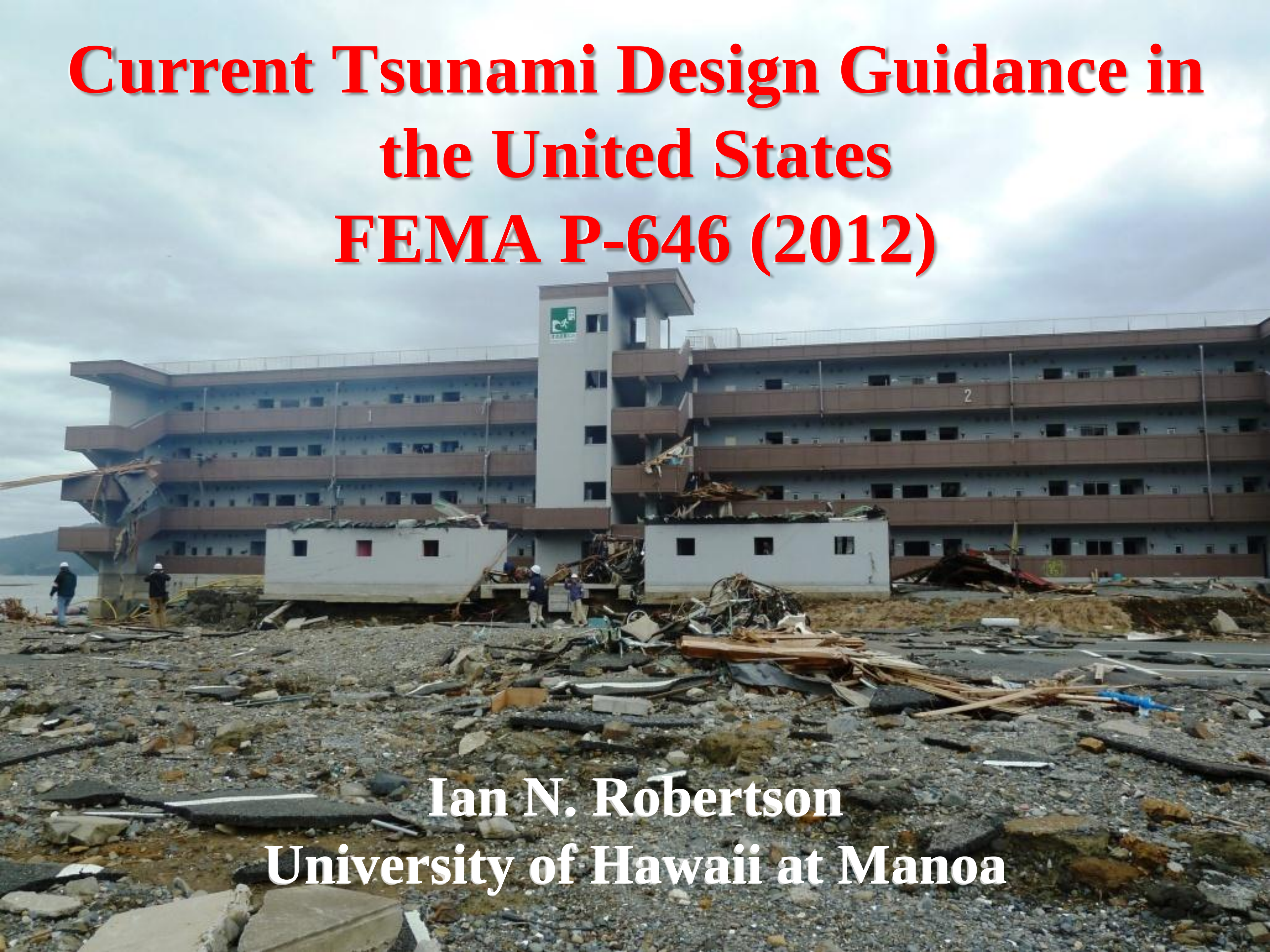


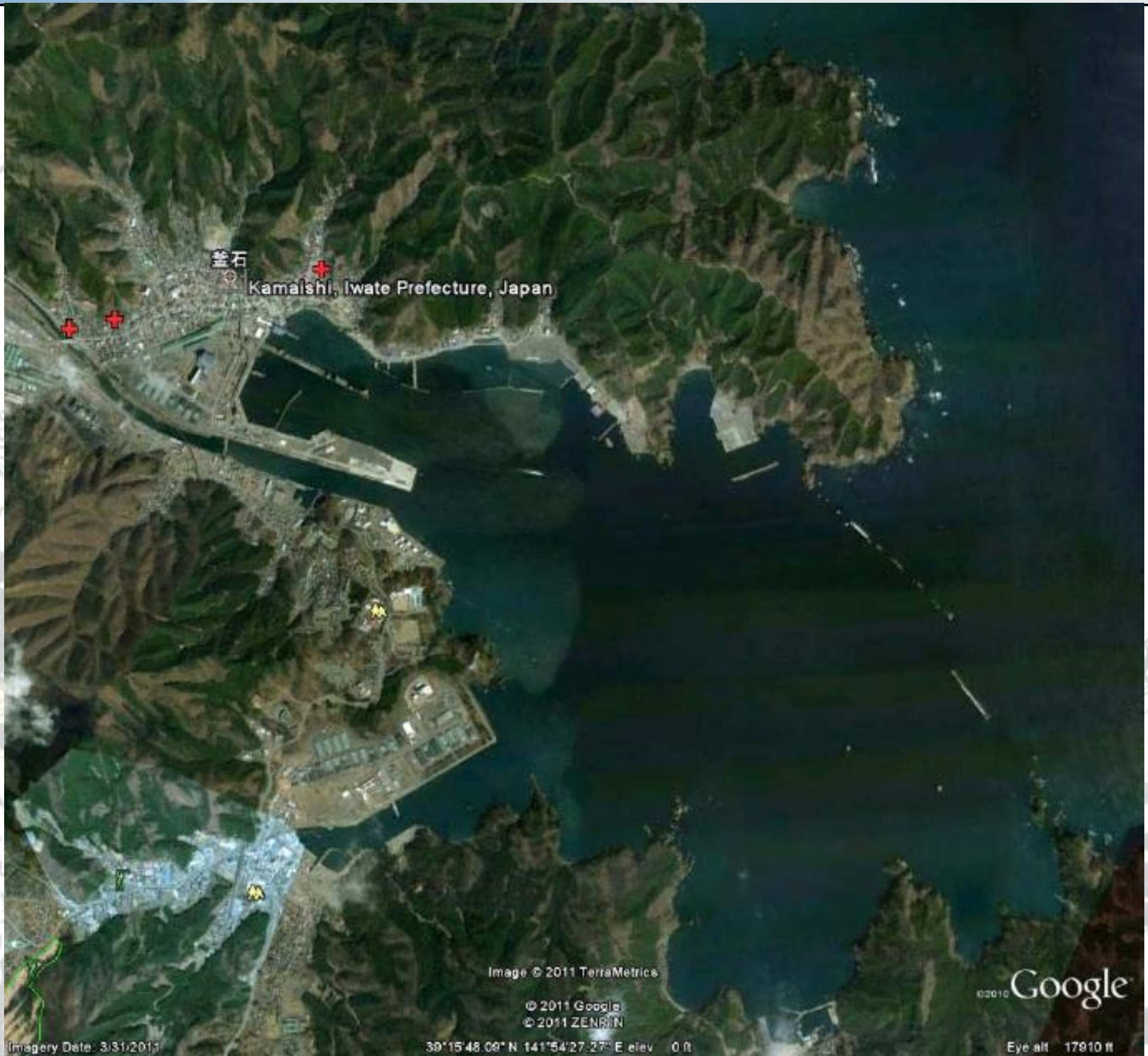
Current Tsunami Design Guidance in the United States FEMA P-646 (2012)

Ian N. Robertson
University of Hawaii at Manoa

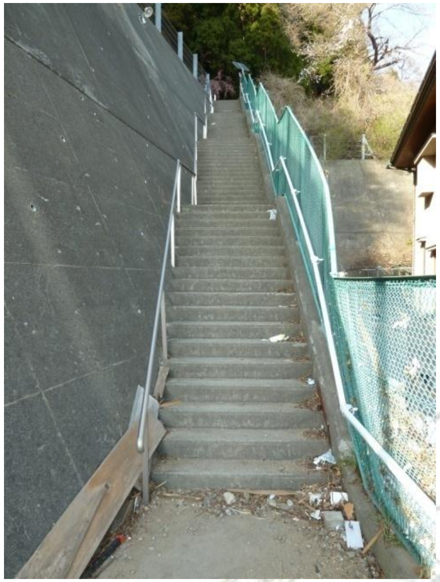
Outline

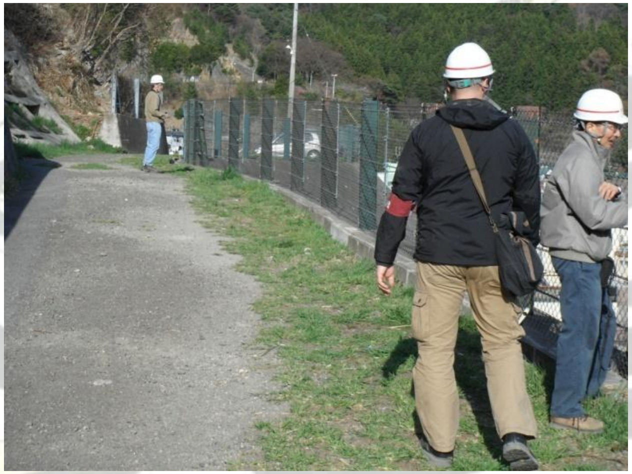
- Performance of Vertical Evacuation Buildings during Tohoku Tsunami
- FEMA P-646 design guidelines
- FEMA P-646 update – Second Edition
- Possible funding mechanisms

