

# *Vertical Evacuation Structures*

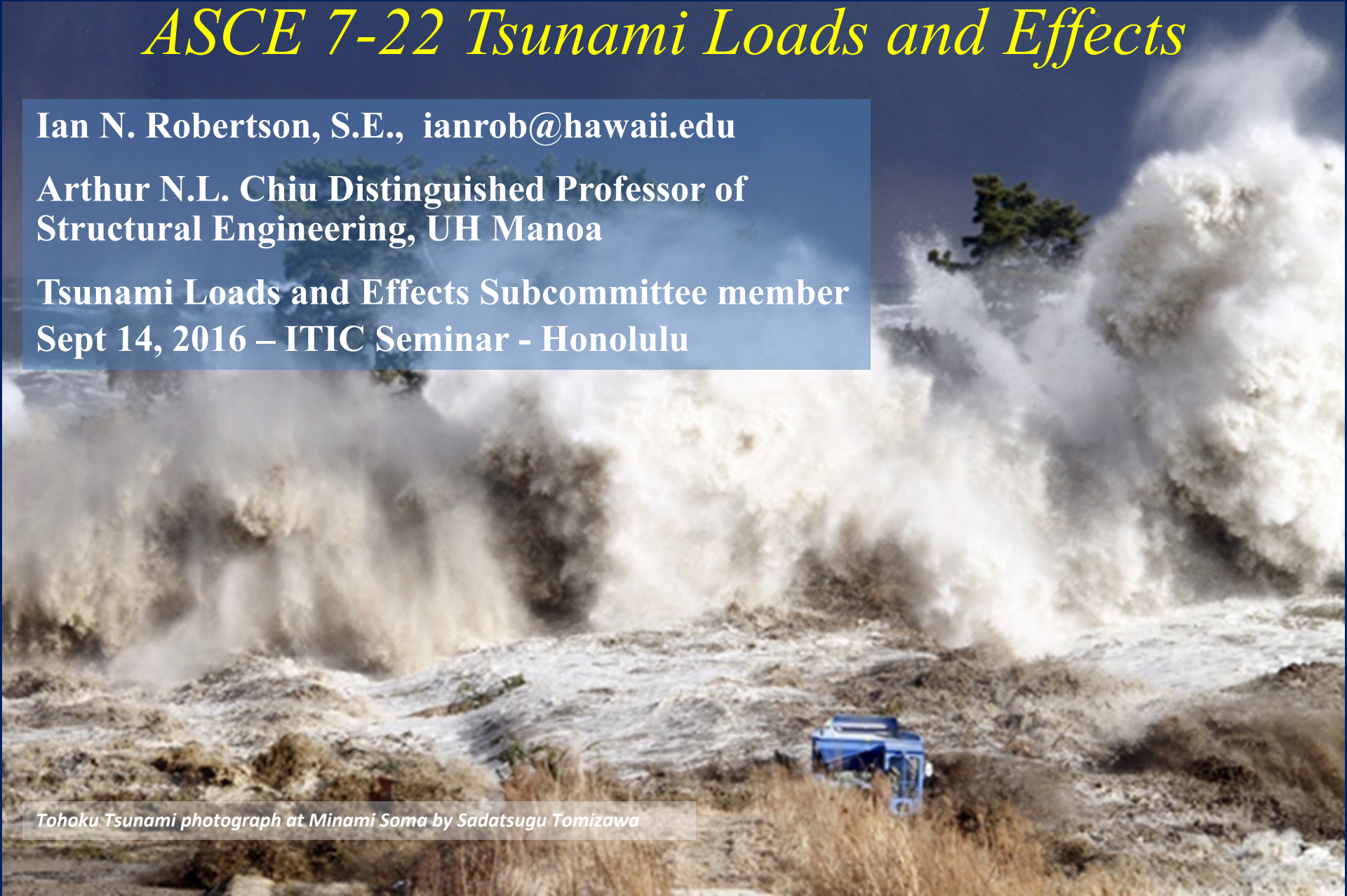
## *ASCE 7-22 Tsunami Loads and Effects*

**Ian N. Robertson, S.E., [ianrob@hawaii.edu](mailto:ianrob@hawaii.edu)**

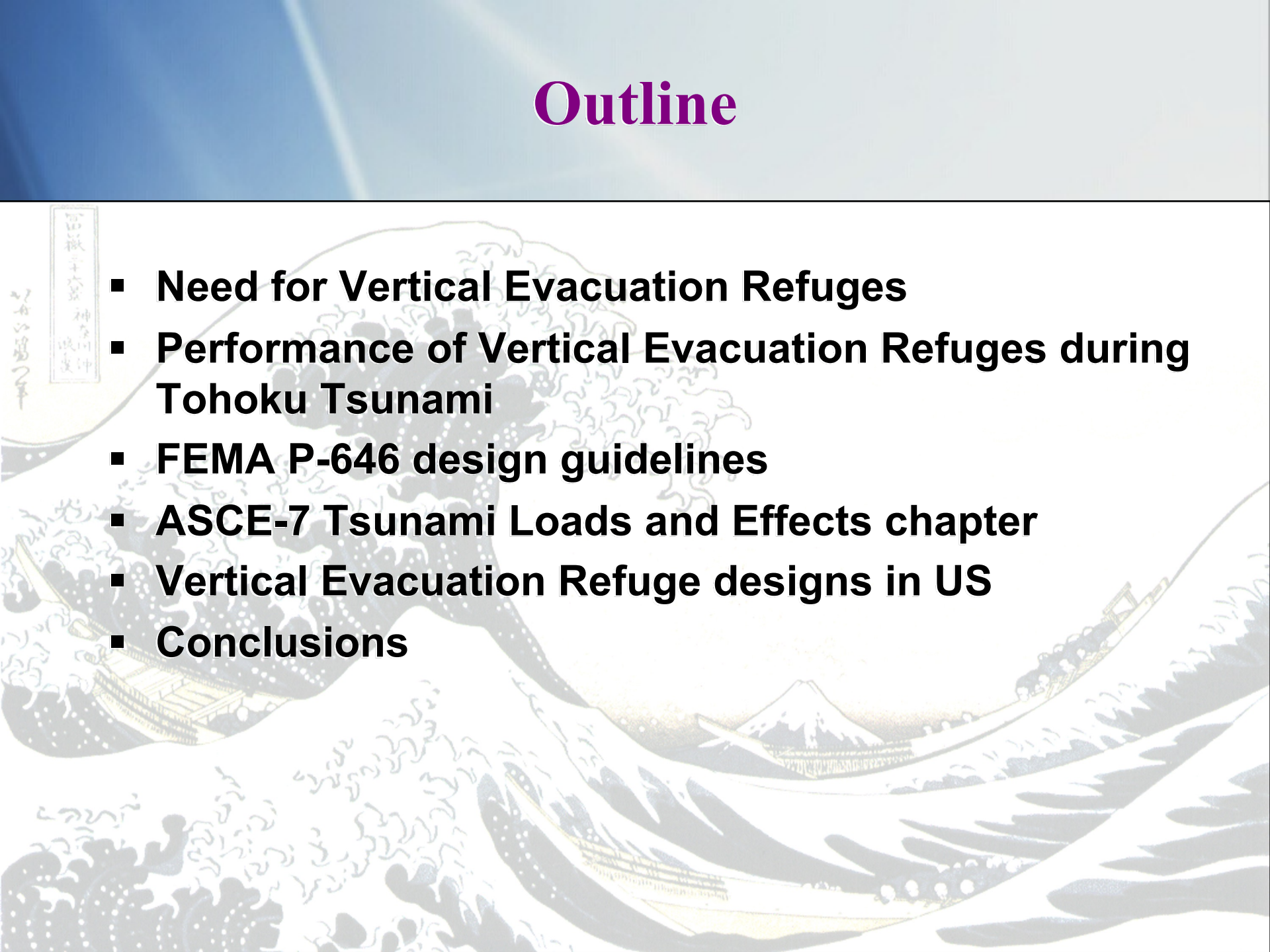
**Arthur N.L. Chiu Distinguished Professor of  
Structural Engineering, UH Manoa**

**Tsunami Loads and Effects Subcommittee member  
Sept 14, 2016 – ITIC Seminar - Honolulu**

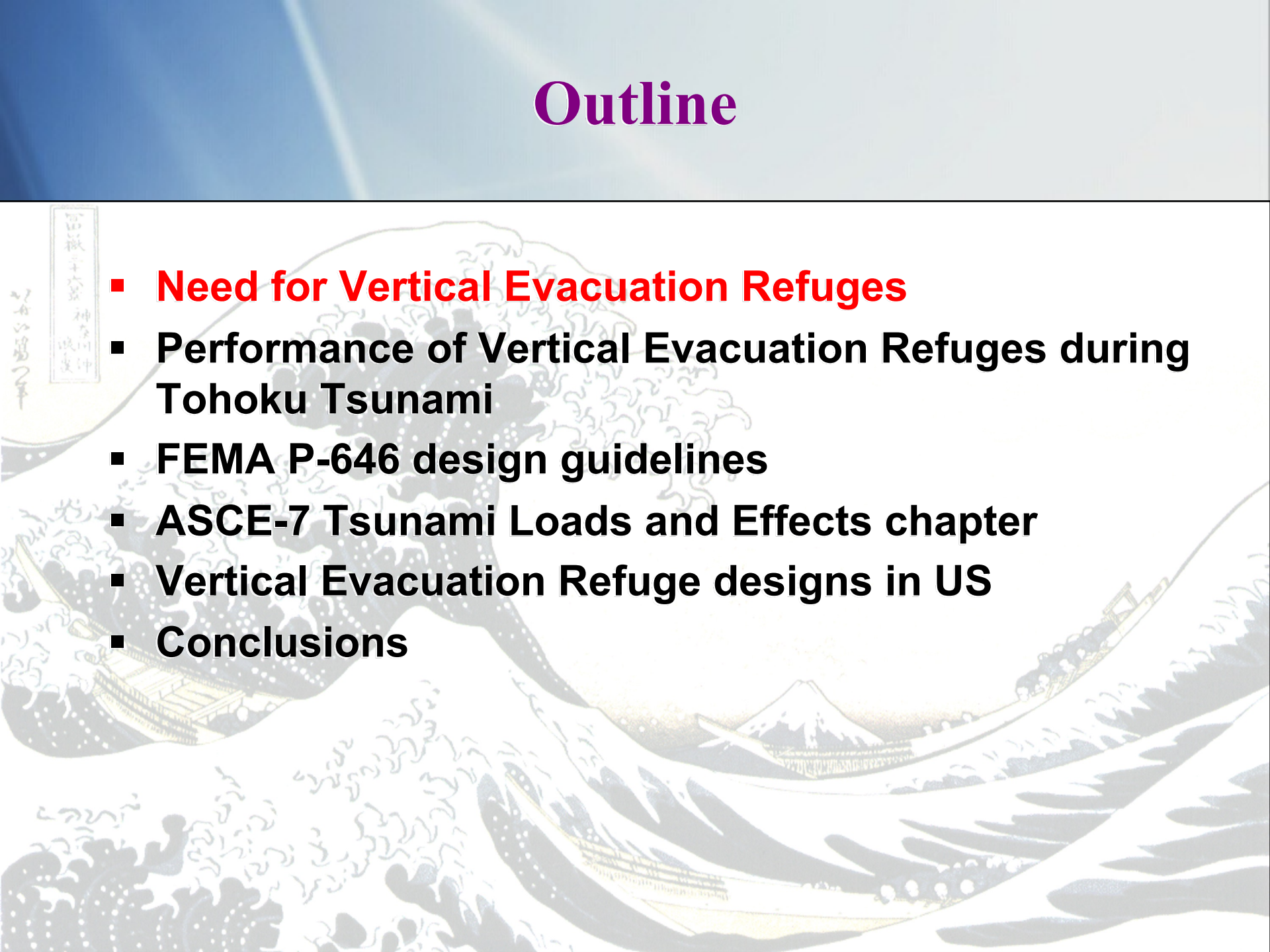
*Tohoku Tsunami photograph at Minami Soma by Sadatsugu Tomizawa*



# Outline

- 
- The background features a traditional Japanese ink wash painting of a massive tsunami wave. Several boats are shown being tossed by the water. In the distance, Mount Fuji is visible under a pale sky. On the left side, there is a vertical inscription in Japanese characters: '富田 敬子 六景 神奈川沖 浪裏 浪裏 浪裏' and a signature '山崎 宗之 画'.
- **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**

# Outline

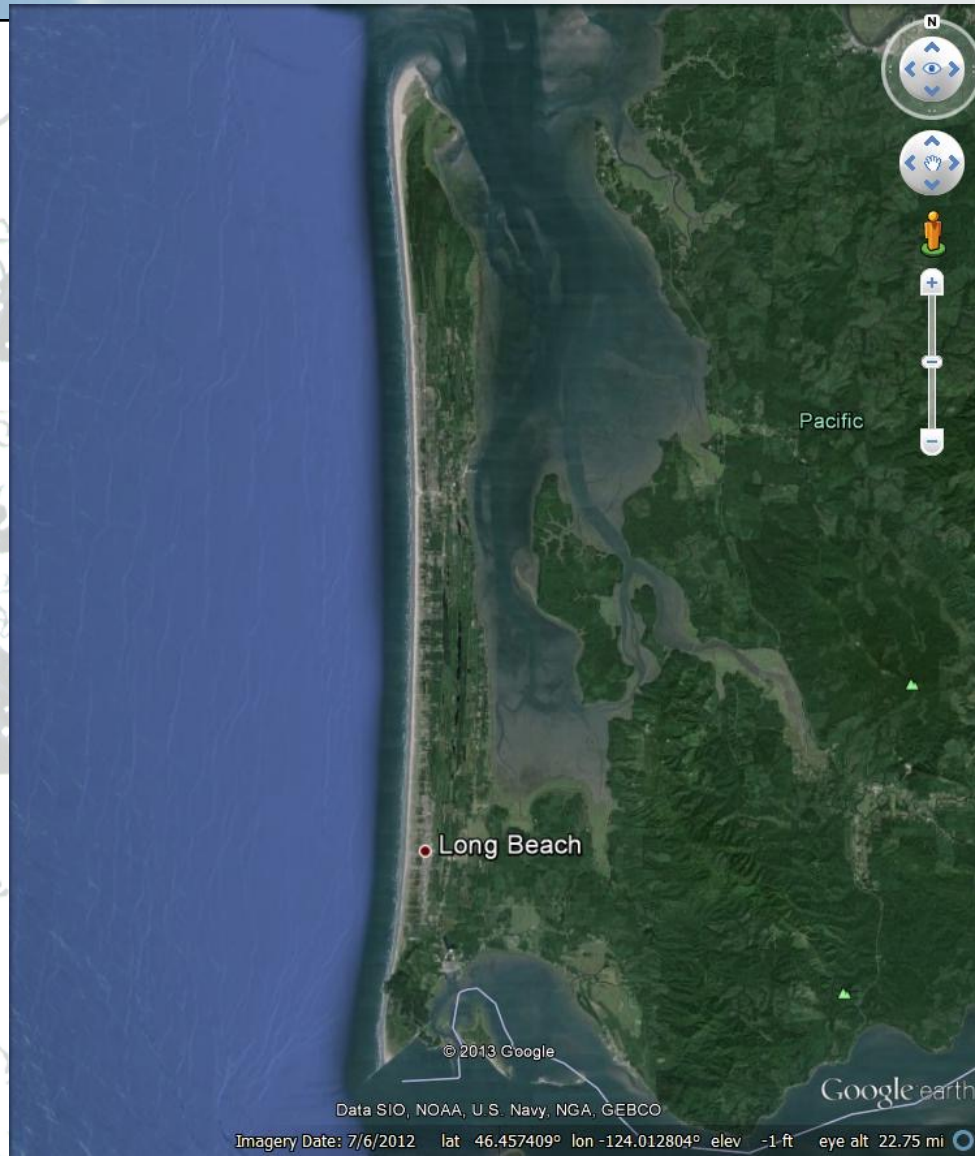
- 
- The background features a traditional Japanese ink wash painting of a massive tsunami wave. A boat is shown being tossed by the waves. In the distance, Mount Fuji is visible under a pale sky. On the left side, there is a vertical inscription in Japanese calligraphy: '富田嶽 千六郎 神奈川沖 浪裏' (Tomida Taketoki, Kanagawa Bay, Inside the Waves).
- **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**

# US West Coast Population exposure to tsunami hazard

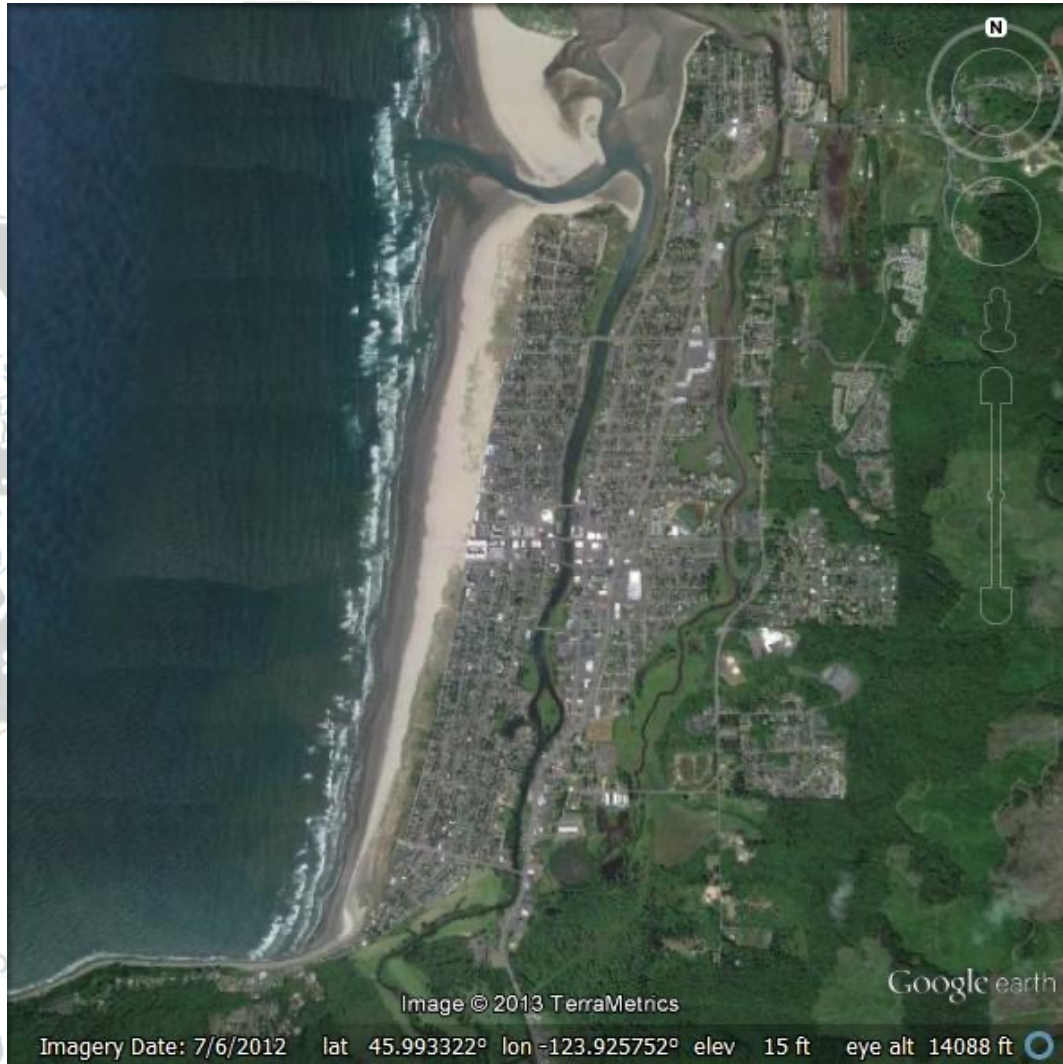
State	Length of Coastline	Population at Risk (in evacuation zone)
California	840 miles	275,000 residents 400,000 to 2,000,000 tourist
Oregon	300 miles	25,000 residents 55,000 tourists
Washington	160 miles	45,000 residents 20,000 tourists
Alaska	6,600 miles	105,000 residents Highly seasonal tourist count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

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

# Long Beach, Washington

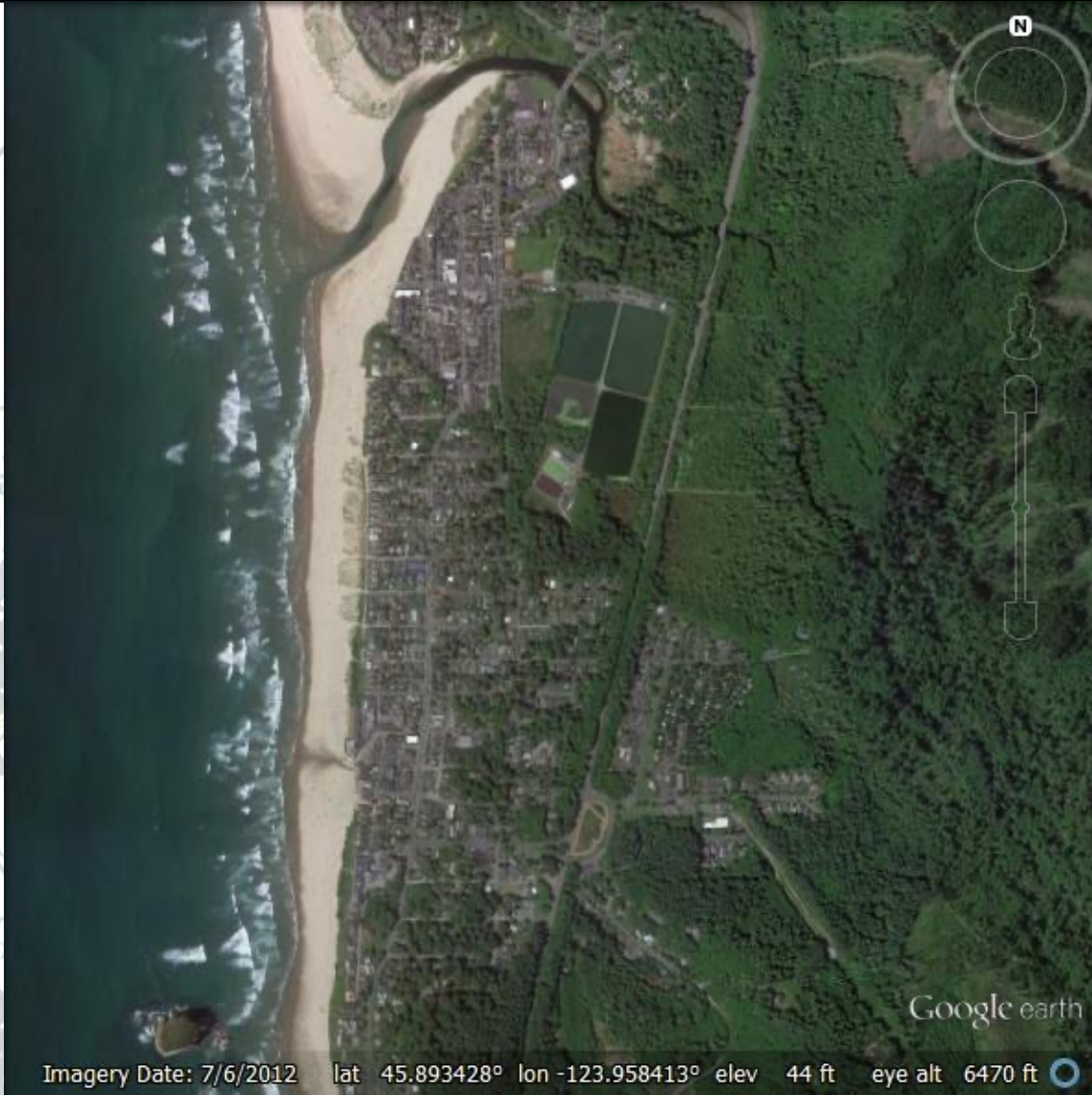


# Seaside, Oregon

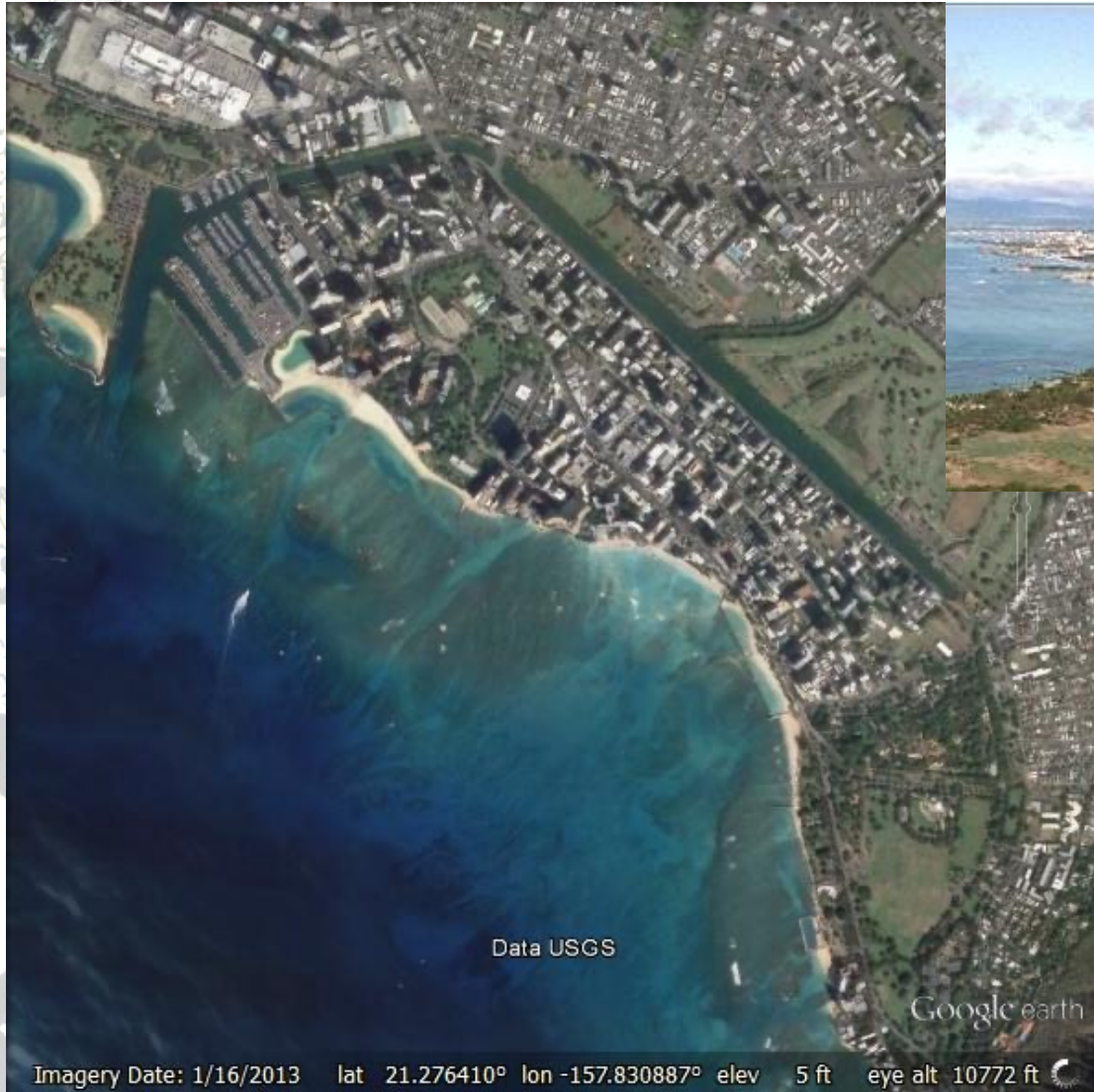


Imagery Date: 7/6/2012 lat 45.993322° lon -123.925752° elev 15 ft eye alt 14088 ft

