UNESCO Intergovernmental Oceanographic Commission

UNESCO-IOC / NOAA ITIC Training Program in Hawaii (ITP-TEWS Hawaii)
TSUNAMI EARLY WARNING SYSTEMS
AND THE PACIFIC TSUNAMI WARNING CENTER (PTWC) ENHANCED PRODUCTS
TSUNAMI EVACUATION PLANNING AND UNESCO IOC TSUNAMI READY PROGRAMME
15-26 September 2025, Honolulu, Hawaii

Vertical Evacuation Structures

ASCE 7 Tsunami Loads and Effects

Ian N. Robertson, Ph.D., S.E.
University of Hawaiʻi at Mānoa (Emeritus Professor)

Pacific Community
Communauté du Pacifique

Outline

- Need for Vertical Evacuation Refuges for Tsunamis (VERT)
- Performance of Vertical Evacuation Refuges during Tohoku Tsunami
- FEMA P-646 design guidelines
- ASCE-7 Tsunami Loads and Effects chapter
- Vertical Evacuation Refuge structures in the U.S.
- Conclusions

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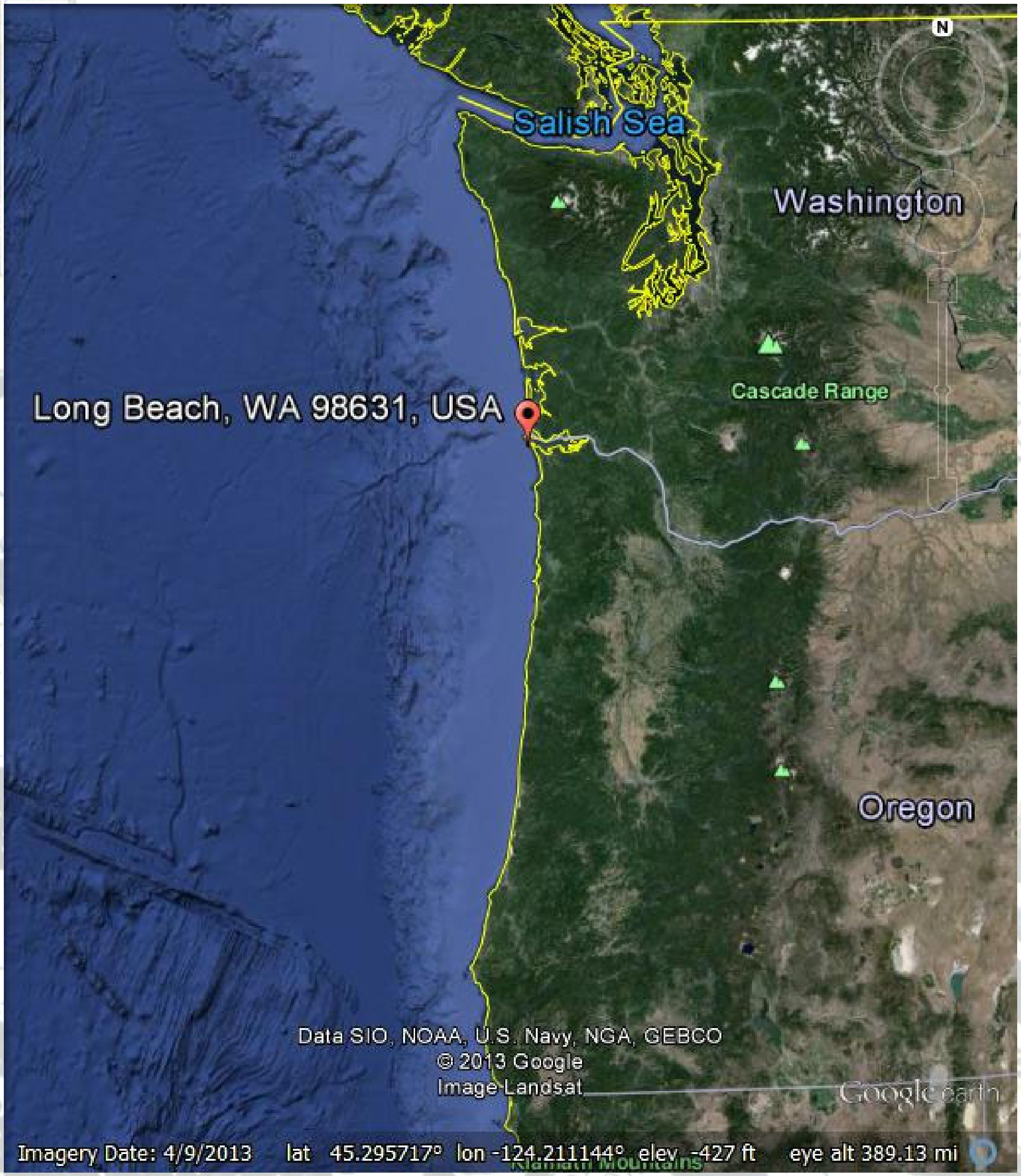
US West Coast Population exposure to tsunami hazard

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 Peninsula Simulation

Harry Yeh, OSU, Tim Fiez and Jonathan Karon, Gartrell Group



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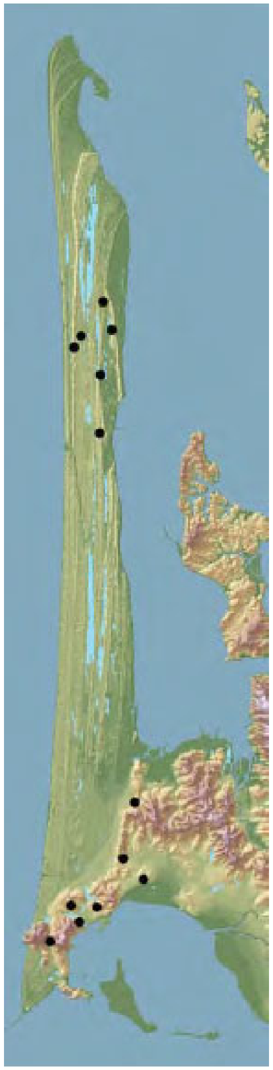
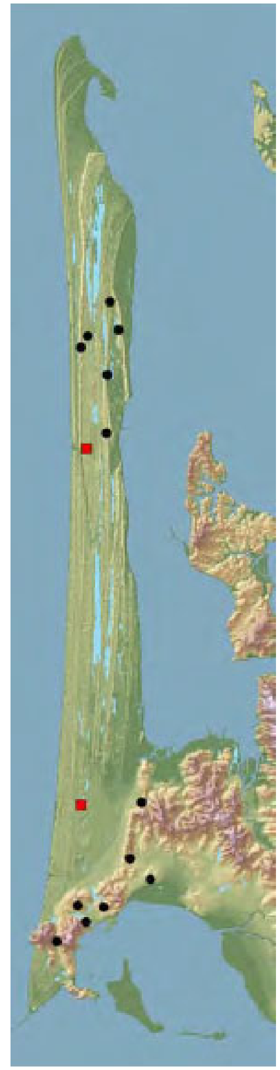