Evacuation to high ground Kamaishi Example



Evacuation to high ground
Kamaishi Example





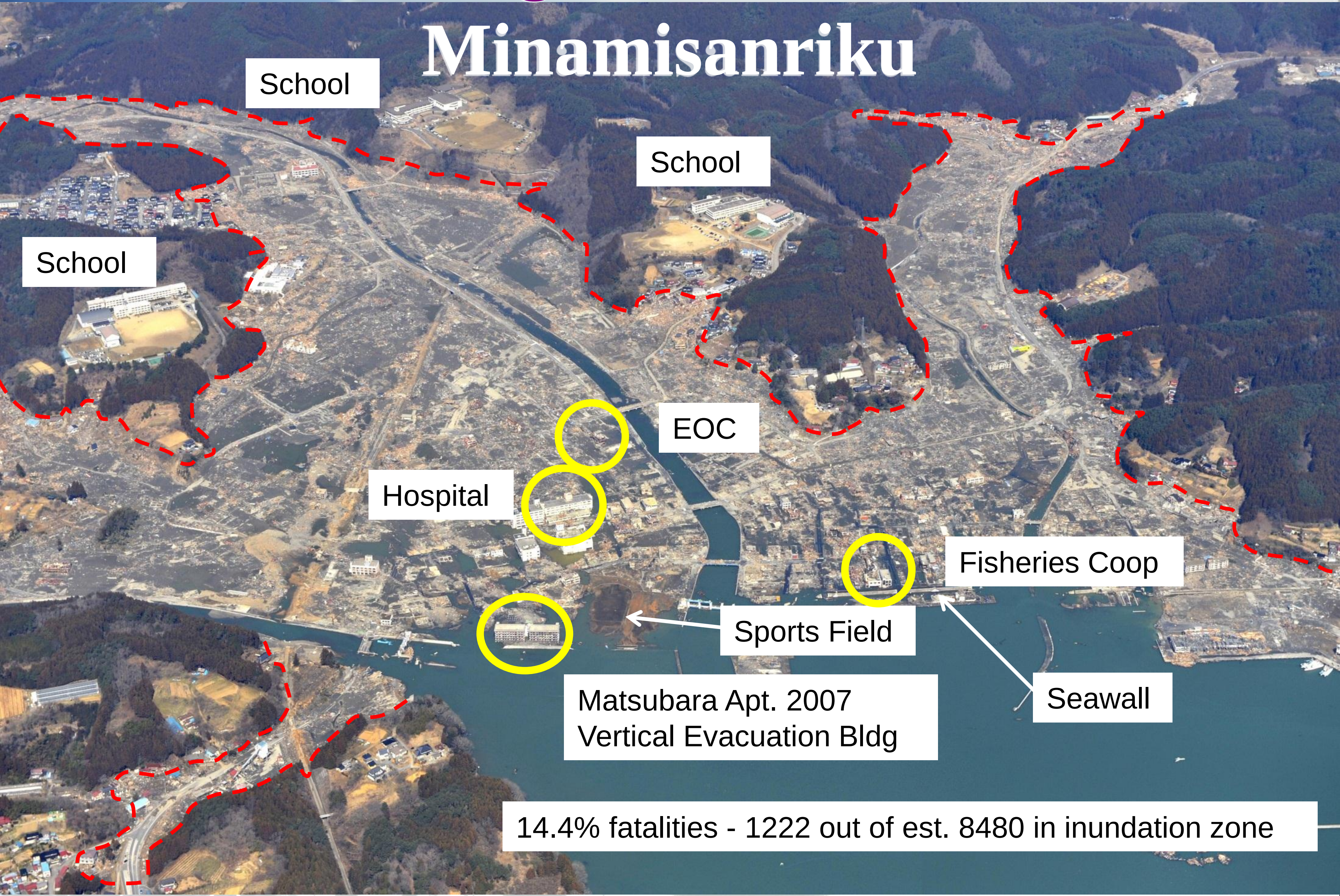
Use of Designated Tsunami Evacuation Buildings

Designated evacuation building

Video

ここは
避難場所
4階
避難場所は
4階以上
津波避難場所
釜石市
津波避難ビル
Tsunami Evacuation Area

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

- 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 Sato and 8 others survived**
- **Tragically large loss of lives at adjacent hospital**

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 full stories of patient drowning fatalities (71 dead)**

Minamisanriku Fisheries Cooperative

- Designated evacuation site, though only 2 floors
- Overtopped by tsunami
- Reportedly not used during the tsunami

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


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

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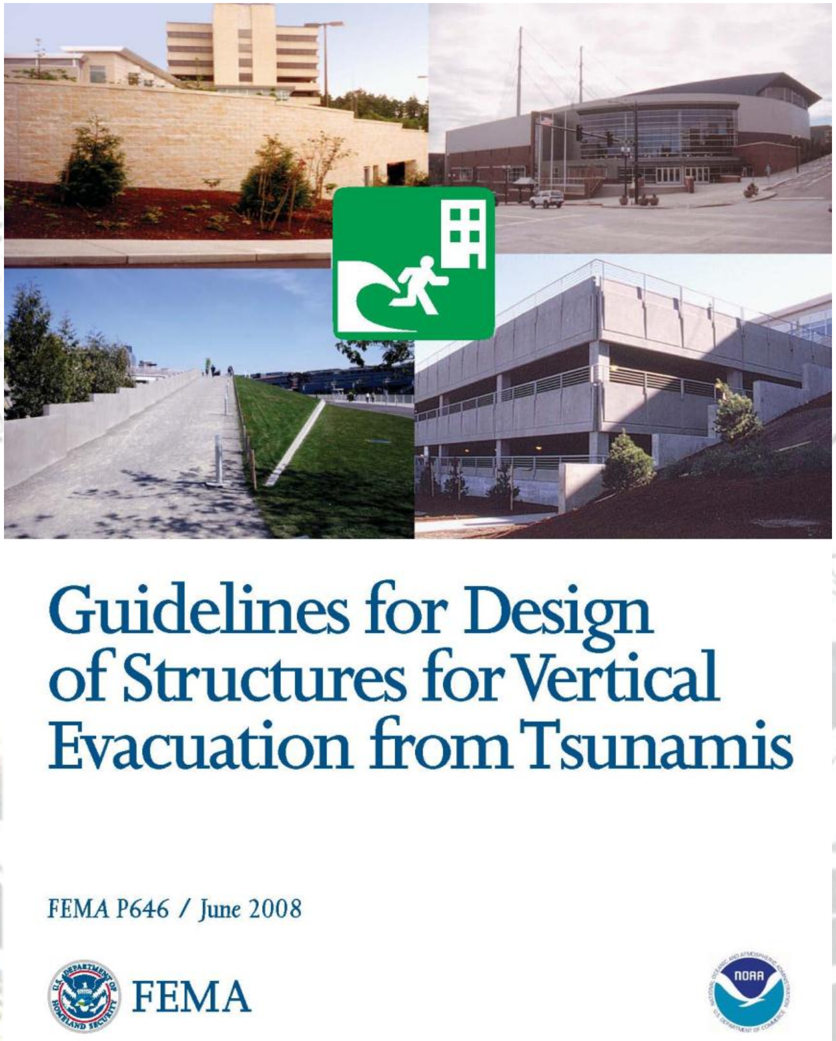
I. Matsuo H. Murakami

