17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

TSUNAMI-RESILIENT BUILDING DESIGN CONSIDERATIONS USING THE ASCE 7 STANDARD

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Abstract

The ASCE/SEI 7 Standards Committee has incorporated a new Chapter 6, "Tsunami Loads and Effects," in the 2016 edition of the ASCE 7 Standard, Minimum Design Loads and Associated Criteria for Buildings and Other Structures. The ASCE 7-16 chapter on "Tsunami Loads and Effects" is the first national, consensus-based standard for tsunami resilience, and it has been adopted in the International Building Code. Using the ASCE 7-16 tsunami design standard in conjunction with local building and zoning codes can provide a risk-informed means of achieving greater tsunami resilience.

It is important that communities in tsunami hazard areas evaluate their risk associated with existing development and start to consider disaster resilience in community planning of future development. Although communities strive to completely evacuate an area during a tsunami, experience has shown that complete evacuation is rarely, if ever, achieved. Taller structures in a community can provide effective secondary alternative refuge when evacuation out of the inundation zone is not possible or practically achievable for the entire population.

In the ASCE 7-16 Standard, tsunami design need not apply to RC II buildings, but the state or local jurisdiction can decide to include tsunami design for a threshold height and occupancy type appropriate for the local tsunami risk. High tsunami hazard poses a combined engineering, community planning, and economic problem to coastal communities, in which there is a particularly relevant role for structural engineering expertise in policy-making. Tsunami design for RC II buildings and structures of designated occupancies exceeding an appropriate mean height can provide more buildings that are life-safe and disaster resilient. Several important technical factors to inform a jurisdiction's decision to establish a threshold height of applicability for RC II buildings and structures require structural engineering expertise. The information provided in this paper can be used for initial guidance in implementing tsunami resilient building codes and development policies. Four options are discussed for implementing resiliency through integrated tsunami strengthening and zoning policies: 1) minimum cost but minimal refuge availability and minimal resilience; 2) maximum refuge availability and maximum disaster resilience; 3) building architectural design utilizing tsunami countermeasures, and 4) adaptive coastal zoning with disaster-resilient objectives in the application of tsunami design codes.

Keywords: tsunami engineering; evacuation; ASCE; coastal engineering; community planning

1. Introduction

Although public safety tsunami risk can be partially mitigated through warning systems and preparedness for evacuation, in many coastal areas complete evacuation with adequate timeliness cannot be assured. Considerations of evacuation egress time, population density, population demographics relating to the physical endurance to sustain robust evacuation speed over significant distance, egress routes, traffic, time of day, post-earthquake damage to infrastructure, tsunami awareness and preparation, knowledge of surroundings, visitor population, and the available time between tsunami warning and tsunami arrival all factor into determining evacuation clearing times and resulting fatalities. When realistic evacuation travel times exceed the available time to tsunami arrival, there is a greater need for vertical evacuation into an ample number of nearby taller buildings. During the 2011 Tohoku Tsunami in Japan, many taller buildings were successfully used as evacuation buildings saving tens of thousands of lives [1]. Studies have shown that concrete and steel buildings can be designed to withstand tsunami forces, while accepting flooding at the base of the buildings [2, 3]. For reliable tsunami life safety in buildings, there is a particularly relevant role for structural engineering expertise. A comprehensive chapter on the tsunami design of structures is included in the 2016 edition of the ASCE 7 Standard, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* [4]. Chapter 6 – Tsunami Loads and Effects is a consensus-based design standard for tsunami resilience. Use of these design provisions with coordination of local building and zoning codes will achieve greater resilience of critical and essential facilities, Tsunami Vertical Evacuation Refuge Structures, and other multi-story building structures subject to tsunami inundation [5].

2. Risk Categories and Building Types

The tsunami analysis and design requirements in the ASCE 7 Standard vary in accordance with Tsunami Risk Category. Tsunami Risk Categories are based on the Risk Categories defined in Section 1.5 of ASCE 7, with a few modifications of Risk Category based on practicality under tsunami conditions. Chapter 16 of the International Building Code has an explicit listing of building Risk Categories based on occupancy and use. Tsunami Risk Category III and Tsunami Risk Category IV buildings and other structures, and if required by a local jurisdiction, taller Risk Category II buildings, located in the Tsunami Design Zone shall be designed to resist the tsunami loads and effects determined for a Maximum Considered Tsunami per Chapter 6 of ASCE 7-16.

