

Issues Encountered with ASCE Compatibility Criteria

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1. Background and Motivation

We have informally engaged members of the Tsunami Loads and Effects Subcommittee (TLES) of the American Society of Civil Engineers (ASCE) and the Structural Engineering Institute (SEI), who have developed criteria for vertical evacuation structure (VES) design and construction that has been published in the ASCE 7-16 standards (ASCE, 2017a) as Chapter 6 "*Tsunami Loads and Effects*." These informal consultations were very helpful in dealing with issues we encountered while applying the current ASCE criteria during on-going site-specific inundation modeling studies of proposed VES sites in two coastal Washington communities (Shoalwater Bay/Tokeland and Aberdeen) threatened by a disastrous Cascadia Subduction Zone (CSZ) great earthquake and tsunami (Adams, et al., 2019a; Adams, et al., 2019b). These TLES members (H.K. Thio, Y. Wei and G. Chock) also provided very helpful feedback on a draft of this report, which we have incorporated into this current version. Some issues remain, however, and we hope that those described below will be formally reviewed, clarified and/or otherwise resolved by the ASCE/SEI 7 TLES.

The State of Washington is assisting at-risk coastal communities that have included the design and construction of tsunami vertical evacuation structures in their hazard mitigation plans. Washington State has not formally adopted the ASCE 7-16 Chapter 6 standard; however, past VES projects have made the decision to meet these standards, as well as TLES-approved ASCE 7 Change Proposals to revise Chapter 6 of the 2022 version, ASCE 7-22 (e.g., Chock, et al., 2018) in anticipation of possible formal approval by the ASCE 7 Main Committee and adoption by the State. As a result, Washington State has been a very active user of the standard, which continues to evolve as the TLES reviews and develops and votes on 7-22 Change Proposals.

We note that the ASCE 7-16 document includes the following disclaimer ...

"While ASCE's process is designed to promote standards that reflect a fair and reasoned consensus among all interested participants, while preserving the public health, safety, and welfare that is paramount to its mission, it has not made an independent assessment of and does not warrant the accuracy, completeness, suitability, or utility of any information, apparatus, product, or process discussed herein. ASCE does not intend, nor should anyone interpret, ASCE's standards to replace the sound judgment of a competent professional, having knowledge and experience in the appropriate field(s) of practice, nor to substitute for the standard of care required of such professionals in interpreting and applying the contents of this standard."

Nonetheless, the purpose of this brief report is to contribute to the ASCE 7 TLES process of improving ASCE Chapter 6 guidance by identifying issues we have encountered with these standards and providing appropriate suggestions that we hope will improve the guidance and ease of use by practitioners.

Chock (2016) has made it clear that an overall goal of the ASCE 7 TLES team is to ensure that the "*ASCE 7 Tsunami Loads and Effects chapter is consistent with the principles of probabilistic hazard analysis, tsunami physics, and fluid mechanics, integrated into a comprehensive set of design provisions.*" In that spirit, we hope to contribute to that goal by providing feedback and suggestions on

issues with ASCE 7-16 Chapter 6 and TLES-approved Change Proposals that we've encountered during modeling studies in support of VES design and construction.

2. ASCE 7 Issues and Suggestions

We do not routinely receive TLES-approved revisions to ASCE 7-22, so the issues discussed in this section may have already been addressed by the TLES. Also, note that the Cascadia Subduction Zone (CSZ) seismic models are our primary concern here, since disaggregation of the ASCE probabilistic seismic models demonstrates that the CSZ dominates the Alaska and Washington tsunami hazard (Wei, et al., 2017).

