Tsunami Resilient Design for High Hazard Regions

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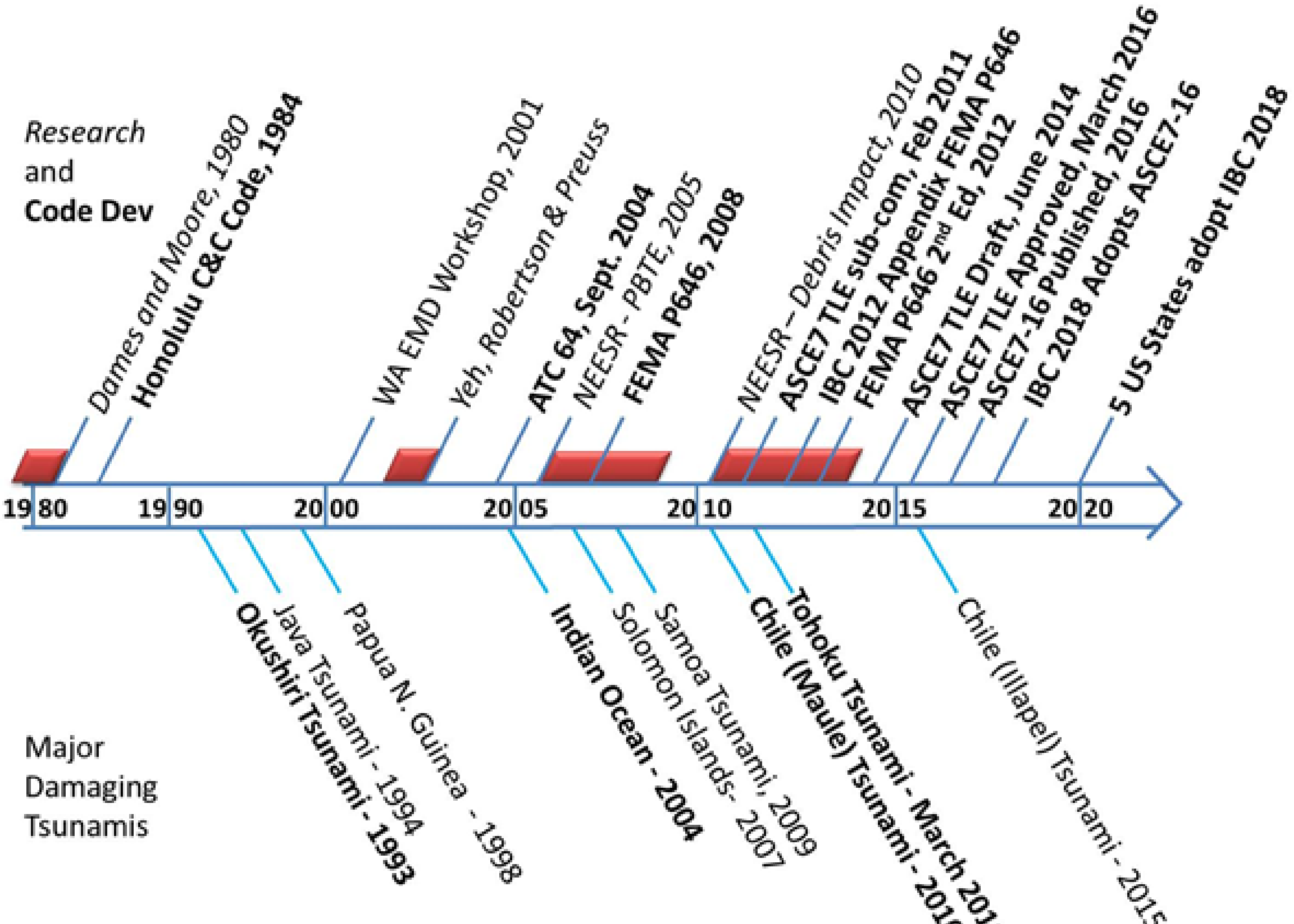
Hilo Bay - 1960 Chile Earthquake
Source: Pacific Tsunami Museum, Hilo, Hawaii
www.tsunami.org

Progression to a Tsunami Design Code for the U.S.