Present Condition

High Ground Only

Scenario 1

One Refuge



Scenario 2

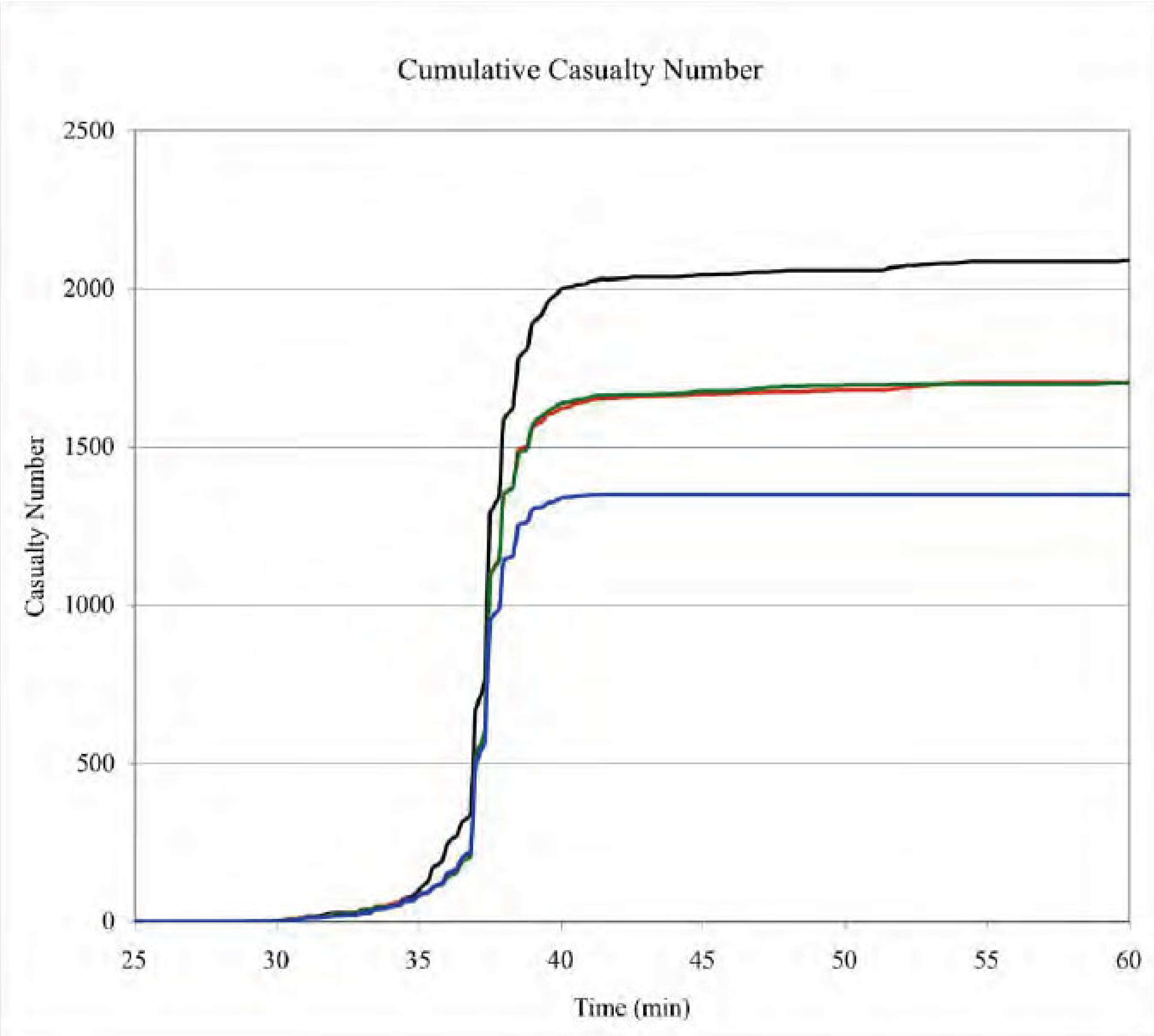
Two Refuges

Scenario 3

Four Refuges

Long Beach Peninsula Simulation

Harry Yeh, OSU, Tim Fiez and Jonathan Karon, Gartrell Group



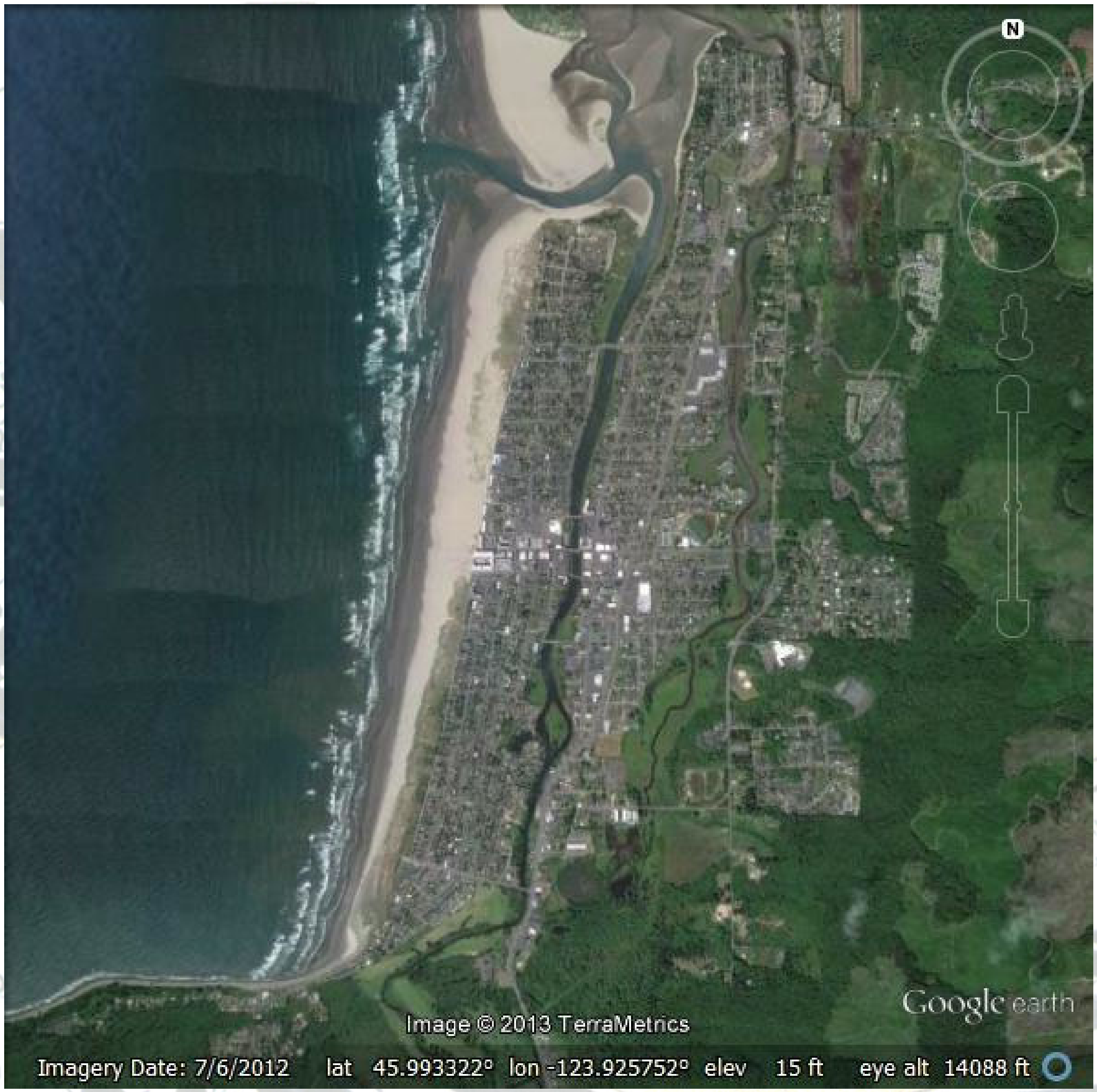
Casualties out of 9097 population

Present Condition - 2077

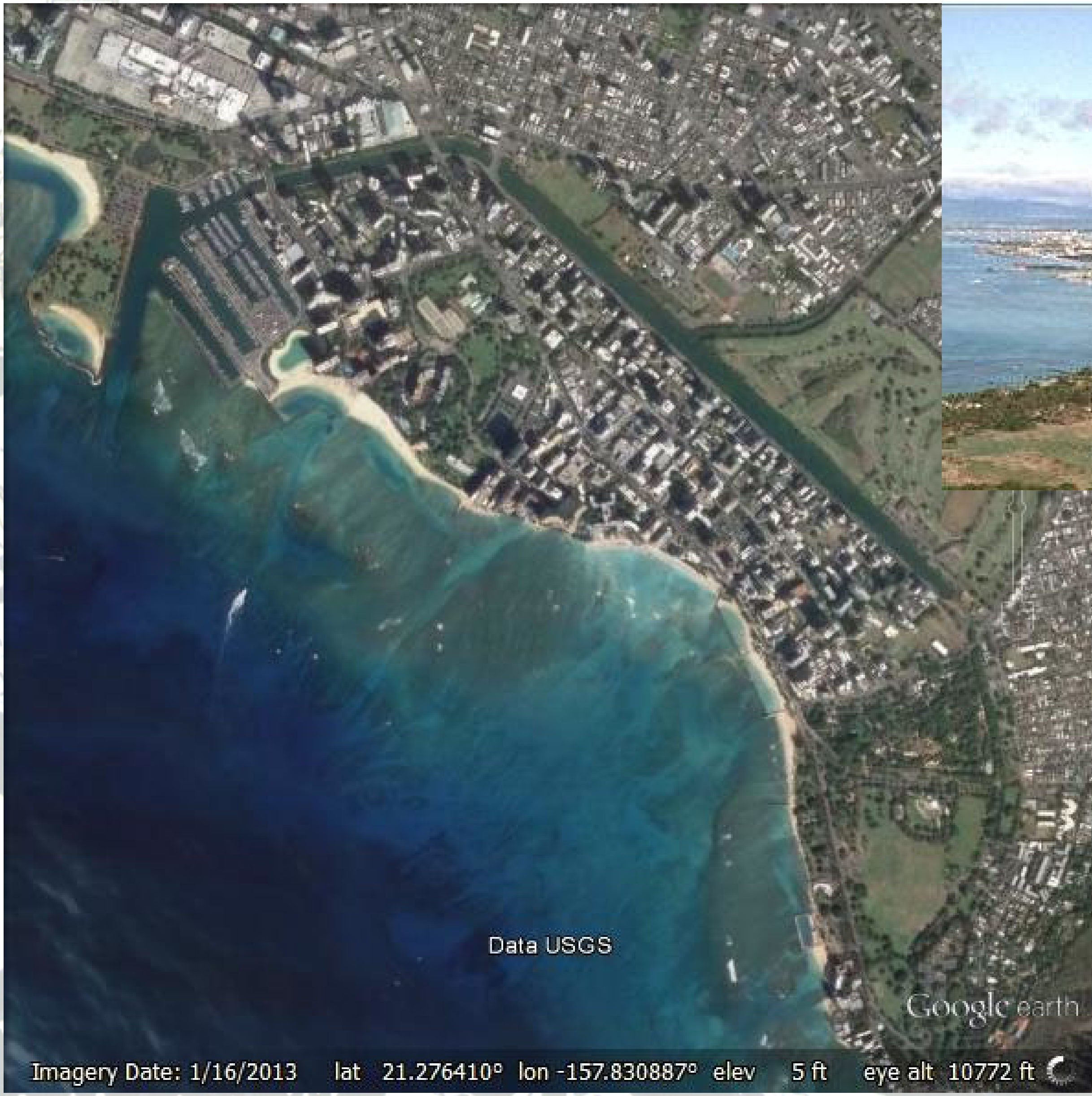
One refuge – 1711
Two refuges – 1717

Four refuges – 1351

Seaside, Oregon



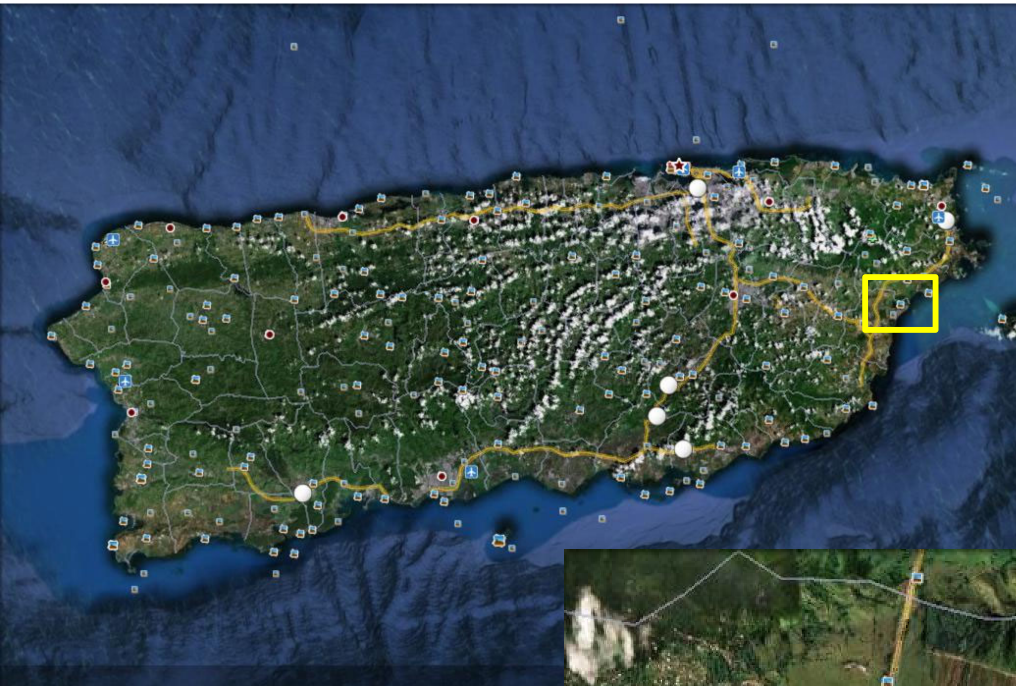
Waikiki, Hawaii

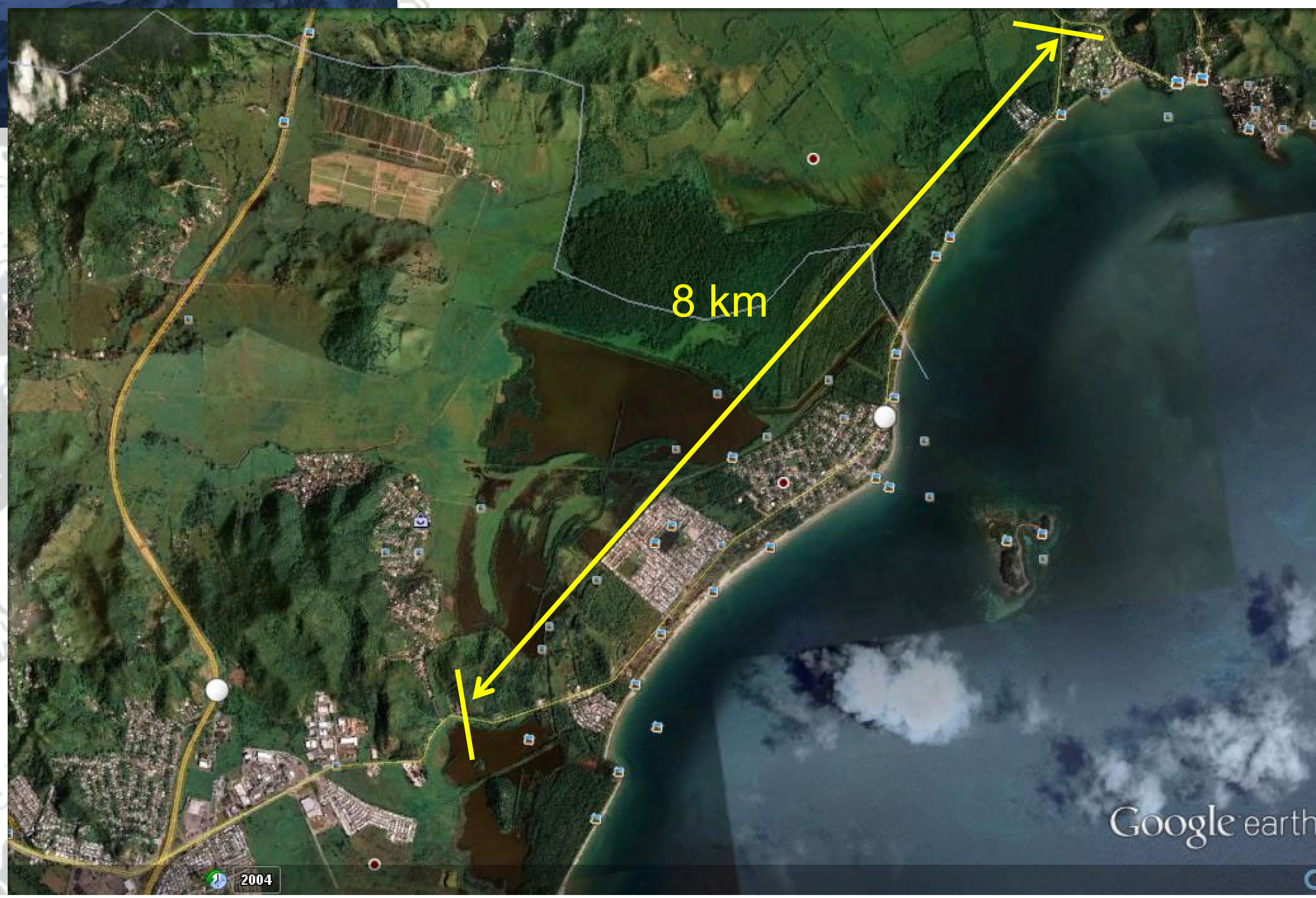


Current Evacuation Guidance

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

Punta Santiago, Puerto Rico





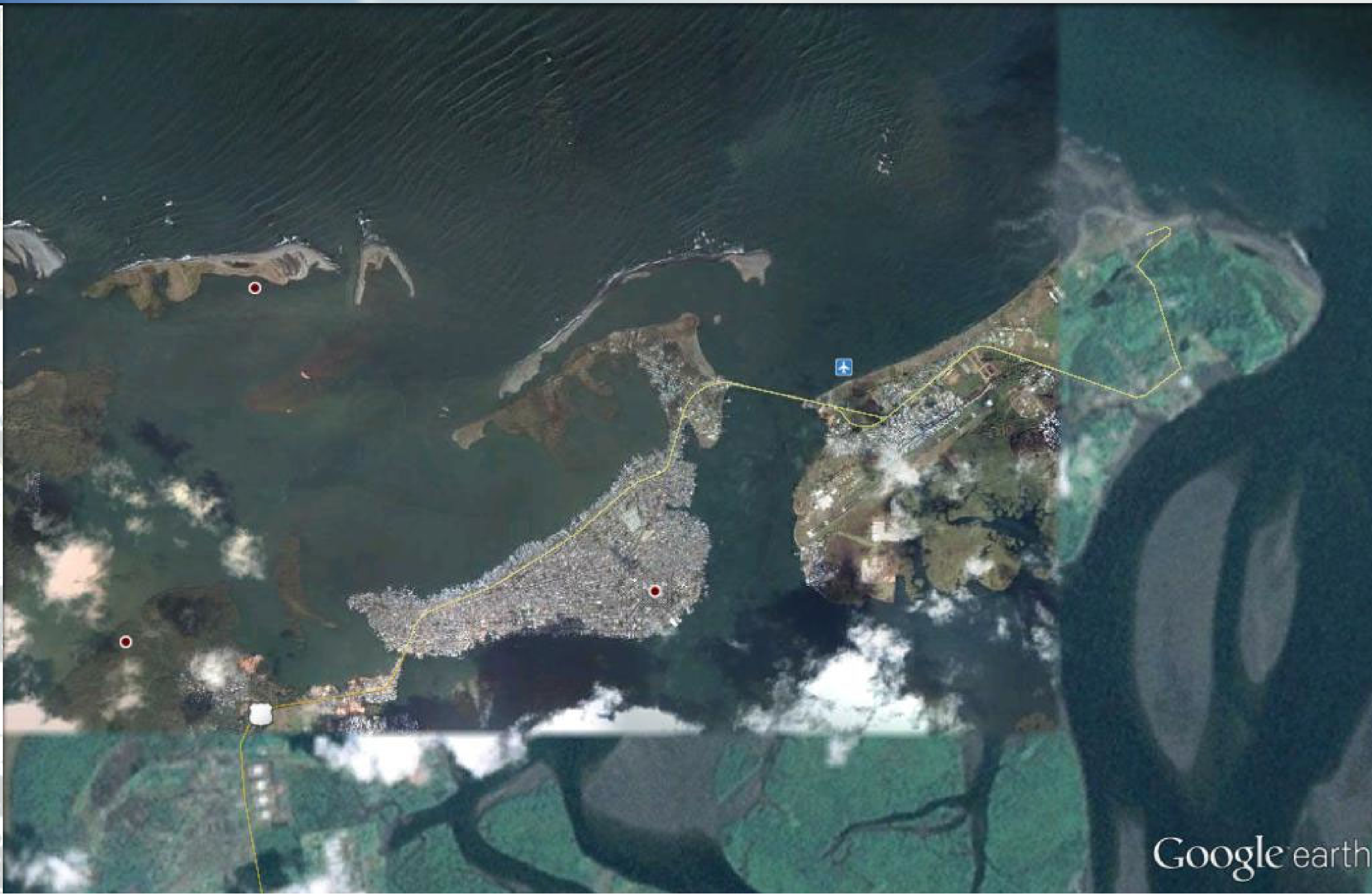
Punta Santiago, Puerto Rico

- Consider multi-story school addition with roof refuge
- Other structures for other neighborhoods

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

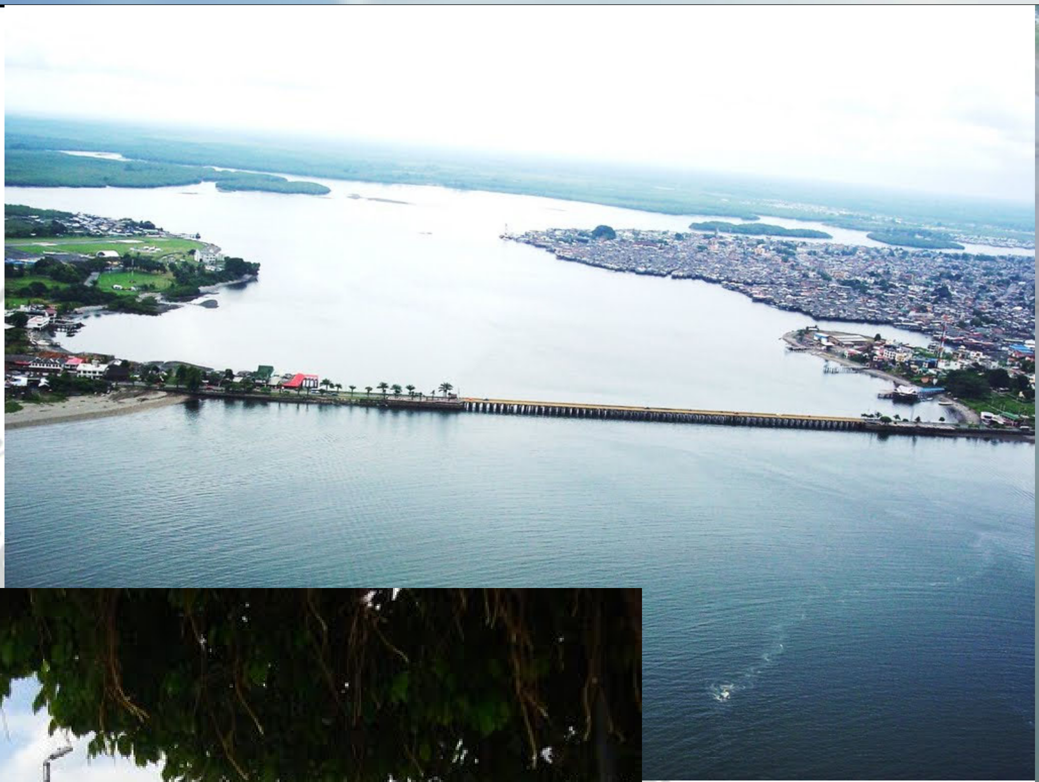
Tumaco – population 205,000



Tumaco – population 160,000

Tumaco Evacuation

Bridge to and from Airport



Causeway to and from Airport

Tumaco Evacuation

Tumaco – Typical Structures

Tumaco – Potential Vertical Evacuation Refuges from Tsunamis

Evacuation sign and taller buildings

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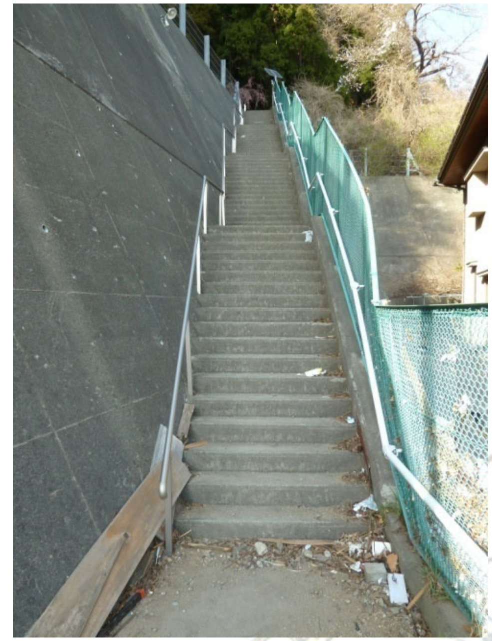
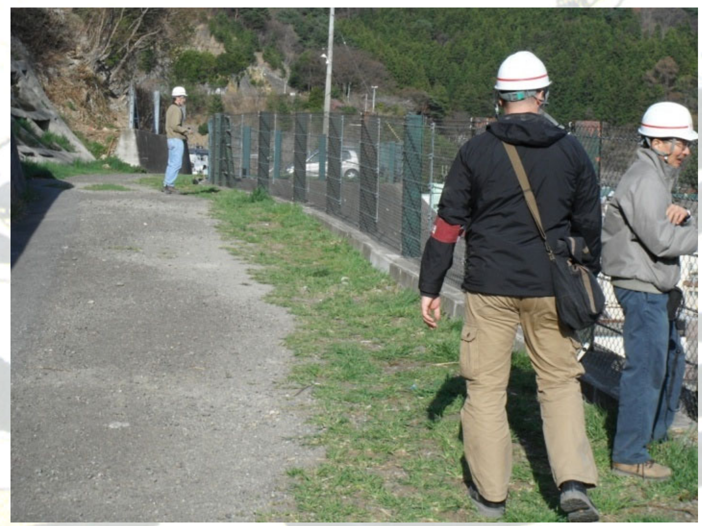
Evacuation to high ground Kamaishi Example

Evacuation to high ground
Kamaishi Example



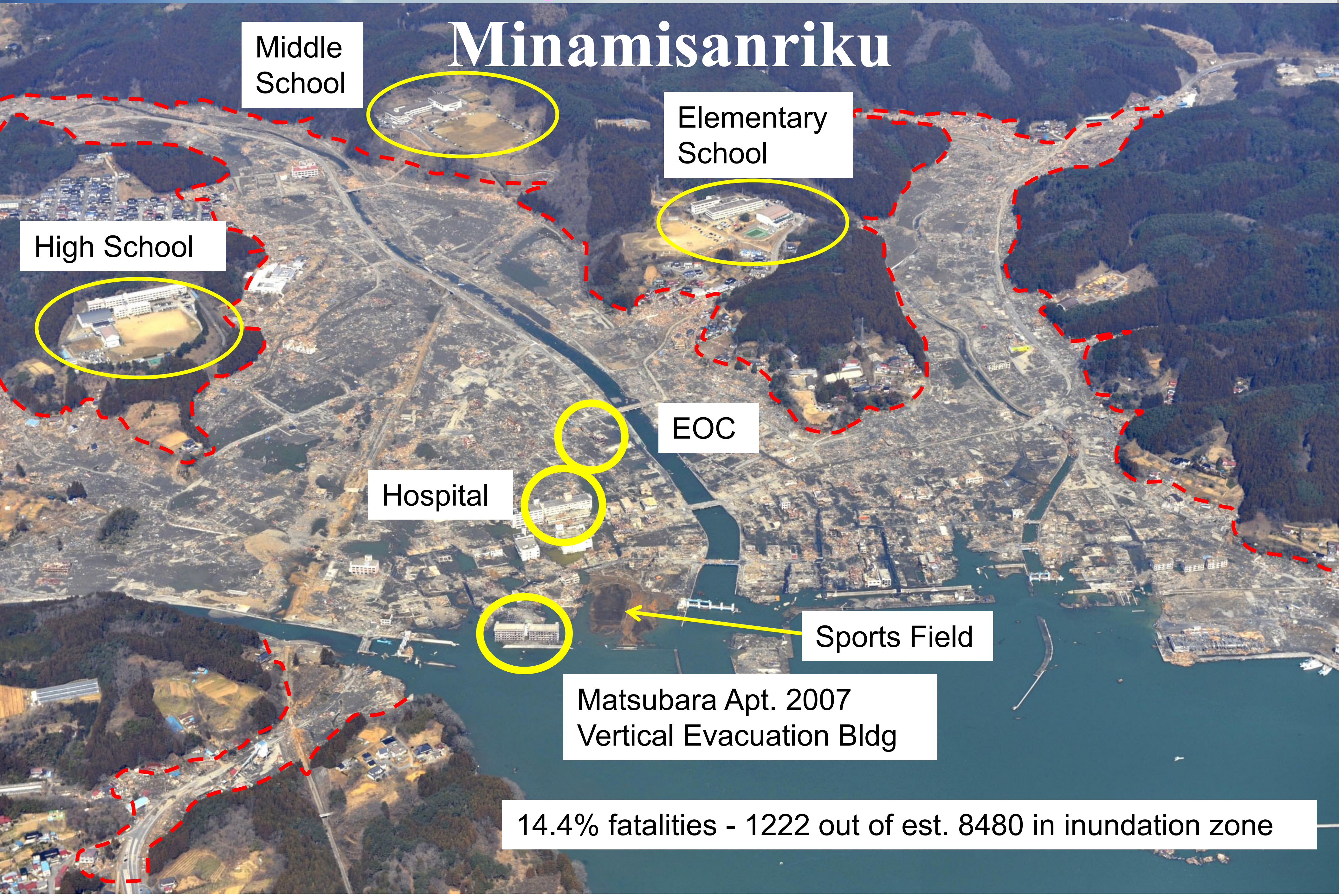


Use of Designated Tsunami Evacuation Buildings

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**

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

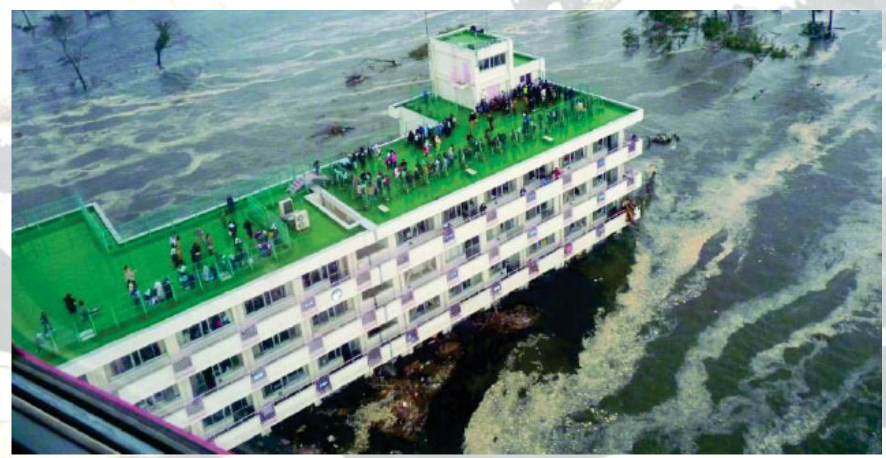
- Hospital was occupied during the tsunami (320 survived)
- Some patients were moved to evacuation zone on roof
- Three stories of patient drowning fatalities (71 dead)

Minamisanriku Fisheries Cooperative

- Designated evacuation site, though only 2 floors
- Overtopped by tsunami
- Unknown number of lives lost

Arahama Elementary School, Sendai

- **Reinforced concrete building with roof designated as tsunami refuge was flooded to the 2nd story.**
- **Over 300 scholars and teachers found refuge in the upper floors and on the roof.**



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.**

Report on Performance of Evacuation Structures in Japan

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

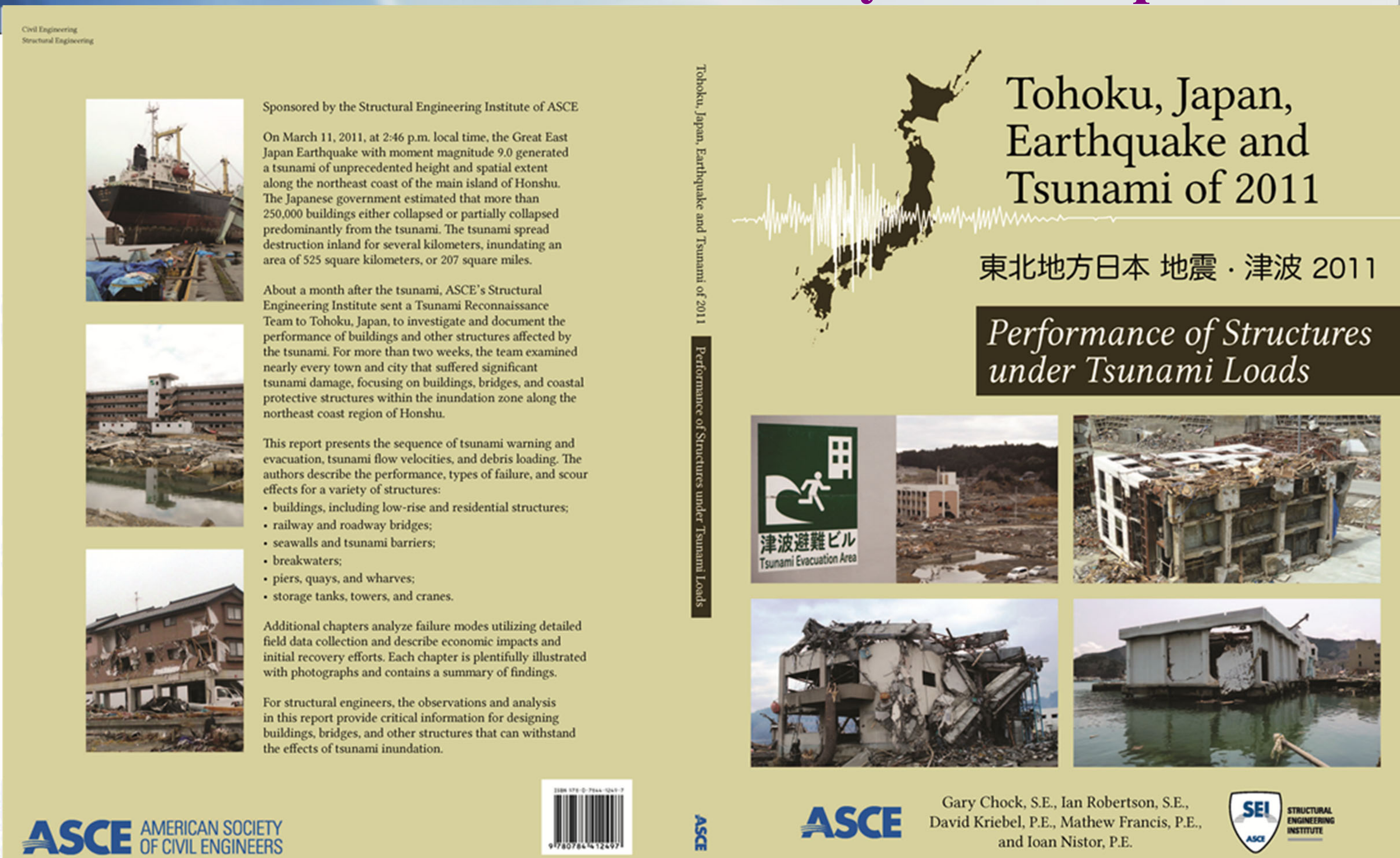
Tsunami evacuation: Lessons from the Great East Japan earthquake and tsunami of March 11th 2011

