Probabilistic Assessment of Near-field Tsunami Hazards: Inundation Depth, Velocity, Momentum Flux, Arrival time, and Duration Applied to Seaside, Oregon.

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Abstract

The generation, propagation and inundation for a probabilistic near-field tsunami hazards assessment (PTHA) at the Cascadia Subduction Zone (CSZ) are analyzed numerically. For the tsunami hazard assessment, a new method is presented to characterize the randomness of the fault slip in terms of the moment magnitude, peak slip location, and a fault slip shape distribution parameterized as a Gaussian distribution. For the tsunami inundation resulting from the seismic event, five tsunami intensity measures (IMs) are estimated: (1) the maximum inundation depth, h_{Max} , (2) the maximum velocity, V_{Max} , (3) the maximum momentum flux, M_{Max} , (4) the initial arrival time exceeding a 1 m inundation depth, T_A , and (5) the duration exceeding a 1 m inundation depth, T_h , and presented in the form of annual exceedance probabilities conditioned on a full-rupture CSZ event. The IMs are generally observed to increase as the moment magnitude increases, as the proximity of the peak slip becomes closer to the study area, and as the distribution of fault shape narrows. Among the IMs, the arrival time (T_A) shows a relatively weak sensitivity to the aleatory uncertainty while the other IMs show significant sensitivity, especially M_{Max} . It is observed at the shoreline that M_{Max} increases by an order of magnitude from the 500-year to the 1,000-year event, while h_{Max} increases by a factor of 3, and T_A decreases by only factor of 0.05. The intensity of IMs generally decreases inland, but there are also varying dependencies on bathymetry. For example, a

32 shorter inundation duration, T_h (< 10 min) is observed at the higher ground level ($z > 3$ m) while a longer
33 T_h (~ 100 min) is observed near the river and creek.

34 **Keywords:** Cascadia Subduction Zone, Near-field Tsunami, Aleatory uncertainty, Resilience, Intensity
35 Measures, Probabilistic Tsunami Hazard Assessment

1. Introduction

1.1 Near-field tsunami hazards at the CSZ

Tsunamis caused by megathrust subduction zone events have a small frequency of occurrence relative to other coastal hazards such as hurricanes, but these events can result in significant loss of life and extensive damage to coastal regions. Loss and damage are particularly serious problems for near-field (local) tsunamis because the tsunami energy is concentrated in a small area and because the arrival time is only tens of minutes after the event, limiting the evacuation time. The destructive power of near-field tsunamis has been reported for recent disasters such as the 2004 Indian Ocean tsunami (e.g., Jaffe et al., 2006; Rosetto et al., 2007) and the 2011 Tohoku tsunami (e.g., Mikami et al., 2012).

The US Pacific Northwest coast is facing the similar threat of an earthquake and near-field tsunami from the Cascadia Subduction Zone (CSZ) along the converging area between Juan de Fuca Plate and North American Plate. The Juan de Fuca Plate generally moves in a northeast direction with the mean rate of 0.004 m/year (Heaton and Hartzell, 1986). It is sinking beneath the North American Plate, and as it moves, it causes elastic potential energy to be accumulated between the two plates. This energy is released in megathrust earthquake events, which cause ground shaking that can be last for 3 to 5 minutes. The rapid motion of the seafloor results in the generation of a tsunami in both offshore and onshore directions. The last such megathrust event at the CSZ occurred on January 26, 1700, with a full rupture event along the entire 1,000 km length of the fault. The range of the moment magnitude (M_W) of that event is estimated to be 8.7 to 9.2 (Satake et al., 2003). The probability of the next event at the CSZ with a M_W 9.0 has been estimated to be 17% in the next 50 years and 25% in the next 100 years (Goldfinger et al., 2012; Kulkarni et al., 2013).

Fig. 1 Regional map of Cascadia Subduction Zone (CSZ) and study area, Seaside, Oregon.

Community resilience is generally defined as the ability of a community to absorb and recover from a natural hazard (e.g., Bruneau et al., 2003). Resilience involves many social, economic, political, ecological, and civil engineering infrastructure systems. In general, there are five infrastructure systems considered to be most important to community resilience: buildings, transportation networks (bridges and roads, harbors, railways, and airports), water and wastewater networks, energy networks (electric power and fuel) and communication networks (radio, landlines and wireless). Similar to the analysis for other hazards such seismic or high wind, we assume that the response of each system can be evaluated stochastically using a fragility analysis based on the intensity measures (IMs) of tsunamis. The most common IMs are the tsunami arrival time, maximum tsunami inundation or run-up, and tsunami inundation depth. These IMs have been used for tsunami evacuation planning, to develop tsunami inundation maps (Tsunami Pilot Study Working Group, 2006; Gonzales et al., 2009; Priest et al., 2010), and to evaluate the building damages or economic loss (e.g., Dominey-Howes et al., 2010; Wiebe and Cox, 2014).

Although arrival time and the extent of inundation have proven useful for evacuation planning, the response of the complex built environment and the five infrastructure systems described earlier requires a more detailed understanding of the IMs within the inundation zone. In case of building damage for example, there are several types of forces on structures induced by the tsunami: hydrodynamic force (drag force imposed by quasi-steady flow), hydrostatic force, buoyant force, impulsive force (due to the transient bore or leading edge of the tsunami), debris impact force, debris damming force, and uplift force (FEMA P-646, 2012). Although these individual forces can be analyzed for structures individually, it is not currently possible to apply these methods at a community scale. Therefore, it is advantageous to apply a fragility analysis, or estimate a probable level of damage for a certain class of structure, at a community scale comprising thousands of individual buildings.

The IMs for estimating tsunami damage have limited availability compared to seismic IMs such as peak ground acceleration due to the complexity of tsunami analysis. Generally, the analysis process comprises of three steps: generation, propagation, and inundation. The propagation step can be considered a “solved problem” in that the tsunami motion in the open ocean is well-described by conventional long wave theory (Titov et al., 2005). The generation and inundation steps, however, contain uncertainties which are classified as either epistemic or aleatory uncertainty. Epistemic uncertainty refers the error involved in our modeling methodology, such as the way to define the initial deformation of the ground motion from the earthquake such as slip, strike, dip, rake, and depth (Goda et al., 2014) or in the accuracy of our computation tsunami inundation models. Thus we can minimize the epistemic uncertainties through the improvement of our modelling methodology. On the other hand, aleatory uncertainty generally arises from the randomness of nature, such as the fault slip distribution of earthquake event, the location of epicenter and hypocenter, or the condition of the tide at the time of tsunami event (Geist and Parsons, 2006). For example, the location of the peak fault slip and distribution of the slips played a significant role in determining the local intensity of the tsunami hazard along the east coast of Japan for the 2011 Tohoku event. The run-up was generally larger for the Iwate and Miyagi prefectures which were in closer proximity to the peak fault slip compared to the smaller run-up observed for Aomori, Fukushima, and Miyagi prefectures located further from the peak (Mori et al., 2011). Of course, local bathymetric and topographic condition also determine the maximum run-up elevations (e.g., Park et al., 2015).

1.2 Previous tsunami studies at CSZ

Geist and Parsons (2006) performed a probabilistic tsunami hazard analysis (PTHA) using both far-field and near-field tsunami sources to estimate the run-up. They utilized 100 randomized slip distributions to account for the aleatory uncertainties (Geist, 2005) of the near-field tsunami conditioned on a M_w 9.0 event. Their study was intended to provide a probabilistic run-up or Peak Nearshore Tsunami Amplitude (PNTA) along the West Coast of the US. González et al. (2009; see also Tsunami Pilot Study Working Group, 2006) used a probabilistic seismic hazard assessment (PSHA) methodology to provide the maximum tsunami inundation map. This study provided inundation depths in terms of an annual probability of exceedance, such as 100 or 500-year event, at Seaside, Oregon. They utilized 14 historic tsunami events as far-field tsunami sources and one near-field tsunami source from the CSZ composed of 12 scenarios. Priest et al. (2010) conducted a PTHA for Cannon Beach, Oregon, in which they provided the confidence levels for their tsunami inundation map as inferred from expert opinion of a 10,000 year record of turbidite events along the CSZ (Goldfinger et al., 2012). They used 25 deterministic scenarios of near-field sources at the CSZ, and two far-field sources in Alaska. In a similar study, Witter et al. (2013) developed inundation maps for Bandon, Oregon, classified into five sizes (S, M, L, XL, and XXL) based on the historical turbidite data (Goldfinger et al., 2012). Both studies utilized a 3-D dislocation model (Wang et al., 2003) of the CSZ for the initial tsunami slip condition and a numerical inundation model (Zhang et al., 2008) to estimate tsunami hazards. They only reported the maximum limits of inundation and the inundation depth as the tsunami IMs for each representative scenario. Although the study focuses on the CSZ, we note that there have been many PTHA conducted throughout the world, including Japan (Annaka et al., 2007), Australia (Burbidge et al., 2008), New Zealand (Power et al., 2007) and Mediterranean region (Sørensen et al., 2012).