TSUNAMI-RESILIENT ENGINEERING SUBJECT MATTER INCORPORATED IN ASCE 7

Scope of ASCE 7 Chapter 6

Sources and Frequency

Tsunami Generation
Distant and Local Subduction Zones

Open Ocean Propagation

Offshore Tsunami Amplitude

Coastal Inundation and Flow Velocities

Fluid-Structure Interaction

Structural Loading

Structural Response

Scour and Erosion

Performance by Risk Category

Consequences
(Life and economic losses)

Warning and Evacuation Capability

Consensus on Seismic Source Assessment by USGS

Maps based on Probabilistic Tsunami Hazard Analysis (PTHA)

Tsunami inundation Modeling to Define Tsunami Design Zones

Loads and Effects incorporating Coastal, Hydraulic, Structural, and Geotechnical Engineering

Structural Reliability Validated

Design for Tsunami Resilience

Tsunami Disaster Resilience is Possible by Design

- ASCE 7, Minimum Design Loads and Associated Criteria for Buildings and Other Structures, Chapter 6, Tsunami Loads and Effects, now constitutes the national standard of practice for professional engineers.
- ASCE 7 provides a means to effectively improve community resilience and the reliability of critical infrastructure in design.
- Apply ASCE 7 tsunami provisions for community planning* of resilient development before a tsunami event as well as in the building code.
- After a tsunami, it can have even more significance as a means to plan, site, and design what is appropriate* and necessary in reconstruction.
- *However, as a technical engineering standard, it is easy for other stakeholders or opponents to ignore or mis-characterize.

Risk Category III and IV structures within the TDZ are subject to the tsunami provisions

Risk Category I	**Buildings and other structures that represent a low risk to humans**
Risk Category II	**All buildings and other structures except those listed in Risk Categories I, III, IV**
Risk Category III	**Buildings and other structures, the failure of which could pose a substantial risk to human life.** **Buildings and other structures with potential to cause a substantial economic impact and/or mass disruption of day-to-day civilian life in the event of failure.**
Risk Category IV	**Buildings and other structures designated as essential facilities** **Buildings and other structures, the failure of which could pose a substantial hazard to the community.**

The International Building Code includes itemization of these Risk Categories by type of occupancy, following the intent of ASCE 7. ***The local jurisdiction needs to specifically adopt requirements for Risk Category II buildings***

Tsunami Loads and Effects

- 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
    - Can act on the building as a whole
    - Also acts on individual components.
  - Lateral Impulsive Forces of Tsunami Bores: Factor of 1.5
  - Hydrodynamic Pressurization by Stagnated Flow – per Bernoulli
  - Shock pressure effect of entrapped bore – (this is a special case)
- 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
- Waterborne Debris Impact Forces (flow speed and √mass)
  - 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)

ASCE7 Tsunami Loads & Effects

- The new ASCE7-16 Chapter 6– Tsunami Loads and Effects is applicable to the five western states.
- Use it to improve resilience of a community for tsunamis in:
  - Planning and Siting
  - Structural Design
  - Post-disaster reconstruction
- ASCE Tsunami Design Geodatabase
  - Maps and criteria in the ASCE 7 design standard are based on engineering risk analysis and reliability targets, rather than deterministic scenarios.
  - Tsunami Design Zone (TDZ) Maps based on 2500-yr Maximum Considered Tsunami (MCT) from probabilistically aggregated sources
- Tsunami hazard to buildings will diminish significantly with distance from the shoreline, due to reduction of inundation depth and velocity

Application of Tsunami Provisions

- Communities having defined TDZs, should first evaluate the feasibility of locating critical facilities outside these zones or towards the rear of the zones.
- Most Category III and IV buildings would be designed to partially flood while locating critical components for functionality above the inundation depth.
- ASCE7 allows local jurisdictions to decide how to apply Tsunami Design Provisions for Risk Category II buildings, depending on their community's tsunami expected losses, tsunami response procedures, and whole community disaster resilience goals.
- ***Local government should determine threshold height and occupancy criteria for where tsunami-resilient design requirements for Risk Category II buildings shall apply, and implement this policy in the statute adopting the building code.***

Evacuation – will it be completed?

- Even when a community plans for evacuation, experience from past tsunamis is that full evacuation is rarely achieved.
- Difficult for people to survive even in shallow tsunami flows.
- Observation is that taller buildings will provide some safety.
- 2011 Tohoku Tsunami examples
  - Kamaishi (photograph)
  - Ishinomaki (260 buildings and building complexes – 50,000 people saved)
- A study looks at what is the most economically achievable for the design of coastal buildings in the Pacific States.