# Cannon Beach, Oregon



# Waikiki, Hawaii



## Current Evacuation Guidance

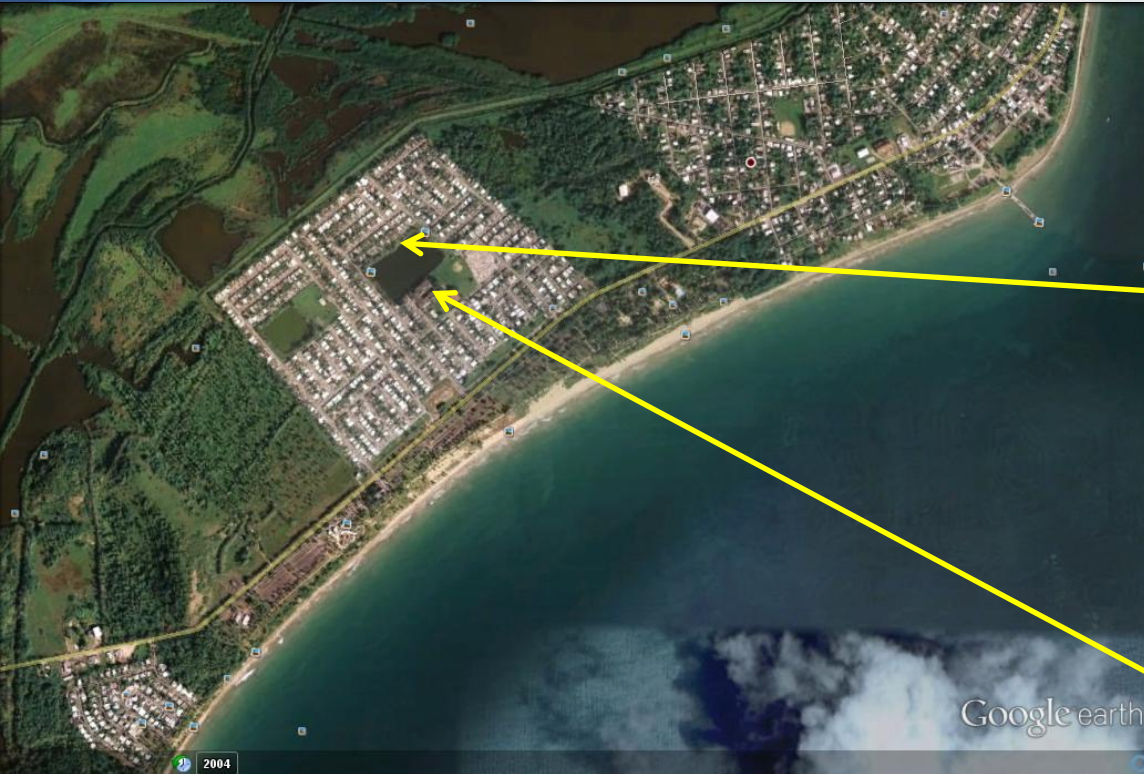
“Structural steel or reinforced concrete buildings of ten or more stories provide increased protection on or above the fourth floor”



# Punta Santiago, Puerto Rico



# Punta Santiago, Puerto Rico



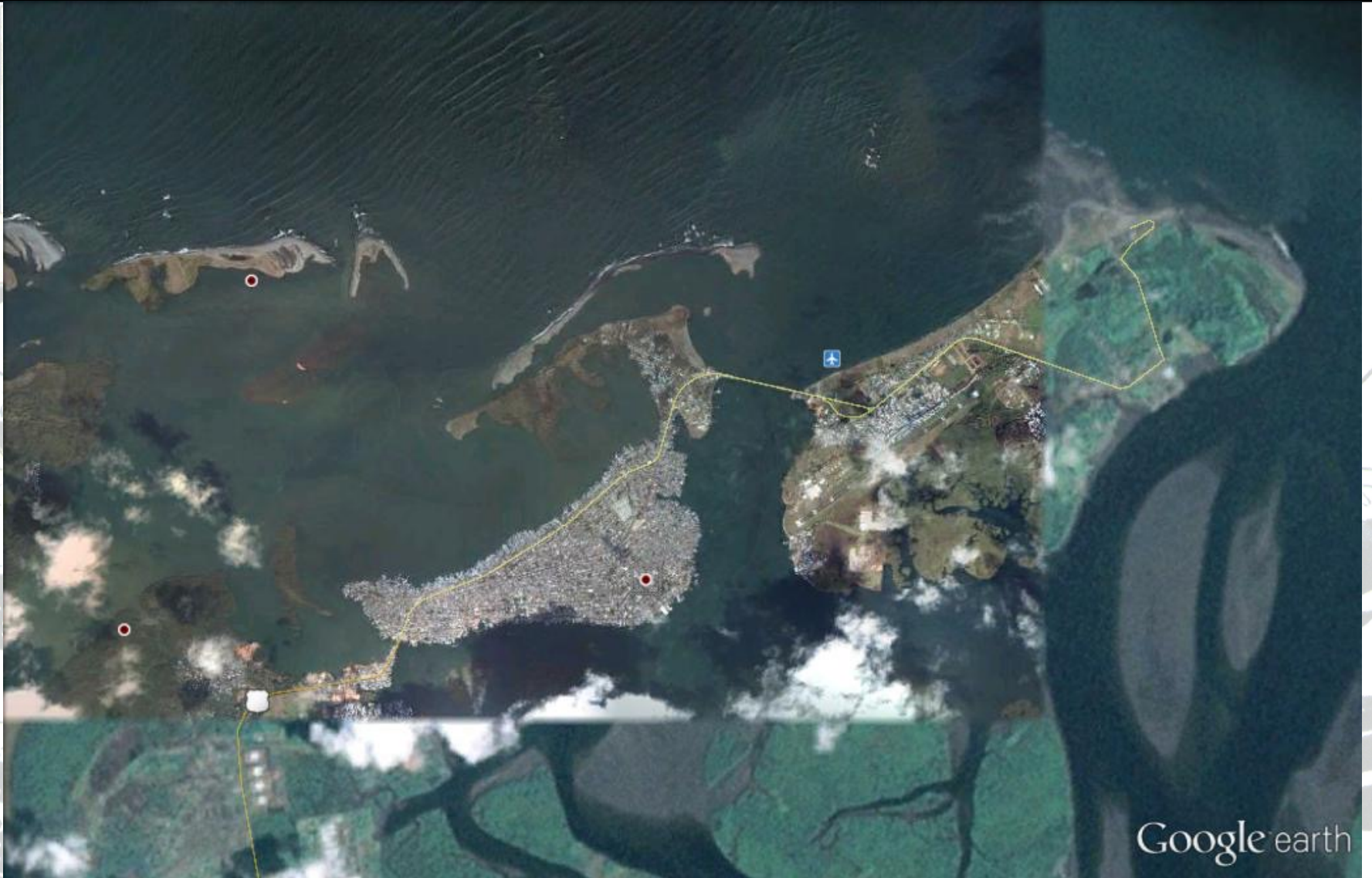
- Consider multi-story school addition with roof refuge
- Other structures for other neighborhoods

# 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



白田嶽子六郎 神奈川沖  
浪の巻

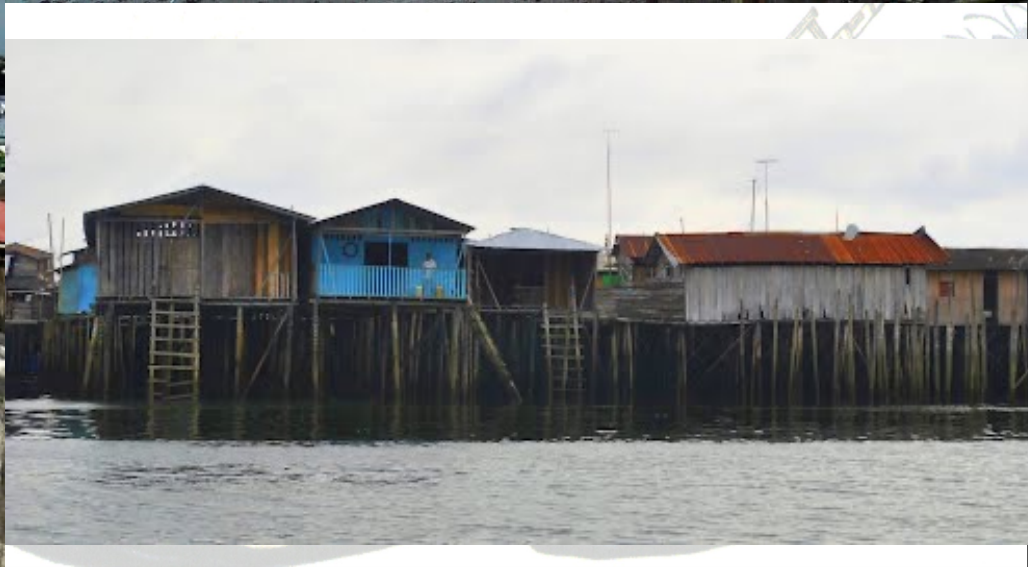
白田嶽子六郎



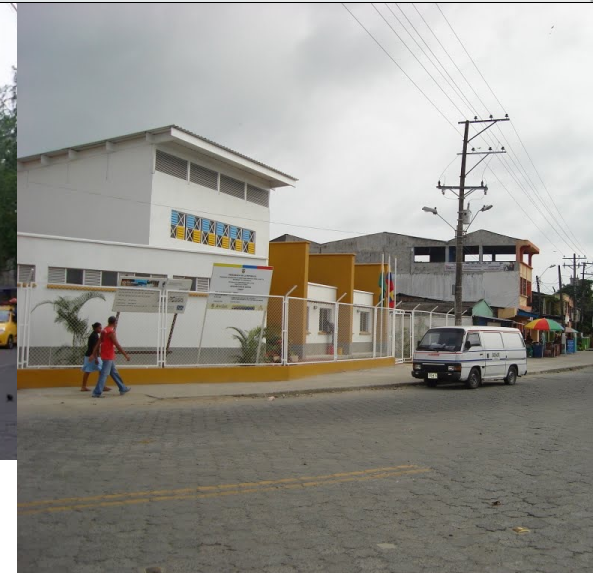
# Tumaco Evacuation



# Tumaco – Typical Structures



# Tumaco – Potential Vertical Evacuation Refuges from Tsunamis

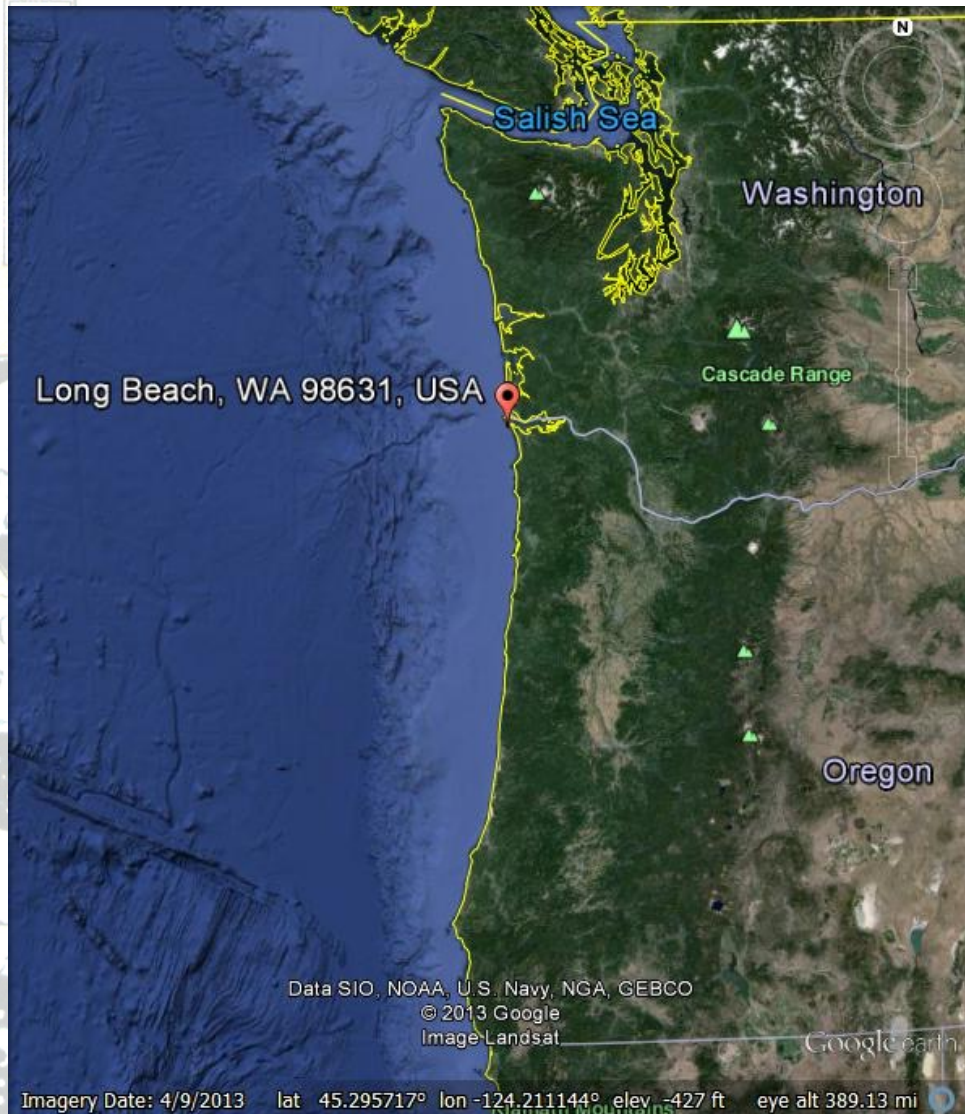


Evacuation sign and taller buildings



# Long Beach Peninsula Simulation

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



# Long Beach Peninsula Simulation

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



Present Condition  
High Ground Only



Scenario 1  
One Refuge



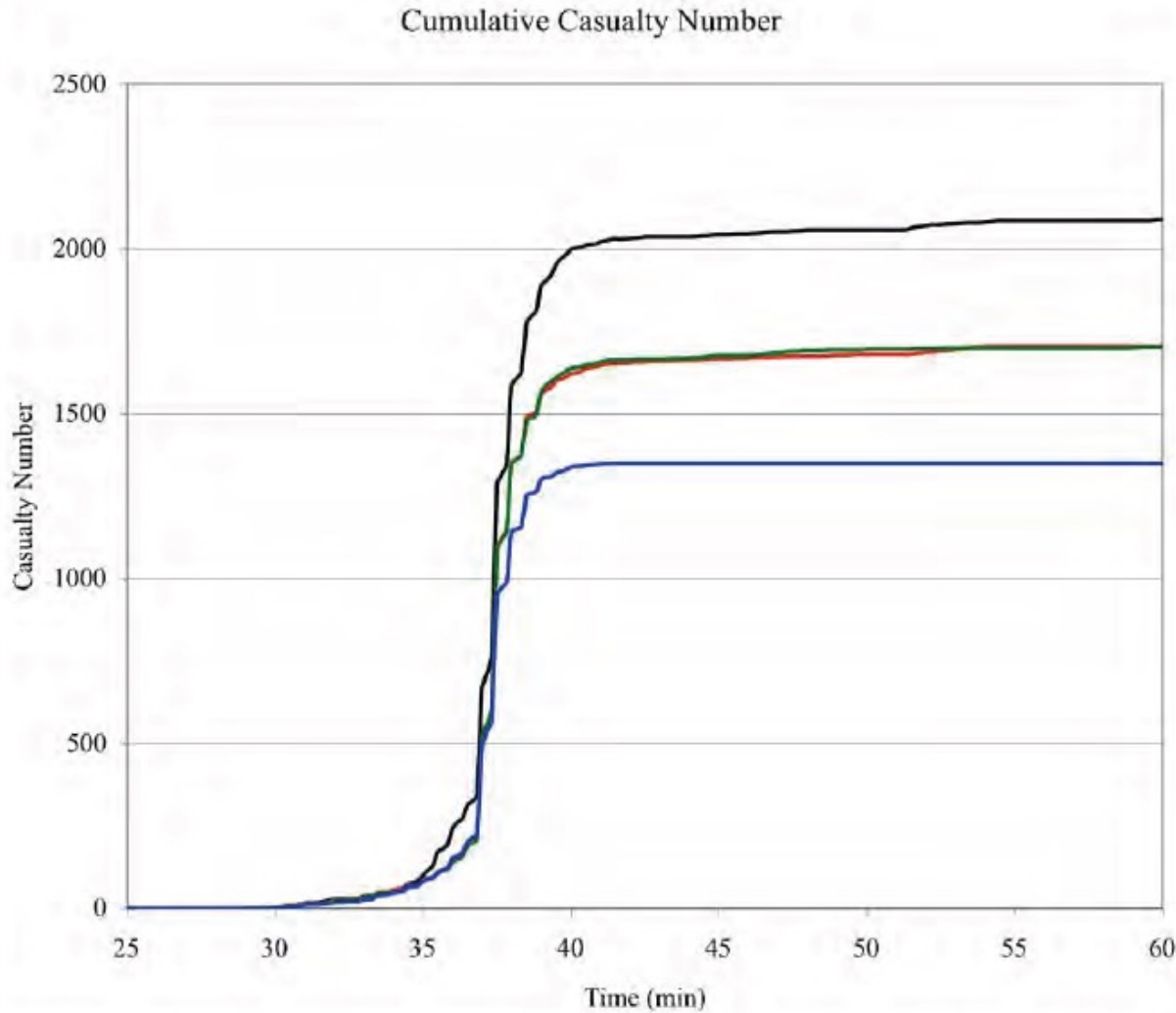
Scenario 2  
Two Refuges



Scenario 3  
Four Refuges

# Long Beach Peninsula Simulation

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



Casualties out of 9097 population

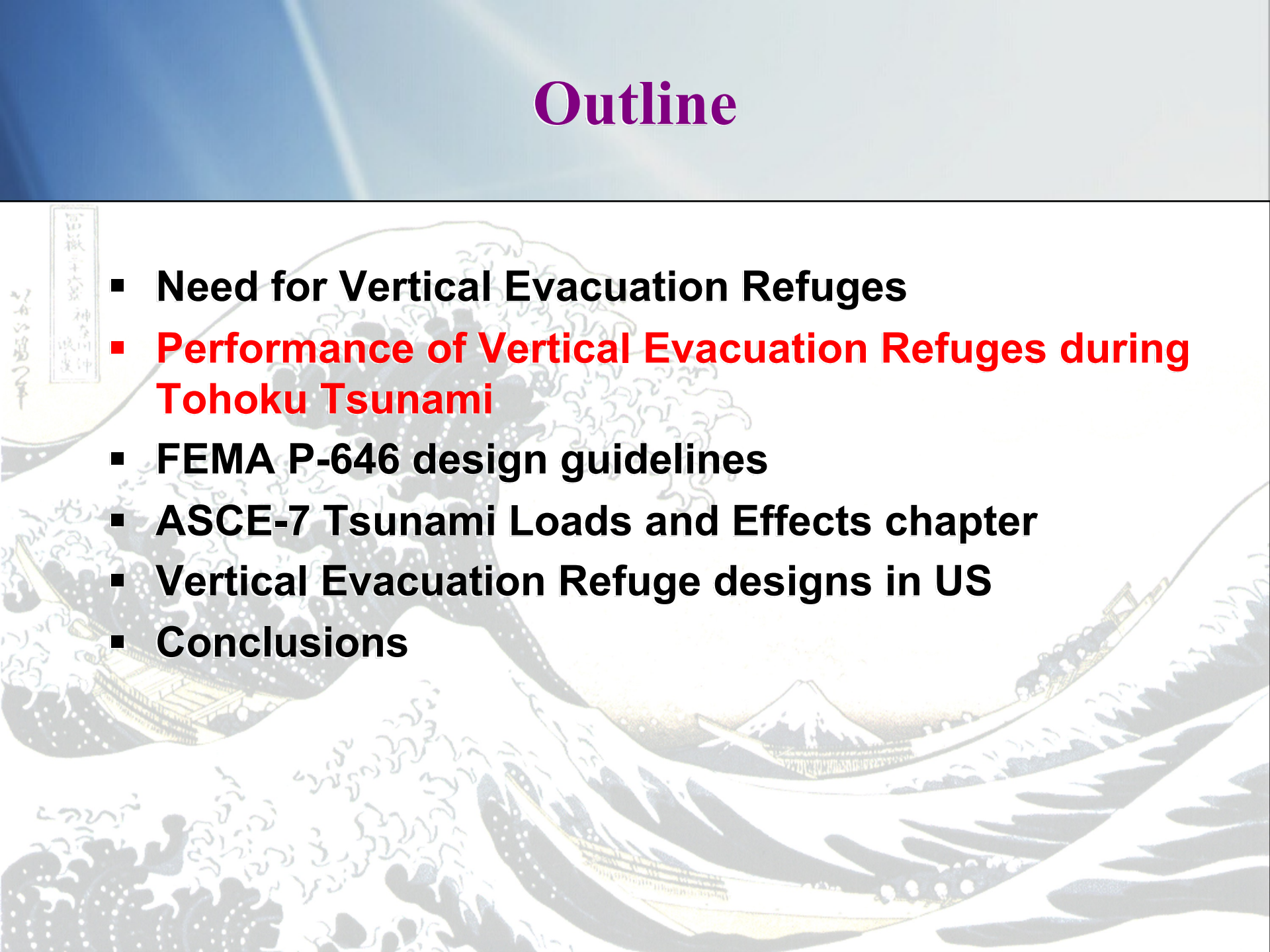
Present Condition - 2077

One refuge – 1711

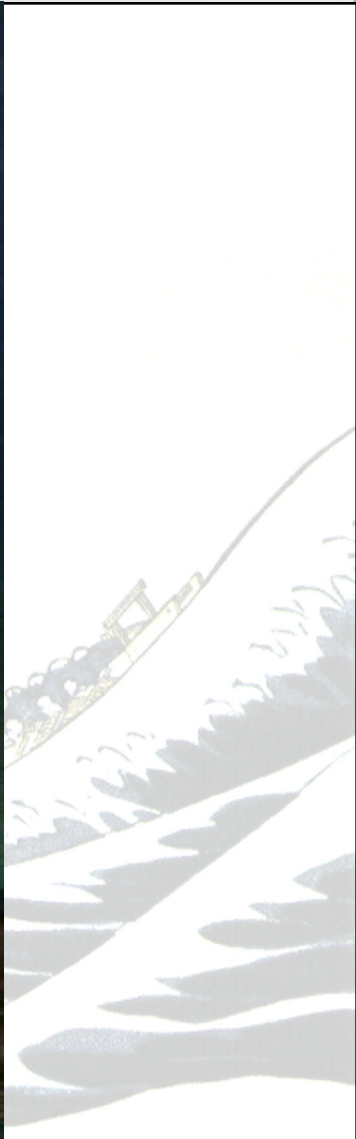
Two refuges – 1717

Four refuges – 1351

# Outline

- 
- The background features a traditional Japanese ink wash illustration of a massive tsunami wave. In the foreground, a boat is shown being tossed by the water. In the distance, Mount Fuji is visible under a pale sky. The style is reminiscent of Edo-period Japanese art.
- **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**

