

Long Beach Berm Modeling Study***Frank I. González¹, Randall J. LeVeque²*****University of Washington Tsunami Modeling Group****UW Departments of****¹Earth and Space Sciences and ²Applied Mathematics**

Abstract. A berm design was developed for compatibility with guidelines published by the Federal Emergency Management Agency (FEMA) for vertical evacuation structures; the design utilized the maximum flooding depth results of a previous modeling assessment of the Long Beach berm site (FEMA, 2012; González, et al., 2013). Recently, the American Society of Civil Engineers (ASCE) published new ASCE 7-16 guidelines that are expected to be adopted in the near future for tsunami vertical evacuation structures (ASCE, 2017). One major difference between the FEMA and ASCE guidance is that ASCE 7-16 imposes exceedance criteria on the maximum wave height values offshore at the 100 m isobath (the “eta100 criteria,” see Appendix A). Tests of the berm design for both FEMA and ASCE minimum height criteria were conducted with the GeoClaw model (Berger, et al., 2010; LeVeque, et al., 2011; Gonzalez, et al., 2011; NOAA, 2011). Several issues arose in the interpretation and application of ASCE 7-16 in the context of hydrodynamic models that provide two-dimensional solutions of tsunami flow depth and other parameters. Nonetheless, we conclude that the new berm design is not compliant with ASCE 7-16 minimum berm height criteria, and is marginally compliant with the FEMA (2012) criteria that guided the berm design.

Background

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 Long Beach and other Washington Pacific coast communities within tens of minutes after the earthquake main shock.

In 2012, the Project Safe Haven planning process resulted in a proposal by the Long Beach School District to construct a vertical evacuation berm behind the Long Beach Elementary School (Project Safe Haven, 2011a). Consequently, the Washington Emergency Management Division funded a study to assess the tsunami hazard at the proposed berm site. This GeoClaw modeling study produced estimates of the maximum flooding and current speeds at the berm site for two earthquake scenarios, a magnitude 9.2 (9.2M) event on the Alaska Aleutian Subduction Zone (AASZ) and a 9M event on the CSZ (Gonzalez, et al., 2013).



Figure 1. Berm location. Small white rectangle is the fine resolution berm DEM, large white rectangle is a coarser grid, designated LB02. North is up. White dot is 2013 berm location. The Long Beach School campus buildings are just east of the berm site.

Subsequently, the City of Long Beach was awarded a FEMA grant for construction of a vertical evacuation berm and PND Engineers were contracted to oversee the berm design and construction (City of Long Beach, 2016a). PND developed a new berm design that differed significantly from the 2013 version, and a new location was selected about 50 m southwest of the original 2013 berm site. Figure 1 presents the Long Beach Elementary School campus and the location and footprint of the PND berm design.

An Environmental Assessment Report was prepared and published in November 2016 (City of Long Beach, 2016b) and FEMA announced a public review period of 28 November - 30 December 2016. On 29 December, FEMA received comments from the lead author of ASCE 7-16 that questioned the new berm design, noting that ASCE 7-16 contained new structural design guidance for vertical evacuation structures that would likely be adopted in the future, superseding the 2012 FEMA guidance. On 28 June 2017, the Mayor of Long Beach submitted a request to the WA Emergency Management Division (EMD) for guidance and assistance in resolving the issue of design criteria for the Long Beach berm. On 21 August 2017, approval was received from the Long Beach mayor for a University of Washington study, specifically to test the new berm design against ASCE 7-16 design criteria.

Minimum Height Requirements

This study focuses on testing the conformance of the berm design with Minimum Height requirements for vertical evacuation structures that are recommended by FEMA (2012) and ASCE 7-16. The FEMA (2012) criteria are given in Section 5.3 Elevation Considerations, as

“The recommended minimum freeboard is one story height, or 10 feet (3 meters) above the tsunami runup elevation used in tsunami force calculations. The recommended minimum elevation for a tsunami refuge area is, therefore, the maximum tsunami runup elevation anticipated at the site, plus 30%, plus 10 feet (3 meters). This should be treated as an absolute minimum, with additional conservatism strongly encouraged.”

and by ASCE7-16 as

“6.14.1 Minimum Inundation Elevation and Depth. Tsunami refuge floors shall be located not less than the greater of 10 ft (3.05 m) or 1-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. This same Maximum Considered Tsunami site specific inundation elevation, factored by 1.3, shall also be used for design of the Tsunami Vertical Evacuation Refuge Structure in accordance with Sections 6.8 to 6.12.

The 3.05 m freeboard recommendation in both 2012 FEMA and 2017 ASCE guidance is due to physical/engineering reasoning that this represents the height of one story in a typical building and, since any inundation of that building level will render occupation of that level unsafe, then the refuge must be on the building floor above that inundated level.

The 1.3 amplification factor is recommended by 2012 FEMA because “Determination of a suitable elevation for tsunami refuge must take into account the uncertainty inherent in

estimation of the tsunami runup elevation ...” A more physical/engineering rationale is given by 2017 ASCE, stating that the purpose of this factor is to “... account for additional buildup of water level at the forward edge of the building ...” (ASCE, 2017 Commentary, Section C6.10.2.2 Drag Force on Components) and adding that “... the additional 30% factor is consistent with the skill level of present-day tsunami inundation models ...” (ASCE, 2017 Commentary, Section C6.14 Tsunami Vertical Evacuation Refuge Structures).

In addition to these two safety factors, 2017 ASCE also sets criteria on the maximum offshore tsunami amplitude, η , at the 100 m isobath, i.e., the “ η_{100} criterion,” discussed below and in Appendix A.

The GeoClaw Model

To meet the goal of this study, above, simulations of tsunami generation, propagation and inundation were conducted with the GeoClaw model, which solves the nonlinear shallow water equations; the code features high-resolution shock-capturing finite volume methods and adaptive mesh refinement (Berger, et al., 2011). GeoClaw has undergone extensive verification and validation (LeVeque and George, 2007; LeVeque, et al., 2011), including multiple benchmark tests as part of a U.S. National Tsunami Hazard Mitigation Program (NTHMP) benchmarking workshop (NTHMP, 2012).

- Bathymetric/Topographic Digital Elevation Models (DEMs)

Digital elevation models (DEMs) of integrated bathymetry and topography information are essential input to the GeoClaw model. This study employed DEMs that included the most recently released 1-minute resolution ETOPO1 data and the 1/3 arc-second DEM known as “Astoria V3”, both downloaded from the website of the National Centers for Environmental Information (NEIC), part of the National Oceanic and Atmospheric Administration (NOAA).

Note that the Astoria V3 DEM is different from the version used in the 2013 modeling. The Astoria DEM available for the 2013 study was found to contain numerous artifacts in the Long Beach area. DNR, working with NGDC, determined that lidar data had not been properly cleaned and contained tree tops and buildings in this region. A modified DEM was provided by DNR for a limited region around the berm site, which was combined with the Astoria DEM elsewhere. Since the completion of the 2013 study, the official Astoria DEM has been modified in the entire Long Beach area. Around the berm site it is very similar to the topography used in 2013, although not identical.

PND provided a DEM of their berm design at a resolution of 1/60 arc-sec, and Table 1 summarizes the characteristics of the DEM. The berm resolution of 1/60 arc-sec at the berm latitude is equivalent to a (longitude, latitude) computational cell size of approximately (0.34 m, 0.51 m) over the berm extent. This DEM was interpolated to a resolution of approximately (0.13 m, 0.20 m) for use in the GeoClaw model (Figure 2).

The PND berm design height above the “Grade Plane” (see definition in Section 6.2, ASCE 7-16) was not provided, so we must estimate this value, because the 2012 FEMA and 2017 ASCE guidance defines the Minimum Vertical Evacuation Structure Heights in terms of

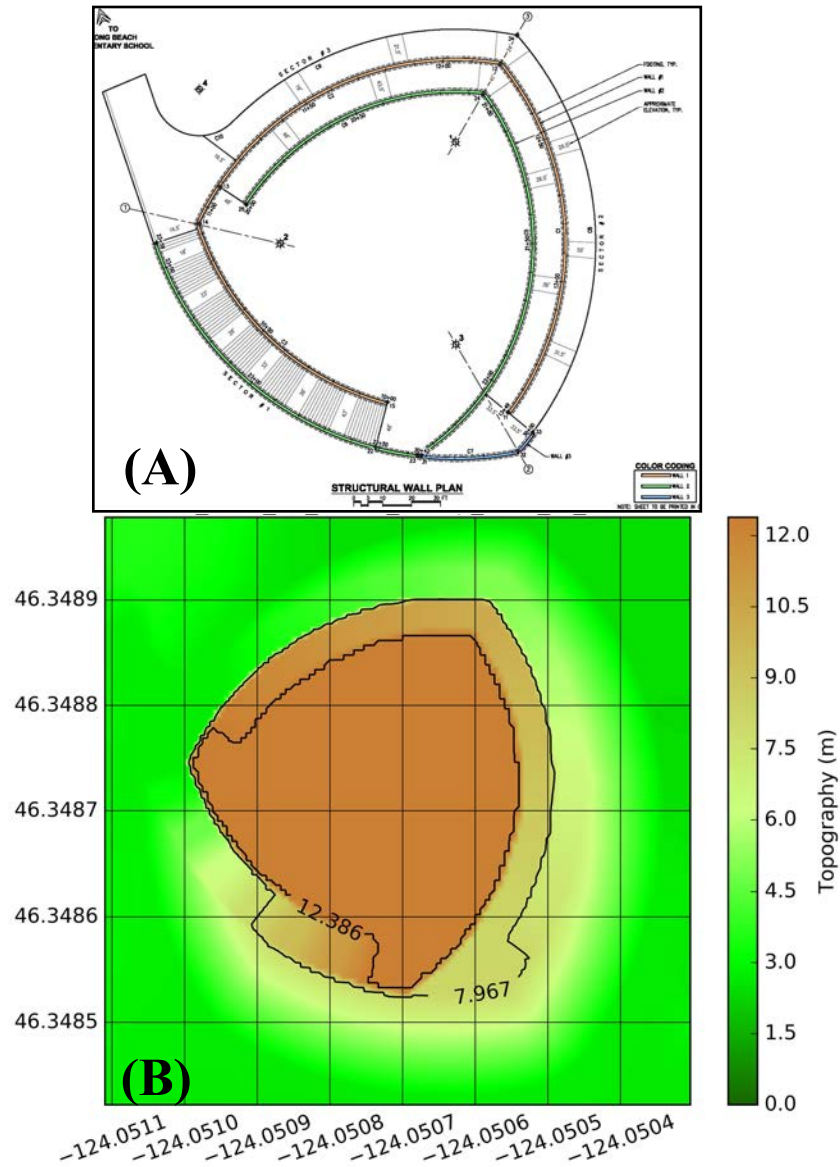


Figure 2. (A): PND berm plan view and elevation (m) with respect to local grade. **(B):** Berm DEM, interpolated to a spatial resolution of approximately 0.13 m.

maximum inundation depth and berm height, both referenced to the Grade Plane level. Table 2 summarizes this estimate, in which we first define the Grade Plane as the mean value of the original topography that underlies the 2,673 square meter area of the berm DEM; this value was $2.76 \text{ m} \pm 22 \text{ cm}$, referenced to mean high water (MHW). Next, because the berm DEM assigns the value 12.39 m above MHW as the maximum height at the flat top of the berm, we take the height of the berm referenced to the local Grade Plane as $12.39 - 2.76 = 9.63 \text{ m}$.