1.3 Objectives of this study.

In this study, we perform a probabilistic near-field tsunami hazard assessment (PTHA) conditioned on the near-field CSZ event because the resulting tsunami hazard is more relevant to life safety and damage to the built environment compared to far-field tsunamis. We examine the impact of aleatory uncertainty on five intensity measures (inundation depth, velocity, momentum flux, arrival time, and duration of inundation). There are four major objectives of this study:

- 1) Provide the framework for probabilistic near-field tsunami hazard assessment (PTHA) at CSZ including aleatory uncertainty, originated from the randomness of the event magnitude, peak slip location, and fault slip distribution.
- 2) Introduce a new method to determine a fault slip distribution parameterized as a Gaussian distribution.
- 3) Quantify tsunami hazard intensity measures (IMs): the maximum inundation depth, h_{Max} , velocity, V_{Max} , momentum flux, M_{Max} , the arrival time of exceeding 1 m inundation depth, T_A , and the total duration of exceeding 1 m inundation depth, T_h .
- 4) Evaluate the annual exceedance probability of each IM, and provide the spatial distribution of IMs over the inundation region.

These objectives are achieved in the following sections. Section 2 introduces the new method to define fault slip distributions to provide the model scenarios utilized in this study. Section 3 introduces the setup of the tsunami model for generation, propagation and inundation. This section also presents estimates of the five IMs at representative observation points. Section 4 introduces the methodology of probabilistic near-field tsunami assessment and provides the result including probabilistic tsunami hazards map of Seaside, Oregon, as a test bed. Section 5 discusses the limitations of the current work, compares to previous studies, and discusses possible future work. Finally, Section 6 provides a general summary and conclusion.

2. Tsunami generation model

Generally, the input source condition for tsunami models is given as an initial surface water displacement. The Okada (1985) model, which is based on the linear co-seismic dislocation of fault slips, is conventionally used for many tsunami generation models. The initial surface displacement is assumed to occur simultaneously along the fault. In this section, we review the possible earthquake fault slip patterns based on inversion models of historic tsunami events, and we parameterize those complex fault slips to provide a general format for the probabilistic model.

2.1 Inversion model and Gaussian distribution

Inversion models provide a co-seismic fault slip distribution over the rupture area where the significant dislocations of faults have occurred due to the earthquake that triggers a tsunami event. Inversion models are comprised of a finite number of sub-faults with the relevant geologic information

(slip, strike, dip, rake, and depth) determined for each sub-faults, and apply a Green's function approach to find the slip distribution that has the minimum error between observation and model (Fujji and Satake, 2007).

To evaluate the general form of the fault slip distribution triggers a tsunami event, we examine the inversion models of recent tsunami events. Fig. 2 shows the fault slip distributions of inversion models (Fig. 2a, c, and e) and the general slip distributions (Fig. 2b, d, and f). Fig. 2a and c presents the fault slip distribution of inversion models for 2011 Tohoku tsunami from Shao et al. (2013) and Hayes (2011), respectively, and Fig. 2e presents the inversion model for the 2010 Chile tsunami from Fujii and Satake (2013). The length of faults along Y' is rupture length, L and the length of fault along X' is rupture width, W . To characterize the fault slip distribution, we examine the cross-profile of fault slip distribution of each sub-fault transect along Y' . We normalized each fault slip (D) by the peak fault slip (D_P) at each transect, and plot it against the normalized Y' by the sub-fault length (dL). The blue dotted lines are the cross-profiles having relatively large fault slips, and the black dotted line is the cross-profile of the peak slip (D_P) among them.

Fig. 2. The left panels show fault slip distributions of inversion models for 2011 Tohoku tsunami from (a) Shao et al., 2013 and (c) Hayes, 2011, and (e) for 2010 Chile tsunami inversion model from Fujii and Satake, 2013. The right panels show the cross-profiles of fault slip distribution from each inversion model. Each blue dashed lines in panel b, d, and f presents the cross-profile of normalized fault slip (D') along the strike direction (Y'/dL), and thick black dash line the fault slip distribution at the peak slip transect. The solid line presents and the fitting curve for cross-profiles with a Gaussian distribution form (Eq. 1).

The figure shows that the normalized fault slip distribution along each transect is generally symmetric at the peak slip, and allows us to parameterize the fault slip shape using a Gaussian distribution. The following probability density function is applied to find the fitted curve (solid line) in Fig. 2b, d, and f

$$f(Y'/dL|\alpha,\beta) = \frac{1}{\beta\sqrt{2\pi}} \exp\left(\frac{-(Y'/dL - \alpha)^2}{2\beta^2}\right) \quad (1)$$

where α and β are the slip distribution parameters of the fitted curve relating to the mean and standard deviation, respectively, of the slip shape along Y' . Parameter α controls the location of the peak slip along Y' . Since we defined Y' as the distance of the rupture length from the north boundary to the south, the distance of the peak slip from the north boundary increases as α increases. Parameter β controls the width of curve along Y' . As β increases, the shape of slip is wider and vice-versa.

Since each inversion model used by the investigators consisted of different sizes for the unit sub-fault, we normalized the distance of the rupture length (Y') by a uniform rupture length, 100 km, to compare the inversion model results at the same scale. We then replace β with β' as a slip shape parameter to indicate this change. Similarly, we introduce α' which is normalized α by the parameter L/dL such that the location parameter ranges $0 \leq \alpha' \leq 1$. When α' is 0.5, the peak slip is located at the center of the rupture area, and when α' is close to zero or unity, the peak slip is near the northern or southern boundary, respectively.

Table 1 summarizes seven cases of the tsunami inversion models and the corresponding slip distribution parameters, α' and β' developed for this study. We limited our study by selecting recent tsunami events whose moment magnitudes were greater than 8.1 and for which we had sufficient access to the inversion model data published in the literature. Generally, both the rupture area ($S = LW$) and the peak slip displacement (D_P) increase as M_W increases. Interestingly, D_P shows a significant deviation for the same tsunami events (2011 Tohoku, v1, 2, 3) while the rupture area (S) shows small deviation. These differences arise from the different inversion model sources such as seismic, geodetic or tsunami data (Koketsu et al., 2011). A more detail relationship between the moment magnitude and rupture area will be examined at Subsection 2.2. For the Kuril, Chile and Tohoku tsunami, α' ranges from 0.4 to 0.6, and for the Indian Ocean tsunami the peak slip was located on southern boundary of rupture area ($\alpha' = 0.92$). The widest slip width was found for the 2004 Indian Ocean tsunami ($\beta' = 2$ or 6), and the three different versions of 2011 Tohoku tsunami show the similar range of β' (0.62 – 0.81). On the other hand, the two different versions of 2010 Chile tsunami show large deviation of slip width ($\beta' = 0.25$ and 0.75).

Table 1. Inversion models information and slip distribution parameters

Tsunami	M_W	D_P	L	dL	W	dW	α'	β'	Fig. 3	Reference
	[-]	[m]	[km]	[km]	[km]	[km]	[-]	[-]		
2004 Indian Ocean	9.3	30	1,400	100	200	100	0.92	2 or 6	(1), (2)	Fujji & Satake, 2007

2007 Kuril	8.1	20	200	8	40	5	0.46	0.13	(8)	Ji, 2011a
2010 Chile, v1	8.8	13	600	50	187	17	0.63	0.74	(5)	Shao et al., 2015
2010 Chile, v2	8.8	22	600	50	150	50	0.42	0.25	(7)	Fujji & Satake, 2013
2011 Tohoku, v1	9.0	32	600	25	260	20	0.46	0.81	(3)	Hayes, 2011
2011 Tohoku, v2	9.1	59	500	25	200	20	0.42	0.62	(6)	Shao et al., 2011
2011 Tohoku, v3	9.0	69	550	50	200	50	0.50	0.75	(4)	Satake et al., 2013

Fig. 3a compares the Gaussian distributions developed for the data sets summarized in Table 1. We set $\alpha' = 0$ for all cases, and we plot the normalized slip, D' , versus the dimensional rupture length, L . The labels (1) to (8) on Fig. 3a indicate the ascending values of β' in Table 1. The estimated range of rupture length from β' in Table 1 shows significant variations depending on the tsunami.