GNS Science Report 2012/17
April 2012

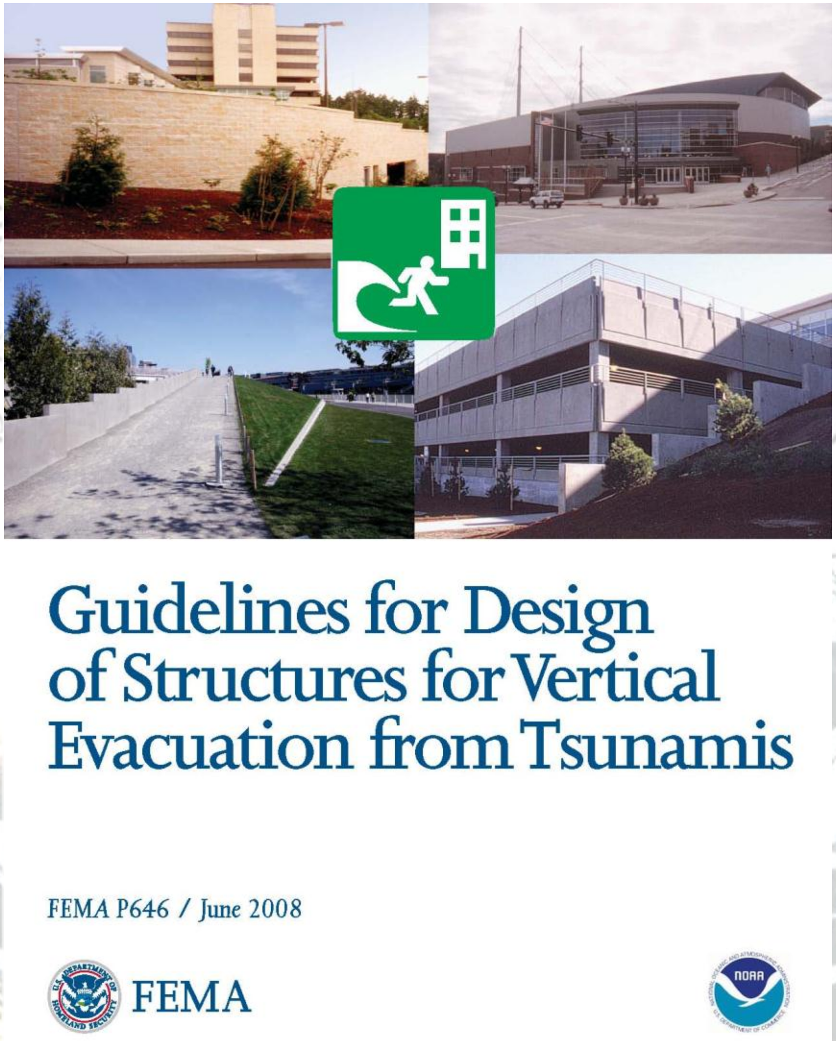
Guidelines for Design of Structures for Vertical Evacuation from Tsunamis (FEMA P646)

- **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**



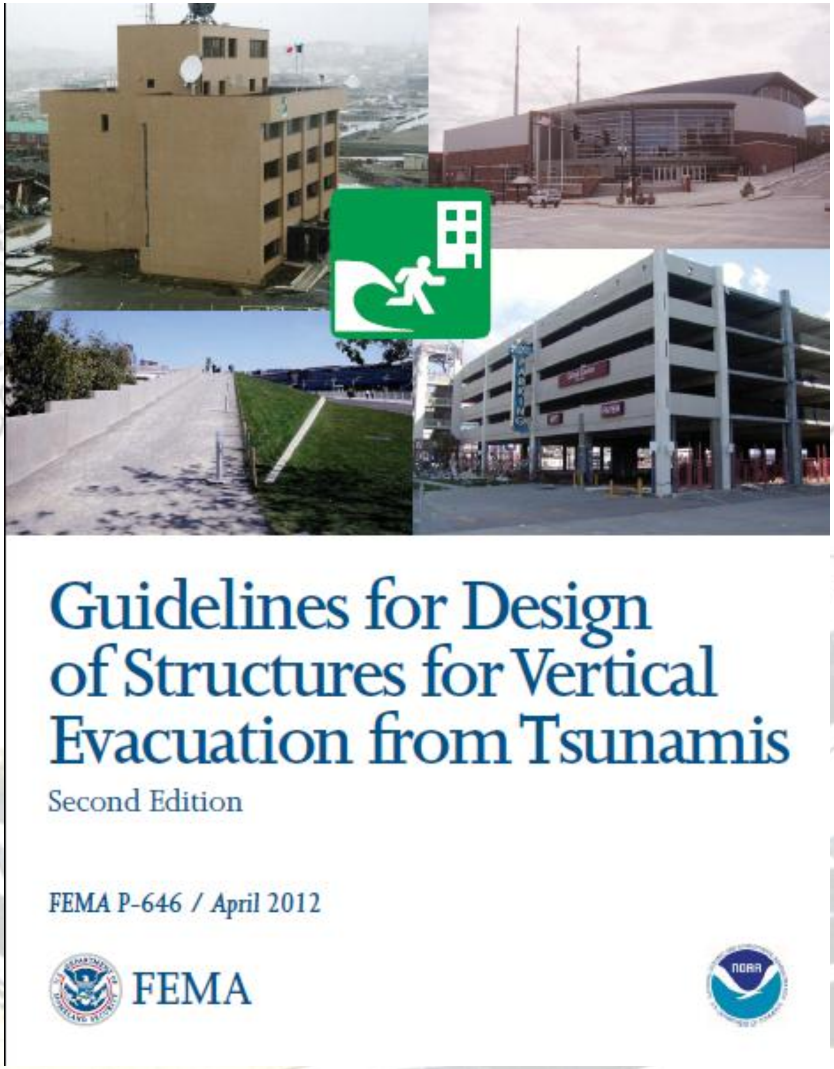
Guidelines for Design of Structures for Vertical Evacuation from Tsunamis (FEMA P646)

- **Project Team**
  - **Steven Baldridge**
  - **Frank Gonzalez**
  - **John Hooper**
  - **Ian Robertson**
  - **Timothy Walsh**
  - **Harry Yeh**
- **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 P-646)

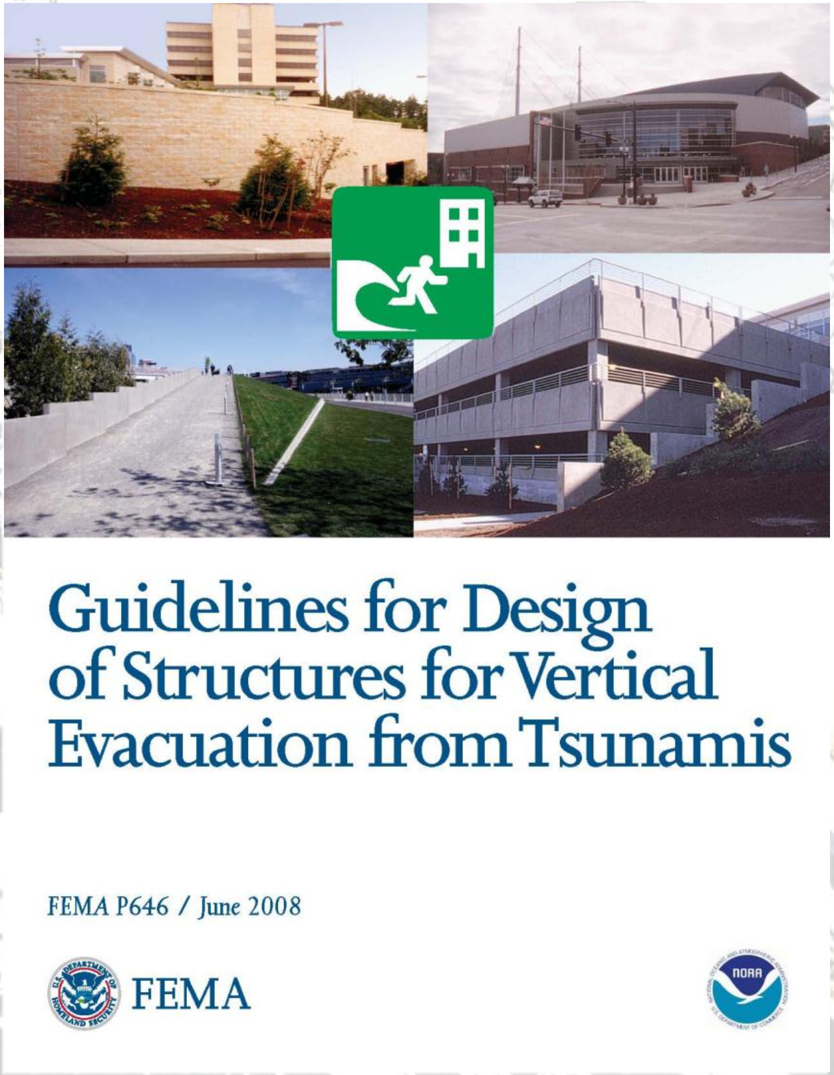
- **Issues raised during design of Cannon Beach refuge and prototypical buildings**
- **Modified as ATC-79**
- **Project Team**
  - **Ian Robertson**
  - **Gary Chock**
  - **John Hooper**
  - **Timothy Walsh**
  - **Harry Yeh**
- **Revised 2012 – in print**

