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

Kamaishi Merchant Marine Dormitory

Designated evacuation building

All buildings destroyed
Warning and Evacuation

Minamisanriku

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

- 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
• 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  
I. Matsuo

G.S. Leonard  
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 / June 2008
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
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 2-27

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 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
Minimum Refuge Elevation

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

All levels that are at least one floor above R can be used as refuge.

1 floor >3m

Refuge design $R = 1.3R^*$

MCT predicted run-up, $R^*$

High Tide
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

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Hydrodynamic Drag

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

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

- \( \rho_s \) – 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 1.3\( R^* \) 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)

\[ F_s = 1.5 F_d \]

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

- Apply to wide elements such as walls
- Rather crude estimate due to lack of test data
Debris Impact Forces
P646 - 2008

Original Version:

\[ F_i = C_m u_{\text{max}} \sqrt{km} \]

- \( C_m \) – added mass coeff. = 2
- \( u_{\text{max}} \) – maximum flow velocity
- \( k \) – effective stiffness
- \( m \) – debris mass

<table>
<thead>
<tr>
<th>Debris</th>
<th>Mass (m) in kg</th>
<th>Eff. Stiffness (k) in kN/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumber or Wood Log</td>
<td>450</td>
<td>2.4</td>
</tr>
<tr>
<td>40-ft Standard Shipping Container</td>
<td>3800 (empty)</td>
<td>650</td>
</tr>
<tr>
<td>20-ft Standard Shipping Container</td>
<td>2200 (empty)</td>
<td>1500</td>
</tr>
<tr>
<td>20-ft Heavy Shipping Container</td>
<td>2400 (empty)</td>
<td>1700</td>
</tr>
</tbody>
</table>
Debris Impact Forces
P-646 - 2012

Revised Version:

\[ F_i = 1.3u_{\text{max}} \sqrt{km_d (1+c)} \]

- \( u_{\text{max}} \) – maximum flow velocity
- \( k \) – effective stiffness
- \( m_d \) – debris mass
- \( c \) – hydrodynamic mass coefficient

<table>
<thead>
<tr>
<th>Debris (Longitudinal)</th>
<th>Mass (m) in kg</th>
<th>Hydro. Mass Coefft. (c)</th>
<th>Eff. Stiff. (k) in kN/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumber or Wood Log</td>
<td>450</td>
<td>0</td>
<td>2.4</td>
</tr>
<tr>
<td>40-ft Std. Shipping Container</td>
<td>3800 (empty)</td>
<td>0.20</td>
<td>60</td>
</tr>
<tr>
<td>20-ft Std. Shipping Container</td>
<td>2200 (empty)</td>
<td>0.30</td>
<td>85</td>
</tr>
<tr>
<td>20-ft Heavy Shipping Container</td>
<td>2400 (empty)</td>
<td>0.30</td>
<td>93</td>
</tr>
</tbody>
</table>
Damming of Waterborne Debris

\[ F_{dm} = \frac{1}{2} \rho_s C_d B_d (hu^2)_{max} \]
Load Combinations

Figure 6-11  Debris dam and drag forces applied to an example building
Load 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
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
Tsunami evacuation signs in Kona, Hawaii, sanctioned by ITIC

Newly installed tsunami evacuation signs in Puerto Rico

Tsunami evacuation signs in Kona, Hawaii, sanctioned by ITIC
Any Questions?

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