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Probabilistic seismic and tsunami damage analysis (PSTDA) of the Cascadia Subduction Zone applied to Seaside, Oregon.

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Abstract
This study presents a probabilistic seismic and tsunami damage analysis (PSTDA) due to both earthquake shaking and tsunami inundation from tsunamigenic earthquake events at a coastal community. In particular, this study evaluates the annual exceedance probability (AEP) of seismic and tsunami hazards through earthquake and tsunami modeling that share the same fault sources. Then, estimates of earthquake and tsunami impact on the built environment utilizing fragility functions is predicted spatially. The PSTDA evaluates the combined impacts of earthquake and tsunami through a stochastic approach that accounts for the accumulated damage due to seismic shaking and subsequent tsunami inundation. A case study is setup and applied to Seaside, Oregon, for tsunamigenic earthquake events originating from the Cascadia Subduction Zone (CSZ) in order to illustrate the application of the PSTDA evaluation framework. The PSTDA integrates as a step within a resilience-focused risk-informed decision making process, which includes the assessment of direct and indirect socio-economic losses due to tsunamigenic earthquake events.

Keywords
Earthquake damage, Multi-hazard, Probabilistic seismic and tsunami damage analysis (PSTDA), Tsunamigenic, Tsunami damage
1. Introduction

1.1 Multi-Hazards and Damage Analysis

Devastating tsunami events such as the 2004 Indian Ocean, 2009 Samoa, 2010 Chile, and 2011 Tohoku earthquake and tsunamis triggered in the aftermath of large seismic events (M > 8.0) at subduction zones have resulted in significant loss of life and damage to coastal communities (e.g., Papadopoulos et al. 2006, Okal et al. 2010, Fritz et al. 2010, Mori et al. 2011). Tsunami events are typically classified as either far-field (distant) or near-field (local) events, depending on the distance of the source of shaking and generated tsunami to the site of a building or an affected community. In general, a near-field tsunami has the potential to cause greater loss of life and more substantial damage to a community because the arrival time is short (typically less than an hour) and the tsunami intensities, such as run-up height and inundation depth can be relatively high. In addition, for near-field tsunamis, the seismic motion itself can induce direct damage on the built environment before the arrival of the leading edge of the tsunami. This pre-damaged condition can enhance the propensity for infrastructure damage due to the tsunami inundation process. Therefore, it is necessary to consider both the seismic and tsunami effects when evaluating the damage to the built environment as well as potential loss of lives of coastal communities that are susceptible to earthquake and tsunami related hazards.

Deterministic scenario-based hazard and damage assessment has been a popular method to estimate future threats of a tsunamigenic earthquake event because of the relative simplicity of quantifying the damage for selected scenarios rather than the complexity involved with probabilistic-based hazard and damage assessment. However, probabilistic analysis is becoming the preferred form of analysis for hazard, damage, and risk quantification because of the large aleatory and epistemic uncertainties associated with the earthquake and tsunami, which are not captured in deterministic scenario-based assessments, including the definitions of the location, size, and resulting intensity of future earthquake at a specific site of interest.

For seismic hazards, the framework for probabilistic seismic hazards analysis (PSHA) has origins in the 1960s (e.g., Cornell 1968) and has widely accepted methodologies to determine the probabilistic seismic hazard intensity for a range of seismic sources (e.g., McGuire 1995, Kramer 1996). The second step in performance-based earthquake engineering is the
probabilistic seismic demand analysis (PSDA) that is used to estimate the probability that seismic demands of several response parameters exceed threshold values on an annualized basis (Cornell and Krawinkler 2000, Krawinkler 2002), by coupling the seismic hazard and seismic demand conditioned on the ground motion intensity measure \((IM)\) to produce the seismic demand hazard curve. In other words, PSDA is a tool for computing the mean annual rate (MAR) of exceedance of specified seismic response parameters, also referred to as engineering demand parameters (EDPs), for a given structure and a specific site. If the threshold demand values are set to threshold damage limit state values, then damage functions known as fragility functions are developed, which provide the probability of exceeding a certain demand parameter conditional on the \(IM\). These fragility functions are developed for specific buildings, or building typologies, and are typically based on nonlinear response history analyses (NRHAs) of a structure under an ensemble of ground motions records. Numerous PSDA studies have been performed to date to quantify the effect of different sources of uncertainty such as record-to-record variability (e.g., Goulet et al. 2007), model parameter uncertainty (e.g., Gokkaya et al. 2016), ground motion duration effects (e.g., Chandramohan et al. 2016a, Chandramohan et al. 2016b, Barbosa et al. 2017, Belejo et al. 2017) on the structural seismic demand. It is worth noting that PSDA, is one of several steps that can then be used to develop a performance-based seismic loss analysis, which can be used to support decisions based on benefit-cost analyses or risk mitigation of built infrastructure component, systems, or communities (e.g., Mitrani-Reiser 2007, Pei and van de Lindt 2009, Li and van de Lindt 2012, Mieler et al. 2015).

It is only recently that methodologies similar to PSHA and PSDA have been developed to create probabilistic tsunami hazard analysis (PTHA). With advancements in computational resources and utilizing statistical frameworks analogous to those developed for PSHA, initial efforts on PTHA focused on maximum tsunami height at the coast or the extent of the maximum inundation as the primary output variables of PTHA (e.g. Geist and Parson 2006, Annaka et al. 2007, Power et al. 2007, Thio et al. 2007). More recent studies have started to include the maximum inundation depth within the inundation zone as a primary intensity measure (e.g. González et al. 2009, Lorito et al. 2014, Goda et al. 2015, Mueller et al. 2015, Park and Cox 2016). A detailed review of developments in PTHA can be found in Mori et al. (2017) and Risi and Goda (2017). Early attempts at probabilistic tsunami damage analysis (PTDA) relied on the non-physics based methods, which identified and ranked the severity of tsunami damage on the
built environment based on expert judgment (e.g. Papathoma and Dominey-Howes 2003, Dominey-Howes et al. 2010), due to the lack of fragility functions developed for tsunamis at the time. More recently, empirical tsunami fragility functions have been developed (e.g., Koshimura, et al. 2009, Suppasri et al. 2012, Macabuag et al. 2016) after major tsunami events, such as 2004 India Ocean Tsunami and 2011 Tohoku Tsunami. These tsunami fragility functions were used to estimate the probability of damage, or lack of operability, of the built environment (e.g. Wiebe and Cox 2014, Fraser et al. 2014, Aránguiz et al. 2018).

1.2 Fragility Functions for Earthquake and Tsunami

A fragility function provides the probability of a damage measure exceeding a certain damage state conditional on an intensity measure ($IM$). In the case of an earthquake, the development of fragility functions has been an active field of research in earthquake engineering over the past four decades (e.g., nuclear power plants: Kennedy et al. 1980, Veneziano et al. 1983; model building types in HAZUS: Kircher et al. 1997; wood structures: Rosowsky et al. 2002; steel structures: Kinali et al. 2007; reinforced concrete structures: Goulet et al. 2007, Alam and Barbosa 2018). For example, lognormal fragility functions specified in FEMA (2011) for model building types with different seismic design code levels (Pre, Low, Moderate, and High code) are widely applied for earthquake damage assessment on buildings. The building damage assessment involves computing damage to structural systems, drift-sensitive non-structural systems, and acceleration-sensitive non-structural systems. The structural damage is often assessed for ground shaking and ground failure induced hazards, whereas the non-structural damage is assessed for ground shaking hazard only. In the case of a tsunami hazard, fragility functions have been widely developed using various $IM$s (e.g., the maximum flow depth $h_{max}$, velocity $V_{max}$, and momentum flux $M_{max}$). Among $IM$s, $h_{max}$, which is defined as the maximum flow depth from the local ground elevation to the maximum water elevation has been widely adapted as a representative intensity measure in the development of initial tsunami fragility functions. The maximum flow depth is typically measured directly from a nearby structure in the fields or estimated through numerical simulations, and it has been used to hindcast the flow velocities. Recently, physics-based tsunami fragility functions have been developed based on the response of finite element structural models subjected to tsunami loading (Park et al. 2012, Macabuag et al. 2014, Attary et al. 2016, Alam et al. 2018). For example, Attary et al. (2016)
proposed a methodology to develop tsunami fragility functions considering various uncertainties on the estimation of tsunami induced force on the structure, and utilized different IMs for fragility function development. Results in Alam et al. (2018) highlighted the importance of considering openings that limit the effects of wave loading as well as structural member failures on tsunami fragility function development. In addition, they indicated that IMs that include the effects of flow speed and flow depth provide the best estimation efficiency in predicting structural damage. Because the development of fragility functions requires advanced calibrated structural models to capture the main characteristics of the nonlinear response, physics-based tsunami fragility curves have been developed only for a limited numbers of specific type of buildings and at specific sites, and thus these are more difficult to apply across a community with thousands of diverse building types.