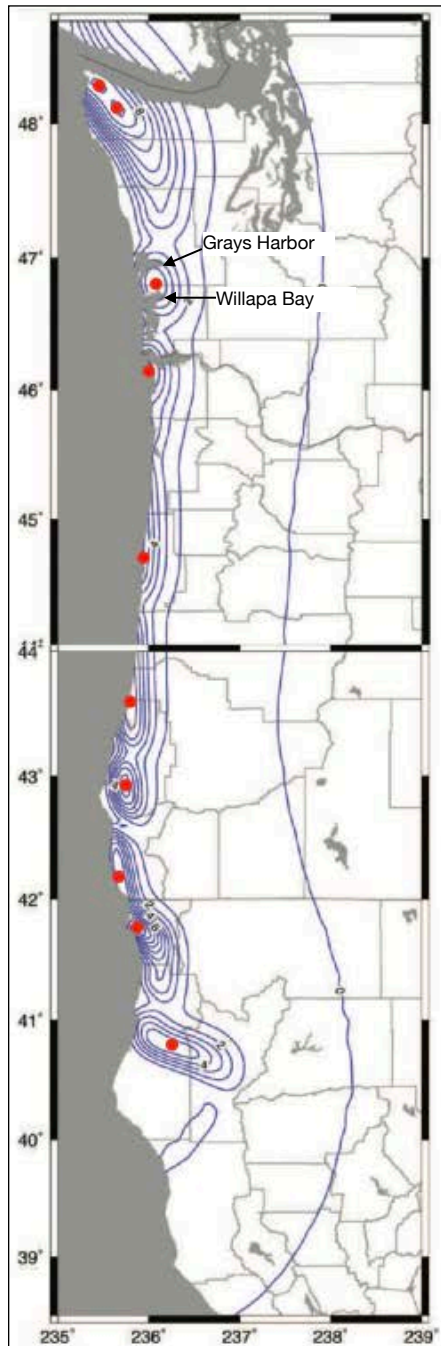


Figure 1. TDG probabilistic co-seismic deformation

Suggestion A: For the benefit of ASCE 7 users that are not active Associate Members of the TLES, please post online and/or distribute Change Proposals to ASCE 7-16 Chapter 6 that are under consideration and/or have been approved by the TLES.

2.1 ASCE Tsunami Design Geodatabase (TDG) (<https://asce7tsunami.online/>).

ASCE 7-16 guidance on co-seismic deformation is found in *Section 6.7.6.2 Seismic Subsidence before Tsunami Arrival*, which states that

"Where the seismic source is a local subduction event, the Maximum Considered Tsunami inundation shall be determined for an overall elevation subsidence value shown in Fig. 6.7-3(a) and 6.7-3(b) or shall be directly computed for the seismic source mechanism."

We note that the phrase *"overall elevation subsidence value"* is ambiguous, although the word *"overall"* suggests a single level, perhaps an average; in contrast, the phrase *"directly computed for the seismic source mechanism"* implies a spatially varying pattern.

There are two issues of concern with TDG content -- extrema in the probabilistic co-seismic deformation and sea level rise (SLR).

(a) Co-seismic deformation extrema. Prominent extrema in the TDG probabilistic subsidence pattern displayed in Figure 1 were identified as problematic during informal discussions with a TLES member (Thio, H.K., personal communication) and local UW CSZ experts. The TLES member pointed out that the pattern was probabilistic, not deterministic, and thus the extrema might be related to the positioning of a movable asperity model in the PTHA methodology.

TDG development by this process has been described in general terms by Thio et al. (2010) and in more detail by Thio et al. (2017) and Thio (in review) and it is clear that, in general, extrema can be expected in probabilistic co-seismic deformation as the result of combining multiple seismic event realizations in a Probabilistic

