Preliminary Modeling Study of a Vertical Evacuation Structure Site for the Aberdeen School District

Final Report
February 2020

L.M. Adams[1], F.I. González[2], R.J. LeVeque[1]
[1]University of Washington Applied Mathematics
[2]University of Washington Earth and Space Sciences

Proposed site of new Stevens Elementary School (SES)

Study funded by the Federal Emergency Management Agency and the Aberdeen School District

Contents

Abstract

A Maximum Considered Tsunami (MCT) scenario was developed for a magnitude 9 tsunamigenic earthquake on the Cascadia Subduction Zone. The development of this MCT scenario is compliant with our current understanding of the American Society of Civil Engineers (ASCE) Building Code 7 published in 2016, i.e., ASCE 7-16. The results of the numerical simulation support the design of a vertical evacuation structure (VES) as part of the new Stevens Elementary School in Aberdeen, WA. Estimates of key hazard design parameters at the site include seismic subsidence of -2.76 m, 75 years of sea level rise to 0.37 m above the current level, maximum flooding of 2.75 m, and maximum current speed of 1.2 m/s. The arrival times of the leading edge and crest of the first wave to arrive at the site are 80 and 91 minutes, respectively, but several waves of increasing amplitude follow; the largest wave arrives almost 4 hours after the earthquake to create the maximum flooding and hazardous tsunami waves may continue to arrive for several hours beyond the 6-hour simulation. Substantial Aberdeen land area will be lost due to permanent flooding at levels that vary twice a day from 0 m (no flooding) at MLW to a maximum of about 3 m at MHW, depending on the location. It must be kept in mind that the simulated MCT scenario is probabilistic in nature, a single realization of an event with an estimated 2,475-year mean recurrence interval, so that the results discussed in this report cannot be taken literally as an accurate, detailed prediction of what *will* happen; rather, valuable general guidance is provided on what *may* happen, but significant uncertainties exist in any seismic or tsunami model result.

1.0 Introduction

The probability that an earthquake of magnitude 8 or greater will occur on the Cascadia Subduction Zone (CSZ) in the next 50 years has been estimated to be 10-14% (Petersen, et al., 2002). The last such event occurred in 1700 (Satake, et al., 2003; Atwater, et al., 2005) and future events are expected to generate a destructive tsunami that will inundate Washington Pacific Coast communities within tens of minutes after the earthquake main shock. Project Safe Haven identified many of these communities and potential sites within each community for Vertical Evacuation Structures (Project Safe Haven Team, 2016).

1.1 Background

The Aberdeen School District was awarded a Federal Emergency Management Agency (FEMA) Hazard Mitigation Assistance (HMA) grant for the design and construction of a new Stevens Elementary School at the site shown in Figure 1 that includes a Vertical Evacuation Structure (VES) tsunami refuge. Structural engineers responsible for the design of a VES require an assessment of the tsunami impact on the proposed site, including estimates of the maximum values of tsunami flooding, current speed and momentum flux that a VES must survive.

This report documents the methodology and results of a tsunami hazard assessment modeling study conducted for the site, including the development of a geophysically credible and defensible Maximum Considered Tsunami (MCT) scenario to provide the information needed by structural engineers to design the VES; these results could also help guide community planning and mitigation of the impact on residents and infrastructure.

1.2 ASCE-compatible Sources and Scenarios

In what follows, we distinguish between *sources* and *scenarios*; *scenarios* are developed by numerical simulation of tsunami generation by a *source* and the subsequent propagation and inundation of the VES site. More generally, however, *a new and distinct scenario is created by any modification of a model that produces a change in the corresponding simulation results*; examples include changes in the topographic grids, friction parameters, reference sea level, etc.

Modeling studies of VES sites differ from community-level hazard assessment modeling studies in that design criteria for VES have been published by the American Society of Civil Engineers (ASCE) Structural Engineering Institute (SEI), in the ASCE 7 Standard "Minimum Design Loads and Associated Criteria for Buildings and Other Structures" completed and approved in 2016 (ASCE 7-16) and published in 2017 (ASCE, 2017). This publication, ASCE 7-16, includes a new Chapter 6, "Tsunami Loads and Effects," as guidance for the design of VES tsunami refuges. The ASCE 7-16 standard has been included in the requirements of the 2018 International Building Code (IBC18) and is applicable to the states of Alaska,Washington, Oregon, California, and Hawaii. In addition, the ASCE/SEI 7 Tsunami Loads and Effects Subcommittee (TLES) periodically reviews and votes on proposed revisions for future versions of the ASCE 7 Standards in order to clarify criteria, resolve ambiguities and address issues that are encountered in the course of proposed VES site hazard assessment studies.

Washington State has not formally adopted the ASCE 7-16 Chapter 6 standard for such studies; nonetheless, this project has adopted these standards as well as proposed changes to the 2022 version of ASCE 7 as described in ASCE 7-22 Balloted Proposals that have been approved by a vote of the TLES, in

Figure 1. Location of Stevens Elementary School (SES) and NOAA Tide Gage station (TG).

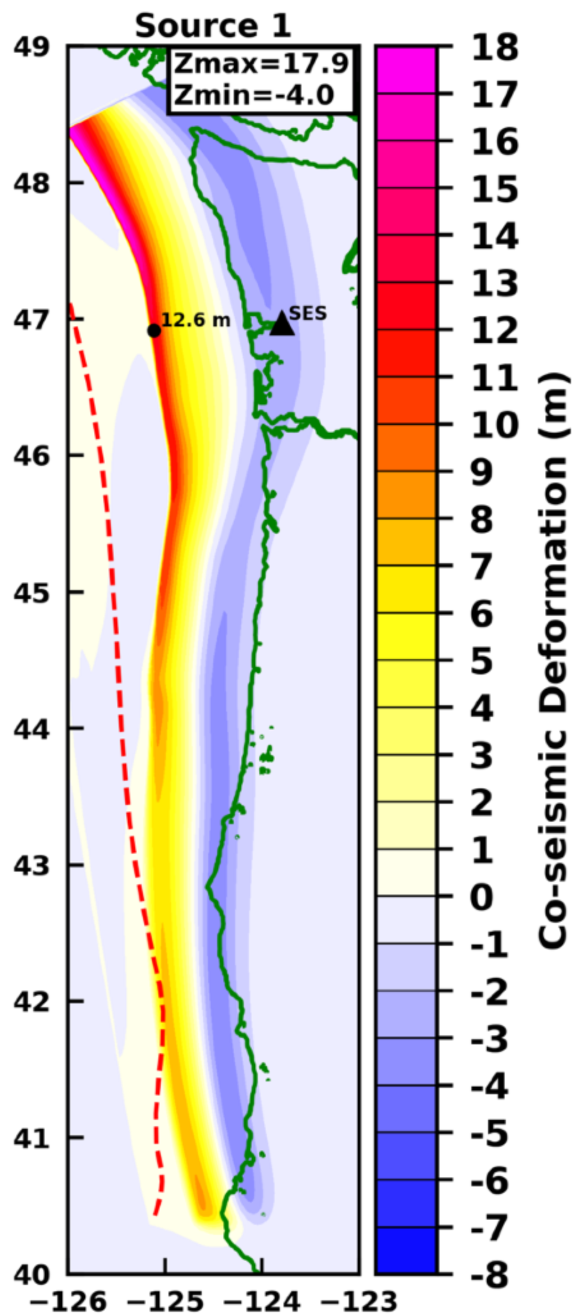

Figure 2. Deformation field of Source 1, which generates the Maximum Considered Tsunami (MCT). Warm colors are uplift, cool colors are subsidence, the white triangle marks the location of the VES site, the solid black dot is the location of maximum tsunami amplitude 12.6 at the latitude of the VES site, and the dashed red line marks the trench and intersection of the Cascadia fault with the ocean floor.

anticipation of their acceptance by the ASCE 7 Main Committee. However, since this ASCE guidance has only recently been developed and published, each application may uncover ambiguities or scientific/ engineering issues that must be addressed in consultations with TLES members in order to move forward and complete the project. Some of these issues have been documented in a separate report (Adams, et al., 2019b) and, not withstanding such ASCE issues that have not been formally resolved, during a previous VES site modeling study (Adams et al., 2020) informal discussions with ASCE 7-16 TLES members provided guidance; we have thus conducted and completed this current study with our best understanding of what is considered ASCE-compatible at this time and, most likely, in 2022; as such, we identify this study and its products and results as "ASCE-compatible."

ASCE 7-16 Chapter 6 provides criteria for development of the MCT based on the probabilistic concept of a scenario characterized by a 2,475-year mean recurrence interval (frequently rounded to a 2,500-year MCT in the literature). Thus, Section 6.2 defines the MCT as *"A probabilistic tsunami having a 2% probability of being exceeded in a 50-year period or a 2,475-year mean recurrence interval."* Section 6.5.3 also requires that *"The direct physical effects of potential relative sea level change shall be considered in determining the maximum inundation depth during the project lifecycle. A project lifecycle of not less than 50 years shall be used."* In addition, Section 6.7.5.1 of ASCE 7-16 provides criteria for the offshore tsunami amplitude (OTA) values that must be met for ASCE-compatibility.

Chock (2016) states 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."* Thio (2010) describes an approach to developing probabilistic tsunami hazard maps for California; this approach was also used to develop the ASCE 2500-

year MCT and an associated online ASCE Tsunami Design Geodatabase (TDG) Version 2016-1.0 (https://asce7tsunami.online/) on which ASCE 7-16 guidance is based. Appendix A discusses these ASCE 7-16 compatibility criteria in more detail.

Figure 2 presents Source 1, which is based on a modified version of the L1seismic model, a hypothetical Magnitude 9 earthquake developed by Witter et al. (2013); when used in a simulation that accounts for sea level rise (*SLR*), this source generates the Maximum Considered Tsunami (MCT) for this study. The development of the MCT scenario is described in Appendix A. Note that the word "considered" in the MCT designation reflects the possibility that a more destructive or less destructive scenario could occur; this is because it is currently impossible to confidently forecast important details of the most fundamental aspects of the geophysical event we study in this report -- i.e., a great tsunamigenic earthquake on the CSZ. In the narrative presented next, we provide a brief description of the temporal evolution of this particular MCT and its impact on the VES site.

1.3 Narrative of Maximum Considered Tsunami Scenario

First, a cautionary note for the reader. The narrative that follows cannot be taken literally as an accurate, detailed prediction of what ***will*** happen; seismic and tsunami models can provide valuable general guidance on what ***may*** happen, but large uncertainties exist in any seismic or tsunami model result. This important caveat is also true for the rest of this document and Section 4.0 briefly describes a number of the most important uncertainties. For this reason, qualifying terms such as "likely" and "may" are used liberally in this narrative. The narrative was developed for non-technical readers as a general but coherent story of how the impacts of a tsunamigenic earthquake on the residents and the physical environment of a community might evolve in time; it is based on collecting and organizing the results of our model simulations and other general, but well-known characteristics of great tsunamigenic earthquakes (such as the severity and duration of ground shaking) into a temporal framework.

The main shock of the M9 earthquake will likely be accompanied by strong shaking that will persist for 5 minutes or longer. There will be uplift offshore that generates a tsunami with a modeled maximum amplitude about 70 km offshore at the latitude of the Grays Harbor entrance of about 12.6 m (Figure 2). The tidal stage will be *MHW*, sea level will have risen by 0.37 m, and subsidence at the VES site will be about 2.8 m; thus, although the VES site is currently about 1.3 m above *MHW*, subsidence of 2.8 m will lower the site to 1.5 m below *MHW*.