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

GNS Science Report 2012/17
April 2012

Tohoku Tsunami

ASCE/SEI Tsunami Survey Final Report



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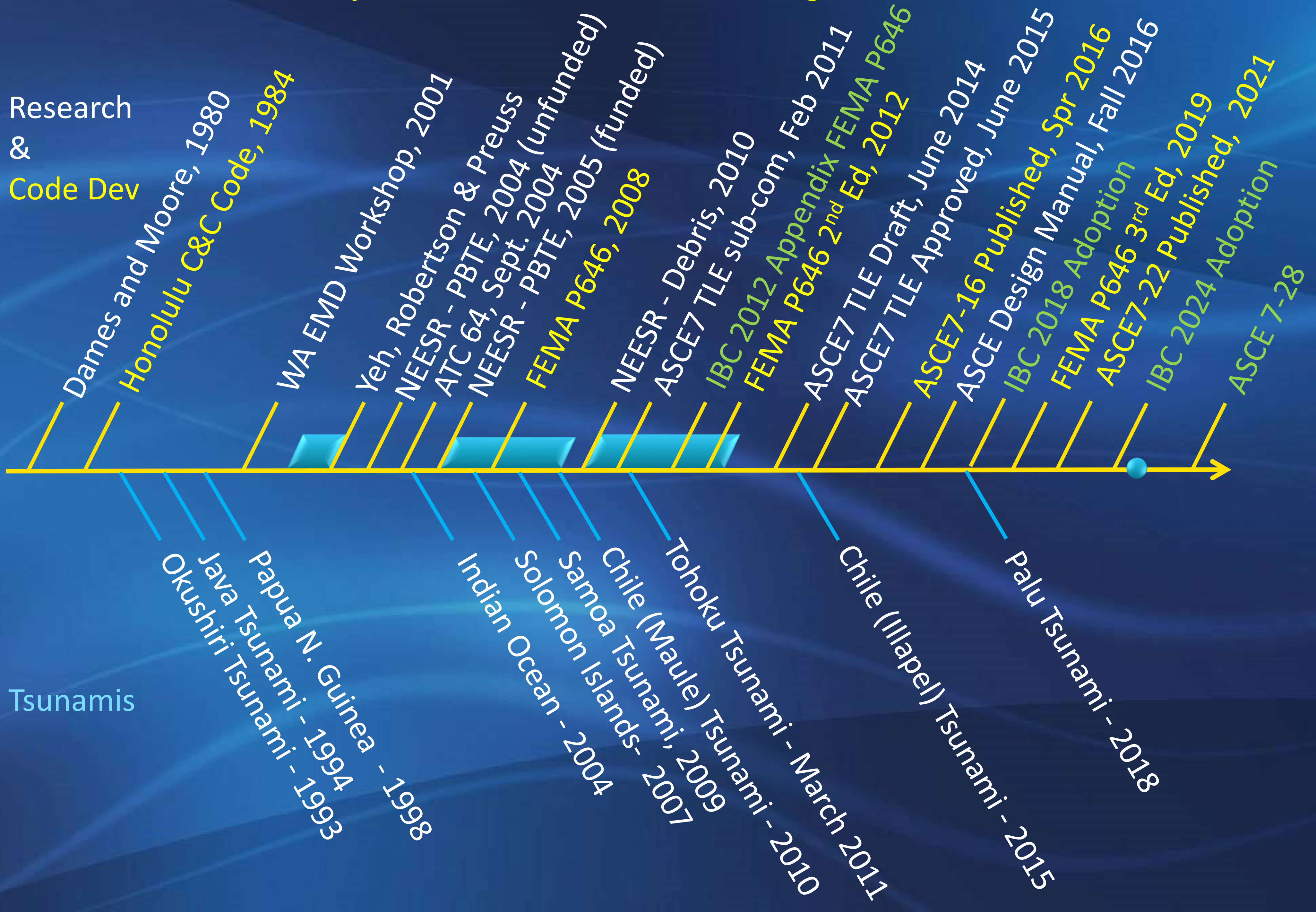
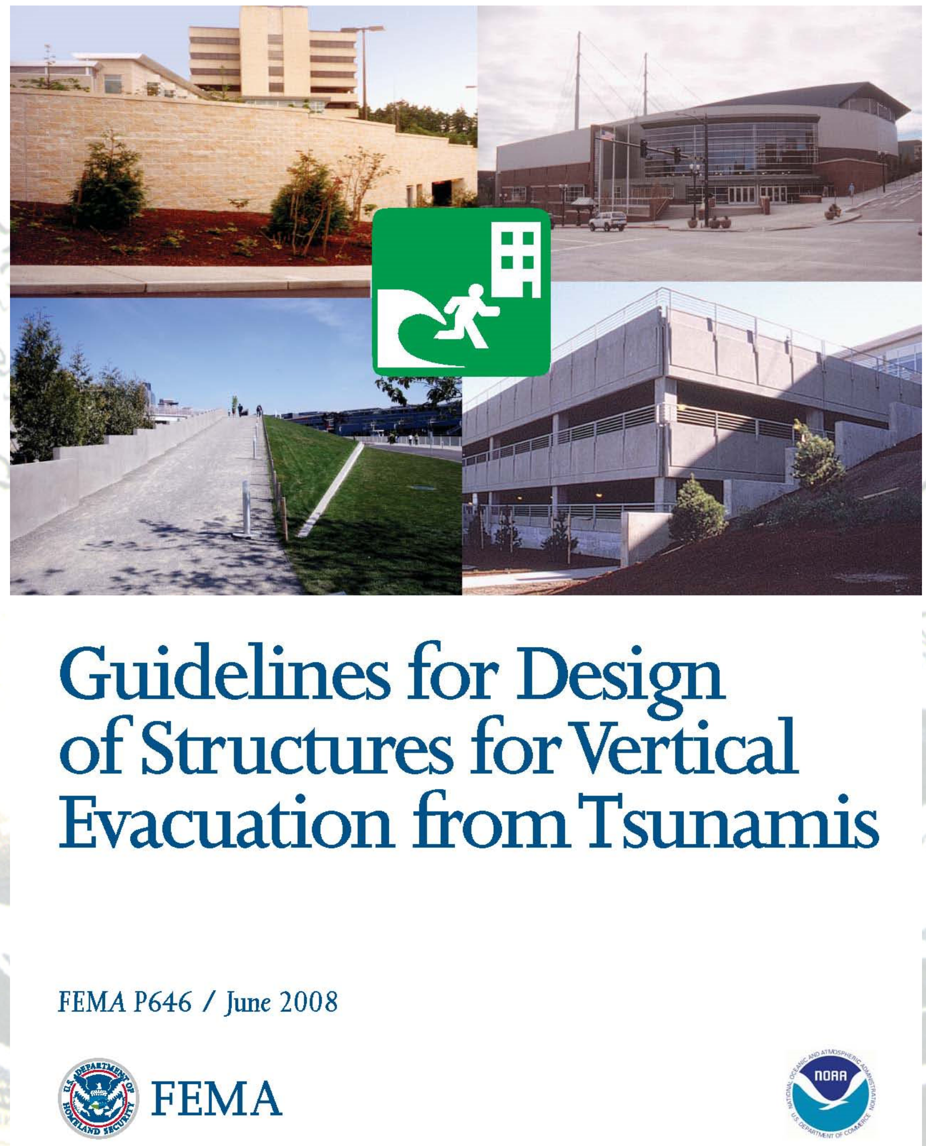
History of Tsunami Design in the US



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
- Specifically developed for vertical evacuation buildings, not general building stock
- Non-mandatory language - Guidelines

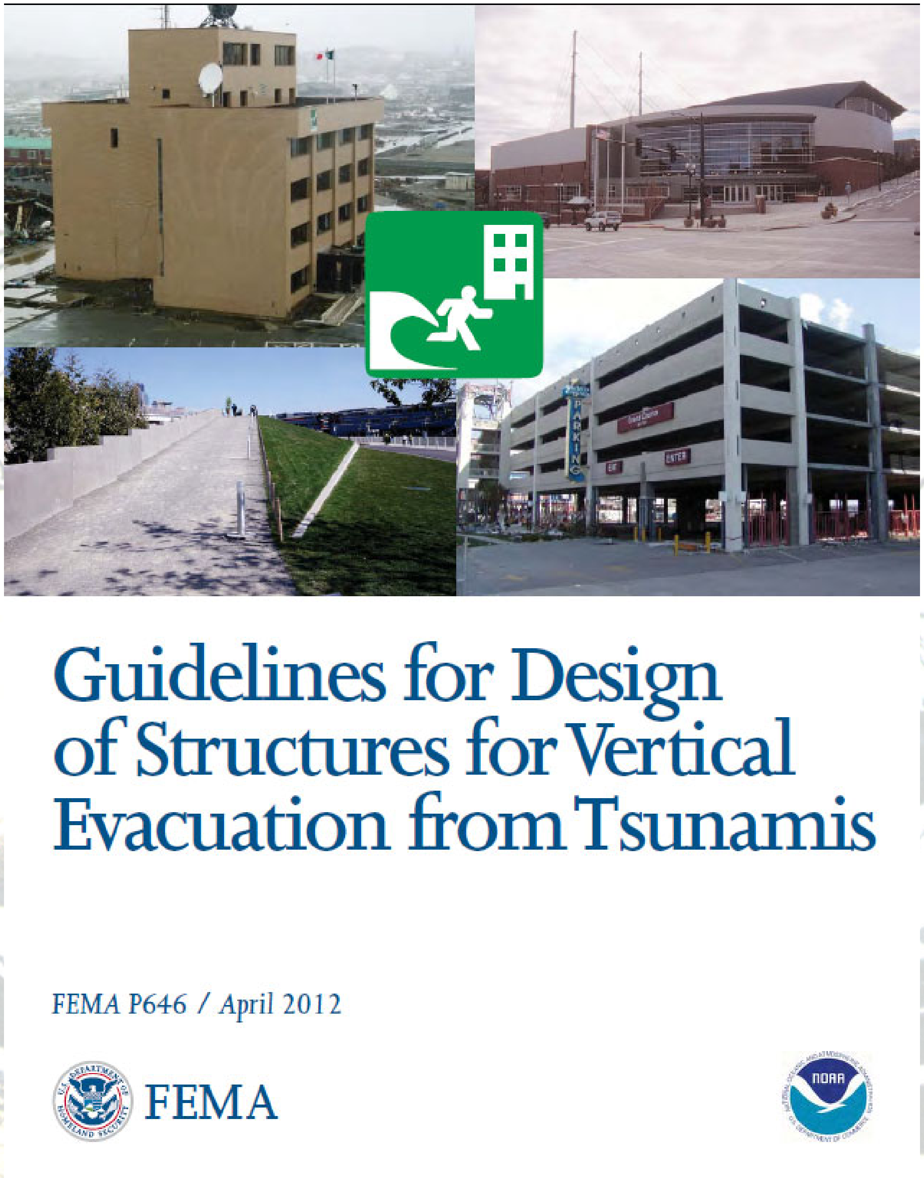

Guidelines for Design of Structures for Vertical Evacuation from Tsunamis

FEMA P646 / June 2008

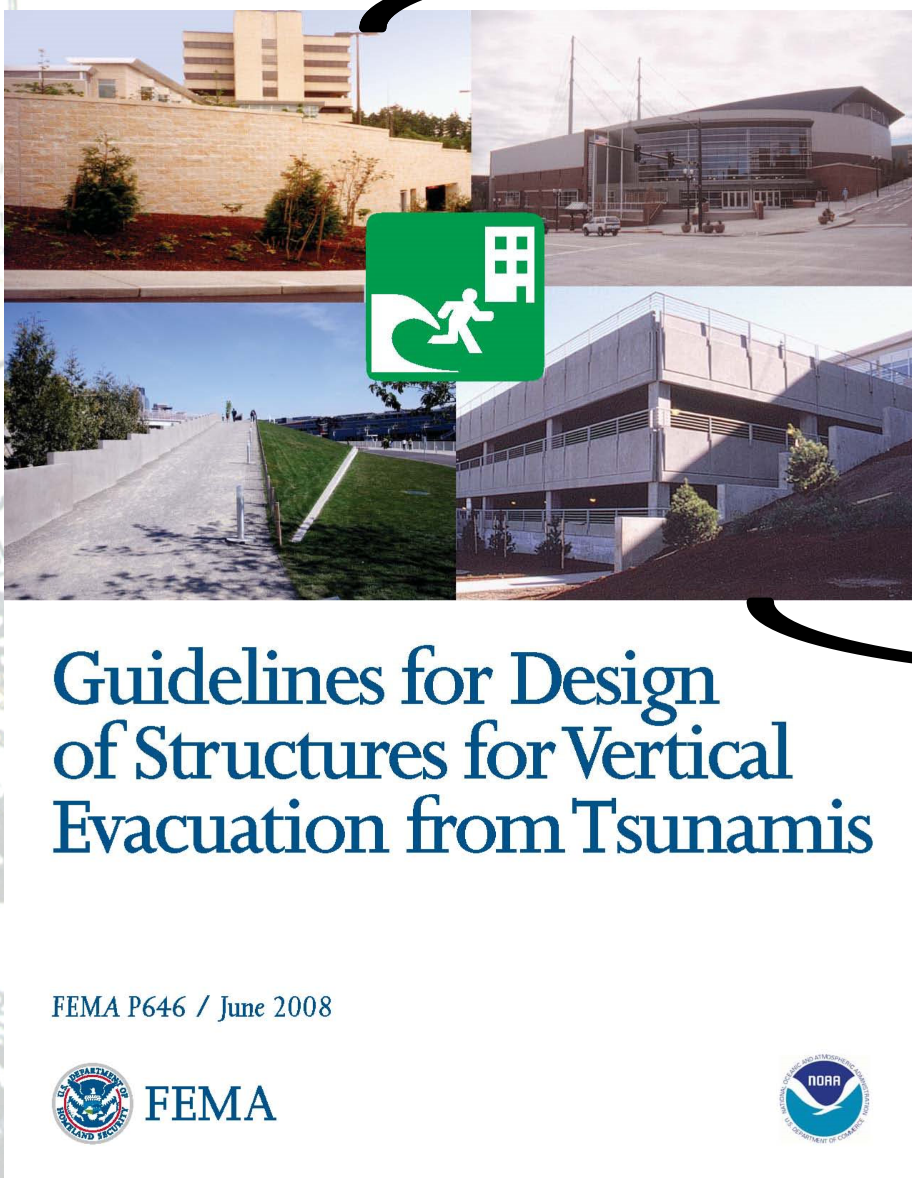
FEMA

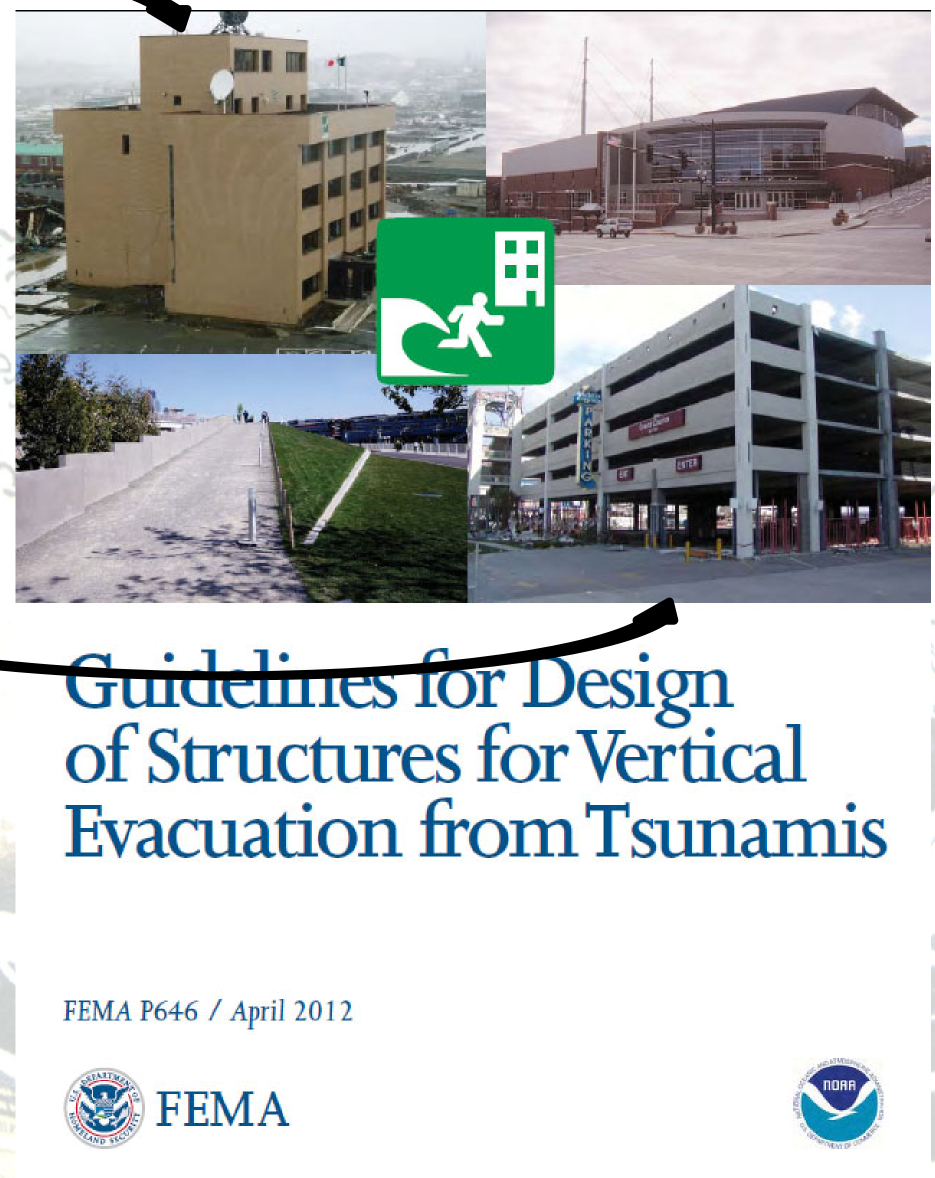
Guidelines for Design of Structures for Vertical Evacuation from Tsunamis (FEMA P646)

- **Modified as ATC-79**
- **Project Team**
  - **Ian Robertson**
  - **Timothy Walsh**
  - **Harry Yeh**
  - **John Hooper**
  - **Gary Chock**
- **Revised 2012 – Second Edition**



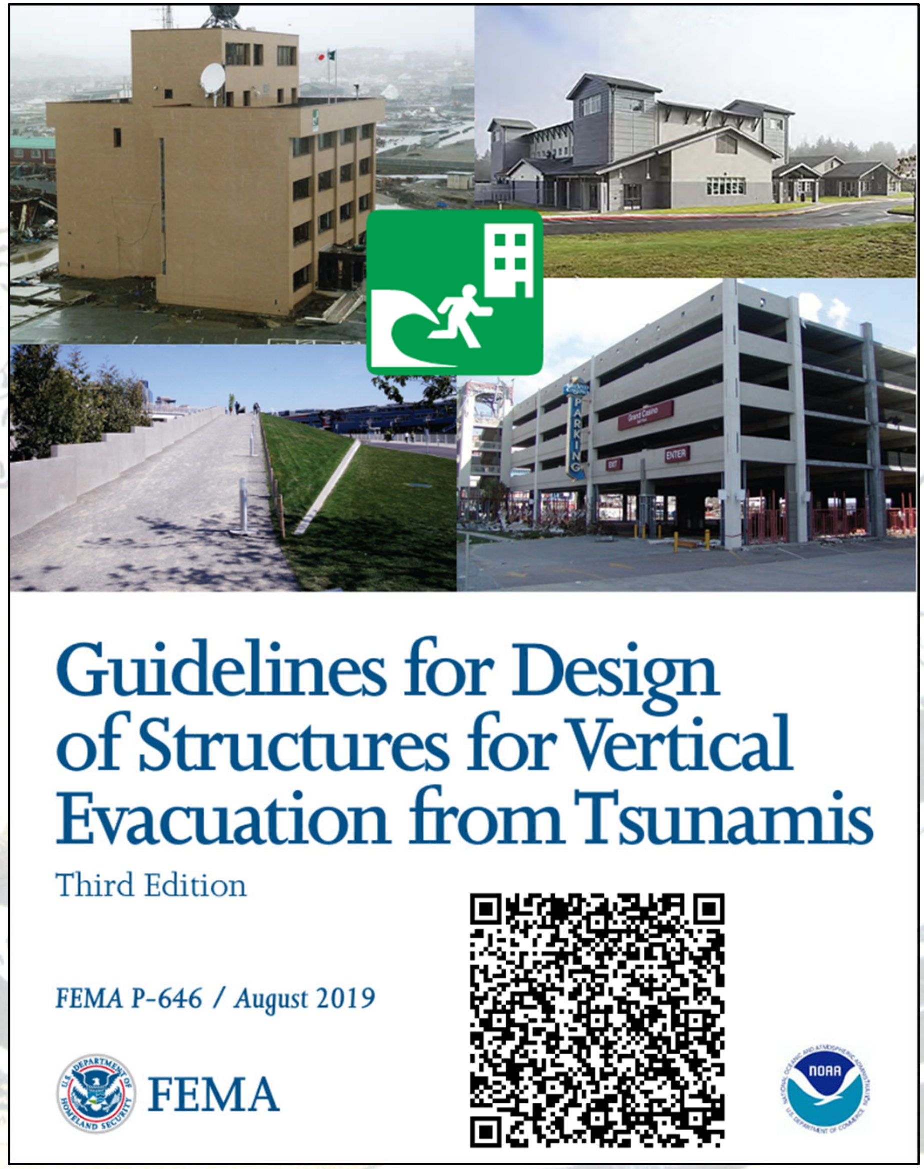
Guidelines for Design of Structures for Vertical Evacuation from Tsunamis (FEMA P646)





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

- In February 2011, ASCE authorized a new Tsunami Loads and Effects subcommittee for ASCE 7, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*.
- This subcommittee developed a new Chapter 6, *Tsunami Loads and Effects*, for ASCE 7-16.
- The loading expressions in ASCE 7 supersede the loading guidance in P-646, so a third edition of P-646 was generated and published in August 2019.