# Evacuation to high ground Kamaishi Example





# Evacuation to high ground Kamaishi Example



# Use of Designated Tsunami Evacuation Buildings

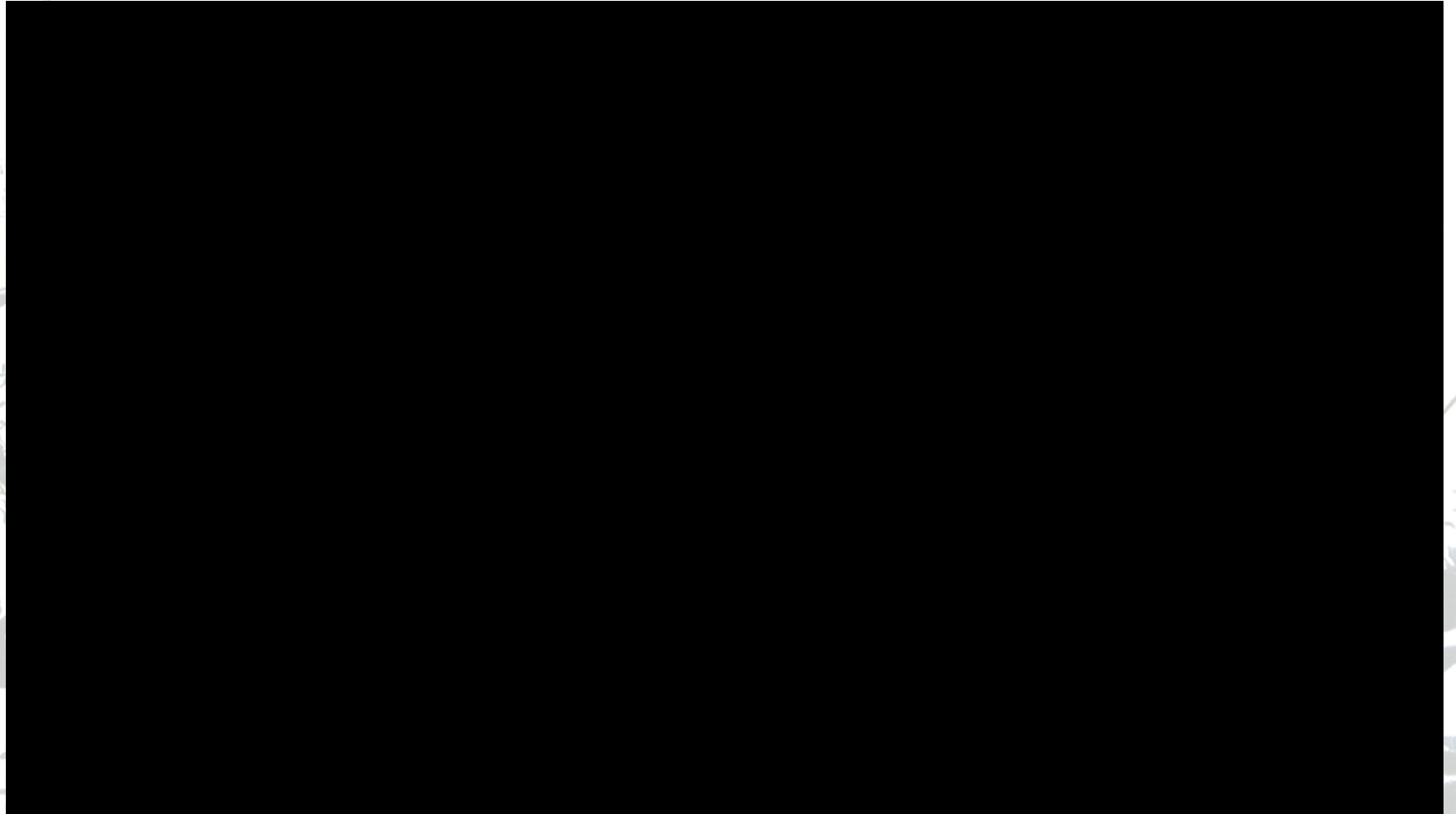


Kamaishi Ship  
Impact

Designated  
evacuation  
building

All buildings  
destroyed

# Kamaishi Survivor Video



# Kamaishi Evacuation Building



# Warning and Evacuation

## Minamisanriku

Middle School

Elementary School

High School

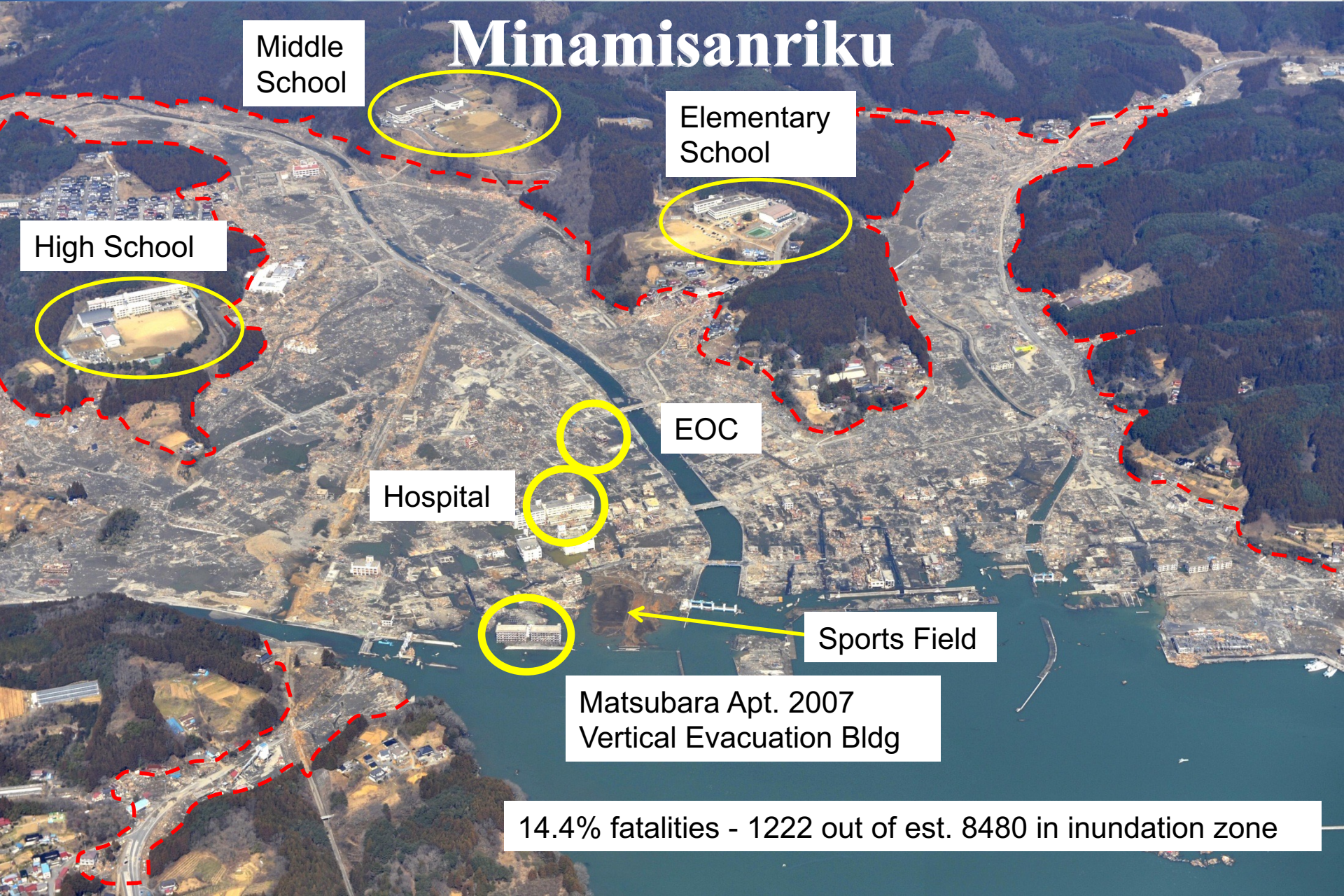
EOC

Hospital

Sports Field

Matsubara Apt. 2007  
Vertical Evacuation Bldg

14.4% fatalities - 1222 out of est. 8480 in inundation zone

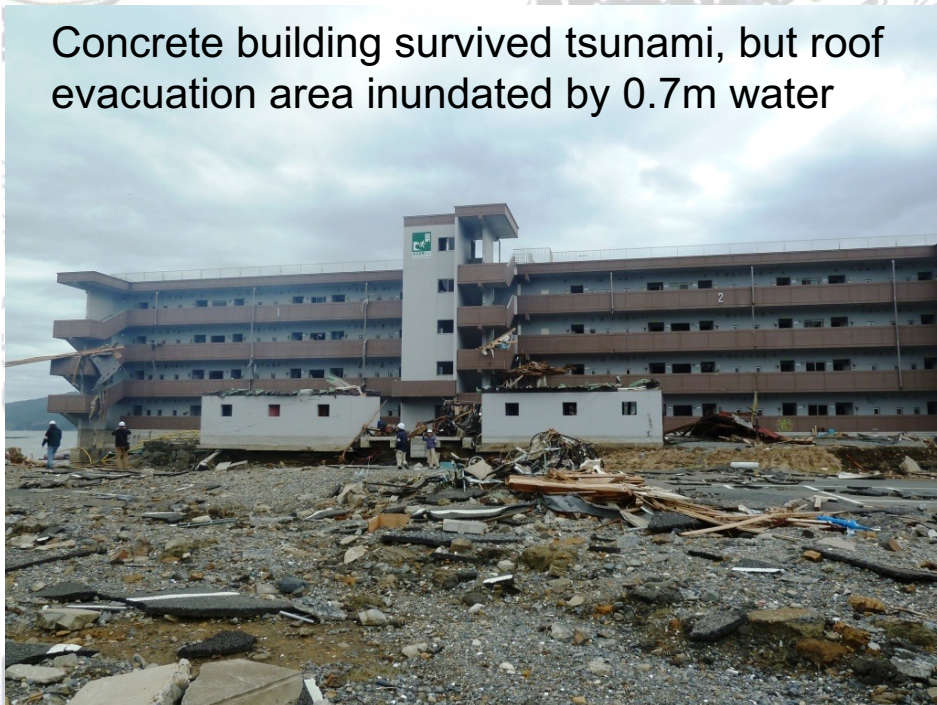


# Effective Vertical Evacuation

## 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)

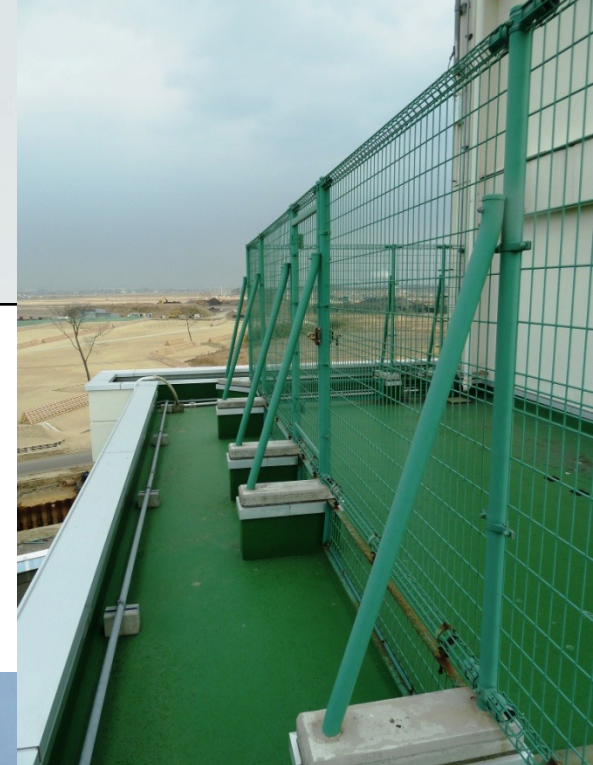


# Minamisanriku Fisheries Cooperative



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

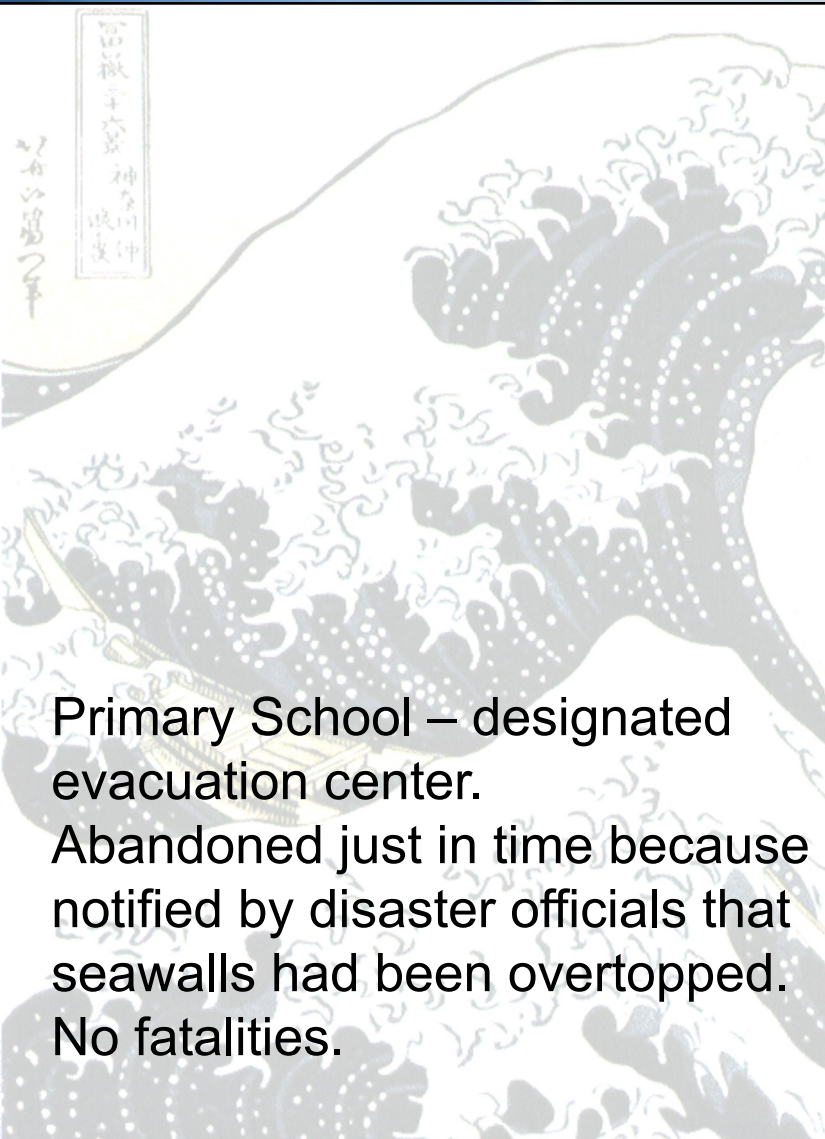
# Arahama Elementary School, Sendai



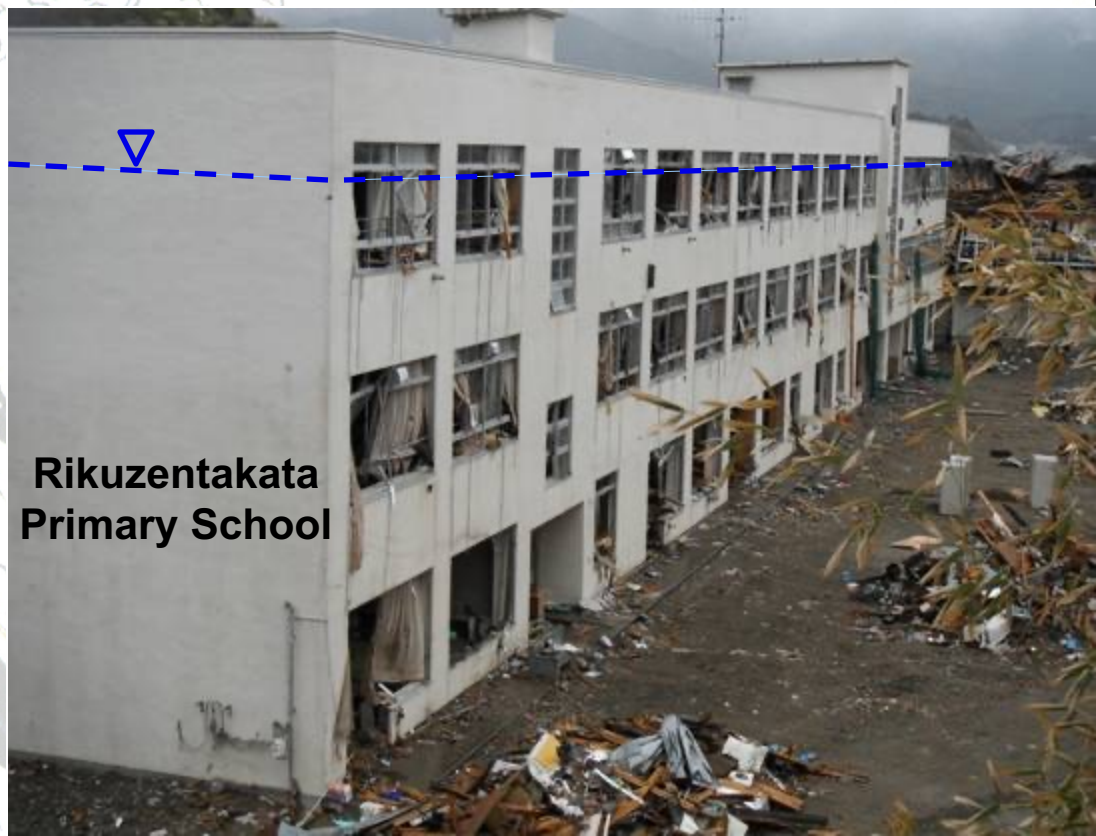
# Rikuzentakata School Building Refuge

## 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  
Primary School



# 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  
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  
I. Matsuo

G.S. Leonard  
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.



Tohoku, Japan, Earthquake and Tsunami of 2011

Performance of Structures under Tsunami Loads



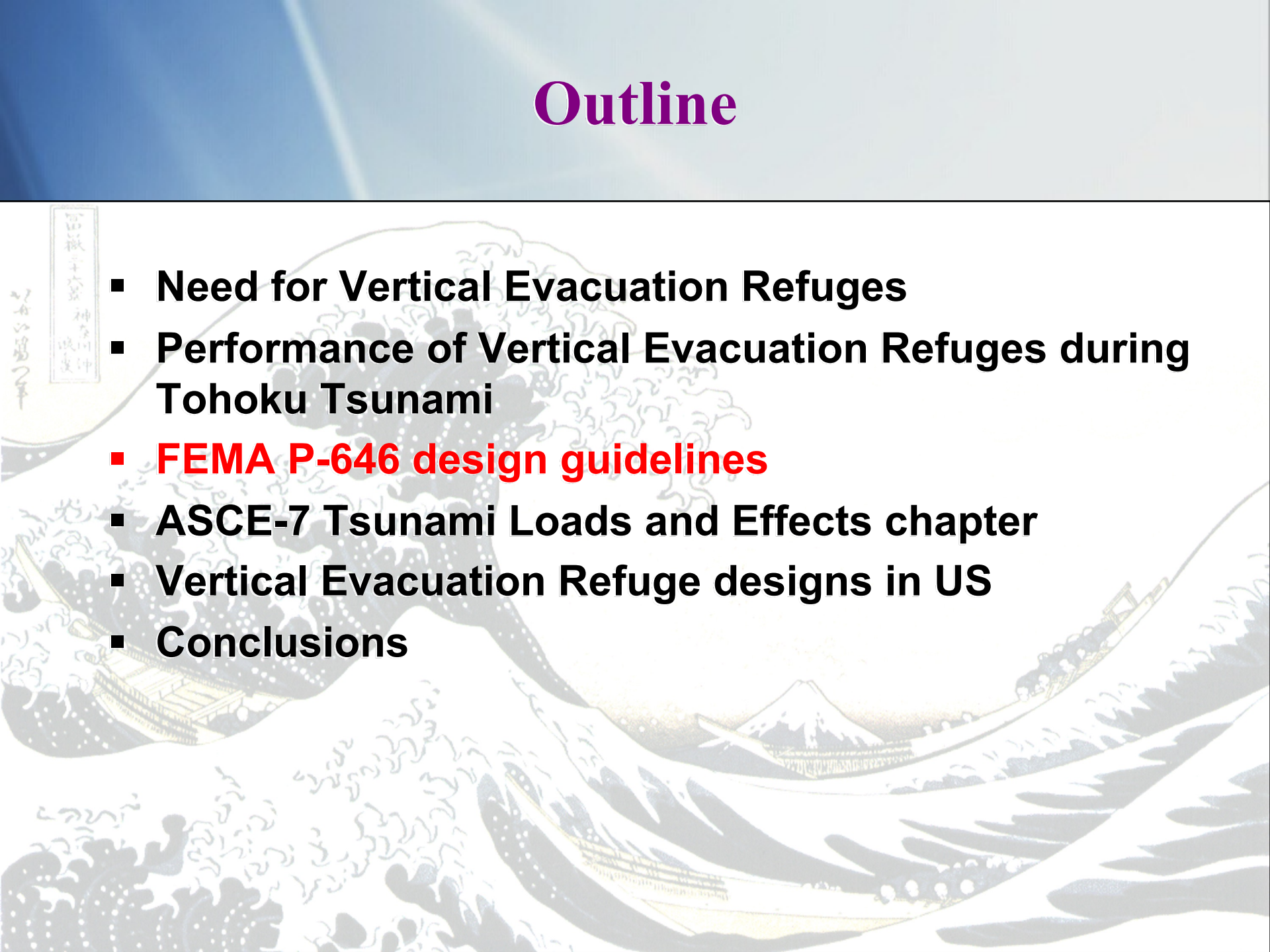
### Tohoku, Japan, Earthquake and Tsunami of 2011

東北地方日本 地震・津波 2011

*Performance of Structures  
under Tsunami Loads*



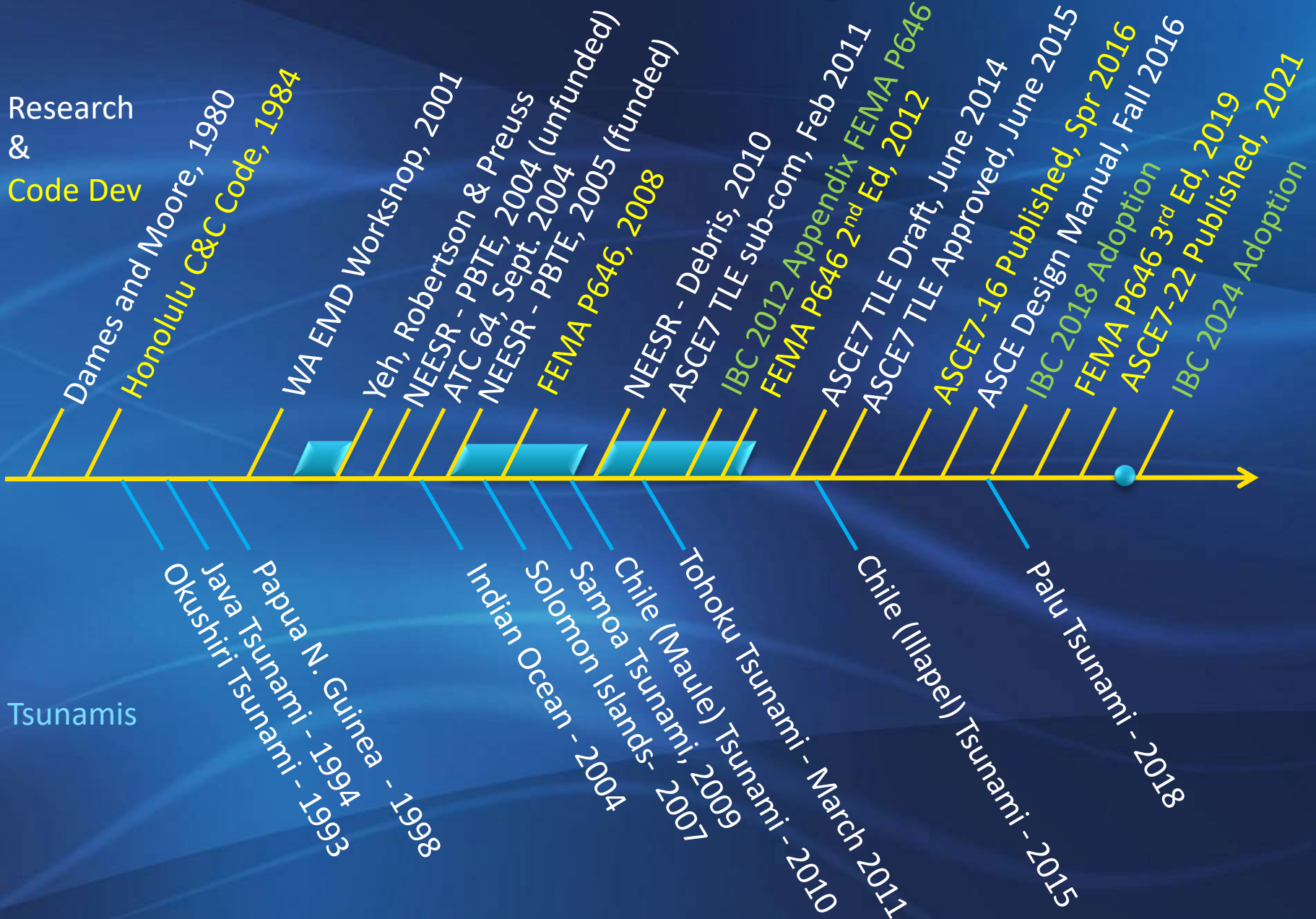
# Outline

- 
- The background features a traditional Japanese ink wash painting of a massive tsunami wave. A boat is shown being tossed by the waves. In the distance, Mount Fuji is visible under a pale sky. On the left side, there is a vertical inscription in Japanese characters: '富田嶽 千六郎 神奈川沖 浪の巻 一八七〇年' (Tomida Taketoki, Kanagawa Bay, Tsunami, 1870).
- **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**