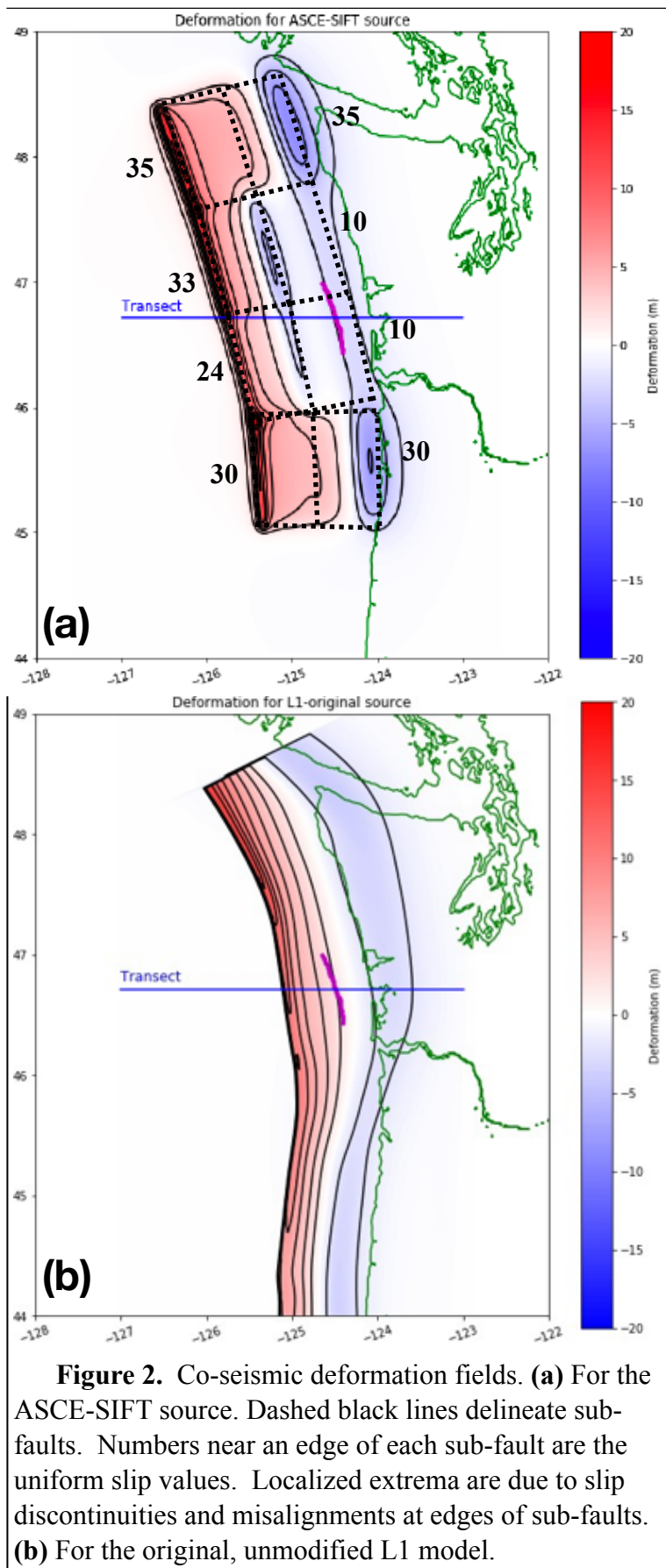


Figure 2. Co-seismic deformation fields. **(a)** For the ASCE-SIFT source. Dashed black lines delineate sub-faults. Numbers near an edge of each sub-fault are the uniform slip values. Localized extrema are due to slip discontinuities and misalignments at edges of sub-faults. **(b)** For the original, unmodified L1 model.

Tsunami Hazard Assessment (PTHA) methodology.

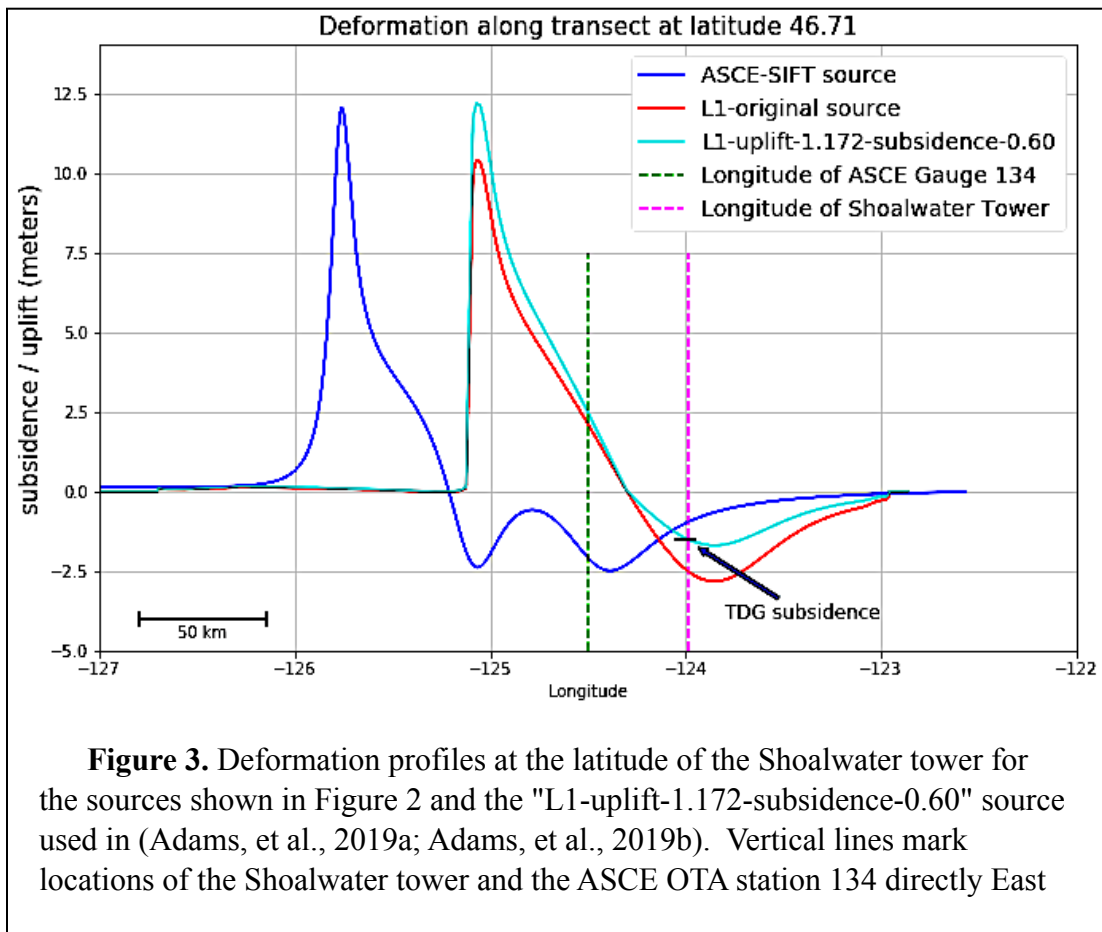
Figure 2 suggests another possible cause of such extrema -- artifacts of slip discontinuities and mismatches at sub-fault edges. Figure 2 (a) presents a co-seismic deformation pattern for seismic model ASCE-SIFT, composed of uniform slip on each of eight 50 x 100 km² Unit Sources of the Short-term Inundation Forecasting of Tsunamis (SIFT) system. This and similar Unit Source seismic models (sometimes specified as Green's functions) were used to initiate inundation simulations for the development of ASCE-compliant Tsunami Design Zones (TDZ) (Wei, et al., 2017; University of Washington Working Group, 2017; ASCE, 2017b); a least-square procedure was applied to specify uniform slip values on each sub-fault that resulted in modeled offshore tsunami amplitude (OTA) values that meet ASCE criteria.