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

Kesennuma Refuge of Opportunity

Adjacent Building used as refuge of opportunity

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

Kesennuma Refuge of Opportunity

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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 - 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

Minimum Design Loads for Buildings and Other Structures

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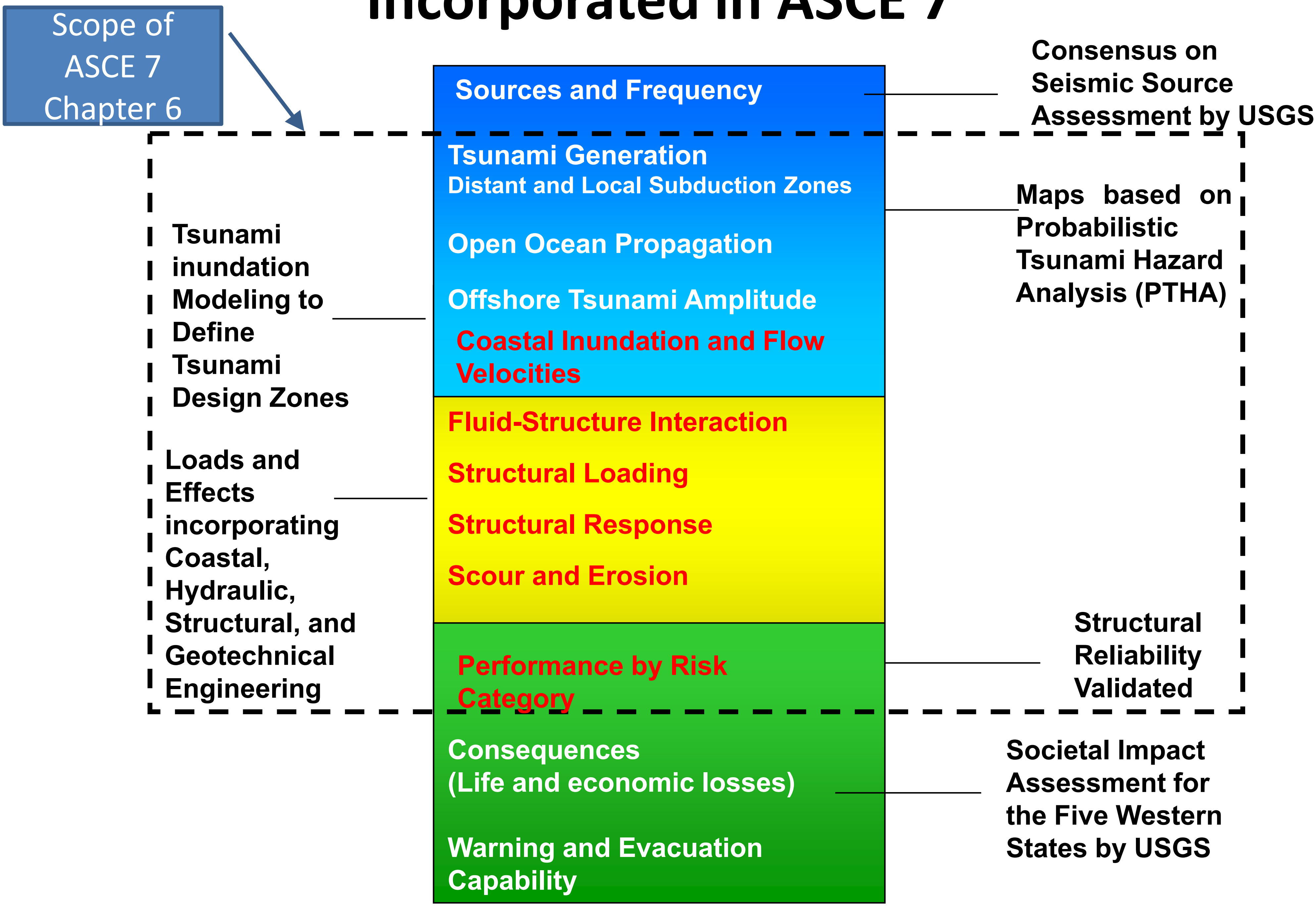
Tsunami-Resilient Engineering Subject Matter Incorporated in ASCE 7



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

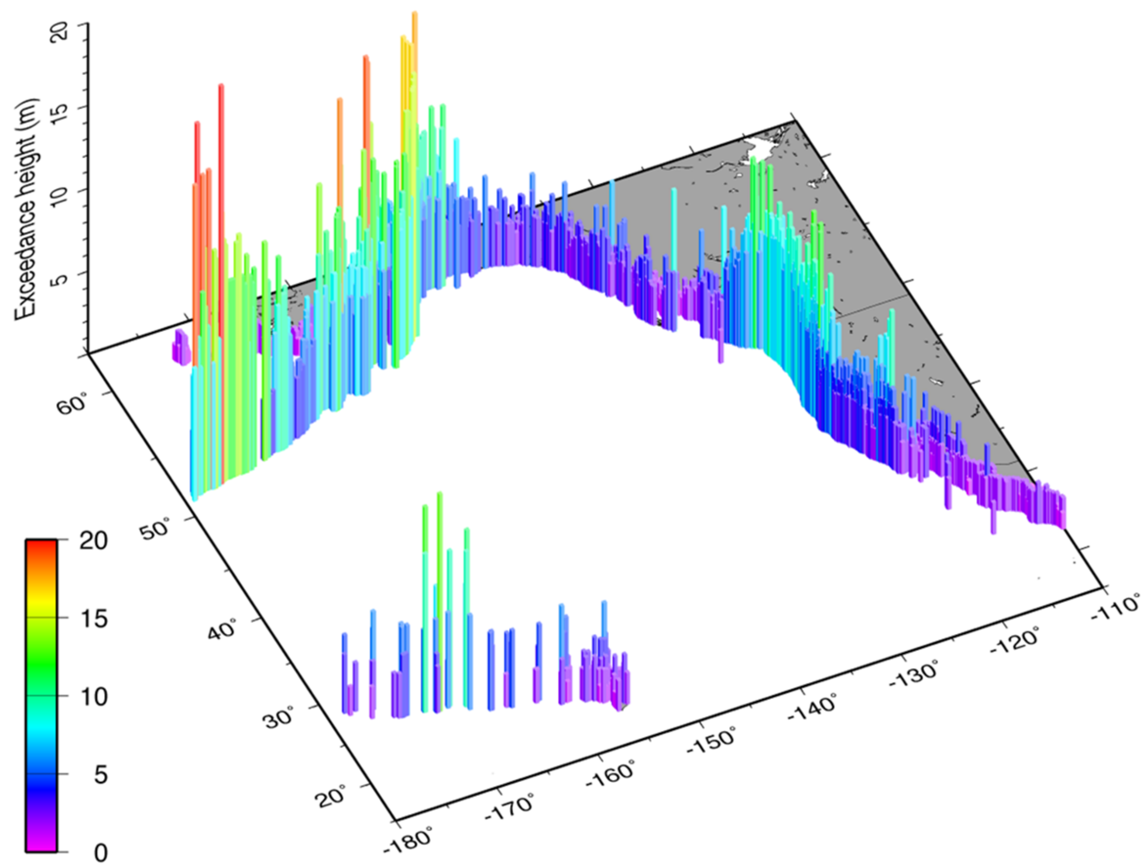
Consequence Guidance on Risk Categories of Buildings Per ASCE 7

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.)

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

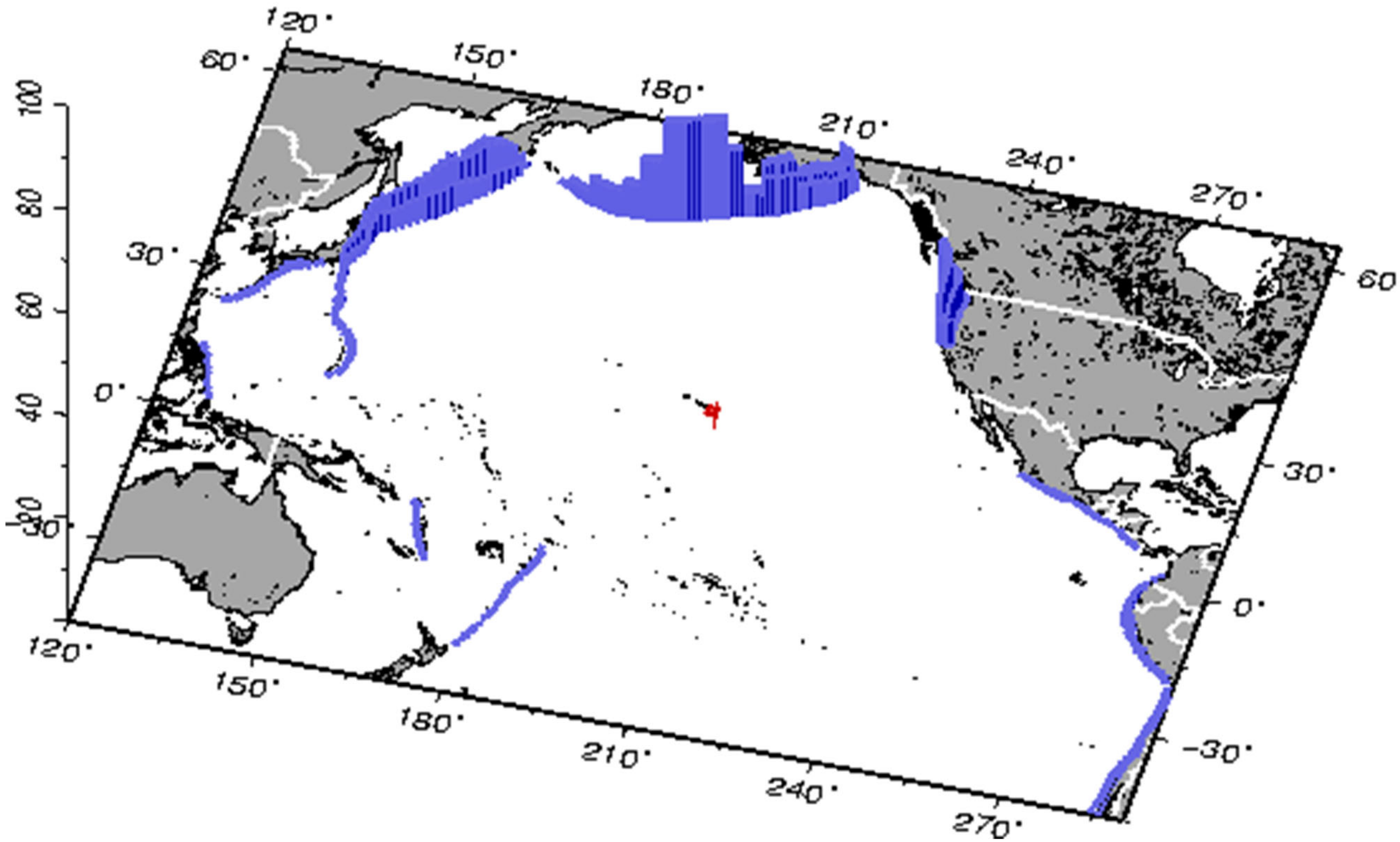
- Recorded history may not provide a sufficient measure of the potential heights of great tsunamis.
- Design must consider the occurrence of events greater than in the historical record
- Therefore, probabilistic physics-based Tsunami Hazard Analysis should be performed in addition to historical event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

Exceedance waveheights: 2500 yr

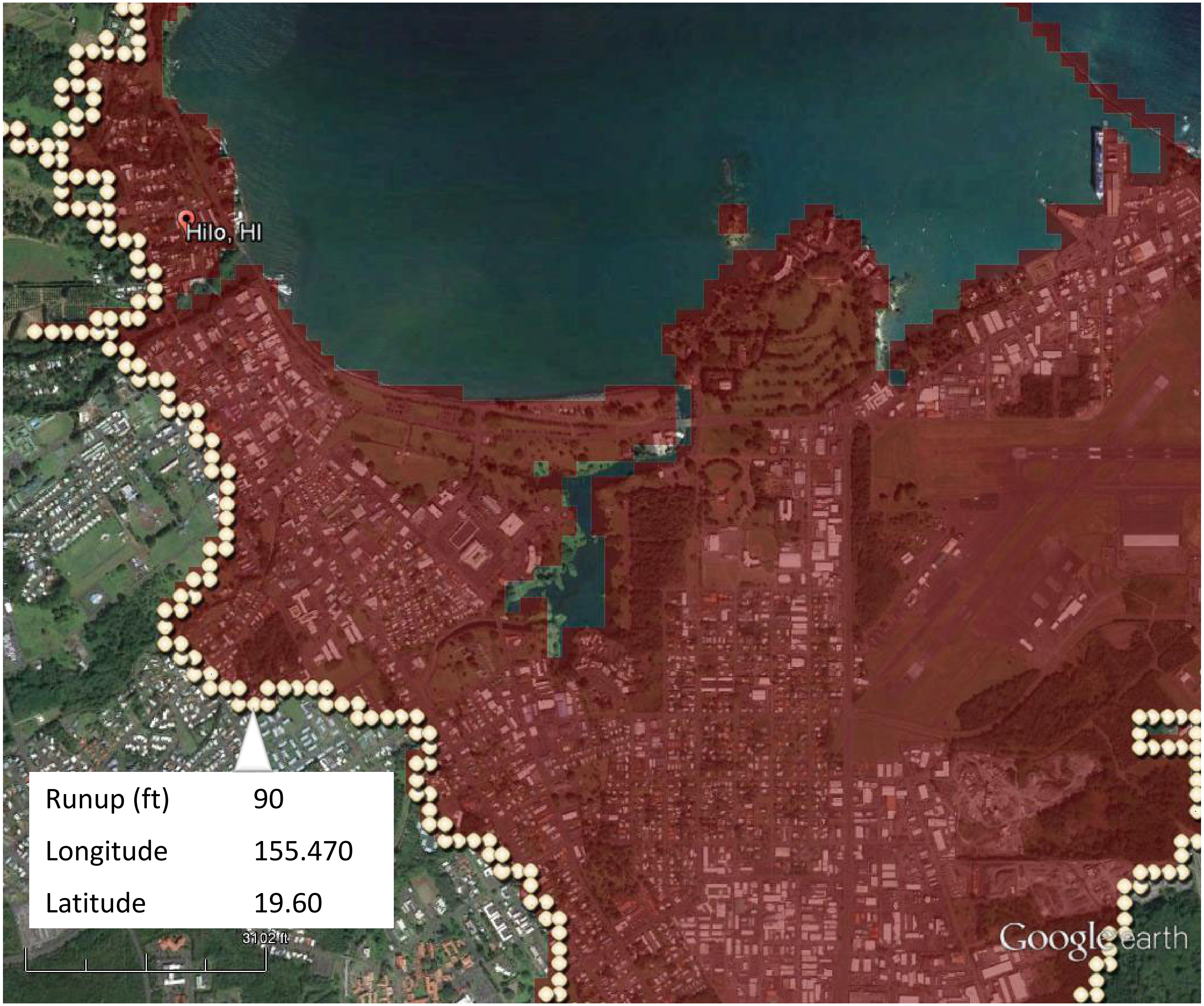


Disaggregated Hazard for Hilo, HI

- Sources: Aleutian, Alaska, and Kamchatka-Kurile



Tsunami Design Zone - Hilo



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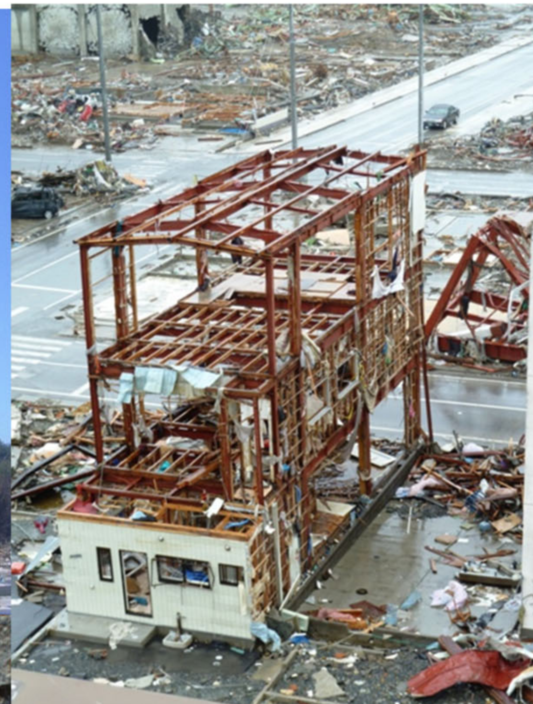
Structural Loads

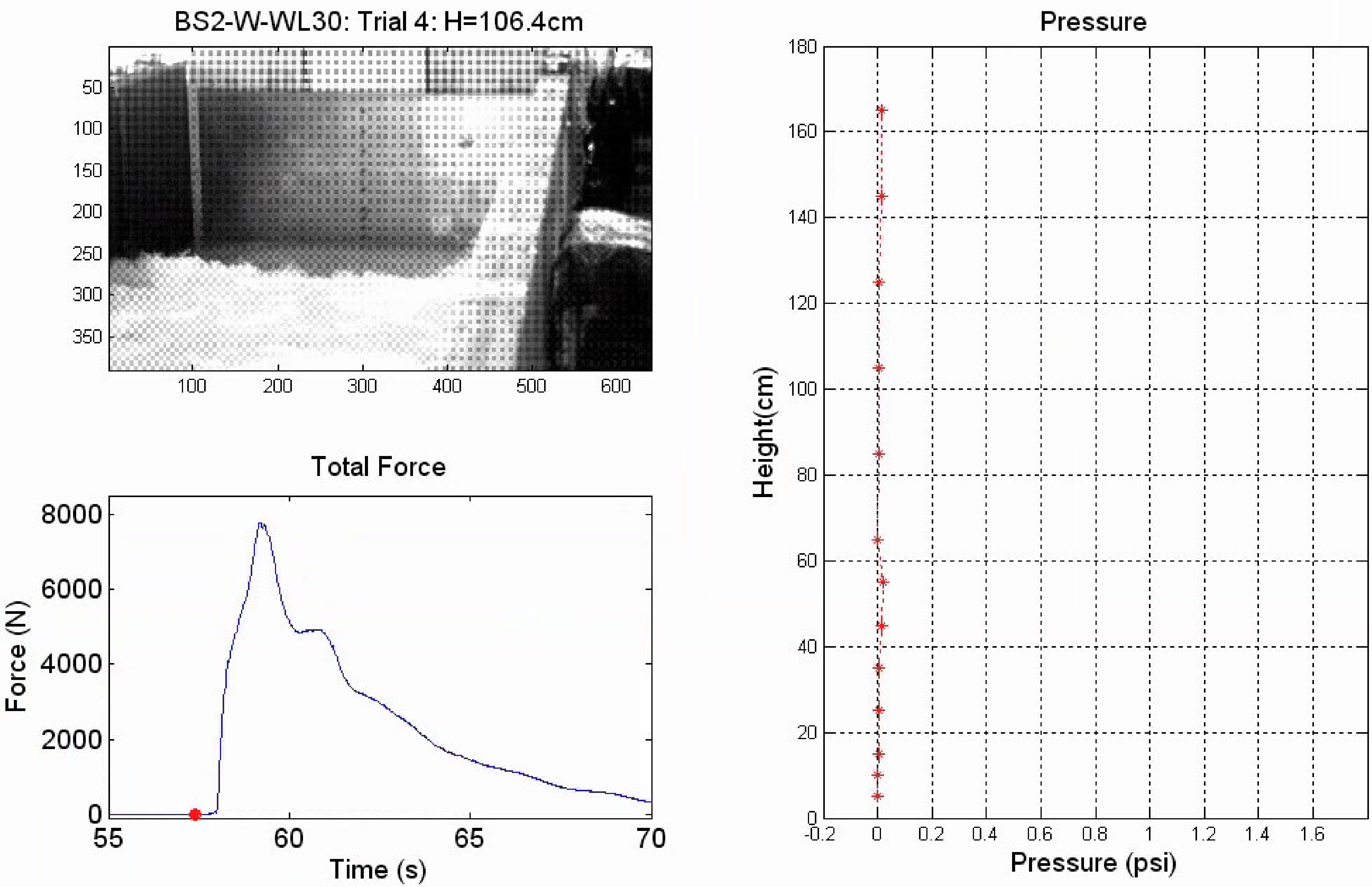


Tsunami Loads and Effects

- 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)