# History of Tsunami Design in the US

Research  
&  
Code Dev

Tsunamis





# 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



## Guidelines for Design of Structures for Vertical Evacuation from Tsunamis

FEMA P646 / June 2008



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

## ■ Project Team

- Steven Baldrige
  - Frank Gonzalez
  - Timothy Walsh
  - Harry Yeh
  - John Hooper
  - Ian Robertson
- 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



# 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**



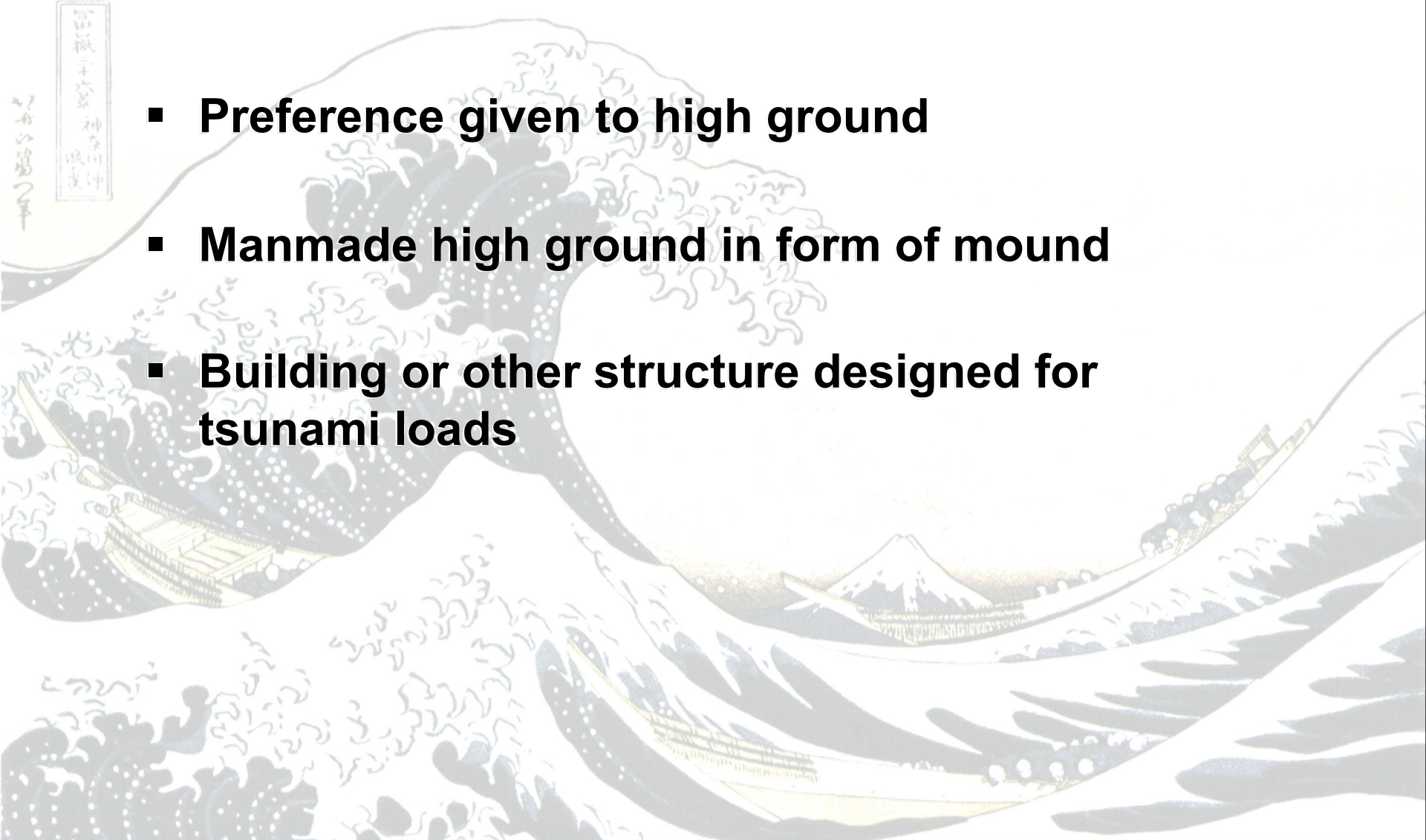
## Guidelines for Design of Structures for Vertical Evacuation from Tsunamis

FEMA P646 / April 2012



# 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



Kesenuma Refuge of Opportunity

# Adjacent Building used as refuge of opportunity

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



Kesenuma 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

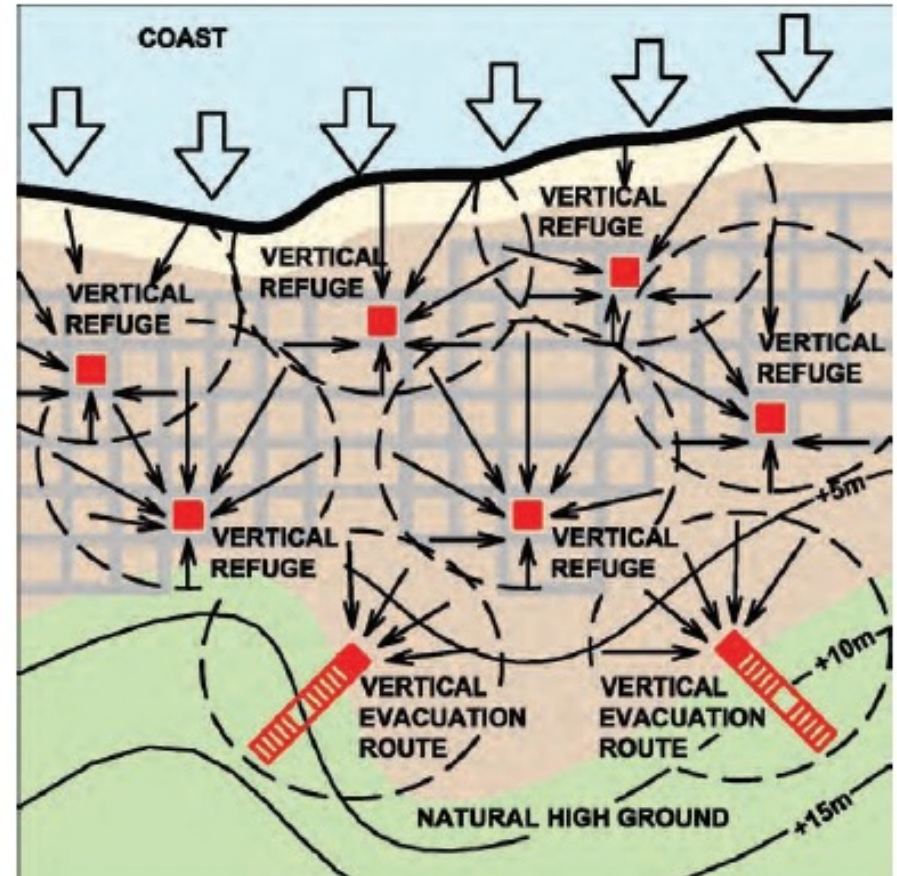


Figure 5-1 Vertical evacuation refuge locations considering travel distance, evacuation behavior, and naturally occurring high ground. Arrows show anticipated vertical evacuation routes.

# Siting and Spacing

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

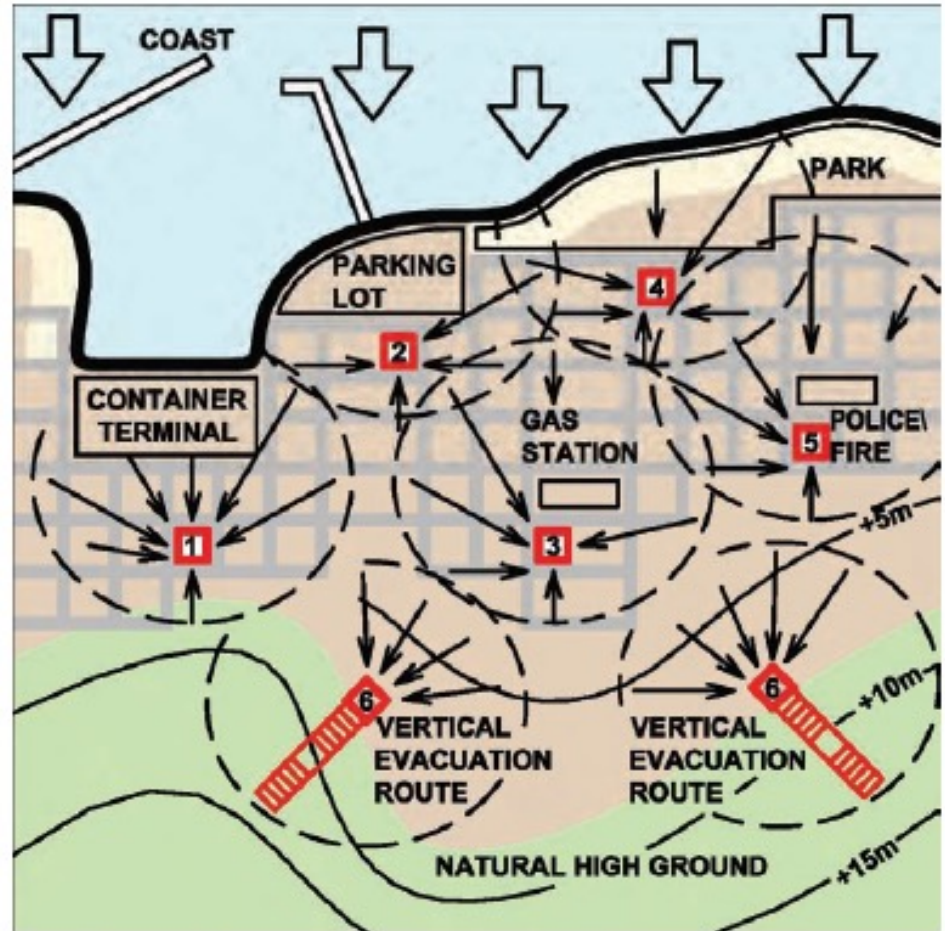
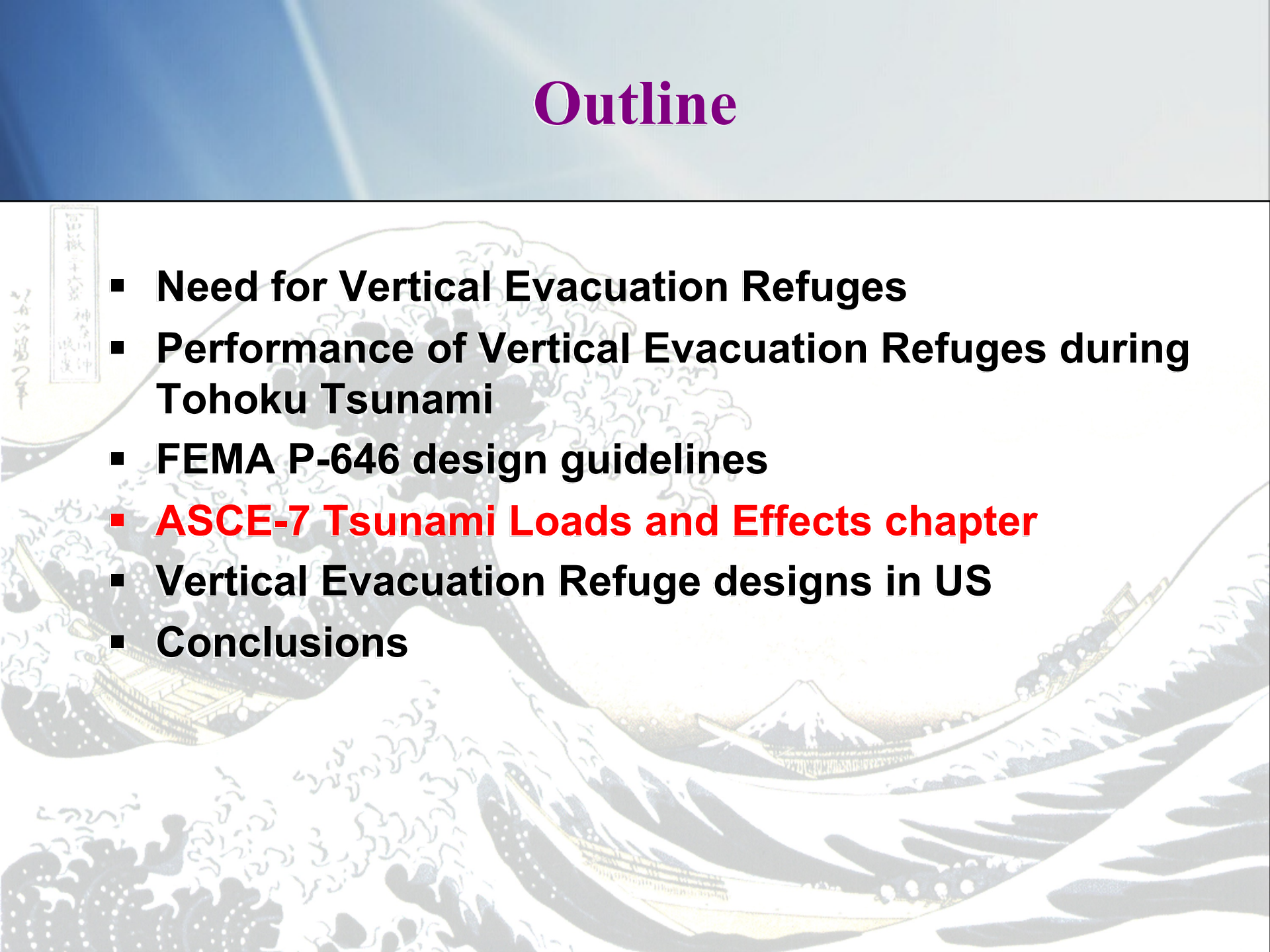


Figure 5-2

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

# Outline

- 
- The background features a traditional Japanese woodblock print style illustration of a massive tsunami wave. A boat is shown being tossed by the waves. In the distance, Mount Fuji is visible under a pale sky. On the left side, there is a vertical inscription in Japanese characters: '富田 敬子 六郎 神奈川 磯波'.
- **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**

# 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

## 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

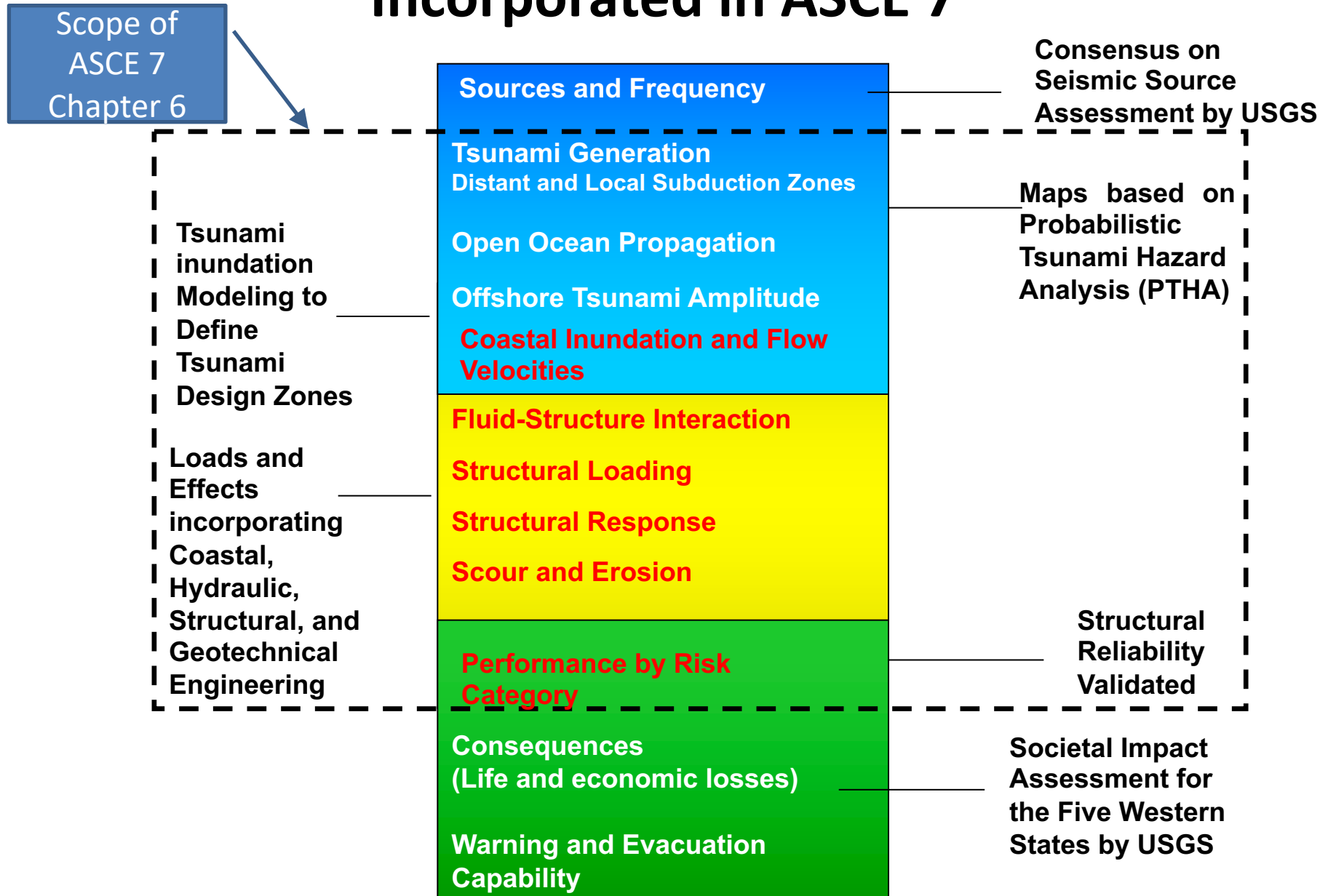
# ASCE 7-10

## 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

<b>Risk Category I</b>	<b>Up to 2 persons affected</b> (e.g., agricultural and minor storage facilities, etc.)
<b>Risk Category II</b> (Tsunami Design Optional)	<b>Approximately 3 to 300 persons affected</b> (e.g., Office buildings, condominiums, hotels, etc.)
<b>Risk Category III</b> (Tsunami Design Required)	<b>Approximately 300 to 5,000+ affected</b> (e.g., Public assembly halls, arenas, high occupancy educational facilities, public utility facilities, etc.)
<b>Risk Category IV</b> (Tsunami Design Required)	<b>Over 5,000 persons affected</b> (e.g., hospitals and emergency shelters, emergency operations centers, first responder facilities, air traffic control, toxic material storage, etc.)

# Risk Category II Buildings

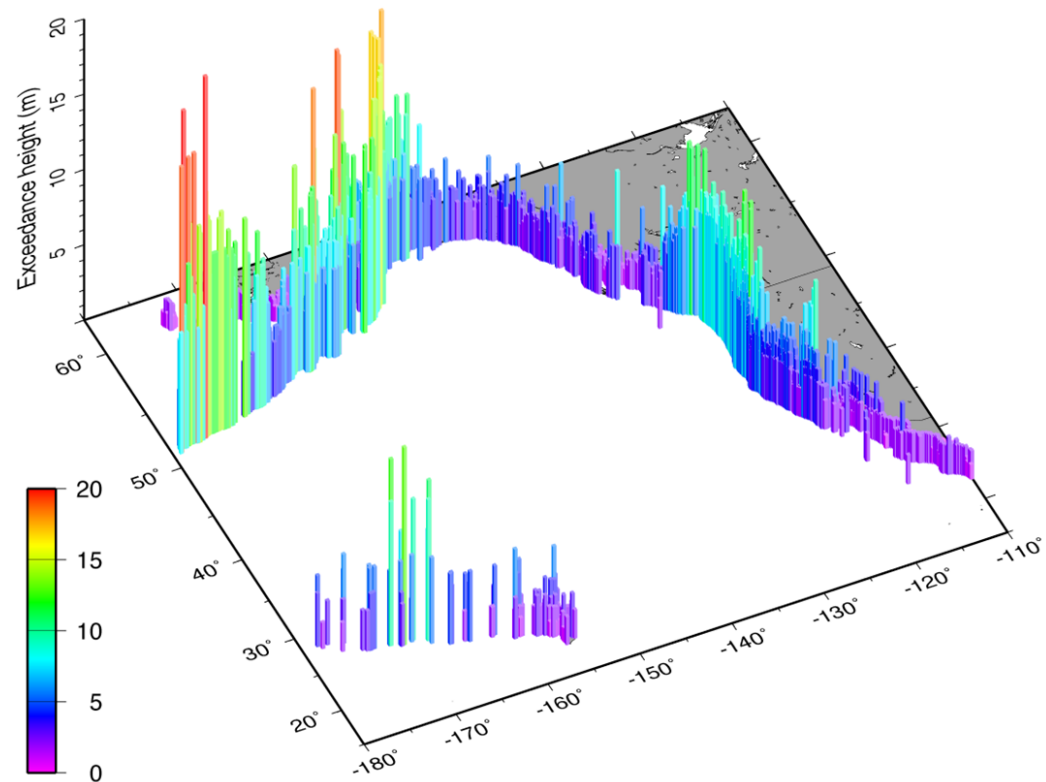
## – Determined by Local Code Adoption

- 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.