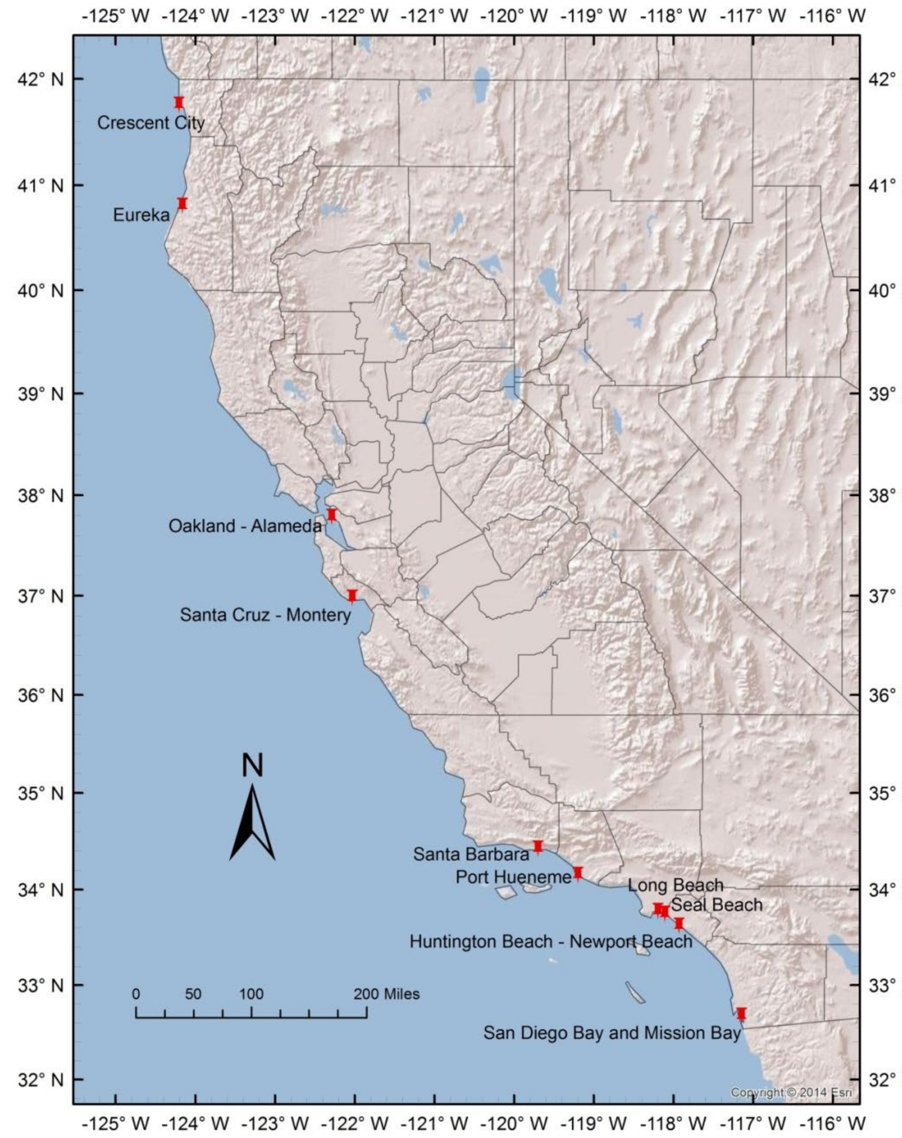
Building Tsunami Resilience Comparisons along the Coast

- Considered 35 locations in the 4 Pacific States (excluding Alaska).
- Developed prototypical reinforced concrete shear wall and steel moment frame buildings, 1 to 7 stories in height.
- Located buildings in the developed coastal area *with the greatest tsunami inundation depth for a given region*.
- Determined the inundation depth and calculated the tsunami loading demand curve for the coastal areas *with the greatest inundation depth*.
- Evaluated the seismic systemic strength available for tsunami resistance.
- Allowed for an additional story height to provide at least one dry level.
- Note that tsunami hazard diminishes with distance from the shoreline, and so could the threshold building height.