Fig. 3. (a) Gaussian distribution curves fitted for the tsunami inversion models along the strike direction and (b) the decay rate of slips along the dip slip direction. Numbered lines correspond to events listed in Table 1. Solid thick line in (b) presents the average of all decay rates of slips excluding (7).

Fig. 3b shows the slip decay in the dip slip direction (positive X' is directed onshore). We calculate the sum of the slip for each transect and then normalized these by the maximum sum of transect. The origin of X' is at along the maximum sum of transect. Overall, the normalized sum of each transect decays shoreward, except for the 2010 Chile v2 event (line (7) in Fig. 3b). The thick line is the average normalized slip for all cases excluding the 2010 Chile v2. For simplicity, we assume that all normalized slip distributions along Y' have the same normalized slip distribution as the peak slip as shown in Fig. 2b. We can then extend the peak slip distribution to the other transects by multiplying the average slip decay ratio, thereby generating a 3-D slip distribution. Application of this method will be discussed in the context of the CSZ event in Subsection 2.3.

2.2 Relation between earthquake intensity and rupture area

The seismic moment (M_0) and moment magnitude (M_w) are representative scale factors to parameterize the intensity of an earthquake. M_0 is defined as

$$M_0 = \mu S \bar{D} \quad (2)$$

where μ is the shear modulus of the rock adjacent to the fault plane and S and $\bar{D}$ are the rupture area and mean slip over the rupture area, respectively. The increase of both rupture area and slip displacement varies linearly with the seismic moment. The moment magnitude M_w is related to the seismic moment M_0 by the following relationship (e.g., Hanks and Kanamori, 1979).

$$M_w = \frac{2}{3}(\log_{10} M_0) - 10.7 \quad (3)$$

Murotani et al. (2008) showed a positive correlation between rupture area and seismic moments from past tsunami events in Japan, suggesting a logarithmic fit between seismic moments and rupture area. However, the data for the fitting curve originated for relatively small magnitude earthquakes ($M_w < 8.5$). Recently, Murotani et al. (2013) modified their previous work by including larger events ($M_w > 8.5$), and their modified fitting curve is

$$S = 1.34 \times 10^{-10} M_0^{2/3} \quad (4)$$

Fig. 4 shows the relation between the rupture area and the moment magnitude. The solid line presents the fitted curve of Murotani et al. (2013) given by Eq. 4. The dots and crosses show the data from Murotani et al. (2008) and Murotani et al. (2013), respectively. Since their works mostly focused on earthquakes in Japan, we add 11 additional inversion model results from the studies listed in Table 2 (asterisk) using a constant shear modulus ($\mu = 4 \times 10^{10} \text{ N/m}^2$). We find a similar fitting curve (dotted line) using the same format of Murotani et al. (2013) which can be given by

$$S = 1.20 \times 10^{-10} M_0^{2/3} \quad (5)$$

Both Eq. 4 and 5 indicate that there is a positive correlation between rupture area and seismic moment. We plot two additional curves as a possible upper and lower limits by multiplying factors 2.0 and 0.5, respectively, to Eq. 4. We find that most inversion model results are located between these lower and upper limits (dashed lines in Fig. 4). If we assume that the next earthquake on the CSZ has a specific

rupture area, we can estimate a reasonable range of the intensity of the earthquake on the CSZ from Fig. 4. It is reported that the maximum full rupture length of the CSZ is approximately 1,000 km from Vancouver Island to northern California, with a rupture width of approximately 120 km (Wang et al., 2003, Witter, et al., 2013). With the given rupture area at the CSZ (filled circle at Fig. 4), the corresponding M_w is nearly 9.0. If we consider the both upper and low limits of rupture area (dashed lines), the range of M_w for the CSZ full-rupture event is approximately $8.6 < M_w < 9.3$. This range is similar to that estimated by Satake et al. (2003) for the most recent CSZ event of 1700 and for the range of values reported by Witter et al. (2013).

Fig. 4. Scaling relationship of rupture area with respect to the moment magnitude. Solid line is the fitting curve (Eq. 4) and dotted line is updated fitting curve in this study (Eq. 5). Blue dashed lines show upper and lower bounds by multiplying Eq. 4 by 2.0 and 0.5, respectively. Red dots present the data from Murotani et al. (2008), and cross symbols are data from Murotani et al. (2013). Asterisk symbols present the data by authors from Table 2, and black solid circle indicates the maximum rupture area at the CSZ (1,000 km $\times$ 120 km).

Table 2. Summary of recent events to update work of Murotani et al. (2013).

Event	M_0 [10^{21} Nm]	M_w [-]	S [10^3 km 2]	Reference
2003 Hokkaido	1.7	8.0	35.2	Yagi, 2004
2004 India Ocean	76.0	9.2	142.4	Grilli et al., 2007
2006 Kuril Island	5.0	8.3	56.0	Baba et al., 2009

2007 Kuril Island	2.6	8.2	22.4	Lay et al., 2009
2007 Solomon Island	2.3	8.2	30.0	Baba et al., 2008
2007 Southern Sumatra	4.2	8.4	70.0	Lorito et al., 2008
2007 Southern Sumatra	4.3	8.4	76.6	Ji, 2011b
2010 Chile	24.0	8.8	120.0	Shao et al., 2015
2011 Tohoku	49.0	9.0	156.0	Hayes, 2011
2011 Tohoku	57.5	9.1	125.9	Shao et al., 2011
2011 Tohoku	39.0	9.0	100.0	Ammon et al., 2011

2.3 Development of a new fault slip method

Our fault slip model for tsunami generation is parameterized by the moment magnitude of earthquake, M_w , the peak slip location, α' , and the slip shape, β' . To generate possible near-field tsunami scenarios at the CSZ, we assume a full-rupture event with the moment magnitude in the range $8.6 < M_w < 9.3$. Although there are more frequent smaller intensity earthquakes at the CSZ ($M_w < 8.6$), especially near southern portion of the CSZ (Nelson et al., 2006), these slip distributions are concentrated on the southern portion and induce a relatively weaker impact on study area. Furthermore, we assume that the slip distributions will follow the Gaussian shape given in Eq. 1. We will discuss the effect of the locations of peak slip and shape of slip for intensity of tsunami on Seaside in Subsection 3.3.

After determining the specific moment magnitude, (e.g. $M_w = 9.0$), we determine three slip shape (β') for each M_w scenarios. For that, we calculate seismic moment (M_0) of the specific moment magnitude from Eq. 3, then calculate the potential rupture area (S) of the seismic moment from Eq. 4, and the mean slip ($\bar{D}$) from Eq. 2. To determine the slip shape (β') of the given rupture area limit (S), we set $\alpha' = 0$, and pick a reasonable β' as an initial trial. With both slip distribution parameters (α' and β') known and with fixed width ($W = 120$ km) for the CSZ, we can generate a single slip distribution along Y' at the peak slip transect. To generate a 3-dimension slip distribution, we extend the profile shape at the peak slip to other cross-profiles by scaling down the slip using an average decay rate of slip (solid line, Fig. 3b). The generated 3-dimension slip distribution has a dimensional rupture length and has non-dimension slip (D'). We multiply the mean slip ($\bar{D}$) to all slip conditions and calculate the seismic moment (M_0) of 3-dimension slip over the rupture area. We iterate this procedure until we find the desired seismic moment (e.g. $M_w = 9.0$) and determine the final β' . In this procedure, we use a constant shear modulus, $\mu = 4 \times 10^{10}$ N/m². We also perform the same procedure to determine β' for both the upper and lower limits of S which ($2S$ and $S/2$, respectively) to obtain three possible slip shape parameters (β') for each moment magnitude.