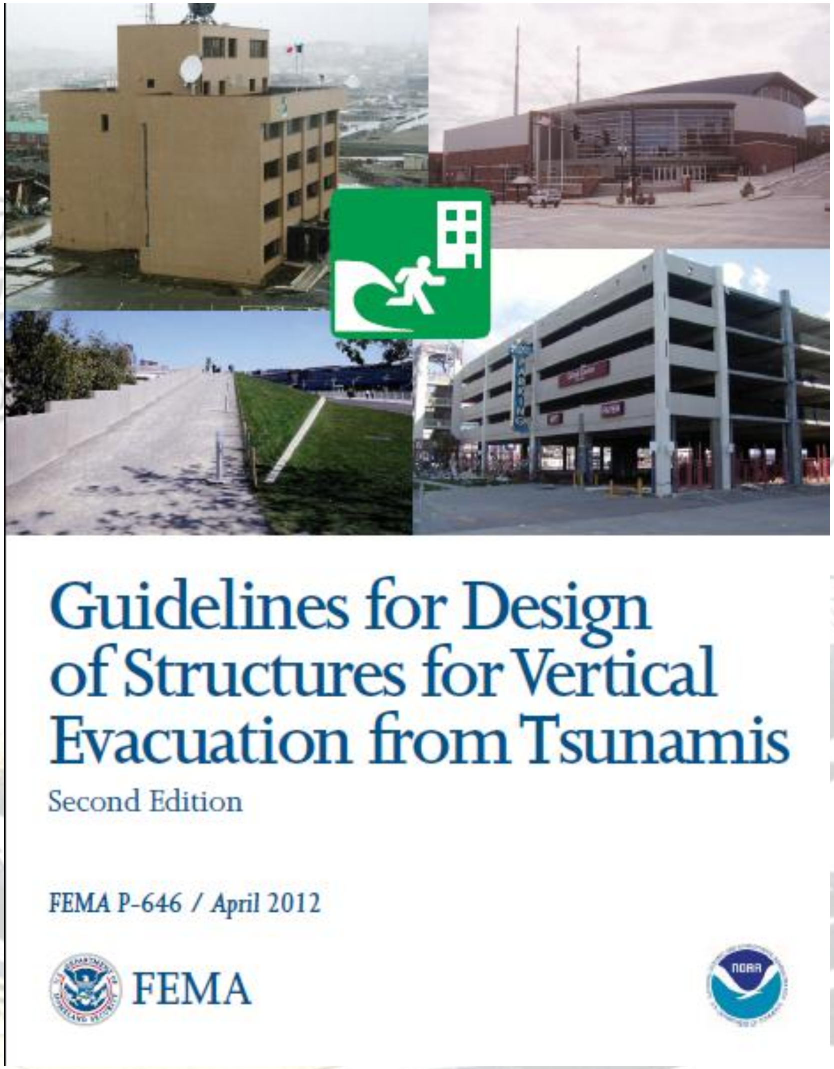


Changes to FEMA P-646 Cover

Old Cover

New Cover





FEMA P-646 - Contents

- **Introduction**
- **Background**
- **Tsunami hazard assessment**
- **Vertical evacuation options**
- **Siting, Spacing, Sizing and Elevation Considerations**
- **Load determination and Structural design considerations**
- **Structural Design Concepts**

Background

- **Lessons learned from past tsunamis**
  - **Indian Ocean – 2004**
  - **Tohoku Tsunami – 2011 (Added in 2012 edition)**

Figure 2-26 Surviving and damaged reinforced concrete buildings in Minamisanriku (photo courtesy of I. Robertson, ASCE, 2012).

Tsunami Hazard

- Hazard level not specified, but 2500 year recommended
- Recommend tsunami inundation modeling
- Recommends 1.3 uncertainty factor on model results
- Alternative analytical approach based on maximum runup elevation (with 1.3 factor)

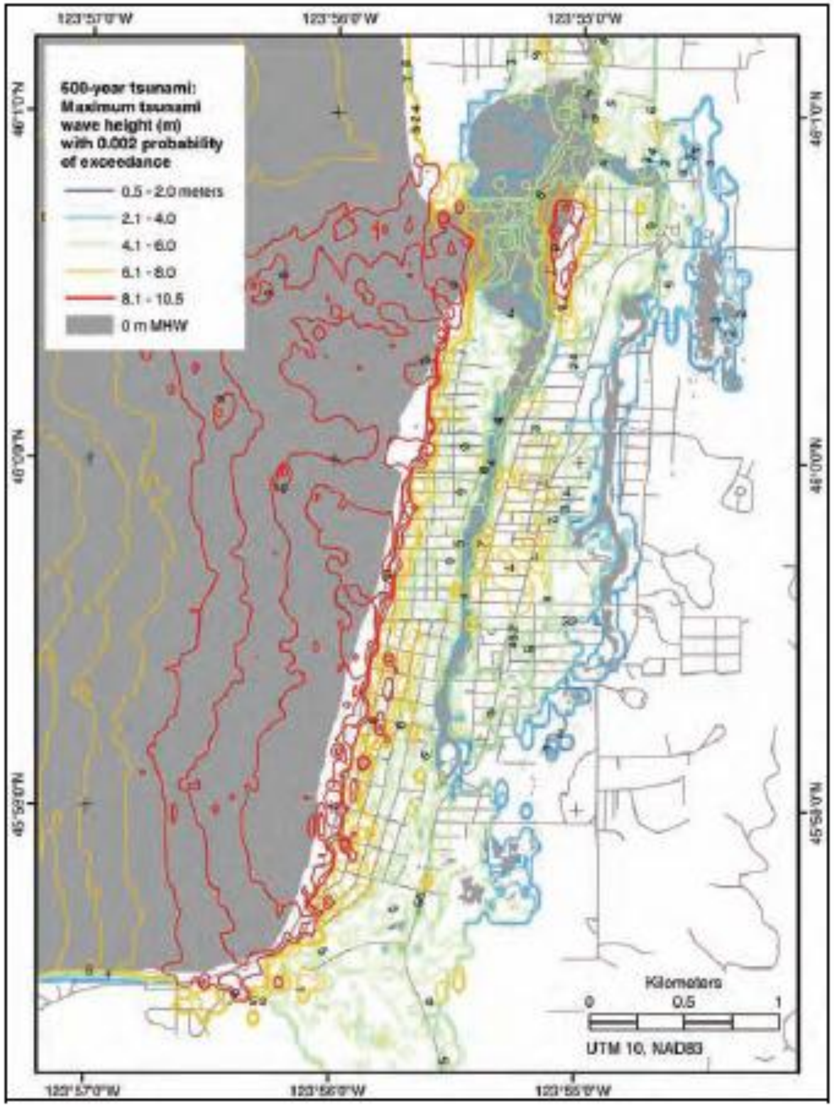


Figure 3-6 The 500-year tsunami map for Seaside, Oregon, depicting maximum wave heights that are met or exceeded at an annual probability of 0.2% (Tsunami Pilot Study Working Group, 2006).