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

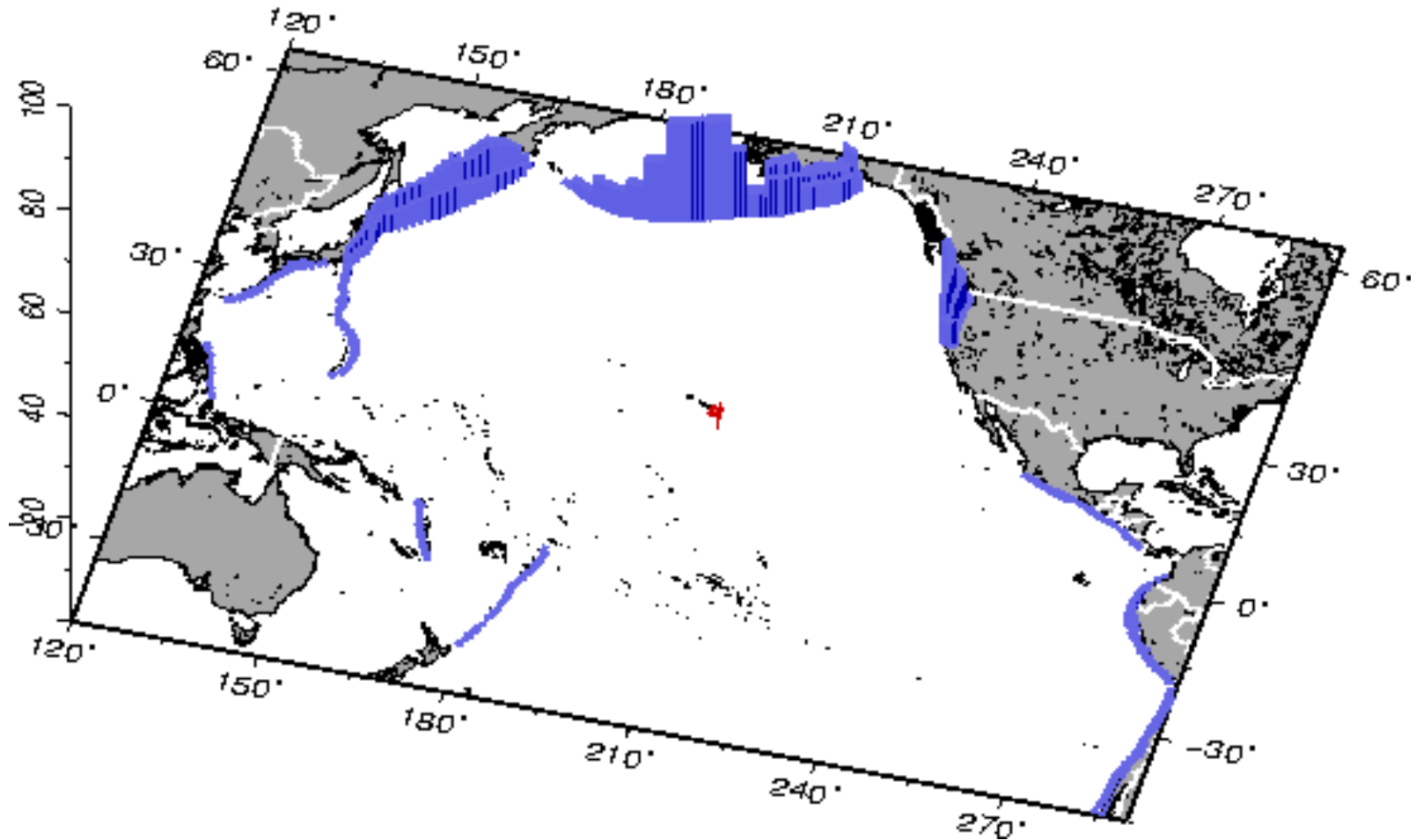
- Recorded history may not provide a sufficient measure of the potential heights of great tsunamis.
- Design must consider the occurrence of events greater than in the historical record
- Therefore, probabilistic physics-based Tsunami Hazard Analysis should be performed in addition to historical event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

Exceedance waveheights: 2500 yr

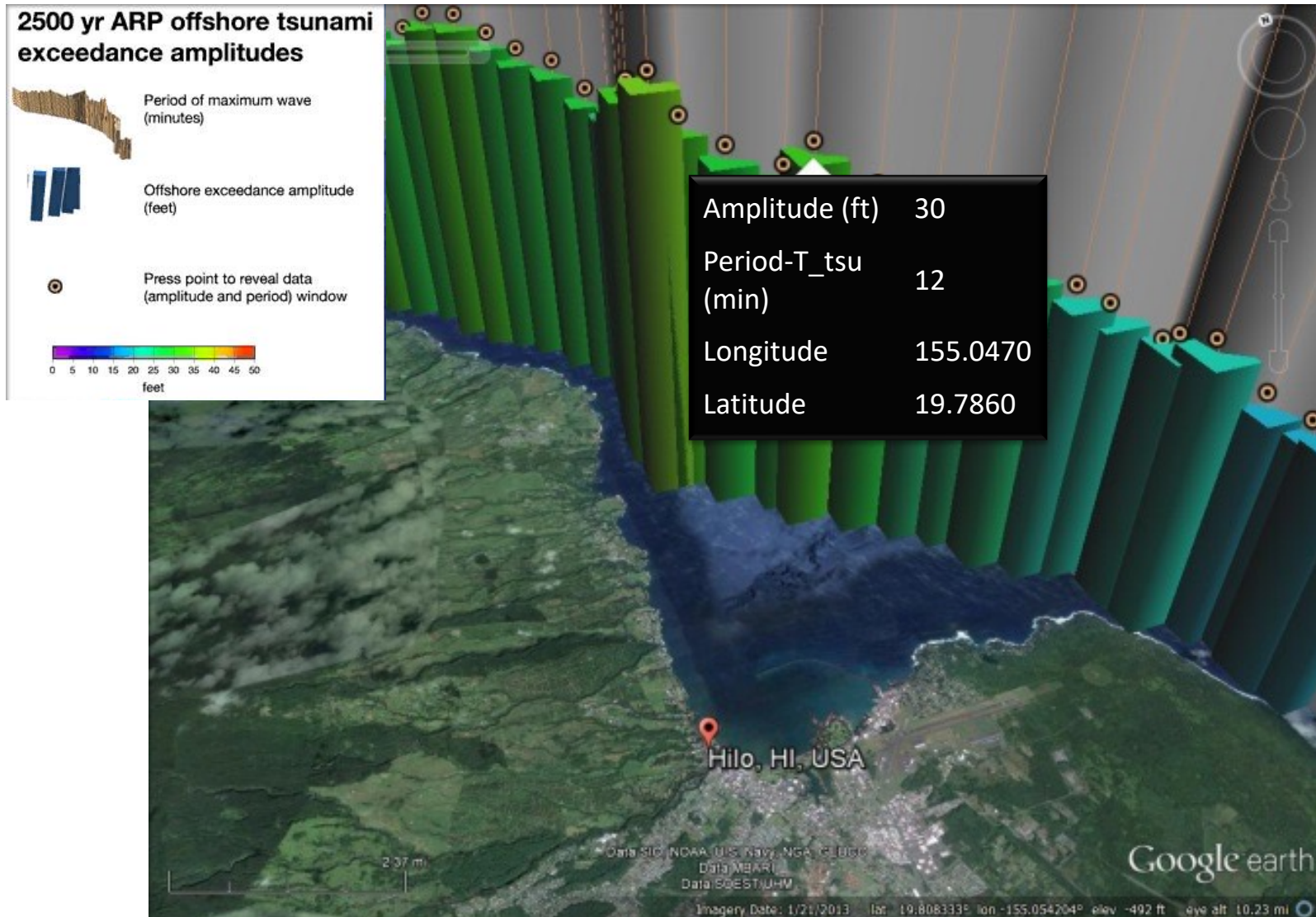


# Disaggregated Hazard for Hilo, HI

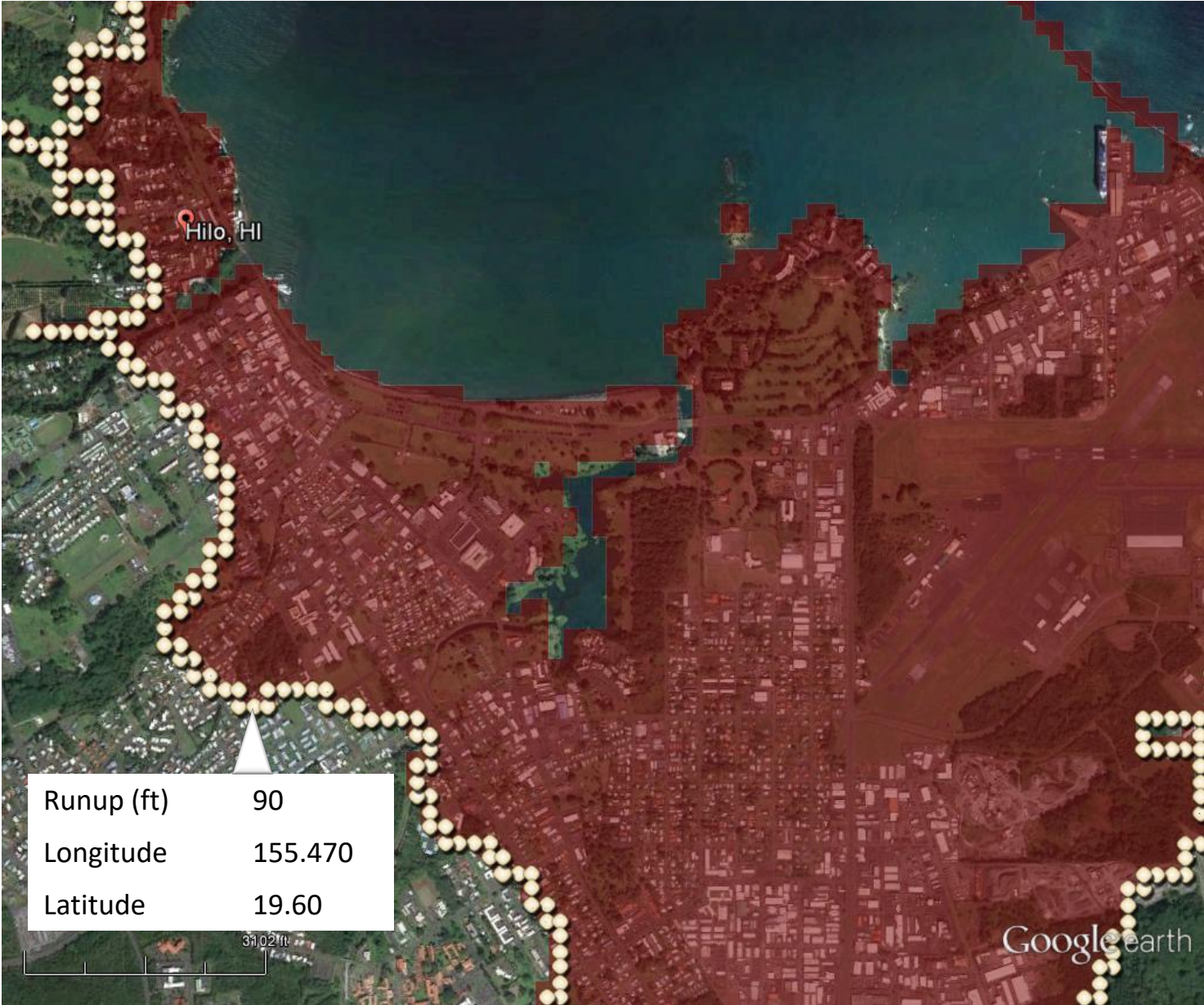
- Sources: Aleutian, Alaska, and Kamchatka-Kurile



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



# Tsunami Design Zone - Hilo





# 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

# Structural Loads



# Tsunami Loads and Effects

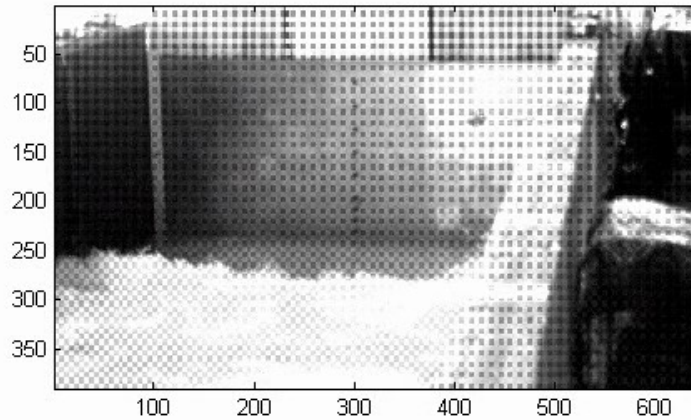
- Hydrostatic Forces (equations of the form  $k_s \rho_{sw} gh$ )
  - Unbalanced Lateral Forces at initial flooding
  - Buoyant Uplift based on displaced volume
  - Residual Water Surcharge Loads on Elevated Floors
- Hydrodynamic Forces (equations of the form  $\frac{1}{2} k_s \rho_{sw} (hu^2)$ )
  - 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)

# NEESR – Development of Performance Based Tsunami Engineering, PBTE

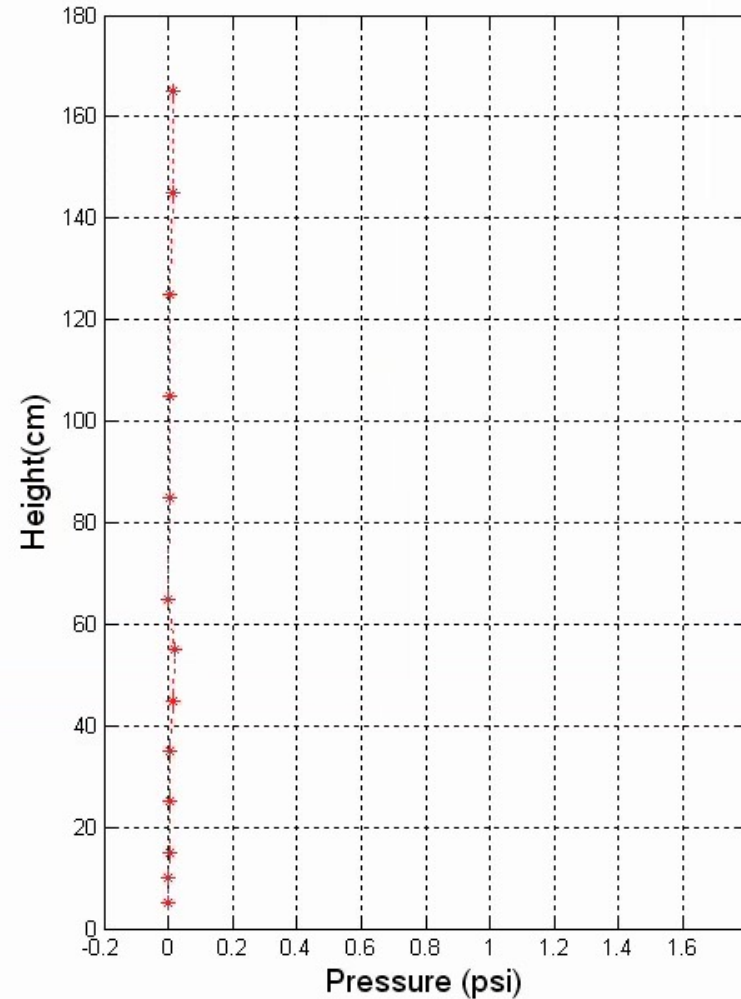


# NEESR – Development of Performance Based Tsunami Engineering, PBTE

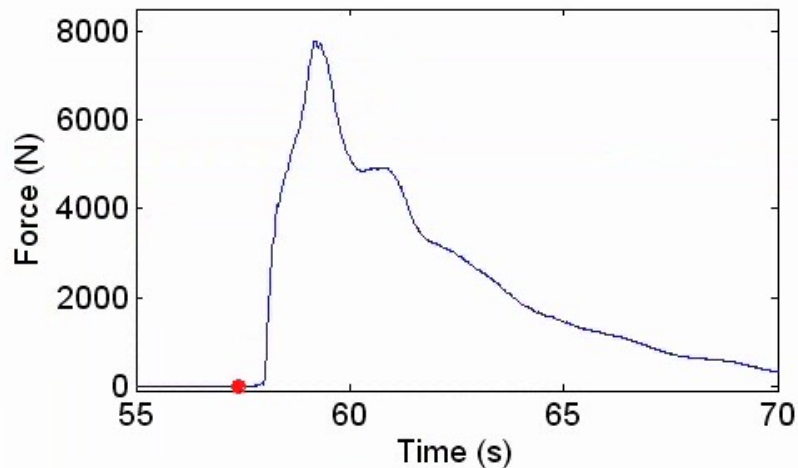
BS2-W-WL30: Trial 4: H=106.4cm



Pressure

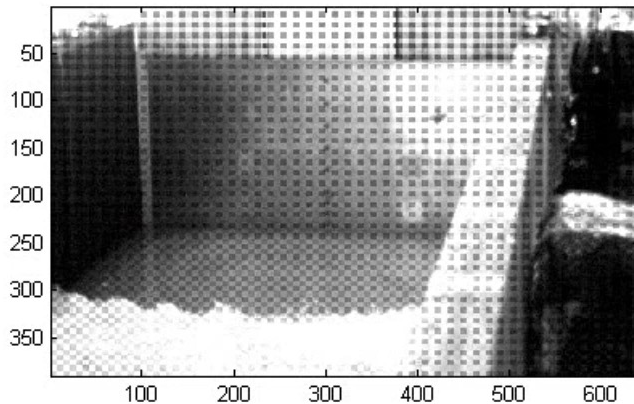


Total Force



# NEESR – Development of Performance Based Tsunami Engineering, PBTE

BS2-W-WL30: Trial 4: H=106.4cm



5 165];

Total Force

8000

```
65 - figure('Color','w')
```

```
video_force_pressure_sync.m x video_force_pressure_sync.m x
```

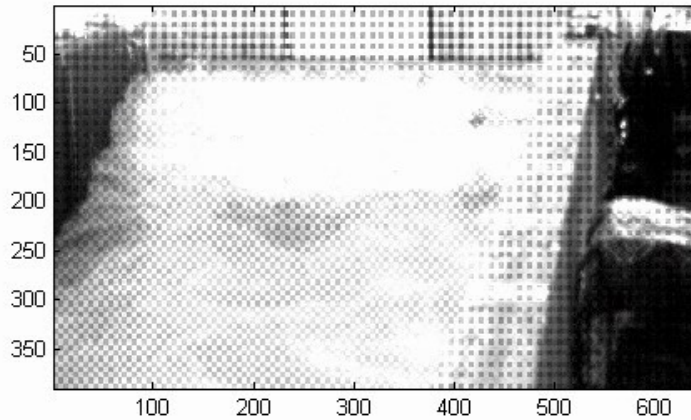
Command Window

```
>>  
for i=aa:11:(550*15)+aa;  
    F_T(i)=Total_F(i);  
    P_T(i,:)=P(i,:);  
    F_Total=[F_Total;F_T(i)];  
    P_Total=[P_Total;P_T(i,:)];  
    Tt(i)=t(i);  
    tt=[tt,t(i)];  
end  
??? Undefined function or variable "P Total".
```

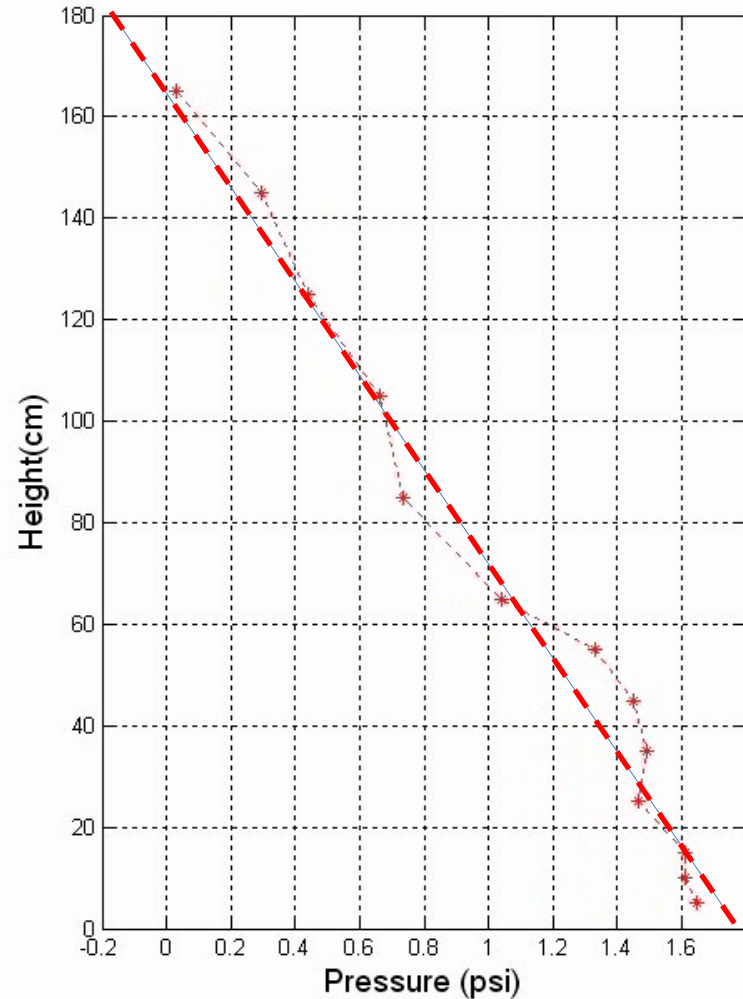
# NEESR - Structural Loading

## Direct Bore Impact on Solid Wall

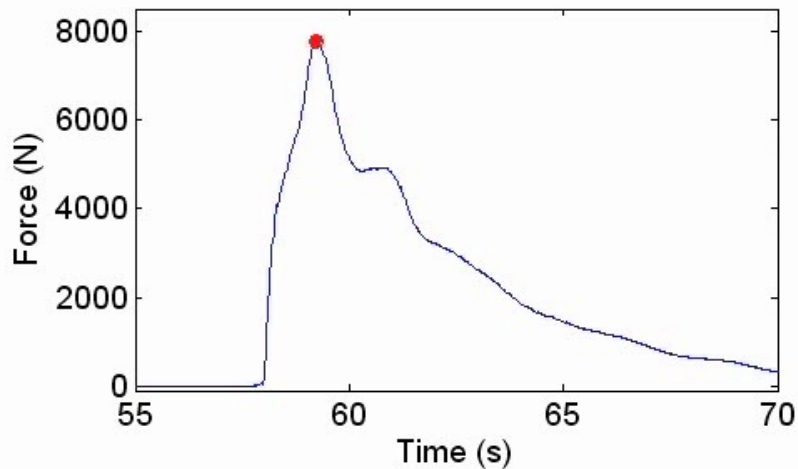
BS2-W-WL30: Trial 4: H=106.4cm



Pressure



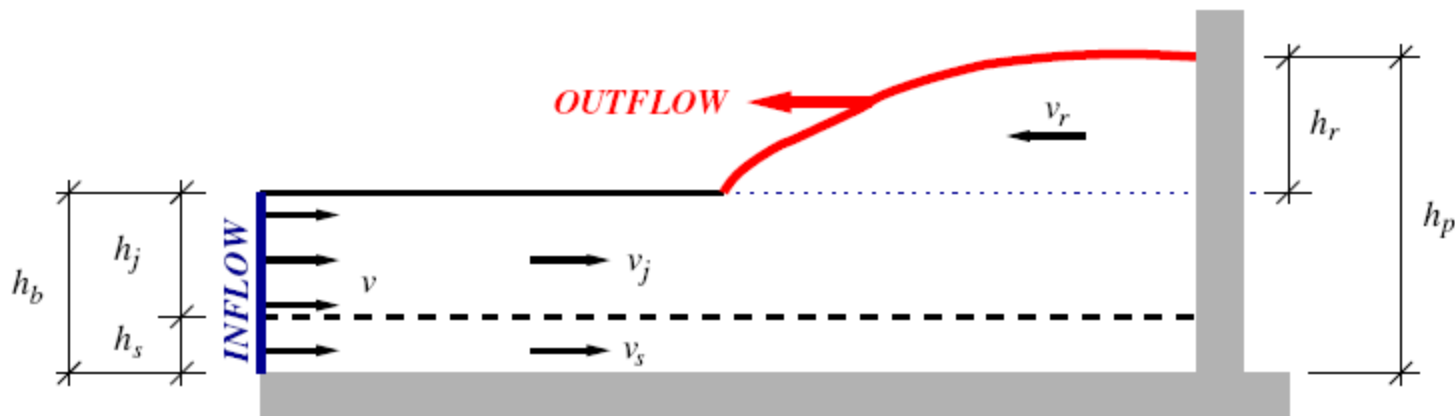
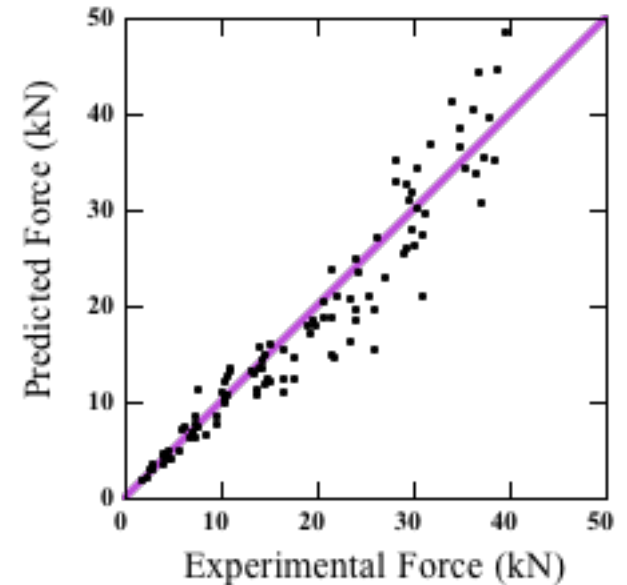
Total Force



