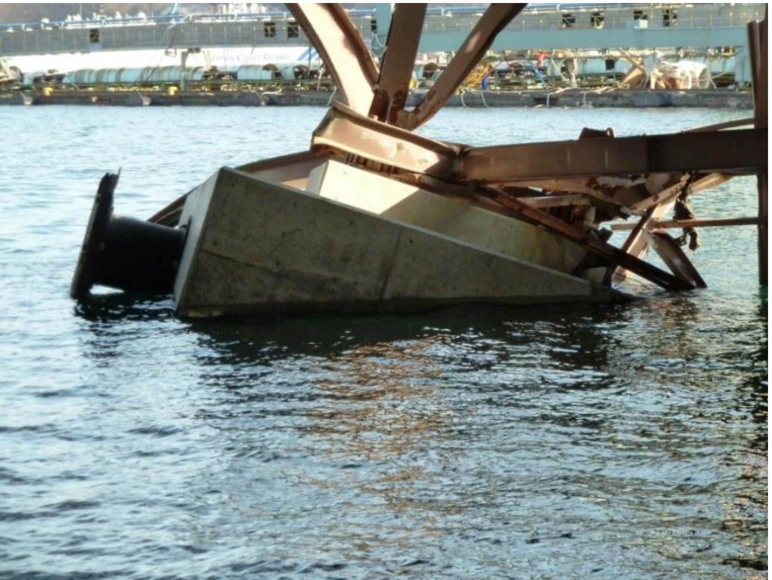
Ship Impact – Sendai Port

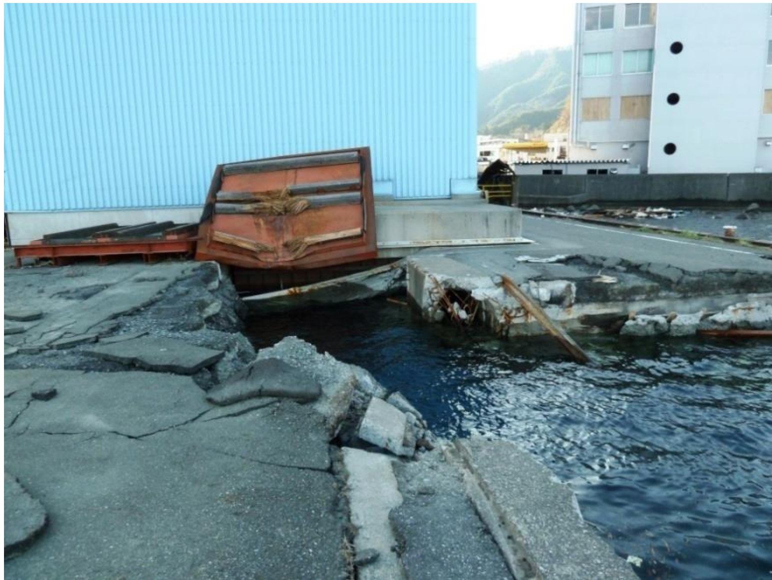


Ship Impact damage - Kamaishi

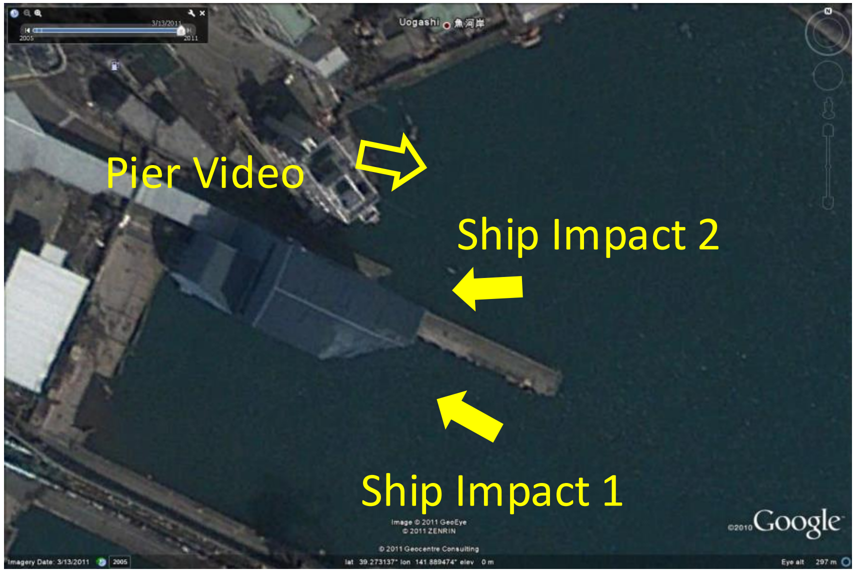


Damage to pier and warehouse due to multiple impacts from single loose ship