However, we note that PND states the intended berm height is “approximately 32 feet” or about 9.75 m, and describes site preparation as a process in which, after some excavation “... structural fill would be placed over an area of approximately 30,500 square feet to restore

Table 1. Characteristics of PND Berm DEM. The naming convention is (x,y) for (Longitude, Latitude).

Quantity	Units	Variables	Value	Value
x Extent	deg	x1,x2	-124.05111	-124.05055
y Extent	deg	y1,y2	46.34842	46.34898
Resolution	deg	dx, dy	4.6296296296E-06	4.6296296296E-06
Resolution	arc-sec	dx, dy	1.6666666667E-02	1.6666666667E-02
Resolution	m	dx, dy	0.35514	0.51450
Dimensions	deg	DX, DY	0.00056	0.00056
Dimensions	m	DX, DY	42.96	62.23
Dimensions	ft	DX, DY	140.94	204.18
Area	m**2	A	2673.45	
Area	ft**2	A	28776.06	

Table 2. Computation of Berm height referenced to Grade Plane, using the Berm DEM and original underlying topographic DEM. Nonetheless, the intended height of 9.75 m is used in computations of compliance with 2012 FEMA and 2017 ASCE. below. See discussion. above.

Height (m)	Height (m)
2017 DEM Berm height, referenced to MHW	12.39
"Grade Plane" referenced to MHW, computed as the mean value of the original topography that underlies the Berm DEM	2.76
Berm height referenced to Grade Plane (DEM Berm height - Grade Plane)	9.63

the original grade level" (see Section 3.3, City of Long Beach, 2016b). This intended height of 9.75 m is 12 cm more than the estimate in Table 2 but within the ± 22 cm uncertainty of the Grade Plane estimate based on the DEM and our definition of the Grade Plane level. Since, presumably, the final berm height can be controlled during construction, in the computations that follow we assume that the construction of the berm would produce the intended height of 9.75 m with respect to the Grade Plane and that the Grade Plane is itself at least 2.76 m above MHW.

- Earthquake Scenarios

Specification of the tsunami generation process is also a critical input to the GeoClaw model. This study used the L1 earthquake scenario developed by Witter, et al (2013); this M9 earthquake on the CSZ is one of 15 peer-reviewed seismic scenarios used in a hazard assessment study of Bandon, OR, and is based on an analysis of data spanning 10,000 years. The length and width of L1 are approximately 1000 km and 85 km, respectively, and salient features of the earthquake crustal deformation (and therefore the sea surface and land deformation) are the coastal subsidence at Long Beach of about 2 m and a north-south zone of more than 10 m maximum tsunami wave height about 100 km west of the Berm site (Figure 3). This L1 scenario is in use by Washington State for previous tsunami hazard assessment studies because (a) the resulting inundation line is interpreted as the 95% confidence level that the inundation will not be exceeded (Witter et al., 2013) and (b) although there is significant uncertainty in the average return period of the L1 scenario, based on a simple analysis of the evidence presented by Witter et al. (2013), a range of 1990–3300 years seems reasonable (R. Witter, personal communication) and brackets the commonly used 2500-year hazard mitigation planning horizon.

A modified version of L1, L1x1.11, was also used, in which L1 was multiplied by 1.11 to meet the ASCE 7-16 criteria for the maximum offshore tsunami amplitude, η , at the 100 m isobath, i.e., the “ η_{100} criterion.” This criterion and the resulting η_{100} values produced by the L1x1.11 source are described in Appendix A. We note here that multiplying the entire L1 deformation field by a single constant factor increases both the initial offshore tsunami wave height and the degree of coastal subsidence and that, in turn, each of these effects tend to increase the maximum inundation flood depth.

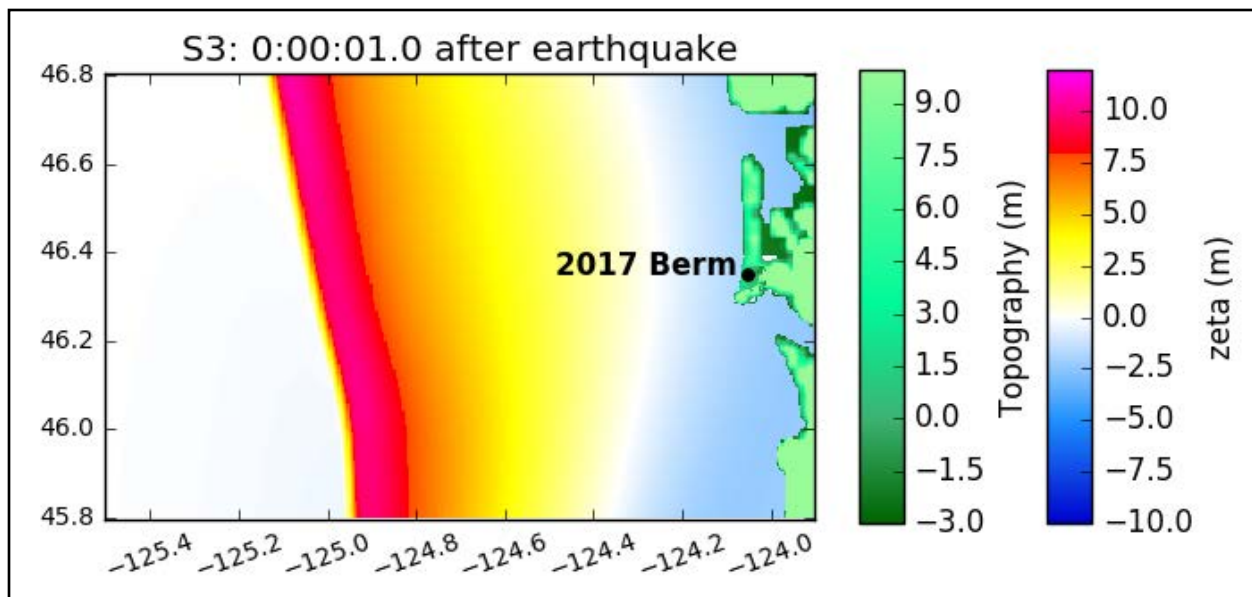


Figure 3. L1 earthquake scenario at 1 second after the main shock, illustrating the sea surface and land deformation.

Study Simulations

Check of 2013 Simulation

Originally, a single simulation was planned to test conformance of the berm design with ASCE 7-16 guidance. However the berm design was found to be out of compliance with ASCE 7-16 in this first simulation, identified as Scenario 1 (S1). Therefore, in light of the significant time and effort expended to reach this point in the Long Beach Berm Project (City of Long Beach, 2016a), Scenario 2 (S2) was developed to check the results of the 2013 GeoClaw Bare Earth study on which the new berm design was based. This test scenario used the latest version of the GeoClaw software, but with the 2013 input — i.e., with the 2013 DEMs for bathymetry/topography and the 2013 internal GeoClaw model settings such as the computational domain extent, the levels of Adaptive Mesh Refinement (AMR) and resolution, friction, dry cell tolerances, etc.

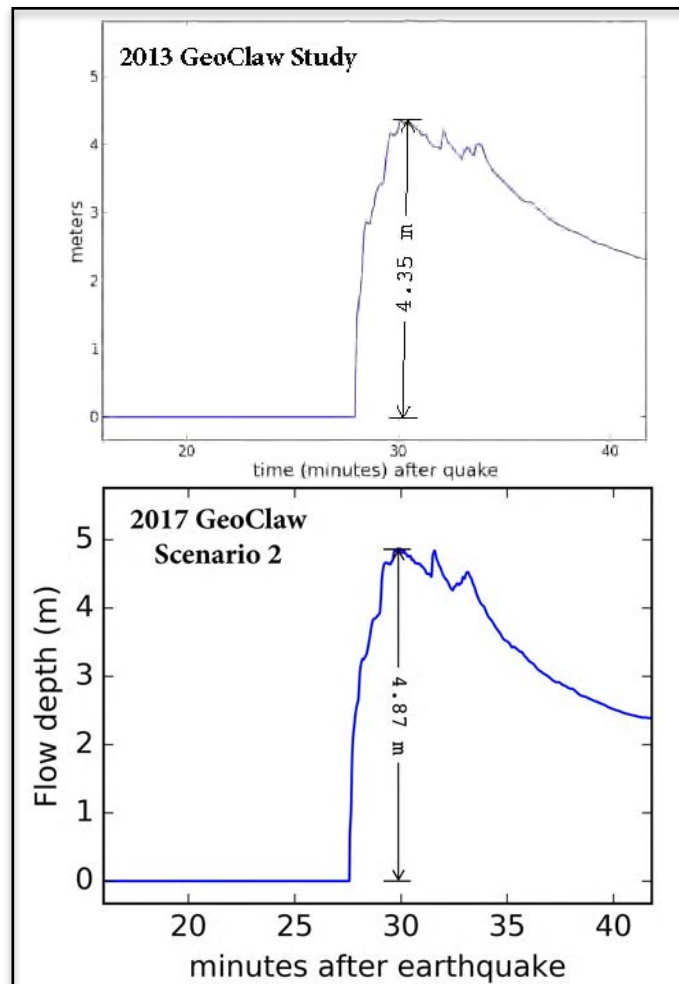


Figure 4. Scenario 2 results — a check on 2013 computations of Bare Earth inundation depth at the 2013 berm site. **Top:** 2013 GeoClaw Bare Earth time series from the original study. **Bottom:** 2017 GeoClaw time series result from this study.