Critical Facilities are buildings and structures that provide services that are designated by federal, state, local, and tribal governments to be essential for the implementation of the response and recovery management plan or for the continued functioning of a community, such as facilities for power, fuel, water, communications, public health, major transportation infrastructure, and essential government operations. Critical facilities comprise all public and private facilities deemed by a community to be essential for the delivery of vital services, protection of special populations, and the provision of other services of importance for that community [6]. They are considered Risk Category III.

Essential Facilities are primarily those facilities necessary for immediate emergency response and do not include all Critical Facilities. They are considered Risk Category IV. Some Essential Facilities do not necessarily need to be included in Tsunami Risk Category IV because they should typically be evacuated prior to the tsunami arrival; per ASCE 7-16 Section 6.4 this includes fire stations, ambulance facilities, and emergency vehicle garages. Essential Facilities not considered Risk Category IV may necessarily be located within the tsunami zone because they must serve the public interest on a timely day-to-day basis, but they may be deemed not uniquely required for post-disaster operations or where such functionality can be sufficiently provided from a post-tsunami alternative facility [6].

Vertical Evacuation Refuge Structures are a special classification of buildings and structures within the tsunami evacuation zone, officially designated as a means of alternative evacuation in communities where sufficiently high ground does not exist, or where the time available after the tsunami warning is not deemed to be adequate for full evacuation prior to tsunami arrival. The ASCE 7 Standard incorporates special technical requirements for such structures that are more stringent than Risk Category IV.

Table 1. Risk Categories [4]

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.

Table 2. Tsunami Performance Levels per Tsunami Risk Category

Hazard Level	**Performance Level Objective**		
Maximum Considered Tsunami	**Immediate Occupancy**	**Damage Control**	**Life Safety**
2,475 year mean recurrence interval	Tsunami Vertical Evacuation Refuge Structures	Risk Category IV, Essential Facilities and Risk Category III, Critical Facilities	Multi-Story Risk Category II

3. Tsunami-Resilient Design

The planning and design process incorporating ASCE 7 criteria and requirements is expected to include the following steps:

- Select a site appropriate and necessary for the structure that considers the tsunami flow depth and speeds at the site
- Determine the maximum flow depth and velocities at the site based on mapped Runup based on a probabilistic tsunami hazard analysis, using the procedures stipulated in the ASCE 7 Standard.
- Select an appropriate structural system mindful of configuration and perform seismic and wind design first
- Check robustness of expected strength within the inundation height to resist hydrostatic and hydrodynamic forces
- Check resistance of lower elements for hydrodynamic pressures and debris impacts to avoid progressive collapse
- Design foundations to resist scour and potential uplift
- Elevate critical equipment as necessary

Defined terms controlling tsunami design criteria include the Inundation Depth, Runup Elevation, and the (maximum horizontal) Inundation Limit (as illustrated in ASCE 7-16 per Figure 1). Inundation Depth is the depth of the tsunami water with respect to the local grade plane. Inundation Limit is the maximum horizontal extent of the inundation zone relative to the shoreline. Runup Elevation is the elevation above reference datum at the tsunami Inundation Limit.

