Design of Buildings for Vertical Evacuation from Tsunamis

FEMA P646 Guidance
International Building Code Development for Tsunami-Resistant Design

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March 11, 2011 Minami Soma photo by Sadatsugu Tomizawa
Evacuation Problem

Issues:

- No high ground exist
- Insufficient time to evacuate to high ground

Solution:

- Vertical Evacuation
Vertical Evacuation Structures

• Are called a Refuge not a Shelter
  – Refuge is for short-term protection (12-24 hours)
  – Shelter is long term

• Has sufficient height to elevate evacuees above the level of tsunami inundation

• Designed to withstand an earthquake and resist tsunamis waves
Historic Building Performance

- **Reinforced Concrete**
  - Complete destruction
  - Minor damage

- **Masonry**
  - Complete destruction
  - Minor damage

- **Wood Frame**
  - Complete destruction
  - Minor damage
Outline

- Performance of Vertical Evacuation Refuges during Tohoku Tsunami
  - FEMA P646 design guidelines
  - FEMA P646 update – Second Edition
  - Laboratory Experiments
  - ASCE7 Tsunami Loads and Effects code development
Evacuation to high ground
Kamaishi Example
Evacuation to high ground
Kamaishi Example
Use of Designated Tsunami Evacuation Buildings

Kamaishi Merchant Marine Dormitory

All buildings destroyed

Designated evacuation building

Video
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
- Unknown number of lives lost
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.
Report on Performance of Evacuation Structures in Japan

- By Fraser, Leonard, Matsuo and Murakami
- GNS Science Report 2012/17
- April 2012
Public Safety Lessons

- Public awareness, education and training in tsunami evacuation saves lives, but **urgency of rapid evacuation must be stressed.**

- Recorded history may not provide a good measure of the potential heights of great tsunamis. Probabilistic Tsunami Hazard Analysis should be performed in addition to historical event scenarios.

- Evacuation sites and buildings should be selected with **conservative minimum elevations.** Overtopping leads to inexcusable loss of life.

- **Consideration of walking time and distance to evacuation sites is critical.** Alternative evacuation locations and efficient routing should be provided in flat coastal areas where evacuation to high ground is not possible.

- Fire following tsunami can be widespread.
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Guidelines for Design of Structures for Vertical Evacuation from Tsunamis (FEMA P646)

- First published 2008
- Updated 2012 to include Japan lessons
- Specifically developed for vertical evacuation buildings, not general building stock
- Non-mandatory language - Guidelines

FEMA P646 / June 2008
FEMA P646 - Contents

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

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

• **Parking Garages**
  – Revenue generating facilities
  – Open structure
  – Ramps - easy ingress, vertical circulation

• **Community Facilities**
  – Enhances quality of life in a community

• **Commercial Facilities**
  – Revenue generating facilities
  – Commercial financing options

• **Existing Buildings**
  – Utilizes existing construction
  – Minimizes impacts on community
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

- Access to high ground
- Guidance - number and location of vertical refuges
- Spacing – based on 2 mph walking speed and expected tsunami warning time
- Consideration given to proximity of large debris, hazardous or flammable materials
### Siting, Spacing, and Sizing Considerations

<table>
<thead>
<tr>
<th>Warning time</th>
<th>Ambulatory Speed*</th>
<th>Travel Distance**</th>
<th>Required Spacing</th>
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<tbody>
<tr>
<td>&gt; 2 hrs</td>
<td>2 mph</td>
<td>4 miles</td>
<td>8 miles</td>
</tr>
<tr>
<td>30 min</td>
<td>2 mph</td>
<td>1 mile</td>
<td>2 miles</td>
</tr>
<tr>
<td>15 min</td>
<td>2 mph</td>
<td>1/2 mile</td>
<td>1 mile</td>
</tr>
</tbody>
</table>

* Assumed average speed of mobility-impaired population  
** Must allow time for vertical circulation within refuge
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
Damming of Waterborne Debris

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

Hurricane Katrina, 2005
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 Loading - Biloxi
Impact induced Progressive Collapse
Cost Considerations

- Structural costs will be higher
- Structural is only a portion of total building costs (5% to 40%)
- Can infer potential costs from available cost studies (seismic and progressive collapse)
- Tsunami-resistant structures would experience about 10% to 20% increase in total constructions costs
Outline

- Need for Vertical Evacuation Refuges in Puerto Rico
- Performance of Vertical Evacuation Refuges during Tohoku Tsunami
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NEESR Tsunami Research (UH, OSU, Princeton)

Focus of NEESR Study

Tsunami Modeling

Tsunami Generation
Open Ocean Propagation
Coastal Inundation
Fluid-Structure Interaction
Structural Loading
Structural Response
Sediment Transport

Performance Levels
Consequences (Life and economic losses)
Warning Systems

Probabilistic Tsunami Hazard Analysis
Performance Based Tsunami Engineering

Social Sciences
Public Policy

Ocean, Hydraulic and Structural Engineering

Funding provided under NSF Grant CMMI-0530759
Oregon State University
Tsunami Wave Basin

1/10 with 10 cm reef crest 1/15 flat reef (no crest)
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ASCE 7 DEVELOPMENT OF TSUNAMI STRUCTURAL DESIGN PROVISIONS FOR THE U.S.