Scenario 2 results are presented in Figure 4. There is an almost exact correspondence in the temporal evolution of inundation depth, but the Scenario 2 maximum inundation depth is about 12% higher than in the 2013 study. Because there are numerous factors that might be responsible for this difference, an investigation of the specific factor or combination of factors responsible would likely be very time-consuming to pursue and is beyond the scope of this study. However, since Scenario 2 used the latest version of GeoClaw, this difference is likely due to the changes and improvements in the GeoClaw software since 2013, and we have confidence in the results of the four simulations, described next.

Bare Earth and Berm Simulations

Structure/tsunami interactions can be extremely important and should always be included when possible; even though such modeling is not mentioned in ASCE 7-16, it may be included in the future because the ASCE 7-16 criteria continue to be clarified and modified by the ASCE 7-16 Panel. However, only Bare Earth modeling results are referenced in the 2017 ASCE design criteria sections, so we developed three more simulations to complete a four-member set of scenarios (S1, S3, S4, S5) for each combination of the two sources (L1x1.11 or L1) and the two physical settings (Berm or Bare Earth). All were conducted with the 2017 GeoClaw software, GeoClaw internal settings and the latest bathy/topo DEMs. Table 3 summarizes the most important features of each scenario, including the purpose of each and the general result of the simulation.

Results and Discussion

Table 4 presents the minimum berm height computations using the criteria presented in the 2012 FEMA and 2017 ASCE guidance (see discussion, above, and Appendix A), the intended berm height of 9.75 m, and the maximum inundation depths obtained in each scenario.

There is substantial variation in the maximum inundation depth over the extent of the Berm DEM and neither 2012 FEMA nor 2017 ASCE provide specific guidance as to which value should be used. Table 4 entries for maximum inundation depth were obtained by first saving the maximum value of inundation depth recorded at each computational cell of the extent of the Berm area during the duration of each simulation, then finding the largest of all these maximum values. In the Bare Earth scenarios, S4 and S5, this resulted in maximum inundation depths that were displaced toward the lower right corner of the Berm DEM; this seemed questionable as a measure of tsunami impact on the berm, so the maximum value at the center of the Berm DEM was also computed; both values are entered in the Bare Earth scenario columns for comparison.

Bare Earth Simulation Results

Scenario 5 is the only scenario in which the berm design is compliant, if the lower value of maximum inundation depth at the center of the berm is taken; this is perhaps unsurprising, since this scenario represents the criteria under which the berm was designed, i.e., the 2012 FEMA Bare Earth L1 scenario. This compliance corresponds to a very small freeboard margin

Table 3. Summary of simulations conducted for this study. The column “GeoClaw settings” refers to internal numerical model details such as computational domain extent, levels of Adaptive Mesh Refinement (AMR) and resolution, friction, dry cell tolerances, etc.

Simulation	Purpose	Source	Bathy/ Topo	GeoClaw settings	Berm or Bare Earth	Result
Scenario 1	Test Compliance with 2017 ASCE Minimum Height	L1x1.11	2017	2017	2017 Berm	Berm design is non-compliant by 4 meters
Scenario 3	Test Compliance with 2012 FEMA Minimum Height	L1	2017	2017	2017 Berm	Berm design is non-compliant by 2.4 meters
Scenario 4	Test Compliance with 2017 ASCE Minimum Height	L1x1.11	2017	2017	Bare Earth	Depending on the maximum inundation height estimate used, the Berm design is non-compliant by 0.9 - 1.6 meters
Scenario 5	Test Compliance with 2012 FEMA Minimum Height	L1	2017	2017	Bare Earth	Depending on the maximum inundation height estimate used, the Berm design is compliant by 0.1 meters or non-compliant by 0.3 m

Table 4. Computations of Minimum Berm Height and Berm Design Compliance. The design Berm height was assumed to be 9.75 m, even though an estimate based on the berm DEM produced a value of 9.63 m (see Table 2 and discussion, above). Maximum Inundation Depth was obtained from computations summarized graphically in Figures 5-8; two values are entered for Bare Earth scenarios, corresponding to the largest maximum over the entire Berm DEM and the maximum value at the center of the Berm DEM.

Parameters (m)	S1 2017 ASCE L1x1.11 Berm (m)	S3 2012 FEMA L1 Berm (m)	S4 2017 ASCE L1X1.11 Bare Earth (m)	S5 2012 FEMA L1 Bare Earth (m)
Max Inund. Depth <i>Over Entire Berm DEM</i> <i>At Center of Berm DEM</i>	8.21	6.99	6.40 5.88	5.40 5.09
Plus 30% of Max Inund. Depth <i>Over Entire Berm DEM</i> <i>At Center of Berm DEM</i>	2.46	2.10	1.92 1.76	1.62 1.53
Plus additional freeboard	3.05	3.05	3.05	3.05
Min Berm Height <i>Over Entire Berm DEM</i> <i>At Center of Berm DEM</i>	13.72	12.14	11.37 10.69	10.07 9.67
Design Berm Ht - Min Berm Ht <i>Over Entire Berm DEM</i> <i>At Center of Berm DEM</i>	-3.97	-2.39	-1.62 -0.94	-0.32 0.08

of only 0.08 m; however, it must be noted that the berm design is based on the original 2013 study, which obtained a lower value of 4.4 m for the maximum inundation depth. Scenario S4, with the larger ASCE-compliant source, L1x1.11, results in non-compliance of the berm design by about 1 - 1.6 m, depending on which of the two values of maximum inundation depth are used..

Berm Simulation Results

Scenarios S1 and S3 are simulations with the berm in place. As expected, the flow depth in front of the berm is higher than the values resulting from the bare earth simulation. From the maximum flood depth entries in Table 4, we can estimate the amplification factors for scenarios S1 and S4 as $8.21/5.89 = 1.39$ and for the S3 and S5 scenarios as $6.99/5.09 = 1.37$, where we have used the maximum inundation depth at the center of the Berm DEM. As a result, we see that the berm is about 4 m too low in Scenario 1 (with source L1x1.11) and 2.4 m too low in Scenario 3 (with source L1).

But it is not clear that the two safety factors should be applied to the Berm simulation results, S1 and S3. The 3.05 m freeboard is for a solid berm wall in this study, not a building floor level subject to flooding, so one might question whether the entire 3.05 meters is necessary as a safety factor. It may also be questionable to apply the 1.3 safety factor to account for tsunami/berm interactions, since the model computes these interactions directly. But alternatively, if the 1.3 factor is applied as a conservative adjustment that accounts for model error, then it could be argued that the 1.3 factor should be applied twice to a Bare Earth result, to account for both the lack of tsunami/berm interaction computations and the possible model error in these computations. Clarification by the ASCE 7-16 Panel is needed on such issues. If the safety factors are deemed necessary, then the berm design does not conform to the ASCE 7-16 requirements for minimum berm height.

Figures 5-8 provide graphic summaries of the results for S1, S3, S4 and S5. The location of the largest maximum inundation depth (referenced to the Grade Plane) for each scenario is indicated as a black circle in Figures 5-8. In the case of the Bare Earth scenarios S4 and S5, these maxima were significantly displaced to the southeast quadrant of the berm DEM, which may not be as relevant as the maximum value at the center of the DEM, so this center maximum value is annotated and marked with a black circle, as well.

To provide some insight into the inundation process, East-West transects of η (referenced to MHW) were also constructed at the latitude of each of these maximum values; snapshots at selected times are presented in Figures 9-12. Note the subsidence that occurs on the coast and at the berm one second after the earthquake occurs, and the reflected wave propagating West from the berm for Scenarios 1 and 3 and from high ground about 3-4 km to the east of the berm site in the Bare Earth Scenarios 4 and 5 (see Figure 9).

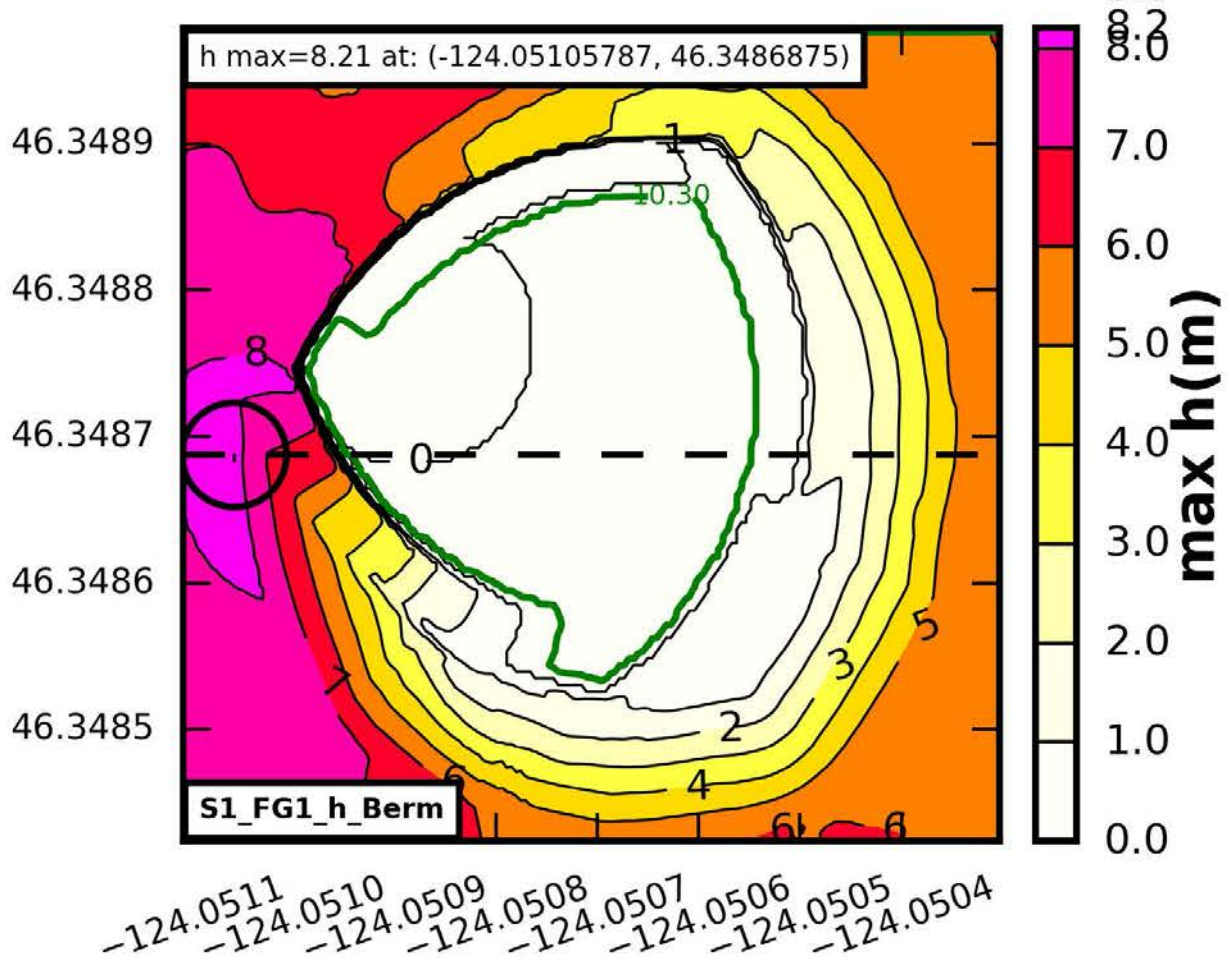


Figure 5a. S1 maximum flow depth values (referenced to the underlying topography) at the berm recorded at each computational grid cell over the duration of the simulation. The value and geographical position of the largest maximum is annotated and also marked by a black circle. The dashed line marks the latitude of the East-West inundation transects presented below in Figure 5b. Note that the apparent flooding of the top is an artifact of the numerical solution which produces a thin film of overtopping water driven by extreme, nonphysical, current speed values at the berm wall. Numerical experiments indicate that the maximum value of 8.21 m located west of the berm wall is sufficiently stable for computing an estimate of the minimum required berm height (Table 4).