Kamaishi Pier



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

Ship Velocity

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

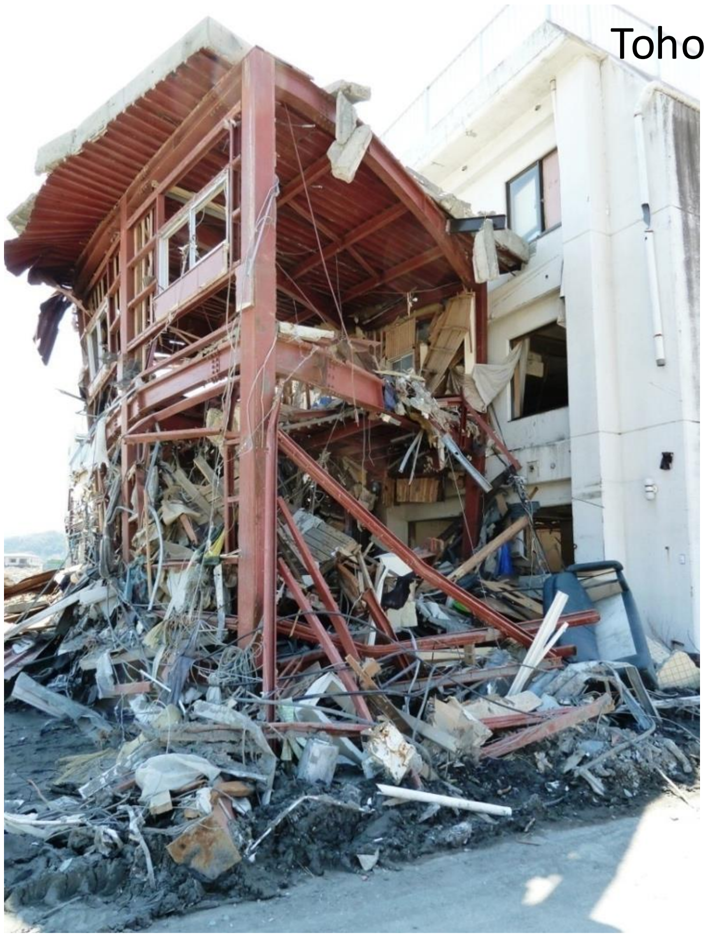
$$\therefore v = \frac{33m}{4.63s} = 7.13m/s = 25.6kph$$