Taken alone, each sub-fault in Figure 2 (a) produces a typical subduction zone thrust event deformation pattern with positive and negative extrema located at the top and bottom down-dip edges, respectively (see, e.g., <https://www.clawpack.org/geoclaw/Okada.html>). Linear summation of such patterns can introduce features at sub-fault length scales that are associated with slip discontinuities and misalignments at neighboring sub-fault edges. We see this effect in the ASCE-SIFT deformation pattern, in which the greater the edge discontinuities and mismatches, the larger the pattern distortion and likelihood that additional extrema will be discernable; these effects are, of course, a matter of degree because they cannot be entirely eliminated in discrete computations.

In contrast, only 1 extrema in the overall thrust event pattern is evident in Figure 2 (b), which presents the co-seismic

deformation of the original, unmodified L1 splay fault model, which has an estimated return period of 3333 years and is one member of a suite of 15 seismic scenarios, each with a different estimated return period (Witter et al., 2013).

Figure 2 (b) is thus a single realization of co-seismic deformation, in contrast to the multiple realizations that were used to create the probabilistic deformation pattern in Figure 1 by a summation process that can certainly create extrema. Nonetheless, it is worth noting that the L1 seismic model shown in Figure 2 (b) was developed on an irregular computational grid that provided finer slip resolution in areas of large slip gradients and coarser resolution in areas of relatively smaller slip gradients. As a result, discontinuities across sub-fault edges were apparently small enough that no discernible artifacts were caused by slip discontinuities or mismatches at sub-fault edges after performing a linear interpolation from the irregular grid data to a rectangular geographic grid with individual cells of dimensions that were relatively small -- i.e., 10 x 10 arc-sec² or about 309 x 219 m² at 45° N. This suggests the possibility that the probabilistic deformation pattern of Figure 1 may also include artifacts on length scales that reflect slip discontinuities and misalignments at the edges of neighboring sub-faults.



One of the TDG extrema in Figure 1 overlays our current study sites of Aberdeen in Grays Harbor and the Shoalwater-Tokeland area in Willapa Bay. Figure 3 presents East-West co-seismic deformation profiles that cross the Shoalwater VES site at latitude 46.71° N. The source designated "L1-uplift-1.172-subsidence-0.6" increases uplift by 17.2% to meet ASCE OTA criteria and reduces subsidence by 40% to match the ASCE TDG value at the Shoalwater VES site.