California Locations

Building Height Threshold for California Locations

Region	Max. Inundation Depth in developed coastal shoreline areas (ft)	Threshold height for RC II Bldg's[1]
Crescent City	19 ft	35[2]
Eureka	14 ft.	30[2]
Oakland -Alameda	Less than 3 ft.	N/A[3]
Santa Cruz-Monterey	14 ft.	30[2]
Port Hueneme/ Santa Barbara	5 ft	25[2]
Long Beach - Seal Beach	8 ft.	25[2]
Huntington/ Newport Beach	8 ft.	25[2]
San Diego Bay/ Mission Bay	Less than 3 ft.	N/A[3]



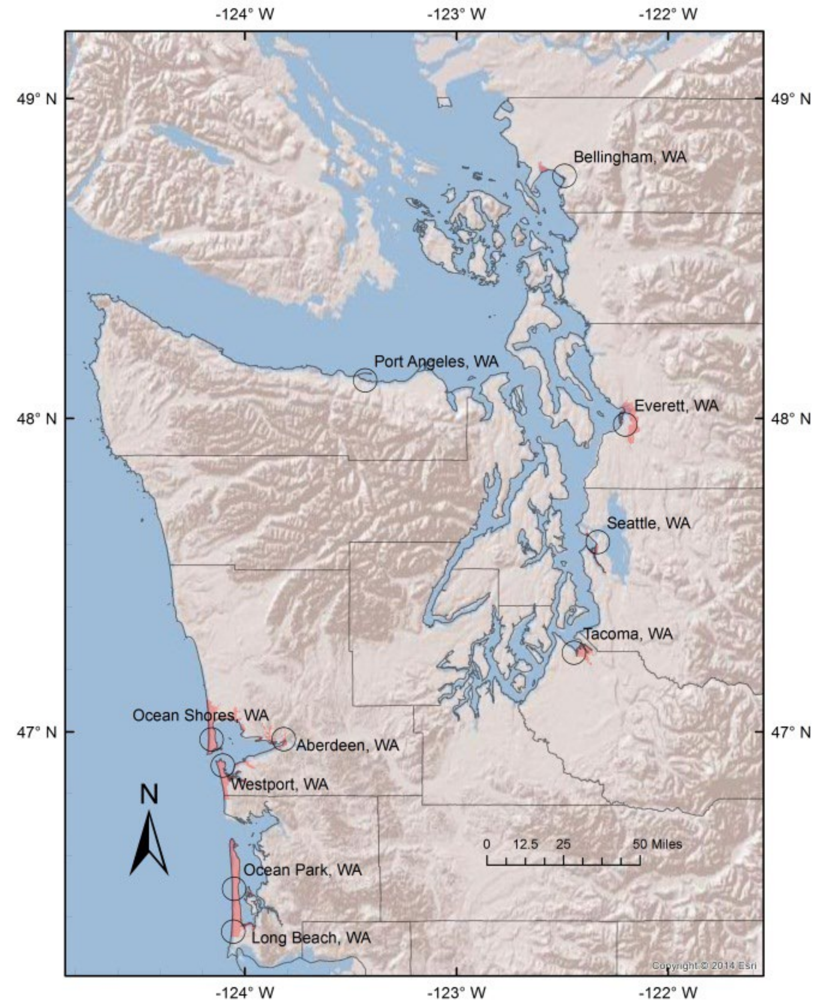
Notes:

1. The threshold is based on the inundation plus 12 ft and not less than 25 ft.
2. For these locations no overall strengthening of the building should be necessary if designed to seismic requirements.
3. For these locations, tsunami design is not required due to low inundation depths.

Washington Locations

Building Height Threshold for Washington Shoreline Locations

Region	Max. Inundation Depth in developed coastal shoreline areas (ft)	Threshold height for RC II Bldg's in the shoreline zone (no setback line)[1]
Everett	2	N/A[3]
Seattle	20	35[2]
Tacoma	11	25[2]
Port Angeles	15	30[2]
Ocean Shores	14	30[2]
Aberdeen	3	N/A[3]
Westport	9	25[2]
Ocean Park	40	55[4]
Long Beach	47	60[4]