Ship Impact in Kamaishi Port

Ship impact damage to steel framed building on piled foundations in Kamaishi

Damming of Waterborne Debris

Tohoku Tsunami



Three-Story Steel MRF collapsed and pushed into concrete building

Three-Story Steel MRF with 5 meters of debris load accumulation wrapping

Damming of Waterborne Debris

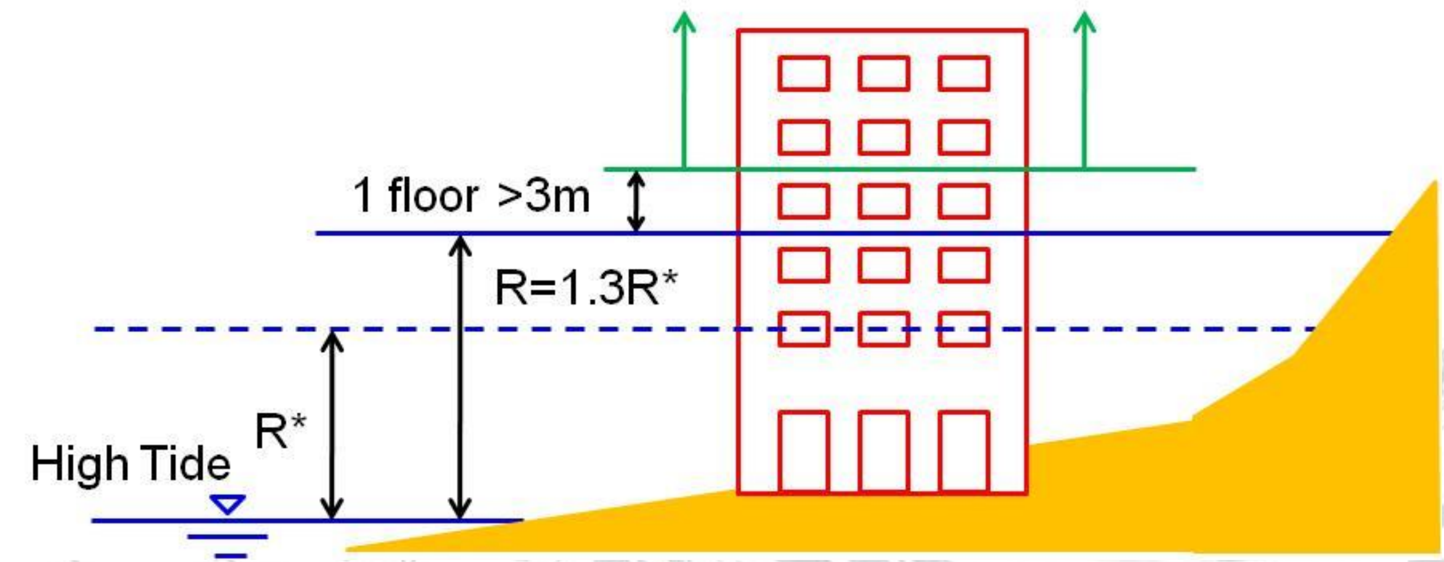
$$F_{dm} = \frac{1}{2}\rho_s C_d B_d (hu^2)_{\max}$$

Where B_d = 40 feet or one structural bay

Hurricane Katrina, 2005

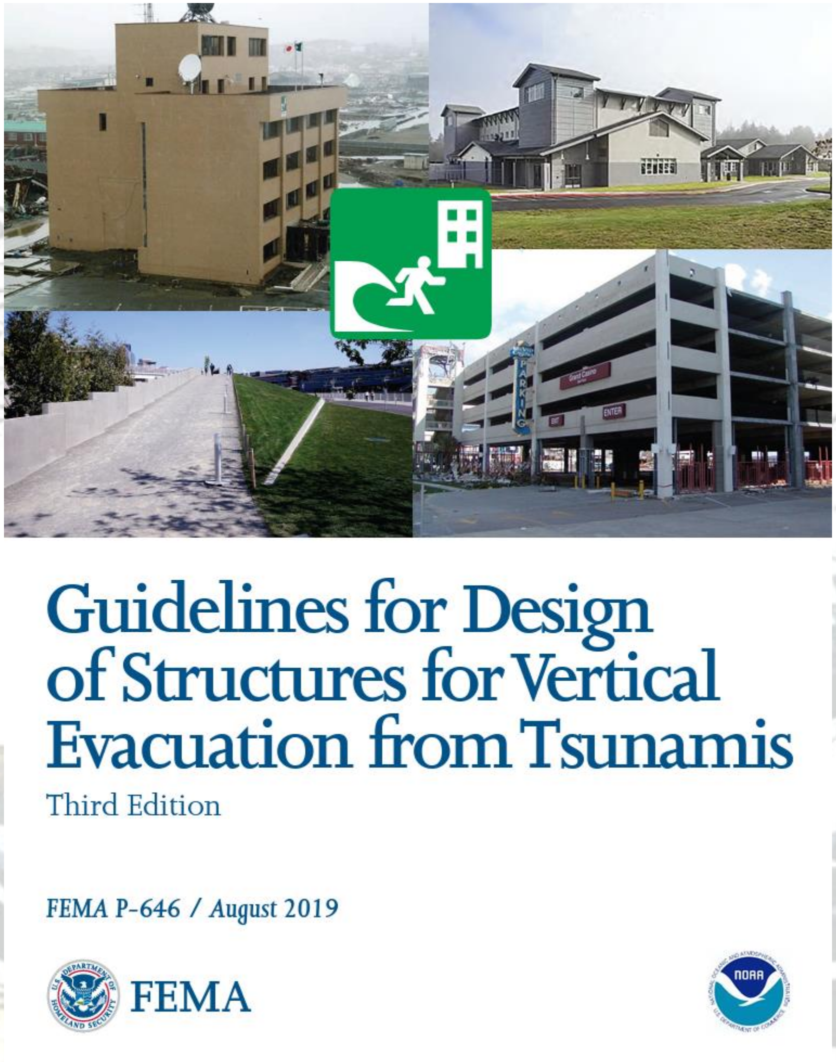
Minimum Refuge Elevation

- **Recommends refuge elevation be 1 story (3m, 10ft) above predicted inundation (with 1.3 uncertainty factor)**