Note that there are two major differences in this model profile and that of the ASCE-SIFT model: the subsidence differs by a factor of 1.5 and there is also more than a fifty kilometer difference between the peak uplift location of these two models. Figure 3 is thus a clear example of the significant differences in seismic models that can occur in spite of the fact that they are each ASCE-compatible. Clearly, co-seismic deformation, whether uplift or subsidence, is critically important in the VES site selection process and in the subsequent structural design and engineering; the locations of offshore extrema relative to the VES site are also an important factor in this decision-making process, since the associated distances to VES sites govern the time available for evacuation of residents to the safety of the VES.

Thus, because local and offshore co-seismic deformation are critical to VES development decisions, and because it is possible that co-seismic deformation extrema in the TDG are artificial to some degree, we offer the following suggestions.

Suggestion B: Please develop criteria for VES co-seismic deformation that includes an assessment of the degree to which extrema of probabilistic co-seismic deformation might be due to computational artifacts as discussed above.

Suggestion C. Please develop a suite of TDZ seismic models for ASCE 7-16 source regions that meet both co-seismic deformation and OTA criteria and provide users with the detailed specifications needed to recreate these ASCE-compliant seismic models for use in VES site assessment studies

In addition, we note that Figure 4, which presents Figure 6.14-1 of the TLES-approved ASCE Change Proposal *TS-CH06-04r00*, does not explicitly include graphic representations of co-seismic deformation (CD) (subsidence or uplift) or sea level rise (SLR). Both SLR and CSD must be accounted for as stated in Sections 6.5.3 *Sea Level Change* and 6.7.6.2 *Seismic Subsidence before Tsunami Arrival*, respectively, in the computation of "Site-Specific Max. Considered Tsunami inundation elevation at the structure [SMIE]" and thus the "minimum elevation [ME] of the lowest occupiable Refuge Level [LORL]". We explicitly model SLR and CD in our VES modeling studies and thus they are implicitly included in the criteria for SMIE and ME, which is given by the relationship

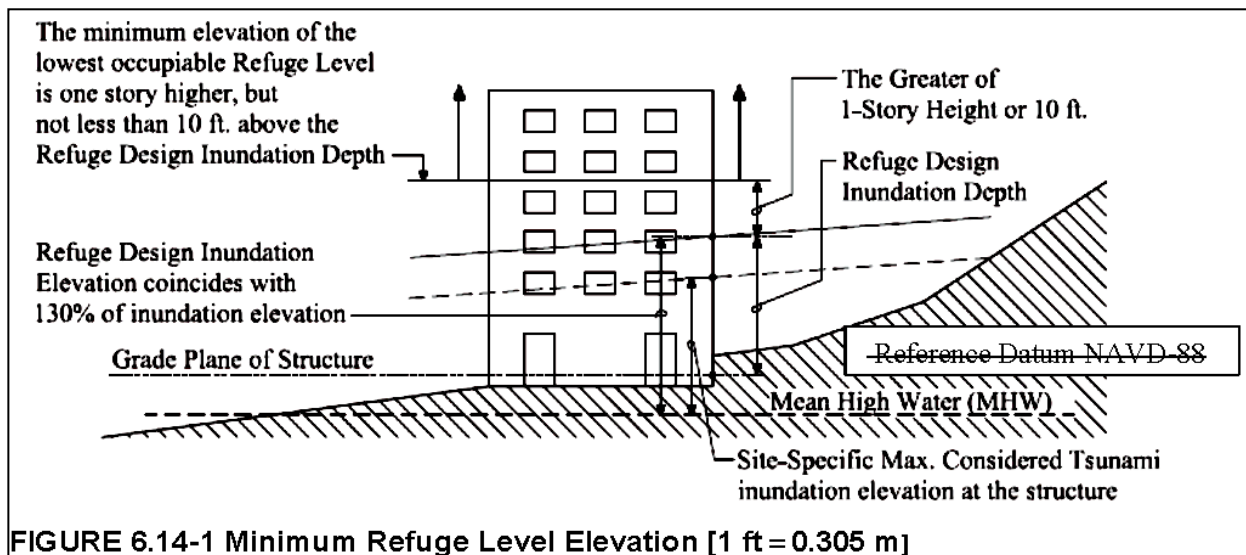


Figure 4. Proposed changes to Figure 6.14-1 that have been approved as a revision to ASCE 7-22. Not explicitly displayed are co-seismic deformation and SLR, which must be taken into account.

$$ME = 1.3 * SMIE + S \quad \text{[equation 1]}$$

where the additional safety factor $S = \max(10 \text{ ft}, 1 \text{ story})$. Also note that the Refuge Design Inundation Depth (RDID) is defined as $1.3 * SMIE$, the first term in [1], in which the factor 1.3 is considered "*consistent with the skill level of present-day tsunami inundation models*" as discussed in the Commentary Section C6.14.