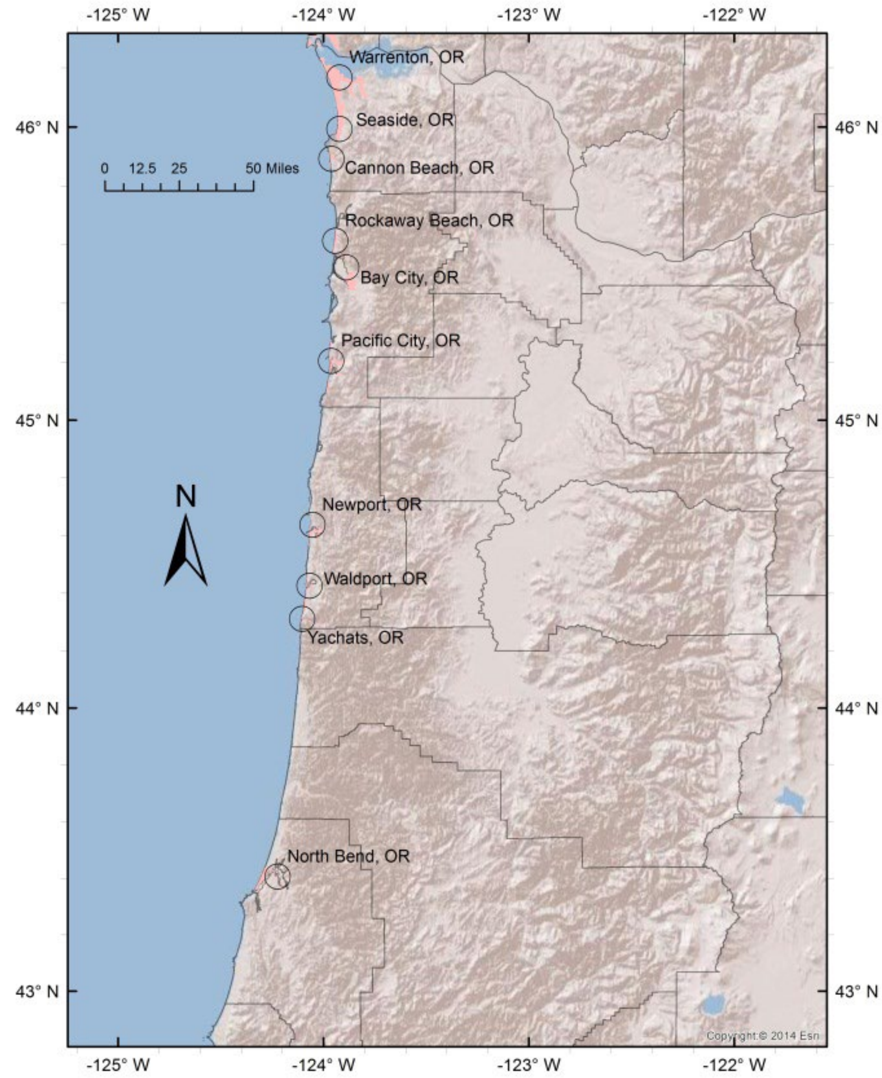
Notes:

1. The threshold is based on the inundation plus 12 ft and building height threshold not less than 25 ft.
2. For these locations no overall strengthening of the building should be necessary if designed to seismic requirements.
3. For these locations, tsunami design is not required due to low inundation depths.
4. For these locations, strengthening of the building system in excess of seismic design requirements may be required to resist tsunami loads.

Oregon Locations

Building Height Thresholds for Oregon Shoreline Locations

Region	Max. Inundation Depth in developed coastal shoreline areas (ft)	Threshold height for RC II Bldg's in the shoreline zone (no setback line)[1]
Warrenton	21	35[2]
Seaside	40	55[4]
Cannon Beach	57	70[4]
Rockaway Beach	39	55[2]
Bay City	8	25[2]
Pacific City	24	40[2]
Newport	18	30[2]
Waldport	45	60[4]
Yachats	47	60[4]
North Bend	35	50[2]