February 2013

Gary Chock
USA Codes and Standards

- International Building Code (IBC)
- ASCE 7 Minimum Design Loads for Buildings and Other Structures (ASCE 7) developed in an ANSI-accredited consensus process

- Other Standards:
  - Material specific design specifications
  - Non-structural installation standards
  - Testing and qualification standards
Design Codes

- National Codes and Standards are *updated* every 3 to 5 years:
  - International Building Code augments and adopts by reference the load and public safety requirements of
    - American Society of Civil Engineers / Structural Engineering Institute ASCE 7 Standard, Minimum Design Loads for Buildings and Other Structures
  - **Model Building Codes** are mandatory *when adopted* by the local jurisdiction as a regulatory ordinance.
  - **Guidelines have no force of law**. Many FEMA documents (such as FEMA P646) are of this type but may represent a path towards a “pre-standard” that may later be converted into a standard referenced by the code.
The Code Development Process

Research & Development

Experience from Design Practice and Post-Disaster Surveys

Codes and Standards
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
- Method of probabilistic tsunami hazard analysis
- Methods for calculating site tsunami inundation depth and velocity
- Structural loading, and analysis techniques for determining building performance developed.
- Multi-hazard performance-based approach for local subduction earthquakes
TOHOKU JAPAN TSUNAMI
OF MARCH 11, 2011
PERFORMANCE OF STRUCTURES
Gary Chock. S.E., Ian Robertson, S.E., David Kriebel, P.E.,
Mathew Francis, P.E. and Ioan Nistor, P.E.

Report now in publication at ASCE
TOHOKU TSUNAMI-INDUCED BUILDING FAILURE ANALYSIS WITH IMPLICATIONS FOR U.S. TSUNAMI AND SEISMIC DESIGN CODES

Authors(s):
Gary Chock M.EERI, Lyle Carden, Ian Robertson M.EERI, Michael J. Olsen M.EERI, and Guangren Yu
EERI SPECTRA Special Issue on the Tohoku-Oki EQ (2013) in publication

Figure 11. Large wall failure in the Takada Matsubara building in Rikuzentakata (photos and renderings courtesy of Chock and ASCE)
**Proposed Scope of the ASCE Tsunami Design Provisions**


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<td>Hydrostatic Loads</td>
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<td>6.16</td>
<td>Non-building critical facility structures</td>
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## Risk Categories for Tsunami

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<tr>
<th>Use or Occupancy of Buildings and Structures</th>
<th>Category</th>
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<tr>
<td>Buildings and other structures that represent a low hazard to human life in the event of failure,</td>
<td>I</td>
</tr>
<tr>
<td>All buildings and other structures except those listed in Risk Categories I, III, and IV</td>
<td>II</td>
</tr>
<tr>
<td>Buildings and other structures, the failure of which could pose a substantial risk to human life, including, but not limited to:</td>
<td>III</td>
</tr>
<tr>
<td>• Buildings and other structures where more than 300 people congregate in one area</td>
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<tr>
<td>• Buildings and other structures with daycare facilities with a capacity greater than 150</td>
<td></td>
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<tr>
<td>• Buildings and other structures with elementary school or secondary school facilities with a capacity greater than 250</td>
<td></td>
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<tr>
<td>• Buildings and other structures with a capacity greater than 500 for colleges or adult education facilities</td>
<td></td>
</tr>
<tr>
<td>• Any other occupancy with an occupant load greater than 5,000 based on net floor area.</td>
<td></td>
</tr>
<tr>
<td>Buildings and other structures specified in Table 1-1</td>
<td></td>
</tr>
<tr>
<td>Buildings and other structures designated as essential facilities, including, but not limited to:</td>
<td>IV</td>
</tr>
<tr>
<td>• Health care facilities with a capacity of 50 or more resident patients</td>
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<tr>
<td>• Hospitals and other health care facilities having surgery or emergency treatment facilities</td>
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<tr>
<td>• Police stations</td>
<td></td>
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<tr>
<td>• Designated tsunami vertical evacuation refuges</td>
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<tr>
<td>• Designated emergency preparedness, communication, and operation centers and other facilities required for emergency response</td>
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<tr>
<td>• Power generating stations and other public utility facilities required in an emergency</td>
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<tr>
<td>• Aviation control towers and air traffic control centers</td>
<td></td>
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<tr>
<td>• Telecommunication centers</td>
<td></td>
</tr>
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Tsunami Risk Category Design Criteria

- Not applicable to any buildings within the scope of the International Residential Code; Not applicable to light-frame residential construction

- Economic impact is anticipated to be nominal to western states since most buildings subject to these requirements will be designed to Seismic Design Category D or greater (design for inelastic ductility).
Indications from Prototype Designs of Risk Category IV and III Buildings for Tsunami

- Low-rise and lower-mass buildings could be governed by tsunami, especially port facilities.
- **Tsunami collapse prevention:**
  - Mid to High-rise design for high seismic conditions may not require any systemic upgrading.
  - Structural Components may need local “enhanced resistance”
  - Ground level shear walls may also require localized detailing for out-of-plane hydrodynamic forces
  - Vertical refuge appears to be a practical alternative use for mid to high-rise concrete buildings that have greater inherent resistance.
- Post-earthquake damage state needs to be considered
Minimum Refuge Elevation

- Recommends refuge elevation be 1 story (3m, 10ft) above predicted inundation (with 1.3 factor)
Future of the ASCE7 Standards Activity

- Fourth meeting on July 27-28, 2012, Seattle, WA
- Rough draft of Chapter 6 - Tsunami Loads and Effects
- Need to develop Commentary
- Anticipated completion in Fall 2013
- Reviewed by ASCE7 main committee in 2014-15
- Hopefully included in ASCE7-16
- Referenced by IBC-2018