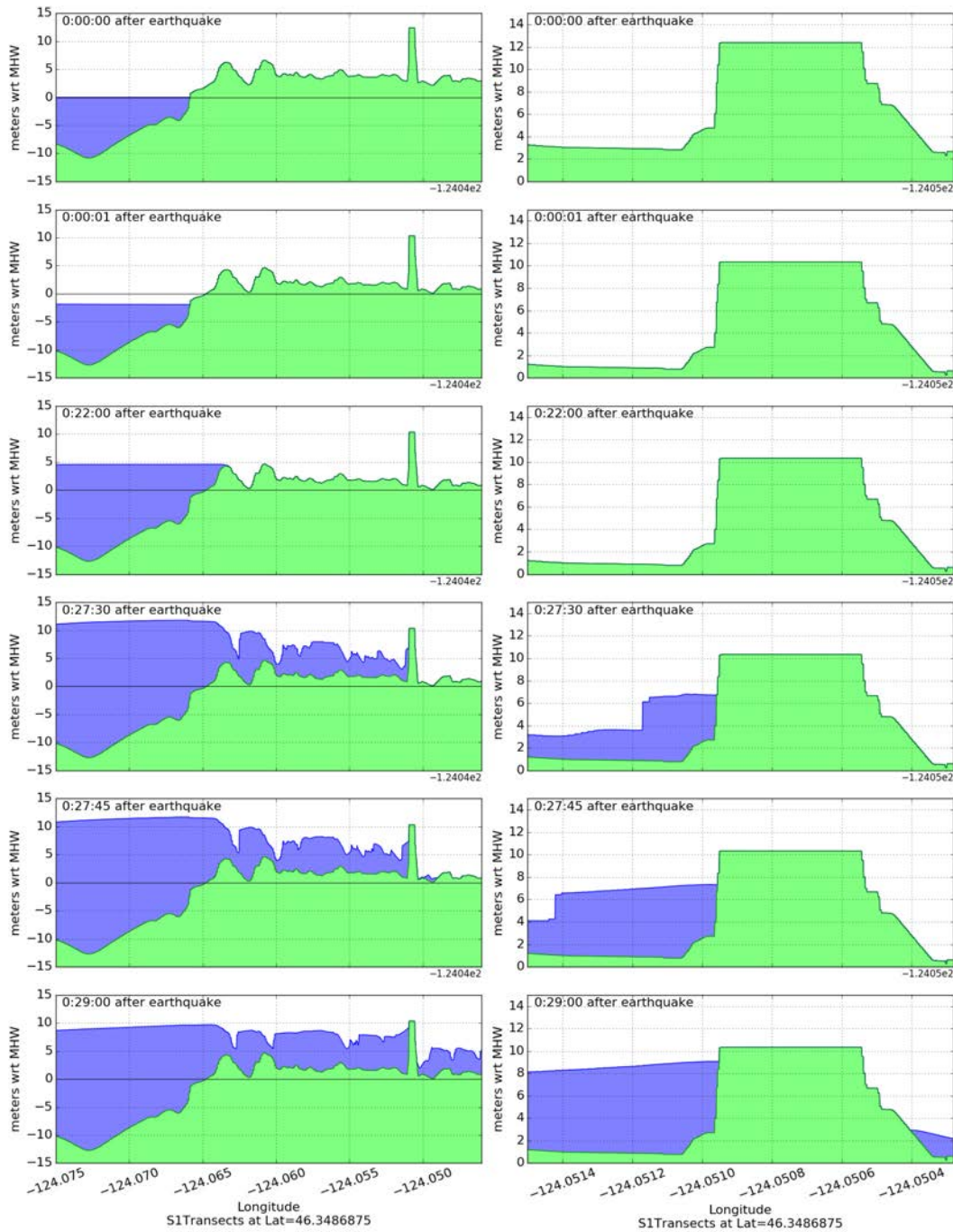


Figure 5b. S1 East-West transects of eta (referenced to MHW) at the latitude of maximum inundation depth as indicated by the dashed line in the top panel of Figure 5a.

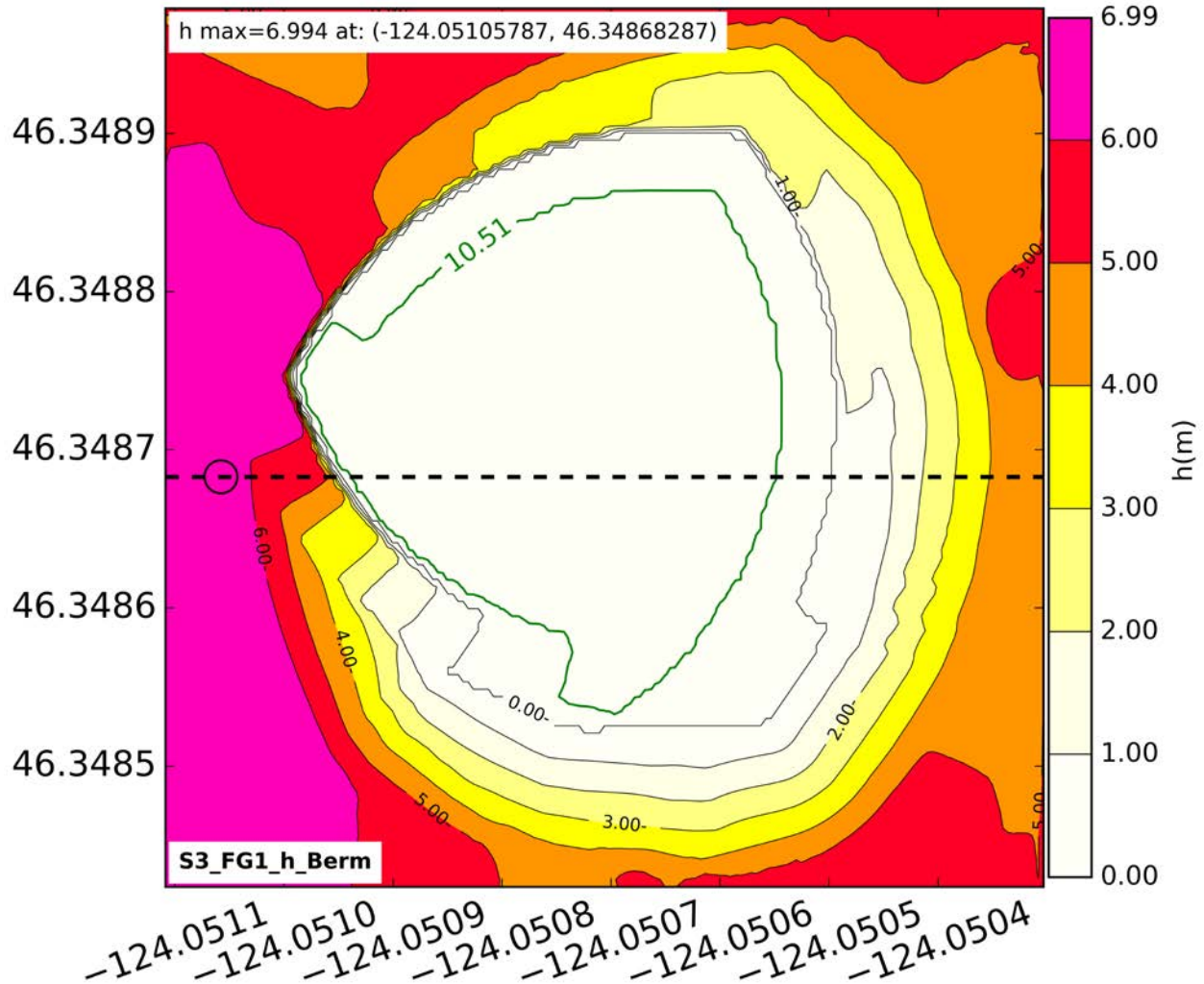


Figure 6a. S3 maximum flow depth values (referenced to the underlying topography) at the berm recorded at each computational grid cell over the duration of the simulation. The value and geographical position of the largest maximum is annotated and also marked by a black circle. The dashed line marks the latitude of the East-West inundation transects presented below in Figure 6b.

