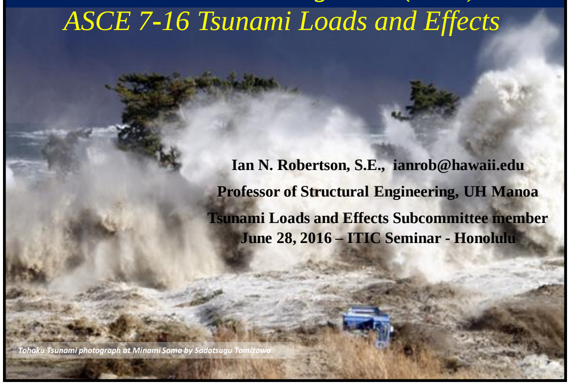
International Building Code (2018): ASCE 7-16 Tsunami Loads and Effects



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Professor of Structural Engineering, UH Manoa
Tsunami Loads and Effects Subcommittee member
June 28, 2016 – ITIC Seminar - Honolulu

Tohoku Tsunami photograph at Minami Soma by Sadatsugu Tomizawa

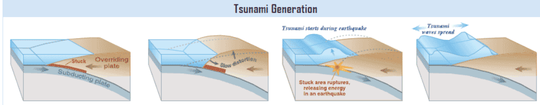
Outline

- Tsunami Background
- Tohoku Tsunami Lessons
- ASCE 7-16 Tsunami Loads and Effects
- Tsunami Design Example
- Summary and Conclusions

History of Tsunami Design in the US

Tsunami Generation Mechanics

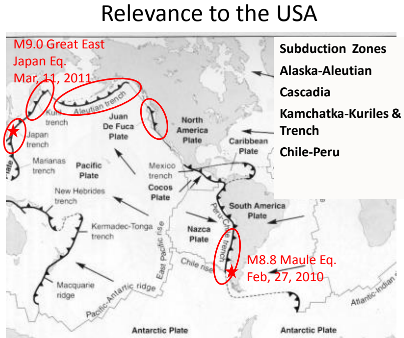
Tsunami Generation



Vertical Slice Through a Subduction Zone	Between Earthquakes	During an Earthquake	Minutes Later
One of the many tectonic plates that make up Earth's outer shell descends, or "subducts," under an adjacent plate. This kind of boundary between plates is called a "subduction zone." When the plates move suddenly in an area where they are usually stuck, an earthquake happens.	Stuck to the subducting plate, the overriding plate gets squeezed. Its leading edge is dragged down, while an area behind bulges upward. This movement goes on for decades or centuries, slowly building up stress.	An earthquake along a subduction zone happens when the leading edge of the overriding plate breaks free and springs seaward, raising the sea floor and the water above it. This uplift starts a tsunami. Meanwhile, the bulge behind the leading edge collapses, thinning the plate and lowering coastal areas.	Part of the tsunami races toward nearby land, growing taller as it comes in to shore. Another part heads across the ocean toward distant shores.

Source: U.S. Geological Survey Circular 1187

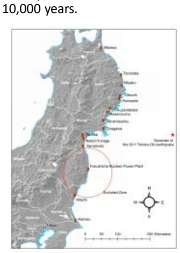
Tsunami-genic Seismic Sources of Principal Relevance to the USA



Subduction Zones
Alaska-Aleutian
Cascadia
Kamchatka-Kuriles & Japan Trench
Chile-Peru

Relevance of Tohoku Lessons to the USA

- Cascadia Subduction Zone is larger than the zone that ruptured in Tohoku
- Cascadia Subduction Zone governs both the MCE and MCT
- 1700 Cascadia Earthquake M9 is only the most recent occurrence of numerous great earthquakes and tsunamis throughout the past 10,000 years.



State	Population at Direct Risk (USGS Lower-bound estimates)	Profile of Economic Assets and Critical Infrastructure
California	275,000 residents plus another 400,000 to 2,000,000 tourists; 840 miles of coastline	>$200 Billion plus 3 major airports (SFO, OAK, SAN) and 1 military port, 5 very large ports, 1 large port, 5 medium ports
	Total resident population of area at immediate risk to post-tsunami impacts: 1,950,000	
Oregon	25,000 residents plus another 55,000 tourists; 300 miles of coastline	$8.5 Billion plus essential facilities, 2 medium ports, 1 fuel depot hub
	Total resident population of area at immediate risk to post-tsunami impacts: 100,000	
Washington	45,000 residents plus another 20,000 tourists; 160 miles of coastline	$4.5 Billion plus essential facilities, 1 military port, 2 very large ports, 1 large port, 3 medium ports
	Total resident population of area at immediate risk to post-tsunami impacts: 900,000	
Hawaii	~200,000 residents plus another 175,000 or more tourists and approximately 1,000 buildings directly relating to the tourism industry; 750 miles of coastline	$40 Billion, plus 3 international airports, and 1 military port, 1 medium port, 4 other container ports, and 1 fuel refinery intake port, 3 regional power plants; 100 government buildings
	Total resident population of area at immediate risk to post-tsunami impacts: 400,000	
Alaska	105,000 residents, plus highly seasonal visitor count; 6,600 miles of coastline	>$10 Billion plus International Airport's fuel depot, 3 medium ports plus 9 other container ports; 55 ports total
	Total resident population of area at immediate risk to post-tsunami impacts: 125,000	