Fragility analysis has been combined with PTHA to yield probabilistic tsunami damage assessment (PTDA) to quantify damage probabilities on built environment at different recurrence period to evaluate the overall risk to the built environment (e.g. Park et al. 2017a, Goda and De Risi 2017). However, there are only few studies that have combined both seismic and tsunami hazards. De Risi and Goda (2016) performed probabilistic seismic and tsunami hazard analysis (PSTHA) by performing PSHA and PTHA, sharing the same characteristics of the earthquake source models when performing the PSHA and PTHA for the east coast of Japan. In the similar manner, Park et al. (2017b) performed PSTHA of a community on the west coast of USA and developed annual exceedance probabilities (AEP) for a series of seismic and tsunami scalar and vector-valued IMs. Following the work of De Risi and Goda (2016), Goda and De Risi (2018) performed a combined seismic and tsunami damage analysis, treating each seismic and tsunami hazard as independent events, and selecting the higher probability of damage or risk between the seismic and tsunami damage analysis results to estimate the combined damage. However, Goda and De Risi (2018) excluded the possible accumulated damage from two subsequent events, thus neglecting the cascading damage effects. Attary et al. (2017a) developed a framework for performance-based damage and risk assessment of individual building structures subjected to earthquake and tsunami cascading hazards, which was based on nonlinear dynamic response history analysis of a structure subjected to the earthquake ground motion accelerations and the subsequent tsunami loading time histories. While the framework is noteworthy, it is extremely
computational intensive and thus mainly implementable for multi-hazard risk assessment of a single structure, but less applicable to damage and risk assessment of a whole communities.

1.3 Main objectives

The main objective of this paper is to present a methodology for probabilistic seismic and tsunami damage analysis (PSTDA) of buildings and apply it to an illustrative community in the Pacific Northwest of the U.S., for which PSTHA results were developed in Park et al. (2017b). In addition, first, this work extends the logic tree used in Park et al. (2017b) by incorporating partial rupture scenarios of the CSZ fault structure in the development of the seismic and tsunami hazards used herein. Then the seismic and tsunami damage are estimated for the accumulated damage from the seismic and tsunami scenario events considered to develop probabilistic estimates of the damage accounting for both seismic and tsunami hazards.

2. Methodology for PSTHA and PSTDA

2.1 Review of PSTHA process

The PSTHA used in this study was introduced in Park et al. (2017b) and is summarized in Fig. 1. A key aspect to the PSTHA process is that the subsequent PSHA and PTHA results (e.g., earthquake shaking, tsunami inundation) share the same source event. The following steps are used for the PSTHA:

- Step 1 – Define earthquake fault source models;
- Step 2 – Characterize the earthquake (seismic) hazard using ground motion prediction equations (GMPEs) and tsunami hazard by modeling through generation, propagation, inundation processes;
- Step 3 – Calculate Annual Exceedance Probability ($AEP$);
- Step 4 – Generate spatially explicit seismic and tsunami hazard maps for given $AEP$.

The first step (Step 1) consists of defining the earthquake fault source models and their fault characteristics. This step includes estimating the occurrence frequency of historic tsunamigenic earthquakes, and preparing the synthetic fault model that provides the detail input of an earthquake ground motion and tsunami modeling. In the case of an earthquake, the various fault slip conditions from the given fault models provide the fundamental input data of the earthquake modeling such as moment magnitude, rupture distance, and soil type. In the case of
tsunami modeling, the initial surface deformation due to the slips within the fault models, and their spatial distributions, are the fundamental input for the tsunami modeling, which includes using numerical simulations performed in Step 2.

The second step (Step 2) consists of performing earthquake ground motion and tsunami modeling with the consistent fault source models. In the case of the earthquake ground motion modeling and for the prediction of ground motion intensity measures (IMs), a quantitative estimation of the ground motion is performed based on source-to-site wave propagation models (e.g. Somerville et al. 2012, Olsen et al. 2008, Delorey et al. 2014) that require large computational effort, or through the use of ground motion prediction equations (GMPEs), which are dependent on the local and regional site conditions. In general terms, the GMPEs serve as surrogate models which capture the underlying physics of the seismic energy propagating. The GMPEs are related to the moment release on an area of the earthquake source and to the source-to-site rupture distances. However, in the case of tsunami modeling, analogous surrogate models do not exist because of the complex transformation of the tsunami flow due to topographic and bathymetric effects. Therefore, in general, numerical model solutions of time-dependent linear or non-linear shallow water wave equations are used to determine hydro-kinematic conditions of tsunami propagation and inundation.

The third step (Step 3) consists in determining the annual exceedance probability (AEP) of earthquake ground motion and tsunami inundation IMs (e.g. Peak ground acceleration or Maximum flow depth, respectively). The Poisson process (Cornell, 1968) is commonly used to estimate the probability of exceedance of both hazards at a particular site in time $t$, which is given by:

$$P[IM > im | t] = 1 - e^{-\lambda t}$$  \hspace{1cm} (1)

where $\lambda$ is the mean rate of occurrence at which the IM exceeds a specific intensity measure value $im$, at a given site, during time, $t$. If $t = 1$ year, then Eq. 1 provides to the annual exceedance probability (AEP).

The mean annual occurrence rate $\lambda_{IM>im}$ of each IM exceeding an intensity measure value $im$ is computed using the Total Probability Theorem (TPT; Benjamin and Cornell, 1970) by
integrating the contributions of all possible tsunamigenic sources, for each of the sources and all
values of moment magnitude considered, and it given by:

\[
\lambda_{m \geq m_{\text{min}}}(m) = \sum_{i=1}^{N_{\text{sources}}} \lambda_i (M \geq m_{\text{min}}) \int_{m_{\text{min}}}^{m_{\text{max}}} P(IM > im|\Theta, M) S_{\Theta}(\Theta|M) f_{M_i}(m) dm
\]  

(2)

where \( f_{M_i}(m) \) denotes the probability density function of the magnitude \( M \) given \( i \)-th source (e.g., Park et al. 2017b); \( S_{\Theta}(\Theta|M) \) is the distribution of the characteristic values of the fault and of the source-to-site distance conditional on the magnitude \( M \) for \( \Theta \) seismic source and source-to-site parameters; \( P(IM > im|\Theta, M) \) represents the complementary cumulative distribution function of \( IM \) exceeding \( im \) conditional on seismic source parameters and source-to-site as well as on the magnitude of the earthquake that is determined using GMPEs for the ground motion shaking or tsunami propagation and inundation modeling depending on the \( IM \) considered; \( \lambda_i (M \geq m_{\text{min}}) \) corresponds to the Gutenberg–Richter law for the \( i \)-th source; and \( N_{\text{source}} \) indicates the total number of sources/scenarios considered in the logic tree model.