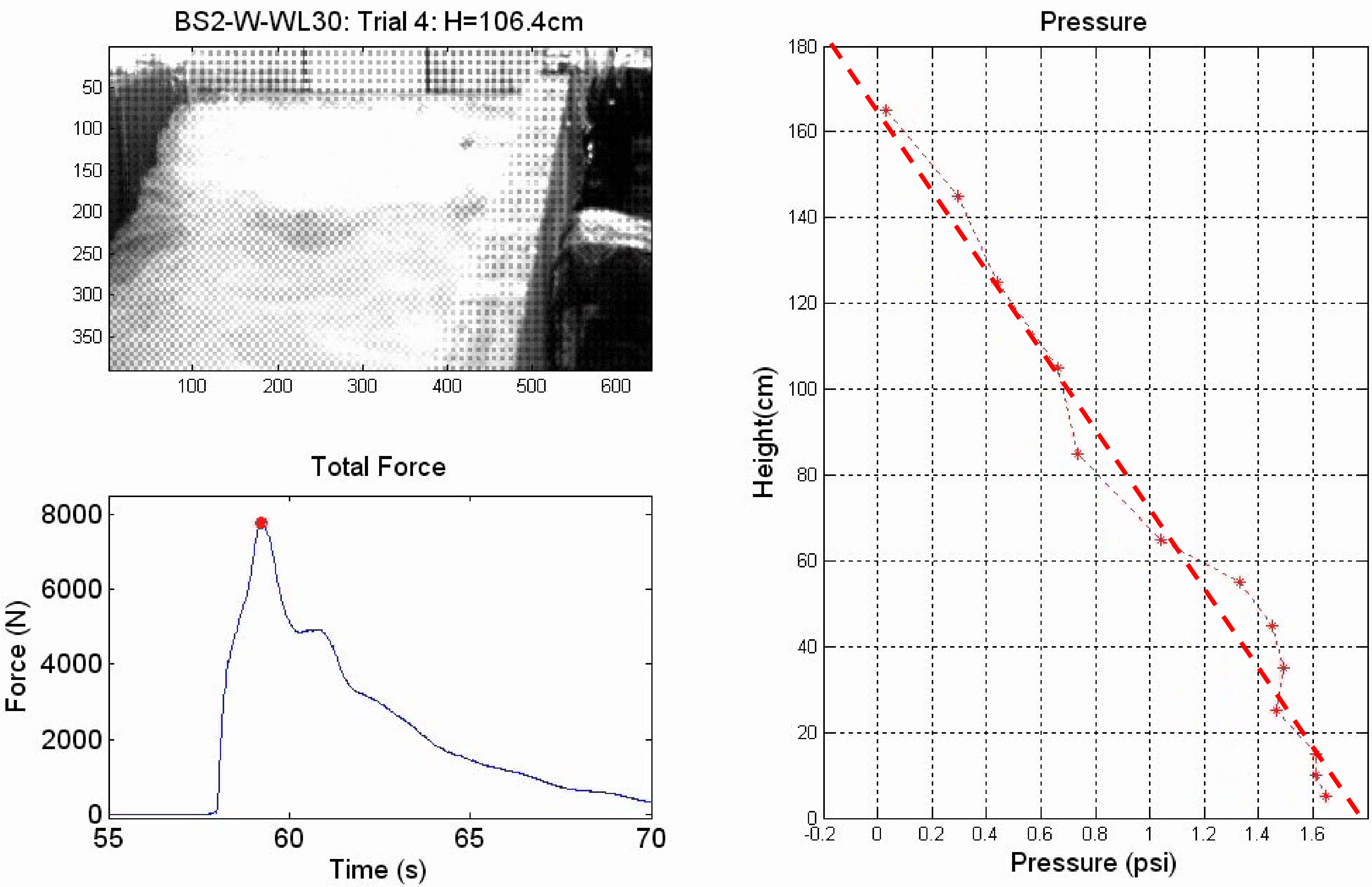
NEESR – Development of Performance Based Tsunami Engineering, PBTE

NEESR – Development of Performance Based Tsunami Engineering, PBTE



NEESR – Development of Performance Based Tsunami Engineering, PBTE

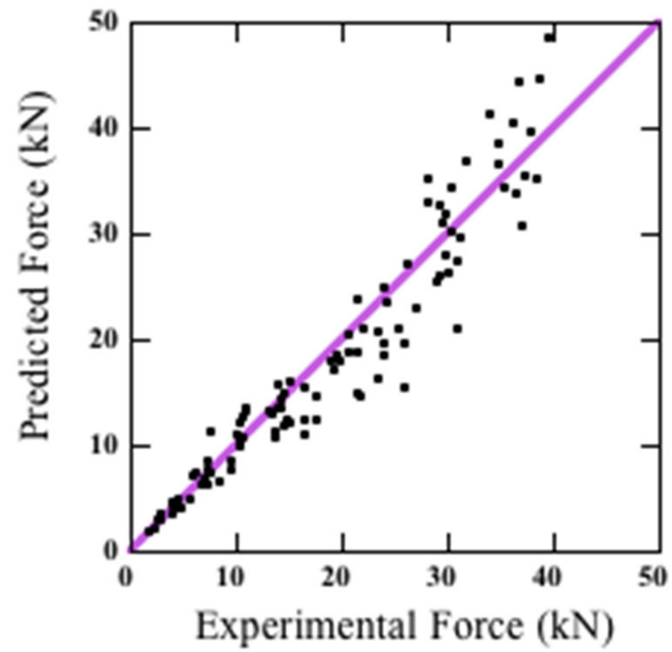
NEESR - Structural Loading
Direct Bore Impact on Solid Wall

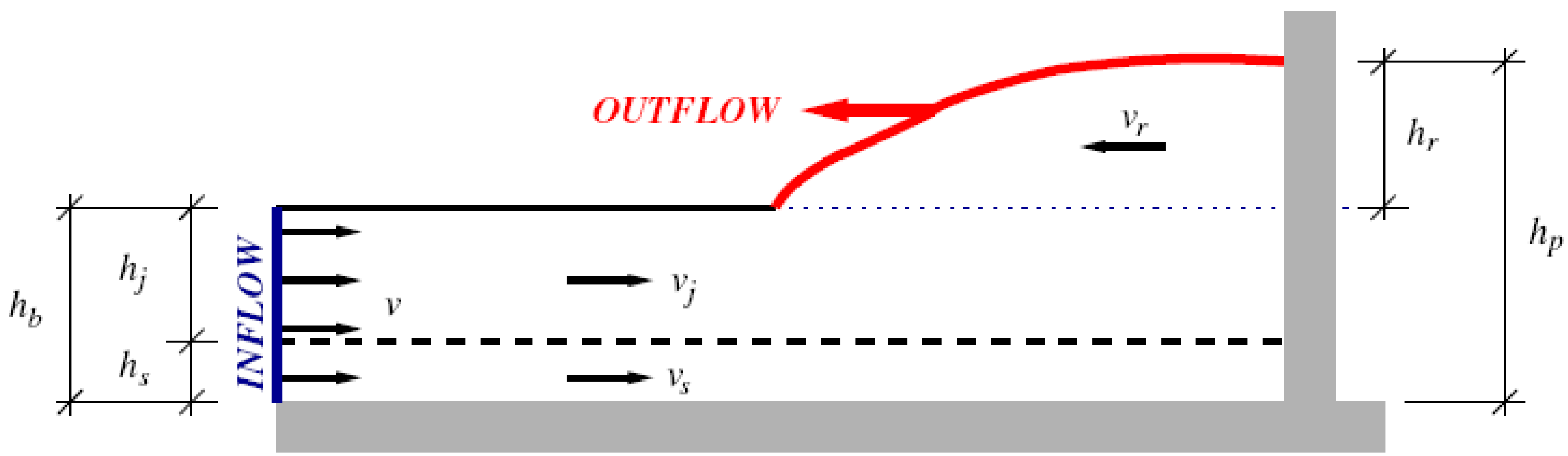


Hydrodynamic Force on Wall due to Bore Impact

- Based on conservation of mass and momentum

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





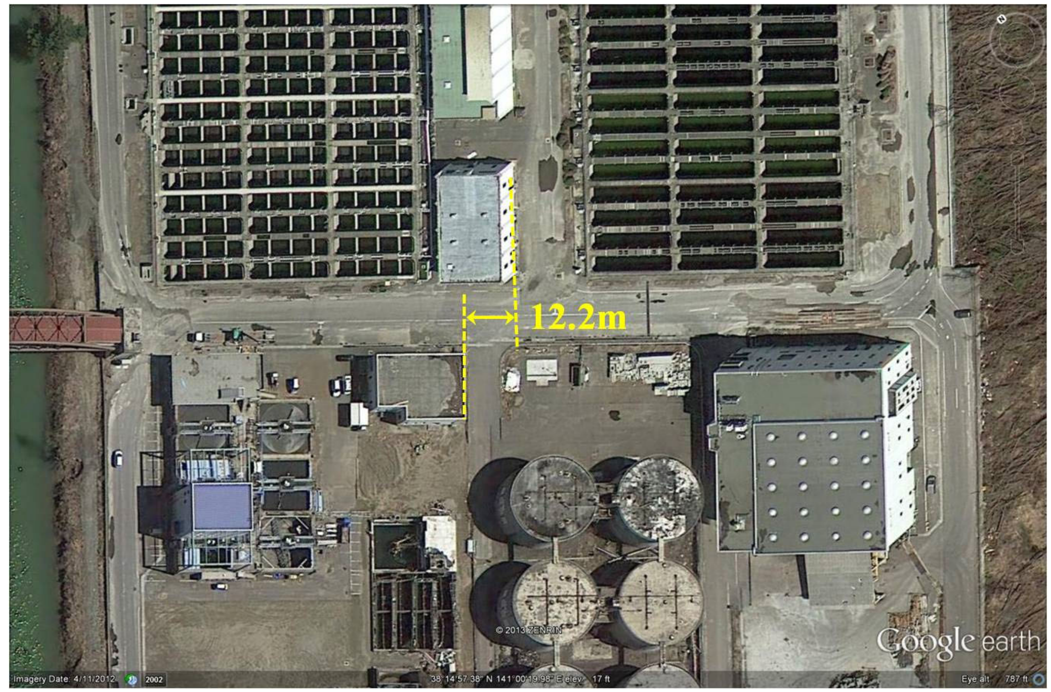
Sendai
Bore Strike on R/C Structure

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

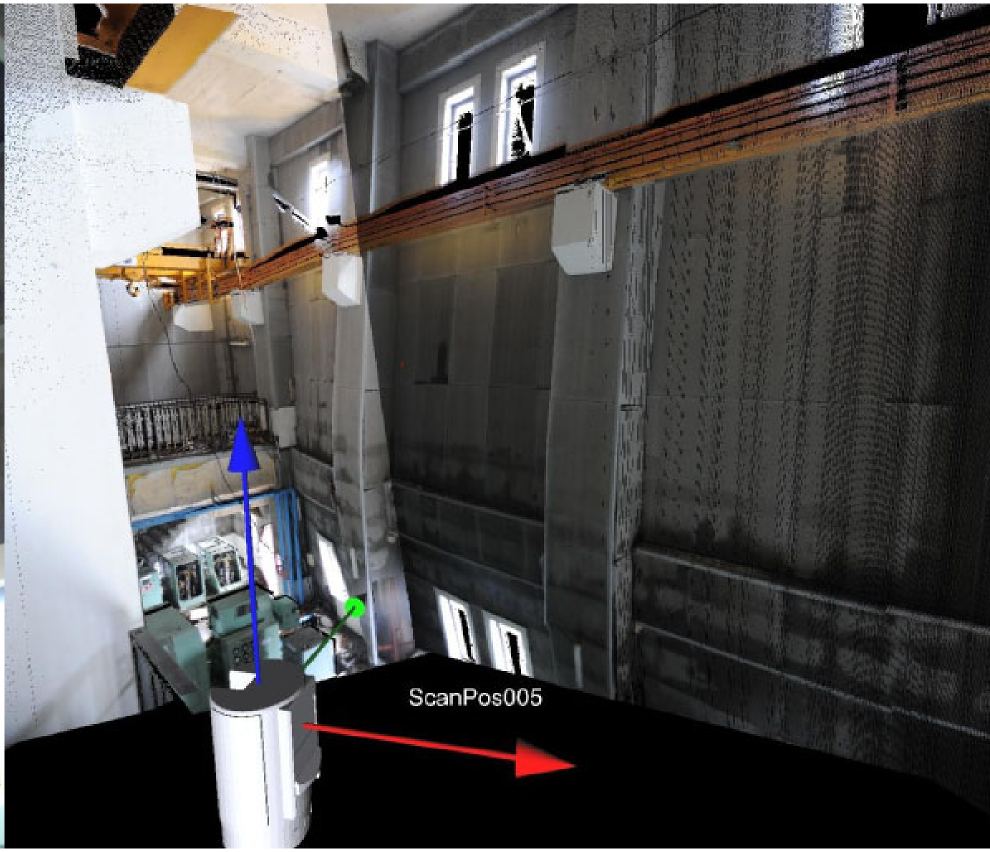
Minami Gamou Wastewater Treatment Plant - subjected to direct bore impact

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

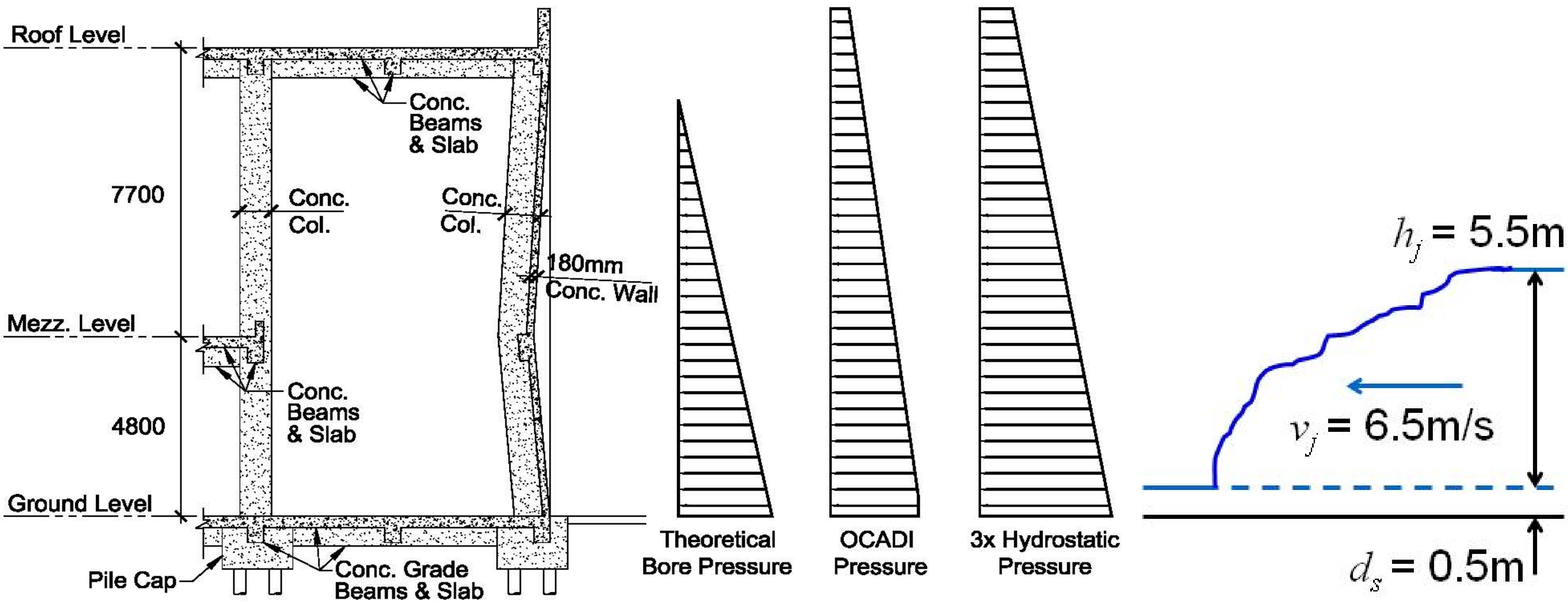


Lidar scan of 2-story wall

Minami Gamou Wastewater Treatment Plant

Bore Impact Forces
Minami Gamou Treatment Plant

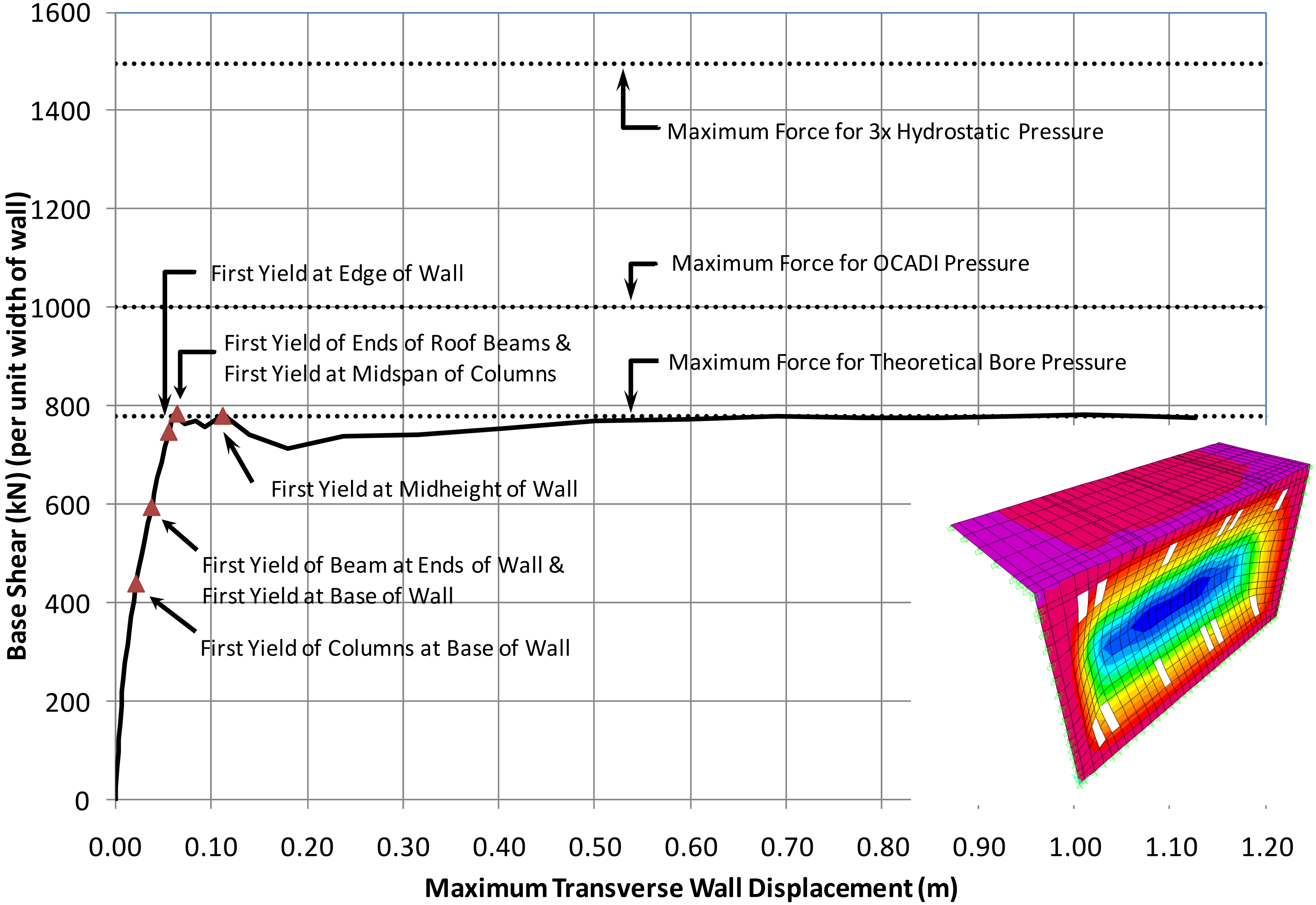
- Comparison with Different Bore Pressures used in Japan Tsunami Standards