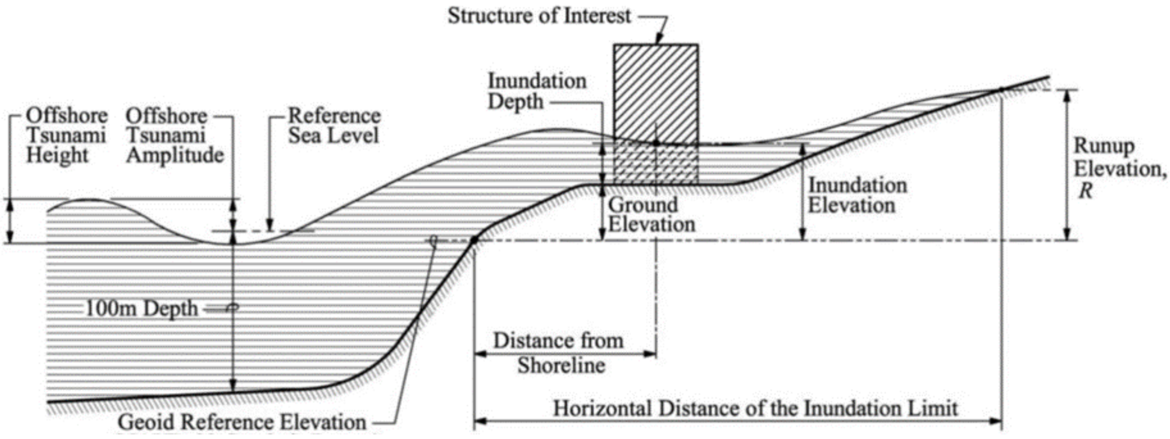

Fig. 1. Key Definitions Illustrated along a Flow Transect of a Tsunami Design Zone [4]

4. Tsunami Hydrodynamic Forces on Buildings

ASCE 7-16 Chapter 6 provides the overall tsunami force on a structure as given by a classic hydrodynamic drag equation (Eq. 1), which is applied as a uniform pressure resultant on the projected inundated area of all structural components and exterior wall assemblies below the inundation depth:

$$F_d = \frac{1}{2}\rho_s I_{tsu} C_d C_{cx} B(hu^2) \quad (1)$$

where:

- F_d Drag force
- ρ_s minimum fluid mass density
- I_{tsu} Importance Factor for tsunami forces
- C_d drag coefficient
- C_{cx} proportional closure coefficient
- B overall building width
- h tsunami inundation depth above grade
- u tsunami flow velocity

The terms h and u, tsunami inundation depth and flow velocity, vary during the time history of inundation at a site. Tsunami inundation is characterized by sustained fluid forces with long period cycles of flow of alternating flow directions. Chapter 6 provides normalized inundation depth and depth-averaged velocity time-history curves that are based on tsunami video analysis, and they are generally consistent with numerical modeling with respect to defining critical stages of structural loading for design purposes. The ASCE 7 tsunami time history curves result in a maximum lateral hydrodynamic force on the structures occurring when the inundation depth is 2/3 of the maximum inundation depth as shown in Fig. 2. (Typically, as the flow reaches the maximum depth, the flow velocity is in the process of reducing before the flow reverses direction.) This maximum force, calculated based on actual inundation depths and velocities, is the basis for comparisons of the tsunami force versus seismic design strength described in the following sections.

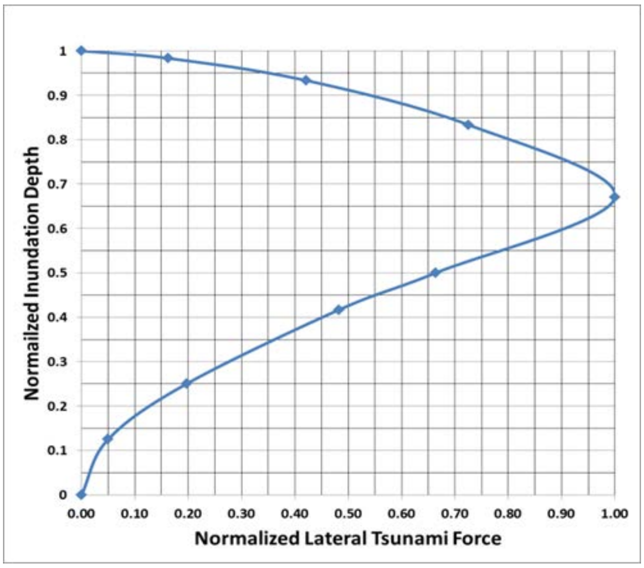

Fig. 2 Normalized Inundation Depth vs. Tsunami Force [5]

Structural elements that resist overall systemic lateral loads generally do so in accordance with their relative stiffness. Tsunami pressures acting on individual elements do so in accordance with the prescribed tributary projected area for that element. During tsunamis, building components of the lateral-force-resisting system can be simultaneously subjected to internal forces generated by the external loading together with the high intensity momentum pressure forces directly exerted on those individual members. Internal actions in structural components of the lateral-force-resisting system resulting from the overall tsunami forces applied on the building or structure should therefore be combined with any resultant structural component actions caused by the local tsunami pressures that directly act on those structural components over the same inundation depth during the concurrent direction of flow. Regardless of whether they are elements of the lateral-force-resisting system, structural components may need local "enhanced resistance" beyond what is necessary for supporting gravity load combinations. The components of the building must have the necessary design strength for tsunami pressures of ASCE 7 that are calculated at an ultimate load level. In addition to these hydrodynamic forces, tsunami design per ASCE 7 includes requirements for hydrostatic forces, waterborne debris impact forces, and scour effects.