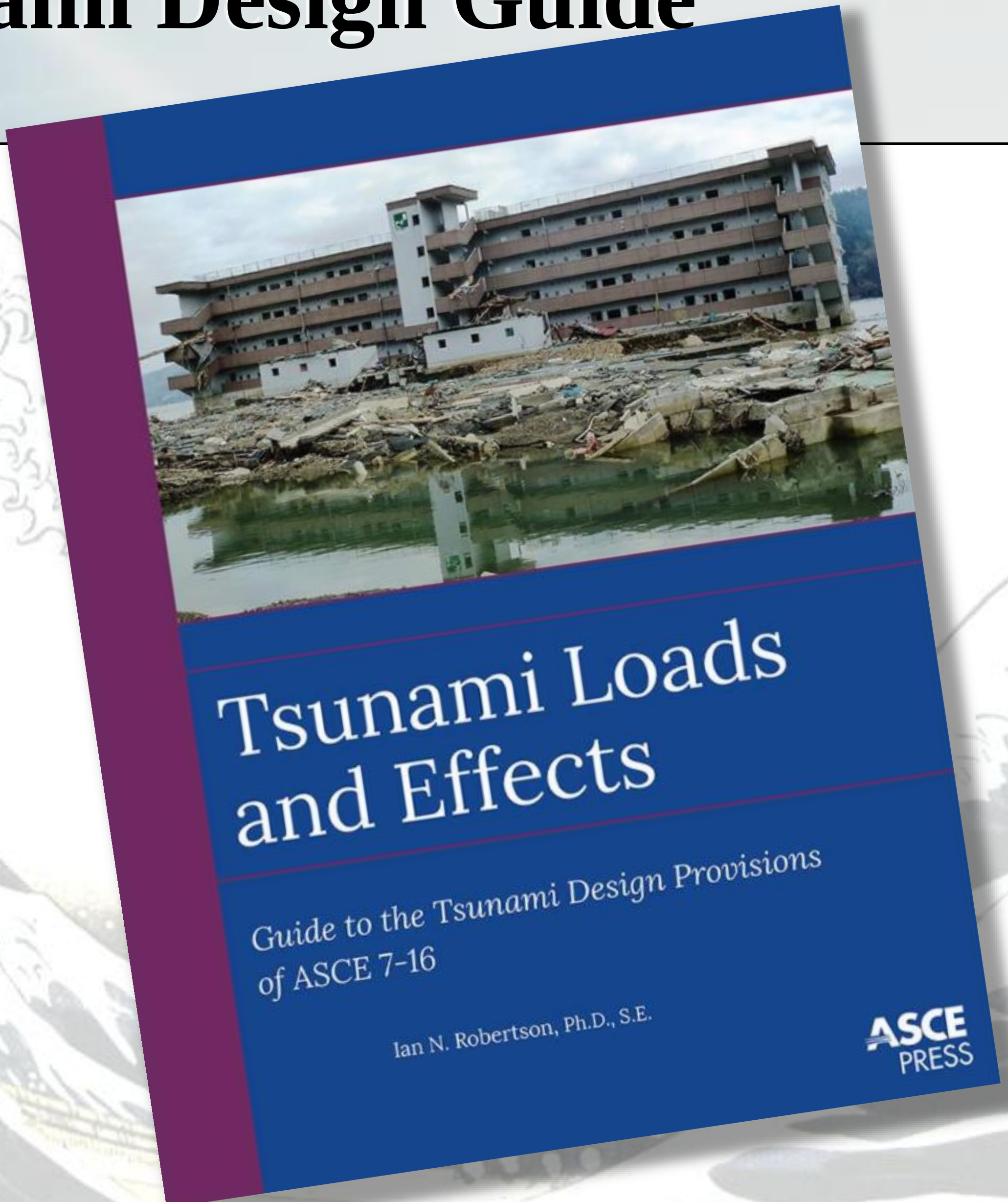
FEMA P646 Third Edition

- FEMA funding to update P-646
- Remove loading expressions
- Combine with P-646A, community planning guide
- Retrofit of Existing Structures
- Quality Assurance for Vertical Evacuation Structures – Peer Review
- Planning considerations
- 24/7 Access and Entry
- Disabled access (ADA)
- Elevation of critical equipment
- Cost considerations and financing