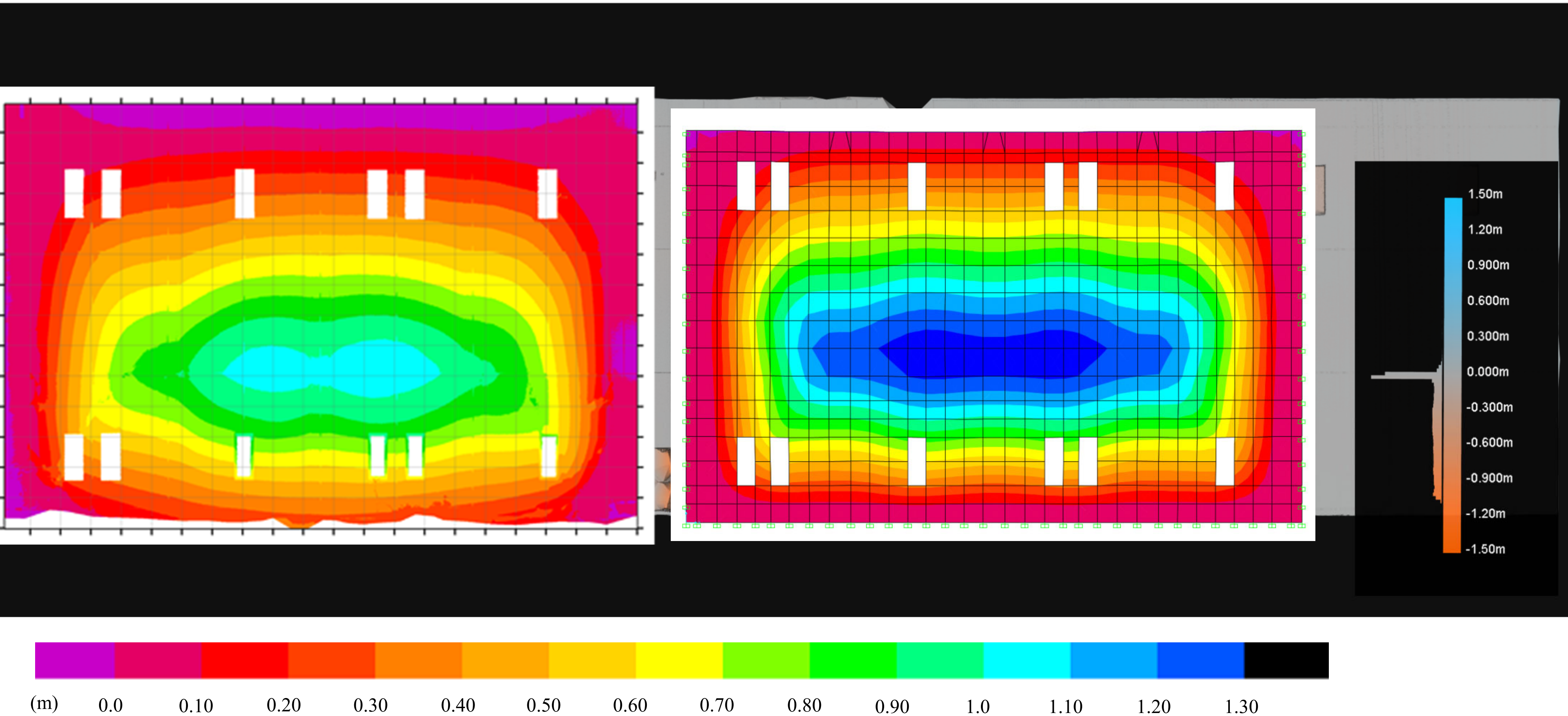
$h_b = h_j + d_s$ = 6.0m

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

Bore Impact Forces
Non-linear Finite Element Analysis



FEA compared with Lidar scan



Out of Plane deformation in meters

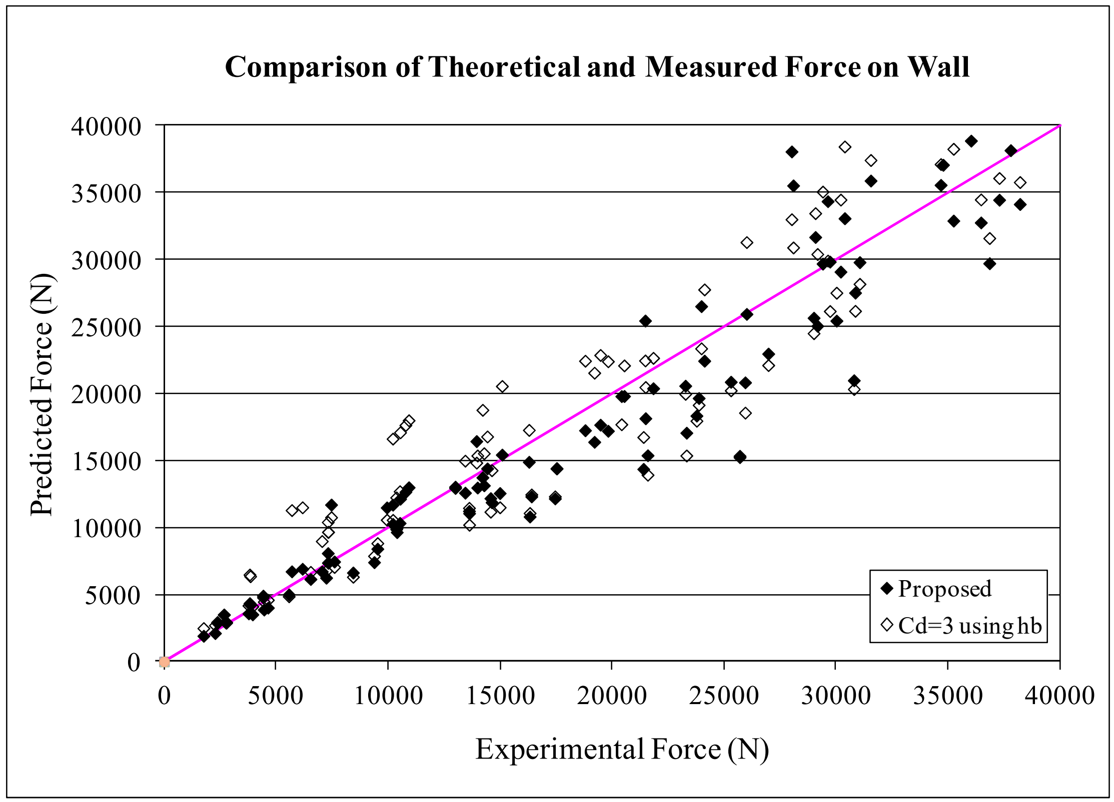
Minami Gamou Wastewater Treatment Plant - subjected to direct bore impact

Simplified Equation for Impulse Load

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

- Apply a factor of 1.5 to the conventional drag force, but as a uniform load rather than as a triangular load