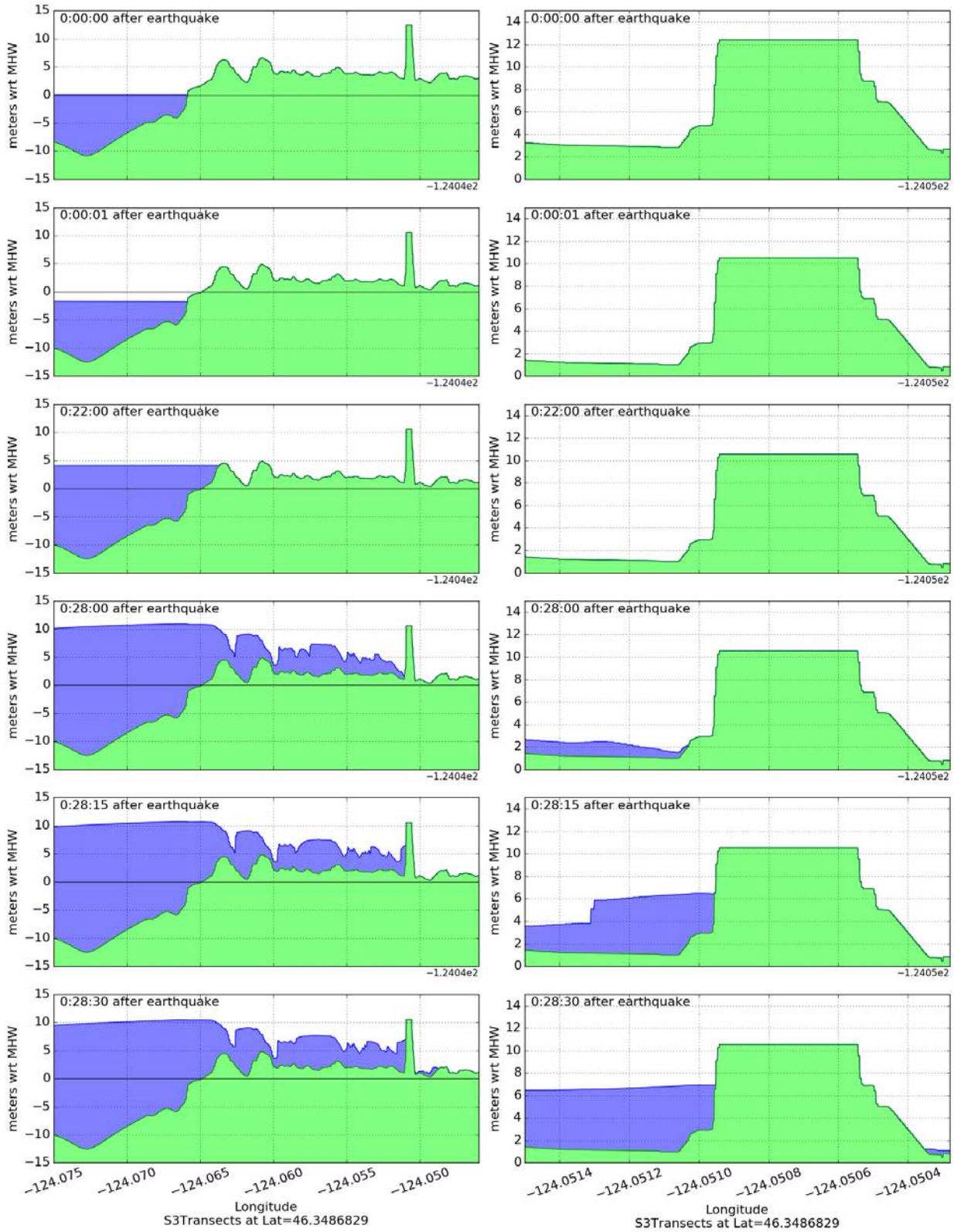


Figure 6b. S3 East-West transects of eta (referenced to MHW) at the latitude of maximum inundation depth as indicated by the dashed line in the top panel of Figure 6a.

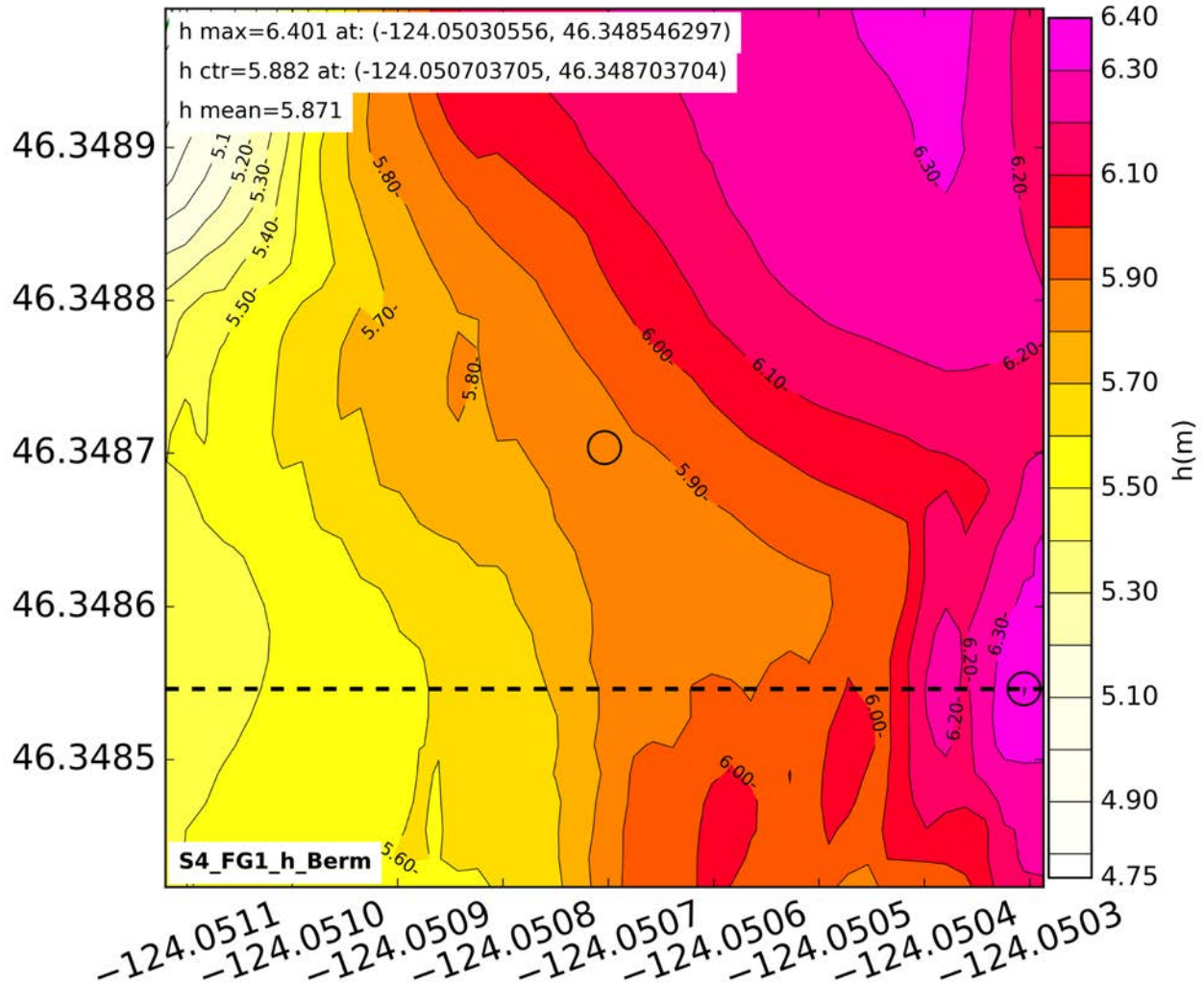


Figure 7a. S4 maximum flow depth values (referenced to the underlying topography) at the berm site recorded at each computational grid cell over the duration of the simulation. The value and geographical position of the largest maximum and the maximum at the center of the berm area are annotated and also marked by black circles; the mean value is also provided in the annotation. The dashed line marks the latitude of the East-West inundation transects presented below in Figure 7b.

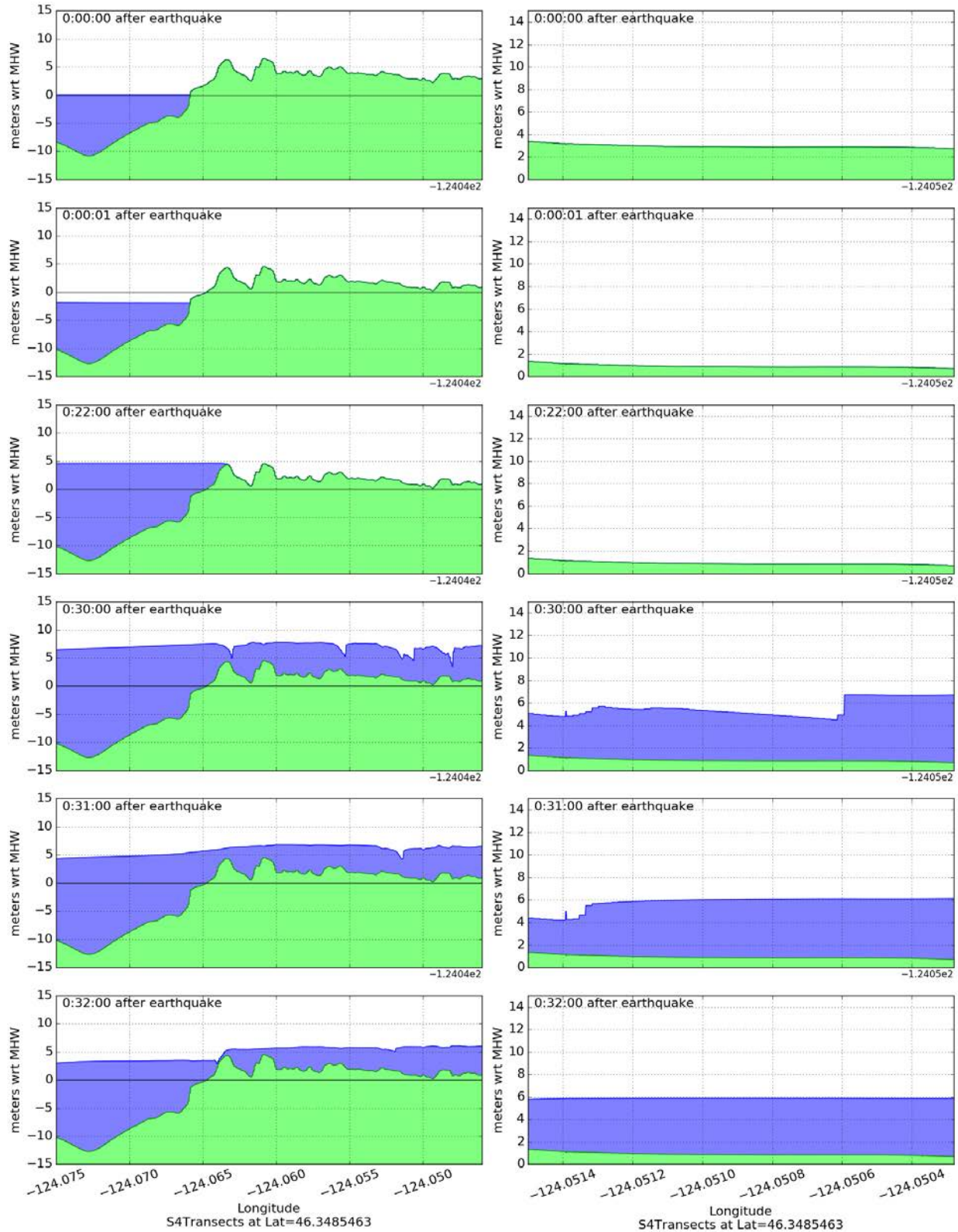


Figure 7b. S4 East-West transects of eta (referenced to MHW) at the latitude of maximum inundation depth as indicated by the dashed line in the top panel of Figure 7a.