Tsunami Modeling Uncertainty

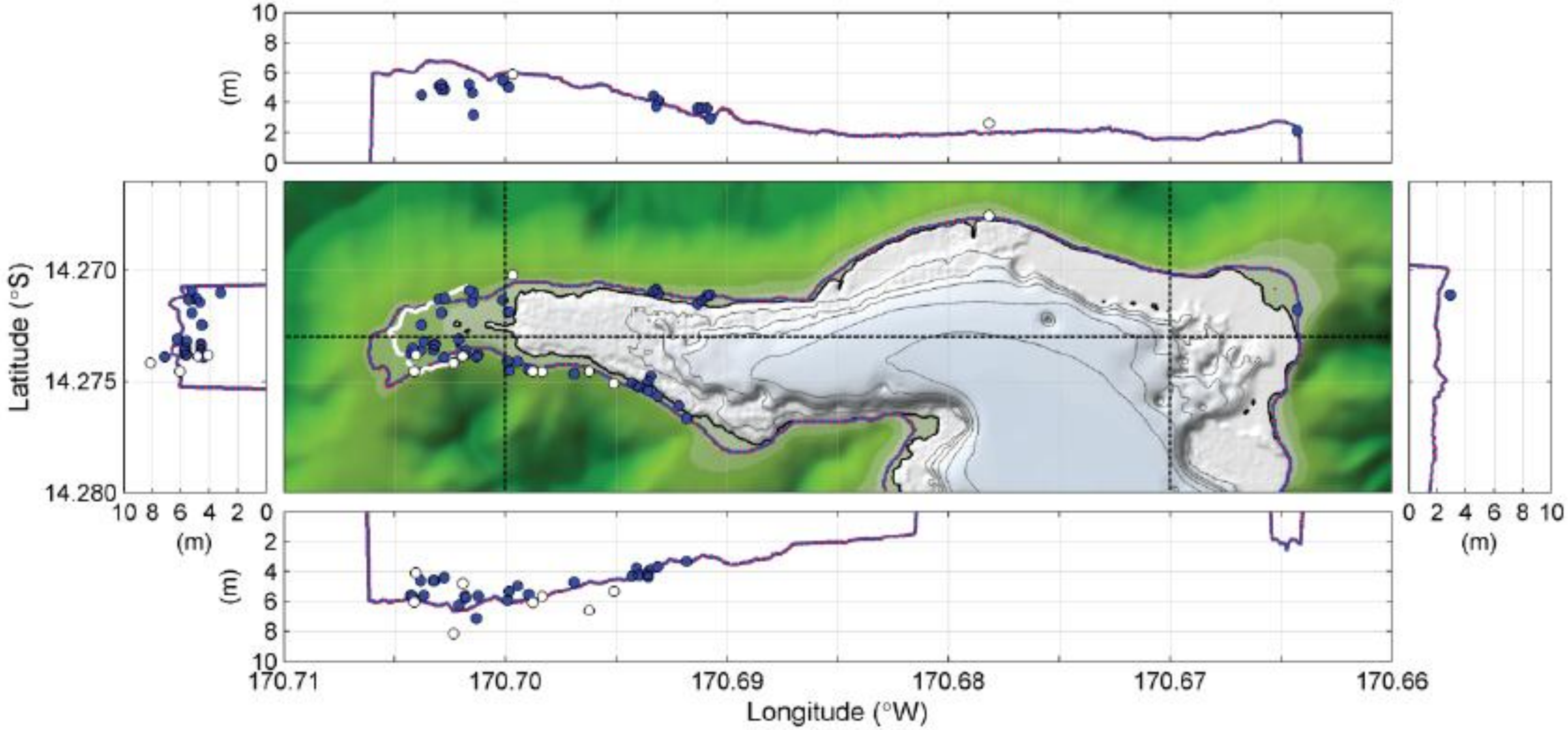


Figure 6-3 Comparison between numerical modeling (blue line) and field measurement of run-up (white dots) and flow elevations (blue dots) at Pago Pago Harbor, American Samoa (Yamazaki et al, 2011).

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.
- Kessenuma, Japan
- Designated as tsunami refuge
- Flooded to third level
- Numerous survivors sought refuge on roof

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**

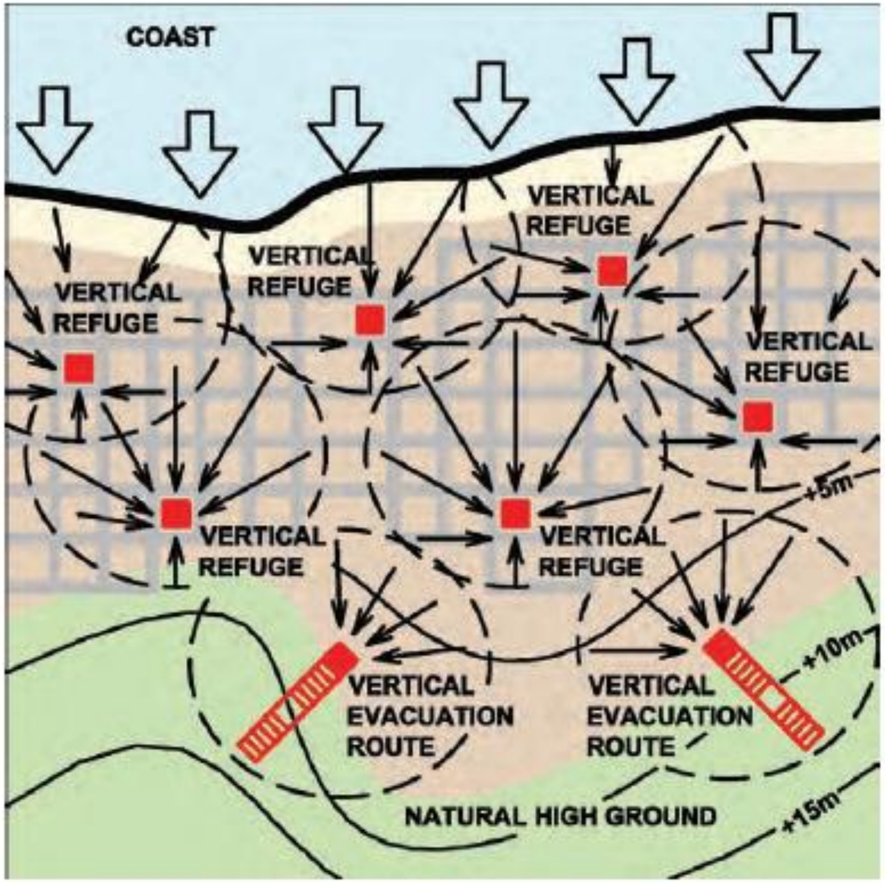


Figure 5-1 Vertical evacuation refuge locations considering travel distance, evacuation behavior, and naturally occurring high ground. Arrows show anticipated vertical evacuation routes.

Siting and Spacing

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

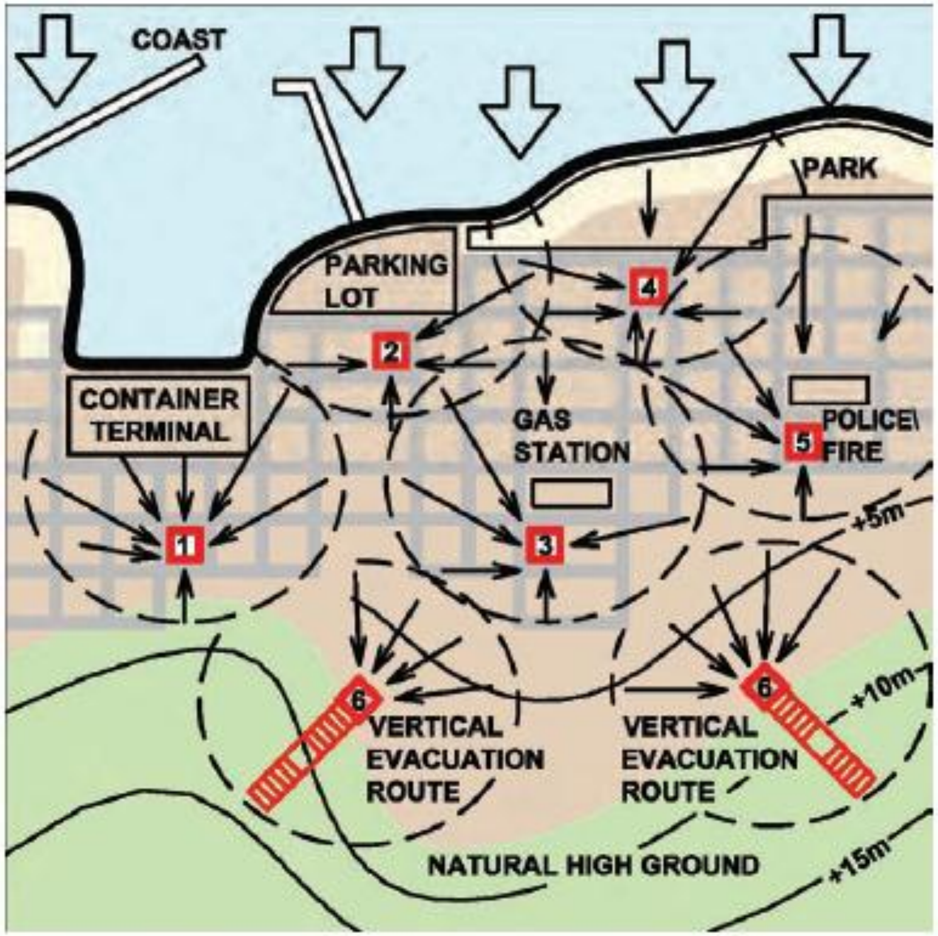
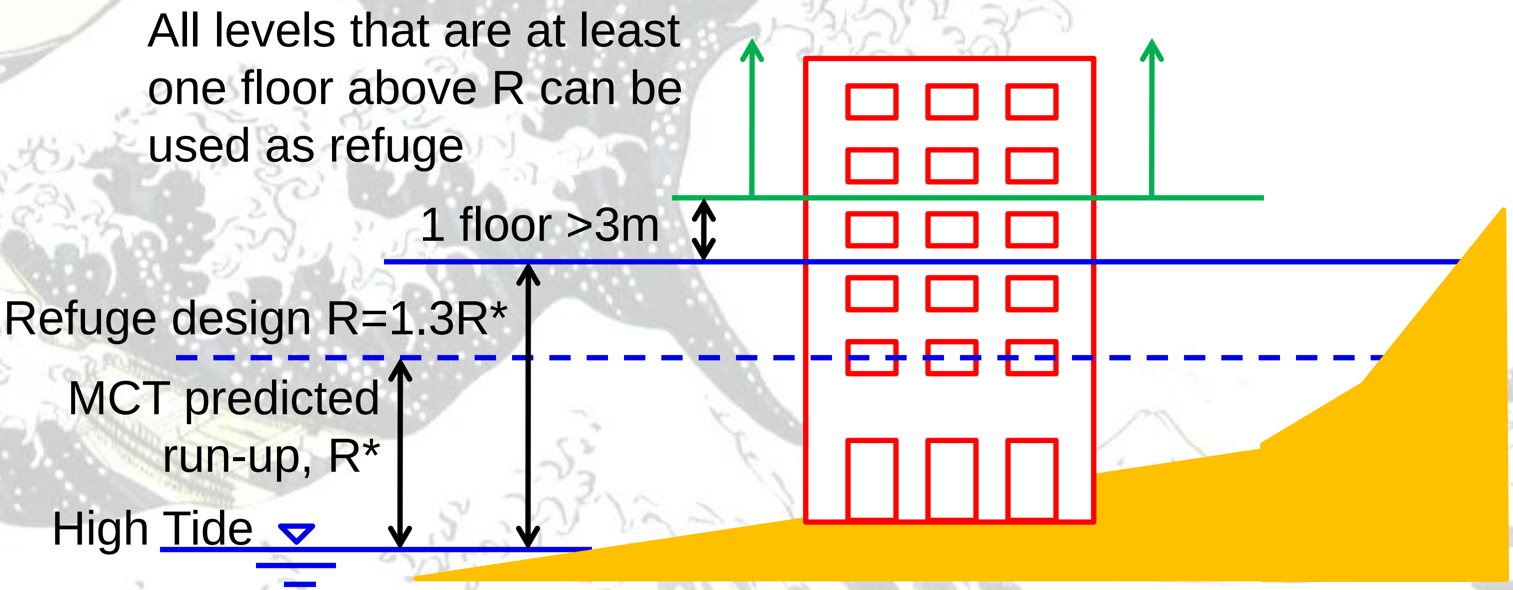