5. Consideration of Seismic Forces on Buildings Towards Systemic Tsunami Strength

One important consideration is the inherent strength of a building resulting from its seismic design requirements. The lateral-force-resisting system is designed for the overall tsunami pressure loading and not just seismic loads. However, if a building is designed for high seismic loads, then it may require little or no strengthening of the lateral-force-resisting system to meet the overall tsunami load on the structure. The techniques demonstrated by Chock [5] and Carden et al. [2] can be used to include the systemic level of tsunami resistance provided by the ASCE 7 seismic design requirements. Recognizing that the seismic and tsunami events are not simultaneous, per the ASCE 7 standard, no additional lateral strength is required for the lateral-force-resisting *system* for tsunamis if the overall lateral tsunami force is less than 75% of overall lateral seismic resistance of the system including seismic overstrength, or as described in Eq. (2):

$$F_{TSU} < 0.75\Omega_o E_h \qquad (2)$$

where:
F_{TSU} is the overall lateral tsunami force.
Ω_o is the system seismic overstrength factor

E_h is the effect of horizontal earthquake forces

The right hand term of Equation 2 is illustrated in Figure 3. It is seen that the key to the expected seismic strength is to have a systemically sustainable lateral resistance and avoid strength degradation. Avoidance of strength degradation in primary structural components is an inherent characteristic in the acceptability criteria of the Life Safety Performance Level that is distinctly different from that of the Collapse Prevention Performance Level [7]. Where the Maximum Considered Earthquake event can be the initiation of the Maximum Considered Tsunami, it is particularly important that systemic strength degradation be avoided by design, and that the means of access and egress to the upper levels be maintained after the seismic event. The "parity heights" of buildings is the demarcation of when the expected seismic horizontal force, $0.75\Omega_o E_h$, just meets the prescribed tsunami horizontal design force on the building, F_{TSU}. This is illustrated in Figure 4. At this point, the seismic lateral force resisting system does not require upgrading in order to provide the required tsunami design force.

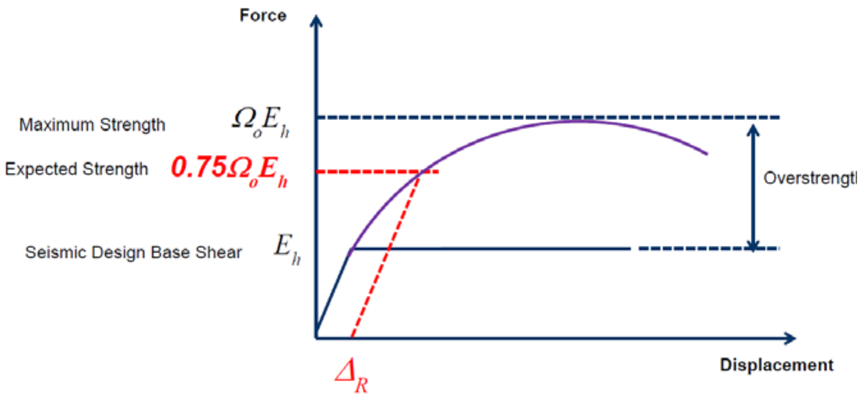

Fig. 3. Illustration of right-hand side of Equation 3, $0.75\Omega_o E_h$ [6]