$$F_d = 1.5(\frac{1}{2}k_s \rho_{sw} C_d bhu^2)$$



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

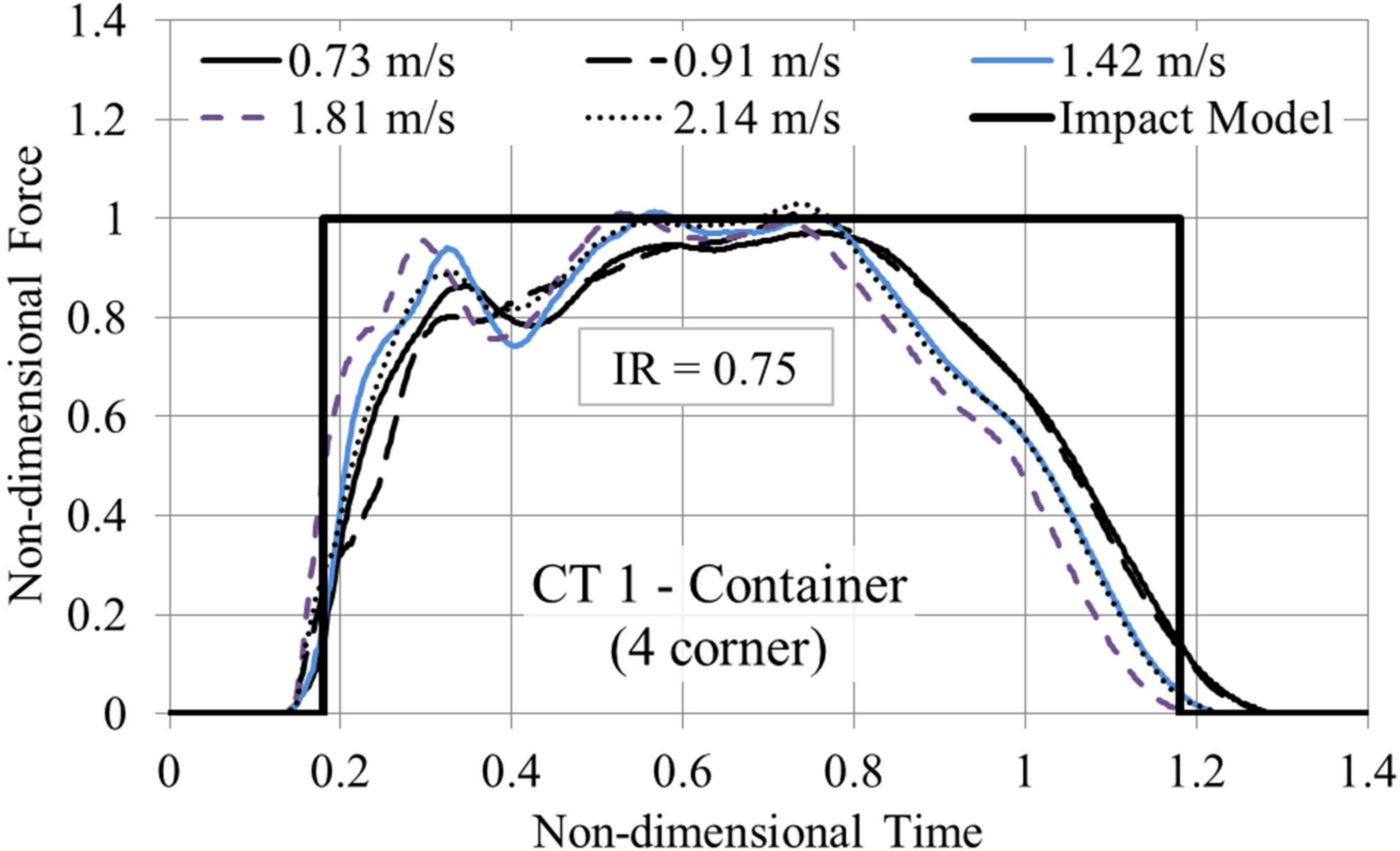
ISO 20-ft Shipping Container

- 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

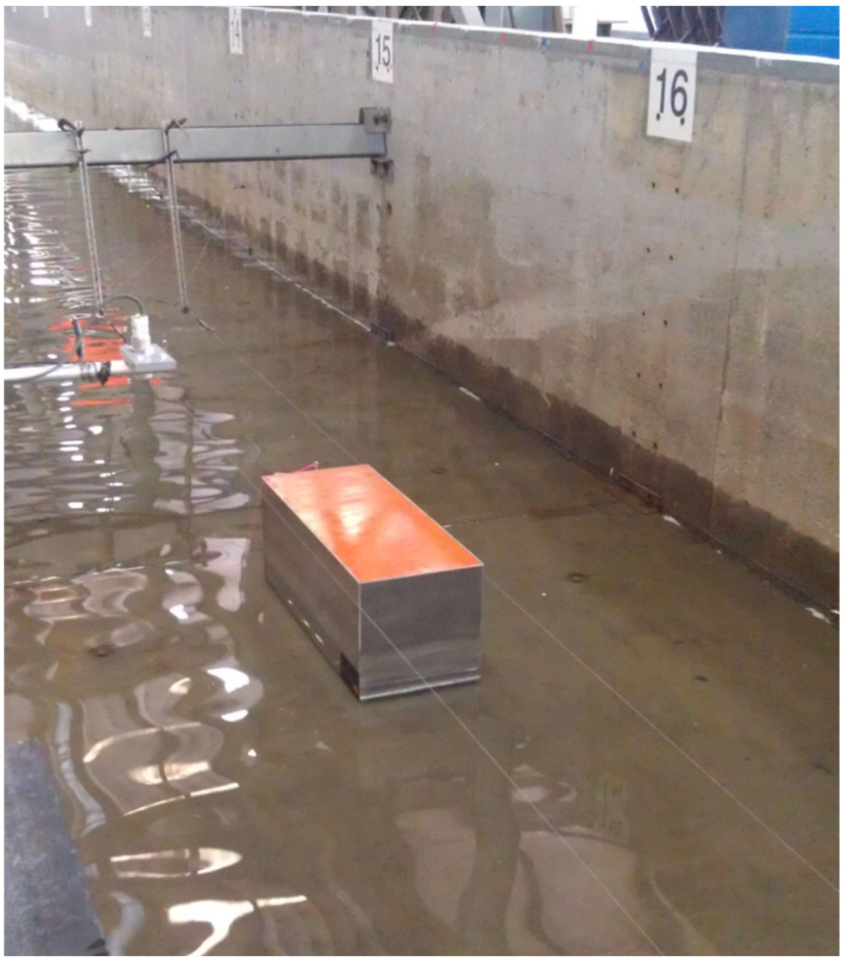
Video

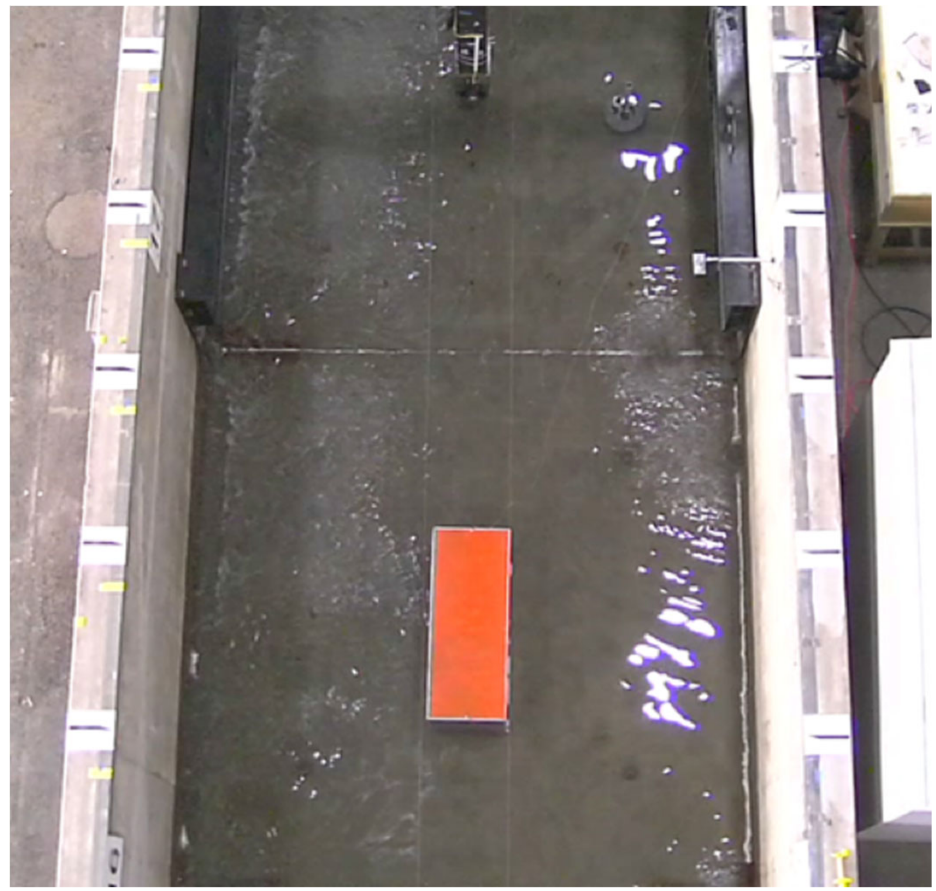
Impact Force Time History



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

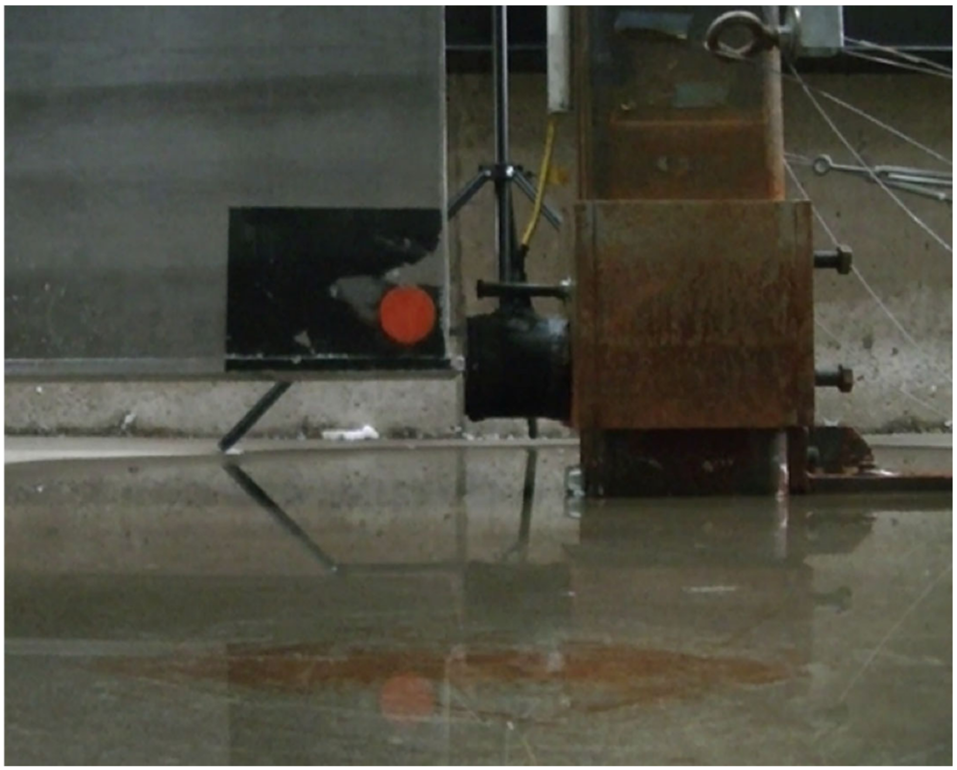




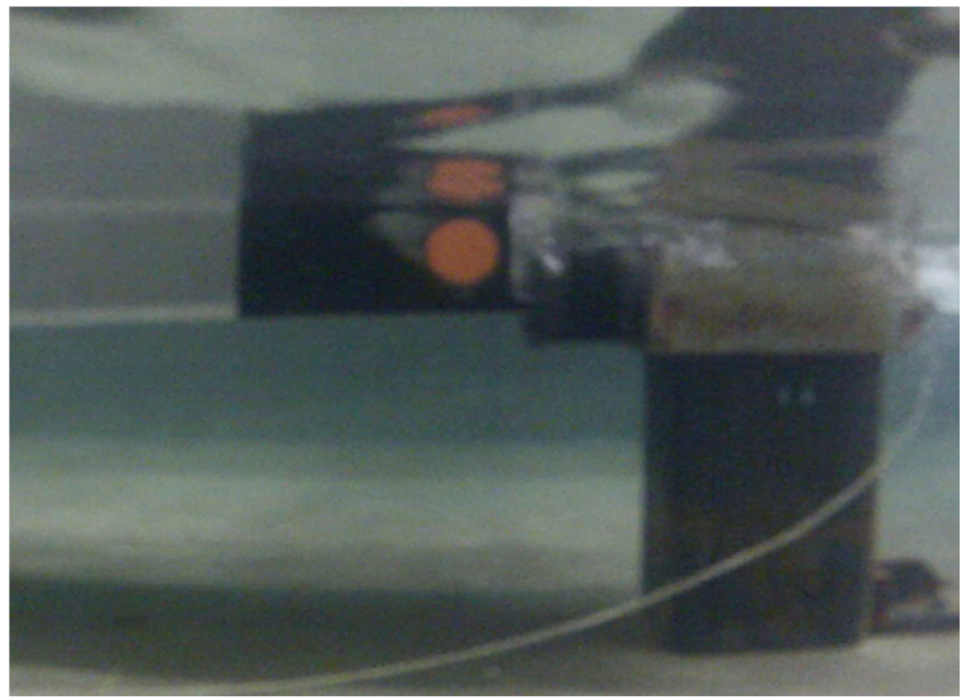
Column and load cell at top of photo

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



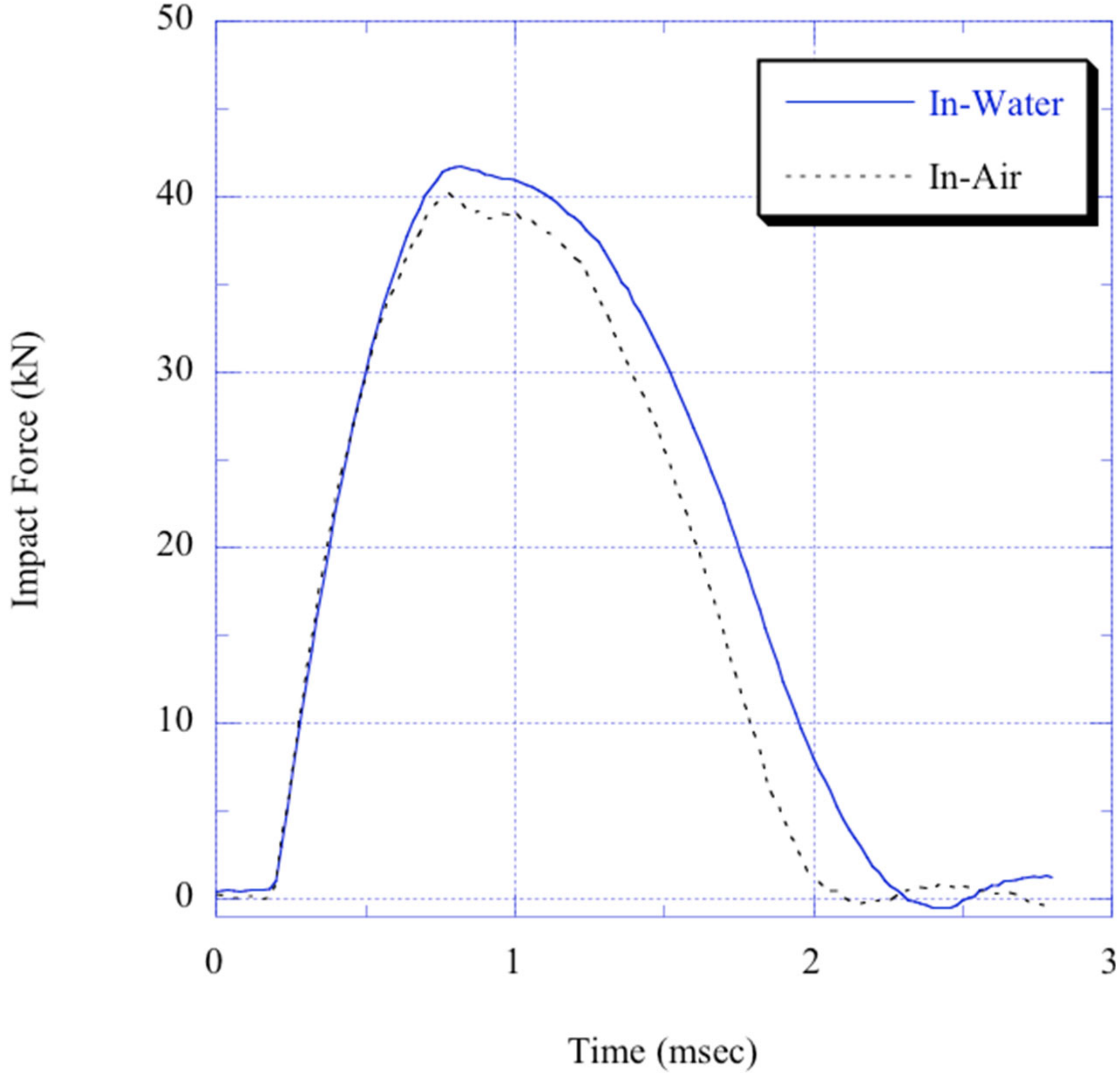
In-water impact

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

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

- 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

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

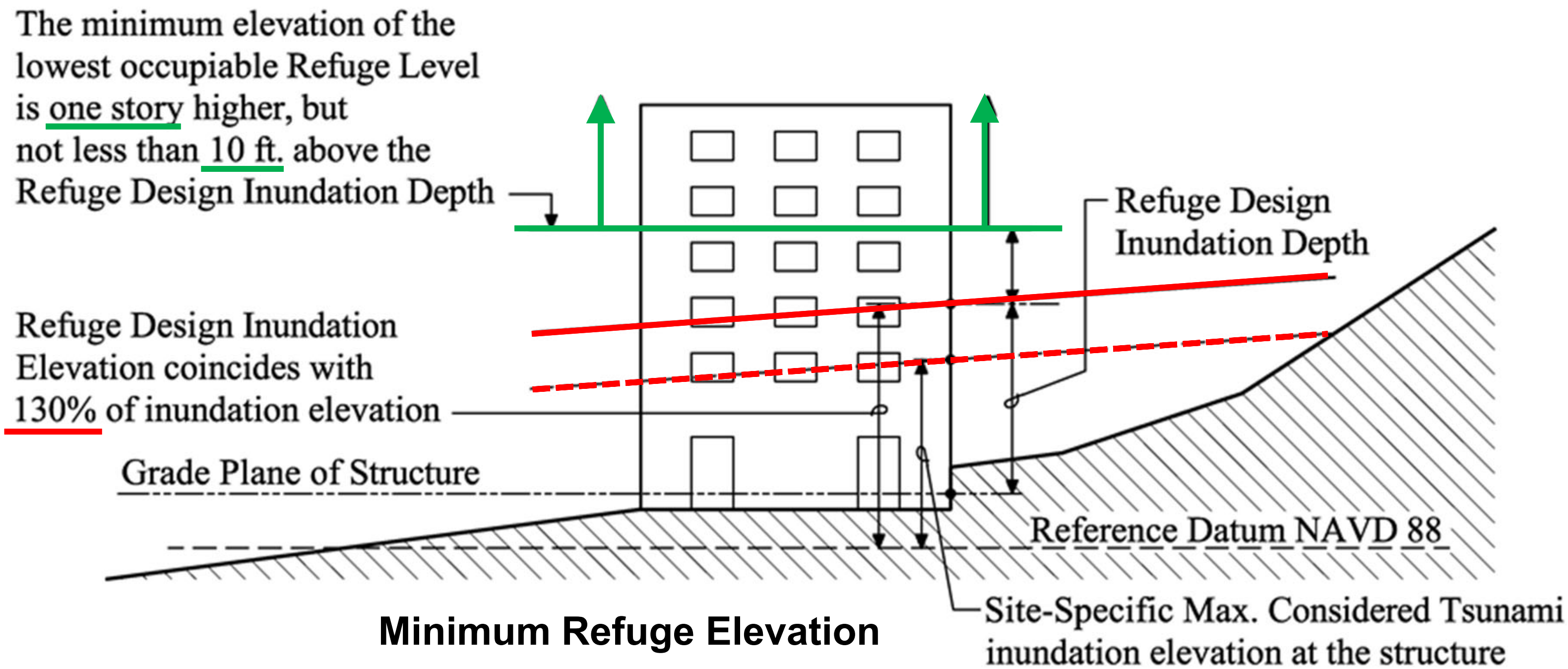
$$F_{dm} = \frac{1}{2} \rho_s C_d B_d (hu^2)_{\max}$$

Where B_d = 40 feet or one structural bay

Hurricane Katrina, 2005

Elevation Considerations

- **A structural reliability of 99% is achieved through site-specific inundation analysis and a 30% increase in the inundation elevation, which increases the loads on the structure.**
- **When the design level tsunami occurs, there is less than 1% chance of failure.**

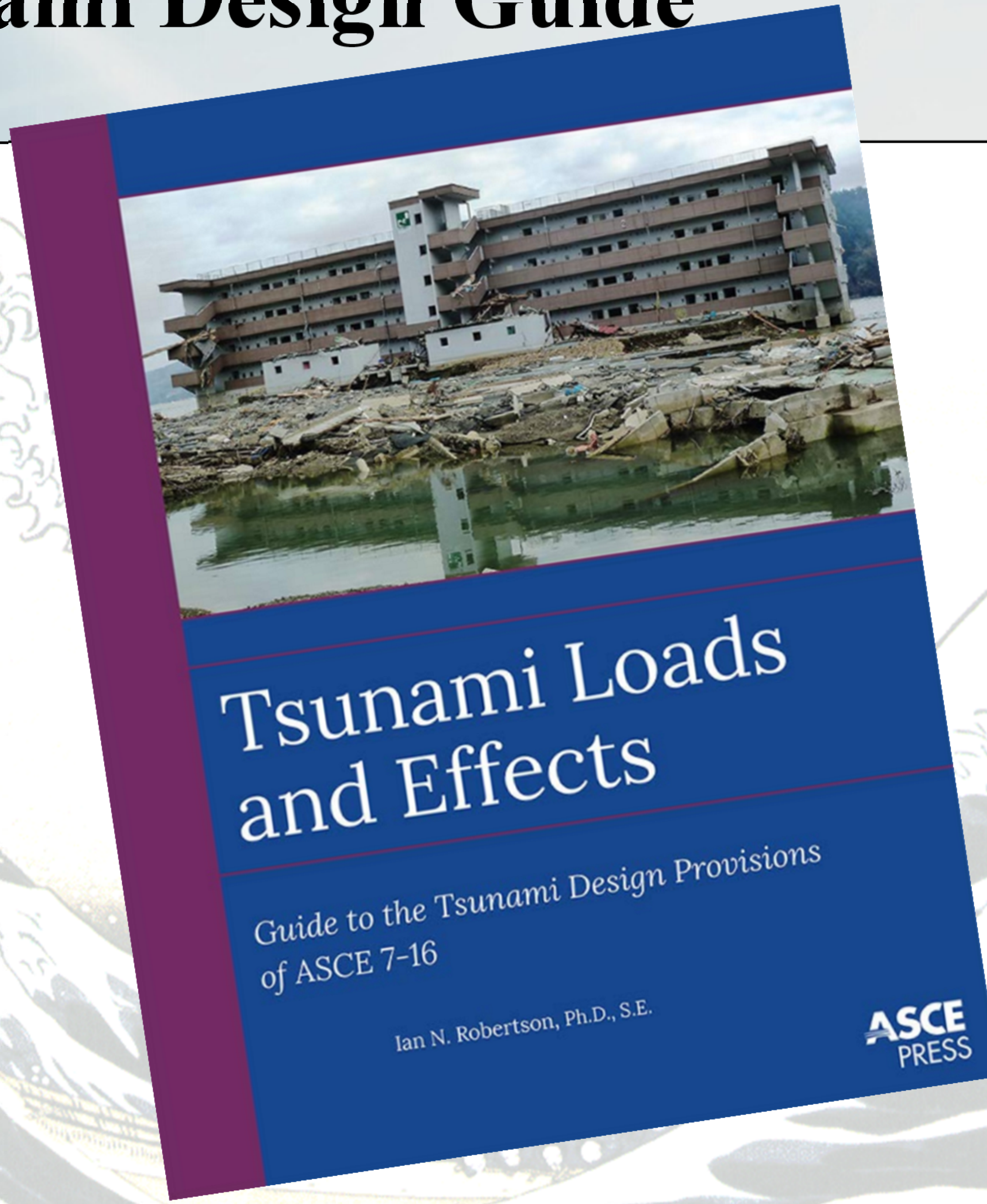


Minimum Refuge Elevation

(FEMA P-646, Fig. 5-3)

ASCE Tsunami Design Guide

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



Outline

- Need for Vertical Evacuation Refuges for Tsunamis (VERT)
- Performance of Vertical Evacuation Refuges during Tohoku Tsunami
- FEMA P-646 design guidelines
- ASCE-7 Tsunami Loads and Effects chapter
- Vertical Evacuation Refuge structures in the U.S.
- Conclusions

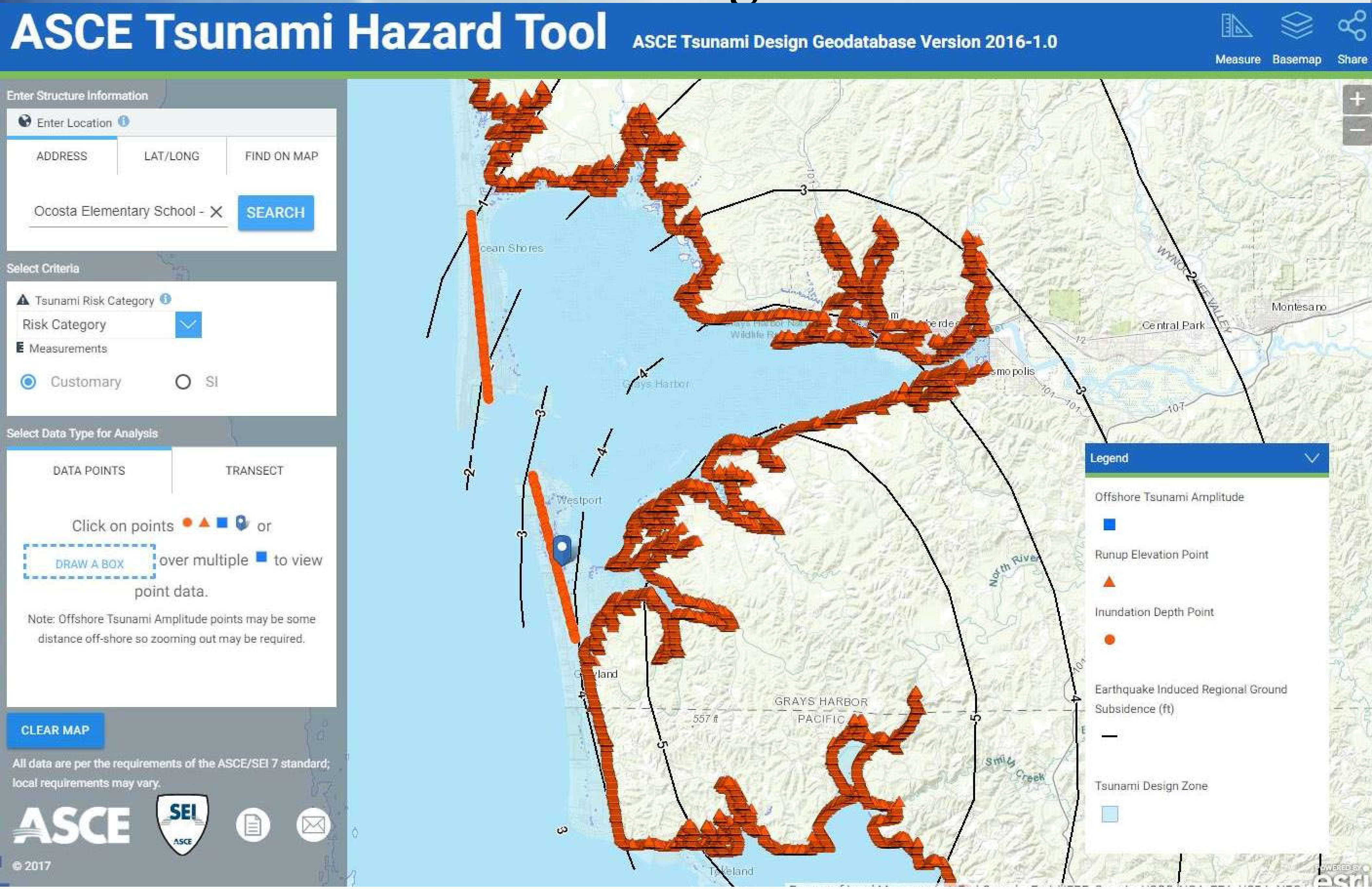
Vertical Evacuation Refuges built to ASCE 7-16

Ocosta Elementary School, Westport, WA

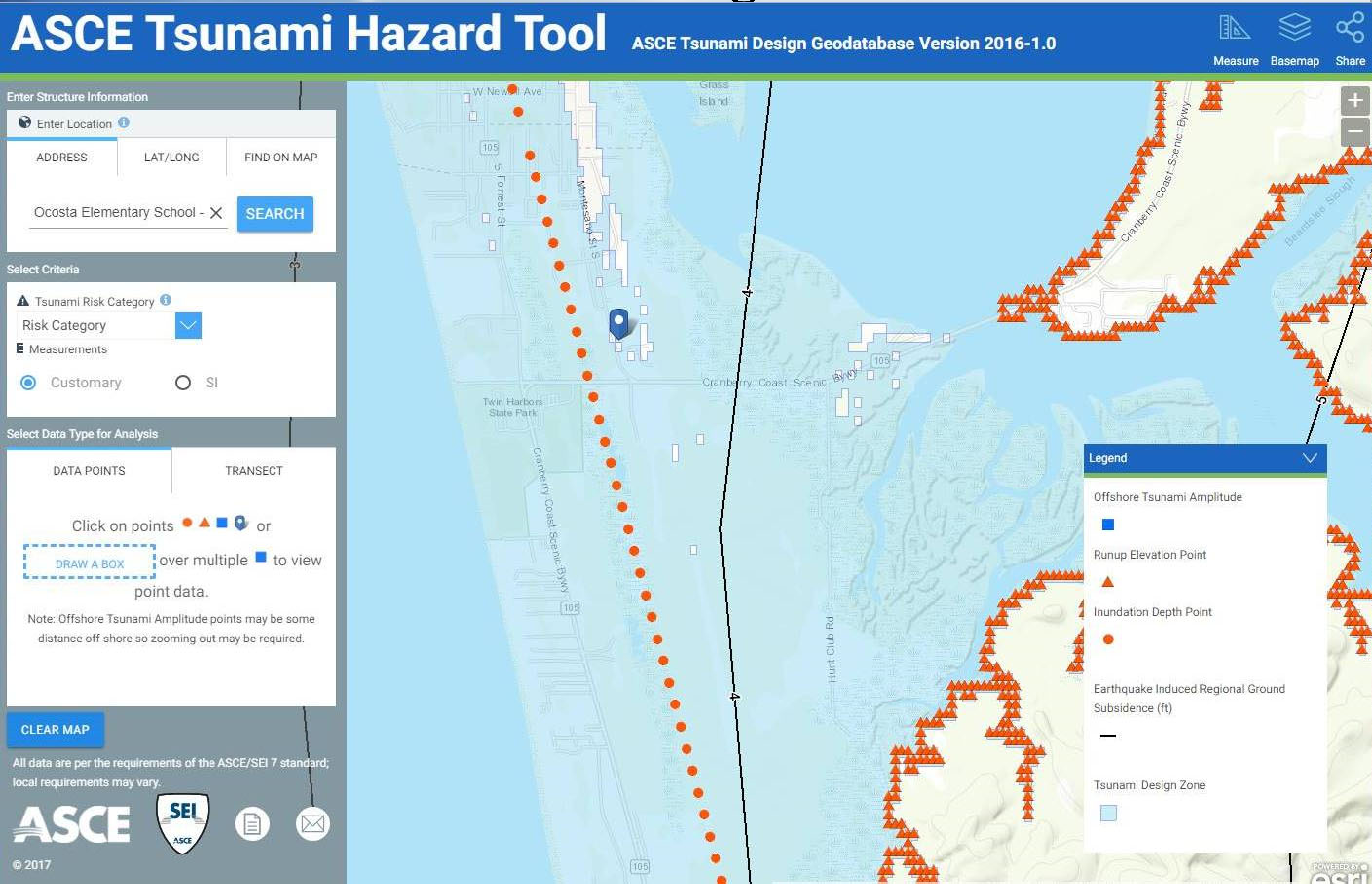
OSU Hatfield Marine Science Building, Newport, WA

Tokeland Evacuation Tower, WA

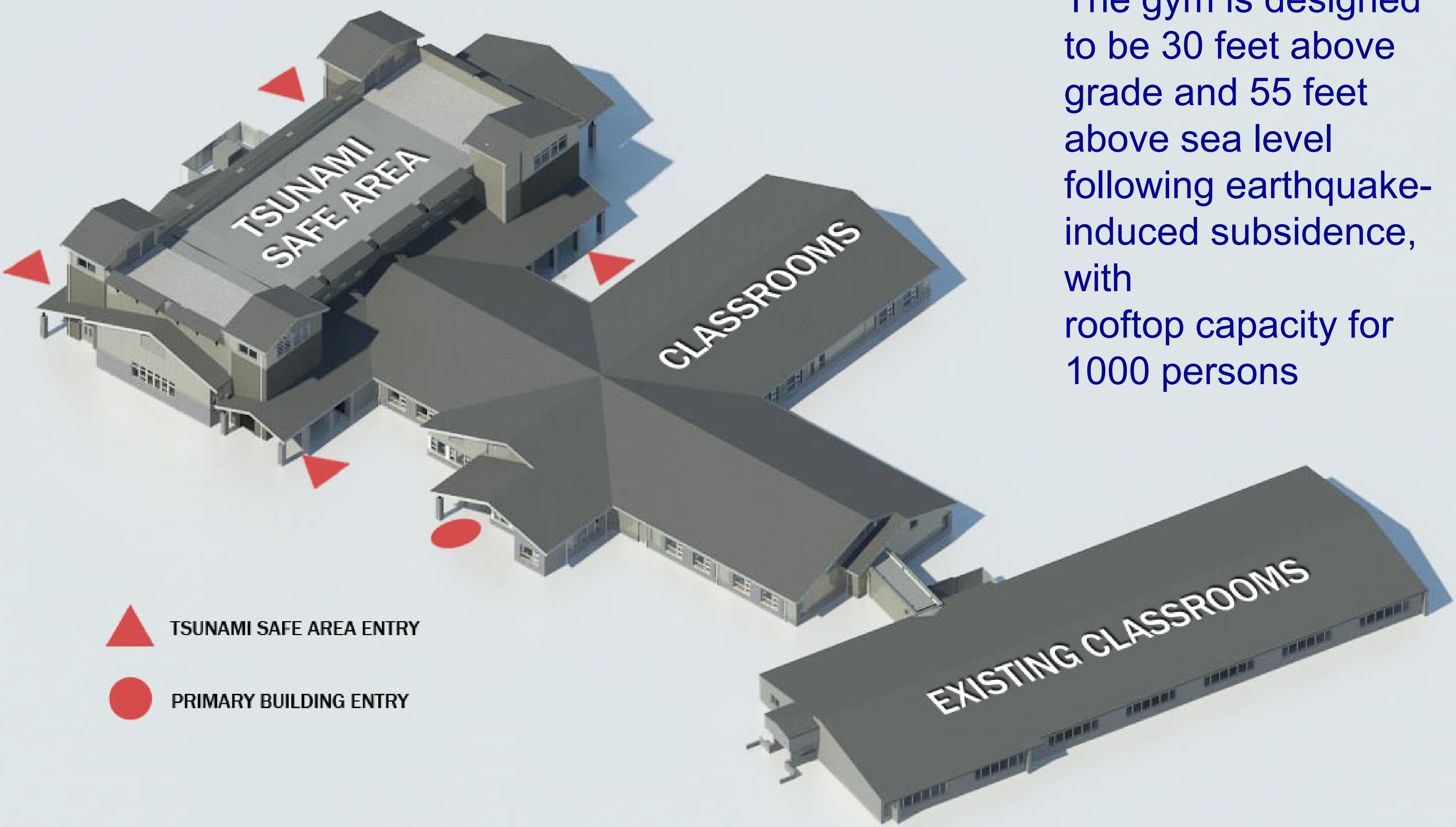
Ocosta Elementary School, Westport, Washington