For the forth step (Step 4), the computation of \( AEP \) is extended to various \( IMs \) for both seismic and tsunami hazards. The \( AEP \) of \( IMs \) is computed for the entire study area, the output is the development of both seismic and tsunami hazards maps with various \( IMs \) at specific \( AEP \) conditions or recurrence year (e.g. 100, 250, 500, 1,000, 2,500 yr). The correlation of the representative \( IM \) and other \( IMs \) or spatial joint distributions of more than two \( IMs \) can also be generated to better understand the combined earthquake and tsunami hazards. Note, that in this step, a vector-valued probabilistic seismic and tsunami hazard analysis can also be developed based on the definition of a mean rate density (Bazkurro 1998, Barbosa 2011) of the multi–hazard given by:

\[
MRD_{\text{IM}_\text{eq}, \text{IM}_\text{ts}}(im_{\text{eq}}, im_{\text{ts}}) = \sum_{i=1}^{N_{\text{source}}} \lambda_i (M \geq m_{\text{min}}) \int_{\Theta} \int_{M} f_{\text{IM}_\text{eq}, \text{IM}_\text{ts}}(im_{\text{eq}}, im_{\text{ts}}|\Theta, M) S_{\Theta}(\Theta|M) f_{M_i}(m) dm d\Theta
\]  

(3)
where \( f_{\mathbf{IM}_{\text{eqk}}, \mathbf{IM}_{\text{tsu}}} (\mathbf{im}_{\text{eqk}}, \mathbf{im}_{\text{tsu}} | \Theta, M) \) is a joint probability density function of the vector of intensity measures \( \mathbf{IM} = \{ \mathbf{IM}_{\text{eqk}}, \mathbf{IM}_{\text{tsu}} \} \) and where \( \mathbf{IM}_{\text{eqk}} \) is a scalar or vector-valued intensity measure related to the seismic shaking hazard and \( \mathbf{IM}_{\text{tsu}} \) is a scalar or vector-valued intensity measure related to the tsunami hazards. Here \( M \) indicates moment magnitude scale.

Depending on the infrastructure component under analysis, these vector-valued intensity measures could incorporate various scalar intensity measures; for example, for building structures a multi-hazard vector-valued intensity measure of interest could include spectral acceleration at selected characteristic periods \( (T_i) \), and the maximum momentum flux \( (M_{\text{max}}) \), \( \mathbf{IM} = \{ S_a (T_i), M_{\text{max}} \} \), which would serve as a good predictor for structural damage due to earthquakes and tsunamis (Attary et al., 2017a).

The results of Step 1 to 4 defined in this section are the AEP of all \( IMs \) of interest considering the fragility functions that are used in probabilistic damage analysis, described in the next subsection. For example, the hazards maps of Peak Ground Acceleration \( (PGA) \) or Spectral Acceleration \( (S_a) \) for earthquake and the maximum flow depth \( (h_{\text{max}}) \) or momentum flux \( (M_{\text{max}}) \) for tsunami, could be prepared for various return periods (e.g., 100, 500, 1,000, 2,500 years) and for providing the hazard function, \( \lambda_{\mathbf{IM} > \mathbf{im}} (\mathbf{im}) \), and then serve as the basis for the probabilistic seismic and tsunami damage analysis procedures described next.
2.2 Probabilistic Seismic and Tsunami Damage Assessment (PSTDA)

The general methodology of PSTDA is summarized in Fig. 2, and the procedure involves:

- Step 5: Prepare inventory of the built environment;
- Step 6: Prepare inventory of fragility functions;
- Step 7: Perform a probabilistic damage analysis.

Figure 1: Overview sketch of the probabilistic seismic and tsunami hazard analysis (PSTHA).
The fifth step (Step 5) in PSTDA consists of preparing or collecting the built environment inventory for the study region. The built environment consists of the inventory of buildings, and lifeline infrastructure systems such as transportation, water, power, and communication networks. Each component of the built environment may exhibit a different damage response, and the analysis may require different IMs and damage descriptions depending on the characteristics of each component. In case of buildings, for example, the response of each building is different depending on building typologies, the main material composing the lateral force resisting system, its size, shape, seismic code level for which the building was designed, age of the building, and so on. However, it is difficult to collect all details of the building inventory at a community scale, and it is difficult to analyze building damage considering all the building attributes collected. Instead, the fundamental information or characteristic of each built environment that affects the performance of each components is needed to be collected at this step.

In the sixth step (Step 6), fragility functions for the damage analysis step are collected or developed. Earthquake and tsunami fragility functions provide the probability of exceeding a certain damage state threshold as a function of an IM, and these are widely developed or under-development for both the earthquake and tsunami hazards, respectively. Thus, for the community of interest, fragility functions may need to be developed for specific infrastructure components. These fragility functions can also be developed for the joint probability of their damage occurring conditional on joint intensity measures, which can include the intensity of the shaking and tsunami inundation effects for example. Nonetheless, there is an extremely limited availability of joint fragility functions, and at this time, the implementation performed considers the combination of the damage originating from earthquake ground motion and tsunami inundation only in the final step.

The final step (Step 7) consists of determining the annual probability of damage of the built environment using structure specific fragility functions for both seismic and tsunami hazards. This step also includes the combination process of the seismic and tsunami induced damage. As part of this step, the spatial damage probability maps of the built environment are developed for specific AEP conditions at discrete damage states. There are four damage states are considered (slight, moderate, extensive, and complete). Each damage state has a qualitative definition of damage associated with it and default values for the damage state parameters that
define the fragility curves are also defined. For example, for a mid-rise building, there are three
damage states defined for tsunami, including moderate, extensive and complete. An excerpt of
the qualitative description of the moderate damage state corresponds to (FEMA, 2013; Table 5.6)
observed “limited, localized damage to elements at lower floors....”; for the extensive damage
state “localized failure of elements at lower floors…”; for the complete damage state “a
significant portion of structural elements exceeded capacities.” In addition, the default values for
the damage state parameters that define the fragility curves used are provided in the tsunami
technical manual (FEMA, 2013; Chapter 5)”.

The general PSTDA formulation provides the mean annual rate that an infrastructure
component experiences earthquake shaking induced and tsunami inundation induced damage
exceeding a certain damage threshold given for a given location affected by multiple
tsunamigenic earthquake sources. The mean annual rate of the damage exceeding and given
damage threshold $ds$ is given by:

$$
\lambda_{ds} (ds) = \int P(DS \geq ds \mid IM) \ d\lambda(im)
$$

where $P(DS \geq ds \mid IM)$ is a fragility surface that provides the probability of exceeding a given
damage state $(DS)$ for a given vector of intensity measures, $IM = \{IM_{Eqke}, IM_{Tsu}\}$. As indicated
in the previous section, the mean annual rate, $\lambda_{ds} (ds)$ can be converted to the annual exceedance
probability using the Poisson process defined in Eq. 1, for example.

Equation 4 as written does not lend itself to being efficiently implemented. The equation
for the seismic and tsunami damage based on a vector-valued can also be given by the following
expression, in which all the terms have been described previously,

$$
\lambda_{ds} (ds) = \int \int P(DS \geq ds \mid IM_{Eqke}, IM_{Tsu}) MRD IM_{Eqke}, IM_{Tsu} (im_{Eqke}, im_{Tsu}) \ d im_{Eqke} \ d im_{Tsu}
$$
where the mean rate density (MRD) terms was described in section 3. The computation of the joint distribution of the $I_{MEqke}$ and $I_{MTsu}$ can be performed based on multiple realizations of ground motion and tsunami inundation and estimation of the $IM$ values for each realization.

**Figure 2.** Overview sketch of the probabilistic seismic and tsunami damage analysis (PSTDA) process. The step is continuing from the step of the PSTHA.
As noted by one of the peer reviewers, the spatial correlation of the intensity measures can be important when performing seismic hazard and tsunami hazard analyses (e.g. Goda and Hong, 2008; Loth and Baker, 2013), especially when performing analyses in a relatively small area of interest, such as the case study city of Seaside. While the correlations of the intensity measure are explicitly considered in the tsunami hazard analysis due to the nature of the modeling performed, this correlation was not considered with respect to the seismic hazard intensity values.

2.3 Combining Earthquake-induced and Tsunami-induced damage

As described earlier, the process of combining the damage incurred from earthquake ground shaking and tsunami inundation is poorly understood due to the complex mechanisms of the two cascading damage processes and also difficulties in post-disaster surveys in distinguishing between earthquake shaking and tsunami related damage. Recently, Goda and De Risi (2018) estimated the combined loss of a building by considering the damage incurred due to earthquake shaking damage and tsunami damage. However, their method excluded the effects of accumulated damage due to the two cascading hazard events.

In this study, the approach suggested in FEMA (2013) is used for combining damage due to two sequential events based on the assumption that damage due to earthquake shaking and damage due to tsunami are statistically independent. The structural and non-structural damage from the tsunami inundation does not depend on the amount of damage that occurred due to the seismic motion before the tsunami arrived. However, these are considered in the equations used to combine the damage, as in Eq. 6, in which the events of damage due to earthquake shaking and damage due to tsunami inundation are assumed to be statistically independent.