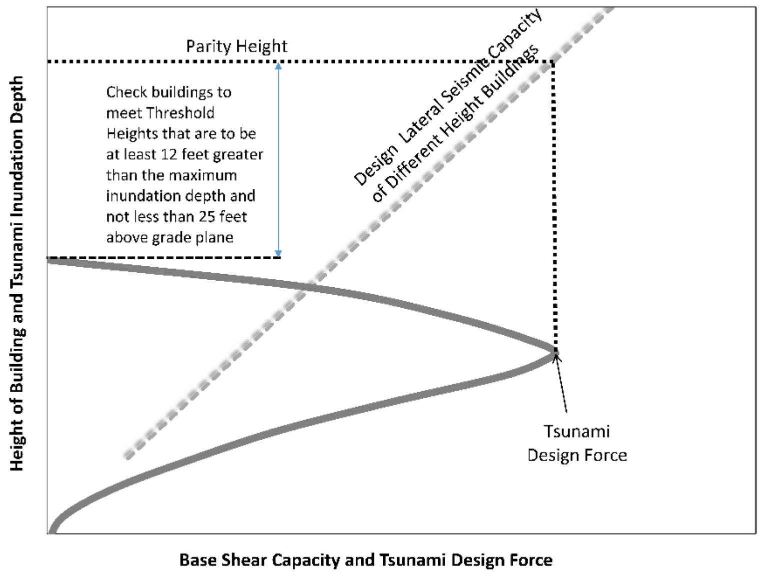

Fig. 4. Illustration of the "Parity Height" with the Building's Seismic Capacity matching the required Tsunami Design Force [5]

The "threshold heights" of buildings represent the heights at which buildings could be designed for the overall lateral tsunami force F_{TSU} with no required increase beyond the prescribed seismic lateral systemic strength, and the buildings would also be expected to provide a safe and dry upper level during the MCT.

The suggested threshold building heights are at least 12 feet greater than the inundation depth, to provide an upper floor level that is not inundated. The threshold height is also not less than 25 feet, such that areas typically zoned for one and two-story single family or duplex type housing would not need to comply with the tsunami design standards. Structural engineering expertise is required to evaluate the important safety considerations relevant to the jurisdiction's decision to establish a threshold height of applicability for Risk Category II buildings and structures; state and local jurisdictions should enlist this necessary expertise so that rational disaster resilient policies can be enacted that are coordinated with zoning.

6. Tsunami-Resilient Planning and Development Policies

There are many options for design or planning purposes where the inherent seismic strength of coastal buildings with heights that provide a dry floor above the projected MCT inundation depth is still insufficient to resist tsunami design forces. Several of these options are conceptually illustrated in Figures 5 a) to c).

The first option (that has minimum cost but results in minimal refuge availability and minimal resilience) is to use an applicable threshold height of buildings to be within the scope of the tsunami design code to match height at which the inherent design (seismic) strength of the building is sufficient for tsunami forces. This option would be based on verifying where maximum inundation is expected to be at a level where buildings of a certain height can be constructed without significant additional strengthening beyond seismic and/or wind, and then enabling that height to be built per the local zoning code. This is illustrated by the higher threshold height in Figure 5a) at the point where the maximum tsunami force equals the design seismic lateral strength. This will provide a greater margin of safety on height and multiple floors above the inundation depth. This concept may also apply to a selection of existing buildings for secondary vertical evacuation, once calibrated to the particular code vintage.

A second option (that provides maximum refuge availability and maximum disaster resilience) is to apply the tsunami design requirements to buildings tall enough to afford dry floor levels, so that all buildings of at least the required threshold height above the maximum inundation depth have sufficient strength to resist tsunamis. This is illustrated by moving the design lateral seismic capacity curve to the right in Figure 5b). In this case the main lateral-force-resisting system of a new building would be specifically designed, or an existing building retrofitted, for the tsunami loads. This would be done along with the local strengthening of components at the lower levels that are typically required for any structure.

A third option (configuring buildings using tsunami structural countermeasures) is to configure the building to reduce tsunami loads. Orienting a building to reduce the projected surface area to the principal flow directions can reduce the overall Tsunami Design Force, as illustrated in Figure 5c). If there is any overstrength in the lateral capacity of the building, it is likely to be in the longitudinal direction of the building, therefore this may derive some additional benefit of inherent strength when the broadest face of the building is not perpendicular to the flow. The design configuration may also be of an "open structure" with "tsunami break away walls" as defined by ASCE 7 Chapter 6, so that the effective flow blockage is reduced from 70% to 50%, resulting in a significant reduction in tsunami forces.