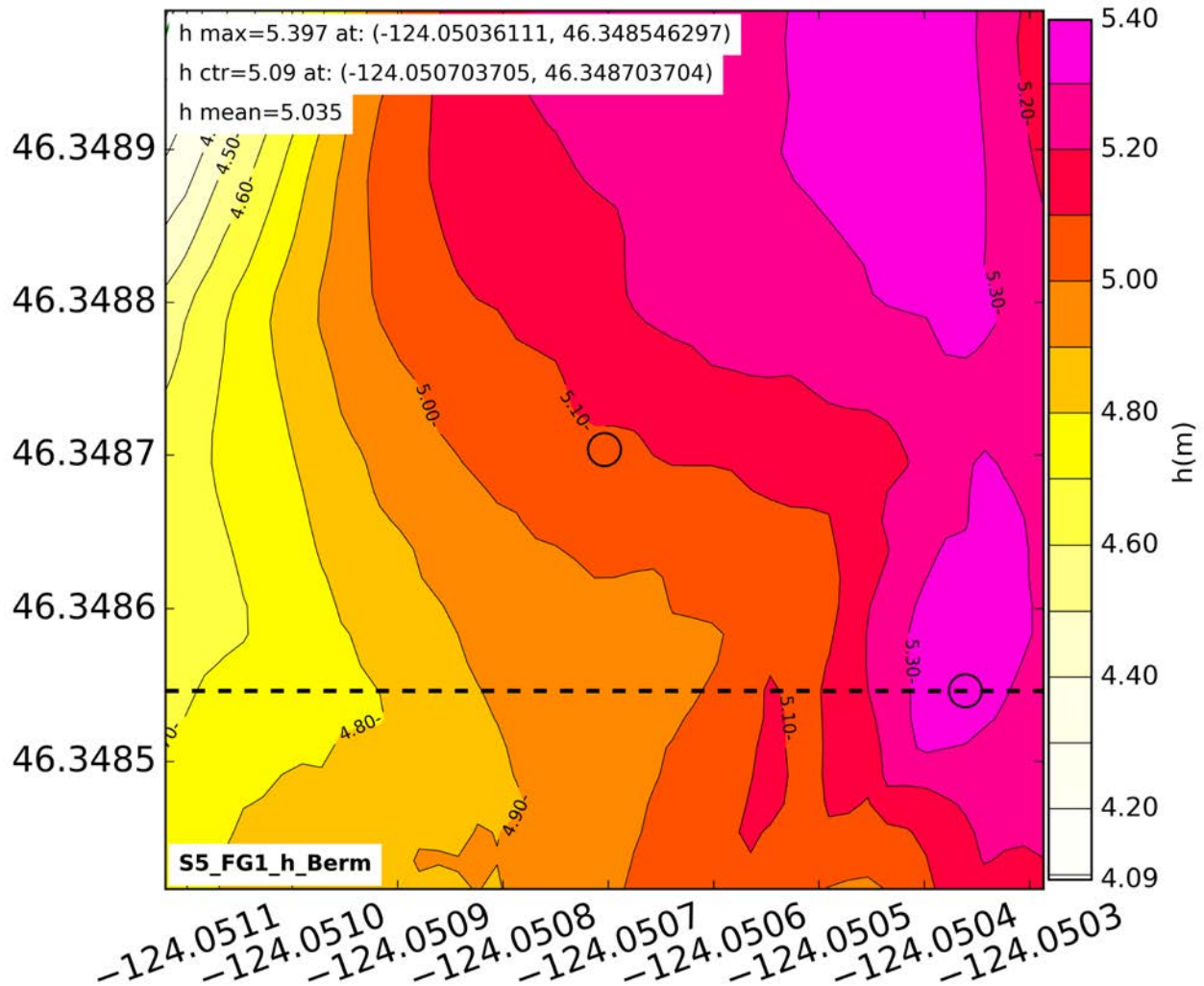


Figure 8a. S5 maximum flow depth values (referenced to the underlying topography) at the berm site recorded at each computational grid cell over the duration of the simulation. The value and geographical position of the largest maximum and the maximum at the center of the berm area are annotated and also marked by black circles; the mean value is also provided in the annotation. The dashed line marks the latitude of the East-West inundation transects presented below in Figure 8b.

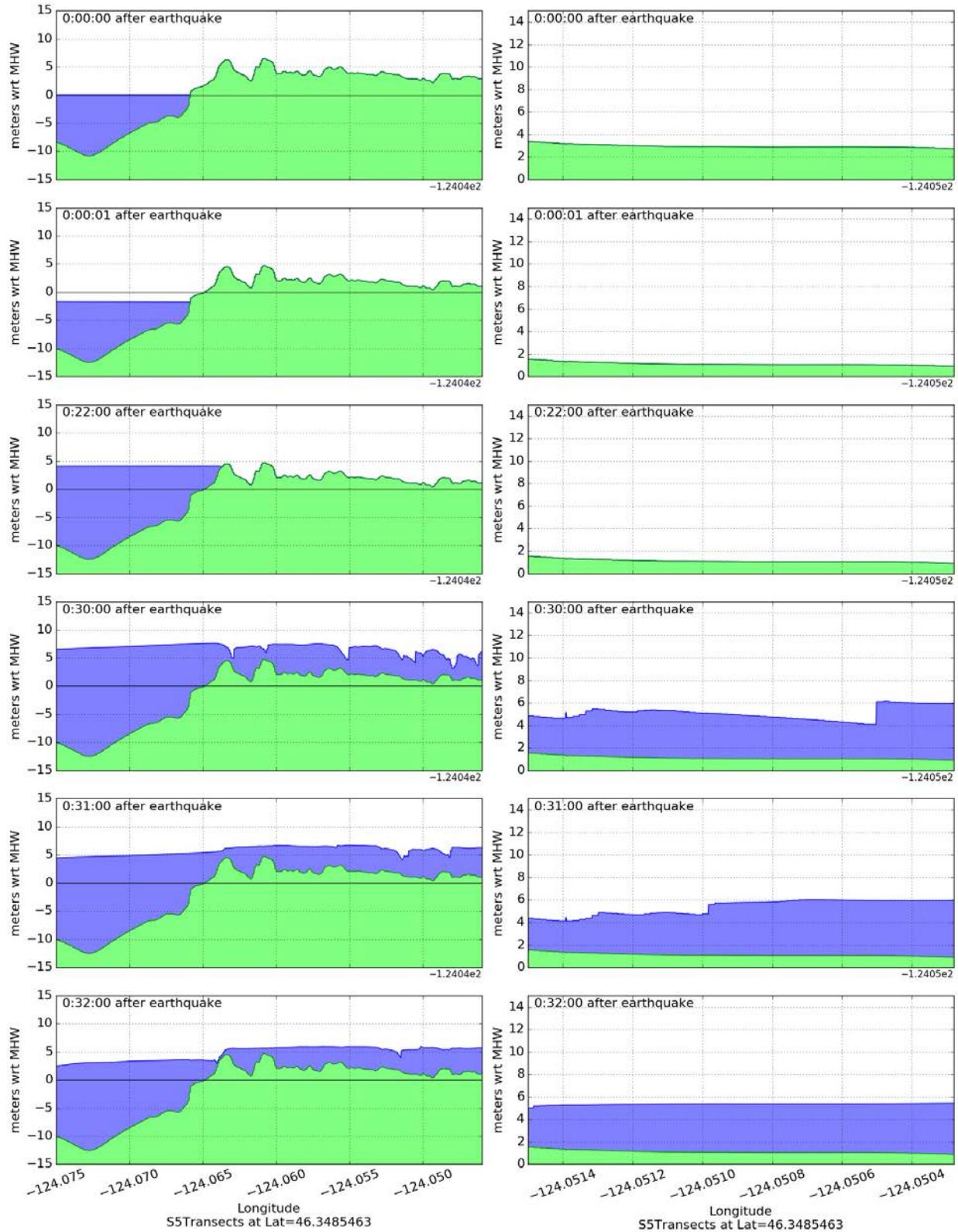


Figure 8b. S5 East-West transects of eta (referenced to MHW) at the latitude of maximum inundation depth as indicated by the dashed line in the top panel of Figure 8a.