The seismic hazard maps developed are site specific and therefore the implemented methods do not carry over to the event-specific dependency of the shaking and tsunami hazards at different locations within an area. This approach assumes that combining the structural and non-structural probabilities of exceeding a damage state due to earthquake shaking and tsunami flow hazards are based on the basic axioms of probability theory, Boolean logic rules, and the assumption of statistical independence between damage incurred from earthquake shaking and tsunami flow hazards. There are two exceptions. The first one is that a specific level of damage state could be generated from the joint lower level damage state. For example, the probability of
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combined complete damage ($DS = \text{Complete}$) also includes the joint probability of extensive damage state ($DS = \text{Extensive}$) due to the tsunami and extensive damage due to the earthquake based on the assumption that both the extensive damage due to the tsunami and earthquake could result in complete damage to the structure. The second exception that the impacts of structural damage could propagate to non-structural damage directly as much as structural damage ratio. Thus, using the abbreviations and terminology defined in Table 1, the combination rules used in the study are for estimating the structural damage are:

\[
P_{\text{comb}}[DS = C_{so}] = P[DS = C_{so} | Eqke] + P[DS = C_{so} | Tsu] - P[DS = C_{so} | Eqke]P[DS = C_{so} | Tsu] + (P[DS \geq E_{so} | Eqke] - P[DS = C_{so} | Eqke])\left(P[DS \geq E_{so} | Tsu] - P[DS = C_{so} | Tsu]\right) \quad (6)
\]

\[
P_{\text{comb}}[DS \geq E_{so}] = P[DS \geq E_{so} | Eqke] + P[DS \geq E_{so} | Tsu] - P[DS \geq E_{so} | Eqke]P[DS \geq E_{so} | Tsu] + (P[DS \geq M_{so} | Eqke] - P[DS \geq E_{so} | Eqke])\left(P[DS \geq M_{so} | Tsu] - P[DS \geq E_{so} | Tsu]\right) \quad (7)
\]

\[
P_{\text{comb}}[DS \geq M_{so}] = P[DS \geq M_{so} | Eqke] + P[DS \geq M_{so} | Tsu] - P[DS \geq M_{so} | Eqke]P[DS \geq M_{so} | Tsu] \quad (8)
\]

\[
P_{\text{comb}}[DS \geq S_{so}] = P[DS \geq S_{so} | Eqke] + P[DS \geq M_{so} | Tsu] - P[DS \geq S_{so} | Eqke]P[DS \geq M_{so} | Tsu] \quad (9)
\]

It is worth noting here that there is no slight damage state ($DS = \text{Slight}$) for tsunami fragility functions. Instead, the moderate damage state is substitute to Eq. (9).

The combination rules used in the study for estimating the non-structural system (NSS) damage from tsunami inundation and earthquake shaking are shown next. In addition, it is worth noting that the non-structural damage from the earthquake shaking is generally divided into acceleration-sensitive and drift-sensitive systems for seismic damage and loss estimations (Aslani 2005, Aslani and Miranda 2005). The combined probability of non-structural
acceleration-sensitive systems (NAS) being in the complete damage state ($C_{NAS}$), extensive
damage state ($E_{NAS}$), moderate damage state ($M_{NAS}$), and slight damage state ($S_{NAS}$) are given by:

$$
P_{\text{Comb}}[DS = C_{NAS}] = P_{\text{Comb}}[DS = C_{Sr}] + (1 - P_{\text{Comb}}[DS = C_{Sr}])
\times \left[ \frac{P[DS = C_{NAS} | Eqke] + P[DS = C_{NAS} | Tsu] - P[DS = C_{NAS} | Eqke]P[DS = C_{NAS} | Tsu]}{P[DS = C_{NAS} | Eqke]P[DS = C_{NAS} | Tsu]} \right]$$

$$(10)$$

$$
P_{\text{Comb}}[DS = E_{NAS}] = P_{\text{Comb}}[DS = C_{Sr}] + (1 - P_{\text{Comb}}[DS = C_{Sr}])
\times \left[ \frac{P[DS = E_{NAS} | Eqke] + P[DS = E_{NAS} | Tsu] - P[DS = E_{NAS} | Eqke]P[DS = E_{NAS} | Tsu]}{P[DS = E_{NAS} | Eqke]P[DS = E_{NAS} | Tsu]} \right]$$

$$(11)$$

$$
P_{\text{Comb}}[DS = M_{NAS}] = P_{\text{Comb}}[DS = C_{Sr}] + (1 - P_{\text{Comb}}[DS = C_{Sr}])
\times \left[ \frac{P[DS = M_{NAS} | Eqke] + P[DS = M_{NAS} | Tsu] - P[DS = M_{NAS} | Eqke]P[DS = M_{NAS} | Tsu]}{P[DS = M_{NAS} | Eqke]P[DS = M_{NAS} | Tsu]} \right]$$

$$(12)$$

$$
P_{\text{Comb}}[DS = S_{NAS}] = P_{\text{Comb}}[DS = C_{Sr}] + (1 - P_{\text{Comb}}[DS = C_{Sr}])
\times \left[ \frac{P[DS = S_{NAS} | Eqke] + P[DS = S_{NAS} | Tsu] - P[DS = S_{NAS} | Eqke]P[DS = S_{NAS} | Tsu]}{P[DS = S_{NAS} | Eqke]P[DS = S_{NAS} | Tsu]} \right]$$

$$(13)$$

The combined probability of non-structural drift-sensitive systems (NDS) being in the complete damage state ($C_{NDS}$), extensive damage state ($E_{NDS}$), moderate damage state ($M_{NDS}$), and slight damage state ($S_{NDS}$) are given by:

$$
P_{\text{Comb}}[DS = C_{NDS}] = P_{\text{Comb}}[DS = C_{Sr}] + (1 - P_{\text{Comb}}[DS = C_{Sr}])
\times \left[ \frac{P[DS = C_{NDS} | Eqke] + P[DS = C_{NDS} | Tsu] - P[DS = C_{NDS} | Eqke]P[DS = C_{NDS} | Tsu]}{P[DS = C_{NDS} | Eqke]P[DS = C_{NDS} | Tsu]} \right]$$

$$(14)$$

$$
P_{\text{Comb}}[DS = E_{NDS}] = P_{\text{Comb}}[DS = C_{Sr}] + (1 - P_{\text{Comb}}[DS = C_{Sr}])
\times \left[ \frac{P[DS = E_{NDS} | Eqke] + P[DS = E_{NDS} | Tsu] - P[DS = E_{NDS} | Eqke]P[DS = E_{NDS} | Tsu]}{P[DS = E_{NDS} | Eqke]P[DS = E_{NDS} | Tsu]} \right]$$

$$(15)$$

$$
P_{\text{Comb}}[DS = M_{NDS}] = P_{\text{Comb}}[DS = C_{Sr}] + (1 - P_{\text{Comb}}[DS = C_{Sr}])
\times \left[ \frac{P[DS = M_{NDS} | Eqke] + P[DS = M_{NDS} | Tsu] - P[DS = M_{NDS} | Eqke]P[DS = M_{NDS} | Tsu]}{P[DS = M_{NDS} | Eqke]P[DS = M_{NDS} | Tsu]} \right]$$

$$(16)$$
The computation of the damage probability for the combined earthquake and tsunami hazards assumed statistical independence, which is a relatively large assumption. Even though, multiple realizations of ground motion and tsunami inundation were performed, the damages probabilities from different IMs were combined from IMs obtained from hazard maps. In this way, the intrinsic correlation between the IMs was not accounted for in the damage probabilities, which tend to overpredict the combined damage probabilities. This is acceptable for community and urban planning purposes, but may induce bias if the correlation is not addressed appropriately in the multi-hazard risk computations.