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Evacuation to high ground

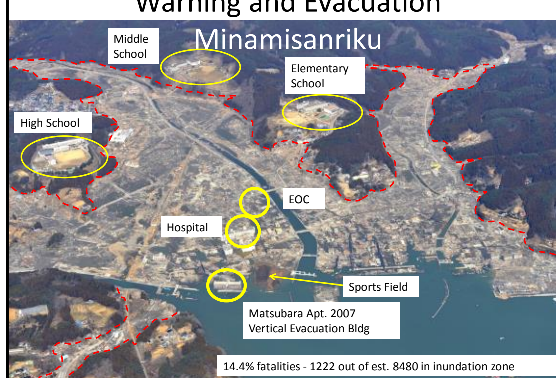
- Evacuation areas readily available and signposted
- However, many not easily accessible for disabled

Designated evacuation building: Kamaishi

Designated evacuation building

Tsunami Video 1

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

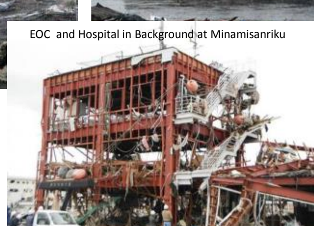
Varied Performance of Reinforced Concrete Buildings

- 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

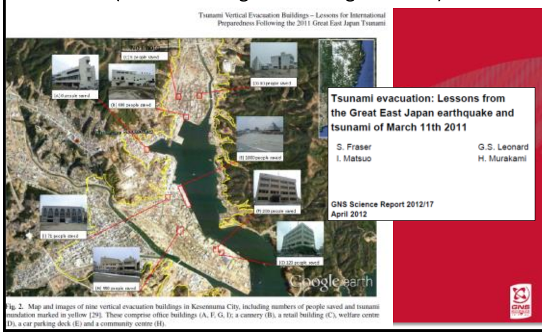
- **But only Sato and 8 others survived**
- **Tragically large loss of lives at adjacent hospital**

Minamisanriku Hospital

RC building with seismic retrofit

- **Hospital was occupied during the tsunami**
- **Some patients were moved to evacuation zone on roof**
- **Three full stories of patient drowning fatalities**

Report on Performance of Taller Structures in Japan used by Evacuees
(whether Designated Refuges or Not)



Tsunami Safety provided by Multi-Story Buildings

- *Tsunami Evacuation: Lessons from the Great East Japan Earthquake and Tsunami of March 11th 2011 (State of Washington sponsored investigation)*
- An example from the City of Ishinomaki (low-lying area similar to coastal communities at risk in the US) near Sendai
- "There was widespread use of buildings for informal (unplanned) vertical evacuation in Ishinomaki on March 11th, 2011. In addition to these three designated buildings, almost any building that is higher than a 2-storey residential structure was used for vertical evacuation in this event. About 260 official and unofficial evacuation places were used in total, providing refuge to around 50,000 people. These included schools, temples, shopping centres and housing."

Tsunami Resilient Engineering Philosophy

- The lesson of recent devastating tsunami is that **historical records alone do not provide a sufficient measure of the potential heights of future tsunamis**. Engineering design must consider the occurrence of events greater than scenarios in the historical record.
- A Probabilistic physics-based Tsunami Hazard Analysis methodology was used for ASCE 7-16
- The ASCE 7-16 national tsunami design provisions utilizes a consistent reliability-based standard of structural performance for disaster resilience of essential facilities and critical infrastructure.

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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

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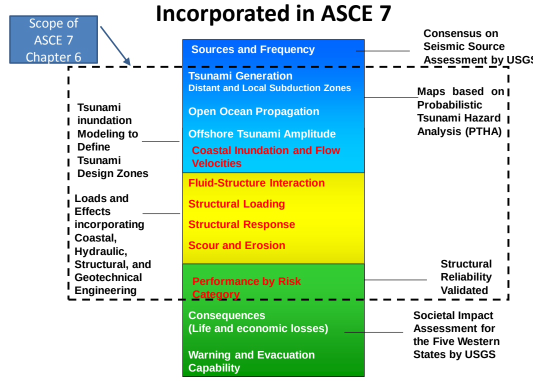
ASCE 7 Tsunami Loads and Effects

- Subcommittee of 16 members and 14 associate members formed in February 2011 (Chair: Gary Chock, S.E.)
- Met 4-5 times per year for three years to develop draft provisions (42 pg Code; 60 pg Commentary)
- Processed 8 consensus ballots through ASCE 7 main committee addressing over 1500 comments
- Final version issued for public comment in Fall 2015.
- Addressed public comments.
- Officially approved for ASCE 7-16 Chapter 6 in March 2016.
- Accepted by ICC Structural Committee for inclusion in IBC 2018
- To be adopted by 5 Western States (AK, WA, OR, CA, and HI) in 2020.
- ASCE will be publishing a design guide in late 2016 with numerous design examples.