Figure 5-2 Site hazards adjacent to vertical evacuation structures (numbered locations). Arrows show anticipated vertical evacuation routes.

Minimum Refuge Elevation

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



Tsunami flow depth

- **Explanation added to 2012 edition of P-646**
- **P-646 assumes condition b)**
- **Prefer site-specific modeling to give expected flow depths**

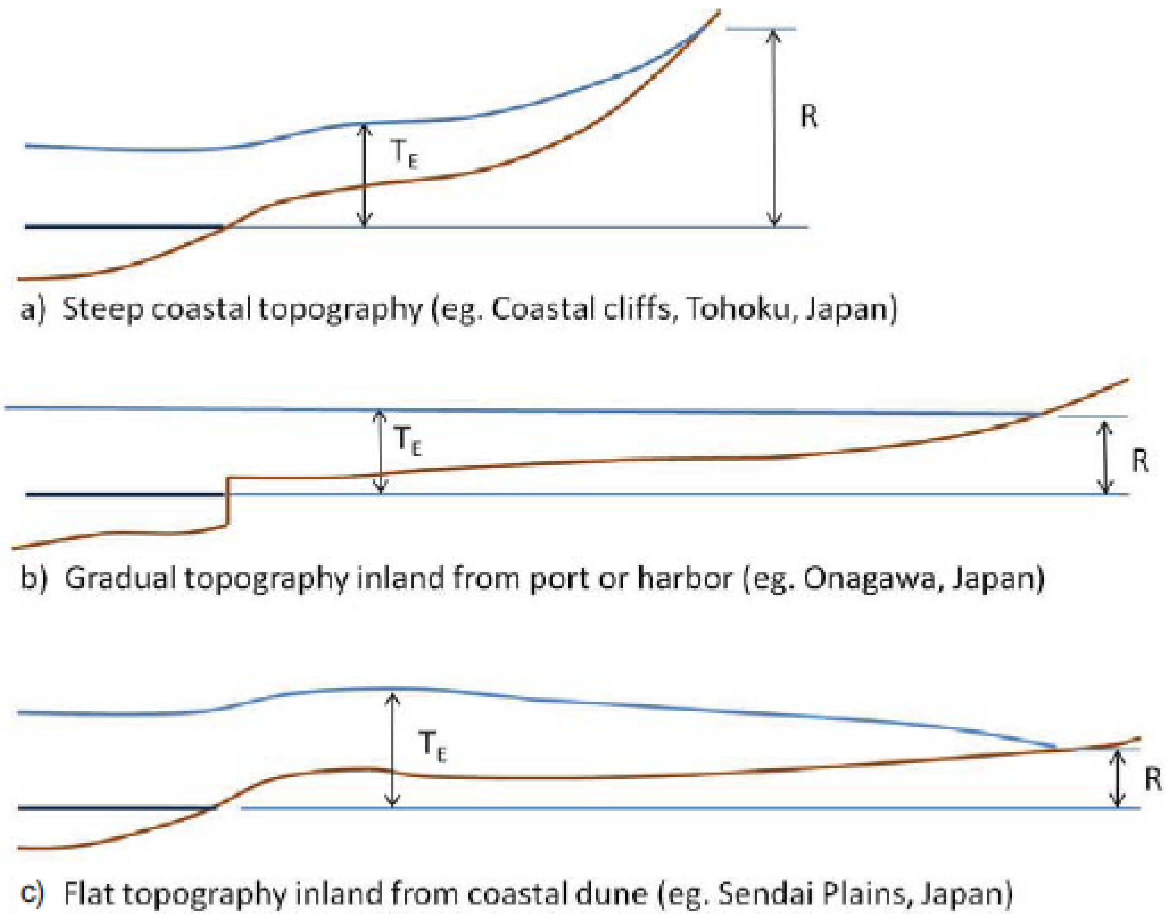


Figure 6-2 Three types of coastal inundation where the tsunami elevation (T_E) at a site of interest could be less than, equal to, or greater than the ultimate inland runup elevation (*R*)

Seismic/Tsunami Design

- **Building must be designed as a critical facility for the 2500 year Maximum Considered Earthquake**
- **Consideration should be given to damage caused by the earthquake if near source tsunami**
- **Recommend design for 2500 year return period Maximum Considered Tsunami**

Tsunami Loads

- Hydrostatic Forces
- Buoyant Forces
- Hydrodynamic Forces
- Impulsive Forces
- Debris Impact Forces
- Damming of Waterborne Debris
- Uplift on Elevated Floors
- Additional Gravity Loads on Elevated Floors

Tsunami Loads

- Hydrostatic Forces
- Buoyant Forces
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- Uplift on Elevated Floors
- Additional Gravity Loads on Elevated Floors

Hydrodynamic Drag

$$F_d = \frac{1}{2}\rho_s C_d B(hu^2)_{\max}$$

$$(hu^2)_{\max} = gR^2\left\{0.125 - 0.235\frac{z}{R} + 0.11\left(\frac{z}{R}\right)^2\right\}$$

- ρ_s – density of seawater with debris and sediment (1,100 kg/m^3)
- B – width of structure or element
- h – bore height
- u – bore velocity
- C_d – drag coefficient (2.0)
- R – runup (taken as 1.3R* to account for mapping uncertainty)
- z – ground elevation at base of structure

Impulsive Force

- Impulsive force to simulate leading edge of broken bore
- Based on tests by Arnason (U. Washington)

$$F_s = 1.5 F_d$$

$$F_d = \frac{1}{2}\rho_s C_d B (hu^2)_{\max}$$

- Apply to wide elements such as walls
- Rather crude estimate due to lack of test data

Debris Impact Forces
P646 - 2008

Original Version:

$$F_i = C_m u_{\max} \sqrt{km}$$

- C_m – added mass coeft. = 2
- u_{max} – maximum flow velocity
- k – effective stiffness
- m – debris mass

Debris	Mass (m) in kg	Eff. Stiffness (k) in kN/mm
Lumber or Wood Log	450	2.4
40-ft Standard Shipping Container	3800 (empty)	650
20-ft Standard Shipping Container	2200 (empty)	1500
20-ft Heavy Shipping Container	2400 (empty)	1700

Debris Impact Forces
P-646 - 2012

Revised Version:

$$F_i = 1.3 u_{\max} \sqrt{k m_d (1+c)}$$

- u_{max} – **maximum flow velocity**
- k – **effective stiffness**
- m_d – **debris mass**
- c – **hydrodynamic mass coefficient**

Debris (Longitudinal)	Mass (m) in kg	Hydro. Mass Coefft. (c)	Eff. Stiff. (k) in kN/mm
Lumber or Wood Log	450	0	2.4
40-ft Std. Shipping Container	3800 (empty)	0.20	60
20-ft Std. Shipping Container	2200 (empty)	0.30	85
20-ft Heavy Shipping Container	2400 (empty)	0.30	93