Model results indicate the leading edge and the crest of the first tsunami wave will arrive at the VES tsunami refuge about 80 minutes after the main earthquake shock, followed in about 2 minutes by the onset of dangerous flood and current speed conditions before arrival of the first crest about 9-10 minutes later; with successive wave arrivals, the flooding level trends upward until the largest wave crest arrives about 4 hours after the main earthquake shock (Figure 4 (a)) . After approximately 5 minutes of severe shaking, the remaining evacuation time to the VES will be about 75 minutes. As waves propagate into and across Aberdeen and South Aberdeen, the maximum flooding and current speeds within Aberdeen can be as high as 4 m and 4 m/s at *MHW;* thus, life-threatening conditions from dangerous flood-flow levels will vary, depending on location (Figure 4 (b)), and are likely to continue for a number of hours beyond the 6-hour duration of the simulation.

Post-tsunami, the seismic model results (Figure 5) indicate that most of the land in Aberdeen will be lost to twice-daily flooding at *MHW;* at *MLW* (mean low water) the VES site will be about 0.9 m above the water level and at *MHW* it will be flooded to a depth of 1.5 m. The *MLW* exposure of the land is due to the mean tide range of 2.42 m at the NOAA Aberdeen tide gage station, which is about 4.9 km east of the VES; the mean tide range is defined as the difference of *MHW* and *MLW* (see https://tidesandcurrents.noaa.gov/datums.html?id=9441187). Assuming post-seismic uplift will occur, it may take decades to centuries to raise the Aberdeen area topography above *MHW*.

2.0 Development of ASCE-compatible CSZ Seismic Sources

Guidance in ASCE 7-16 §6.7.2 recommends that hazard assessment studies of Washington sites use Cascadia, Alaska, and Kamchatka-Kuril seismic sources. The ASCE Tsunami Design Geodatabase provides Disaggregated Hazard Source Contributions information in the form of figures such as Figure 3, for an Offshore Tsunami Amplitude (OTA) station due west of the Grays Harbor entrance and the proposed VES site. Not surprisingly, it is clear that Cascadia Subduction Zone (CSZ) seismic events dominate the contribution to OTA, compared to any far-field source regions. Consequently, we here ignore the far-field source regions and conduct this study using only near-field seismic events in the CSZ; similarly, Wei, et al. (2017) also ignored far-field source regions in their study to produce the Tsunami Hazard Zones included in

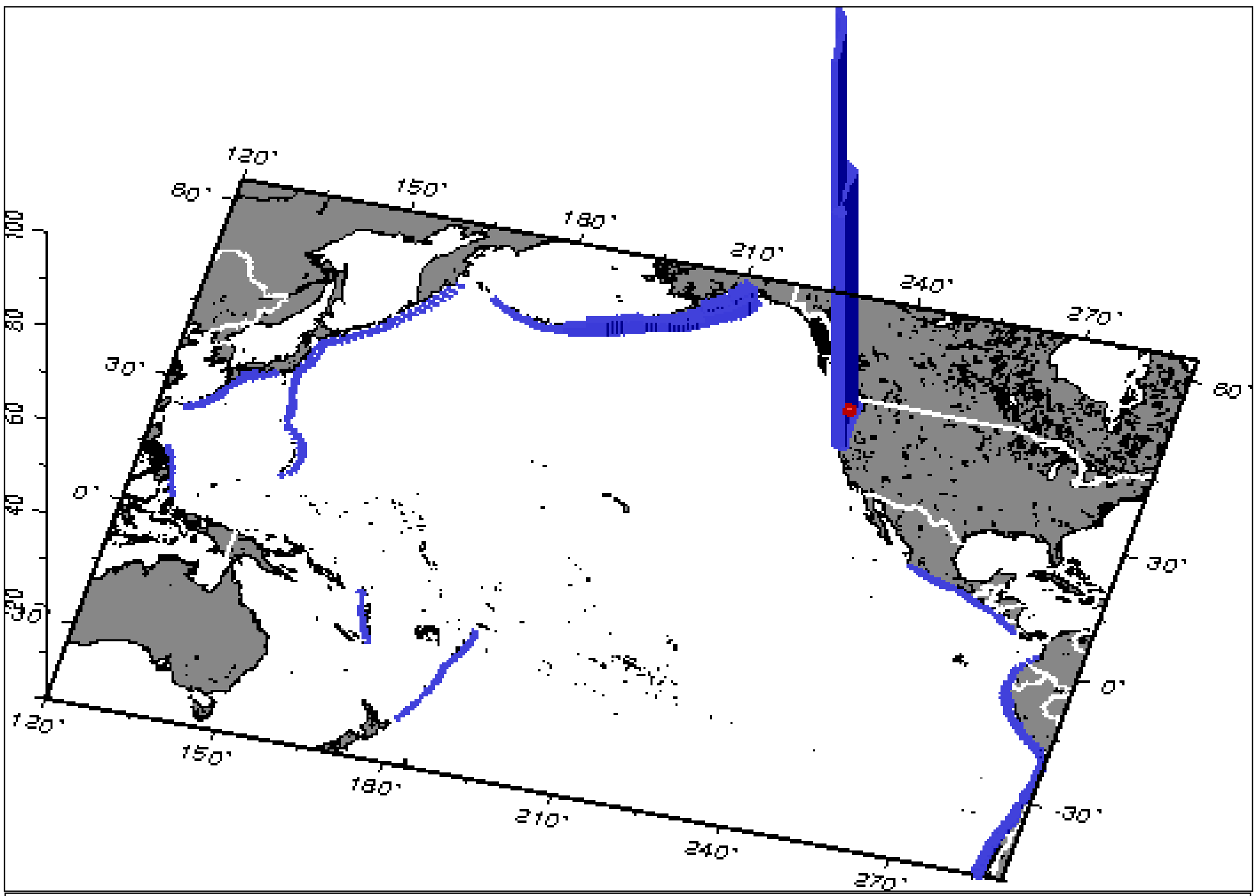

Figure 3. Disaggregated Hazard Source contributions (blue vertical bars) to an ASCE OTA station offshore of the Grays Harbor entrance at latitude 46.913 in100 m water depth, demonstrating the dominance of CSZ contributions to the OTA values.

the TDG.

For this modeling study of the VES site, the most important aspect of ASCE7-16 guidance is development of the tsunamigenic seismic source. This is because the fundamental output parameters of tsunami modeling simulations can be dependent on spatial and temporal details of the source. In mathematical terms, the source specifies the initial conditions required to start the numerical computation of solutions to the governing partial differential equations in time and space and, generally speaking, different initial conditions produce different solutions that describe tsunami generation, propagation and runup and, thus, the site-specific tsunami impact.

With regards to other possible tsunami sources, ASCE 7-16, Section 6.7.2, states that other sources such as *"Local, nonsubduction zone seismic fault sources capable of moment magnitude of 7 or greater, including offshore and/or submarine fault sources that are tsunamigenic"* and *"Local coastal and submarine landslide sources documented in the recognized literature as being tsunamigenic of similar runup, as determined by historical evidence or having estimated probabilities within an order of magnitude of the principal seismic fault sources"* shall be considered *"to the extent that probabilistic hazards are documented in the recognized literature."* We are aware that submarine landslides could occur during an M9 earthquake, but we are not aware of any recognized literature that provides reliable specifications for modeling such a source for the CSZ; consequently, only earthquake sources are considered in this study.

Witter et al. (2013) summarize the development of a suite of 15 seismic scenarios (5 magnitudes, each with 3 fault mechanisms) used in a study of Bandon, OR. Two of these scenarios, the ”medium” size M1 and the “large” L1, are "splay fault" seismic models with estimated (magnitudes, recurrence periods) of (8.9 Mw, 1000 yrs) and (9.0 Mw, 3333 yrs), respectively. Because their maximum inundation lines encompass 80%–95% of the inundation lines of the other simulated tsunami inundation scenarios, Witter et al. (2013) suggest these as a credible alternative to consider for future revisions to coastal construction standards. Consequently, the peer-reviewed L1 scenario of Witter et al. (2013) has been used in a number of Washington State tsunami hazard assessment modeling studies (e.g., Gica and Arcas, 2016; Titov, et al., 23018; Adams, et al., 2019a). For this study, the L1 vertical deformation field is represented on a 10 arc-sec resolution rectangular grid as positive and negative values for uplift and subsidence, respectively. The grid was created by linear interpolation of an irregular grid of (longitude, latitude, vertical displacement) values provided as a supplement to the Witter, et al. (2011) report.

Modifications to the L1 deformation field were then made to develop seismic sources that are compatible with ASCE guidance. In particular, an ASCE-compatible source generates a tsunami such that the modeled Offshore Tsunami Amplitude (OTA) meets the criteria found in Section 6.7.5.1 of ASCE 7-16 Chapter 6 and the Balloted Proposal §6.7.5.1/2 for inclusion in the 2022 version, ASCE 7-22. Appendix A provides details of the development of these sources and the selection of Source 1 (Figure 2) as the basis for the MCT; see, in particular, Section A.1 and Table A1.

3.0 The MCT Scenario and Simulation Results

This study conducted all simulations with the GeoClaw model, which is part of Clawpack (Clawpack Development Team, 2017), and has undergone extensive verification and validation (e.g., Berger, et al., 2010; LeVeque, et al., 2011). GeoClaw has been accepted as a validated model by the US National Tsunami Hazard Mitigation Program (NTHMP) after conducting multiple benchmark tests as part of an

NTHMP benchmarking workshop (González, et al., 2011). GeoClaw uses finite volume methods with adaptive mesh refinement and the finest grid resolution in and around the VES site was set to (longitude res, latitude res) = (1/3", 1/3") = (7.1 m, 10.3 m) at the latitude of the VES site.

3.1 MCT Scenario Impact on the VES Site.

Figure 4(a) presents results of the MCT scenario simulation based on Source 1 (Figure 2) in the form of time series of the flow depth referenced to the topography, h, the current speed, s, and the momentum flux, ϕ (Greek phi), recorded by Gauge 501 at the VES site; Figure 4 (b) provides Aberdeen area contour maps of the maximum values (denoted by a caret), $\widehat{\zeta}$ (Greek zeta), $\widehat{s}$ and $\widehat{\phi}$, computed over the 6-hour simulation period; this area is also the fine resolution computational domain in which each rectangular cell is 1/3 arc-sec in longitude and latitude. Here ζ is defined as h when onshore (pre-event) and as η, the wave amplitude referenced to *MHW*, when offshore (pre-event). Land loss to flooding will be significant in the Aberdeen area due to the combined effects of subsidence and *SLR*. Figure 5 presents the current and post-seismic Aberdeen topography below and above *MHW* and *MLW*. Only a small percentage of land below the 4 m level will remain dry at *MHW*, although most will resurface above *MLW*, including the VES site.

Table 1 summarizes key MCT Scenario D simulation input parameters and output results; this table satisfies the primary goal of providing ASCE-compatible MCT parameters $\hat{h}$, $\hat{s}$ and $\hat{\varphi}$ at the VES site that are needed for the VES design process. Table A1 in Appendix A, from which Table 1 is extracted, provides the same parameter summary for the 5 Scenarios that were developed as candidates for the MCT. All sources in Table A1 are, in principal, ASCE-compatible. However, as in our recent hazard assessment study of a VES site in the Shoalwater-Tokeland area (Adams, 2020), an analysis focused primarily on geophysical credibility and defensibility narrowed the candidates for the MCT scenario down to Source 1; the inclusion

Table 1. Summary of input and output parameters for the MCT Scenario D, extracted from Table A1, which summarizes the five scenarios developed for this study. All scenarios used ASCE-compatible sources; however, only the MCT is ASCE-compatible because it accounts for *SLR*. The first 2 columns, *Sc* and *N*, provide the scenario and source model designations, respectively. Source 1 is based on the L1 seismic model in which uplift and subsidence values are multiplied by the factors *up* and *sb*, respectively. Simulation output was recorded by gauge 501 at the VES site shown in Figure 1. The parameters B_0, ΔB and B are the initial, co-seismic vertical displacement, and final values of the topography referenced to *MHW*, respectively. *SLR* is the sea level rise projected over 75 years. The next 4 columns provide maximum values (denoted by a caret over the parameter symbols) recorded during the entire 6-hour simulation -- they are: $\widehat{h}$, the flow depth referenced to the local topography; $\widehat{s}$, the current speed; $\widehat{\phi}$, the momentum flux, and $\widehat{\eta}$ the wave amplitude referenced to *MHW*. The minimum height (*MH)* and minimum build elevation (*MBE)*, are quantities derived from the model output and are discussed in Section A.3, below.