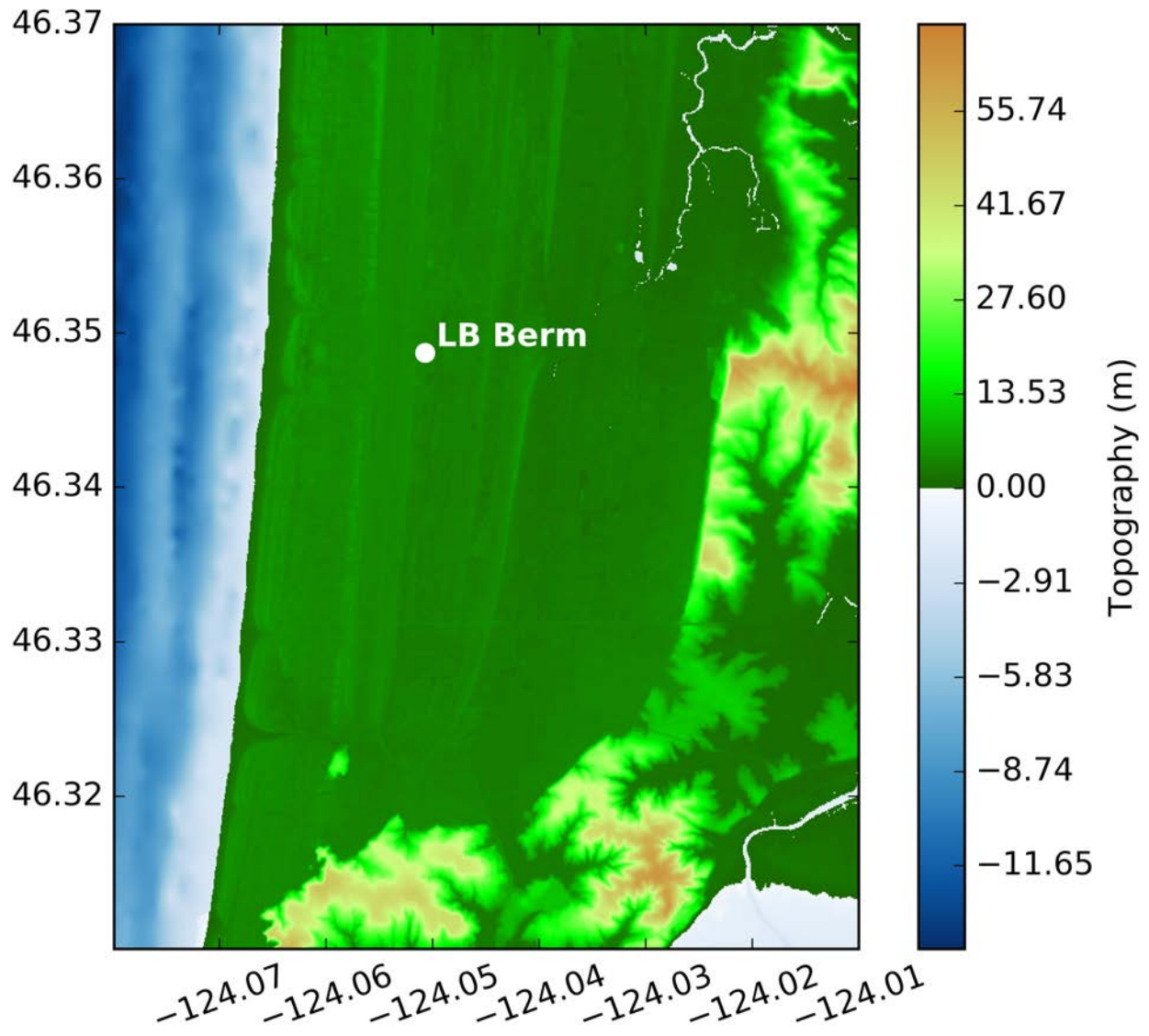


Figure 9. Topography of the Long Beach area. Note the high ground about 3-4 km to the east of the berm location. The reflected tsunami from this high ground can be seen propagating west in the transects of Figures 7b and 8b at 30-31 minutes after the earthquake.

Uncertainties and Limitations

Numerical models do not produce perfect simulations of any natural process. Here we discuss some of the uncertainties and limitations most important to this specific study and, where possible, their probable influence on the model output.

Source Specification

This is likely the largest source of uncertainty in the study. Variations in the value of certain earthquake parameters can produce large differences in the subsequent tsunami flooding.

Earthquake Magnitude and Recurrence Interval

In general, the greater the earthquake magnitude, the larger the initial wave amplitude (but see the discussion of slip distribution uncertainty, below, for exceptions to this general rule). With regard to the CSZ event, however, larger events would be associated with larger recurrence intervals than the estimated 1990-3300 years (R. Witter, personal communication). In addition, Witter et al. (2011) estimate that "...the L1 scenario captures 95 percent of the hazard and more severe events are extremely unlikely."

In this new study we again modeled the tsunami with the original L1 scenario (using the new berm design and location), and also used the amplified L1 scenario with an 11% increase in amplification in order to exceed the η_{100} values as specified in the ASCE 7-16 guidelines.

Earthquake Slip Distribution

The vertical displacement of the earth's crust presented in Figure 1 (a) is the direct result of a Pacific oceanic tectonic plate slipping (or subducting) beneath the North American continental plate, deforming both plates in the process. But the amount of slip is not distributed evenly on the common surface, known as the fault plane, where the two plates are in direct contact. There are patches on the fault plane, known as asperities, in which the two plates are more tightly locked by friction or protrusions of one plate into the other. But the relentless movement of the tectonic plates over decades and centuries continues to build up stress until the rock in the asperity region breaks and the plates slip past one another, releasing a local maxima of energy.

A significant amount of earthquake energy is released by the slip in asperities, which concentrates the energy in a relatively small patch. As a consequence, details of the slip distribution can make a significant difference in the initial amplitude of a tsunami; for example, if the slip is distributed evenly over the entire fault plane, then the initial tsunami amplitude will be about half the amplitude of a tsunami generated by slip distributed evenly over half of the fault plane (if the earthquake magnitude is the same in each case). In particular, high slip values concentrated in an asperity region are associated with large values of vertical displacement of the ocean floor and a higher initial tsunami wave in the region.

Thus, the location of a coastal community relative to an asperity and the associated high wave region can have a direct effect on the severity of flooding in the community. Details of the near-field slip distribution for the CSZ scenario L1 can strongly affect the degree of Long Beach inundation. For example, offshore of Long Beach there is a maxima of 10-12 m in

crustal deformation and the initial tsunami waveform (Figure 1(a)); if this maxima was located closer to or farther from Long Beach, the inundation would likely increase or decrease, respectively. Similarly, if the concentration of slip (and therefore earthquake energy) resulted in a larger or smaller maximum value, then a corresponding increase or decrease in flooding would be expected. However, it is not possible to make a reliable prediction of slip distribution at this level of detail, and conducting numerical experiments to estimate the sensitivity of flooding to such changes is beyond the scope of this study.

Landslide sources

This study did not include modeling of local landslides that are triggered by earthquake shaking. For the near-field CSZ events considered in this study, submarine landslides occurring offshore Long Beach could increase the severity of flooding. If the earthquake triggers a very large submarine mass failure on the continental slope then this could increase wave amplitudes substantially.

Model Physics

Several important geophysical parameters must be set in the GeoClaw software, and some physical processes are not included in these simulations, which use the two-dimensional shallow water equations. These are discussed below along with their potential effect on the modeling results.

Tide Stage

The simulations were conducted with the background sea level set to MHW. This 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.

Sea Level Rise

In this study we have not explored the effect that sea level rise would have on the results. These could be significant over the expected lifetime of the berm. As a simple approximation, it might be expected that if sea level (and hence MHW) is increased by some amount then the flow depth at the berm location will increase by roughly the same amount. This is probably a good approximation for small sea level rise (a few cm) but is not true in general since the onshore fluid dynamics is highly nonlinear. New simulations would be required to properly assess the effect of a larger rise in sea level.

Friction

Manning's coefficient of friction was set to 0.025, a standard value used in tsunami modeling that corresponds to gravelly earth. This choice of 0.025 is conservative in some sense, because the presence of trees, structures and vegetation to the west of the Long Beach Elementary School campus 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. A

sensitivity study for the berm location has not been performed.

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 walls) 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.

Structures west of the berm

Buildings west of the berm were not included in the simulations. The presence of these structures will alter tsunami flow patterns and generally impede inland flow. To some extent the lack of these 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.

Incorporating existing buildings (given the appropriate data) into the two-dimensional shallow water wave model would be possible, but these equations are generally not adequate for accurately modeling the complex flow through a built environment. The flow is generally fully three-dimensional and turbulent around structures.

Three-dimensional modeling is beyond the scope of the ASCE 7-16 requirements, and has not been performed in this study. Modeling tsunami flow around structures is still very much a research topic in the tsunami modeling community. Another fundamental difficulty with incorporating existing structures into a tsunami simulation is that many structures will be knocked down by the force of the tsunami. At this point, they are no longer fixed obstacles to the flow and instead become debris. Accurately modeling this process for a large set of buildings is well beyond current tsunami modeling capabilities.

Debris

Large tsunamis inevitably create fields of debris that act as battering rams, multiplying the destructive impact. Smaller debris and entrained sediment increases the density of the fluid, potentially leading to greater hydrodynamic forces on structures such as the berm. On the other hand, the process of creating and carrying debris also requires the expenditure of tsunami energy, which would tend to reduce the inland extent of the inundation. In this study we have not attempted to incorporate debris.

Hydrodynamic Equations

The two-dimensional shallow water equations used in GeoClaw are generally a good model for simulating tsunamis with long wave lengths, such as those generated by a CSZ event, and have been found to be a reasonable model for inundation on bare earth. The GeoClaw model has been validated by the NTHMP for tsunami studies of this nature.

However, it is not clear that the shallow water equations are adequate to model the interaction of the flow with a small scale, steep-walled feature such as this berm, as discussed above. Ideally, a 3-dimensional fluid model would be coupled to GeoClaw in order to more accurately model the response around the berm. Such an effort was beyond the scope of this study.

We believe that the GeoClaw results give a reasonable estimate of the flooding depth around the berm on the otherwise bare earth topography used here. This topography is relatively flat in the region around the berm and the resulting flow is relatively smooth except for hydraulic jumps at the wave front and in the reflections from the berm itself. These jumps can be well captured by shallow water equations and more complex three-dimensional effects may be minimal.

We stress, however, that these simulations ignore other existing structures (including the large school building just northwest of the berm) that could have a significant effect on the fluid dynamics.

Summary and Conclusions

Four simulations were conducted for the purpose of testing compliance of the design of the Long Beach Elementary School Berm with FEMA (2012) and ASCE (2017) criteria for the recommended minimum berm height. The scenarios represent four possible combinations of an earthquake source pair (L1 and L1x1.11) and the presence or absence of the Berm DEM in the simulation (Bare Earth or Berm).

The results indicate that the berm design was marginally compliant only for the (L1, Bare Earth) scenario that embodies the FEMA (2012) criteria, for which the berm was, in fact, designed.

We thus conclude that if it is a priority to comply with ASCE 7-16 guidance that is expected to be adopted in the future, then either the current berm design height must be increased or the berm must be modified or re-designed.

An important caveat to this conclusion is that the ASCE 7-16 criteria governing the recommended minimum structure height are not entirely clear. This is especially true in the context of hydrodynamic models such as GeoClaw that provide two-dimensional solutions of tsunami flow depth and other parameters. In particular, more detailed guidance is needed on the following issues that were encountered during the course of this study.

- eta100 criteria for maximum offshore wave amplitude at the 100 m isobath are apparently still under discussion by the ASCE 7-16 Panel
- physical/engineering reasoning regarding the application of safety factors (or not) to results of tsunami/structure interaction modeling
- significant spatial variability of the maximum inundation depth in the vicinity of the structure

Judgements made on each of these issues have a significant effect on the minimum berm height computation and, therefore, on the determination of whether a structure is or is not compliant with the ASCE 7-16 criteria.