Note that the Grade Plane (GP) of Structure in Figure 4 is not the underlying level of topography; rather, the definition in Section 6.2 *DEFINITIONS* states that it is "*... the average elevation of finished ground level adjoining the structure at all exterior walls ...*" with additional instructions for including sloping or more complex topography outside the walls. Also, this SMIE definition is apparently the same as that for "*INUNDATION ELEVATION: The elevation of the design tsunami water surface, including relative sea level change, with respect to vertical datum at Mean High Water (MHW).*" We assume that "*relative sea level change*" is SLR. Although Figure C6.1-2 does include both SLR and co-seismic deformation, we found it difficult and time-consuming to search through Chapter 6 and the associated Commentary to clarify the inclusion of SLR and co-seismic deformation in the modeling. We feel that the Chapter should be self-contained, presenting both textual explanations and illustrative graphics for all basic requirements and criteria.

Suggestion D: Please follow the example of Figure C6.1-2 and revise Figures 6.2.1, 6.6.1, and 6.14.1 to explicitly indicate possible SLR and co-seismic deformation at the VES site.

In Aberdeen, WA, our on-going study of the proposed VES site demonstrates that subduction can lower a structure below MHW. Figure 5 portrays the Aberdeen situation schematically, in which the subsidence is relatively large and lowers the structure below MHW but the MCT amplitude is small at the VES site. This is a somewhat counter-intuitive and unexpected scenario, but can occur in locations such as Aberdeen. The tsunami, although much larger at the coast, travels through Grays Harbor and overland before reaching the structure, and has a flow depth that is less than the subsidence at the proposed VES location.

The SMIE and RDID are thus correspondingly small, although the addition of the safety factor S results in an ME that prevents flooding of the LORL by raising it above MHW and the MCT (see Figure 5).

Note that, since MHW is essentially constant for decades and sea level returns to MHW when the tsunami dissipates, then

$$SMIE \cong MHW \quad \text{"always"}$$

and it follows from equation [1] that, even in the limiting case in which $SMIE = MHW = 0$, we have

$$ME \cong S > MHW \quad \text{"always"}$$

This implies that in order for the LORL to be (temporarily) flooded the MCT must underestimate an actual future tsunami amplitude by at least $S = \max(10 \text{ ft}, 1 \text{ story})$; similarly, flooding of the LORL could also occur if the VES modeling study underestimates the subsidence. In fact, tsunami amplitude and coastal subsidence might both be underestimated, increasing the likelihood that the LORL is flooded; this is because, conceptually, maximum tsunami amplitude and maximum subsidence are positively correlated, albeit loosely, in the sense that a (larger, smaller) earthquake would tend to generate (larger, smaller) maximum tsunami amplitude and maximum subsidence.

The rationale for increasing the modeled MCT by 130% in equation [1] is based on published studies of inundation model accuracy and expert consensus, but we could find no similar rationale for the safety factor $S = \max(10 \text{ ft}, 1 \text{ story})$ in ASCE (2017a).

Suggestion E: Please consider the concerns raised here regarding equation [1], including the possibility that the term $1.3 \cdot \text{SMIE}$ does not provide the intended level of safety for very small SMIE, especially when the flow depth h at the structure is greater than SMIE. Also, please provide the rationale for the term $S = \max(10 \text{ ft}, 1 \text{ story})$ and, if appropriate, discuss this issue in the Commentary.