2.4 Tsunami scenarios at the CSZ

We constrain the earthquake intensity in the range $8.6 < M_W < 9.3$ from the relation between the maximum rupture area and moment magnitude shown in Section 2.2. This range of moment magnitude agrees with the range of CSZ events which occurred with a full-length rupture condition during the past 10,000 years (Goldfinger et al., 2012). To discretize the possible M_W conditions in this range, we consider three moment magnitudes $M_W = 8.8, 9.0$, and 9.2 . Following the tsunami generation model procedure mentioned at Section 2.3, we calculate the three slip shape parameters (β') for each moment magnitude. We use eight possible locations for the peak slip ($\alpha' = 0.15, 0.25, 0.35, 0.45, 0.55, 0.65, 0.75$, and 0.85). The full-length rupture length, L , is 1,000 km, and we exclude both the north and south boundary limits ($\alpha' = 0.05$ and 0.95) as peak slip locations. A total of 72 scenarios (three moment magnitudes times three slip shapes times eight locations) are proposed here for the full-length rupture CSZ event. Fig. 5 shows the logic tree for a full-rupture CSZ event, and Table 3 lists the details of the model parameters.

Fig. 5. Logic tree of the CSZ event at Seaside, OR.

Table 3. Summary of slip distribution parameters and weighting factors

$M_W (P_W)$	$\beta' (P_W)$	$\alpha' (P_W)$	N_S
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9.2 (0.06)	1.34 (0.25), 2.45 (0.5), 5.00 (0.25)	0.15 – 0.85 (0.125)	24
9.0 (0.68)	0.81 (0.25), 1.73 (0.5), 3.46 (0.25)	0.15 – 0.85 (0.125)	24
8.8 (0.26)	0.52 (0.25), 0.98 (0.5), 2.00 (0.25)	0.15 – 0.85 (0.125)	24

^{a)} $\alpha' = 0.15, 0.25, 0.35, 0.45, 0.55, 0.65, 0.75, \text{ and } 0.85$

Since each of the 72 scenarios does not have an equal probability of occurrence, it is necessary to provide a weighting factor (P_w) for each scenario. During the past 10,000 years, a total of 19 full-length rupture CSZ events are considered to have occurred based on turbidite data (Goldfinger et al., 2012). The intensity of each of the 19 events was estimated from the density of turbidite (Priest et al., 2010; Goldfinger et al., 2012; Witter et al., 2103). Witter et al. (2013) suggested five sizes of earthquake intensity and an associated time interval: Small (300 years), Medium (425 – 525 years), Large (650 – 800 years), Extra-large (1,050 – 1,200 years), and Extra Extra-large (1,200 years). Of the 19 events, only one event is classified as Extra extra-large and Extra-large, and we relate this to a M_w 9.2 scenario. Thirteen events are classified as Medium and Large, and we relate these to M_w 9.0. The last five events are classified as Small, and we relate these to M_w 8.8. We applied weighting factors (P_w) based on these estimated occurrence rates, so the M_w 9.2, 9.0 and 8.8 scenarios has a weighting factor of 0.06 (1/19), 0.68 (13/19), and 0.26 (5/19), respectively.

In case of the weighting factors of slip shapes, we set 0.5 for the middle steepness shape which is estimated from the S (Eq. 4), and applied 0.25 for other two which are estimated from the upper and lower limits ($2S$, and $S/2$). In case of weighting factors for the peak slip location, we set an equal weighting factor (0.125) for all. These default weighting factors, particularly for slip shape and location are subjective and based on the opinions of the authors. The methodology can be re-weighted if sufficient data become available to determine the specific weighting factors for each scenario.

Fig. 6a, b, c shows examples of full-rupture scenarios at the CSZ for M_w 8.8, 9.0, and 9.2, respectively, for three slip shapes (β') at a given peak slip ($\alpha' = 0.35$). The solid line represents the smallest β' which generates the narrowest slip shape per each M_w scenario. Blue dash and red dot line presents the middle and largest values of β' . As β' increases, the rupture length increases and correspondingly the peak slip decreases. This is significant, for example, because for a given moment magnitude as β' decreases, the resulting tsunami energy will be concentrated at a particular location along the CSZ. The range of peak slip among three slip shapes were 10 – 40 m ($M_w = 8.8$), 15 – 54 m ($M_w = 9.0$), and 22 – 59 m ($M_w = 9.2$). Overall, the displacement of slip over the rupture area increases as the moment magnitude increases. Note that in implementing this methodology in the next section, the

continuous curves shown in Fig. 6 are discretized at each sub-fault, resulting in a stair-step distribution, similar to what is shown in Fig. 2a, c, e.

Fig. 6. Examples of the slip shapes at peak slip transect for (a) M_w 8.8, (b) M_w 9.0, and (c) M_w 9.2 with $\alpha'=0.35$. Solid line presents the smallest β' among three β' per each M_w scenarios. Blue dash and red dot line presents the middle and largest β' , respectively.

3. Numerical model setup for tsunami generation, propagation, and inundation

3.1 Numerical models

In this study, we use the ComMIT/MOST model for the tsunami generation and propagation analysis (Titov et al., 2011), and utilized COULWAVE (Lynett et al., 2002) for the inundation analysis. Fig. 7 shows the numerical model bathymetries and grid maps applied for this study. The ComMIT/MOST model is based on the non-linear shallow water equations implemented with a finite difference scheme. The tsunami generation model is embedded using the Okada (1985) elastic dislocation model. The ComMIT/MOST model has been verified with benchmark tests based on field observations and laboratory experiments (Synolakis et al., 2008). The model is maintained by the NOAA Center for Tsunami Research (NCTR) and is used for tsunami forecasting and mapping due to its accuracy and high calculation speed (Titov et al., 2011). It also has been applied for the PTHA study in Seaside, Oregon, by

González et al. (2009) and for the damage estimation of building at Seaside for a set of hypothetical tsunamis M_W 8.8 – 9.2 with a uniform distribution by Wiebe and Cox (2014).

COULWAVE solves a set of Boussinesq equations and includes bottom friction effects with a high-order finite-volume method. It has been validated with fundamental benchmark problems for the run-up and inundation problem using both field and experimental data including velocity and momentum flux on inundation zone (Lynett et al., 2002; Lynett and Liu, 2005) and to investigate the inundation through macro-roughness due to the built environment (Park et al., 2013).

3.2 Model setup

We employ our new method of determining the spatially varying slip conditions (Fig. 5, 6 & Table 3) and apply these as a discretized slip fault as an input to the ComMIT/MOST model. Fig 7a shows the unit sub-fault utilized in ComMIT/MOST along the CSZ. A total of 27 sub-faults are arranged along the CSZ in ComMIT/MOST, each with 100 km unit length and 50 km unit width. Each sub-fault has a constant but spatially varying strike, dip and depth conditions. The rake is fixed as 90° for all sub-faults. The detailed parameters for each sub-fault are provided in Table 4 (Appendix). The tsunami generation and propagation analysis have performed by ComMIT/MOST model and it consists of three nested grids: A-Grid, B-Grid, and C-Grid (Fig. 7a, b, and c). The ComMIT/MOST model output from the C-Grid is not used and is replaced by the COULWAVE results.

Fig. 7. Numerical model bathymetry and grid map for (a) A-Grid, (b) B-Grid, and (c) C-Grid.

For the inundation analysis, we utilized the ComMIT/MOST model output of the B-Grid for the input seaward boundary condition for COULWAVE using the C-Grid for the final inundation. The bathymetry data were obtained from NOAA's National Geophysical Data Center (NGDC). The Coastal Relief Model from the NGDC was used to construct the A-Grid and B-Grid. The Digital Elevation Model for the Seaside area was used for the C-Grid. The size and dimension of each A, B, and C-Grids were 1 min (400×400), 3sec (800×800), and 24 m (416×390), respectively. There are two observation points A and B identified in the C-Grid in Fig. 7c. Point A is located near the seaward boundary of the C-Grid where the water depth was $z = -35$ m, and Point B was located at the shoreline $z = 0$ m at Seaside.

The tide condition at the time of tsunami event is the one of aleatory uncertainties for the tsunami hazard assessment (Geist and Parsons, 2006; González et al., 2009). However, we only focus on the one

of the aleatory uncertainty due to the slip distributions, so the DEMs are referenced to mean high water (MHW) to provide a conservative estimate of tsunami hazards (e.g., Wiebe and Cox, 2014).