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Appendix A. ASCE 7-16 Earthquake Source Requirements

Section 6.2 defines a Maximum Considered Tsunami (MCT) as

MAXIMUM CONSIDERED TSUNAMI: *A probabilistic tsunami having a 2% probability of being exceeded in a 50-year period or a 2,475-year mean recurrence interval.*

This mean recurrence interval falls within the range of the L1 earthquake mean recurrence interval of 1990-3300 years.

The offshore amplitude of the MCT, is defined as

OFFSHORE TSUNAMI AMPLITUDE: *Maximum Considered Tsunami amplitude relative to the Reference Sea Level, measured where the undisturbed water depth is 328 ft (100 m).*

where Reference Sea Level is

REFERENCE SEA LEVEL: *The sea level datum used in site-specific inundation modeling that is typically taken to be Mean High Water Level (MHWL).*

This offshore tsunami amplitude determines compliance of the offshore wave amplitude with ASCE 7-16 as follows

6.7.5.2 Direct Computation of Probabilistic Inundation and Runup. *It shall be permitted to compute probabilistic inundation and runup directly from a probabilistic set of sources, source characterizations, and uncertainties consistent with Section 6.7.2, Section 6.7.4, and the computing conditions set out in Section 6.7.6. The offshore wave amplitudes computed shall not be lower than 80% of the wave amplitudes given in Fig. 6.7-1.*

Figure A1 reproduces ASCE 7-16 Figure 6.2-1, which graphically illustrates the definitions of the maximum tsunami wave amplitude at the 100 m isobath. The symbol H_T is used in ASCE 7-16 to refer to this parameter but instead of the symbol H_T we here adopt the designation “eta100”; this is because the letter H is frequently used for the peak-to-trough wave “height”, also illustrated in Figure A1 and the amplitude — i.e., the vertical sea surface deviation from a reference sea level — is frequently denoted by the Greek letter “eta” (see, for example, equation 6.7-1 of ASCE 7-16).

Because the crucial last sentence of 6.7.5.2 is somewhat ambiguous, WA State contacted the authors of ASCE 7-16 for clarification; this resulted in the interpretation used in this study — namely, that compliance is achieved if the maximum tsunami wave heights associated with the L1 source at ASCE 7 stations located offshore in 100 m water depth that are within $\pm 22.5^\circ$ bearing from the Long Beach Berm site are equal to or greater than 80% of the value of each of the individual ASCE 7-16 values. However, at a recent ASCE Panel meeting, a recommendation was discussed to use the average ASCE 7-16 value in the $\pm 22.5^\circ$ sector, rather than each of the individual ASCE 7-16 values. If adopted, this recommendation would

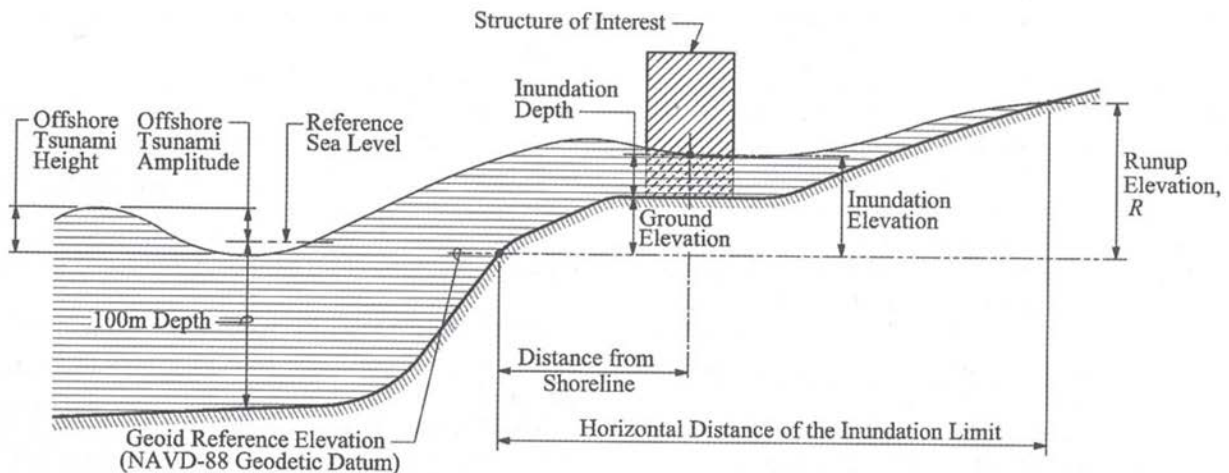


Figure A1. Reproduction of ASCE 7-16 “FIGURE 6.2-1 Illustration of Key Definitions along a Flow Transect in a Tsunami Design Zone”

result in a smaller offshore wave height requirement. Apparently, this matter continues to be under discussion, so we must consider this important criteria to be unclear and/or subject to change.

Nonetheless, we addressed the offshore wave amplitude guidance using the understanding by WA State of the ASCE 7-16 criteria, as stated above. In particular, a GeoClaw tsunami simulation with the L1 source was conducted to generate time series of the wave amplitude, η_{100} , at the ASCE stations and it was found that some GeoClaw η_{100} values fell below the ASCE 7-16 η_{100} values. Therefore, to satisfy the ASCE 7-16 η_{100} criteria, the deformation field of L1 was multiplied by the factor 1.11. Note that this increased both the maximum wave amplitudes and the degree of subsidence by 11 %. Figure A2 presents the results of this modification of L1.

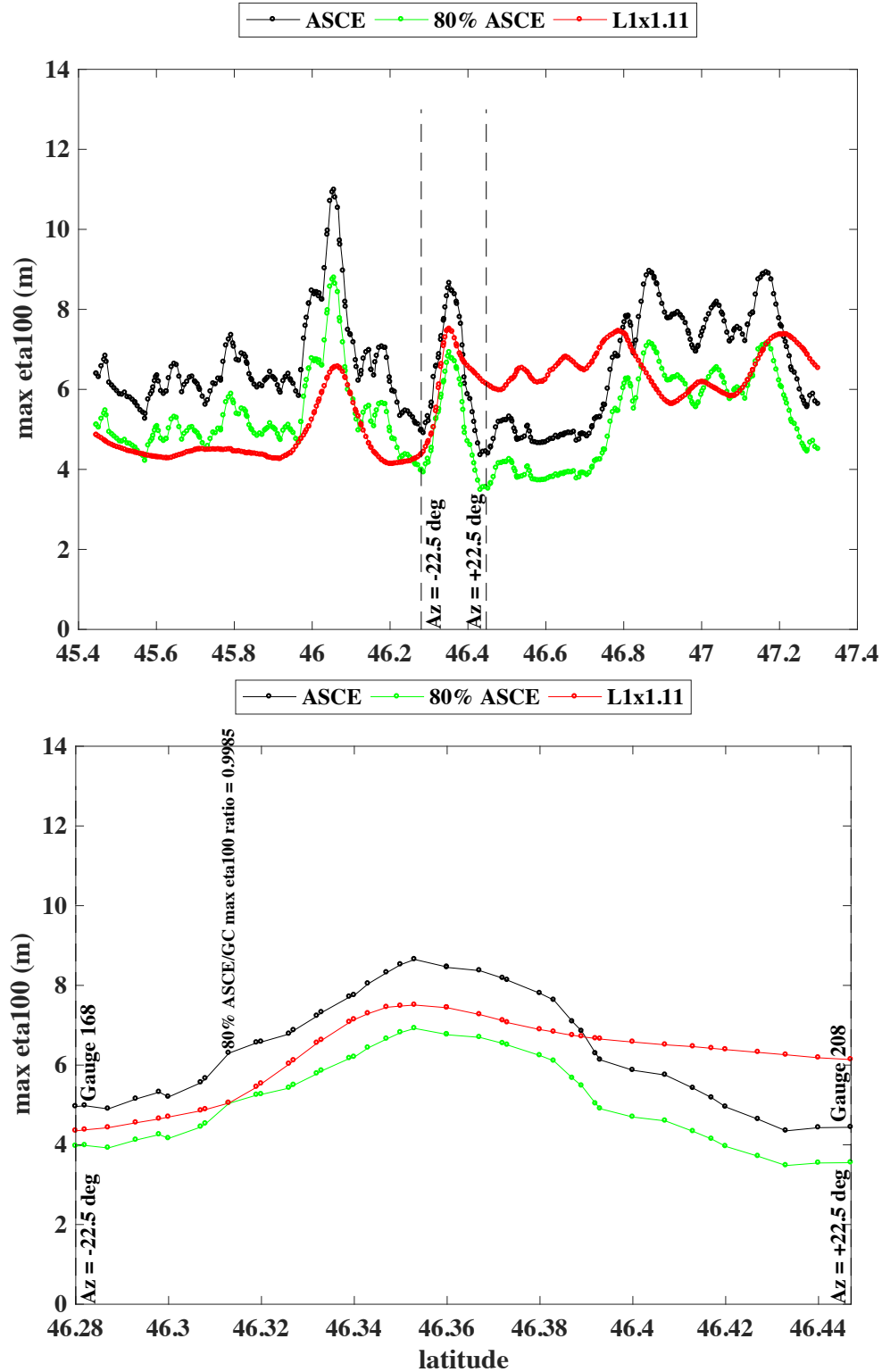


Figure A. Top: η_{100} for source L1x1.11 and the ASCE 7-16 Geodatabase.

Bottom: Zoomed view of the $\pm 22.5^\circ$ sector with vertex at the Long Beach berm

Appendix B. Online Model Data Products

As part of the deliverables, we have worked with WA DNR to develop the following standard products to be used in the development of additional derived products and to be archived for future distribution and use.

Digital text files

1. Maximum value data (See <http://www.clawpack.org/fgmax.html#fgmax>), including the following files:

fgmax_grid1.data: *grid details, geographical extent, resolution, etc.*

fort.FG0001.valuemax: *maximum values of tsunami parameters*

fort.FG0001.aux1: *grid bathymetry*

xxxxx.data : *model simulation parameter options selected in “setrun.py” (See http://www.clawpack.org/v5.4.1/setrun_geoclaw.html)*

2. Gauge data (See <http://www.clawpack.org/gauges.html?highlight=gauge>)

3. Other study-specific files that might be needed.

Graphical products (See <http://www.clawpack.org/v5.4.1/setplot.html>)

1. Maximum values

Plan view plots

Transects

2. Animations

Computational region and sub-regions of interest

fgmax grids

3. Other study-specific graphics that might be needed.