Scenario	Source Model			Site Ground Deformation			*SLR* (m)	Simulation Output				*MH* Computations				
	N	up	sb	B_0 (m)	ΔB (m)	B (m)		$\widehat{h}$ (m)	$\widehat{s}$ (m/s)	$\widehat{\phi}$ (m^3/s^2)	$\widehat{\eta}$ (m)	*S* *(m)*	*MH* *(m)*	*MH* (ft)	*MBE* *(m)*	*MBE* *(ft)*
D	1	1.172	1.000	1.27	-2.76	-1.49	0.37	2.75	1.20	3.75	1.25	3.05	6.17	20.23	7.44	24.40

of a projected 75-year *SLR* of 0.37 m (Miller, et al., 2018) in the Source 1 simulation then created the ASCE-compatible MCT Scenario D (see Section A.1).

Note that *SLR* was incorporated into the GeoClaw simulations of the MCT by increasing the initial water level for the simulation above MHW by 0.37 m, the projected SLR over 75 years. But also note that all elevations are still referenced to the present-day MHW, which is the vertical datum of the coastal topography DEM. Hence B_0 still refers to the present-day elevation of the topography and B to the post-quake elevation that incorporates subsidence, also relative to present-day *MHW*. The values of B_0 and B in Table A1 are therefore the same for the MCT as for the scenarios without SLR, and Figure 4 contours are of the present-day B_0 (not a future B_0 coastline after *SLR)*. Also note that the change in tidal dynamics due to the associated increase in water depth is small, and so we assume that *MHW* rises by the same amount (0.37 m) as mean sea level (*MSL*) rises. This is justified by modeling experiments conducted by Pickering, et al. (2017), in which changes in MHW on the US West Coast were estimated to agree with changes in MSL to within 1% even for much greater changes in MSL (see Figure 2 in their report).

3.2 Warning, Tsunami Arrival and Evacuation Times

Tsunami arrival times are also extremely important, as they provide estimates of the time available for evacuation to the VES refuge. Figure 4(a) indicates the leading edge of the first wave will arrive at the VES site about 80 minutes after the main shock and that the onset of hazardous conditions, i.e. flooding depth and current speed (*h,s*) at levels of (0.5 m, 0.5 m/s) will occur within minutes of the leading edge arrival. Therefore, the evacuation time, i.e., the actual length of time available to reach the VES refuge, is about 80 minutes minus the warning time or the duration of strong shaking, whichever is longest. It is most likely that strong shaking will provide the early warning and evacuation will be delayed until the severity of an expected 5-6 minutes of shaking decreases to an allowable level; in this case, then, the maximum time available to reach the VES site will be about 75 minutes. It is unlikely that a so-called "tsunami earthquake" or "silent earthquake" will occur (Kanamori, 1972), in which the severity of coastal shaking can be too low to detect or to cause alarm; but if the earthquake is tsunamigenic, then it is large enough to be detected instrumentally, and a warning will be issued. In this case, then, evacuation would be delayed by the effectiveness of an earthquake and tsunami early warning (ETEW) system to deliver the warning to individual residents (LeVeque, et al., 2018).

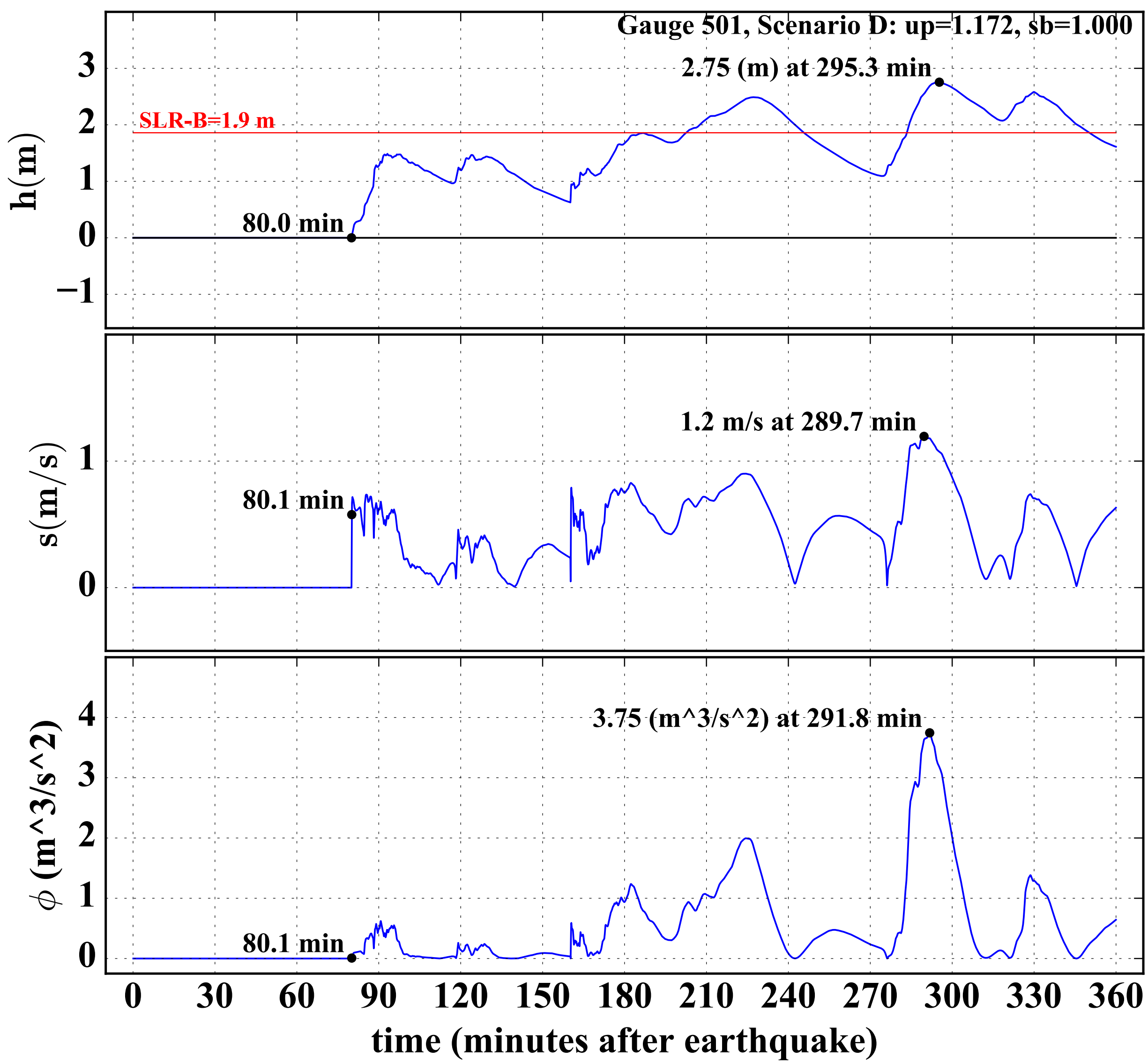

Figure 4 (a). Modeled time series at Gauge 501 for the MCT Scenario D for the flood depth, *h (*which is referenced to the local, post-seismic topography, B), the current speed, *s,* and the momentum flux, ϕ*,* Red horizontal line in the top panel is the flooding depth at MHW for this particular geographical position once the tsunami event is over, i.e., when tsunami waves no longer propagate to the gauge; since the post-seismic topography, B, is spatially variable, the twice daily flood level at MHW will also vary spatially, depending on the geographic position, as shown in the top panel of Figure 4(b).

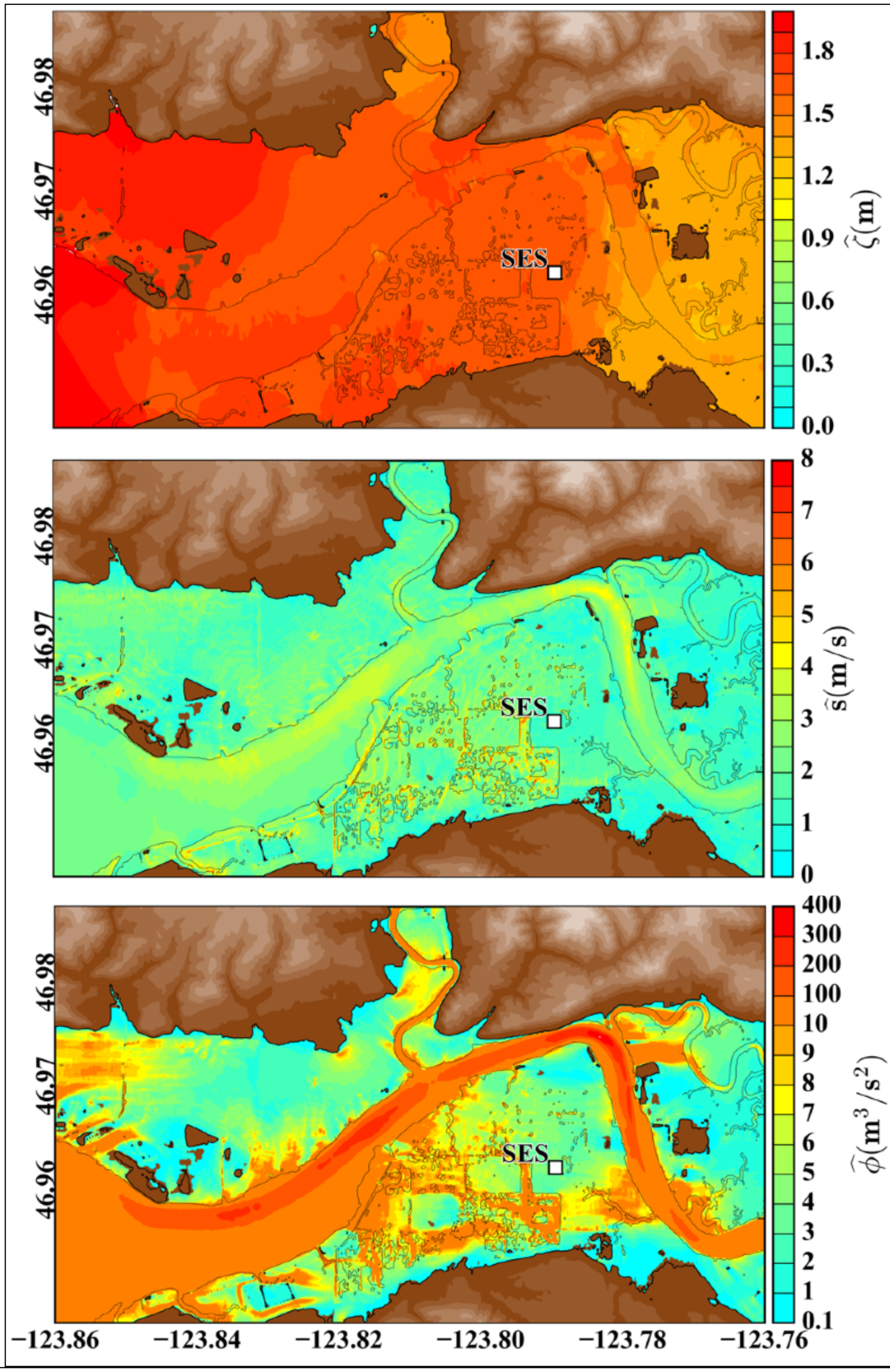

Figure 4 (b). MCT Scenario D maximum values of (flood level, current speed, momentum flux), ($\widehat{\zeta}$, $\widehat{s}$, $\widehat{\phi}$), over the 6-hr simulation. White square labeled SES marks the site of the new Stevens Elementary School and Gauge 501. Pre- and post-earthquake coastlines are thin and thick black lines, respectively. The computational domain is 1/3 arc-sec resolution.