# 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



**Minami Gamou Wastewater Treatment Plant - subjected to direct bore impact**

# Sendai Bore Strike on R/C Structure



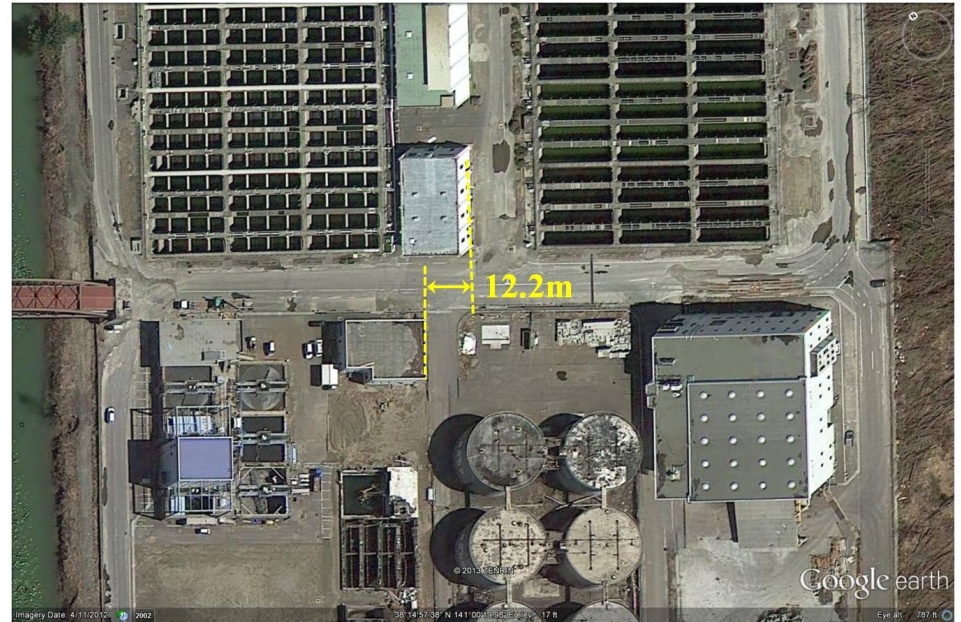
# Velocity Analysis



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**

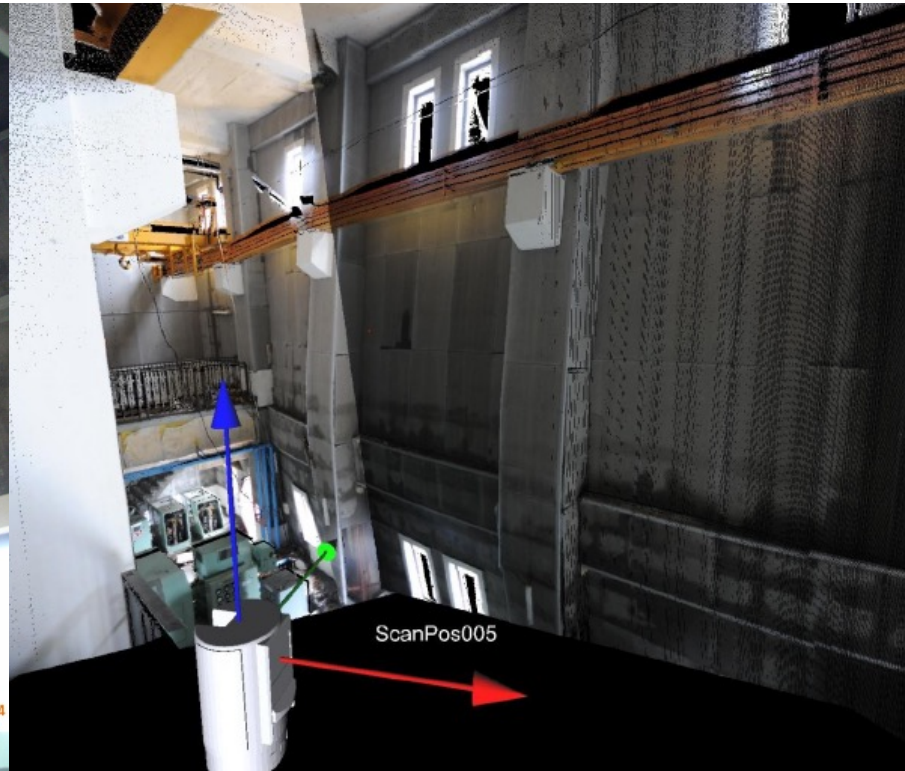


**Structural drawings obtained from the  
Wastewater Treatment Plant**

# Bore Strike on R/C Structure



Interior view of 2-story wall



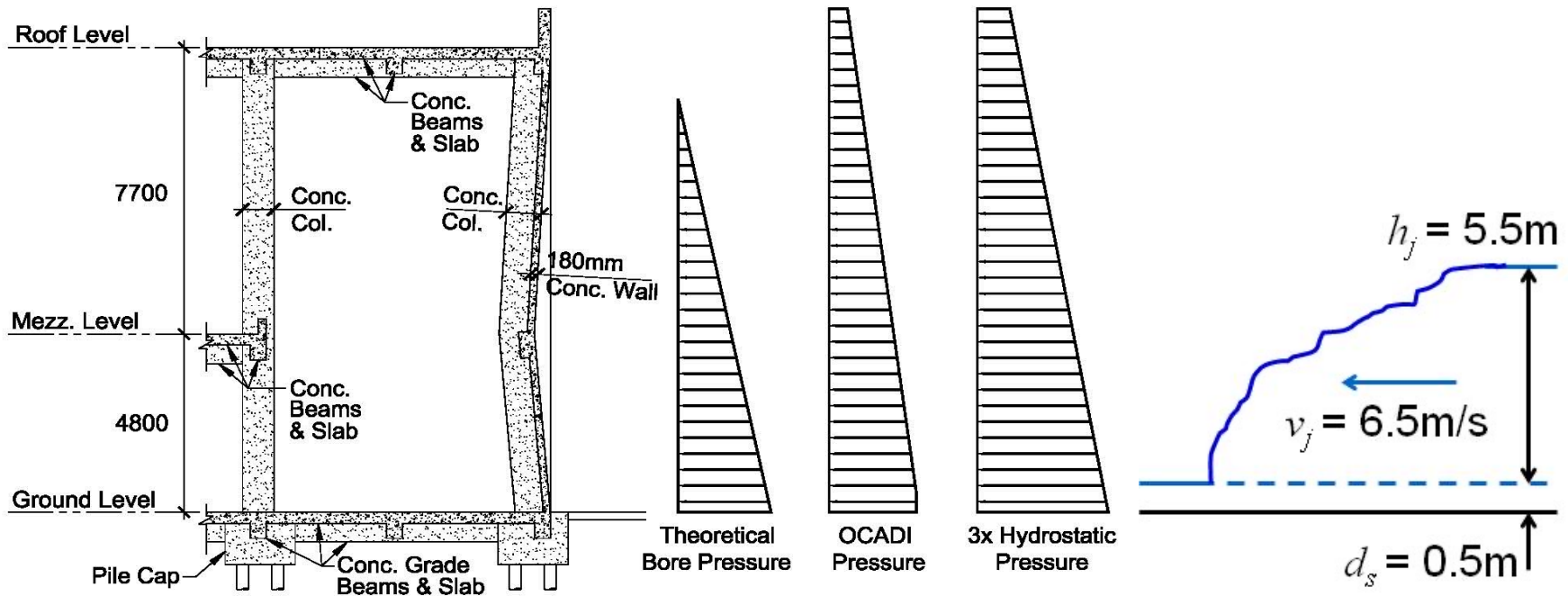
Lidar scan of 2-story wall

**Minami Gamou Wastewater Treatment Plant**

# Bore Impact Forces

## Minami Gamou Treatment Plant

- Comparison with Different Bore Pressures used in Japan Tsunami Standards

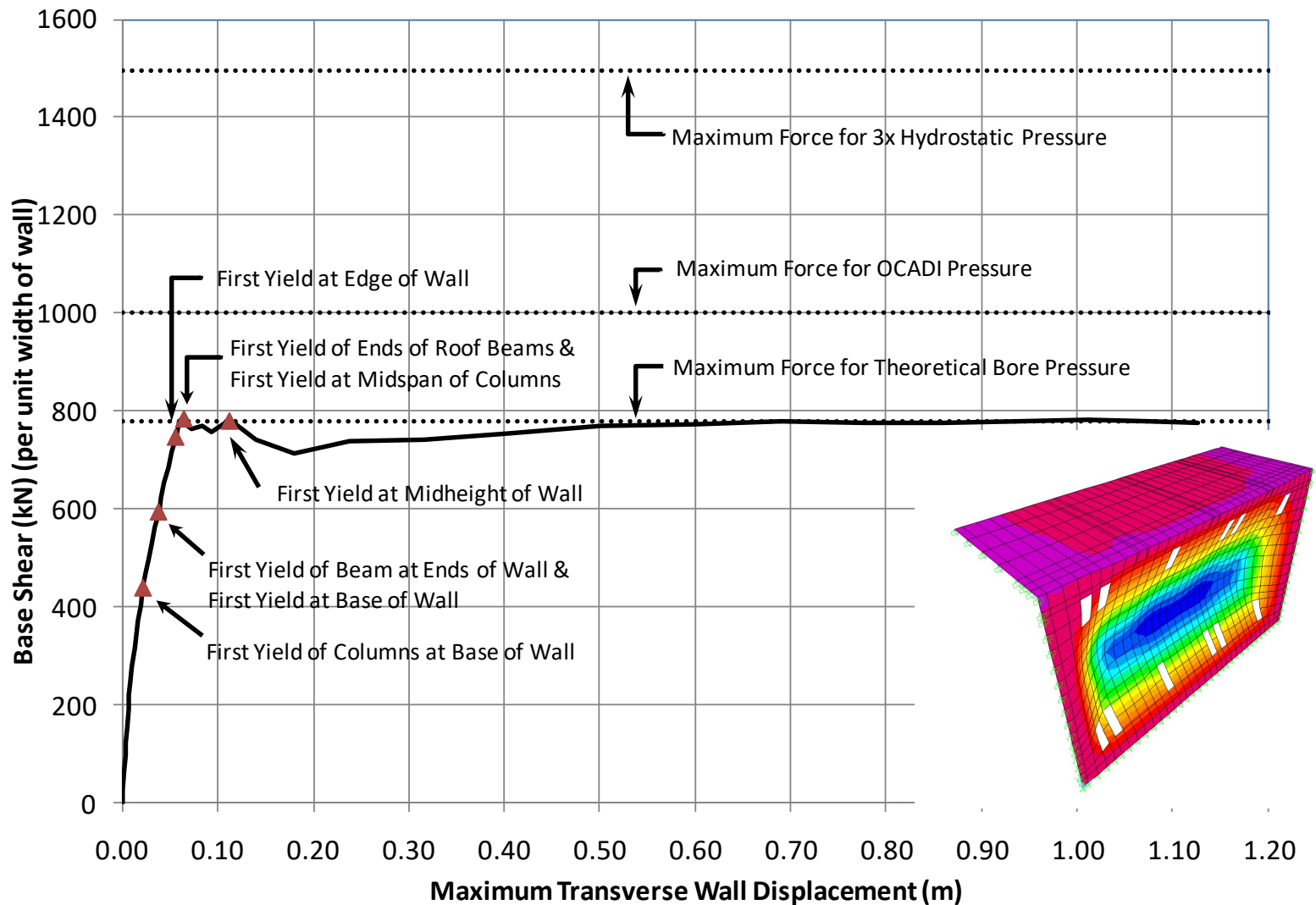


$$F_w = \rho_{sw} \left( \frac{1}{2} g h_b^2 + h_j v_j^2 + g^{1/3} (h_j v_j)^{4/3} \right)$$

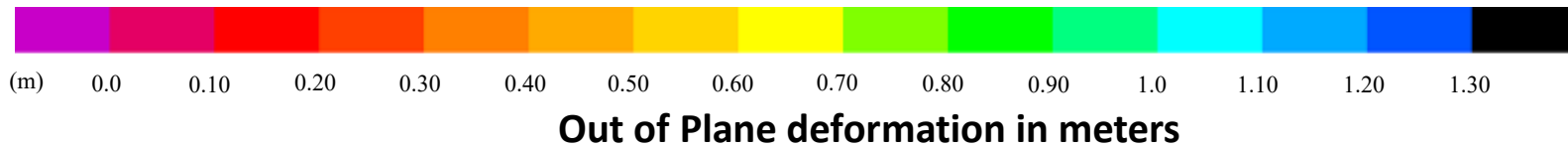
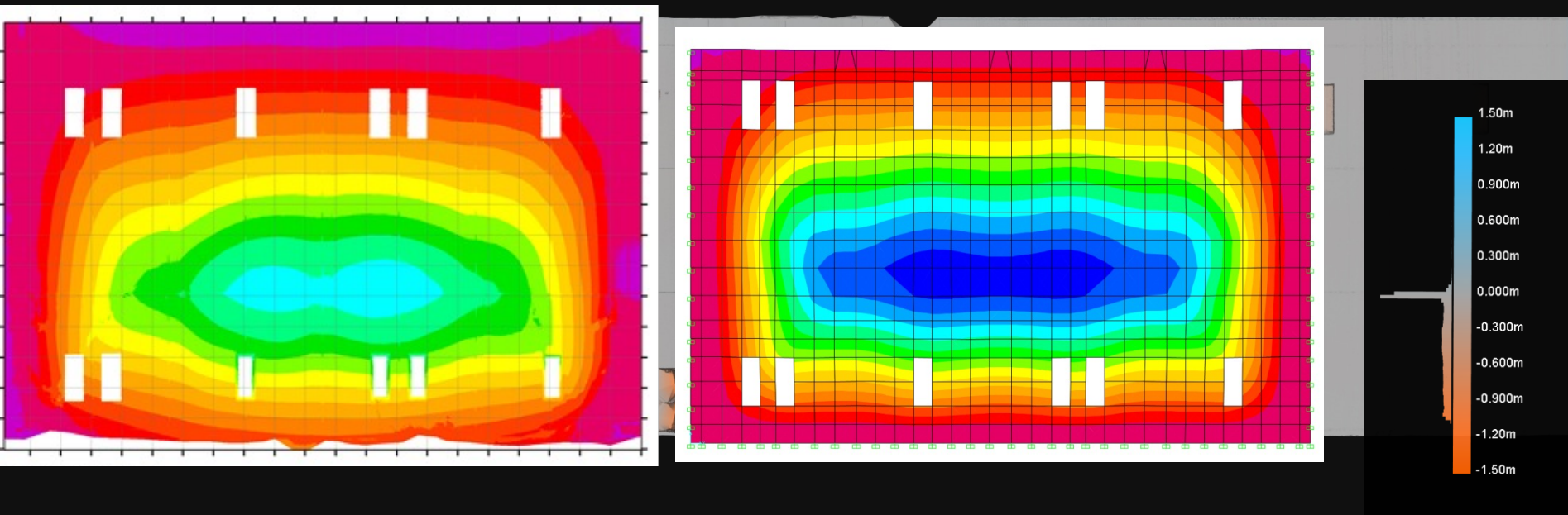
$$h_b = h_j + d_s = 6.0\text{m}$$

# Bore Impact Forces

## Non-linear Finite Element Analysis



# FEA compared with Lidar scan



**Minami Gamou Wastewater Treatment Plant - subjected to direct bore impact**

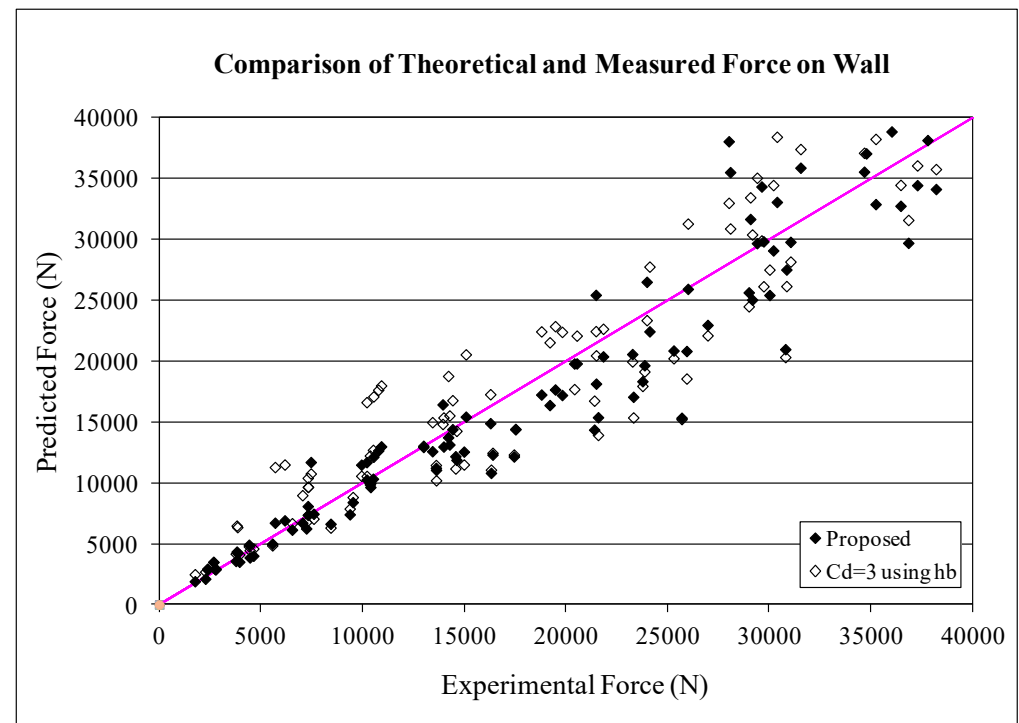


# Simplified Equation for Impulse Load

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

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

$$F_d = 1.5 \left( \frac{1}{2} k_s \rho_{sw} C_d b h u^2 \right)$$



# 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



(Samoa)

(Japan)

# 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)

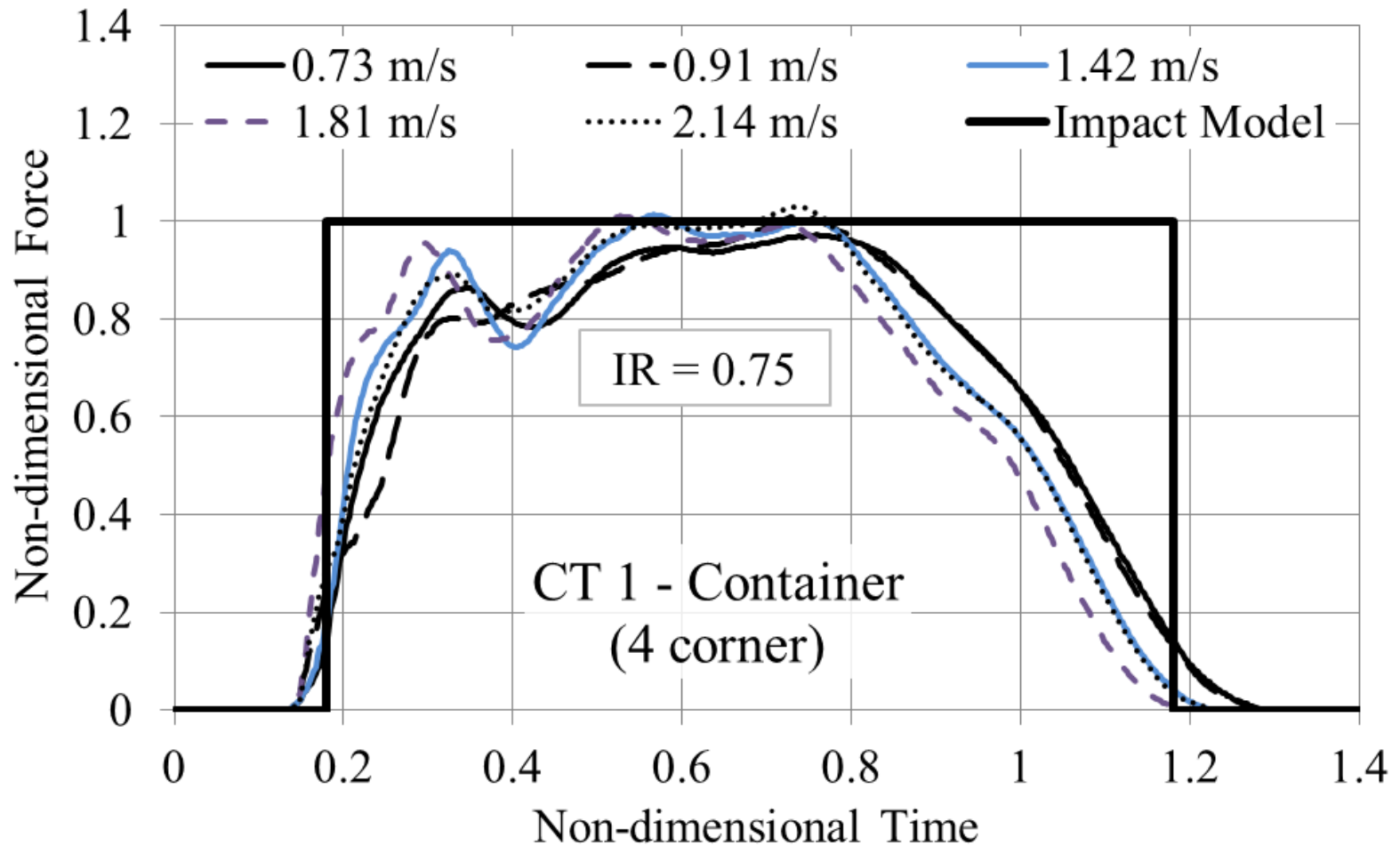


# Shipping Container Impact

[Video](#)