ASCE Tsunami Design Guide

- **Tsunami design guide published by ASCE in 2020 with numerous design examples.**



Outline

- Need for Vertical Evacuation Refuges
- Performance of Vertical Evacuation Refuges during Tohoku Tsunami
- FEMA P-646 design guidelines
- ASCE-7 Tsunami Loads and Effects chapter
- Vertical Evacuation Refuge designs in US
- Conclusions

Cannon Beach Experience

Cannon Beach City Hall/TEB conceptual Design – Ecola Architects, PC (2008)

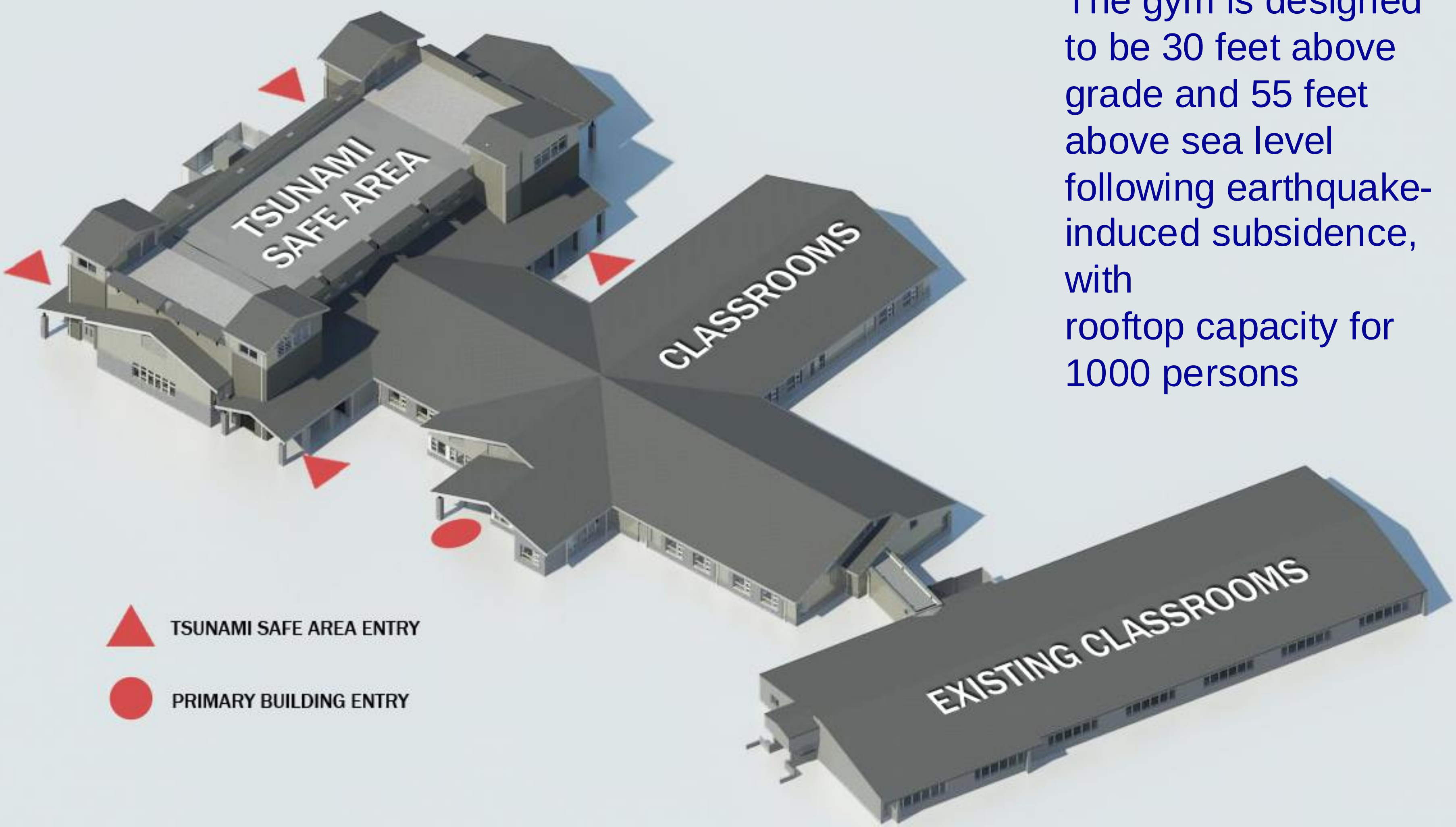
Vertical Evacuation Refuges built to ASCE 7-16