Fig. 8a shows a satellite image of the Seaside study area. The flow (free surface and velocity) is computed everywhere in the domain, but we indicated Point B from Fig. 7c and nine representative inland observation points to be presented in detail in this study. Fig. 8a (inset) lists the ground level of the observation points referenced to MHW. Points 1 – 3 are aligned parallel to the shoreline and are located west of the Necanicum River, Points 4 – 6 are also shore parallel and located between the Necanicum River and Neawanna Creek, and Points 7 – 9 are shore parallel and located east of the Neawanna Creek. The urban center of the city is located near the Points 2 and 5. Fig. 8b shows the detailed bathymetry at the same region as Fig. 8a. The black contour lines show the zero elevation referenced to MHW, and red dot lines show the contours 3 m above MHW. The bathymetric and topographic conditions of Seaside make it particularly vulnerable to tsunami inundation due to low elevations and the two streams crossing the town (Tsunami Pilot Study Working Group, 2006).

Fig. 8. (a) Satellite image of Seaside, OR with representative observation points and (b) detail bathymetry applied in COULWAVE. Dotted lines in Fig. 8b present 3 m contours above the MHW.

3.3 Example of model output time series at Points A and B.

Figure 9 shows inundation time series for the three scenarios presented in Fig. 6b. The scenarios are for the same intensity (M_W 9.0) and peak slip location ($\alpha'=0.35$), but three different slip shapes, $\beta' = 0.81$ (black solid), 1.73 (blue dash) and 3.46 (red dash-dot). Fig. 9 shows time series of (a) the free surface elevation (η) at Point A, (b) the inundation depth, h , at B, (c) velocity, V , at B and (d) the momentum flux, $M = hV^2$, at B. Here, the inundation depth (h) is the net elevation of the free surface elevation (η) above the local land elevation (z) over the inundation area. In regions submerged below the MHW, the inundation depth h is defined to be the water level η above MHW. In other words, $h = \eta - z$ at sea. $h = d$ at sea.

Fig. 9. Time series of (a) free surface elevation, η , at point A, (b) inundation depth, h , (c) velocity, V , and (d) momentum flux, M each at Point B. Scenarios are for $\beta' = 0.81$ (black solid), 1.73 (blue dash) and 3.46 (red dash-dot) with M_W 9.0 and $\alpha'=0.35$.

The first peak of the free surface elevation at Point A is observed at 30 min after the initial surface deformation, and the second peak of the free surface elevation is observed at 120 min (Fig. 9a). The intensity of the peak is sensitive to β' but the arrival time is not. A short time later, the peak of the free surface elevation arrives at Point B (Fig 9b) and the corresponding maximum velocity and momentum flux are found during this first peak (Fig 9c, d). Although each scenario has the same moment magnitude and peak slip location, the largest intensity is found for $\beta' = 0.81$ (black solid line) correspond to the narrowest shape condition with the highest peak slip (54 m). The smallest intensity is found for $\beta' = 3.46$ (red dash dot line) which corresponds to the widest shape with the lowest peak slip (15 m). This highlights how slip shape affects the tsunami hazard intensity. It is noted that the arrival time of the peak is relatively insensitive to β' compared to the magnitude of the peak. Moreover, the maximum of the momentum flux varies by an order of magnitude for the scenarios shown.

To evaluate the sensitivity of hazards due to the moment magnitude of earthquake, slip shapes, and locations of the peak slip, the characteristics of surface elevation at Point A are shown in Fig. 10. Fig. 10 shows (a) the maximum surface elevation η_{Max} (b) representative period of tsunami, T_R , and (c) Iribarren number, ξ at Point A. Fig. 10d shows the regional map of Seaside, OR with the latitude position of the peak slip from the north to south ($\alpha' = 0.15 - 0.85$). Each triangle, square, and circle presents the three slip shape parameter (β') for each M_W scenario from the narrow (the smallest β') to wide (the largest β') slip shape, and each black, yellow, and white color presents three moment magnitudes such as M_W 8.8, 9.0 and 9.2. Note that the x-axis of Fig 10a, b, and c indicates the origin (latitude) of the peak slip, not the location of the inundation. In other words, all of the values shown in Fig. 10a, b, and c are computed at Point A in the C-grid as shown in Fig. 7c. Point A, is at 46 degree latitude and due west of the study area as shown in Fig. 7c.

Fig. 10. Initial tsunami wave conditions at the COULWAVE model boundary (Point A, in Fig. 7) for the CSZ tsunami scenarios against the latitude positions of peak slip. Panel a, b, and c shows the maximum surface elevation (η_{Max}), representative period of tsunami (T_R), and Iribarren number (ζ) of 72 scenarios. Panel d shows the regional map of Seaside, OR. Top x-axis of panel d shows the eight peak slip location in terms of α' . Symbols represents a different β' as triangle (smallest β'), square, and circle (largest), and color presents a different M_W 8.8 (white), 9.0 (yellow), and 9.2 (black).

Fig. 10a shows η_{Max} along the eight peak slip locations. Generally the higher η_{Max} is observed at the highest moment magnitude conditions (M_W 9.2) and narrowest slip shape (triangles). The maximum η_{Max} is found at $\alpha' = 0.35$ for M_W 9.2 and $\beta' = 1.34$. The overall range of η_{Max} for all 72 scenarios is 0.2 to 18 m. Among the same peak locations, the largest deviation of η_{Max} is found at $\alpha' = 0.35$, while the smallest deviations are found at $\alpha' = 0.85$, which means that the sensitivity of M_W and slip shape are significant as the peak slip is located near the target area and vise-versa. As it was referred earlier, we observe that η increases as the shape of slip becomes narrower at $\alpha' = 0.35$ (Fig. 9a). We also find a similar pattern at $\alpha' = 0.45$ and 0.55 in Fig. 10a where the study area (Seaside, OR) is closest to the peak slip. However, this pattern is reversed when the location of the peak slip is far from the target area. We

find that the widest shape condition (circle) among three shapes results in the highest η_{Max} at the study area when the peak slip locations are further from the study area at $\alpha' = 0.15, 0.75$ and 0.85 .

Fig. 10b shows the variations of representative tsunami period, T_R , where T_R is the duration of the surface elevation exceeding 1% of the peak amplitude (e.g. Park et al., 2015). The overall range of T_R is 10 to 70 min, and T_R changes due to the different slip distributions. T_R shows small deviation when the peak slip is closest to the target area (at $\alpha' = 0.35$, and 0.45).

Fig. 10c shows the Iribarren number (ζ) which is a function of slope, η_{Max} and T_R . The Iribarren number relates to the type of tsunami waves (breaking or non-breaking) and can be used to estimate the tsunami run-up (Fuhrman and Madsen, 2008; Madsen and Schaffer, 2010; Park et al., 2015). Here we evaluate ζ following the notation of Park et al. (2015) which is

$$\zeta = \frac{\gamma}{\sqrt{2\eta_{Max} / (gT_R^2 / 2\pi)}} \quad (6)$$

where g is gravity acceleration, and γ is the slope from shoreline to 100 m water depth (approximately 1/170 for Seaside). Overall, ζ is less than 0.5 for most scenarios and it is classified as a breaking tsunami wave condition. Fig. 2.10c shows that ζ is uniformly small when the location of peak slip is near the study area, and that there is large deviation in ζ as the peak slip location is further from the study area, particularly to the south.

Fig. 11 shows the five intensity measures (IMs) at Point B for the 72 scenarios plotted against the latitude of the peak slip using a similar format with Fig. 10. Fig. 11a – e shows the maximum inundation depth (h_{Max}), velocity (V_{Max}), momentum flux (M_{Max}), the first arrival time of exceeding a 1 m inundation depth (T_A), and the total duration exceeding 1 m inundation depth (T_h), respectively. Generally, each IM shows a large deviation depending on the scenario. The largest deviations are found for M_{Max} , especially when the location of peak slip is close to target area ($\alpha' = 0.35$, and 0.45). Deviations for M_{Max} decrease as the location of peak slip is far from the target area ($\alpha' = 0.75$, and 0.85), consistent with our observation of η_{Max} in Fig. 10. Observations for T_A show the opposite trend, where the smallest deviations in T_A are observed when the location of slip is close to the target area and the deviations in T_A increase as the peak slip is further away the target area. The minimum arrival time is $T_A = 20$ min, and most values of T_A are less than 50 min with the exception of a few scenarios whose peak slip located at the south (e.g. $\alpha' = 0.75$, and 0.85). Overall, the IMs are sensitive to moment magnitude, slip shape and peak location. These variations in the IMs represent the aleatory uncertainty involved in the tsunami generation process. This

work highlights the necessity to consider various slip shapes and locations of the peak slip for probabilistic tsunami hazard assessment.