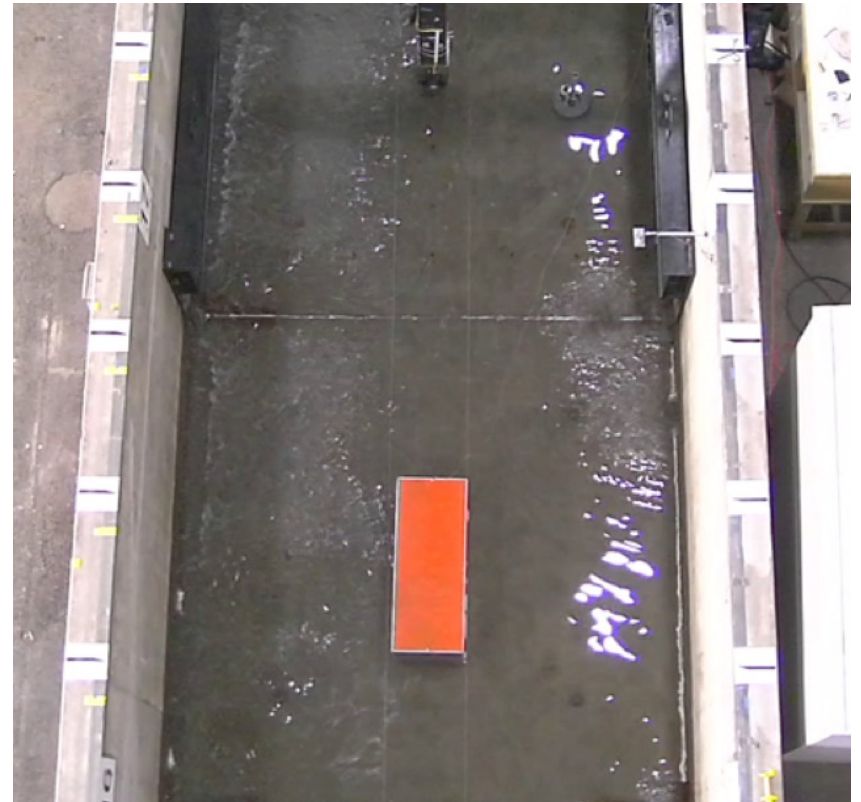
# Impact Force Time History





# 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



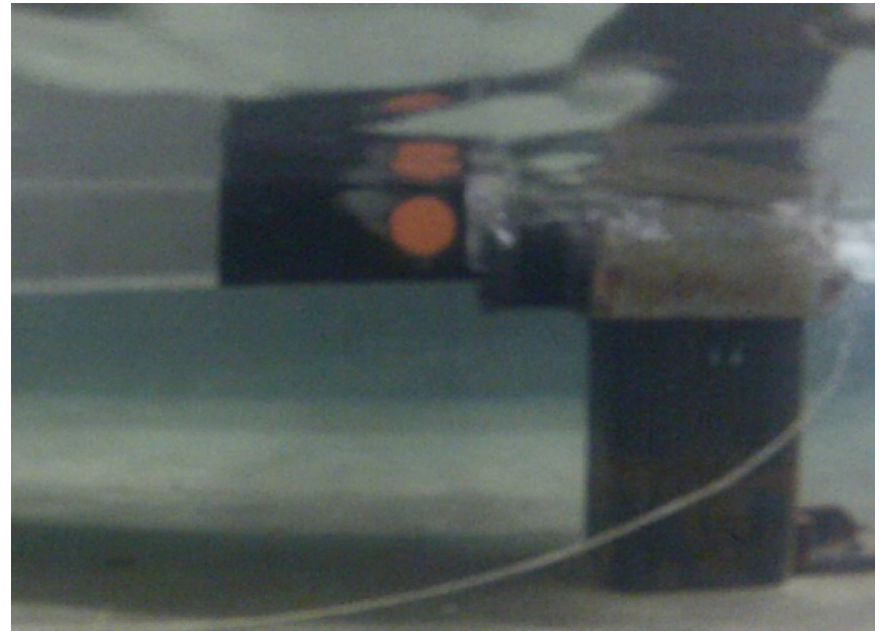
Column and load cell at top of photo

# 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

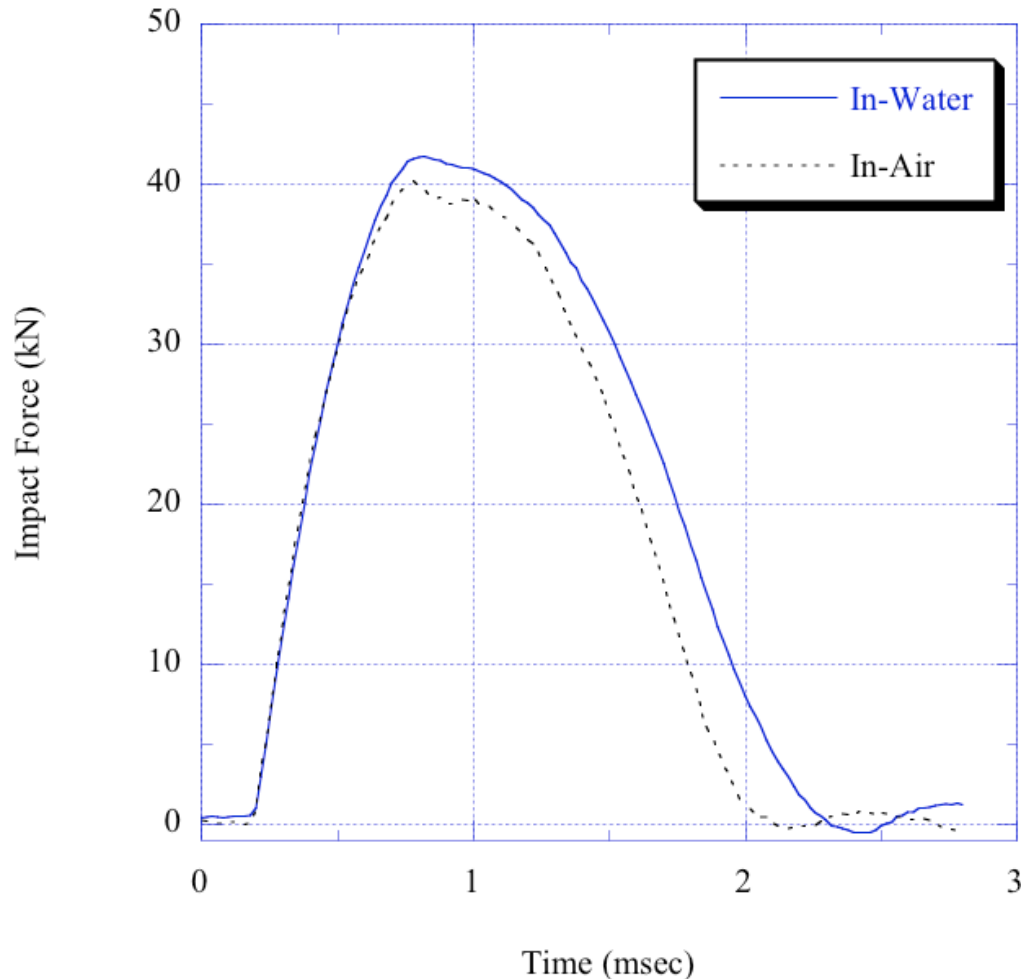


# Side View



# 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:  $F_i = 330C_o I_{TSU}$

- Wooden Log:  $F_i = 165C_o I_{TSU}$

- Where:  $C_o = 0.65$ , Impact orientation factor

- Contents increase impact duration but not force

# Impact induced Progressive Collapse

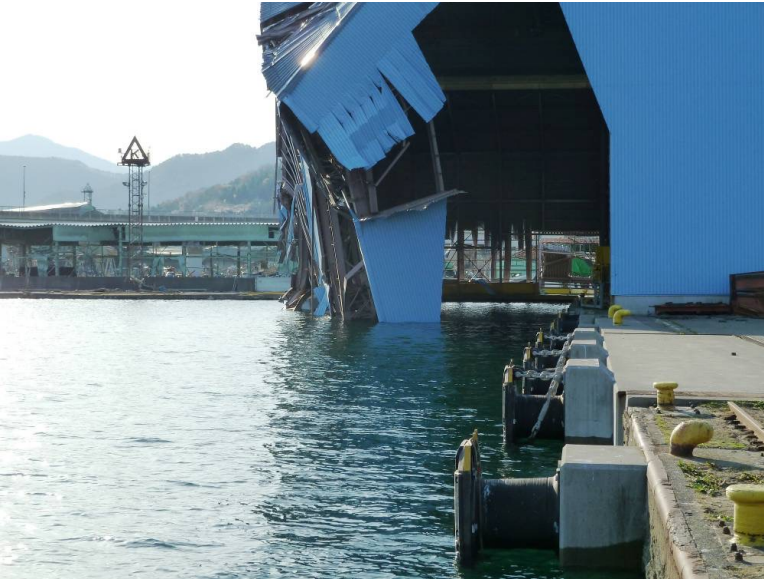


# Ship Impact – Sendai Port





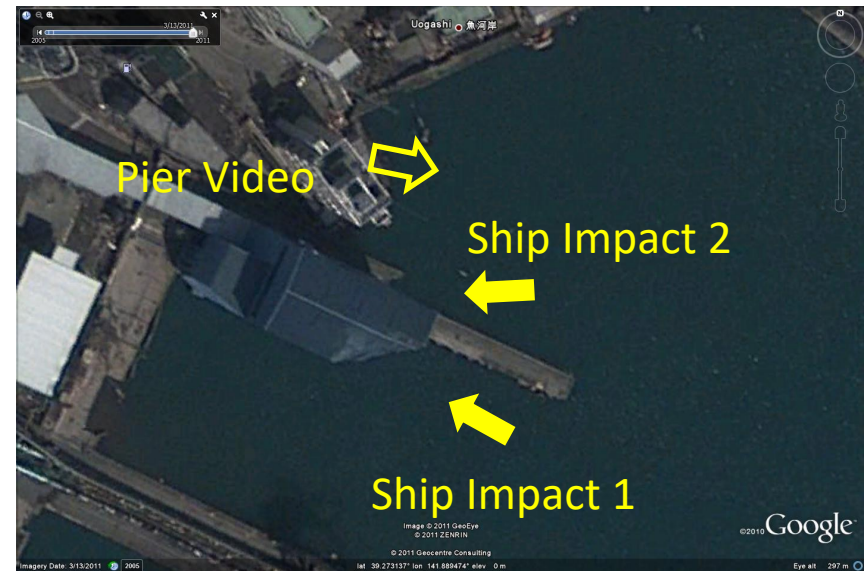
# Ship Impact damage - Kamaishi



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

# Kamaishi Ship Impact



# Ship Velocity



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

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

# 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

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

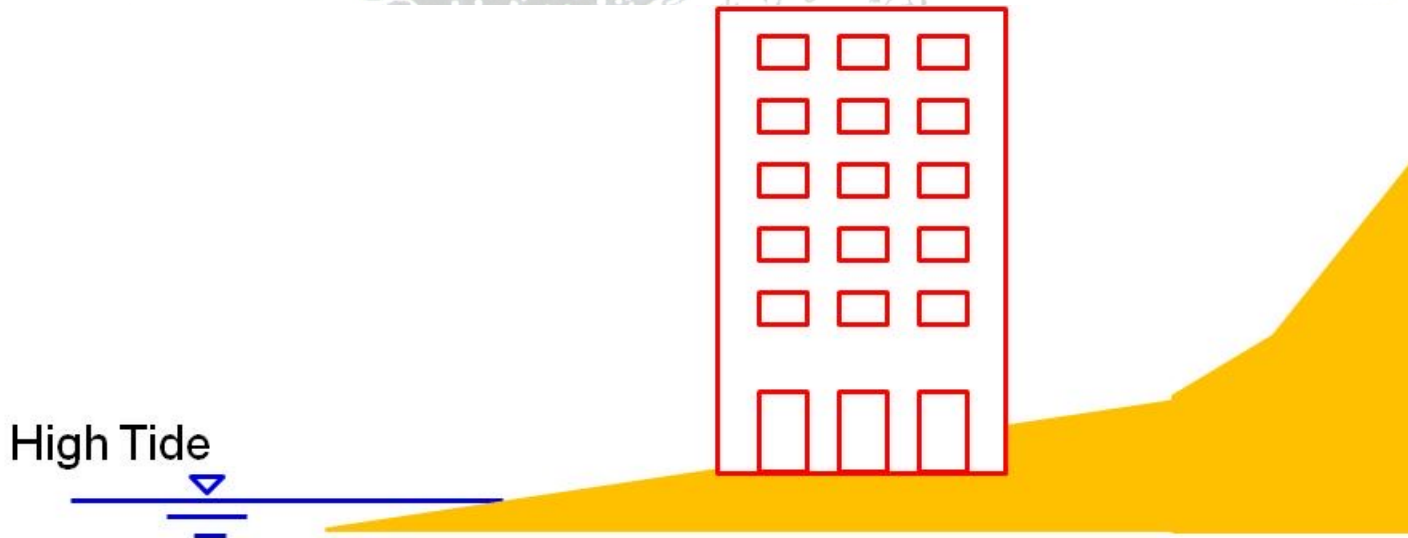
Where  $B_d = 40$  feet or one structural bay



**Hurricane Katrina, 2005**

# Minimum Refuge Elevation

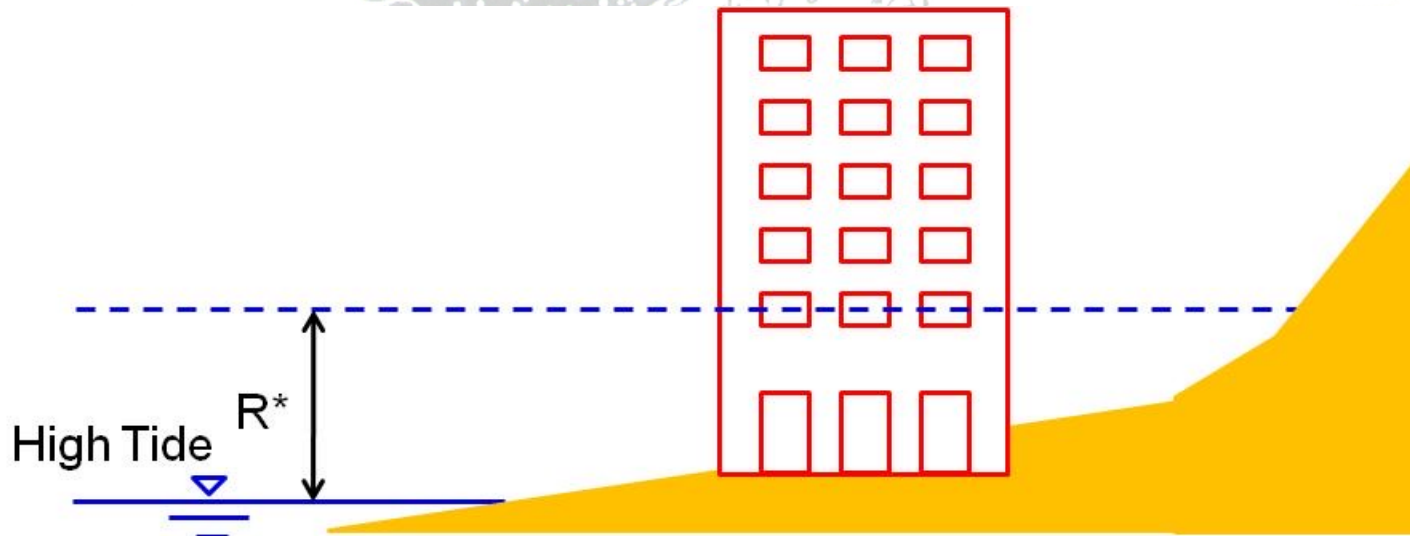
- Recommends refuge elevation be 1 story (3m, 10ft) above predicted inundation (with 1.3 uncertainty factor)





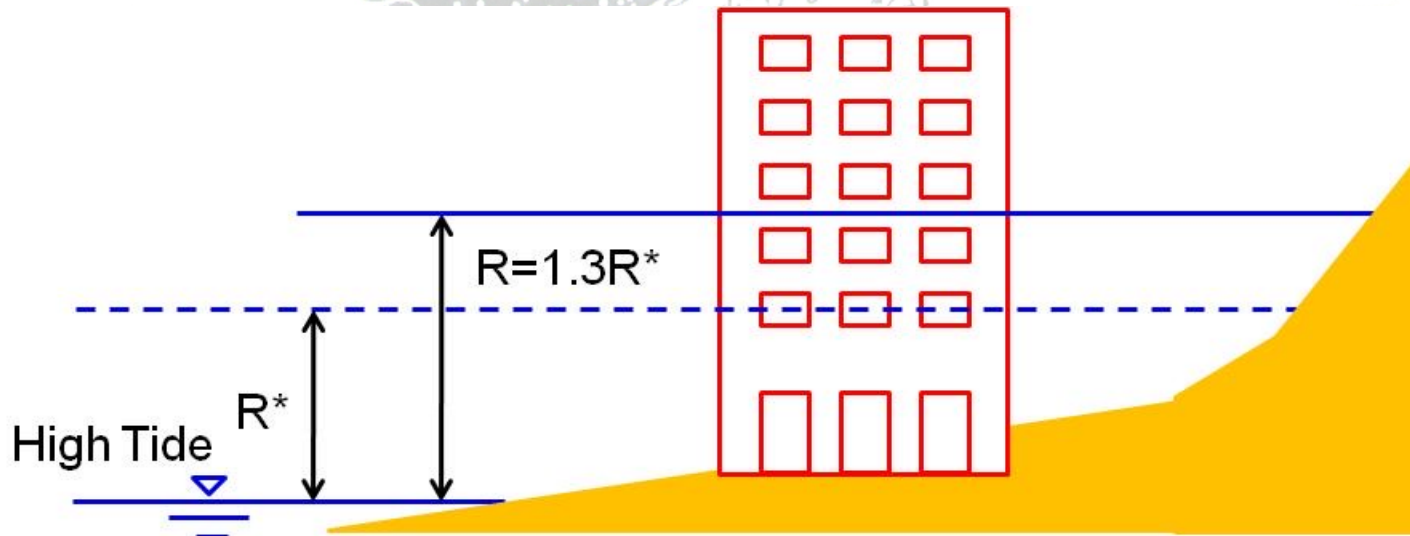
# Minimum Refuge Elevation

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



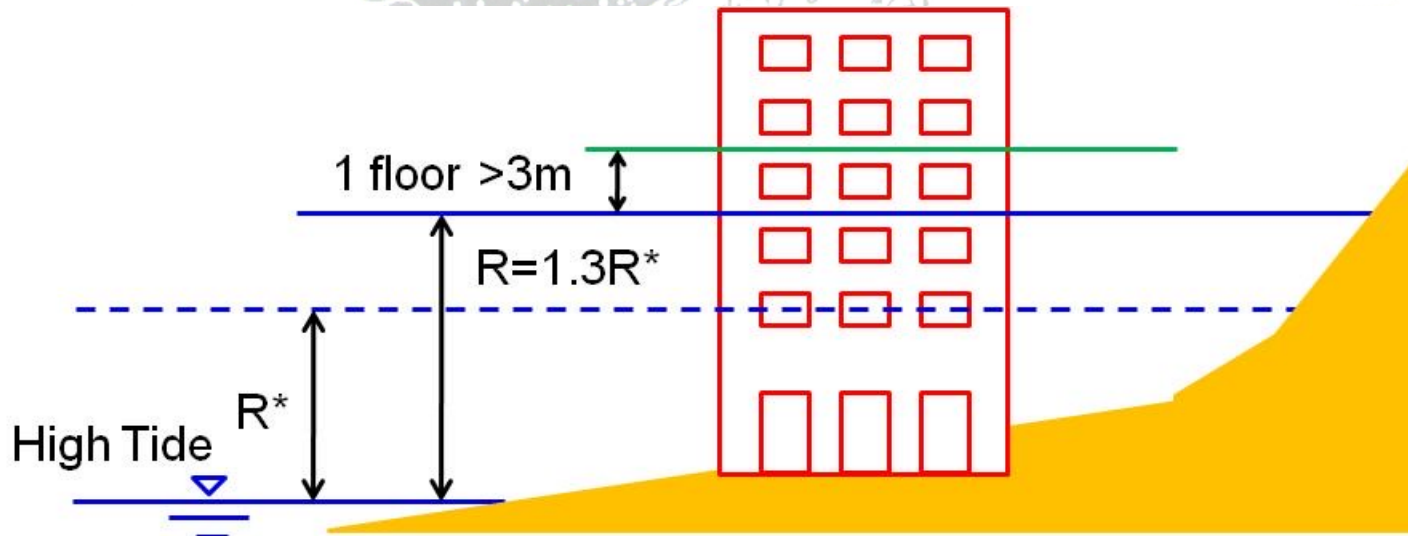
# Minimum Refuge Elevation

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



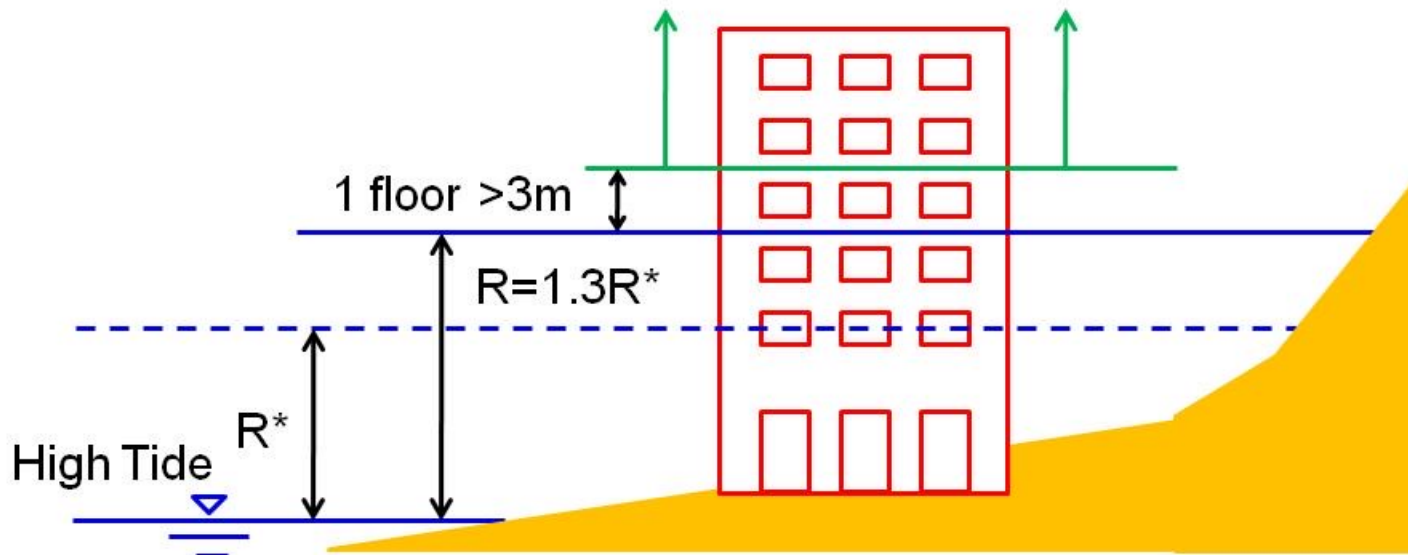
# Minimum Refuge Elevation

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



# 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



## Guidelines for Design of Structures for Vertical Evacuation from Tsunamis

Third Edition

FEMA P-646 / August 2019

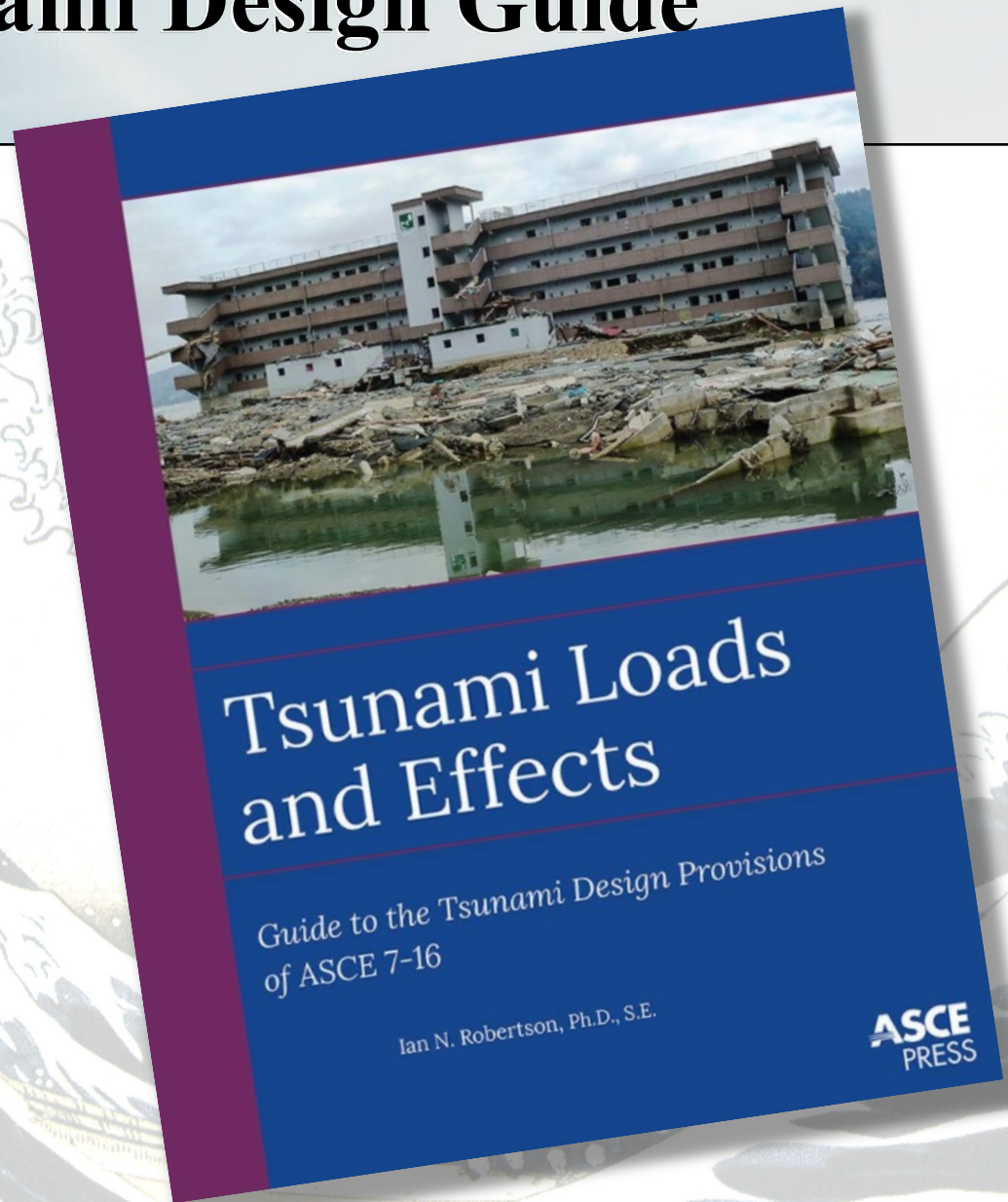


FEMA



# ASCE Tsunami Design Guide

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





# 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

## ASCE Tsunami Hazard Tool

ASCE Tsunami Design Geodatabase Version 2016-1.0

Measure Basemap Share

Enter Structure Information

Enter Location *i*

ADDRESS LAT/LONG FIND ON MAP

Ocosta Elementary School - X **SEARCH**

Select Criteria

Tsunami Risk Category *i*

Risk Category *v*

Measurements

Customary  SI

Select Data Type for Analysis

DATA POINTS TRANSECT

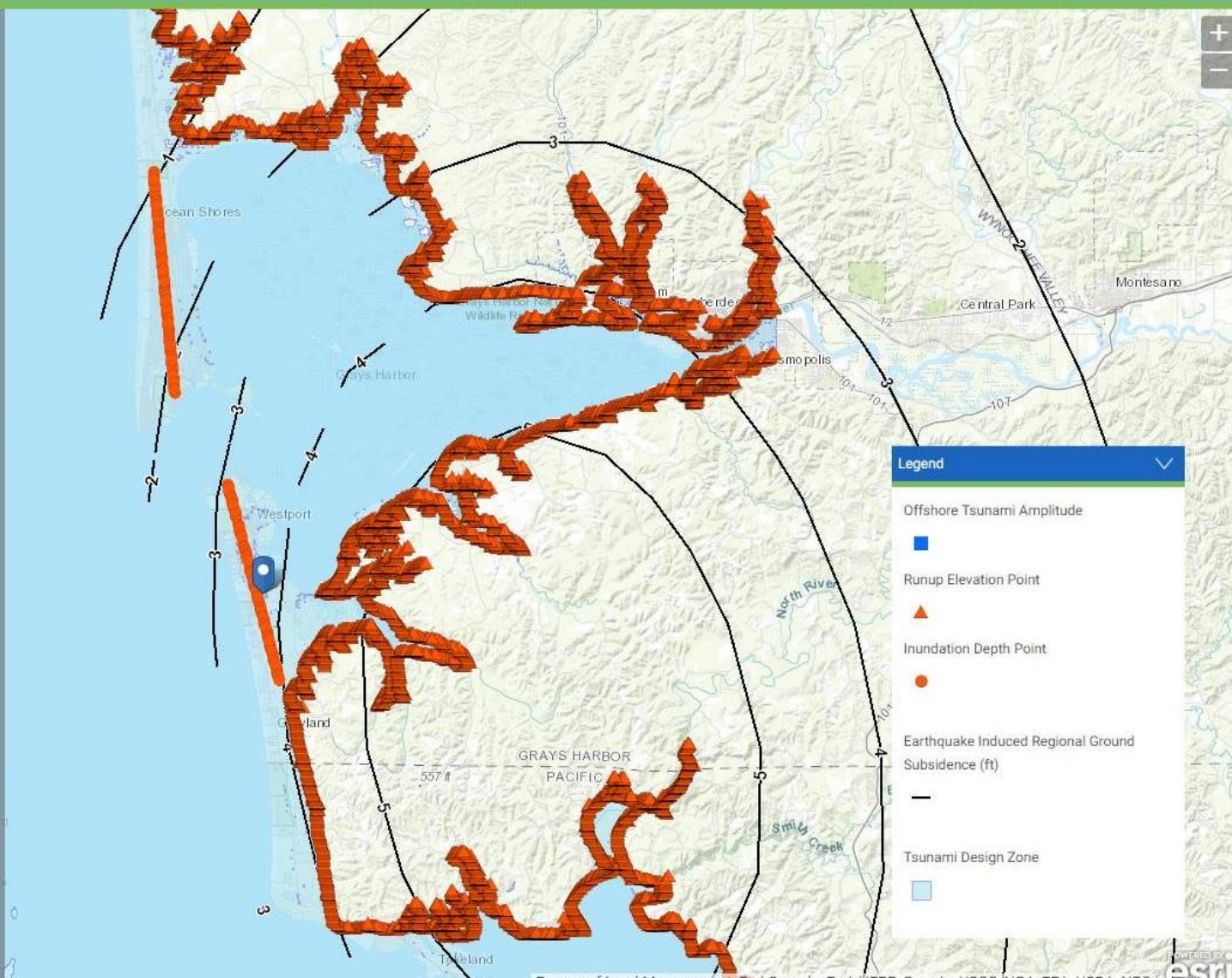
Click on points *o* *▲* *●* *■* or *□*

**DRAW A BOX** over multiple *■* to view point data.

Note: Offshore Tsunami Amplitude points may be some distance off-shore so zooming out may be required.