- **Ocosta Elementary School**
  Westport, WA

- **OSU Hatfield Marine Science Building**
  Newport, WA

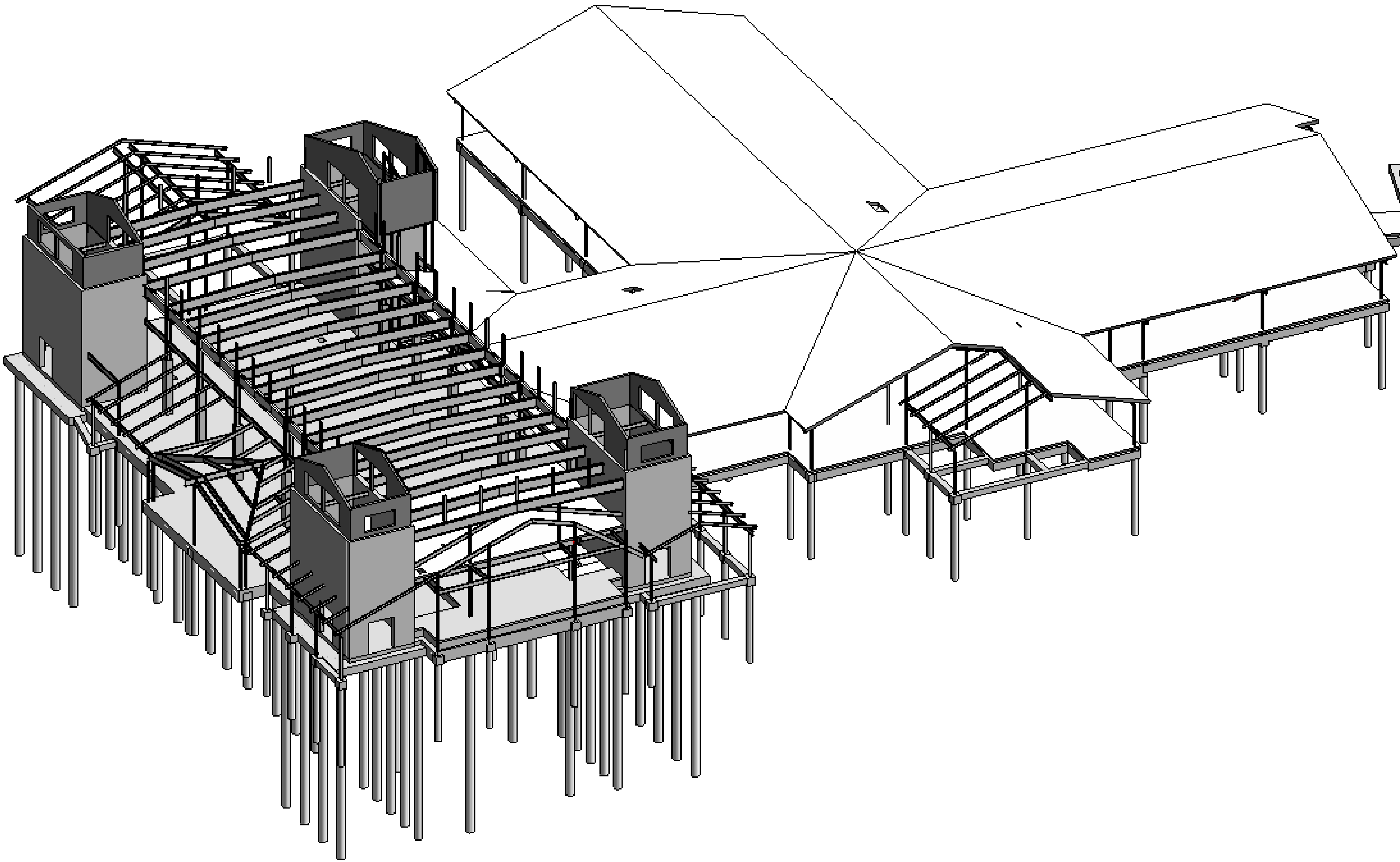
Ocosta Elementary School
Westport, Washington