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
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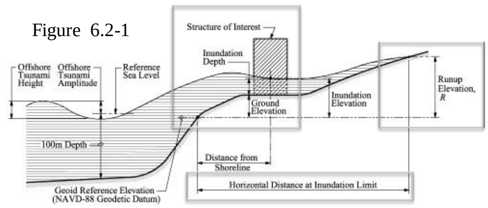
MCT and Tsunami Design Zone

- The ASCE 7 Tsunami Loads and Effects Chapter is applicable only to the states of Alaska, Washington, Oregon, California, and Hawaii, which are tsunami-prone regions that have quantifiable hazards.
- The Maximum Considered Tsunami (MCT) has a 2% probability of being exceeded in a 50-year period, or a ~2500 year average return period.
- The Maximum Considered Tsunami is the design basis event, characterized by the inundation depths and flow velocities at the stages of in-flow and outflow most critical to the structure.
- The Tsunami Design Zone is the area vulnerable to being flooded or inundated by the Maximum Considered Tsunami. The runup for this hazard probability is used to define a Tsunami Design Zone map.

Terminology

- RUNUP ELEVATION: Difference between the elevation of maximum tsunami inundation limit and the (NAVD-88) reference datum
- INUNDATION DEPTH: The depth of design tsunami water level with respect to the grade plane at the structure
- INUNDATION LIMIT: The horizontal inland distance from the shoreline inundated by the tsunami
- Froude number: F_r ; A dimensionless number defined by $u/\sqrt{(gh)}$, where u is the flow velocity and h is the inundation depth

Figure 6.2-1



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.)

Visual 20.34

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.

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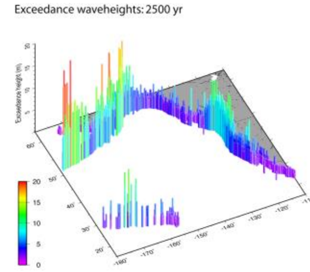
Tsunami Design Zone: Lessons from the Tohoku, Chile, and Sumatra Tsunamis

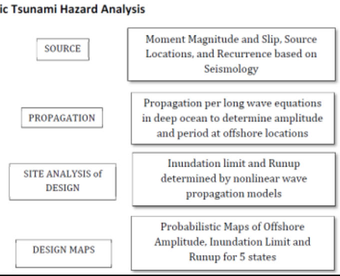
- Recorded history may not provide a sufficient measure of the potential heights of great tsunamis.
- Design must consider the occurrence of events greater than in the historical record
- Therefore, probabilistic physics-based Tsunami Hazard Analysis should be performed in addition to historical event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

Exceedance waveheights: 2500 yr

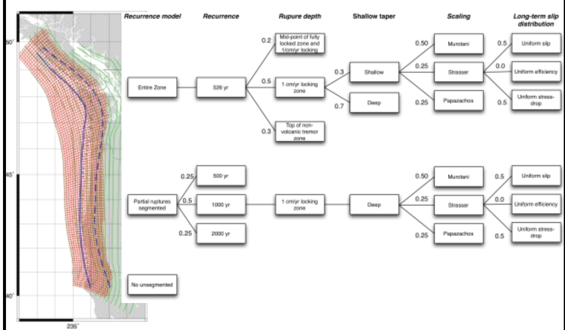


PTHA derived Max. Considered Tsunami

- The ASCE PTHA procedure was peer reviewed by a broad stakeholder group convened by the NOAA National Tsunami Hazard Mitigation Program, and included independent comparative pilot studies.
- Subduction Zone Earthquake Sources are consistent with USGS Probabilistic Seismic Hazard model.