Damming of Waterborne Debris

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

Hurricane Katrina, 2005

Load Combinations

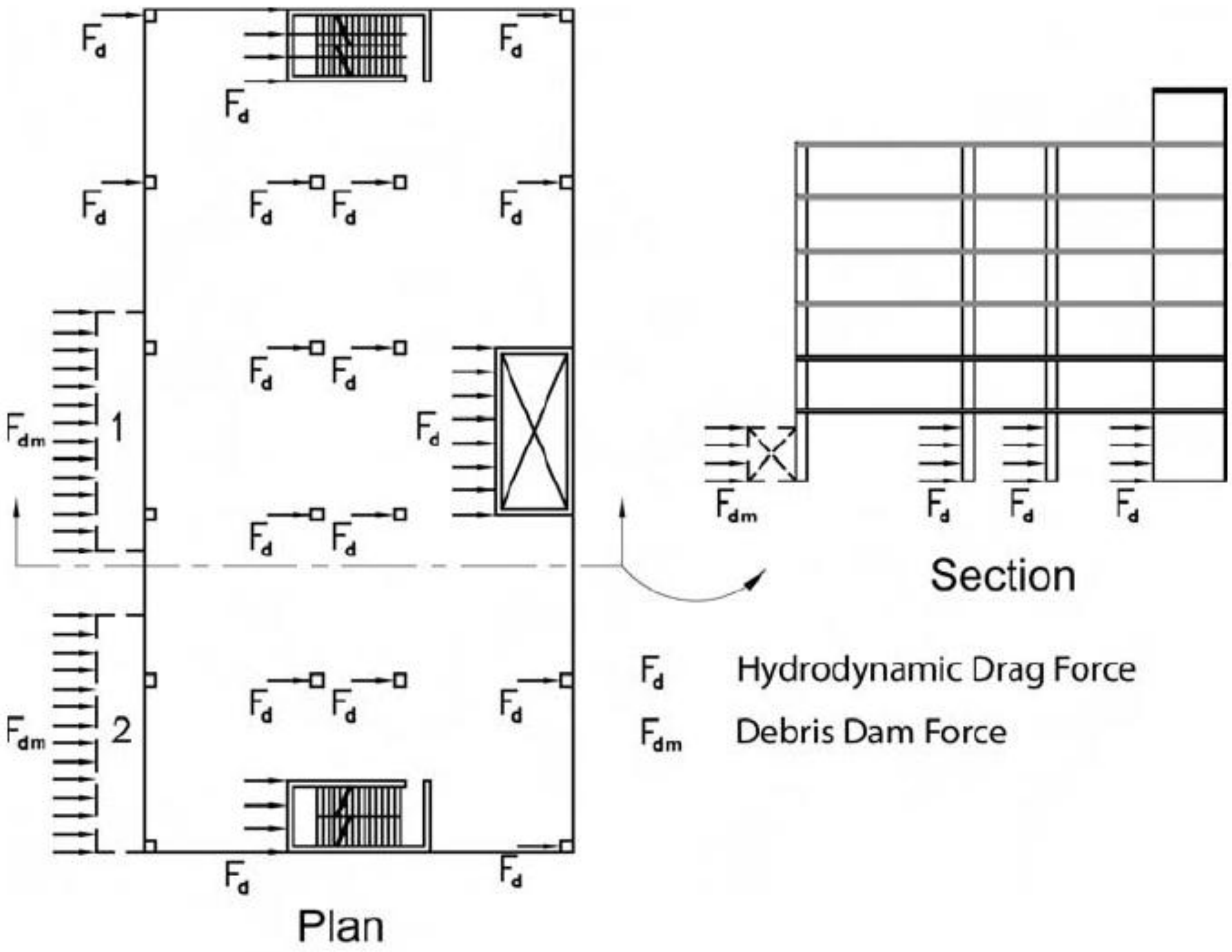


Figure 6-11 Debris dam and drag forces applied to an example building

Load Combinations

Combinations:

Load Combination 1: $1.2D + 1.0T_s + 1.0L_{REF} + 0.25L$

Load Combination 2: $0.9D + 1.0T_s$

where D is the dead load effect, T_s is the tsunami load effect, L_{REF} is the live load effect in refuge area (assembly loading), and L is the live load effect outside of the refuge area.

Progressive Collapse Prevention

- Impact and other extreme loads are uncertain
- Progressive collapse preventive design required
- Missing column or tie-force method
- Follow US DoD guidelines

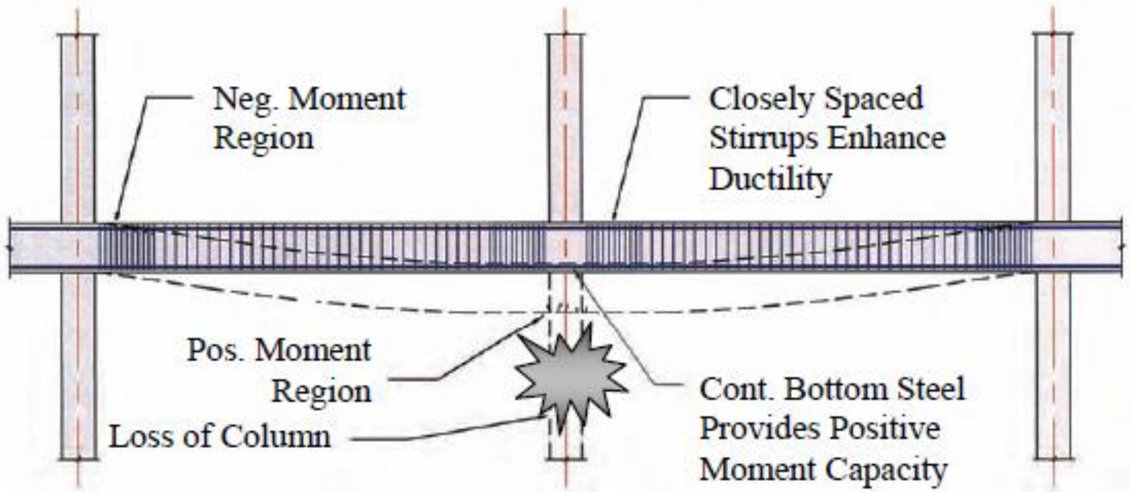


Figure 6-13 Detailing of reinforcing steel for potential loss of a supporting column