Ocosta Elementary School Westport, Washington America's first tsunami refuge

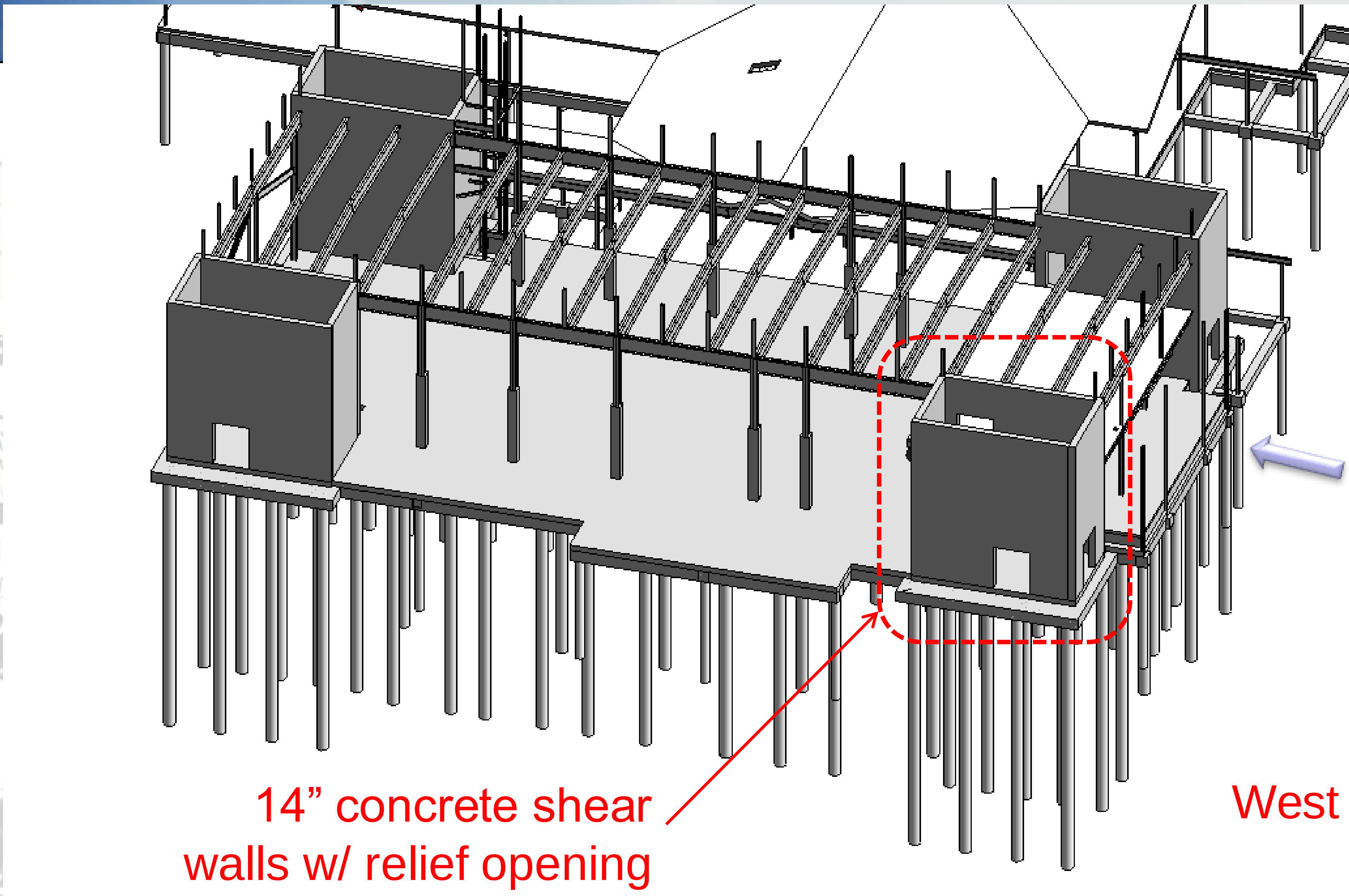


The gym is designed to be 30 feet above grade and 55 feet above sea level following earthquake-induced subsidence, with
rooftop capacity for 1000 persons