Fig. 11. Tsunami IMs at the shoreline of Seaside, OR (Point B) for all scenarios against the latitude positions of peak slip for (a) inundation depth (h_{Max}), (b) velocity (V_{Max}), (c) momentum flux (M_{Max}), (d) arrival time exceeding 1 m inundation depth (T_A), and (e) total duration exceeding 1 m inundation depth (T_h). Symbols are the same as Fig. 10.

4. Probabilistic near-field tsunami hazard assessment (PTHA)

4.1 Methodology of PTHA

We assume that the occurrence rate, ν , of the tsunami hazard follows the Poisson arrival process (Cornell, 1964). Admittedly, this is a somewhat crude assumption and neglects the complex subduction zone processes. Nevertheless, this assumption is consistent with what is considered in seismic engineering

(McGuire, R.K., 2004) and provides a reasonable starting point for this study. The probability, P , of a number of events, N , in a fixed time, t , can be given as

$$P[N = n] = \frac{e^{-\nu t} (\nu t)^n}{n!}, \quad n = 0, 1, 2, \dots \quad (7)$$

when those events occur n times with a known average occurrence rate (ν) and independently of the time since the last event. The probability of the maximum hazard exceeding a certain level of that hazard is equal to the probability of at least one event occurring during t , and can be expressed as

$$P[\text{Hazard} > \text{hazard}_i] = 1 - e^{-\nu t} \quad (8)$$

where the subscript i describes the specific level of hazard or particular hazard bin used for the analysis. In case of the maximum inundation depth (h_{Max}), the exceedance probability of the specific inundation depth (h_i) during the time, t is

$$P[h_{Max} > h_i] = 1 - e^{-\nu t} \quad (9)$$

The mean occurrence rate is

$$\nu = -\ln(P[h_{Max} \leq h_i]) / t \quad (10)$$

where $P[h_{Max} \leq h_i]$ is the non-exceedance probability of the maximum inundation depth over a specific inundation depth (h_i) and ν denotes the mean occurrence rate of the tsunami hazard.

To find the mean occurrence rate (ν) of a tsunami conditioned on a full-rupture CSZ event, we can estimate $t = 526$ year since there were 19 full-rupture events identified in the past 10,000 years (Witter et al., 2013). Using the discretized form of Eq. 10 for each moment magnitude scenario (M_w 8.8, 9.0, and 9.2), the sum of each mean occurrence rate (ν) in Eq. 10 are

$$\nu_{M_w=8.8} = -\ln(P[h_{Max} \leq h_i] | M_w = 8.8) / t \quad (11)$$

$$\nu_{M_w=9.0} = -\ln(P[h_{Max} \leq h_i] | M_w = 9.0) / t \quad (12)$$

$$\nu_{M_w=9.2} = -\ln(P[h_{Max} \leq h_i] | M_w = 9.2) / t \quad (13)$$

Here, we set the unit bin of the inundation depth (h_i) equal to 0.2 m. Total sum of each mean occurrence rate (ν) is calculated by the sum of each discretized mean occurrence rate with a weighting factor and is given by.

$$\nu = \sum \nu_{M_w} \cdot P[M_w] \quad (14)$$

where $P[M_w]$ is the weighting factor. For this analysis, the weighting factors for each moment magnitude are shown in Fig. 5 and Table 2.3 and are 0.06 for M_w 8.8, 0.68 for M_w 9.0, and 0.28 for M_w 9.2.

Fig. 12 shows an example of the non-exceedance probability of the maximum inundation depth at Point B for M_w 8.8 (green circle), 9.0 (blue square), and 9.2 (red triangle). Each discrete point shows the non-exceedance probability for a given scenario reflecting variations in slip distribution weighting factors described in Fig. 5 and Table 3.

Fig. 12. Non-exceedance probability of the maximum inundation depth at Point B with the given three moment magnitudes. Each symbol presents the scenarios with M_w 8.8 (green circle), 9.0 (blue square), and 9.2 (red triangle).

As an intermediate step, Fig. 13 presents the mean occurrence rate (ν) of the maximum inundation depth at Point B corresponding to Figure 12. The dash-dot, dash, and dot lines represent mean

occurrence rate of M_w 8.8, 9.0, and 9.2, and the solid black line shows the total mean occurrence rate (ν) from Eq. 14 with the correct weighting factors.

Fig. 14 shows the annual exceedance probability of the maximum inundation depth at Point B using Eq. 9 with the total mean occurrence rate ν from Eq. 14 shown as the solid black line in Fig. 13. In Fig. 14, the x -axis is the maximum inundation depth and the y -axis is the probability that an inundation depth will exceed h_{Max} in a given year at Point B conditioned on the CSZ event of M_w 8.8 to 9.2. For example, there is a 0.001 annual probability of exceeding a 9.2 m inundation depth at Point B (nominally called the “1,000-year event”), and 0.002 annual probability of exceeding a 6.4 m inundation depth at point B (“500-year event”). It is worth noting that for this work, the probability is conditioned on the CSZ event with the full-length rupture area, and if additional tsunami sources were considered (including other near-field and all far-field sources), the exceedance probability curve would be different.

Fig. 13. Total mean occurrence rate of the max inundation depth at Point B (thick solid line). Three thin lines present the mean occurrence rate of the scenarios with M_w 8.8 (green dash-dot), 9.0 (blue dash), and 9.2 (red dot).

Fig. 14. Annual exceedance probability of the maximum inundation depth at Point B.

The same procedure from Eq. 9 to 14 can be performed for all IMs throughout the inundation area. For illustration, we will present the annual exceedance probability at Points 1 through 9 (Fig. 8a) using the following unit bin for each IM: h_{Max} (0.2 m), V_{Max} (0.1 m/s), M_{Max} (1.0 m³/s²), T_A (0.5 min), and T_h (0.5 min). In addition, we consider the Froude number, F , at the time of the maximum momentum flux to examine the relation among inundation depth, flow velocity, and exceedance probability. For this study, the Froude number is defined as

$$F = \frac{V_m}{\sqrt{gh_m}} \quad (15)$$

where subscription, m denotes the value at the time of the maximum momentum flux. The unit bin of F is 0.1 for these examples.

4.2 PTHA results at observation points

Fig. 15 shows the annual exceedance probability (P) of the five IMs and the Froude number at Point 1 (black solid), Point 2 (red dash), and Point 3 (blue dash-dot). These observation points are oriented parallel to the shoreline and located between the shoreline and the Necanicum River. The

elevations are 3.71, 2.12, and 2.40 m above MHW for Points 1 to 3, respectively (Fig. 8). The figure shows the annual exceedance probability for (a) the maximum inundation depth, (b) velocity, (c) momentum flux, (d) duration, (e) arrival time, and (f) Froude number.

Fig. 15. Annual exceedance probability of (a) h_{Max} , (b) V_{Max} , (c) M_{Max} , (d) T_h , (e) T_A , (f) Froude number, F at Points 1 (black solid), 2 (red dash), and 3 (blue dash-dot).

The IMs generally increase as the annual exceedance probability decreases, and the figure shows a qualitatively similar pattern of distribution among the three observation points because of the similar

bathymetric conditions and distance from the shoreline. The arrival time (T_A), however, shown in Fig. 15e, shows a different distribution compared to the others. The arrival time is less sensitive to the exceedance probability, and the maximum momentum flux (M_{Max}) is the most sensitive. For example at Point 2, h_{Max} changes from 1.7 m for $P = 0.002$ to 4.8 m for $P = 0.001$, an increase of about a factor of three, while M_{Max} changes from $4.5 \text{ m}^3/\text{s}^2$ for $P = 0.002$ to $49.2 \text{ m}^3/\text{s}^2$ for $P = 0.001$, an increase of order of magnitude. However, the arrival time decreases from $T_A = 41 \text{ min}$ to $T_A = 39 \text{ min}$, a decrease of about 5% over the same range of exceedance probabilities. Another notable observation of Fig. 15 is that the duration (T_h) at Point 1 is significantly less compared with the other two points (Fig. 15d). For example, for $P = 0.001$ at Point 1, T_h is approximately 10 min, while Point 2 and Point 3, T_h is more than 60 min. This difference occurs because Point 1 is approximately 1.5 m higher than other two observation points. Thus, Point 2 and 3 are more likely to be submerged due to their low elevation conditions. This information may be relevant, for example, for search and rescue operations and highlights that while the initial tsunami intensity may be similar in some cases (Fig. 15a, b, c), the system may have different responses. Fig. 15f shows the Froude number at the time of maximum momentum flux. For most of the conditions, F is less than 1.0 with the lowest limit of 0.4 at three observation points. This suggests that the flow is subcritical at the time of the maximum momentum flux, and these values are generally consistent with the observation from 2011 Tohoku tsunami (Fritz et al., 2012).