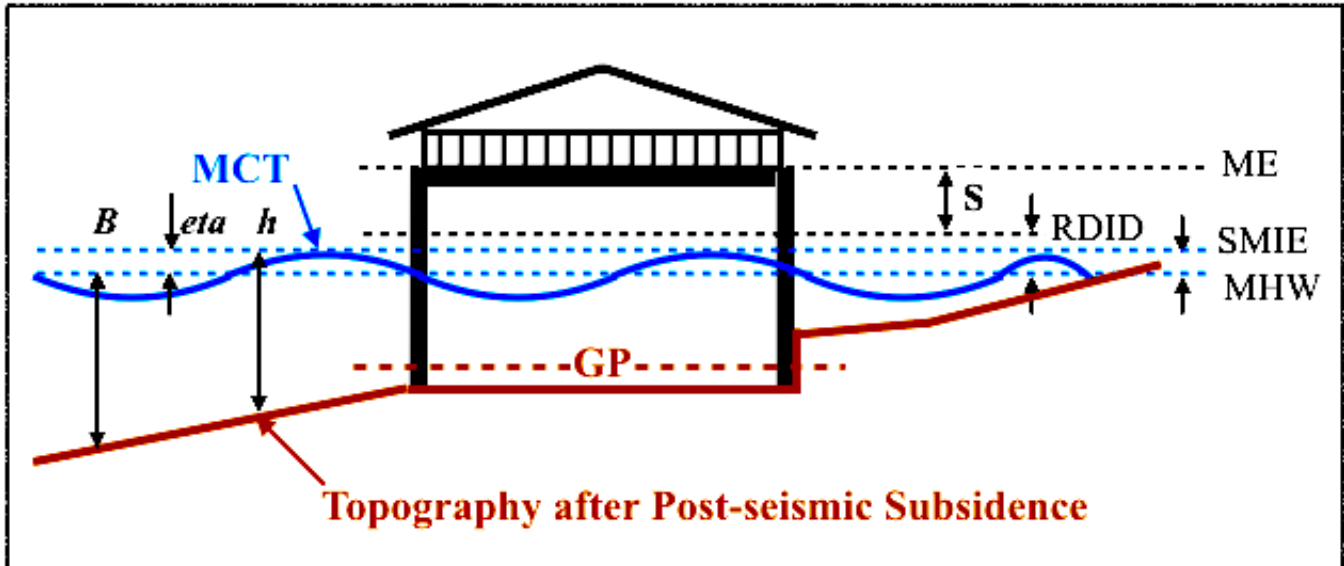


Figure 5. Hypothetical VES modeling study in which subsidence drops the structure below MHW and MCT is small. MHW is the reference level, B is the topography, η is the tsunami amplitude and h is the total water depth. See text for discussion.

2.2 Applicability to Near-field sources of Section 6.7.5.1

The title of this section is "Offshore Tsunami Amplitude for Distant Seismic Sources." A published example of using this section to develop near-field sources is Wei, et al (2017), who ignored contributions from distant sources and developed CSZ near-field unit sources that met ASCE Offshore Tsunami Amplitudes (OTA) criteria using data provided by the online ASCE Tsunami Design Geodatabase Version 2016-1.0 (<https://asce7tsunami.online/>). The report states that this was done to reconstruct "valid source(s)" for assessment of the 2500-year tsunami hazards along the coastal regions of Washington, Oregon and northern California.

Suggestion F: Please clarify whether or not this section applies to near-field sources; if it is applicable then modify the title, if it is not applicable then develop a separate section that details near-field seismic source criteria.

2.3 Definition of Extent of Offshore Tsunami Amplitude Points. The wording in TS-CH06-05r00 includes the requirement:

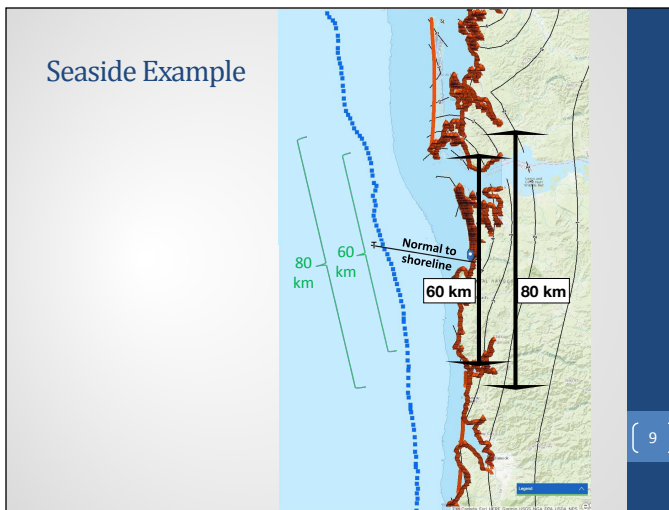


Figure 6. Two interpretations of the extent of offshore tsunami amplitude gauges given by the definition of the Balloted Proposal §6.7.5.1/2 (see text, above). Green extents and "Normal to shoreline" arrow are the intended ASCE 7 TLES geometry and black extents are an interpretation of the written guidance, respectively.

"(a) For sites within Washington, Oregon, California, and Hawaii, the extent shall include points within at least 60 km but not exceeding 80 km of projected length along the coastline, centered within a tolerance of plus or minus 10 km on the site;"

This wording was confusing to us for the following reasons:

(1) "the extent shall include points within at least 60 km..." Due to the use of the word "within," this could be interpreted to mean the extent should include points in a circle of radius at least 60 km centered at some point, since all of these points are within 60 km of the center. We suggest clarifying to say the *length* of the extent should be at least 60 km, not that it should include points within 60 km.