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2. For these locations no overall strengthening of the building should be necessary if designed to seismic requirements.
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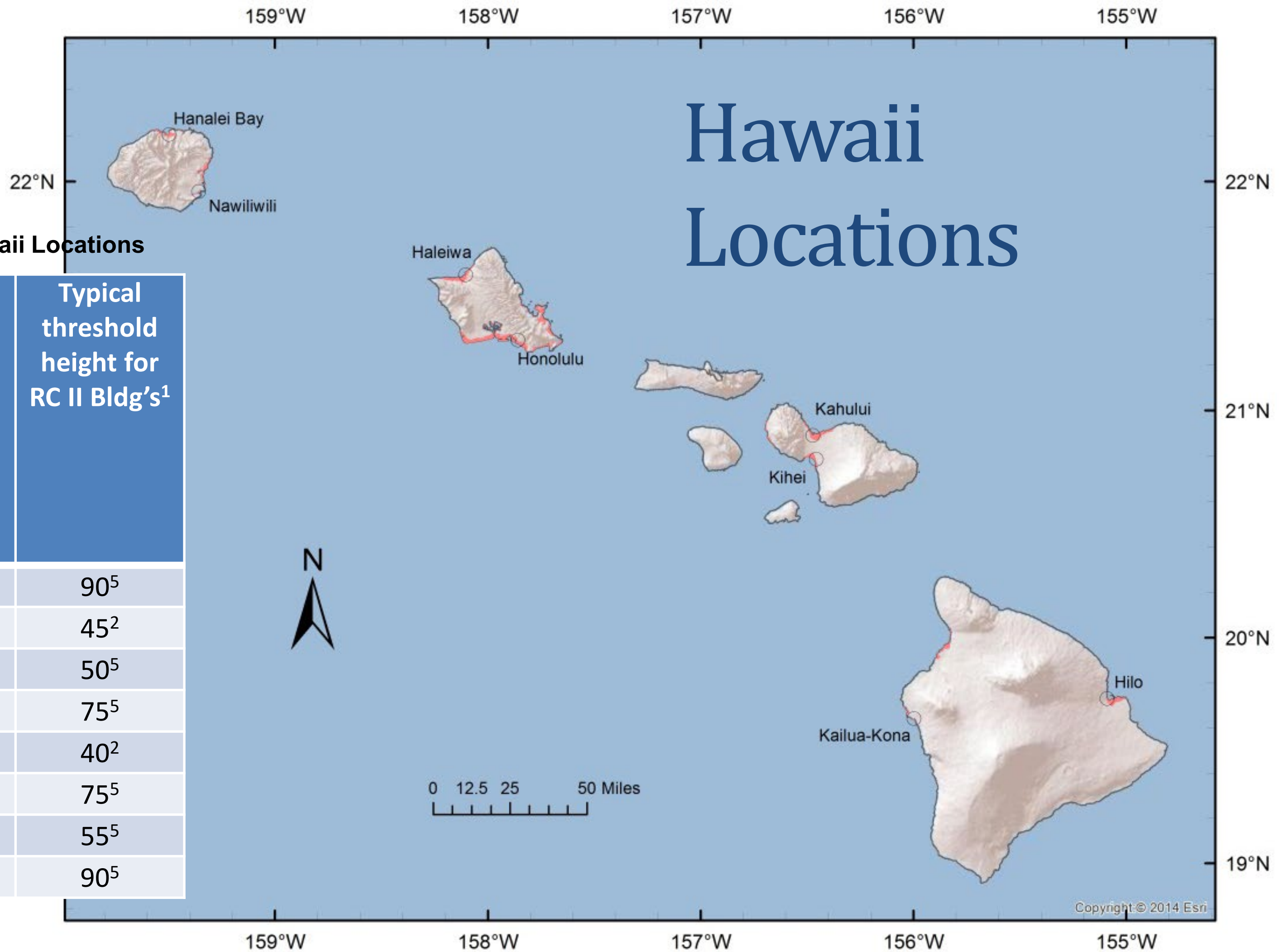
4. For these locations, strengthening of the building system in excess of seismic design requirements may be required to resist tsunami loads.

Zoning Height Restrictions for Pacific Coast Communities in WA and OR and N. CA – may need coordination with the building code

- **Westport WA**
  - All residential – 35ft
  - Commercial – 35ft (some areas allow 50ft)
- **Long Beach WA**
  - OT Zone – 35ft limit (all structures)
  - OTW zone – 45ft limit within 30ft of Ocean Blvd, 55ft limit elsewhere
- **Seaside OR**
  - Residential - 35ft
  - Commercial - 45ft
- **Cannon Beach OR**
  - Residential – 24ft (flat roof), 28ft (sloped roof)
  - Residential Motel – 32 ft
  - Commercial –32ft
- **Florence OR**
  - All Residential/Commercial – 2 stories (30ft)
- **Crescent City CA**
  - Single family residential – 35ft
  - Multi-family residential – 35ft
  - Office –35ft
  - Commercial – 40ft
  - Light Industrial 45 ft
  - P:ublic Buildings –40ft
  - Agricultural -35 ft
- **Eureka CA**
  - Single family residential – 35ft
  - Multi-family residential – 75ft
  - Office – 100ft
  - Other Commercial – 35ft
  - Downtown commercial – 100
  - Waterfront commercial – 100
  - Service commercial – 100 ft
  - Hospital – 75ft
  - Other medical -25
  - Industrial – 35