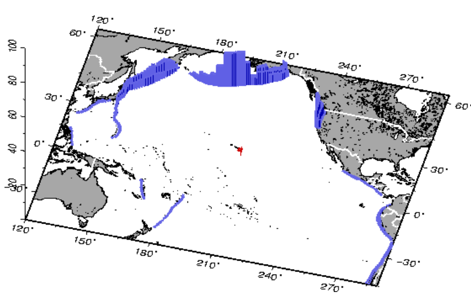


USGS Logic Tree for Cascadia adapted for Tsunamis

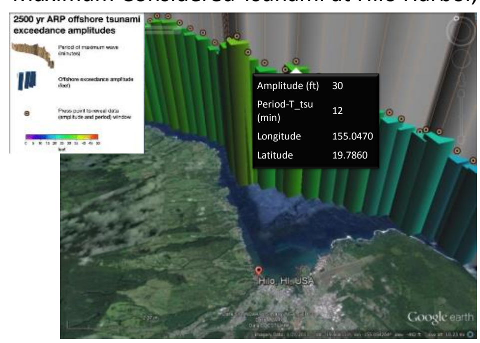


Disaggregated Hazard for Hilo, HI

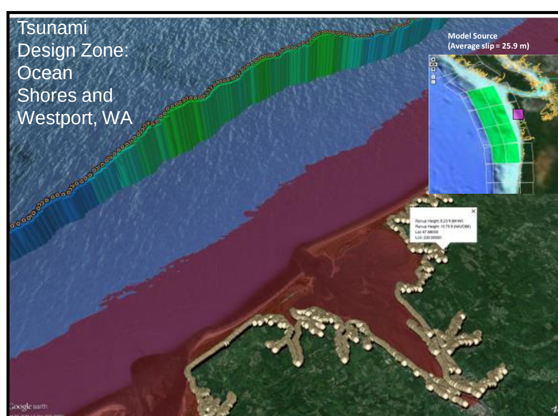
- Sources: Aleutian, Alaska, and Kamchatka-Kurile

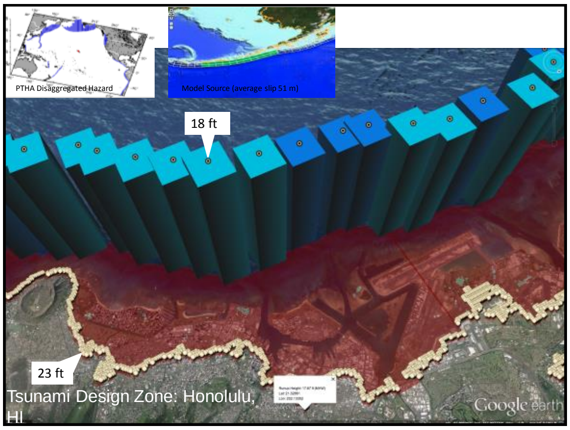


Offshore Tsunami Amplitude and Period for the Maximum Considered Tsunami at Hilo Harbor, HI



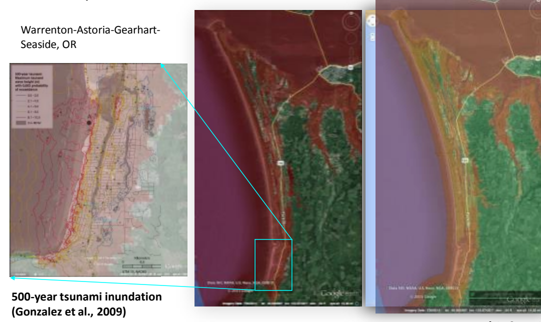
Tsunami Design Zone - Hilo





Oregon: The tsunami inundation zones indicated by the ASCE TDZ maps are between the zones of L1 and XXL1.

Warrenton-Astoria-Gearhart-Seaside, OR

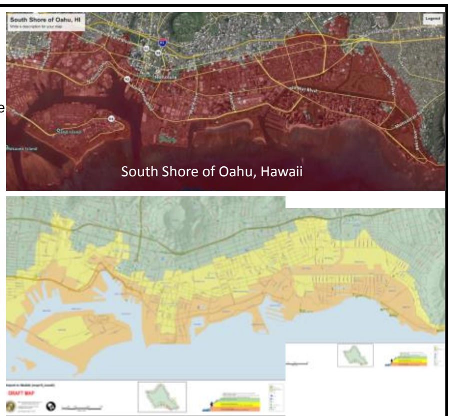


500-year tsunami inundation (Gonzalez et al., 2009)

ASCE TDZ

OR Evacuation map (defined by XXL1)
http://nvs.nanoos.org/TsunamiEvac

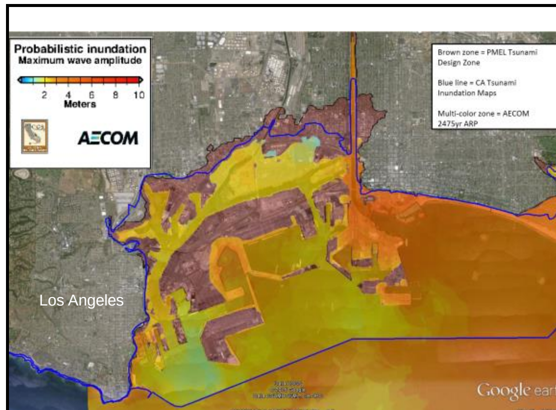
TDZ based on PTHA 2,475-yr offshore amplitude



Extreme Tsunami Evacuation Zone (Courtesy of City and County of Honolulu)