### Table 1. Abbreviations used in Equations 6 to 17 and corresponding descriptions.

<table>
<thead>
<tr>
<th>Hazards</th>
<th>System</th>
<th>Damage states (DS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eqke</td>
<td>Earthquake</td>
<td>C Complete</td>
</tr>
<tr>
<td>Tsu</td>
<td>Tsunami</td>
<td>E Extensive</td>
</tr>
<tr>
<td>Str</td>
<td>Structural system</td>
<td>M Moderate</td>
</tr>
<tr>
<td>NSS</td>
<td>Non-structural system</td>
<td>S Slight</td>
</tr>
<tr>
<td>NDS</td>
<td>Non-structural drift-sensitive system</td>
<td></td>
</tr>
<tr>
<td>NAS</td>
<td>Non-structural acceleration-sensitive system</td>
<td></td>
</tr>
</tbody>
</table>

3. Application of PSTDA to Seaside, OR, subjected to CSZ Megathrust Earthquake Shaking and Tsunami Inundation

In this section, details of the application of the methodologies described in the previous section are provided for the PSTDA of the building stock for the coastal city of Seaside, Oregon, when subjected to the tsunamigenic earthquake events originating from the Cascadia Subduction Zone (CSZ). Seaside is a low lying coastal city with 87% of land located within a potential tsunami inundation region and the city has been studied widely as one of the most vulnerable coastal cities in the US Pacific Northwest to future tsunami events (González et al. 2009, Wiebe and Cox 2014).
3.1 Probabilistic Seismic and Tsunami Hazard Analysis (PSTHA) of Seaside, Oregon

For the PSTHA of Seaside, Oregon, the work presented in Park et al. (2017b) was extended by including 48 additional fault slip scenarios in the developed logic tree model to account for the partial CSZ rupture conditions. Consequently, a total of 120 fault slip scenarios were developed for the logic tree model (Figure A1 in Appendix) based on five discretized moment magnitudes ($M_w$), three slip distributions along the strike direction (narrow, medium, and wide) and eight possible peak slip locations with variable weighting factors at CSZ. The same logic tree model is utilized in the recent PTHA study at Newport, Oregon (Park et al., 2018). The mean recurrence interval for the partial rupture events related to $M_w$ 8.1 and 8.5 events were determined based on the tapered Gutenberg–Richter (TGR) relationship explained in Park et al. (2017b). The mean recurrence interval (year) of full-rupture events ($M_w$. 8.8, 9.0, and 9.2) was 526 years, which was determined from 19 paleo-tsunami records during the past 10,000 years based on turbidites records (Goldfinger et al. 2012). Far-field tsunami generating sources from across the Pacific Ocean, such as Alaska, Hawaii, Japan, and Chile, are not included, since the combined seismic and tsunami damage is expected to be controlled by the near-field tsunamis generated by the CSZ. Thus, the PSTHA analysis performed is conditioned on the occurrence of an earthquake scenario on the CSZ. The fault slip conditions of each scenario provide the fundamental input data of the earthquake ground shaking and tsunami inundation modeling. As described previously, the earthquake ground shaking IMs are computed using ground motion prediction equations (GMPEs) such as moment magnitude, rupture distance, and other source parameters. In addition, the tsunami inundation modeling and computation of the tsunami IMs is based on the same earthquake scenario conditions that are used to define the input (initial water surface deformation) to the tsunami numerical simulation. More details of the logic tree model scenarios including fault source modeling and geometric conditions are available in (Park and Cox 2016, Park et al. 2017b, and Park et al. 2018). However, with limited aleatory variability in this study, which is only based on varying the slip models for each scenario, the hazard curve for each IMs could be relatively steep and the corresponding damage ratio of buildings from the tsunamis or seismic motion would be underestimated at the longer return periods. For the earthquake shaking modeling, the GMPE developed in Abrahamson et al. (2016) is used to estimate the ground-motion IMs. In the case of tsunami modeling, surrogate models analogous to GMPEs do not currently exist because of the complex transformation of the
tsunamis due to bathymetric and topographic effects on the propagation and inundation modeling. Thus, to characterize the tsunami hazards, time-dependent non-linear shallow water wave equations were used, combining the use of ComMIT/MOST (Titov et al. 2011) for tsunami generation and propagation from the source to the near coastal region and COULWAVE (Lynett et al. 2002) for the inundation process near and on-shore region. For tsunami generation, we setup the co-seismic dislocation of fault slips (Okada, 1985) were used, and a constant friction (Manning number, \(n = 0.03\)) over the entire computation domain was assigned to the both ComMIT/MOST and COULWAVE models. The model domains consisted of three nested grids, named A, B, and C-Grid and the size and dimension of each grids were 1 min (400 × 400), 3 sec (800 × 800), and 24 m (416 × 390), respectively. The total simulation time was set to two or three hours depending on the arrival time of first peak waves. The ComMIT/MOST model output from the C-Grid was not used and was replaced by the COULWAVE results. The more discussion on limitations regarding the current tsunami numerical modeling setup were carefully discussed in Park and Cox (2016).

3.2 Building Inventory at Seaside, Oregon

The building inventory at Seaside, Oregon, described in Park et al. (2017a) is used herein. The building inventory is matched to fragility functions for each building typology and to estimate the damage state probability for each building at the study region for both earthquake shaking and tsunami inundation. Three sources of input (tax lot data, images from Google Street View, and a field survey based on an adapted version of the FEMA-154 Rapid Visual Screening) were used to develop the buildings inventory at Seaside. Fig. 3 provides the information of building attributes, such as material building types (left top panel), number of stories (right top panel), and building seismic design code levels based on the date of construction (right bottom panel). The rectangle in Fig. 3 indicates the study region, which is divided into three regions (Region A, Region B, and Region C) by the Necanicum River and Neawanna creek that traverse the region in approximately South to North direction, which are near parallel to the shoreline. These three regions are used for the regional damage deaggregation study performed in Section 4.
3.3 Fragility Functions for the Seaside, Oregon, Building Inventory

For the earthquake shaking induced structural damage assessment, lognormal fragility functions provided in FEMA (2011) for high-code, moderate-code, low-code, and pre-code seismic design levels were used. These fragility functions are defined by the parameters, $\bar{S}_{d,ds}$ and $\sigma_{\ln S_{d,ds}}$, which are the median value of the spectral displacement and the standard deviation of the natural logarithm of spectral displacement corresponding to a specific damage state ($ds$), respectively. The 5% of critical damping linear response spectral acceleration $S_d(T)$ values obtained using the GMPEs for each building location, at selected characteristic periods $T$ for each building typology, were converted to spectral displacement values $S_{d}(T)$ in order to perform the structural damage assessment due to ground shaking. Structural damage due to permanent ground deformation ($PGD$) was also evaluated using specific fragility functions available in FEMA (2011). For this purpose, $PGD$ due to lateral spreading and ground settlement was evaluated at each building location in the study area using the $PGA$ values estimated using the GMPEs and guidelines presented in Chapter 4 of FEMA (2011) to perform the conversion from $PGA$ to $PGD$. There are great uncertainties associated with the estimation of PGD and
corresponding damage associated ground deformation estimates. Even though the methods presented are sound, the future users should be aware of these uncertainties and potential biases involved with PGD estimates.

For the earthquake shaking induced non-structural damage assessment, two sets of fragility function are provided in FEMA (2011) for non-structural systems, namely drift-sensitive systems (NDS) and acceleration sensitive systems (NAS). The fragility function parameters used for drift-sensitive non-structural systems, \( \xi_{\text{NDS}}, \beta_{\text{NDS}} \), are the median value of spectral displacement and the standard deviation of the natural logarithm of spectral displacement corresponding to a specific damage state \( (ds) \), respectively. For acceleration sensitive non-structural systems, the fragility function parameters, \( \xi_{\text{NAS}}, \beta_{\text{NAS}} \) were used, which are the median value of peak floor acceleration \( (PFA) \) and the standard deviation of the natural logarithm of \( PFA \) corresponding to damage state \( (ds) \), respectively. PGA at each building location was used to compute \( PFA \) following the formulation presented in Rodriguez et al. (2002) for acceleration-sensitive non-structural system damage assessment.