In Oregon, the zoning height limit may be less than the tsunami-safe height – nearer the shoreline, precluding the ability to be tsunami-resilient



Building Height Threshold for Hawaii Locations

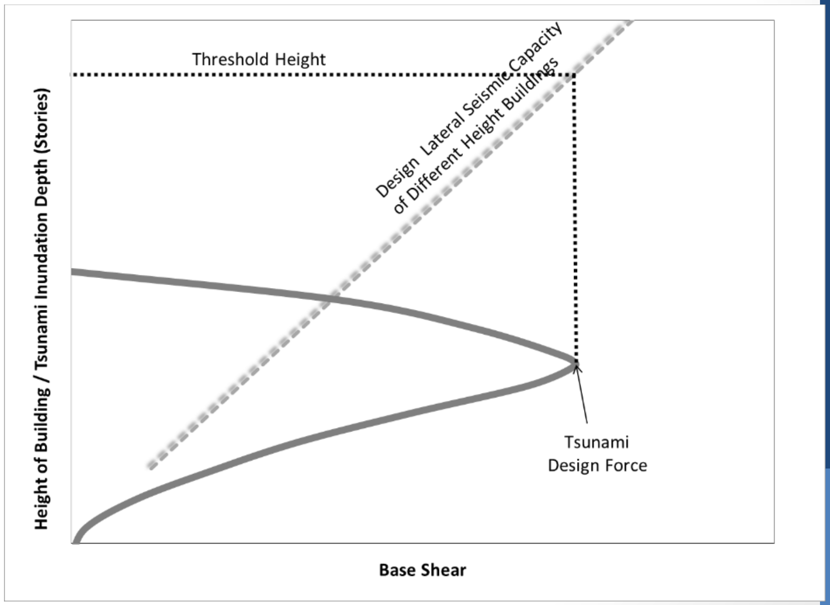
Region	Max. Inundation Depth in developed coastal shoreline areas (ft)	Typical threshold height for RC II Bldg's[1]
Hilo	72	90[5]
Kailua-Kona	30	45[2]
Kihei	32	50[5]
Kahului	60	75[5]
Honolulu	24	40[2]
Haleiwa	61	75[5]
Nawiliwili	40	55[5]
Hanalei Bay	71	90[5]

Notes:

1. The threshold is based on the inundation plus 12 ft and not less than 25 ft.
2. For these locations no overall strengthening of the building should be necessary if designed to seismic requirements.
3. For these locations, tsunami design is not required due to low inundation depths.
4. For these locations, strengthening of the building system in excess of seismic design requirements may be required to resist tsunami loads.
5. . For these locations, due to extreme excess of tsunami forces versus seismic capacity, design for tsunamis for RC II buildings along the shoreline would have significant added economic costs, so greater setback from the shoreline would be advised