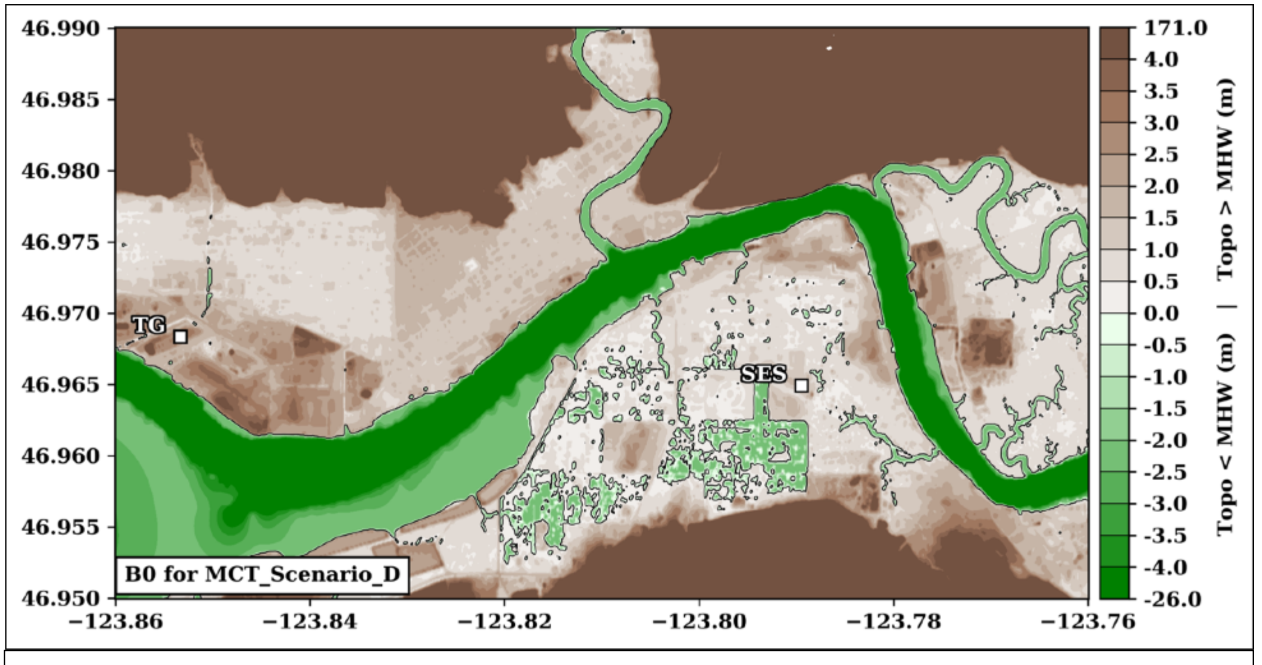

Figure 5(a). Current topography in the Abderdeen area, B_0 , at MHW.

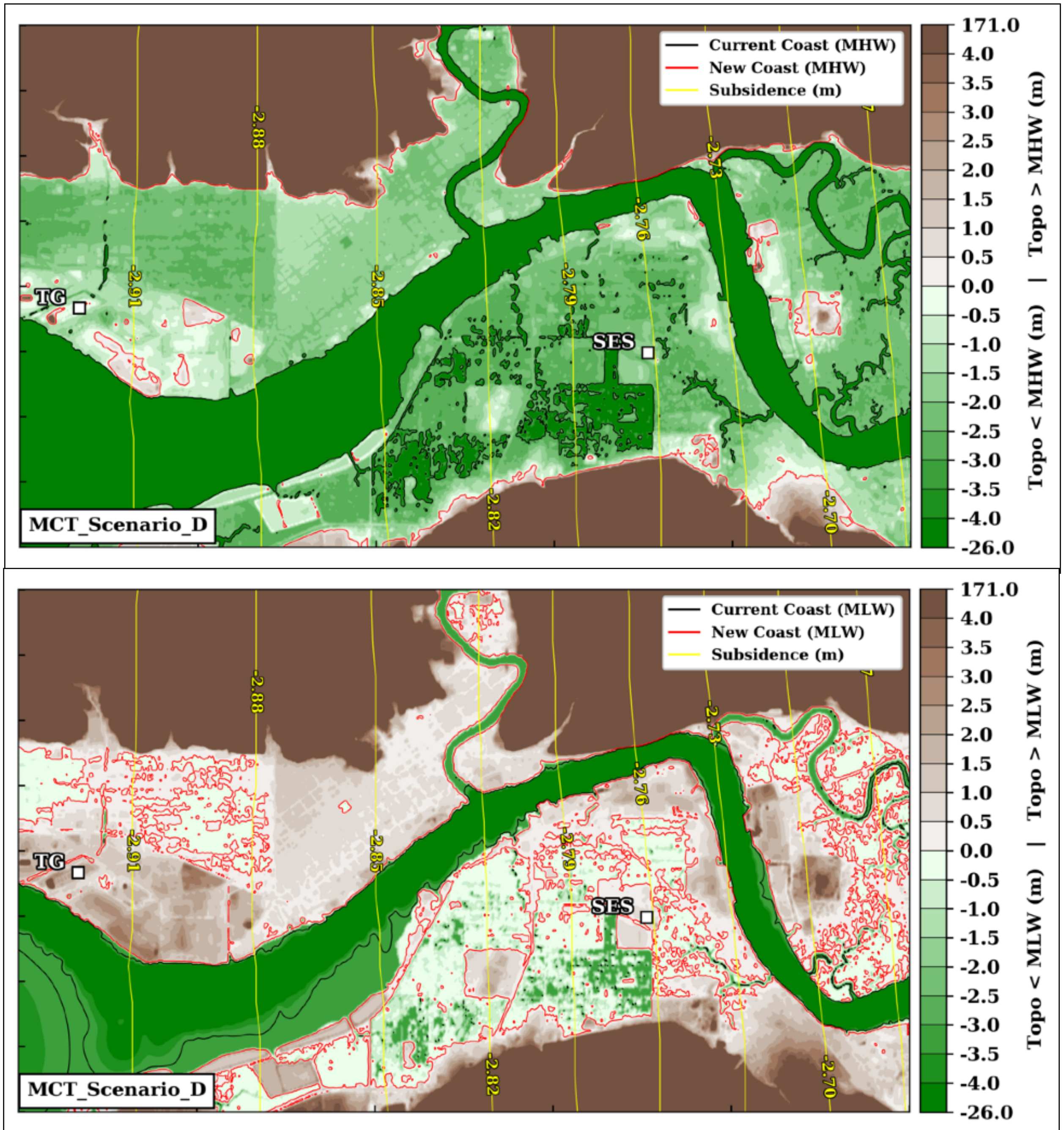

Figure 5(b). MCT post-seismic Aberdeen topography at MHW and MLW levels. Note that the current coastline does not include the 75-year projected *SLR*, but the new coastline does account for the *SLR*.

4.0 Modeling Uncertainties and Limitations

GeoClaw uses the shallow water equations to model the tsunami, which is an approximation of the three-dimensional fluid dynamics, but one that has been found to be sufficiently accurate for inundation studies of this nature in previous studies, including validation and benchmarking workshops. However, it is only an approximation to the correct physics. A number of other assumptions or approximations are also made, as summarized below.

4.1 Tide stage

The simulations were conducted with the background sea level set to *MHW* for all Scenarios listed in Table A1 except the MCT Scenaro D, which was set to *MHW + SLR*. The *MHW* value is conservative, in the sense that the severity of inundation will generally increase with a higher background sea level. Larger tide levels do occasionally occur, but the assumption of *MHW* is standard practice in studies of this type.

4.2 Subsidence and uplift

This ground motion is taken into account in all source models used, and it is the underwater vertical motion that generates the tsunami. For all events, the details of the motion depend on the hypothetical earthquake source model, and this is the biggest source of uncertainty in the model results since the next earthquake may be very different from the ones that have been modeled.

4.3 Structures

Buildings were not included in the simulations, the topographic DEMs provided for this study are "bare earth." The presence of structures will alter tsunami flow patterns and generally impede inland flow. To some extent the lack of structures in the model is therefore a conservative feature, in that their inclusion would generally reduce inland penetration of the tsunami wave. However, as in the case of the friction coefficient, impeding the flow can also result in deeper flow in some areas. It can also lead to higher fluid velocities, particularly in regions where the flow is channelized, such as when flowing up streets that are bounded by buildings.

4.4 Bottom friction

Mannings coefficient of friction was set to 0.025 in GeoClaw, a standard value used in tsunami modeling that corresponds to gravelly earth. This value is conservative in some sense, because the presence of trees, structures and vegetation would justify the use of a larger value, which might tend to reduce the inland flow. On the other hand, larger friction values can lead to deeper flow in some areas, since the water may pile up more as it advances more slowly across the topography.

4.5 Tsunami modification of bathymetry and topography

Severe scouring and deposition are known to occur during a tsunami, undermining structures and altering the flow pattern of the tsunami itself. Again, this movement of material requires an expenditure of tsunami energy that tends to reduce the inland extent of inundation. On the other hand, if natural berms or ridges along the coastline (or man-made levies or dikes) are eroded by the tsunami, then some areas can experience much more extensive flooding. There is no erosion or deposition included in the simulations presented here.

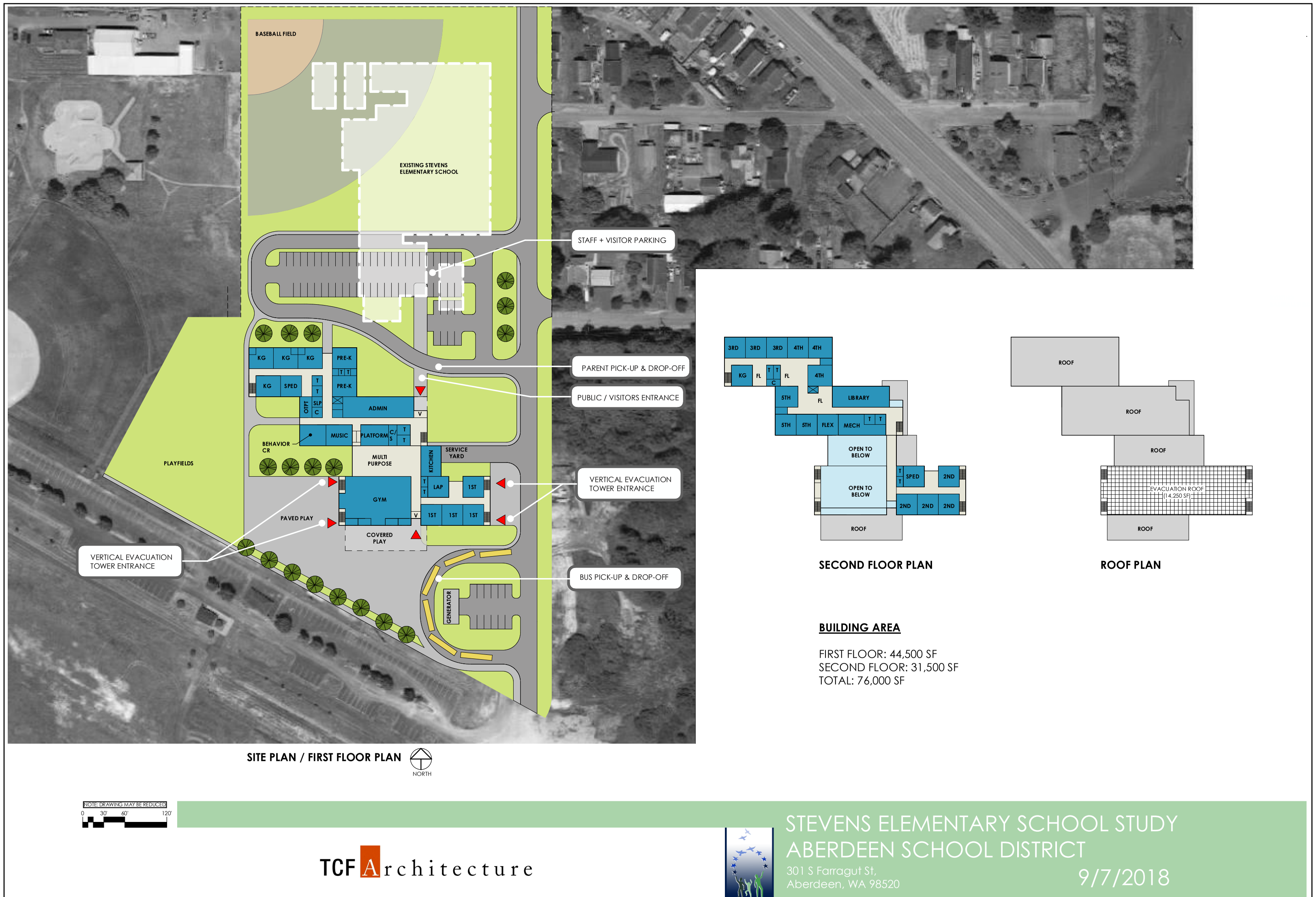

Figure 6. TCF Architecture Study of Stevens Elementary School (Aberdeen School District (2019)).