Impact induced Progressive Collapse

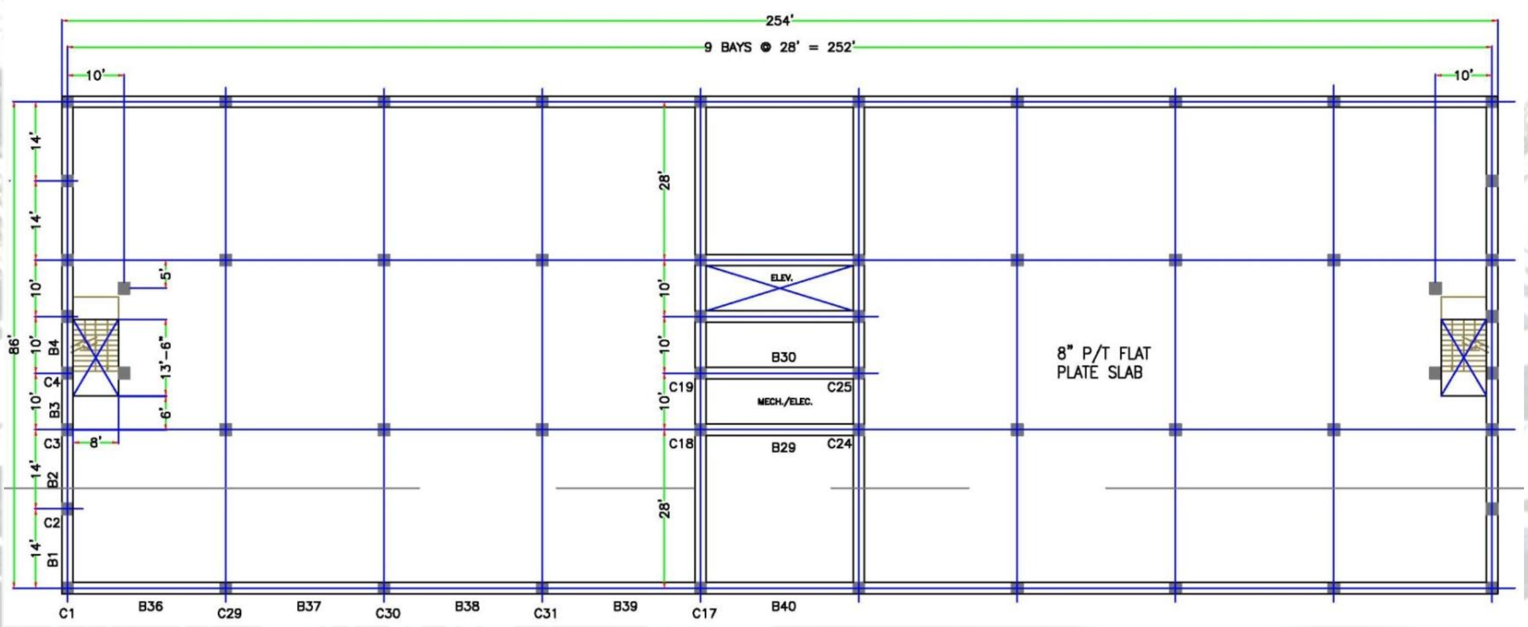
Cost Implications of Tsunami Design

Prototypical Buildings

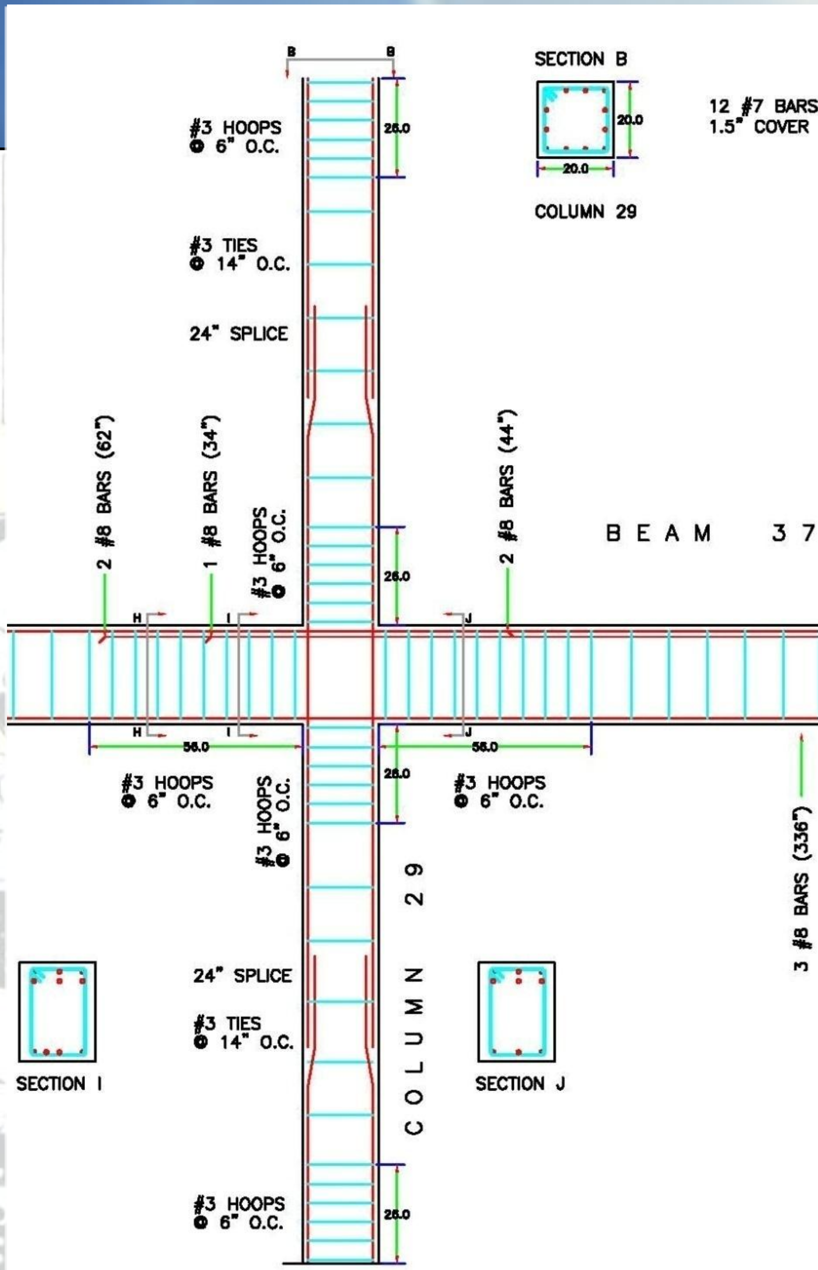
- **12 Story RC Office Building (MRF)**
- **12 Story RC Residential Building (Shear Walls)**
- **12 Story Steel Office Building (EBF)**
- **4 Story Steel Shopping Mall (Concentric BF)**
- **4 Story PC Parking Structure (CIP, PT)**
- **4 Story PC Parking Structure (Precast)**
- **3 Story RC School Building**

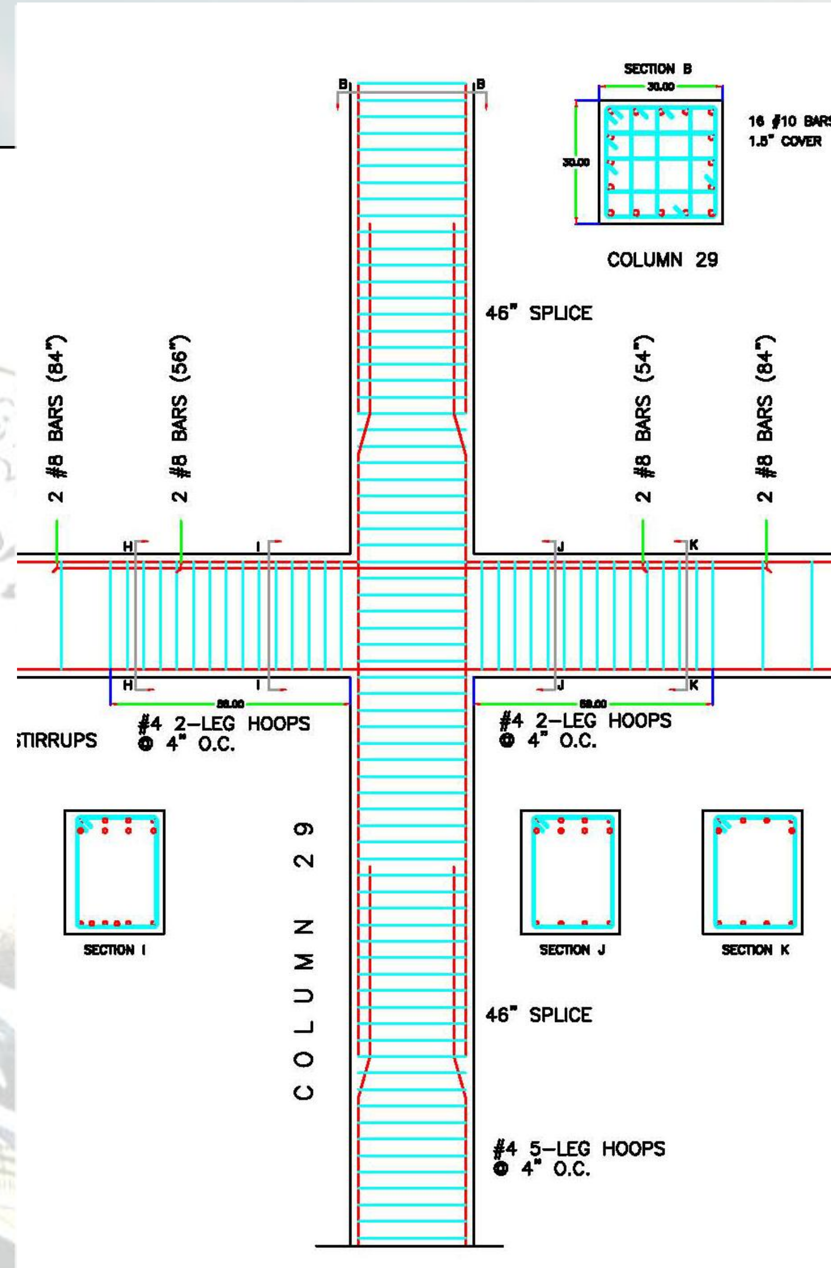
Prototypical
RC MRF Building Design

- 12 Story Office Building (Corporate, Commercial)
- Cast-in-place concrete
- Moment resisting frame/flat plate floor
- SDC – Soil Type
  - C – B
  - C – D (Waikiki)
  - D – D (Hilo)



Intermediate and Special Detailing





Conclusions

- Multi-story concrete and steel buildings can be designed to survive tsunamis.
- Special moment resisting frames designed for high seismic conditions may not require any upgrading.
- Tsunami design resulted in < 2% increase in total cost for 12 story buildings using RC intermediate MRF and shear walls.
- Low-rise and lower-mass buildings would likely require more expensive strengthening.

Possible Funding Mechanisms

- **Coastal Hotels, Condos, Parking structures**
  - **Offer waiver of height limits in exchange for public access to roof and upper levels as tsunami refuge**
  - **Building must be designed to P-646 provisions**
  - **All additional construction costs borne by developer**
- **City, State or Federal Buildings**
  - **Consolidate multiple functions into single taller building**
  - **Leverage FEMA Pre-disaster mitigation funds to cover added cost of P-646 tsunami resistance**
- **Mound in City Park**
  - **Offer low-rate or free dumping of demolished concrete, masonry, soil and other suitable fill materials**
  - **Build mound using these waste materials**

Any Questions?

Tampered sign at Waikaloa Resort, Kona, Hawaii

Newly installed tsunami evacuation signs in Puerto Rico

Tsunami evacuation signs in Kona, Hawaii, sanctioned by ITIC

Any Questions?

Tampered sign at Waikaloa Resort, Kona, Hawaii