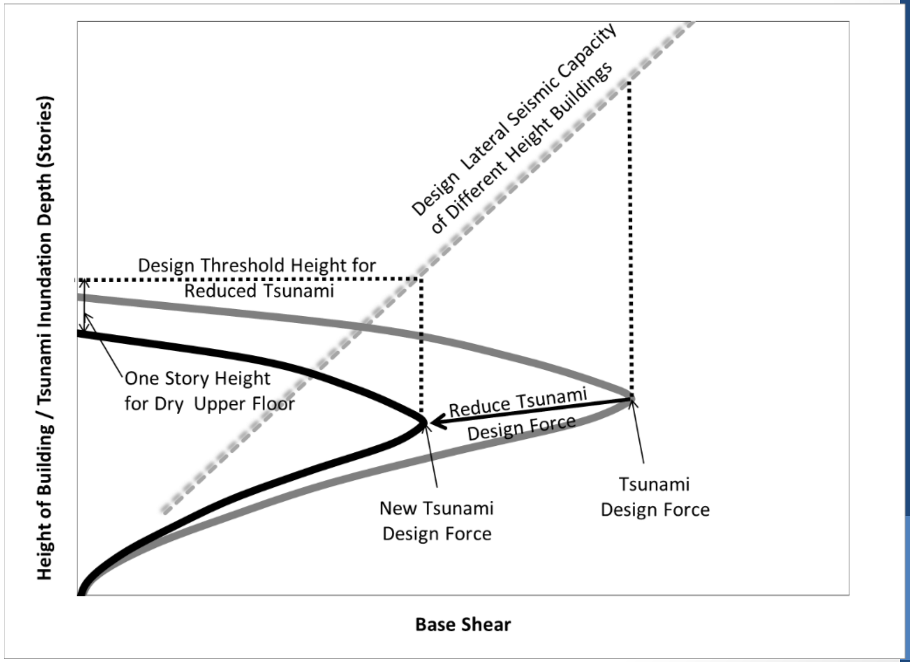
Conceptual Community Planning Option 1

- Require Tsunami Design of Tall Concrete and Steel Buildings where the inherent overall seismic strength exceeds the Tsunami Design Strength.
- Locally Strengthen components of the building for tsunami loads and impact forces
- This has minimal economic impact
- However, this policy would not result in any risk mitigation in the highest tsunami hazard areas.



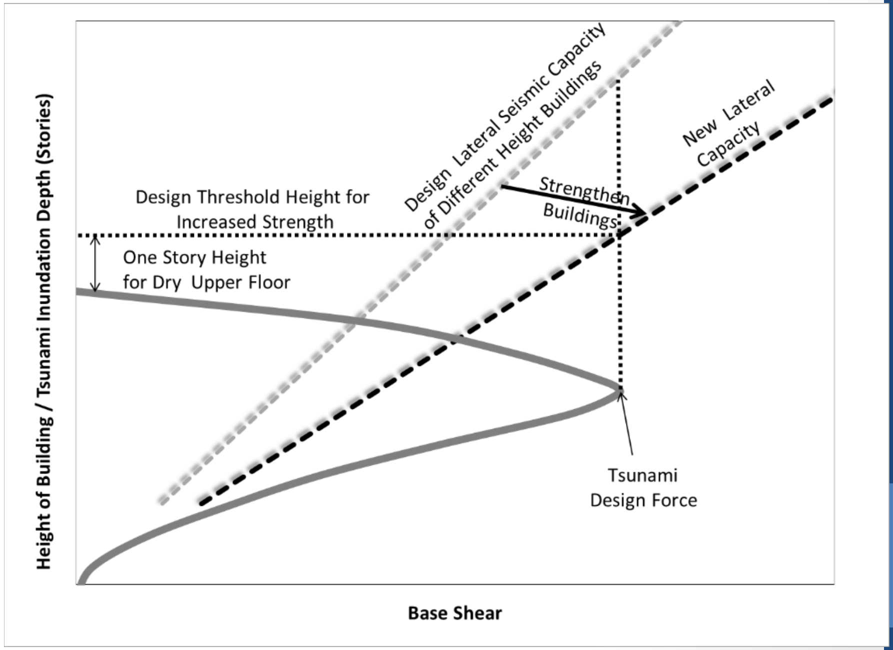
Conceptual Community Planning Option 2

- Effectively reduce tsunami design force by determining inundation depth contour where inherent seismic strength is adequate for buildings of a threshold height.
- Require taller building tsunami design starting at this depth contour.
- Locally Strengthen components of the building for tsunami loads and impact forces
- This results in minimal economic impact
- However, it may result in contradictory development where coastal areas with highest tsunami hazard have tall buildings that are not safe in tsunamis



Conceptual Community Planning Option 3

- Utilize a lower threshold height of applicability for tsunami design, knowing some buildings will need to be strengthened compared to seismic forces.
- Ensure that the threshold height is still one story above maximum inundation depth.
- Locally Strengthen components of the building for tsunami loads and impact forces
- Economic impact is still relatively nominal
- This policy would benefit communities with high tsunami hazard, especially where evacuation is difficult



Summary and Conclusions

- It should be important for communities to evaluate tsunami risk in future development policies for improved disaster resilience.
- There may be a preference to limit development in tsunami inundation zones. However, that may not be economical and it will probably be contradictory to existing zoning entitlements.
- Anywhere complete evacuation is not practical, build community facilities to serve as Tsunami Vertical Evacuation Refuge Structures (TVERS), and include tsunami design of taller RCII structures that can serve as additional refuge places. (TVERS have an additional margin of reliability per ASCE 7 but with added cost.)
- Buildings taller than the inundation depth in many locations in California, Oregon and Washington and Honolulu have sufficient inherent seismic strength to resist the overall tsunami shear.
- Isolated locations in Washington, Oregon, and Hawaii north shore bays would need added strengthening beyond seismic force levels. A tsunami-resilient building architecture would favor taller structures.
- There are several risk-based development rule options for tsunami design that can be utilized to enable tsunami-resilience.