5.0 Recommendations for Final Modeling Study

To be clear, the Maximum Considered Tsunami scenario scenario is not certain to occur; the actual future event may be less severe or more severe than this particular MCT, which is only one of many that could be developed based on the probabilistic concept of a 2500-year event and the tsunami modeling standards published in ASCE (2017). Nontheless, it is prudent to consider a scientifically defensible worst case considered scenario when planning the design and construction of structures to reduce the loss of life.

The MCT developed for this preliminary study produces a hazardous situation in the Aberdeen area, and residents would have about 75 minutes to reach the Vertical Evacuation Structure refuge at the school site before the onset of significant flooding and strong currents (Figure 4). And most Aberdeen land, including in and around the site of the proposed new Stevens Elementary School, would be lost to permanent, twice-daily flooding at Mean High Water due to seismic subsidence of 2.75 m plus Sea Level Rise of 0.37 m (Figure 5).

The basic design parameters provided by this report, i.e., maximum values of flooding, current speed, and momentum flux at the site, are important as a fundamental first step in the structural design and engineering process for the school building and VES refuge. However, all simulations leading up to and including the MCT scenario were based on "bare earth" conditions, i.e., no structures were included. But the presence of structures can alter flow and flood patterns by increasing and decreasing current speed and direction and flooding depth, and the flow can alter structures by scouring around foundations, damaging the building, and creating debris that might be borne by later waves to batter structures.

Such tsunami-structure interactions are an extremely complex physical process to model. The current state of both the numerical modeling and the underlying fundamental science is limited, but can nonetheless provide valuable additional information to the design process through improved understanding of the conditions a structure must survive.

To focus on the kinds of questions such studies might address, consider Figure 6, which presents a design study by TCF Arichitecture for the new SES. How would such a structure interact with the MCT tsunami flooding and associated currents ? What part of the structure offers the best chance of survival for a VES refuge and occupants ? Where should access doors to the refuge be located and what parts of the structure are least likely to collect debris that would block access ? Might the shape and orientation of the SES structure be designed to minimize the impact of such floating debris and the trapping of debris against the structure that might pose additional hazards, such as fires ? Fires are a frequent hazardous aspect of tsunamis due to the potential for electrical short circuits and the presence of flammable debris like oil and gas from storage tanks, boats and automobiles; during the 2011 Tohoku tsunami, vehicles were trapped against buildings and, especially hybrid cars with lithium ion batteries, created fires that then spread to structures.

At small scales, three-dimensional (3D) modeling provides the best description of tsunami interaction with structures and estimates of the forces on the structure; at larger, community- and regional-size scales, 2-dimensional (2D) simulations can contribute in a more general way to our overall understanding and insight into the potential tsunami impact (Qin, et al., 2018). Thus, although preliminary in nature, this study motivated an effort to develop additional 2D analysis software for a preliminary look at tsunami flooding and current patterns at the new Stevens Elementary School site. The first tool under development

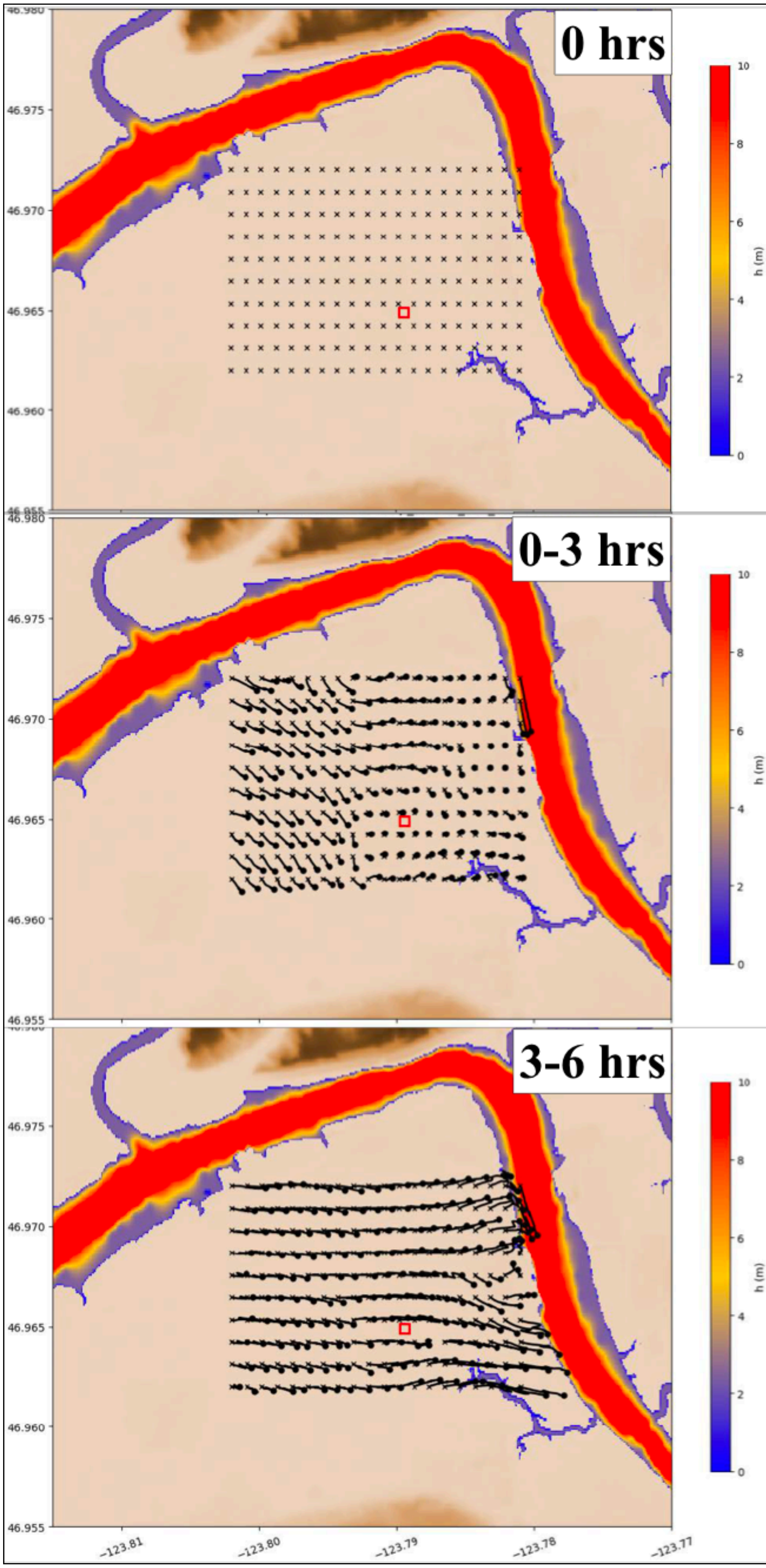

Figure 7. Particle tracks during the period shown in the upper right-hand corner of each panel. Red open square marks the location of the new Stevens elementary school. Over the 6-hr time periods, the flood depth and current speed were variable up to a maximum of 1 m and 1.2 m/s, respectively. The background map represents the original, pre-seismic topography referenced to *MHW*. Shades of brown represent land above *MHW* and the shade darkens with height; the colors of the vertical bar labeled h (m) represent the initial water depth in the river.

implements a particle-tracking algorithm that estimates and displays the tracks of particles in the tsunami current field. These estimates are based on assumptions such as, e.g., that the particles are massless and move exactly with the flow; while these assumptions are idealized and therefore somewhat non-physical, the results do provide useful information on overall flow characteristics. Figure 7 displays particle tracks at the SES site during the 6-hour MCT simulation. This software is still in the development and testing stage; additional capabilities are planned, such as the inclusion of structures, exploration of effective combinations of visualizing multiple parameters, and the development of animations.

5.1 Recommendations.

We recommend a pre-construction follow-up study, as follows.

Phase 1: 2D modeling. In which the goal is to (a) gain a better understanding of tsunami-structure interactions and the associated flood-flow patterns and forces on simple models of existing nearby buildings and (b) determine whether or not more sophisticated 3D modeling is needed to guide the structural engineering and design of the new SES and VES refuge. We will

A. extend the capabilities of the preliminary particle-tracking software to improve our understanding of large scale flood-flow patterns, first with "bare earth" simulations and improved 2D analyses and visualization capabilities.

B. Introduce simple structures based on the vertical extension of footprint walls as an integral part of the topography.

C. Conduct 2D scenario simulations.

- Model results will provide estimates of tsunami parameters needed for structural engineering and design -- flooding depth, current speed and momentum flux.
- Sensitivity studies to quantify the effect on model results to parameters such as friction, resolution, etc.
- Inclusion of candidate structure designs. Successive designs might possibly be introduced in an iterative fashion, as previous simulation results dictate.

D. Assess whether or not there is a need to perform additional 3D modeling for more accurate, finer resolution estimates of flow patterns and forces on structures as additional input to the design process and subsequent testing of the revised designs.

Phase 2: 3D/2D Modeling. If the need for 3D modeling is established in Phase 1, then the goal of this phase will be to identify and simulate high priority scenarios that will focus on the development of 2D input to fine-scale 3D modeling in order to provide flood-flow patterns at the site and estimates of forces on candidate structure designs.

6.0 Summary

A tsunami hazard assessment modeling study was conducted to support the structural engineering design of a VES refuge to be incorporated as part of the proposed new Stevens Elementary School in Aberdeen, WA. An ASCE-compatible "Maximum Considered Tsunami" scenario designated as Scenario D was developed and modeled. The MCT simulation provided output that included key hazard design parameters: 75 years of sea level rise by 0.37 m, seismic subsidence of -2.8 m, maximum flooding of 2.8 m and maximum current speed of 1.2 m/s. The onset of hazardous conditions at the site due to flooding depth and current speed levels occurs about 80 minutes after the earthquake main shock; the effective time for residents to reach the VES refuge is thus 80 minutes minus either the time for expected severe seismic shaking to cease (5-6 minutes) or, in the unlikely case of a "silent earthquake" with little or no shaking, the time for an early warning system to issue a warning. Post-seismically, most land in Aberdeen will be lost to twice-daily flooding, due to subsidence and sea level rise.

The results of this study are preliminary and recommendations are provided for a follow-on final study that focuses on a better understanding of the tsunami-structure interaction and the corresponding forces that the structure must withstand.

Acknowledgements.