**CLEAR MAP**

All data are per the requirements of the ASCE/SEI 7 standard; local requirements may vary.



# Ocosta Elementary School, Westport, Washington

## ASCE Tsunami Hazard Tool

ASCE Tsunami Design Geodatabase Version 2016-1.0

Measure Basemap Share

Enter Structure Information

Enter Location ?

ADDRESS LAT/LONG FIND ON MAP

Ocosta Elementary School - ✕ SEARCH

Select Criteria

Tsunami Risk Category ?

Risk Category ▾

Measurements

Customary  SI

Select Data Type for Analysis

DATA POINTS

TRANSECT

Click on points ● ▲ ■ ⊖ or

DRAW A BOX over multiple ■ to view point data.

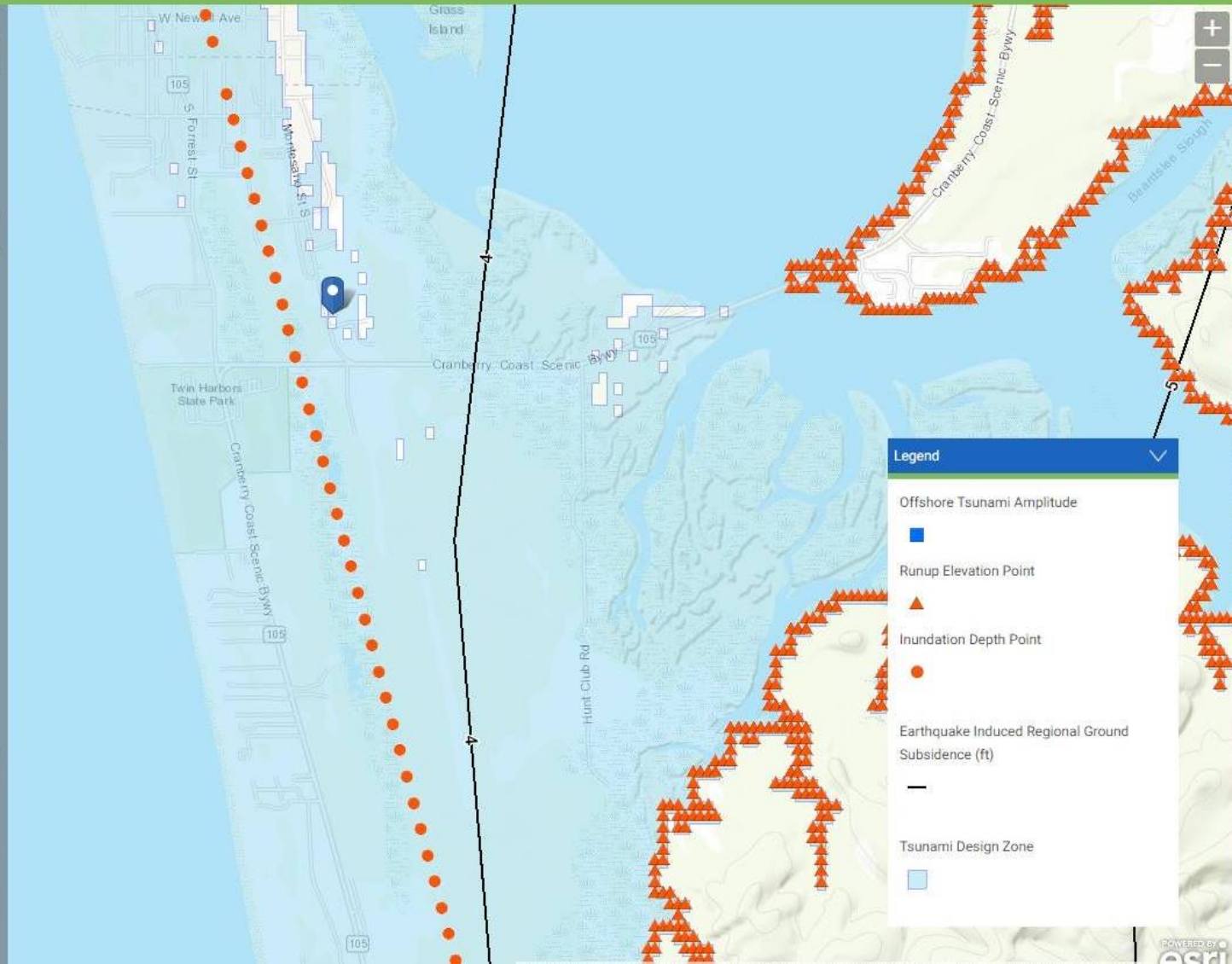
Note: Offshore Tsunami Amplitude points may be some distance off-shore so zooming out may be required.

CLEAR MAP

All data are per the requirements of the ASCE/SEI 7 standard; local requirements may vary.



© 2017

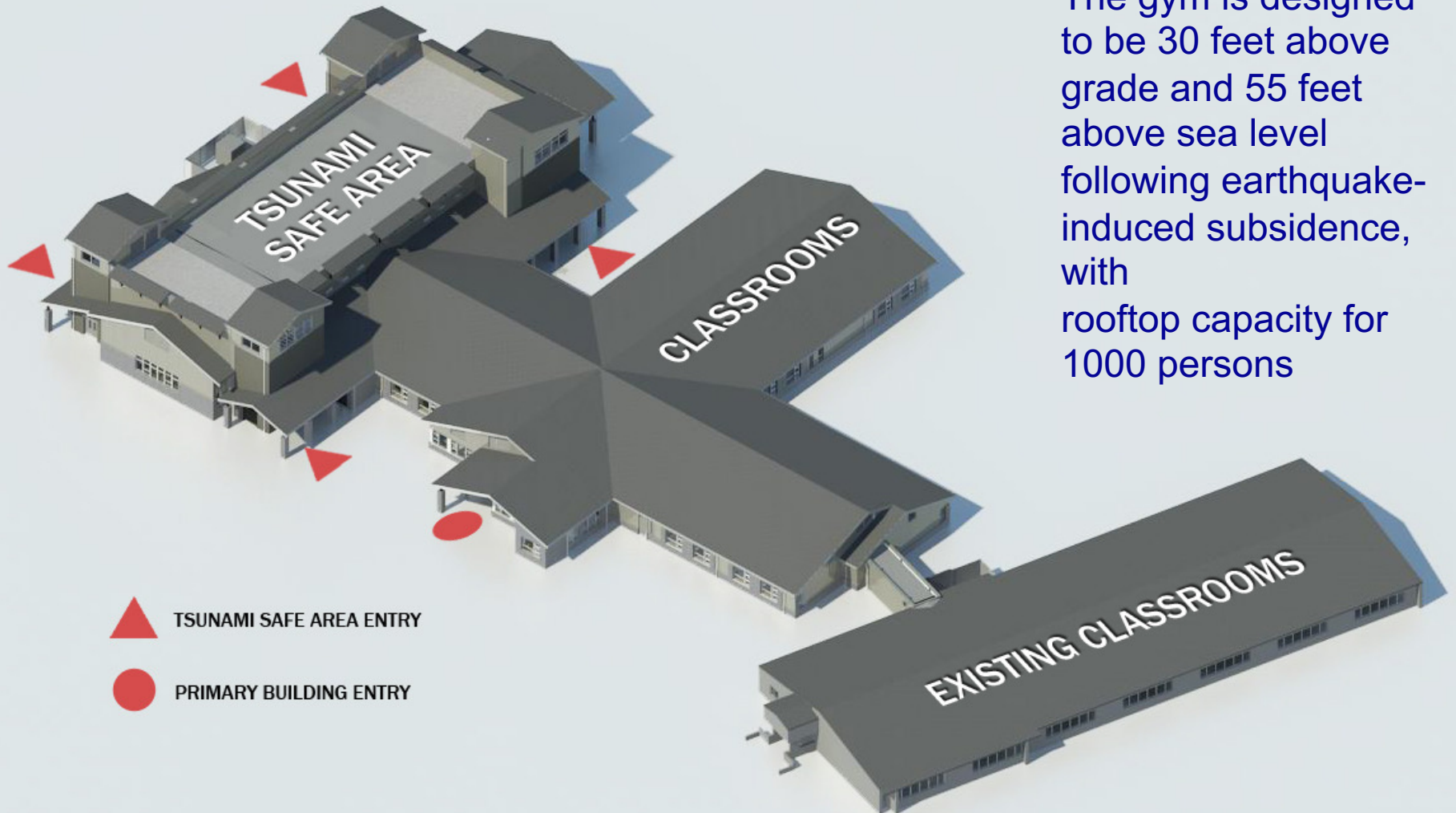


**Legend** ▾

- Offshore Tsunami Amplitude ■
- Runup Elevation Point ▲
- Inundation Depth Point ●
- Earthquake Induced Regional Ground Subsidence (ft) —
- Tsunami Design Zone □

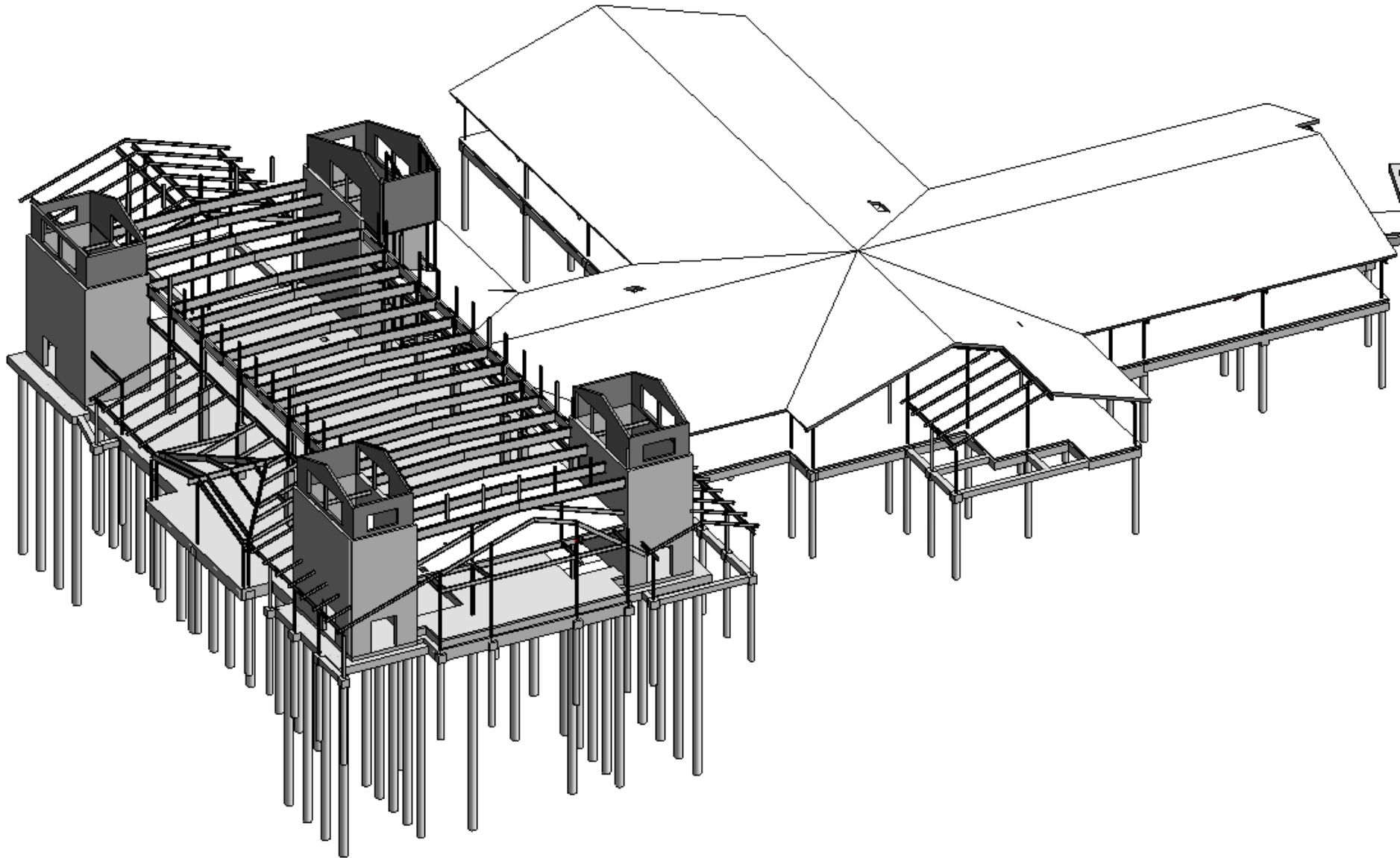
POWERED BY esri

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

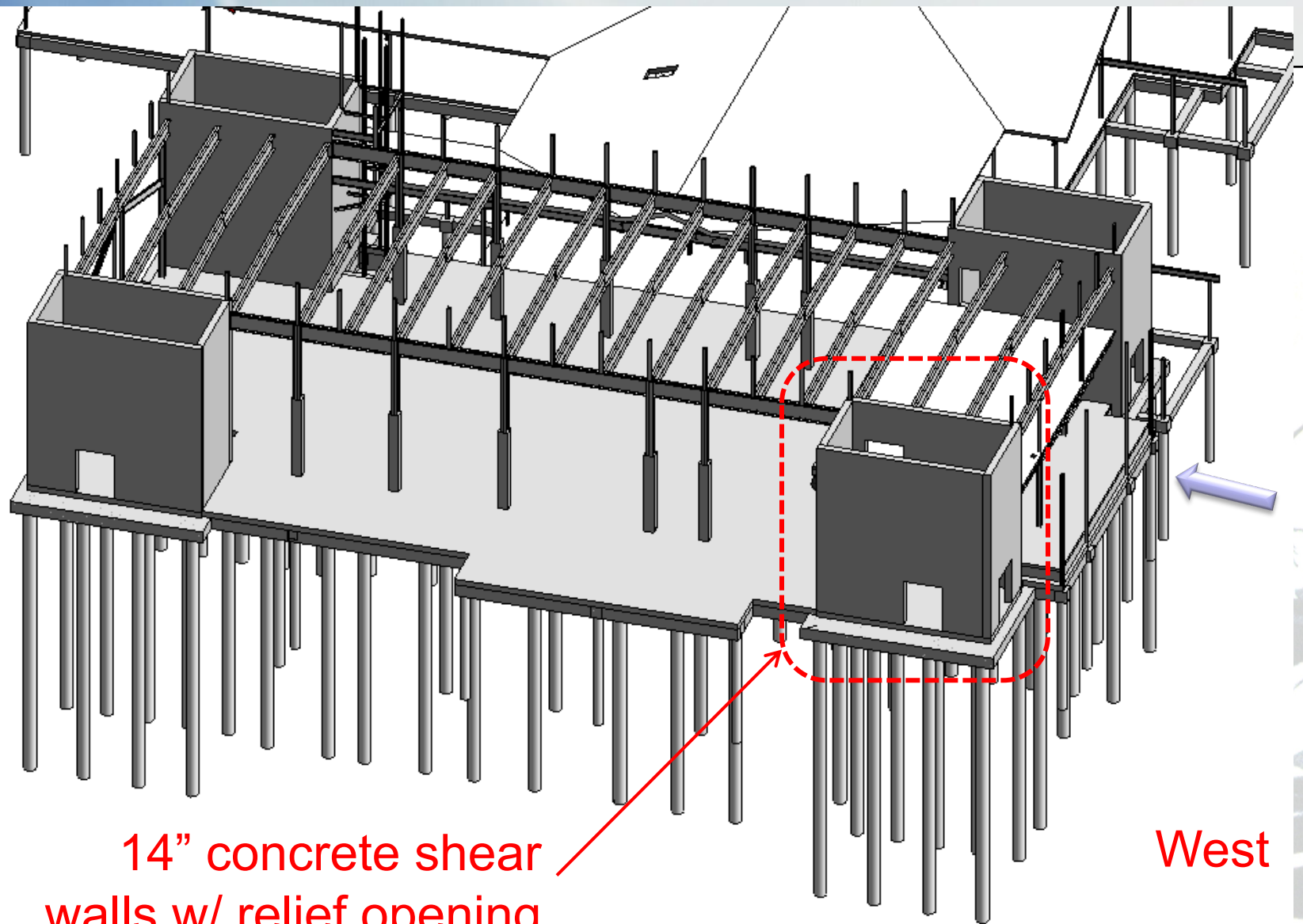


The gym is designed to be 30 feet above grade and 55 feet above sea level following earthquake-induced subsidence, with rooftop capacity for 1000 persons

# Foundation Design



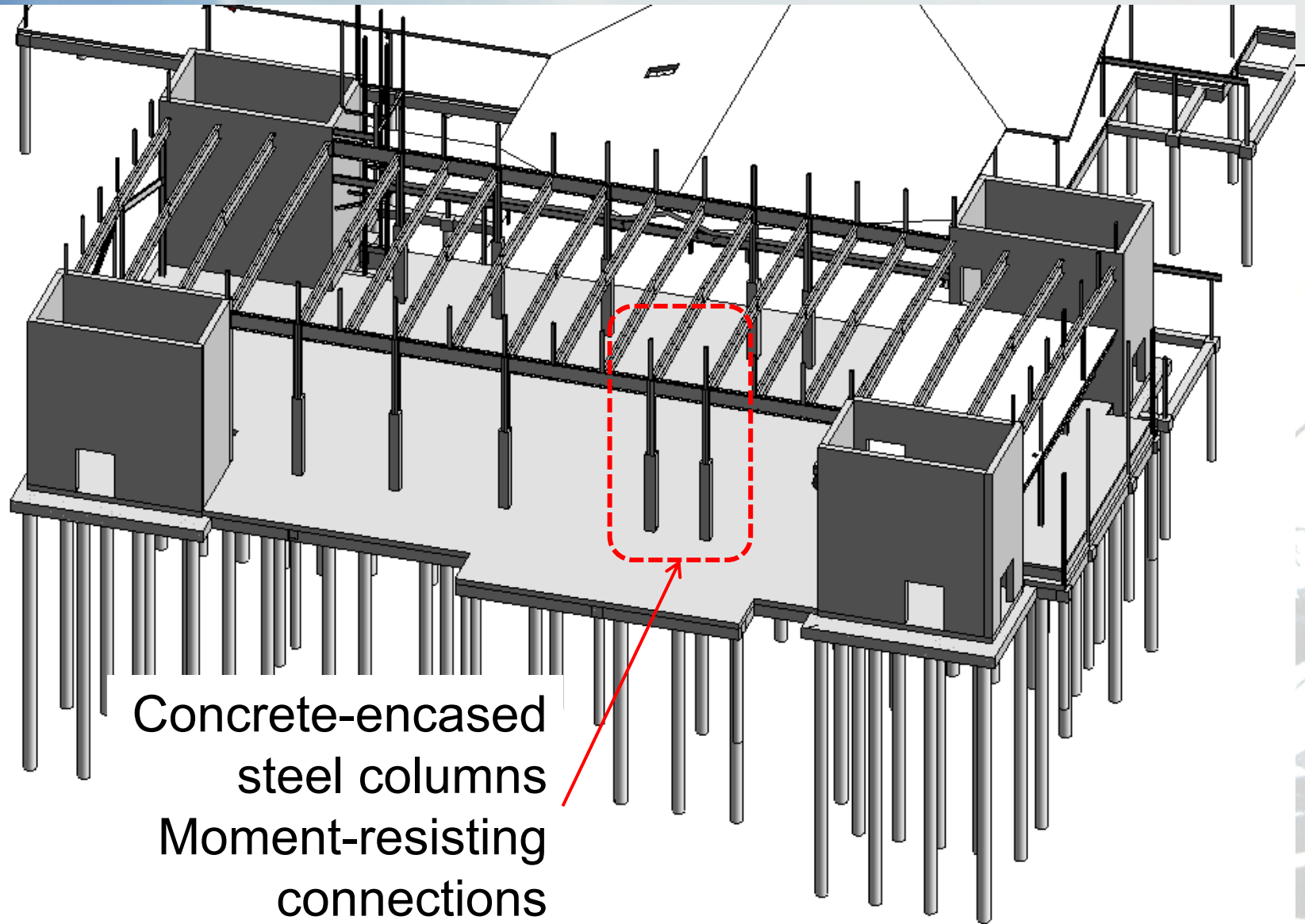
# Structural Lateral System



14" concrete shear walls w/ relief opening

West

# Structural Gravity System



# Ocosta Elementary School Westport, Washington





# OSU Hatfield Marine Science Center, Newport, Oregon, USA

## ASCE Tsunami Hazard Tool

ASCE Tsunami Design Geodatabase Version 2016-1.0



### Enter Structure Information

Enter Location ⓘ

ADDRESS	LAT/LONG	FIND ON MAP
---------	----------	-------------

Click on Map to select location

### Select Criteria

Tsunami Risk Category ⓘ

Risk Category

Measurements

Customary  SI

### Select Data Type for Analysis

DATA POINTS  TRANSECT

Click on points    or  or

DRAW A BOX over multiple  to view point data.

Note: Offshore Tsunami Amplitude points may be some distance off-shore so zooming out may be required.

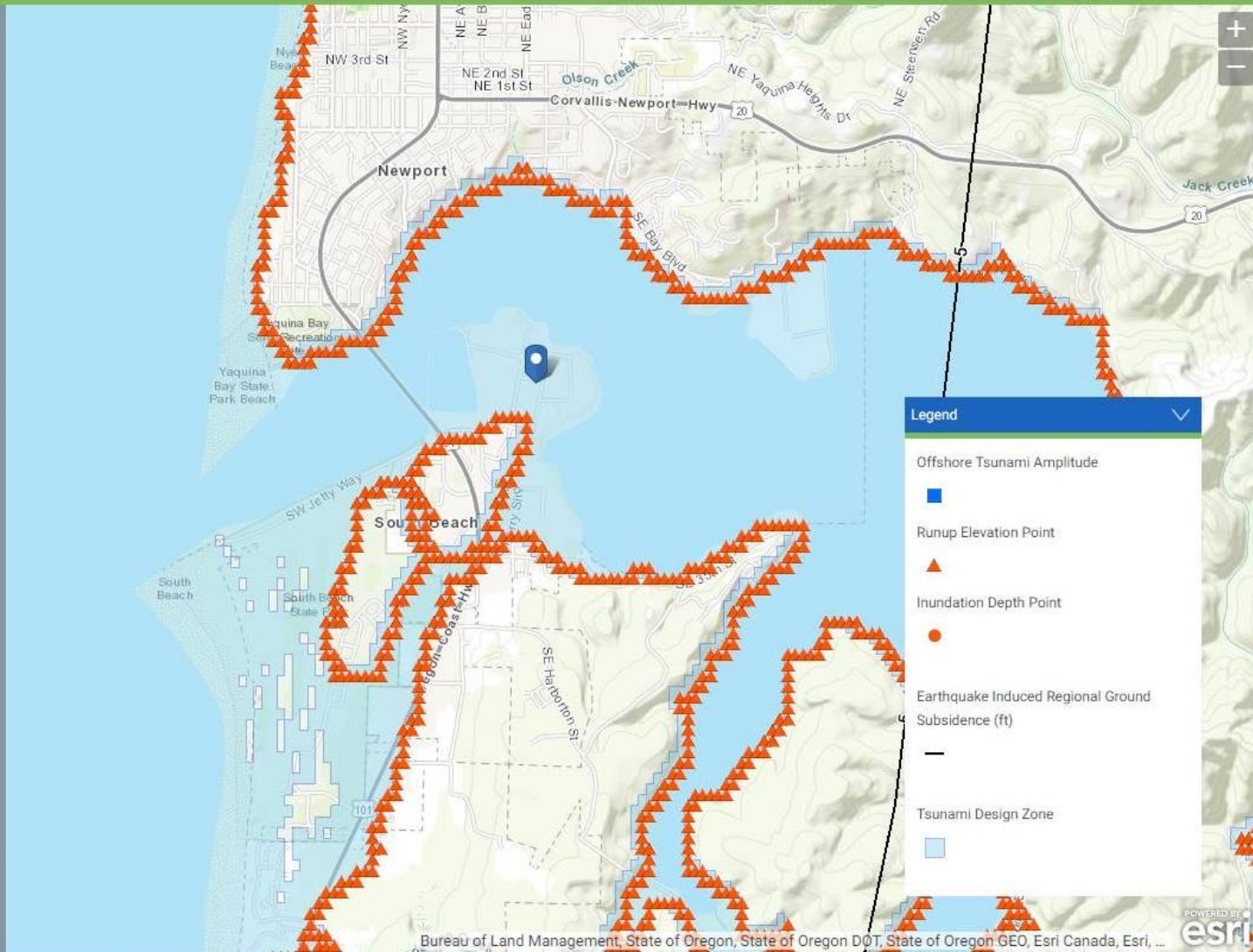
CLEAR MAP

DISPLAY PROTRACTOR GUIDE

All data are per the requirements of the ASCE/SEI 7 standard; local requirements may vary.



© 2017



# OSU Hatfield Marine Science Center, Newport, Oregon, USA



# 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!**



**Go VERT!**  
Tsunami Evacuation Area



# Any Questions?



Tampered sign at Waikaloa Resort, Kona, Hawaii

# Thank-You

## Questions?



白田嶽子六郎 神奈川  
誠心堂

明治の留髪二年