Extreme Tsunami Evacuation Zone

Tsunami Evacuation Zone



Tsunami Design Geodatabase being hosted by ASCE on an electronic database

- Probabilistic Subsidence Maps
- PTHA Offshore Tsunami Amplitude and Predominant Period
- Disaggregated source figures
- Runup, or Inundation depth reference points for overwashed peninsulas and/or islands to be presented in an electronic map
- Tsunami Design Zones organized by state (all applicable areas in the five western states)
- 62 nondigital Tsunami Design Zone pdf maps for specific areas that are equivalent to the digital maps

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Tsunami Flow Characteristics

Two approaches to determine flow depth and velocity

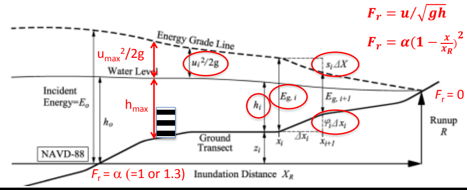
- **Energy Grade Line Analysis method** based on pre-calculated runup from the Tsunami Design Zone maps
- **Site-Specific Probabilistic Hazard Analysis**
  - Required for TRC IV
  - Optional for other TRCs
  - Velocity lower limit of 75-90% EGL method

Energy Grade Line Analysis

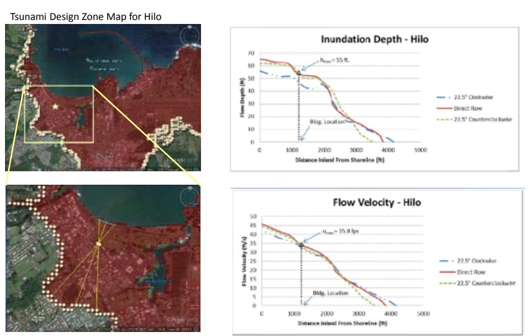
- Re-accumulate the hydraulic head required to reach the inundation limit and runup elevation
- Sum the energy lost to altitude ($\varphi_i \Delta X_i$) and friction ($s_i \Delta X_i$) during inflow
- Total energy at any location along the transect is then:

$$E_{g,i} = E_{g,i+1} + (\varphi_i + s_i)\Delta X_i$$

- Validated to be conservative through field data & 36,000 numerical simulations yielding 700,000 data points



An Example of the Energy Grade Line Method - Hilo, HI



Site-Specific Probabilistic Tsunami Hazard Analysis

- Can be run as a nonlinear time history inundation model analysis using Hazard Consistent Tsunami matching the defined probabilistic waveform
  - Offshore Tsunami Amplitude & effective Wave Period Relative amplitudes of crest and trough for each region
- Can be run as a complete probabilistic simulation from the seismic source slip event, calibrated to match the defined probabilistic Offshore Tsunami Amplitude
- In either case, time histories of site-specific flow parameters are generated.

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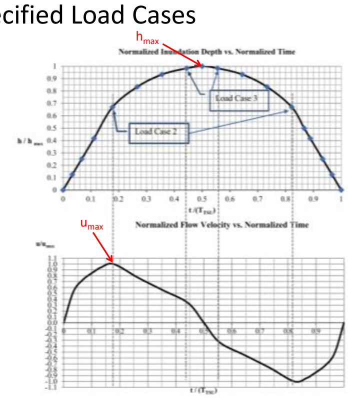
Specified Load Cases

- Normalized prototypical time history of depth and flow velocity as a function of the maximum values determined from the Energy Grade Line Analysis
- 3 discrete governing stages of flow
- Load Case 1 is a max. buoyancy check during initial flow
- LC 2 and 3 shown



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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)

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Hydrodynamic Loads

- Formulations for detailed calculations on the building and for loads on components
  - Typically of the standard form drag (h - inundation depth and u – flow velocity for each load case)

$$f_{dx} = \frac{1}{2}\rho_s C_d C_{cx} B(hu^2)$$

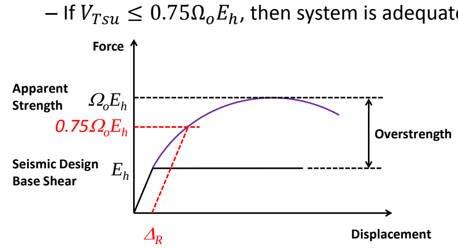
Where $C_{cx} = \frac{\sum(A_{col}+A_{wall})+1.5A_{beam}}{Bh_{sx}}$

$C_{cx} \nless 0.7\ \textit{for regular structure}$

$C_{cx} \nless 0.5\ \textit{for open structure}$

Hydrodynamic Loads

- Lateral Framing System Evaluation
  - Compare tsunami base shear, V_{Tsu}, with seismic non-linear capacity
  - If $V_{Tsu} \le 0.75\Omega_o E_h$, then system is adequate



Hydrodynamic Loads

- Component Evaluation
  - Apply hydrodynamic drag to individual members
    - Exterior members - include debris accumulation
    - Interior members - no debris accumulation
  - Evaluate members using conventional strength design
    - Load considered as sustained static load
    - include appropriate load combinations and factors
    - include material strength reduction factors (ϕ)
  - Increase member strength if necessary