(2) What does "projected length along the coastline" mean? Projection assumes there is a

well defined normal to the coast. How is this to be defined in general? In particular if the proposed VES is set back from a jagged coastline.

(3) The normal direction will generally vary along the coastline, perhaps by quite a bit over the course of 60-80 km (particularly in Hawaii), so is the projection at all points along the coast defined by a single normal, defined somehow in relation to the location of the VES? Or is each gauge projected to the coast using the normal at the point to which the gauge location is projected? The latter is perhaps not well defined since on a curved coastline a gauge could be offshore in the normal direction from several points on shore.

(4) One way to interpret the intent of this wording might be to go offshore in the normal direction from the VES to the nearest gauge, and then use all gauges within a circle of radius 30-40 km centered on this gauge. The green lines on Figure 6 seem to indicate this. [Figure 6 is taken from slide 9 of the webinar presentation "Technical Briefing on 5 upcoming Chapter 6 Ballot Items Update Cycle for the ASCE 7-22 Standard," G. Chock and I. Robertson, 12 September 2018]. We have also added black lines to this figure to indicate extents of length 60 and 80 km along the coast (corresponding to circles of radius 30-40 km centered on land). Because the gauges run roughly parallel to the coast in this region, the projection of the green lines is similar to the black lines, but this depends on the topography of the continental shelf and may not always be true.

(5) Part (a) quoted above says "...centered within a tolerance of plus or minus 10 km on the site", which seems to imply the black lines in Figure 6, whereas part (c) goes on to say "For sites within bays, the designated center of the computed offshore tsunami amplitude points shall be taken...", which makes it sound like circles are to be centered at an offshore gauge rather than at a point on the shore, i.e. the green lines in Figure 6.

(6) The phrase "centered within a tolerance of plus or minus 10 km on the site" is also ambiguous if the VES site is set far back from the coast. Does this mean the coastal point used as a center (and/or for defining a normal) should be within 10 km of the VES site itself, or within 10 km of the coastal point closest to the VES site?

Suggestion G: Please clarify this wording, and we suggest adding a figure with an example or two to the standards document to help users understand the intent.

2.4 Predominant wave period criteria.

For complex waves, defining the wave period is notoriously difficult and ambiguous; there are multiple methods (zero-crossing, half-cycle, spectral peaks, etc.) and, in general, different methods produce different results. Furthermore, for complex seismic sources that involve a range of spatial length scales for vertical deformation there can be correspondingly large spatial variability in wave periods.

Suggestion H: If wave period criteria must be met, then please include in ASCE 7-22 (a) the physics/engineering rationale for establishing the criteria, (b) the wave period estimation method(s) that should be used and (c) the method (presumably the same as (b)) that was used to generate the wave period data in the ASCE online database. If wave period criteria do not have to be met in specific situations, then please clearly state this in the text.

2.5 Sea Level Rise (SLR)

Recently, Miller, et al. (2018) provided estimates of SLR accompanied by probabilities that these values would be exceeded within specific periods of time, i.e., the SLR Probability of Exceedance. In this context, we note that, since tsunami and SLR events are independent, the combined probability of exceedance for the simultaneous occurrence of both a 2500-year tsunami and a particular SLR value would be the product of the two probabilities, and would thus represent an event with a return period of more than 2500 years. This suggests that, when SLR Probability of Exceedance estimates are available they may have to be accounted for as an integral part of the probabilistic methodology computations.

Suggestion I: Please provide guidance on this issue for future revisions of ASCE-7 and the TDG database.

2.6-Two-Dimensional Definition of the Site-specific Minimum Inundation Elevation Level

In Section 6.7.6.8 *Determining Site-Specific Inundation Flow Parameters*, references to the required flow parameter are couched in terms of general phrases such as " ... at the site ...". This general description is ambiguous and, especially for large structures, does not take into account the fact that site-specific inundation model studies usually provide output values on a 2-dimensional computational grid. In this context, therefore, the SMIE is not well-defined by ASCE 7 guidance.

Suggestion J: Please provide 2-dimensional definitions for the SMIE and all related quantities of interest, for example -- maximum point value(s), spatial average, spatial median, ... etc., and the areal extent that should be considered ... the VES footprint, a larger rectangle enclosing the VES footprint, ... etc.

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