This project was jointly funded by the Federal Emergency Management Agency and the Aberdeen, WA, School District and was conducted in consultation with Cale Ash and Hee Jae Yang of Degenkolb Engineers. Discussions with Yong Wei (UW JISAO and NOAA/PMEL) were also very helpful, and he kindly provided the parameters of the seismic source developed by Wei et. al. (2017) designated in this study as Source 2.

References

Aberdeen School District (2019): Request for Qualifications (RFQ) For Geotechnical Engineering Services, Stevens Elementary School Replacement, January 11, 2019, 10 pp., https://www.asd5.org/Page/9065 .

Adams, L., F. Gonzalez, and R. LeVeque (2019a), Tsunami Hazard Assessment of Whatcom County, Washington, Project Report – Version 2, http://staff.washington.edu/rjl/pubs/THA_Whatcom .

Adams, L.M., F.I. González, R.J. LeVeque (2019b): Issues in the Development of ASCE-Compatible Seismic Sources, University of Washington ResearchWorks Archive: http://hdl.handle.net/1773/43827.

Adams, L.M., F.I. González, R.J. LeVeque (2020): Modeling Study of a Proposed Vertical Evacuation Structure Site for the Shoalwater Bay Tribe, Final Report, University of Washington ResearchWorks Archive, http://hdl.handle.net/1773/45287 .

ASCE (2017): Minimum design loads and associated criteria for buildings and other structures. ASCE/SEI 7-16. Reston, VA: ASCE.

Atwater, Brian F., Musumi-Rokkaku Satoko, Kenji Satake, Tsuji Yoshinobu, Ueda Kazue, and David K Yamaguchi (2005): USGS Professional Paper 1707, pp 1–144.

Berger, M. J., D. L. George, R. J. LeVeque, and K. T. Mandli (2010): The GeoClaw software for depth-averaged flows with adaptive refinement. Preprint and simulations: www.clawpack.org/links/papers/awr10 .

Chock, Gary Y. K. (2016): Design for Tsunami Loads and Effects in the ASCE 7-16 Standard, J. Struct. Eng., 2016, 142(11): 04016093.

Clawpack Development Team, Clawpack software, 2017, https://doi.org/10.5281/zenodo.820730, http: //www.clawpack.org. Version 5.4.1.

The Daily World (2018): "Stevens Elementary will not be moving far from its current location," http://www.thedailyworld.com/news/stevens-elementary-will-not-be-moving-far-from-its-current-location/ .

Gica, E. and D. Arcas(2016): Tsunami Inundation Modeling of Anacortes and Bellingham, Washington due to a Cascadia Subduction Zone Earthquake. PMEL Tech report, ftp://newportftp.pmel.noaa.gov/tsunami/WaEMD/Anacortes_Bellingham/documentation/ Anacortes_Bellingham_Washington_Report.pdf.

González, F., R. J. LeVeque, J. Varkovitzky, P. Chamberlain, B. Hirai, and D. L. George, (2011): GeoClaw Results for the NTHMP Tsunami Benchmark Problems, http://depts.washington.edu/clawpack/links/ nthmp-benchmarks/geoclaw-results.pdf .

Kanamori, H., (1972): Mechanism of tsunami earthquakes, Physics of the Earth and Planetary Interiors, 6, 346-359.

LeVeque, R. J., D. L. George, and M. J. Berger, (2011): Tsunami modeling with adaptively refined finite volume methods, Acta Numerica, pp. 211–289.

LeVeque, R.J., P. Bodin, G. Cram, B.W. Crowell, F.I. Gonzalez, M. Harrington, D. Manalang, D. Melgar, D.A. Schmidt, J.E. Vidale, C.J. Vogl, and W.S.D. Wilcock, (2018): Developing a Warning System for Inbound Tsunamis from the Cascadia Subduction Zone, Oceans 2018 conference, http://hdl.handle.net/1773/43181 .

Miller, I.M., Morgan, H., Mauger, G., Newton, T., Weldon, R., Schmidt, D., Welch, M., Grossman, E. (2018): Projected Sea Level Rise for Washington State – A 2018 Assessment. A collaboration of Washington Sea Grant, University of Washington Climate Impacts Group, Oregon State University, University of Washington, and US Geological Survey. Prepared for the Washington Coastal Resilience Project. http://www.wacoastalnetwork.com/wcrp-documents.html

Petersen, M. D., C. H. Cramer, and A. D. Frankel (2002): Simulations of Seismic Hazard for the Pacific Northwest of the United States from Earthquakes Associated with the Cascadia Subduction Zone. Pure Appl. Geophys., 159, 2147-2168. https://doi.org/10.1007/s00024-002-8728-5.

Pickering, M.D., K.J. Horsburgh, J.R. Blundell, J.J.-M. Hirschi, R.J. Nicholls, M. Verlaane, N.C. Wells (2017): The impact of future sea-level rise on the global tides, Continental Shelf Research 142, 50–68.

Project Safe Haven Team (2016): Project Safe Haven: Tsunami Vertical Evacuation on the Washington Coast, 42 pp, https://mil.wa.gov/uploads/pdf/emergency-management/final-report-2016-11-21-16.pdf

Qin, X. S., M. R. Motley, R. J. LeVeque, F. Gonzalez, and K. Mueller (2018): A comparison of a two-dimensional depth-averaged flow model and a three-dimensional RANS model for predicting tsunami inundation and fluid forces, *Nat. Hazards Earth Syst. Sci.,* 18, pp. 2489-2506,

Satake, Kenji, Kelin Wang and Brian F Atwater (2003): Fault Slip and Seismic Moment of the 1700 Cascadia Earthquake Inferred From Japanese Tsunami Descriptions, Journal of Geophysical Research 108 (B11): 1–17. doi:10.1029/2003JB002521.

Titov, V., D. Arcas, C. Moore, R. LeVeque, L. Adams, and F. Gonzalez, Tsunami Hazard Assessment of Bainbridge Island, Washington, Project Report, 2018, http://staff.washington.edu/ rjl/pubs/THA_Bainbridge.

Wang, P.-L., S. E. Engelhart, K. Wang, A. D. Hawkes, B. P. Horton, A. R. Nelson, and R. C. Witter (2013): Heterogeneous rupture in the great Cascadia earthquake of 1700 inferred from coastal subsidence estimates, J. Geophys. Res. Solid Earth, 118, 2460–2473, doi:10.1002/jgrb.50101.

Wei, Y., H. Thio, V. Titov, G. Chock, H. Zhou, L. Tang, and C. Moore (2017): Inundation Modeling to Create 2,500-Year Return Period Tsunami Design Zone Maps for the ASCE 7-16 Standard, 16th World Conference on Earthquake Engineering, 16WCEE 2017, Santiago Chile, January 9th to 13th, 2017, Paper No. 450, 10 pp.

Witter, R. C., et al. (2013). "Simulated tsunami inundation for a range of Cascadia megathrust earthquake scenarios at Bandon, Oregon, USA." Geosphere 9(6): 1783-1803.

Witter, R. C., Y. Zhang, K. Wang, G. R. Priest, C. Goldfinger, L. L. Stimely, J. T. English, and P. A. Ferro (2011): Special Paper 43, Simulating tsunami inundation at Bandon, Coos County, Oregon, using hypothetical Cascadia and Alaska earthquake scenarios, 57 p. with supplement, including plates, GIS and data files, and animations (https://www.oregongeology.org/pubs/sp/p-SP-43.htm).

Appendix A. ASCE 7 Compliance

A.1 Source Compliance with Offshore Tsunami Amplitude Criteria

The ASCE criteria for offshore tsunami amplitude (OTA) are as follows:

> ***OTA Criteria 1.*** *The extent of offshore tsunami amplitude points considered for the site 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*
>
> ***OTA Criteria 2.*** *The values of computed OTA shall be not less than 80% of the coinciding OTA values given by the ASCE TDG.*
>
> ***OTA Criteria 3.*** *The mean value of the computed OTA shall be at least 100% of the mean value for the coinciding OTA data provided in the ASCE TDG.*

Figure A1 presents the physical setting in which conformance with these criteria was developed, i.e., the locations of the OTA data provided in the online ASCE TDG relative to the VES site location. Also shown is the Miller, et al. (2018) SLR station closest to the VES site; the data for this site were used to satisfy the additional ASCE SLR criteria, as discussed in Section A.2, below.

Table A1 summarizes key input and output parameters associated with sources and scenarios developed in this study and the values of minimum *height* (*MH*) and minimum built *elevation* (*MBE*) of the lowest refuge level, which are discussed in Section A.3, below. Source 0 is the original, unmodified L1 model developed by Witter, et al. (2013) from which Sources 1, 3 and 4 were derived by multiplying the uplift and subsidence of the L1 deformation filed by the factors *up* and *sb*, respectively; Source 2 is the ASCE-compatible seismic model developed by Wei et al., (2017). A brief discussion of each source follows.

Source 0 is based on the original, unmodified L1 seismic model of Witter et al., (203) for which the irregularly spaced deformation model data, ($x,y,\Delta B$) = (*longitude, latitude, vertical crustal deformation)*, was interpolated to a computational grid with 10 arc-second resolution.

Source 1 is a modification of Source 0 in which the uplift values were multiplied by the factor 1.172 to meet the ASCE criteria for Offshore Tsunami Amplitude and the original, unaltered subsidence values were retained to conform more closely to subsidence estimates at the site in peer-reviewed studies (see the discussion and justification for this approach, below).

Source 2 was developed on a 10 arc-sec grid using a linear combination of unit sources from the Short-term Inundation Forecasting for Tsunamis (SIFT) database (https://nctr.pmel.noaa.gov/tsunami-forecast.html). The seismic slip parameters were those determined by Wei, et al. (2017) to develop a source that is consistent with the ASCE guidelines for a portion of the Washington coast, for the purpose of developing maps of the Tsunami Design Zone (TDZ) that reside in the online ASCE Tsunami Design Geodatabase. Essentially, the TDZ maps define the maximum inland limits of flooding due to this source, and the purpose of the TDZ maps is described in the first paragraph of ASCE 7-16, Chapter 6, Section 6.1.1 Scope as *"The following buildings and other structures located within the Tsunami Design Zone shall be designed for the effects of Maximum Considered Tsunami, including hydrostatic and hydrodynamic forces, waterborne debris accumulation and impact loads, subsidence, and scour effects in accordance with this chapter: ... "* Thus, the question of whether or not a structure should be designed and constructed to be ASCE-compatible is governed by the TDZ maps, i.e., by whether or not the structure is inside the TDZ area.

Source 3 is a modification of Source 0 obtained by multiplying the uplift values by the factor *up*=1.172 to meet the ASCE criteria for Offshore Tsunami Amplitude and multiplying the subsidence values by the factor *sb*=0.367; this brought the modeled subsidence to the value provided in the ASCE Tsunami Geodatabase of 3.33 ft or 1.01 m.

Figure A1. Location of the Stevens Elementary School (SES) site (Blue rectangle), the offshore ASCE OTA stations 90-143 (numbered circles) and the Miller, et al., 2018 *SLR* station closest to the VES site (blue diamond).