Sendai
Bore Strike on R/C Structure

Sendai
Bore Strike on R/C Structure

Video 1 Minami Gamou

Velocity Analysis

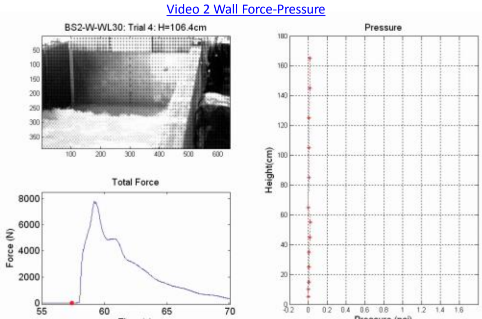
Frame 260 – First Building Impact

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

NEESR – Development of Performance Based Tsunami Engineering, PBTE

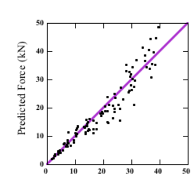
Video 2 Wall Force-Pressure

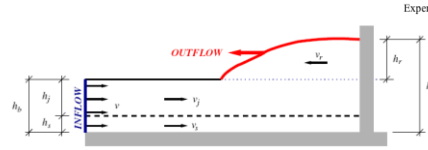


Hydrodynamic Force on Wall due to Bore Impact

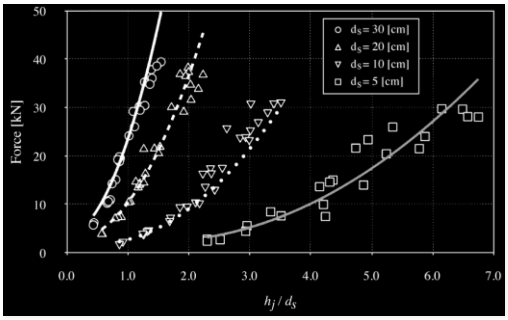
- Based on conservation of mass and momentum

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





Wall load expression comparison with experimental data



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

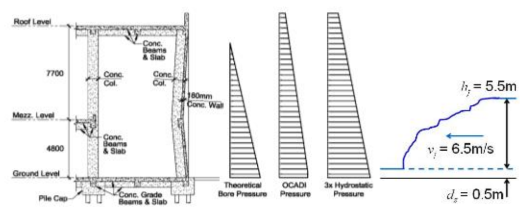
Bore Strike on R/C Structure

Interior view of 2-story wall **Lidar scan of 2-story wall**

Minami Gamou Wastewater Treatment Plant

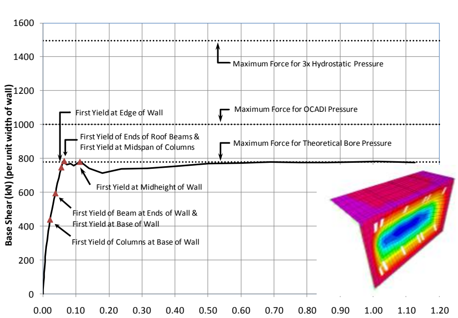
Bore Impact Forces
Minami Gamou Treatment Plant

- Comparison with Different Bore Pressures used in Japan Tsunami Standards

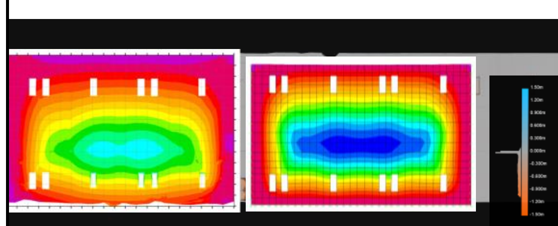


$$F_w = \rho_{sw}\left(\frac{1}{2}gh_b^2 + h_j v_j^2 + g^{1/3}(h_j v_j)^{4/3}\right)$$

Bore Impact Forces
Non-linear Finite Element Analysis



FEA compared with Lidar scan



Out of Plane deformation in meters

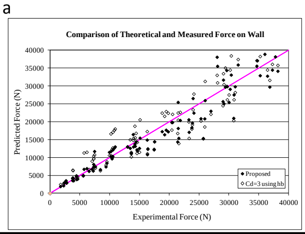
Minami Gamou Wastewater Treatment Plant - subjected to direct bore impact

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

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



Types of Floating Debris

Logs and Shipping Containers




Types of Rolling Debris

Rocks and Concrete Debris



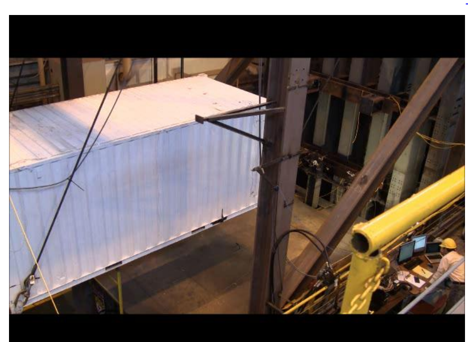
May 16, 2013 https://nees.org/resources/6277/