Fig. 16 provides the annual exceedance probability of the five IMs and the Froude number at Point 2 (black solid), 5 (red dash), and 8 (blue dash-dot). These points are aligned shore-normal along the urban center of Seaside from the shoreline to the inland (Fig. 8). Point 2 is located between the shoreline and the Necanicum River, Point 5 is located between the Necanicum River and Neawanna Creek, and Point 8 is located between Neawanna Creek, and the edge of inundation zone. Each panel has the same format as Fig. 15. Generally, the largest hazard intensity is found at Point 2 (closest to the shoreline) and decreases landward toward the edge of the inundation zone. For the maximum inundation depth in Fig. 16a, the three observation points show different trends for more frequent events (e.g., $P = 0.0005$) with small inundation depths ($h_{Max} < 4 \text{ m}$). However, for lower probability events with larger inundation depths in the range $5 < h_{Max} < 10 \text{ m}$, Points 5 and 8 have nearly the same exceedance probability for a given inundation depth in this range. This is due to local bathymetric effects, including effects of the river and creek effects at Points 5 and 8. On the other hand, the velocity (Fig. 16b) does not show a similar trend: the three curves are distinct for each location. Similarly, the momentum flux (Fig. 16c) also shows three distinct curves. We also found a similar and more distinct pattern between Point 4 ($z = 4.12 \text{ m}$) and

7 ($z = 1.39$ m) where Point 7 has a much lower elevation and is close to the Neawanna creek. This observation underscores the importance of understanding more than just the inundation depth during the tsunami inundation. For example, when trying to estimate damage to the built environment within this zone, the sharp gradation in momentum flux for a given value of P shown in Fig. 16c suggests that there should be a corresponding gradation of damage (assuming a constant building type, for example) if the damage is related to the momentum flux. Fig. 16a, on the other hand, suggests that there would be little difference in observed damages between Point 5 and 8 (4 and 7) because the inundation depths are similar for a given value of P .

Fig. 16. Annual exceedance probability of the h_{Max} (panel a), V_{Max} (panel b), M_{Max} (panel c), T_h (panel d), T_A (panel e) and Froude number, F (panel f) at Points 2 (black solid line), 5 (red dash line), and 8 (blue dash-dot line).

Fig. 16d shows significant variations in the duration of inundation T_h . For $P = 0.0001$, for example, $T_h = 140, 70$, and 35 min along Point 2, 5, and 8, respectively. In other words, there is about a factor 2 difference in the inundation duration between Point 5 and 8 even though the maximum inundation level is about the same (Fig. 16a). Fig. 16e shows that the arrival time T_A increases from Point 2 to 8. In other words it takes longer for the tsunami to reach further inland. Although this result is

somewhat expected, it shows that the presence of the Necanicum River and Neawanna Creek does not have a significant effect on the tsunami arrival time. This is because the river and creek are shallow (0.5 to 2.0 m from NAVD88) and do not allow the bore to propagate upstream quickly. Instead, the main bore exceeding 1 m depth is due to the inundation from the shoreline. Fig. 16f shows that the Froude number decreases from the shoreline landward for a given value of P . The Froude number is generally in the range $0.1 < F < 1.0$ and is subcritical at the time of maximum momentum flux.

4.3 Spatial distributions of IMs for Seaside, OR

Fig. 17a, b shows the spatial distributions of the maximum inundation depth at Seaside, Oregon, based on the $P = 0.002$ (“500-year”) and 0.001 (“1,000-year”) exceedance probabilities, respectively. The solid line shows the MHW. The dotted line in each panel shows the maximum inundation limit, defined here as the contour line for which is $h_{Max} = 0.3$ m. In both cases, h_{Max} is largest at the shoreline and decreases as it inundates across the shoreline, particularly the first 100 m of shoreline. It is noted that h_{Max} is larger near the Necanicum River and reaches a value of 6 m for $P = 0.001$. In general, though, the maximum inundation depth is somewhat uniform at about 5 m for much of the inundation zone, consistent with Fig. 16a.

Fig. 17. Spatial distributions of h_{Max} for (a) $P = 0.002$ and (b) $P = 0.0001$.

Fig. 18a, b shows the spatial distributions of the maximum velocity for $P = 0.002$ and 0.001 , respectively. The dotted line contour is set for $V_{Max} = 0.3$ m/s. Similar to Fig. 17, the velocity is strongest at the shoreline. There is also large velocity in the center of peninsula between the shoreline and the Necanicum River. The velocity within the river running parallel to the shoreline, however, is not strong. The maximum velocity in the mouth of river is strong, and large scour would likely develop here.

Fig. 18. Spatial distribution of V_{Max} for (a) $P = 0.002$ and (b) $P = 0.001$.

Fig. 19a, b shows the spatial distributions of the maximum momentum flux for the two cases. The dotted contour line is $M_{Max} = 1 \text{ m}^3/\text{s}^2$. Similar to the maximum velocity in Fig. 18, the momentum flux is strongest at the shoreline and decreases as the tsunami reaches the Necanicum River (Fig. 19b). The maximum momentum flux abruptly decreases near the river and shows a larger deviation over the inundation region compared to the inundation depth or velocity. The momentum flux in the range $0 < M < 70 \text{ m}^3/\text{s}^2$ at the inundation area. For a typical wood frame residential structure, according to a FEMA study (FEMA, 2013), there is a 50% probability of complete damage with the momentum flux is $M = 25 \text{ m}^3/\text{s}^2$. For steel reinforced concrete, a similar probability of complete damage would occur for $M = 150 \text{ m}^3/\text{s}^2$.

Fig. 19. Spatial distribution of M_{Max} for (a) $P = 0.002$ and (b) $P = 0.001$.

Fig. 20a, b shows the spatial distribution of the total duration exceeding a 1 m inundation depth (T_h) for the two cases. The dotted line is set with the duration limit of $T_h = 0.5$ min. Fig. 20b, in particular, shows the effect of the low elevation near Necanicum River and Neawanna creek. Here, the inundation duration exceeds more than 100 min and can have significant implications for the immediate response after the event. Moreover, Fig. 20b clearly shows an isolated region (white region) between the Necanicum River and Neawanna creek which would presumably impede immediate response to this area.

Fig. 20. Spatial distribution of T_h for (a) $P = 0.002$ and (b) $P = 0.001$.

5. Discussion

5.1 Uncertainties on the input slip conditions

Our new method to determine the fault slip distribution at the CSZ is developed by utilizing the inversion model results from different study groups, thus the inversion model results may contain epistemic uncertainties from their own inversion process. Some of the inversion models utilized finer resolution of unit sub-faults than our model setup (100 km length, and 50 km width). In this study, we do not attempt to find the certain type of slip distribution which matches with observation data. Instead, we focus on characterizing possible tsunami scenarios at the CSZ considering the effects of varying M_w , location of peak slip, and slip shape. For this study, we used the default setup for sub-faults provided in ComMIT/MOST. Moreover, we considered instantaneous fault rupture along the entire length of the CSZ.

For future work, it would be interesting to evaluate the effect of sub-faults size and a time-dependent rupture scenario.

In addition, there are possible uncertainties resulting from the sub-fault information such as strike, dip, rake and depth (Goda et al., 2014). In our study, we did not account for the effect of variations of the sub-fault information as a possible epistemic uncertainty. We used the constant but spatially varying sub-fault condition, following the embedded tsunami generation model in ComMIT/MOST for the CSZ (Section 7, Appendix). The accuracy of sub-fault information could be further investigated in future studies.