For tsunami inundation induced damage assessment, the tsunami fragility functions provided in FEMA (2013) were adopted. The FEMA (2013) fragility functions use maximum momentum flux \( M_{\text{max}} \) and maximum inundation depth \( h_{\text{max}} \) for the structural and non-structural damage analysis, respectively. Specifically, the \( M_{\text{max}} \) for the structural damage fragility function is an indicator of the lateral force induced from the inundation flow. The example application of structural fragility functions and their performance for building damage estimation are described in a previous work of the authors (Park et al. 2017a). The net maximum flood inundation depth \( (H_F) \) from the bottom of the 1st floor of each building is used to represent the impact of flooding to the non-structural systems (NSS) and building content. Here \( H_F \) is calculated as \( H_F = h_{\text{max}} - h_F \), where \( h_F \) is the elevation to the base of 1st floor of the building from the local ground elevation. In this study, \( h_F \) is set as 1 m as a default setup for the simplicity. FEMA (2013) provides structural and non-structural fragility functions for 36 model building typologies (materials type and floor levels) for four seismic design code levels and for three damage states (Moderate, Extensive, and Complete). These are the same model building typologies used in FEMA (2011), which were used for evaluating the earthquake induced damage for the study area. Thus, the building damage from earthquake and tsunami was combined in a consistent manner following the formulation presented in Section 2.4.
3.4 Probabilistic Seismic and Tsunami Damage Analysis (PSTDA) of Seaside, Oregon

3.4.1 Structural damage

Following Steps 5 to 7 for both the PSTDA, the probability of building damage for the earthquake shaking and tsunami inundation were used to compute the probability of equaling or exceeding a given damage state. As an example, Fig. 4 shows the probability of achieving or exceeding the complete structural damage state for the study area for the 500-year return period. In this figure, results are reported for the structural damage due to earthquake ground shaking \( (E_{q}^{\text{GS}}) \) in Fig. 4a, earthquake ground deformation \( (E_{q}^{\text{GD}}) \) in Fig. 4b, and also for the tsunami inundation maximum momentum flux \( (M_{\text{max}}) \) in Fig. 4c. Lastly, Fig 4d shows the joint probabilities of achieving or exceeding structural damage limit states for the combined effects of earthquake shaking and tsunami inundation \( (E_{q} \cup T_{s}) \). Here, \( E_{q} \) indicates the combined impact of ground shaking and ground deformation \( (E_{q}^{\text{GS}} \cup E_{q}^{\text{GD}}) \) representing the joint probability of structural damage induced from earthquake shaking.

In Fig. 4, it can be observed that the damage due to \( E_{q}^{\text{GS}} \) and \( E_{q}^{\text{GD}} \) is close to uniform over the entire study region, while the building damage due to \( T_{s} \) is highest near the shoreline and at the vicinity of the two rivers. To be specific, \( E_{q}^{\text{GD}} \) shows a lower and uniformly distributed damage states for the building damage \( (P < 0.1) \), while \( E_{q}^{\text{GS}} \) shows slightly higher and less even distributions of building damage due to the variations of building typology (e.g. materials, floor levels, and seismic design code levels) presented in Fig. 3. Therefore, the ground deformation component of the damage is quite insensitive to building typology compared ground shaking induced damage. For the tsunami damage, higher damage probabilities are observable near coastline, and the level of damage diminishes as one moves inland. In case of combined damage estimates due to \( E_{q} \cup T_{s} \), damage can be observed over the entire region, with the highest intensity being observed near the shoreline. One interesting feature is that the coast area that experiences relatively higher damage from \( T_{s} \), however, experiences relatively lower damage from both \( E_{q}^{\text{GS}} \) and \( E_{q}^{\text{GD}} \). This different aspect of damage pattern is due to the relatively stronger resilience of wood structures against the ground shaking compared to tsunami inundation flow, and conversely larger resilience to tsunami loading of the taller non-ductile to low-code RC structures near the shoreline, which are however, more sensitive to larger shaking intensities. Therefore, the combined \( E_{q} \) and \( T_{s} \)
result in uniformly severe damage probabilities of buildings near the coastline regardless of their building materials, and relatively milder damage and more uniform distribution for the rest of city area because of the damage from Eqke.

Figure 4. Structural damage probability of complete damage state at 500-year event; (a) \textit{Eqke_{GS}}, (b) \textit{Eqke_{GD}}, (c) Tsu, (d) \textit{Eqke} \cup Tsu.

Fig. 5 summarizes the structural damage probabilities for the complete damage state for five \textit{AEP} levels for the focus area delimited by the rectangle in Fig. 4. Here, each row shows the results for \textit{AEP} equal to 0.01, 0.004, 0.002, 0.001, and 0.0004 corresponding to return periods of 100-, 250-, 500-, 1000-, and 2500-year, respectively. Each column shows the structural damage
probabilities from different hazard types ($Eqke_{GS}$, $Eqke_{GD}$, $Tsu$, and $Eqke \cup Tsu$) as shown in Fig. 4 for the 500 year return period.

Fig. 5 shows there is a general trend of an increase in probability of damage over the entire study region as the recurrence interval increases. However, the damage probabilities of $Eqke_{GD}$ show less sensitivity to the level of AEP and are uniformly distributed over the entire study region. Almost no damage occurs at the 100-year and 250-year $Tsu$ events, as can be seen in Fig. 5c and Fig. 5g, respectively. On the contrary, minor damage (probabilities < 0.2) occur over the entire study region for the 100-year and 250-year return interval for $Eqke_{GS}$ (see Fig. 5a, 5e). At the 500-year recurrence interval, the $Tsu$ case results in higher probability of damage near the coast region (Region A) than $Eqke_{GS}$, with little to no damage observed in Region B and Region C for $Tsu$ (Fig. 5k) even though in Region B and Region C the probability of damage for $Eqke_{GS}$ reaches 0.4 in for some building typologies (Fig. 5i). At 1,000-year and 2,500-year recurrence interval, $Tsu$ results show significant damage at Region A and B with results indicating that many buildings experience more than 90% completely damage. On the other hand, there are still little to no building damage at Region C (Fig. 5o and s) because the most of buildings in Region C are located outside of the maximum inundation zone even at these large recurrence intervals. The probabilities of damage for $Eqke_{GS}$ also indicate larger damage in Region A, but overall damage probabilities are increased over the entire region (Fig. 5q), and therefore the spatial variability is not as pronounced as the one observed for $Tsu$.

The combined $Eqke$ and $Tsu$ probabilities of damage show the same pattern of damage that have already been described for $Eqke_{GS}$, $Eqke_{GD}$ and $Tsu$. Up to 250-year recurrence interval, the combined structural damage is almost solely due to $Eqke_{GS}$ and $Eqke_{GD}$. For the 500-year recurrence interval and higher, as the hazard intensity increases with the return periods, significant damage occurs at Region A due to $Tsu$, with overall increase of damage at Region B and C. To be specific, almost all wood buildings experience more than 90% complete damage, but the most of RC buildings experience less than 60% of complete damage in Region A at 1,000-year recurrence interval. At 2,500-year recurrence interval, most buildings experience more than 90% complete damage in Region A and B, but some of RC buildings whose floor levels and building codes are high exhibit relatively lower probability damage, at approximately 60%, even at Region A.
Although additional analysis would be necessary, Fig. 5 can be related to the potential for disaster risk reduction due to the combined earthquake and tsunami hazard. The column on the right shows increasing damage (5d, h1, p, t), with the “worst case” at the 2,500-year event with nearly complete damage of the building stock. On the other hand, the AEP is decreasing from 0.01 to 0.0004, so the “worst risk” where the risk is calculated as the probability times the negative consequence would correspond to the AEP=0.002 (or the “500-year” event) shown in Fig. 5l. Such an understanding of the maximum risk could help a community better define cost-effective mitigation strategies rather than focus on ‘worst case scenario’ discussions (Fig. 5t) which may be cost prohibitive.