Ocosta Elementary School, Westport, Washington

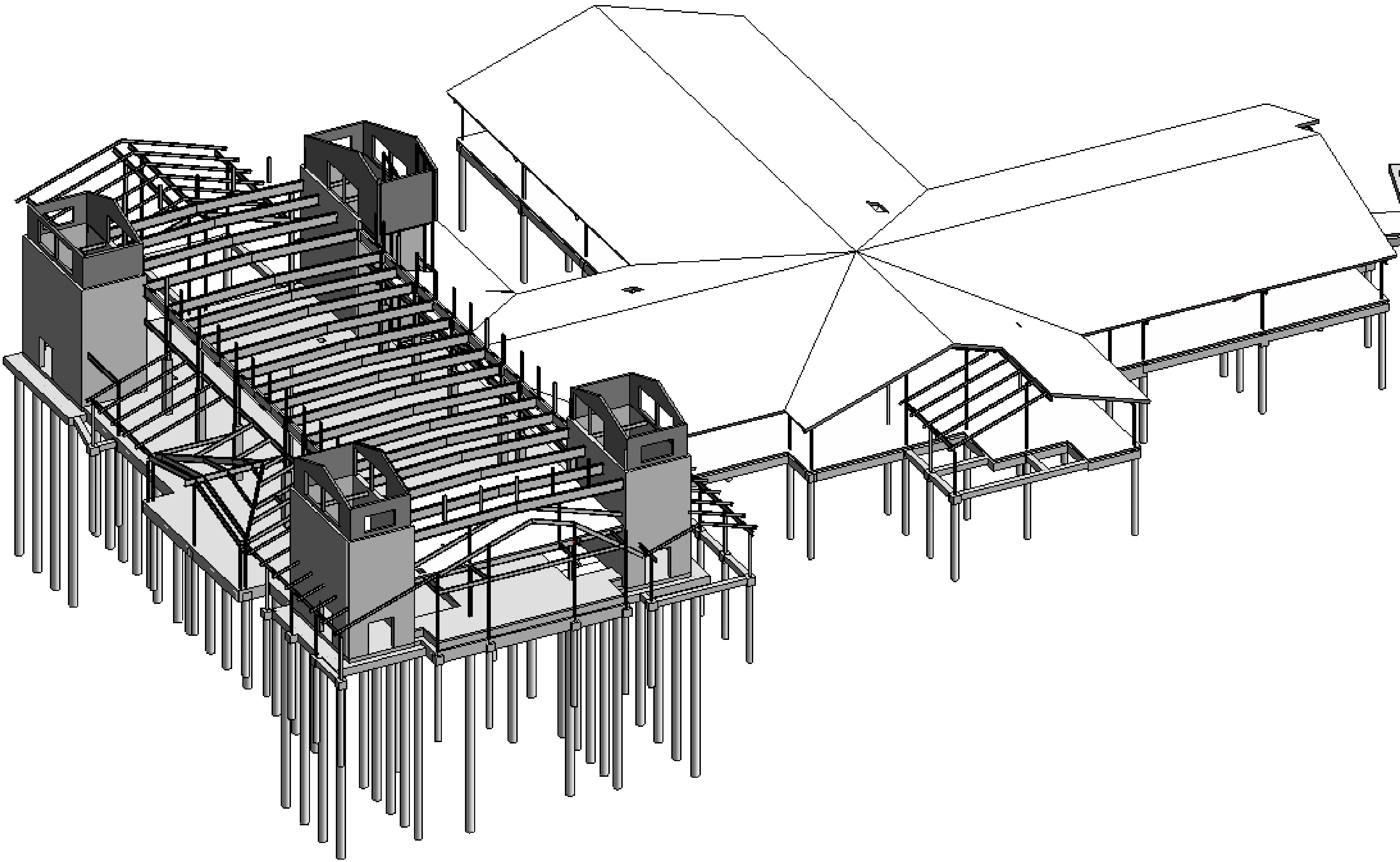


Ocosta Elementary School
Westport, Washington
America's first tsunami refuge

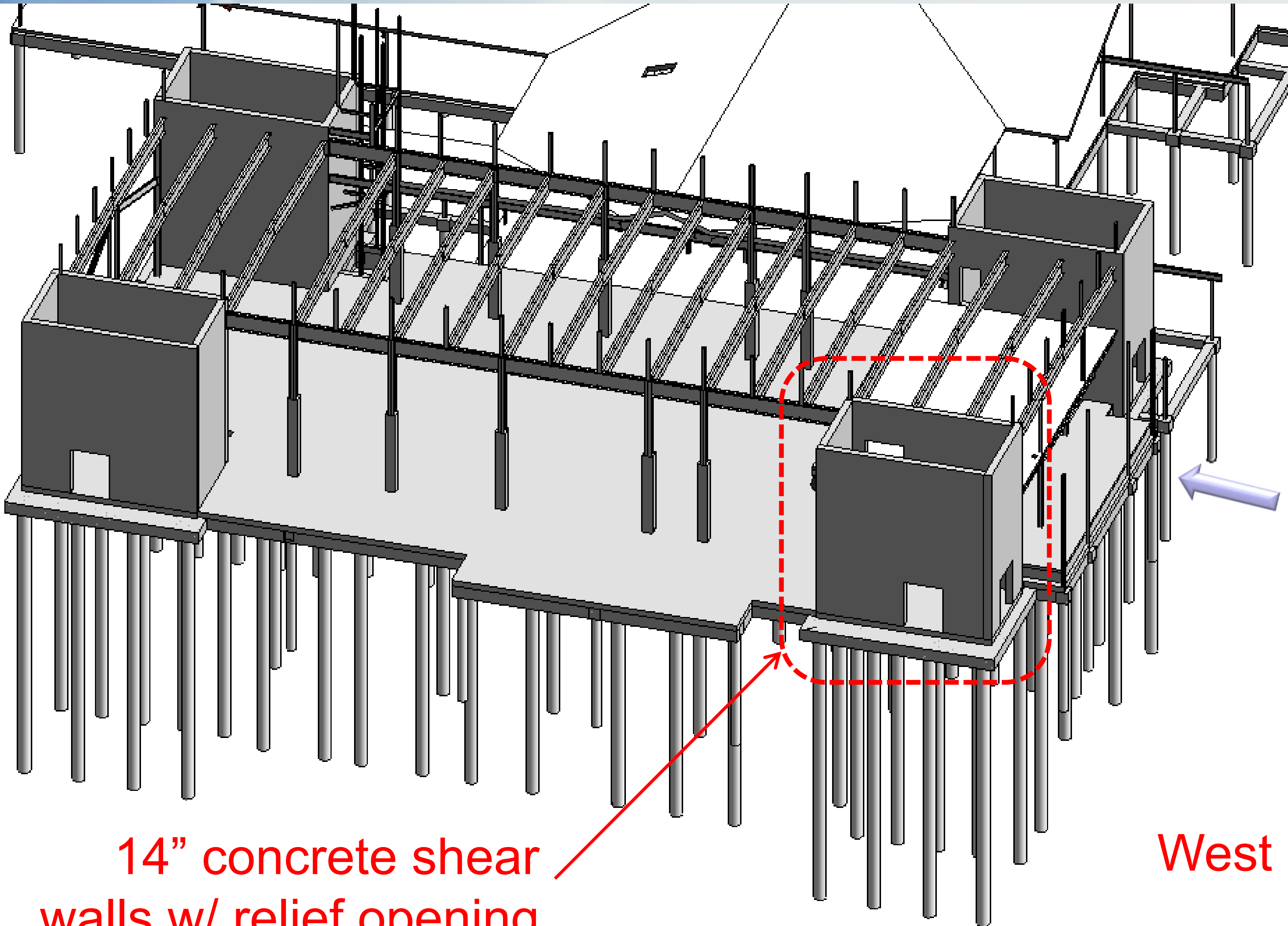


The gym is designed to be 30 feet above grade and 55 feet above sea level following earthquake-induced subsidence, with
rooftop capacity for 1000 persons

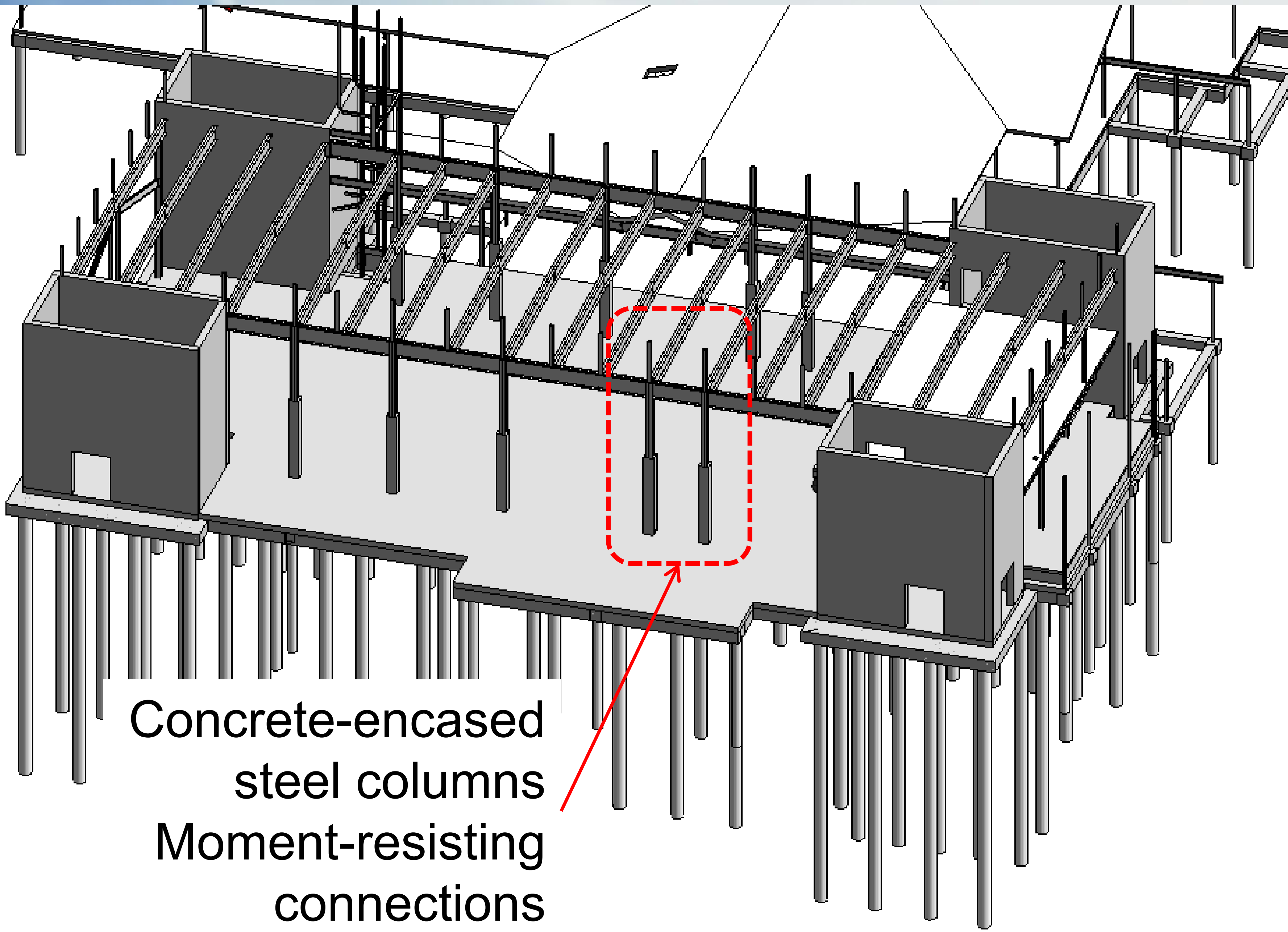
Foundation Design



Structural Lateral System

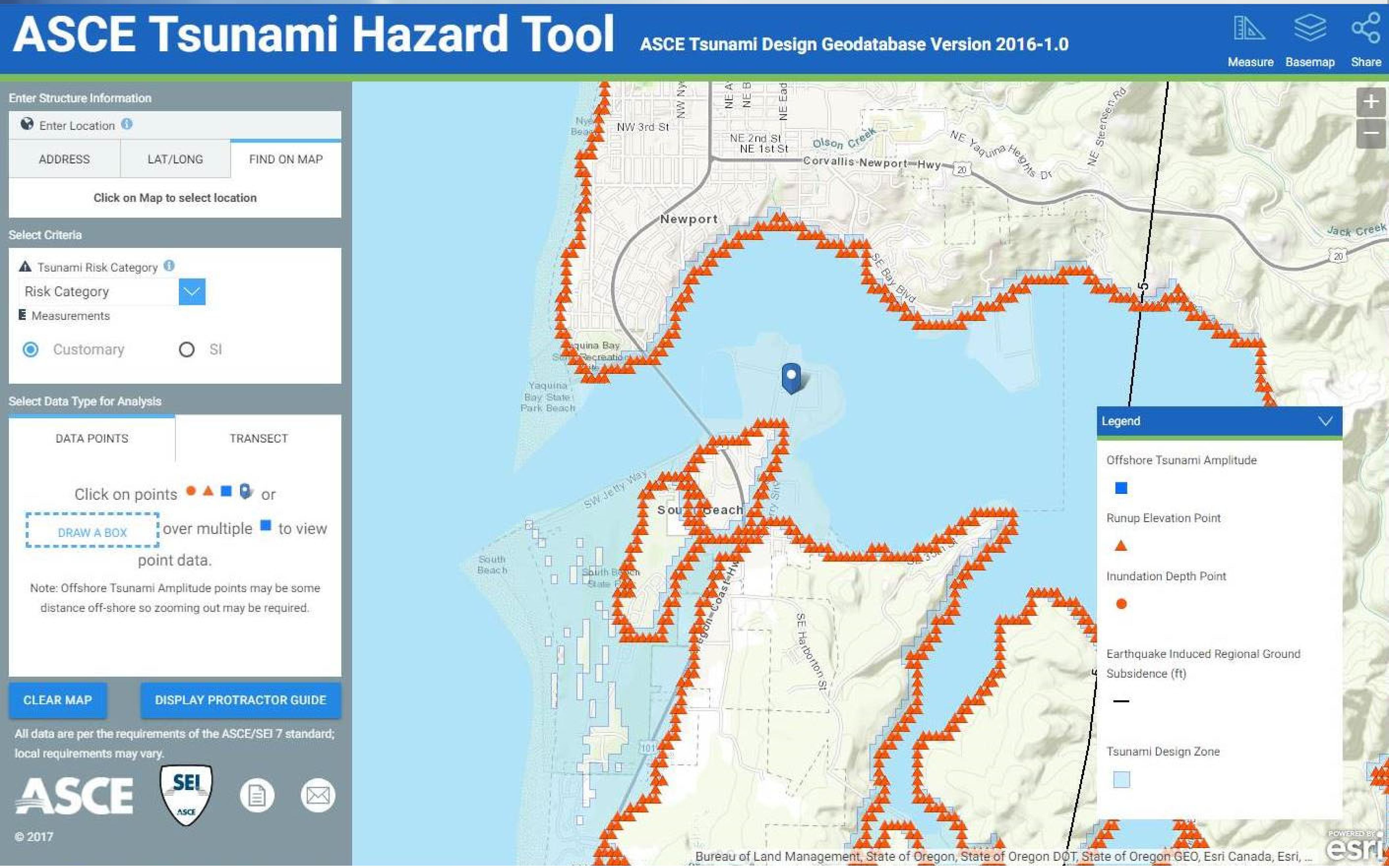


Structural Gravity System



Ocosta Elementary School
Westport, Washington

OSU Hatfield Marine Science Center, Newport, Oregon, USA

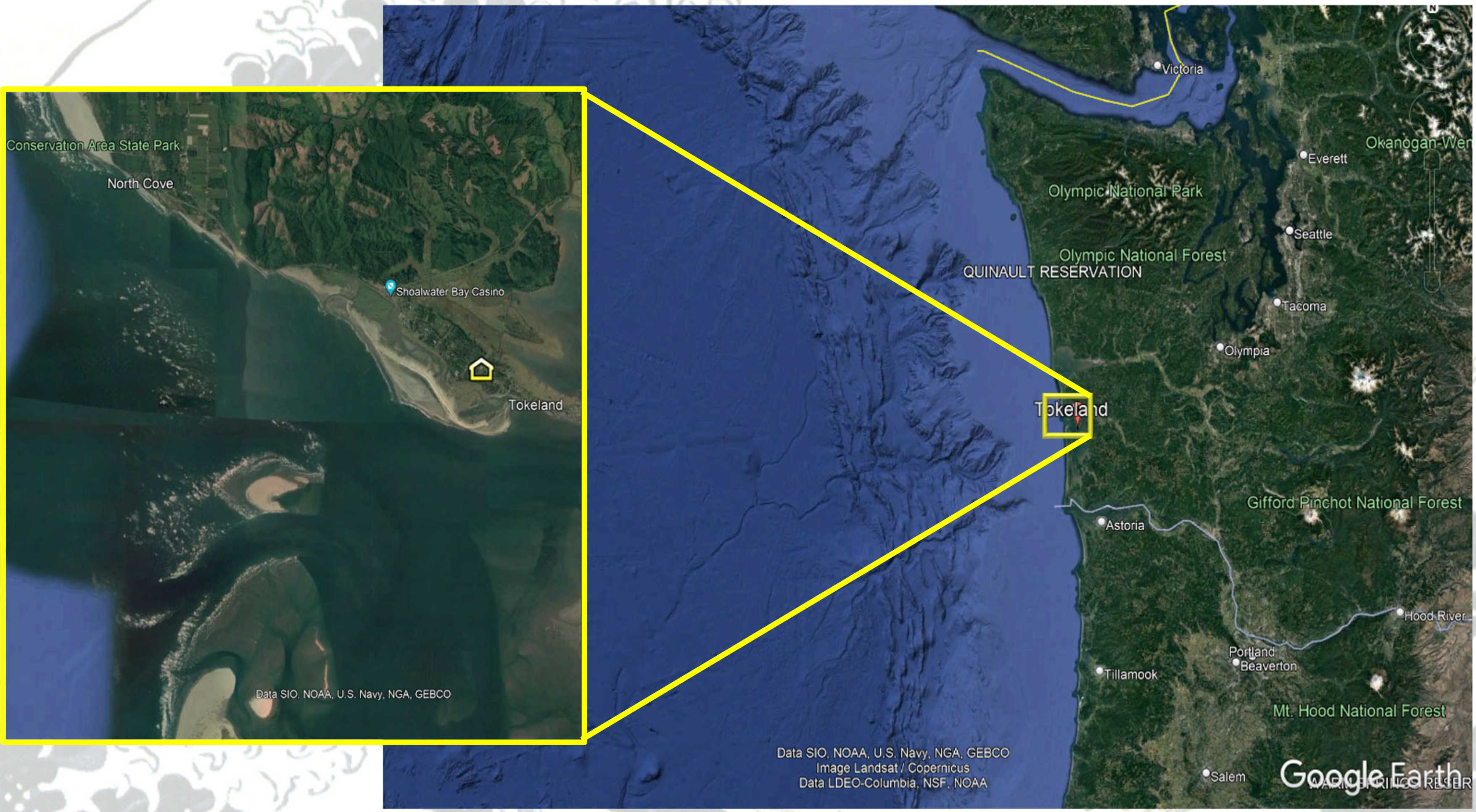


OSU Hatfield Marine Science Center, Newport, Oregon, USA

OSU Hatfield Marine Science Center, Newport, Oregon, USA

Tokeland Vertical Evacuation Tower, Washington

- **Shoalwater Bay Indian Tribe**



Tokeland Vertical Evacuation Tower, WA

- A large staircase leads to two evacuation levels meeting P-646 elevation requirements
- Capacity for over 400 persons, exceeding the local tribal population
- Built with FEMA funding

Credit for photos: Washington Emergency Management Division

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

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