5.2 Uncertainties on the weighting factors

We performed a total of 72 scenarios with the weighting factors for each scenario based on the occurrence rate of the three moment magnitudes of earthquake, eight possible peak slip locations and three slip shapes. The weighting of the moment magnitude was consistent with earlier work (e.g., Witter et al., 2013) and the weighting of the slip shape and location was based on the authors' judgement. Although these are somewhat crude assumptions, we note that a previous PTHA study at Seaside, OR by González et al. (2009) utilized only 12 scenarios with $M_w = 9.1$ conditions for the CSZ without attention to weighting factors. In future studies, the uncertainties involved in the weighting factors may be decreased by modifying or updating the weighting factor based on the relevant studies without the need to re-run the inundation models.

5.3 Uncertainties on the initial conditions of numerical models

We do not include the aleatory uncertainties due to the tide condition. As mentioned earlier, our study assumes a constant mean high water level (MHW) resulting in conservative estimates of the inundation. However, the real tide level may change significantly during the inundation process depending on the bathymetry condition. It may locally accelerate or decelerate IMs, thus the detail interaction of tide and tsunami wave is complex to be modeled exactly.

We applied ComMIT/MOST model for the tsunami generation and propagation analysis, and COULWAVE for the tsunami inundation analysis. Both numerical models may contain uncertainties generated from the computation process due to the input and default model setup. We used a bare-earth bathymetry condition for each model, which means that models do not reflect any structures or vegetation

which create complex flows, sheltering, concentrating or dissipations during real tsunami inundation. In addition, we setup the default friction term as a Manning number, $n = 0.03$ for all models (ComMIT/MOST and COULWAVE). This value may reasonable for the sea bottom, but it is a relatively small value for the inundation over the urban area (Koshimura et al., 2009; Bricker et al., 2015). There are two possible ways to improve the model results. The first one would be to apply a spatial varying Manning number depending on land conditions, and the other is to use a refined mesh to include the structures in the inundation modelling (Park et al., 2013). The fact that the structures are damaged and can be washed away during the inundation event would result in a temporally varying friction factor or grid, adding further complexity to the problem. For simplicity in this study, we utilized a constant Manning number.

6. Conclusions

This study highlights the significance of the uncertainty on tsunami hazards analysis regarding the randomness of the tsunami generation (aleatory uncertainty). We introduce a new method to determine the initial fault slip to simplify the randomness of tsunami slip condition. We determine range of moment magnitudes of earthquakes at the CSZ using the relation between the rupture area and seismic moment of historic tsunami events. We characterize the peak slip locations and slip shapes from inversion model results. We utilize 72 scenarios as tsunami sources with different weighting factors assigned based on the occurrence rate of historic events at the CSZ and slip distributions based on expert opinion of the authors. We estimate the exceedance probability for 5 intensity measures, assuming a Poisson arrival process. The main conclusions of this work are:

1. The new method for the fault slip distributions accounts for some of the aleatory uncertainty in tsunami generation. Using published slip models of recent earthquakes, we characterize the fault slip distribution as a Gaussian distribution with moment magnitude (M_w), and two slip distribution parameters, α' and β' .
2. We perform a probabilistic near-field tsunami hazards assessment (PTHA) at Seaside, Oregon, to illustrate our general methodology and examine five tsunami intensity measures (IMs): the maximum inundation depth (h_{Max}), the maximum velocity (V_{Max}), the maximum momentum flux (M_{Max}), the arrival time exceeding a 1 m inundation depth (T_A), and total duration exceeding a 1 m inundation depth (T_h).

3. The intensity of IMs are observed to increase as the moment magnitude (M_W) increase, as the peak slip location becomes closer to the study area, and as the slip shape becomes narrower.
4. Among the IMs, the arrival time (T_A) shows relatively weak sensitivity to the aleatory uncertainty, while other IMs shows significant sensitivity, especially momentum flux (M_{Max}). We observed that M_{Max} increases by an order of magnitude from the 500-year to 1,000-year event, while h_{Max} increases by a factor of 3 and T_A decreases by a factor of 0.05.
5. The inundation duration T_h can vary due to the local bathymetric conditions and can range a relatively short duration (< 10 min) to a relatively longer duration (~ 100 min) observed near the river and creek where the elevation is closed to the sea-level.

This study provides the probabilistic spatial distributions of each IM at Seaside, Oregon, and can be utilized for damage or loss estimation. In particular, the maximum inundation depth, velocity, or momentum flux are applicable for tsunami building damage estimation at a community scale. Arrival time and duration are utilized for the evacuation planning. Future work may consider a more refined model for tsunami generation, including a refined sub-fault model and a time-varying rupture. Future work for the tsunami inundation model should consider the effects of macro-roughness and a time-varying roughness due to damage during the inundation process.

7. Appendix

The following table provides the geologic information on sub-faults used in the ComMIT/MOST model v. 1.7.0. Each sub-fault is 100 km length and 50 km width. Rake is 90° for all sub-faults. Here each coordinate indicates the left top corner of each sub-fault.

Table 4. Sub-fault information for Aleutian–Alaska–Cascadia Subduction Zone (ACSZ).

Sub-faults	Longitude ($^\circ E$)	Latitude ($^\circ N$)	Strike ($^\circ$)	Dip ($^\circ$)	Depth (m)
acsz-56a	234.0588	49.1702	315	11	12.82
acsz-56b	233.5849	48.8584	315	9	5.00
acsz-56c	234.5230	49.4727	315	18	22.36
acsz-57a	234.9041	48.2596	341	11	12.82
acsz-57b	234.2797	48.1161	341	9	5.00
acsz-57c	235.5249	48.4018	341	14	22.36
acsz-58a	235.3021	47.3812	344	11	12.82
acsz-58b	234.6776	47.2597	344	9	5.00
acsz-58c	235.9298	47.5029	344	11	22.36
acsz-59a	235.6432	46.5082	345	11	12.82
acsz-59b	235.0257	46.3941	345	9	5.00

acsz-59c	236.2591	46.6216	345	13	22.36
acsz-60a	235.8640	45.5429	356	11	12.82
acsz-60b	235.2363	45.5121	356	9	5.00
acsz-60c	236.4860	45.5734	356	14	22.36
acsz-61a	235.9106	44.6227	359	11	12.82
acsz-61b	235.2913	44.6150	359	9	5.00
acsz-61c	236.5211	44.6303	359	15	22.36
acsz-62a	235.9229	43.7245	359	11	12.82
acsz-62b	235.3130	43.7168	359	9	5.00
acsz-62c	236.5213	43.7321	359	16	22.36
acsz-63a	236.0220	42.9020	350	11	12.82
acsz-63b	235.4300	42.8254	350	9	5.00
acsz-64a	235.9638	41.9818	345	11	12.82
acsz-64b	235.3919	41.8677	345	9	5.00
acsz-65a	236.2643	41.1141	345	11	12.82
acsz-65b	235.7000	41.0000	345	9	5.00

756

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9. Nomenclature

Symbol	Descriptions	Unit
D	Fault slip displacement	L
D'	Normalized D by D_p	-
D_p	Peak fault slip displacement	L
dL	Unit rupture length	L
dW	Unit rupture width	L
h	Inundation depth	L
L	Rupture length	L
Lat	Latitude	L
$Long$	Longitude	L
M	Momentum flux	L^3T^{-2}
M_w	Moment magnitude	-
M_0	Seismic moment	ML^2T^{-2}
min	Minute	T
N	Number of occurrence	-
N_s	Numbers of scenarios	-
P	Probability	-
P_w	Weighting factor	-
S	Rupture area	L^2
s	Second	T
T_A	The first arrival time of exceeding 1 m inundation	T
T_h	Duration of exceeding 1 m of inundation depth	T
T_R	Representative tsunami period	T
V	Velocity	LT^{-1}
W	Rupture width	L
X'	Dip direction	L
Y'	Strike direction	L
z	Ground elevation from referenced level	L
α	Mean of Gaussian distribution	L
α'	Peak slip location parameter, normalized α	-
β	Standard deviation of Gaussian distribution	L
β'	Slip shape parameter	-
ξ	Iribarren number	-
η	Surface elevation	L
μ	Shear modulus of the rock	$ML^{-1}T^{-2}$
ν	Mean occurrence rate	-
$(\bar{})$	Mean of ()	-
$()_{Max}$	Maximum value of ()	-