ISO 20-ft Shipping Container

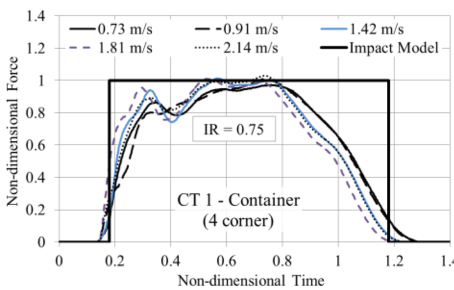
- 6.1 m x 2.4 m x 2.6 m and 2300 kg empty
- Containers have 2 bottom rails and 2 top rails
- Pendulum setup; longitudinal rails strike load cell(s)

Shipping Container Impact

Video

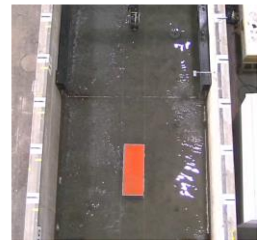


Impact Force Time History



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

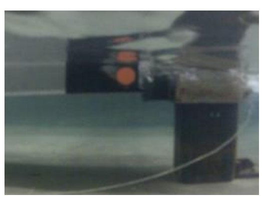


Column and load cell at top of photo

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



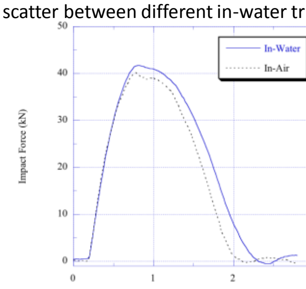
In-water impact

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

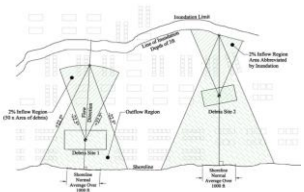


Debris Impact Force

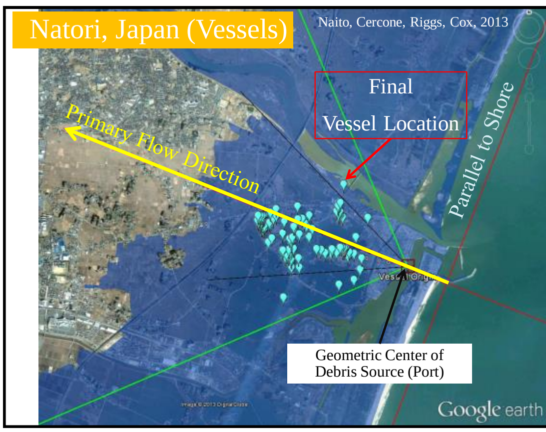
- Nominal maximum impact force
$$F_{ni} = u_{max}\sqrt{km_d}$$
- Factored design force based on importance factor
$$F_i = I_{TSU}F_{ni}$$
- Impact duration
$$t_d = \frac{2m_d u_{max}}{F_{ni}}$$
- Force capped based on strength of debris
  - Shipping Container: $F_i = 330C_o I_{TSU}$
  - Wooden Log: $F_i = 165C_o I_{TSU}$
  - Where: C_o=0.65, Impact orientation factor
- Contents increase impact duration but not force

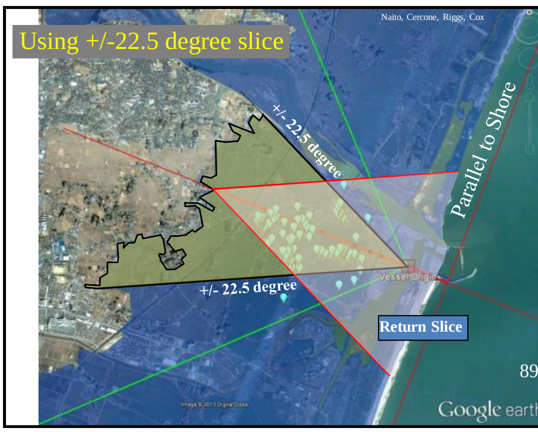
Assessment for Containers and Ships

- Point source of debris
  - Shipping container yards
  - Ports with barges/ships



- Approximate probabilistic site assessment procedure based on proximity and amount of potential floating objects
  - Determine potential debris plan area
    - Number of containers * area of a container
  - 2% concentration defines debris dispersion zone





Outline

- Tsunami Background
- Tohoku Tsunami Lessons
- ASCE 7-16 Tsunami Loads and Effects
- Tsunami Design Example
- Summary and Conclusions

Tsunami Design

- Vertical Component Design
  - Exterior Columns and Shear Walls
    - Hydrodynamic drag including effects of debris damming
    - Debris Impact including orientation factor
  - Interior Columns and Shear Walls
    - Hydrodynamic drag *without* debris damming
    - No debris impact loads
    (therefore, interior shear walls are favorable)

Load Combinations [Strength Design]