Table A1. Summary of Scenario input and output parameters, including the MCT for this study, Scenario D. All Scenarios used ASCE-compatible sources; however, only the MCT Scenario D is ASCE-compatible because it accounts for *SLR*. The first 2 columns, *Sc* and *N*, provide the scenario and source model designations, respectively. All source models except Source 2 are based on the L1 seismic model in which uplift and subsidence values are multiplied by the factors *up* and *sb*, respectively; Scenario C uses Source 2, the model developed by Wei et al., (2017). Simulation output was recorded by gauge 501 at the VES site shown in Figure 1. The parameters B_0, ΔB and B are the initial, co-seismic vertical displacement, and final values of the topography referenced to *MHW*, respectively. *SLR* is the sea level rise projected over 75 years. The next 4 columns provide maximum values (denoted by a caret over the parameter symbols) recorded during the entire 6-hour simulation -- they are: $\widehat{h}$, the flow depth referenced to the local topography; $\widehat{s}$, the current speed; $\widehat{\phi}$, the momentum flux, and $\widehat{\eta}$ the wave amplitude referenced to *MHW*. The minimum height (*MH)* and minimum build elevation (*MBE)*, are quantities derived from the model output and are

Scenario	Source Model			Site Ground Deformation			*SLR* (m)	Simulation Output				*MH* Computations				
	N	up	sb	B_0 (m)	ΔB (m)	B (m)		$\widehat{h}$ (m)	$\widehat{s}$ (m/s)	$\widehat{\phi}$ (m^3/s^2)	$\widehat{\eta}$ (m)	*S (m)*	*MH (m)*	*MH* (ft)	*MBE (m)*	*MBE (ft)*
A	0	1.000	1.000	1.27	-2.76	-1.49	0.00	2.23	0.99	1.91	0.73	3.05	5.49	18.01	6.76	22.18
B	1	1.172	1.000	1.27	-2.76	-1.49	0.00	2.32	1.02	2.17	0.81	3.05	5.59	18.35	6.86	22.52
C	2	1.000	1.000	1.27	-0.42	0.85	0.00	0.19	0.17	0.00	1.03	3.05	3.54	11.61	4.81	15.78
D	1	1.172	1.000	1.27	-2.76	-1.49	0.37	2.75	1.20	3.75	1.25	3.05	6.17	20.23	7.44	24.40
E	3	1.172	0.367	1.27	-1.01	0.26	0.00	0.59	0.36	0.03	0.83	3.05	3.87	12.70	5.14	16.87

Figure A2 compares OTA values for Sources 1 and 2 against the ASCE OTA data, demonstrating that that OTA Criteria 2 and 3 are satisfied by each source. For this ASCE OTA criteria test, the GeoClaw model resolution was set to 6 arc-seconds, i.e., (longitude, latitude) = (6", 6") = approximately (127 m, 185 m).

Although Sources 1 and 2 are both ASCE-compatible, they are quite different; this can be seen in the deformation patterns for the two Sources presented in Figure A3 for comparison. As discussed in Adams, et al. (2019b), there are multiple extrema in the deformation field of Source 2 that may be artifacts of slip discontinuities and mismatches at sub-fault edges. Moreover, the slip of Source 2 was placed primarily on the subfaults farther offshore (closer to the trench), which resulted in the associated subsidence being shifted farther off-shore relative to Source 1; Source 2 also caused considerably less subsidence at the VES site than Source 1 (Table A1). As a consequence of these differences, the potential impact on the Washington coast and on the Aberdeen VES site by Source 2 is less severe.

Because Source 1 has a greater impact on the VES site than Source 2 and because Washington State has used the L1 source in a number of tsunami hazard assessment studies, we did not use Source 2 to develop an ASCE-compatible MCT scenario. Rather, as indicated in Table A1, Source 1 was used to develop Scenario D, the ASCE-compatible MCT Scenario, by including the effects of *SLR* (see Section A.2).

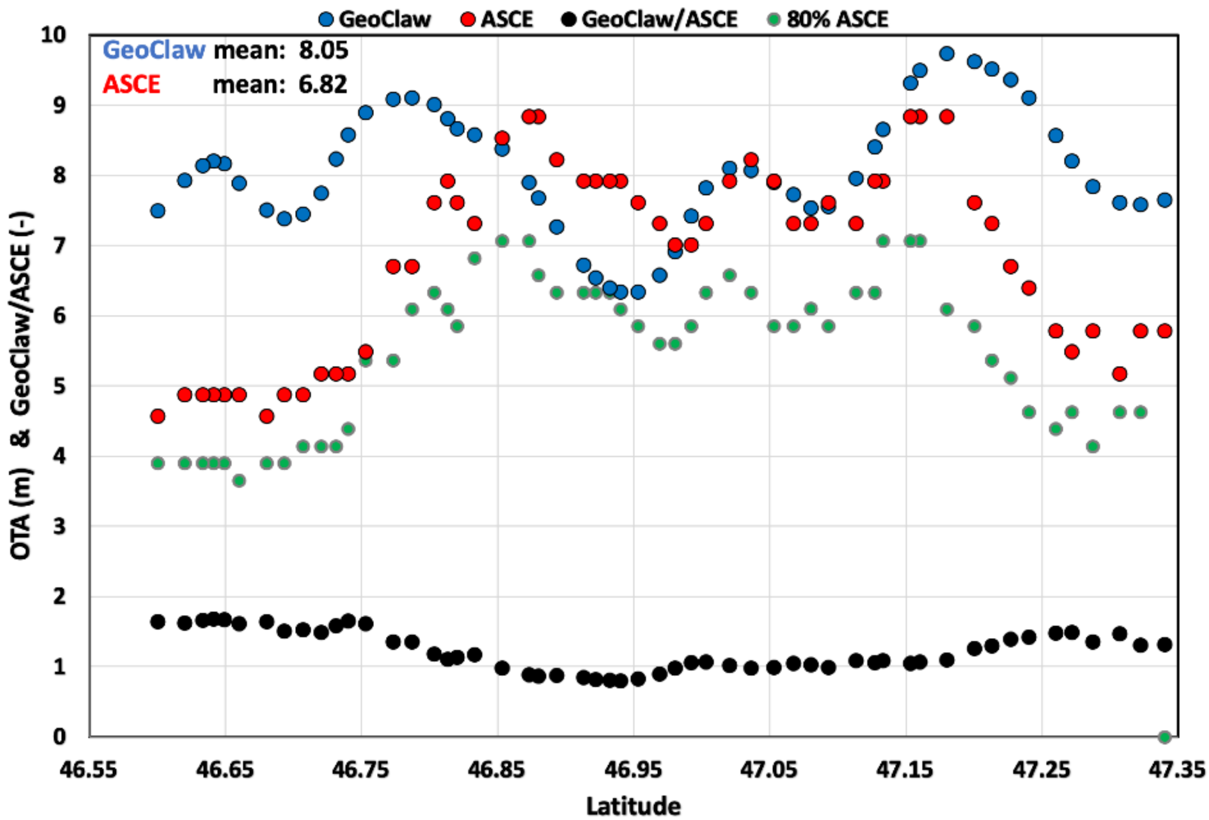

Figure A2. MCT Scenario D Offshore Tsunami Amplitude (OTA) values for the GeoClaw model and the ASCE online database at the offshore positions shown in Figure A1, illustrating that Criteria 2 and 3, above, are satisfied.

A few features of Source 1 are noteworthy. For 54 gauges spanning 80 km centered on the VES site latitude, the Source 1 mean OTA is 18% greater than the mean ASCE OTA. Note, however, that for 41 gauges spanning 60 km centered on the VES site latitude the Source 1 mean OTA is only 10% greater than the mean ASCE OTA (not shown in Figure 2A). The 10% value is more relevant here, since the importance of OTA on the VES site likely decreases with north-south distance from the VES latitude. In the study by Adams, et al., (2020) the MCT source OTA was found to be conservative by 25%, but it was approved by ASCE TLES members and community officials. It thus appears that the 10-18% conservativism of Source 1 is acceptable.

Second, the uplift of subsidence of Source 1 is mulitplied by 1.172 but the subsidence is not and the original subsidence values are retained. Note that this is geophysically questionable, because it implies that the processes of uplift and subsidence during a seismic event are independent. But the subsidence of 2.76 m at the VES site appears too large in the context of recent peer-reviewed literature on the topic of Cascadia coseismic coastal deformation. Adams, et al., (2020) provide a brief review of the literature on this topic that suggests an upper limit for subsidence is likely in the range of 1-2 m; Wang et al. (2013) provides a a more comprehensive review. Because the 2.49 m subsidence at their VES site was also above this range limit, they also used Source 1 of this study for their MCT scenario and showed by comparison with a source

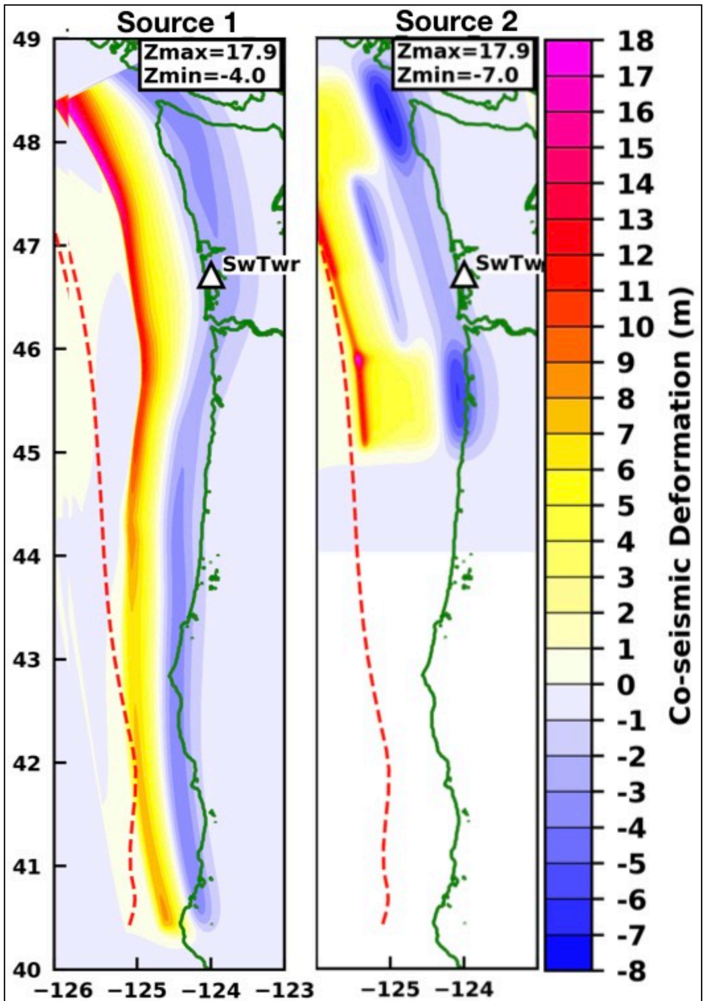

Figure A3 Sources 1 and 2 deformation fields, in which warm colors are uplift and cool colors are subsidence. Source 1 is a modified version of the Witter et al. (2018) L1 seismic model and source 2 was developed by Wei, et al., (2017).

for which both uplift and subsidence were multiplied by 1.172 that it made essentially no difference in the VES site time series of the flooding, current speed and momentum flux (*h*, *s*, *ϕ*) at the VES site. Because of the Adams, et al., 2020 result, because multiplying Source 1 subsidence by 1.172 would result in a subsidence of 3.23 m at the VES site that exceeds this estimated upper limit even more and render the resulting source also geophysically questionable, and because there is significant and inherent uncertainty in seismic source specification, Source 1 was used for the development of the MCT scenario.

A.2 Compliance with Sea Level Rise Criteria

Although Source 1 conforms to the ASCE OTA criteria and is therefore ASCE-compatible, a *Scenario* must also account for projected *SLR* over the project lifecycle in order to be ASCE compatible. ASCE 7-16 Section 6.5.3 states that *"The direct physical effects of potential relative sea level change shall be considered in determining the maximum inundation depth during the project lifecycle. A project lifecycle of not less than 50 years shall be used."* The project lifecycle for this project was chosen to be the design life of the VES, i.e., 75 years. Assuming construction is completed in 2020, the *SLR* projection corresponds to the year 2095.

The projections of Miller, et al. (2018) are summarized in a series of excel files that can be downloaded at http://www.wacoastalnetwork.com/wcrp-documents.html . They were produced for each of 171 coastal locations on a 0.1-degree grid for two greenhouse gas Representative Concentration Pathway (RCP) scenarios corresponding to low and high levels of emissions designated as RCP 4.5 and RCP 8.5, respectively.