A fourth option (adaptive coastal zoning for high tsunami hazard regions) is to set up zoning restrictions so that buildings that the public would logically see as potential evacuation buildings are not built in locations coinciding with the maximum inundation depth, but sufficiently taller buildings designed for tsunami resistance are still built that are reachable within the necessary time. These taller buildings would exist for vertical evacuation as necessary, close enough to the coastline to provide people enough evacuation egress time to safely reach the buildings within the anticipated warning period for a region. Selective siting effectively reduces the design tsunami forces on a building that can then be more economically designed for locations further inland, indicated by the modified tsunami force curve in Figure 5c). The boundary for the area of maximum tsunami inundations for the zoning height restrictions may be defined by a tsunami inundation depth contour line, beyond which buildings taller than a designated height would be designed for tsunami effects within this regime of reduced tsunami inundation depth. Zoning restrictions can be established with disaster-resilient objectives so that buildings of sufficient height for tsunami safety and of the appropriate occupancy type for access are permitted to be developed along that contour location and further inland. These taller buildings could act as beacons of safety, being the first of the taller buildings beyond a coastal setback that provide safety for people within the tsunami inundation zone. The severe area with maximum inundation depth can be treated much like a floodway zone, where there is less development or alternative development.

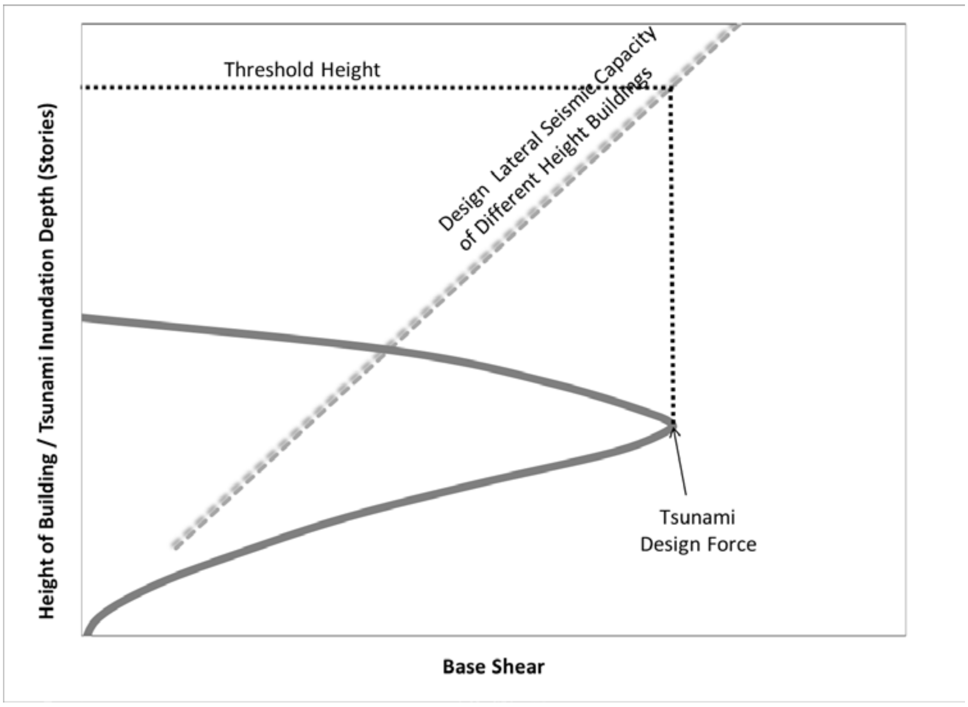

Fig. 5a)