Figure 5. Structural damage probabilities of complete damage state for $\text{Eqke}_{GS}$, $\text{Eqke}_{GD}$, $\text{Tsu}$, and $\text{Eqke \& Tsu}$ (columns) for recurrence intervals of 100, 250, 500, 1,000, and 2,500 years (rows).
3.4.2 Non-Structural Damage at Seaside, Oregon

Fig. 6 shows the complete damage state probabilities of non-structural systems (NSS) at 500-year recurrence interval. Fig. 6a, b, c, and d present the complete damage state probabilities of acceleration-sensitive non-structural system (Eqke\textsubscript{NAS}), drift-sensitive non-structural system for earthquake (Eqke\textsubscript{NDS}), non-structural system (Tsu\textsubscript{NSS}), and the combined results of Eqke\textsubscript{NAS} and Tsu\textsubscript{NSS} using Eq. 10. The non-structural damage for combined Eqke\textsubscript{NDS} and Tsu\textsubscript{NSS} was also computed using Eq. 14, but results are not shown Fig. 6 in the interest of brevity.

Similar to the structural damage results shown in Fig. 4, the earthquake induced non-structural damage for both the acceleration sensitivity system and drift-sensitivity system in Fig 6 are uniformly distributed over the entire study area (Fig. 6a and 6b), while the tsunami induced non-structural system damage are concentrated in Region A. Overall, complete damage state probabilities of each Eqke\textsubscript{NAS}, Eqke\textsubscript{NDS}, and Tsu\textsubscript{NSS} do not exceed 30%. However, the combined earthquake and tsunami non-structural complete damage (Eqke\textsubscript{NAS} \cup Tsu\textsubscript{NSS}) are more significant than the direct sum of each Eqke\textsubscript{NAS} and Tsu\textsubscript{NSS} complete damage state probabilities, especially at Region A. This significant increase in combined complete damage state probabilities of NSS is due to the added structural damage portion in the non-structural damage analysis as defined in Eq. 10 to 17. For example, if the complete structural damage probability is 30% for a given building, then as per Eq. 10 to 17, the building will experience 30% complete non-structural damage in addition to the complete non-structural damage only due to earthquake ground shaking and tsunami inundation. This additional damage on NSS from structural damage is only considered for combined NSS damage estimation. Therefore, high non-structural complete damage probabilities can be observed for Eqke\textsubscript{NAS} \cup Tsu\textsubscript{NSS} in Fig. 6d in comparison to the simple summing of non-structural damage probabilities of each Eqke\textsubscript{NAS} (Fig. 6a) and Tsu\textsubscript{NSS} (Fig. 6c).
Figure 6. Non-structural complete damage (DS = Complete) at 500-year recurrence interval: (a) $Eqke_{NAS}$, (b) $Eqke_{NDS}$, (c) $Tsu_{NSS}$, (d) $Eqke_{NAS} \cup Tsu_{NSS}$.

Fig. 7 summarizes the non-structural complete damage probabilities with each row corresponding to five AEP conditions, similar to Fig. 5 for structural damage, and each column corresponding to the damage from different hazards ($Eqke_{NAS}$, $Eqke_{NDS}$, $Tsu_{NSS}$, and $Eqke_{NAS} \cup Tsu_{NSS}$). Similar to the structural damage, the overall damage probabilities of NSS increase over the entire study region with increase in recurrence interval. The damage probabilities of both $Eqke_{NAS}$ and $Eqke_{NDS}$ show quite similar pattern each other, but $Eqke_{NDS}$ is more uniformly
distributed than the results of $Eqke_{NAS}$. For the case of combined $Eqke_{NAS}$ and $Tsu_{NSS}$, more severe damage can be observed at Region A, with most of buildings experiencing more than 70% non-structural complete damage at 1,000-year recurrence interval (Fig. 7p). Both Regions A and B experience mostly 90% complete non-structural damage at 2,500-year event (Fig. 7t) following the similar complete structural damage results in Fig. 5p and 5t.

Figure 7. Non-structural damage probabilities of complete damage (DS = Complete) for $Eqke_{NAS}$, $Eqke_{NDS}$, $Tsu_{NSS}$, $Eqke_{NAS} \cup Tsu_{NSS}$ (columns) for recurrence intervals of 100, 250, 500, 1,000, and 2,500 years (rows).
4. Deaggregation analysis

The figures presented in Section 3 at the specific recurrence intervals and damage states are useful for understanding the spatial characteristics of damage distributions with different geologic and building conditions. However, these are aggregated results for various model building types (materials, building height, and seismic design code levels) using a representative damage state (e.g., complete damage state). To gain a deeper understanding of the multi-hazard impacts on structural and non-structural building damage, results of deaggregation analyses are presented in this section, through the deaggregation of the damage results by building construction material of the lateral resisting system, damage states, regions, and seismic design code levels. The section focuses on deaggregation of results for structural damage, but similar deaggregations could be shown for non-structural damage, but the latter are not shown here in the interest of brevity.

Fig. 8 provides the deaggregation of the probability (%) of complete (DS = Complete) structural damage over the focus study region, shown by the rectangle area in Fig. 4, for two material types (wood and reinforced concrete), as a function of recurrence intervals (100, 250, 500, 1,000, and 2,500 years). For wood buildings (Fig. 8a), the overall structural damage is governed by tsunami induced damage, \textit{Tsu (W)} for recurrence intervals at or above 500-year, while earthquake induced damage \textit{Eqke (W)} is dominant at lower hazard recurrence intervals at or below 250-year. This is somewhat expected results because there is no significant inundation until 500-year event. On the other hand, results in Fig. 8b indicate that for reinforced concrete buildings, the structural damage is mainly due to the earthquake shaking rather than the tsunami inundation. Similarly, to the observations in Fig. 8a for the wood buildings, damage due to tsunami is only noticeable for the recurrence intervals of 500 year or higher. In addition, \textit{Eqke}_{GD} (RC) remains nearly constant at and above the 500-year event, while \textit{Eqke}_{GS} (RC) increases slightly with the increase in the return period. As pointed out by one of the peer reviewers, the earthquake IMs could be relatively insensitive to the magnitude scaling (e.g. from M 8 to M 9) at relatively shorter distances (e.g., less than 50 km), while the tsunami IMs show much sensitivity to the magnitude scaling. Nonetheless, overall combined earthquake damage to RC structures increases as the recurrence year increases and is higher than the tsunami induced damage.
Figure 8. Probability (%) of complete (DS = Complete) structural damage at the detailed study region for (a) wood structures; and (b) RC structures. Symbols indicate deaggregated structural damage from $Eqke_{GS}$ (red square), $Eqke_{GD}$ (green diamond), $Eqke (Eqke_{GS} U Eqke_{GD})$ (magenta inverted triangle), $Tsu$ (blue triangle), and $Eqke U Tsu$ (black circle).

Fig. 9 provides the deaggregated probability (%) of complete (DS = Complete) structural damage in Region A (9a, b), Region B (9c, d), and Region C (9e, f) where the left panels (9a, c, e) show results for the wood structures and right panel (9b, d, f) show results for RC structures. In Region A, the overall pattern of damage probabilities is quite similar to the results of Fig. 8 in that $Tsu$ (blue triangle) is the dominant hazard for the structural damage for wood buildings, and $Eqke$ (magenta inverted triangle) is the dominant hazard for RC buildings. In Region B, the trends observed in Region A are similar, but the tsunami damage is much lower; for example, for the 1000-year recurrence interval, approximately 30% damage probability is observed for wood buildings in Region B compared to the nearly 100% damage probability in Region A. At Region C, furthest from the shoreline, there is almost no damage from $Tsu$ for both wood and reinforced concrete buildings even at 2,500-year recurrence interval, as discussed before. However, the damage probabilities of $Eqke_{GS}$, $Eqke_{GD}$, and $Eqke$ are similar to the results at Region A and B. These differences imply the need to consider the granularity at different levels for the different hazards when estimating damage from multi-hazard events. In other words, for the seismic...
damage, there is not much difference between the overall RC damage shown in Figure 8b and the deaggregated statistics shown in Figures 9b, d, f because the hazard is more or less uniform across the community. However, the deaggregated statistics for the tsunami damage to wood structures shown in Figs 9a, c, e are different than the summary damage probabilities shown in Fig. 8a.

Figure 9. Complete damage state probability (%) for buildings in three study regions: Region A (a, b, solid), Region B (c, d, dashed), and Region C (e, f dashed dot) for wood (a, c, e), and RC (b, d, f) buildings for from $\text{Eqke}_{\text{GS}}$ (red square), $\text{Eqke}_{\text{GD}}$ (green diamond), $\text{Eqke}$ ($\text{Eqke}_{\text{GS}} \cup \text{Eqke}_{\text{GD}}$), (magenta inverted triangle), $\text{Tsu}$ (blue triangle), and $\text{Eqke} \cup \text{Tsu}$ (black circle).