Principal Tsunami Forces and Effects shall be combined with other specified loads in accordance with the load combinations of Eq. 6.8.3.3-1:

$0.9D + \mathbf{F_{TSU}} + 1.0\,H_{TSU}$ (Eq. 6.8.3.3-1a)

$1.2D + \mathbf{F_{TSU}} + 0.5L + 0.2S + 1.0\,H_{TSU}$ (Eq. 6.3.3.3-1b)

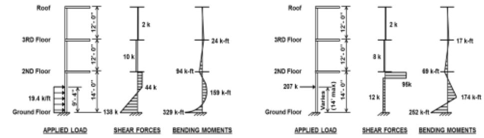
where,

F_{TSU} =tsunami load effect for incoming and receding directions of flow

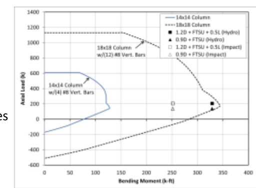
H_{TSU} = load due to tsunami-induced lateral foundation pressures developed under submerged conditions. Where the net effect of H_{TSU} counteracts the principal load effect, the load factor for H_{TSU} shall be 0.9

Typical Exterior Column Design (3-stories)

- Hydrodynamic Pressure
- Debris Impact (simplified)



Reinforced Concrete Minimum Gravity-Load Column increases from 14" Sq. to 18" Sq.

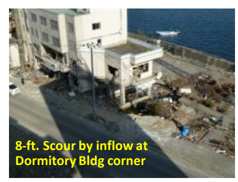


Structural Steel Minimum Gravity Load Column W14 x 61 section is upgraded to a W14 x 68 section

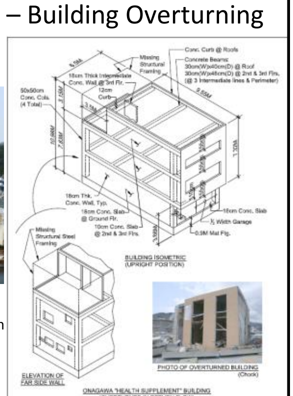
ASCE 7 Chapter 6- Tsunami Loads and Effects

- 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

Foundation Design – Scour Examples



Building Performance – Building Overturning



Three-Story Concrete Retail Building (2050 kN deadweight) on mat foundation overturned during return flow when submerged in 8 m/s flow; would have toppled at only 3 m/s

Structural Response

Foundation Failure

Onagawa overturned steel building

Hollow pipe compression piles

Foundation Design

- General Site Erosion
- Local Scour
- Plunging Scour (i.e., overtoppin a wall)
- Under-seepage Forces
- Loss of Strength due to pore pressure softening during drawdown

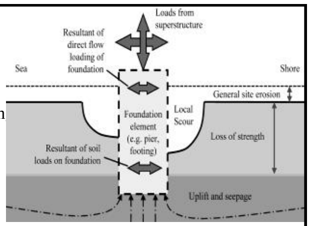


Figure C6.12-1. Schematic of tsunami loading condition for a foundation element

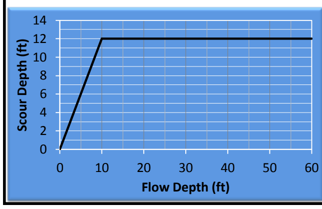


Figure 6.12-1 Local Scour Depth due to Sustained Flow and Pore Pressure Softening

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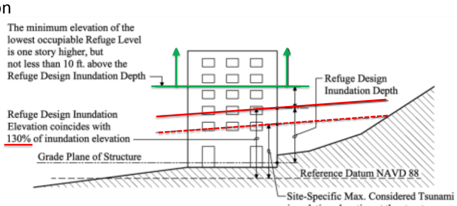
Tsunami Vertical Evacuation Refuge Structures

- Tsunami Vertical Evacuation Refuge Structures - ASCE 7 Chapter 6 is intended to supersede both FEMA P646 structural guidelines and IBC Appendix M
- Additional reliability (99%) is achieved through site-specific inundation analysis and an increase in the design inundation elevation



6.14-1. Minimum Refuge Elevation

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- **6.16 Non-Building Structures**

Basic Lessons for Design of Buildings from Past Tsunami and confirmed in Design Examples

- It is feasible to design certain buildings to withstand tsunami events
- Multi-story (and larger buildings) with robust structural systems can survive.
- Seismic design has significant benefits to tsunami resistance of the lateral-force-resisting system.
- Local structural components may need local “enhanced resistance”
- Foundation system should consider uplift and scour effects particularly at corners.

Summary

- The ASCE 7 provisions constitute a comprehensive method for reliable tsunami structural resilience, making tsunamis a required consideration in planning, siting, and design of coastal structures in the five western states.
- Probabilistic Tsunami Hazard Analysis is the basis for the development of 2475-yr MRI Tsunami Design Zone maps.
- 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, especially where horizontal egress inland to safe ground takes longer than the travel time of the tsunami.

Thank-You