The Excel file corresponding to the high greenhouse gas emission scenario RCP 8.5 for the coastal station closest to the VES site (47.0 N, 123.8 W) was used. The original projections are given as *SLR* values in feet that are associated with probabilities that range from 0.1% - 99% that a value will be exceeded by a given year ranging from 2010 - 2150, in decadal increments. The range of probabilities were those identified in the study as members of the "likely" category. For the ASCE-compatible Scenario D, this hazard assessment study chose to use the intermediate "Central Estimate" of 50% as the probability that *SLR* will exceed a given value over the next 75 years. The value for 2095 of 1.2 ft (0.37 m) was obtained by linear interpolation between 2090 and 2100.

Coastal uplift (or, less likely, subsidence) can occur between earthquakes, as part of the "earthquake deformation cycle" and can be an important component of the apparent changes in background sea level changes. Typically, a subduction zone earthquake creates sudden coastal land subsidence, which is then followed by decades or centuries of slow coastal land uplift. Miller et al. (2018) take this interseismic land deformation into account and thus formally designate their estimates as "Relative Sea Level Change." ASCE 7 guidance uses this formal term in definitions, but Sea Level Rise in discussion of criteria. Since only sea level rise occurs in the region of interest, we adopt the term Sea Level Rise (*SLR*).

For compatibility with ASCE 7, Section C6.5.3 suggests the historic sea level trend presented by https://tidesandcurrents.noaa.gov/sltrends/sltrends.html be used for a minimum 50 year life cycle. The nearest NOAA Sea Level Trend Station is at Toke Point and the trend is given as 0.43 mm/year with a confidence interval of +/- 0.85 mm/year, for a maximum trend of 1.28 mm/year that results in a 75-year projection of 96 mm, much less than the 370 mm projection used here.

A.3 Determination of *MH,* the Minimum Height of the Lowest Occupiable Level

It is essential to have a value for the minimum *height* of the lowest refuge level (*MH*) before construction as part of the required input to the design of the structure. ASCE 7-16 does not provide such an expression explicitly, but it can be derived from the definition of the minimum *elevation* (*ME*) of the lowest refuge level defined in Section 6.14.1 *"Minimum Inundation Elevation and Depth"* of ASCE 7-16, which states that

> *"Tsunami refuge floors shall be located not less than the greater of 10 ft (3.05 m) or one-story height above 1.3 times the Maximum Considered Tsunami inundation elevation at the site as determined by a site-specific inundation analysis, as indicated in Fig. 6.14-1."*

Thus *ME*, the minimum *elevation* of the lowest refuge level, is defined as

$$ME = 1.3\,\hat{\eta} + S \qquad (1)$$

where the overhead caret symbol is adopted to denote maximum values of parameters, so that $\hat{\eta}$ is the maximum inundation *elevation* referenced to *MHW*, and S = max(10 feet, 1 story) is a safety factor.

Note that a distinction is made between *elevation* and *height* or *depth* levels throughout Chapter 6 of ASCE 7-16; levels referenced to *MHW* are designated *elevations* and levels referenced to the grade plane (*GP*) are designated *heights* or *depths*. Thus, the required *MH* is referenced to the *GP* and, for pre-construction design purposes, we need an expression of *MH* as a function of the site-specific modeling results. (Since the exact grade plane elevation, *GP*, is unknown before construction, we assume in what follows that *GP* is coincident with the existing local topography and we caution that any changes to the existing local topography that creates a non-coincident *GP* must be taken into account when computing the *MH*.)

The physical setting for (1) is illustrated in Figure A6, which reproduces a revised version of Figure 6.14.-1 provided in the ASCE 7 Change Proposal Form, *File TS-CH06-04r00, Relating to revising the*

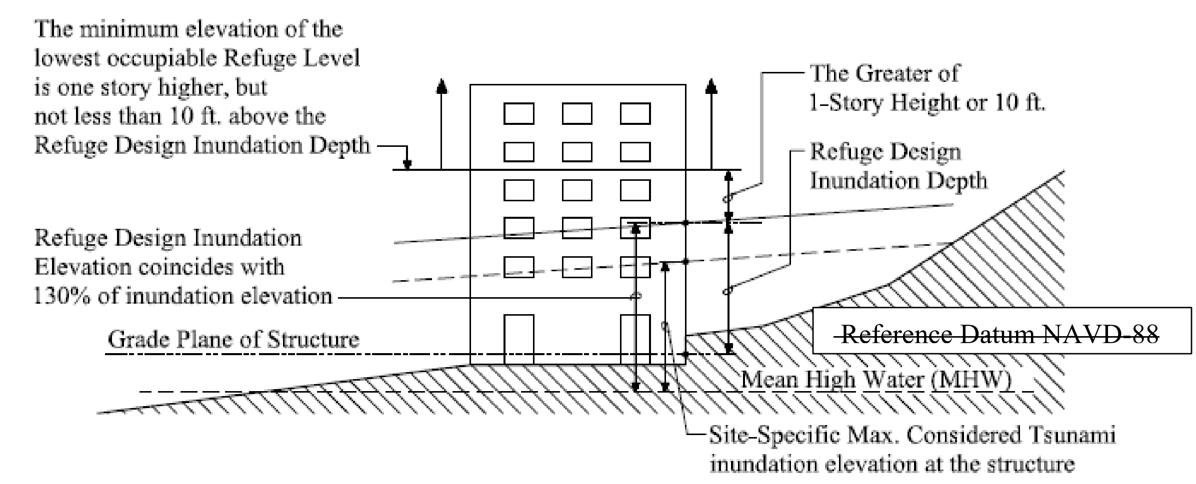

FIGURE 6.14-1 Minimum Refuge Level Elevation [1 ft = 0.305 m]

Figure A6. Reproduction of Figure 6.14-1 as presented in ASCE 7 Change Proposal Form, identified as *File TS-CH06-04r00, Relating to revising the reference datum from NAVD88 to Mean High Water (MHW)*. Strike-throughs denote the existing ASCE 7-16 text and underlines denote proposed changes to the existing text to be published in the revised 2022 version, i.e., ASCE 7-22

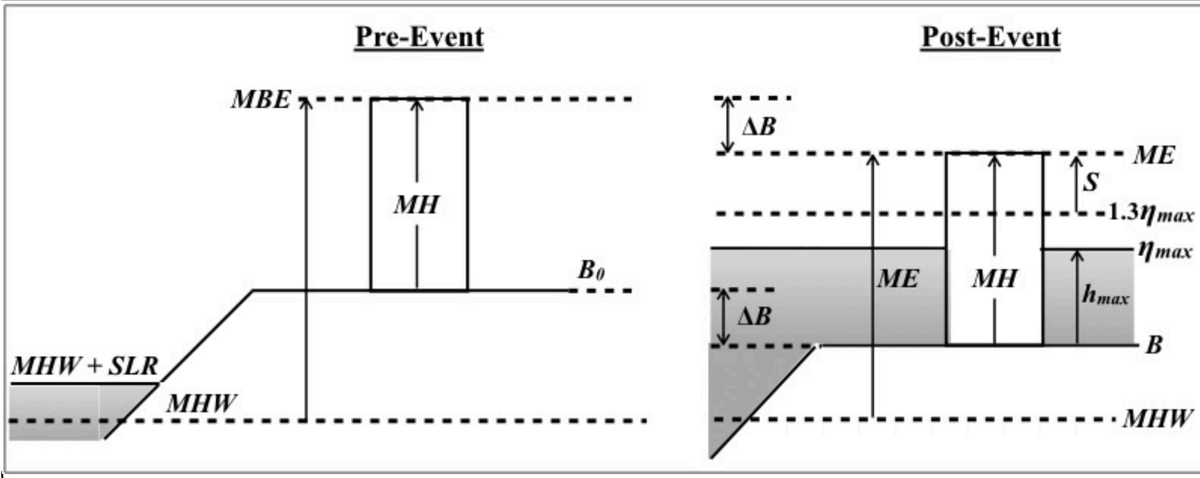

Figure A7. Left: Pre-Event geometry, showing VES minimum *height* to the lowest refuge level, *MH,* referenced to local topography, B_0. (Local grade plane level, *GP,* is assumed accounted for by B_0.) Before performing the tsunami simulation, water level is adjusted to include *SLR*. **Right:** Post-Event geometry with co-seismic subsidence $\Delta B < 0$. Here $B = B_0 + \Delta B$ is the subsided elevation, and $\hat{\eta}$ is the maximum tsunami *inundation elevation* at this location. **Note:** *Inundation elevation* η is related to the *inundation depth, h,* by $\eta = h + B$ and the values B_0, B, η, *ME*, and *MBE* are all *elevations* relative to the unchanging vertical datum *MHW*, while *MH* and *h* are respectively a *height* and water *depth* referenced to the local topography. This figure is for the case when $\Delta B < 0$ and the subsided topography is still above MHW, but the formulas hold in other cases as well, including $\Delta B \geq 0$.

reference datum from NAVD88 to Mean High Water (MHW). This document was submitted to the ASCE 7 Main Committee on 9/13/2018 to propose the following revision to ASCE 7-16

> *INUNDATION ELEVATION: The elevation of the design tsunami water surface, including relative sea level change, with respect to vertical datum* <u>*at*</u> ~~*in North American Vertical Datum (NAVD 88*~~ <u>*Mean High Water (MHW)*</u>*.*

in which strike-throughs denote the existing ASCE 7-16 text and underlines denote the proposed changes to be published in the revised 2022 version, i.e., ASCE 7-22. Note that the above definition of *inundation elevation* requires that *relative sea level change* must be taken into account. In this study, the change is due to sea level rise, *SLR*. Therefore, with regards to equation (1), it is important to note that

(a) it accounts for both co-seismic deformation and *SLR* because the numerical simulation of all scenarios is conducted with the co-seismic deformation inherent in the earthquake source and the initial water level adjusted by *SLR,* and

(b) it applies specifically to the Post-Event situation, i.e., after the tsunami has flooded the site to the maximum depth, $\hat{h}$, and after any alteration of the VES site topography has occurred by co-seismic deformation, and that

(c) if co-seismic deformation does move the structure vertically with respect to the constant reference level, *MHW* in this study, then the Pre-Event value of ME will differ from the Post-Event value by the local deformation, ΔB (as determined in the discussion that follows).

Figure A7 schematically illustrates the Pre- and Post-Event situation at the VES site and we first examine the Post-Event panel on the right, in which we see that the minimum *elevation* of the lowest refuge level (*ME*) has been constructed according to the definition given by (1) and that the minimum height, *MH,* is given by

$$MH = ME - B$$

To obtain *MH* as a function of the site-specific inundation modeling output, we insert equation (1) for *ME* to obtain

$$MH = 1.3\,\hat{\eta} + S - B \qquad (2)$$

as the minimum *height* of the lowest occupiable refuge level, *MH*, in an expression that allows computation and use in the design process before construction. It is important to note in Figure A7 that the maximum depth of the water is $\hat{\eta}$ minus the post-quake elevation of the site, *B*, and that when computing this depth (and the required height of the first occupiable level of the VES), one must use the post-quake (subsided) site elevation *B*, not the initial pre-quake elevation, B_0.

Turning to the Pre-Event panel we see that, once the structure has been built, the minimum *build elevation* of the lowest refuge level, here designated *MBE*, will be

$$MBE = MH + B_0$$

and by inserting (2) for *MH* and using $B = B_0 + \Delta B$, we obtain *MBE* in terms of the site-specific modeling results as

$$MBE = 1.3\,\hat{\eta} + S - \Delta B$$

or, using (1)

$$MBE = ME - \Delta B$$

which, as mentioned above, identifies the difference between Pre- and Post-Event *ME* values as the local deformation value, ΔB. In the case of subsidence, $\Delta B < 0$ and so $MBE > ME$; with this in mind, we can see this graphically by comparing the Pre- and Post-Event panels in Figure A7.

Table A1 provides *MH* and *MBE* for the Scenarios developed during this study and described in Section A.1. As indicated in Table A1, the *MBE* value for Scenario D, the MCT for this study, is 7.44 m or 24.40 ft.