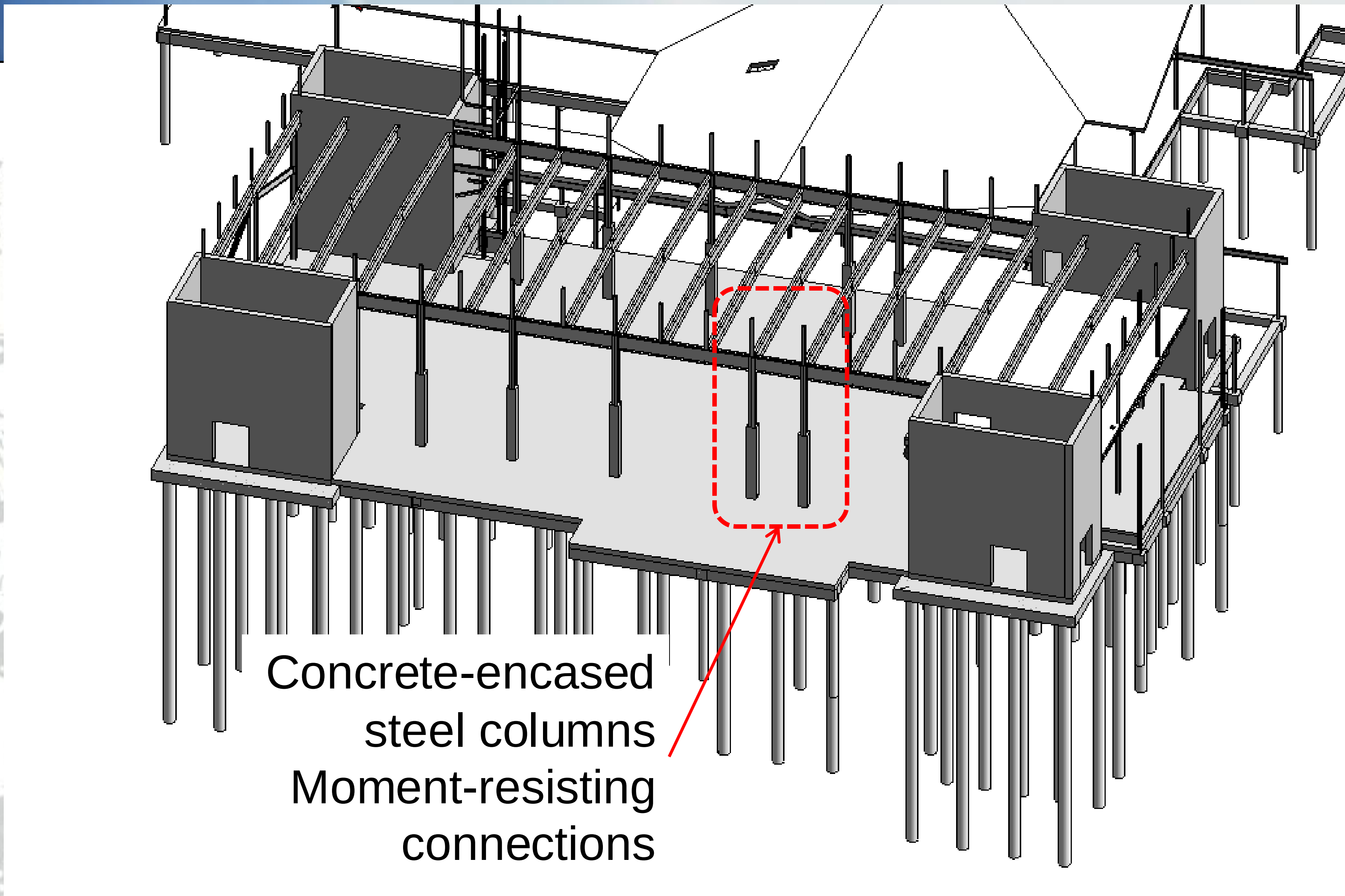
Foundation Design



Structural Lateral System



Structural Gravity System



OSU Hatfield Marine Science Center, Newport, Oregon, USA

Conclusions

- With natural hazards, history does not repeat itself
- Probabilistic Tsunami Hazard Analysis is the basis for the development of 2500-yr Tsunami Design Zone maps.
- The ASCE 7 provisions constitute a comprehensive method for reliable tsunami structural resilience, making tsunamis a required consideration for design of structures in the five western states.
- 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.
- FEMA P-646 provides planning guidance for communities developing Vertical Evacuation Refuges for Tsunamis (VERTs)

Thank-You