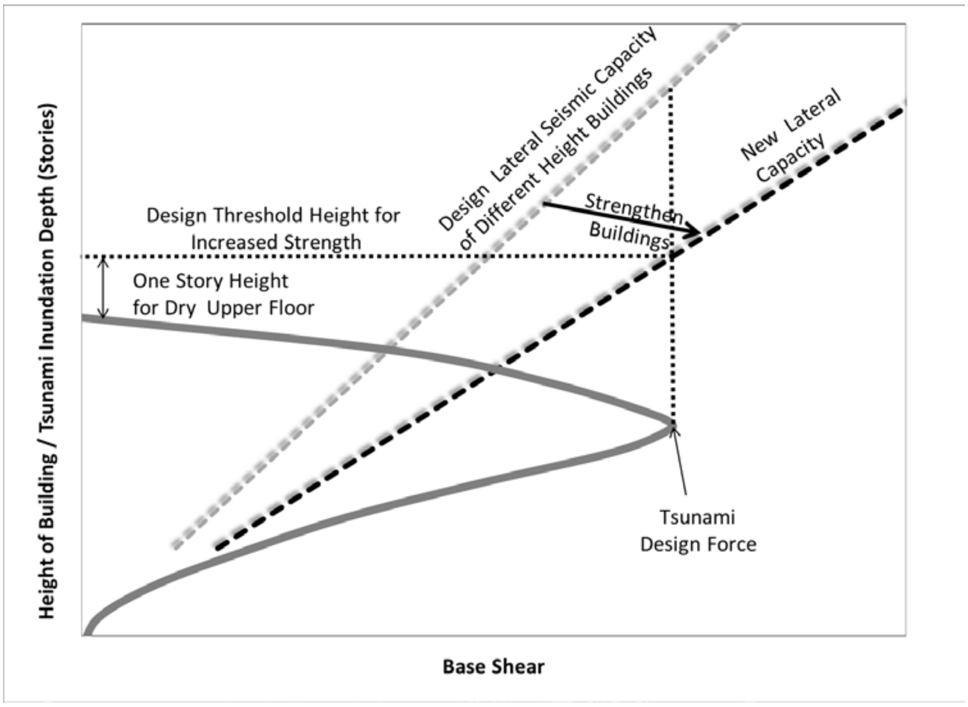

Fig. 5b)

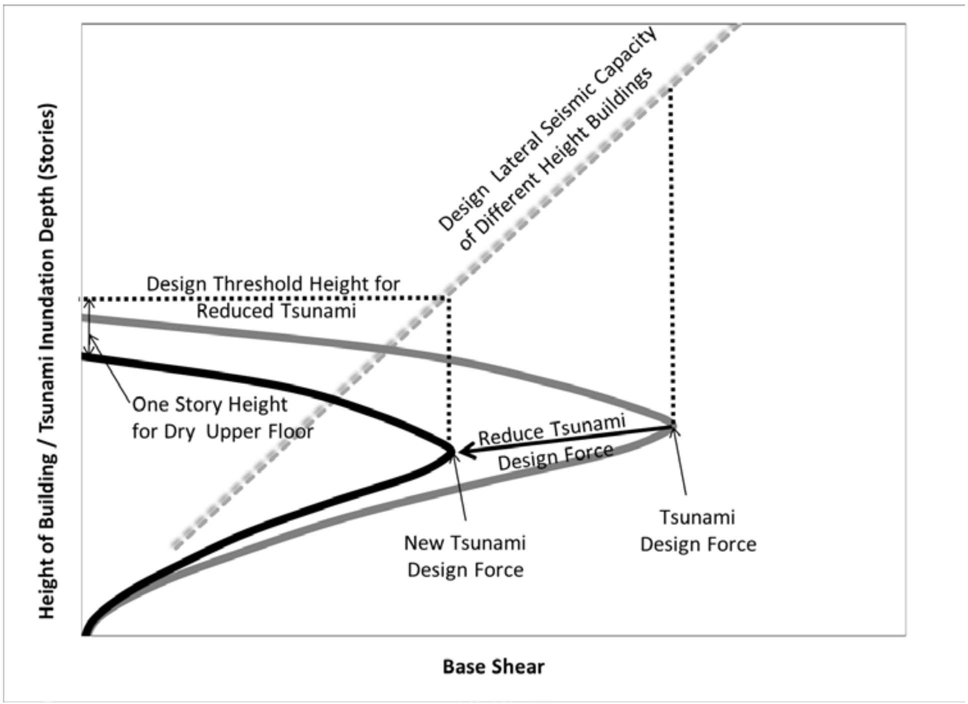

Fig. 5c)

Fig. 5. Conceptual Options for Tsunami Design Resilient Policy [5]

7. Conclusions

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. The tsunami design requirements of ASCE 7 Chapter 6 can improve the tsunami resilience of a community by:

- Preventing failures of multistory buildings during tsunamis
- Creating tsunami refuges with high reliability
- Implementing of risk reduction in planning and siting of essential and critical facilities
- Designing to mitigate damage to infrastructure
- Designing defense countermeasures for infrastructure
- Build Back Better post-disaster reconstruction

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.

8. Acknowledgements

The support of the American Society of Civil Engineers, Structural Engineering Institute and the Coasts, Oceans, Ports, and Rivers Institute, towards the development of the tsunami design provisions in ASCE 7-16 by the Tsunami Loads and Effects Subcommittee is gratefully acknowledged.

9. Copyrights

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