Fig. 10 shows the probabilities (%) of complete structural damage deaggregated over seismic design code levels: high code (a, b), moderate code (c, d), low code (e, f, and pre code (g, h) for wood (a, c, e, g) and RC structures (b, d, f, h). Figure 10 shows that there are lower probabilities of damage, as expected, for higher design code level, which is indicative of the larger capacity of such designs to resist tsunami and earthquake loading. In the case of wood buildings, the pre-code structures (Fig. 10g) show the highest damage among four different types
of design codes, but other three conditions show quite similar damage probabilities each other
for all recurrence intervals. Similar to previous results (Fig. 8a and 9a), the tsunami is the
dominant hazard for wood buildings, and we can observe relatively high tsunami induced
damage probabilities in pre code structures. Among the three other code levels, damage patterns
were similar and overall lower than the pre code structures. Damage induced from the
earthquake, show quite similar damage distributions among different design codes for wood
structures. For RC structures, Fig. 10h shows that there are relatively higher mean damage
probabilities in pre code compared to the three other code levels in 10b, d, f for tsunami damage.
This may be a function of both the lower capacity of the pre code structures to resist the tsunami
forces and also the spatial distribution of pre code RC structures subjected to higher tsunami
hazards in Region A.
Figure 10. Probability (%) of structural damage for various seismic building code conditions: (a) High code wood structures (solid lines); (b) High code RC structures (solid lines); (c) Moderate code wood structures (dashed lines); (d) Moderate code RC structures (solid lines); (e) Low code wood structures (dashed-dot lines), (f) Low code RC structures (dashed-dot lines); (g) Pre code wood structures (dotted lines); and (h) Pre code RC structures. Markers correspond to: $E_{\text{eqk}G}$ (red square), $E_{\text{eqk}G}$ (green diamond), $E_{\text{eqk}} = \{E_{\text{eqk}G} \cup E_{\text{eqk}G}\}$ (magenta reverse triangle), $T_{\text{su}}$ (blue triangle), and $E_{\text{eqk}} \cup T_{\text{su}}$ (black circle).

Fig. 11 shows the probability (%) of the structural damage deaggregated over three damage states: moderate (a, b, dashed lines), extensive (c, d dashed dot lines), and complete (e, f, solid lines) for wood (a, c, e) and RC (d, f) structures. From these figures similar observations can be made with respect to those made from the deaggregation in Fig. 9 and Fig. 10, which are that the damage in wood buildings is governed by tsunami inundation and RC structures by earthquake shaking. Interestingly, for the moderate damage limit state at large return periods (2,000-years and above), the tsunami inundation dominates the contribution to the damage.
probabilities, but at low return periods (500-years and below) the earthquake shaking contributes most to the probabilities of damage. The reasons for the latter are twofold. First, the tsunami inundation is relatively small for lower recurrence intervals, as has been discussed before. In addition, seismic code design is performed for life-safety and for a 10% probability of collapse for the 500-year return periods. Thus, it would be expected that even for the 500-year return periods, the moderate damage due to seismic shaking is expected to be large, which has been attributed as one of the main reasons for large economic losses in recent earthquakes.

Figure 11. Probability (%) of structural damage for Moderate (a, b, dashed), Extensive (c, d, dashed dot), and Complete (e, f, solid) damage states, and complete. Left panels show results for wood structures and right panels for reinforced concrete structures. Markers correspond to: $\text{Eqke}_{GS}$ (red square), $\text{Eqke}_{GD}$ (green diamond), $\text{Eqke} = \{\text{Eqke}_{GS} \cup \text{Eqke}_{GD}\}$ (magenta reverse triangle), $\text{Tsu}$ (blue triangle), and $\text{Eqke} \cup \text{Tsu}$ (black circle).

5. Conclusion and Future work
This paper presents a framework for combined probabilistic seismic and tsunami damage analysis (PSTDA). In this work, the probabilistic seismic and tsunami hazards analysis (PSTHA), and a methodology for combining earthquake shaking and tsunami induced damage analysis results were introduced and applied to Seaside, Oregon, which is a coastal community exposed to tsunamigenic earthquake events originating from the Cascadia Subduction Zone. We used existing methods with minor modifications to combine earthquake and tsunami induced damage. However, this is the first time to apply the combined methods to evaluate the deaggregation of damage due to different IMs, building attributes, and return periods, which provides new insight and understanding to the multi-hazard damage analyses. We repeated this analysis over several return periods to improve our understanding of risk.

The PSTDA provides the probabilities of both structural and non-structural damage at each building due to the earthquake shaking only, tsunami inundation only, and combined earthquake shaking and tsunami inundation at specific return periods. The main conclusions from this work are:

1. Earthquake shaking is the dominant hazard for RC buildings, while tsunami inundation is the dominant hazard for structural damage to wood buildings (Fig. 4), especially at large recurrence intervals. Consequently, the combined earthquake shaking and tsunami inundation damage ($\text{Eqke} \oplus \text{Tsu}$) analysis shows significant damage across the region for the predominant building typologies for the study region (Fig. 5).

2. At lower recurrence intervals, earthquake shaking is the dominant hazard for both wood and RC buildings over the entire study region. However, the proportion of tsunami induced damage is increased with the increase in recurrence interval, and tsunami is dominant hazard for wood building near the coast (Region A and B) at higher recurrence intervals (> 1,000-yr) (Fig. 8).

3. While it is known that tsunami induced damage is sensitive to building typology, recurrence interval, and geospatial location such as the distance from the coast line (e.g. Region A, B, and C in this study), this can now be quantified using the method presented in this study (Fig. 5).
4. Using the formulation developed, the combined results of earthquake shaking and tsunami inundation damage to non-structural system (e.g. $Eqke_{NAS} \cup Tsu_{NSS}$) shows more significant damage rather than the direct sum of each $Eqke_{NAS}$ and $Tsu_{NSS}$ because the combined structural damage ($Eqke \cup Tsu$) is also aggregated when determining non-structural damage (Fig. 6).

5. A consequence of the observation in point 4 is that the computed non-structural damage is mostly governed by structural damage at larger recurrence intervals (> 500-yr), especially for wood buildings, due to relatively large estimates of structural damage (Fig. 7).

The combined earthquake shaking and tsunami inundation damage analysis for this study is based on the assumption that the events are statistically independent and then through the developed combination rules. Thus, the methods proposed do not directly account for the sequential damage analysis due to earthquake shaking and tsunami inundation at the building scale. Instead, the developed formulation treats each earthquake shaking and tsunami inundation damage analysis at the site as a statistically independent event sharing the same initial fault geometry conditions, thus triggering both earthquake shaking and tsunami inundation and allowing for consistent hazard estimates, and a proposed rational approach for combining the damage and damage levels for the estimated structural and non-structural damage.

In addition, ground failure due to potential liquefaction and scouring or impacts of potential debris damage generated during the earthquake shaking and subsequent advections by the tsunami within the community are not currently accounted for in current damage assessment. These assumptions and limitations may generate significant uncertainties on the damage assessment, but the validation of the methodology of combining earthquake shaking and tsunami inundation impacts is beyond current study. In a future work at a community scale, the effects of sequential damage estimation for individual structures, or at least of different building typologies, could be developed in the future using the physics-based fragility curves for earthquake shaking and tsunami inundation (e.g. Attary et al. 2016, 2017b; Alam et al. 2017) and the damage combined using an extended version of the approach developed in this study for combining damage.
The PSTDA could be extended to other type of systems in the built environment, such as transportation, power, water networks, and communication networks, which are fundamental to evaluate the initial response and functionality of each system in the community, as well as the functionality of social and economic system. In addition, the damage to the natural environment can also be examined to understand ecological consequences, particularly for coastal communities with economies tied to marine fisheries, agriculture, and eco-tourism. Loss and damage assessment based on PSTDA are fundamental input data decision-support on mitigation and for the recovery studies. Furthermore, PSTDA could also be extended to larger scales, such as county or state level to provide the essential damage and loss information to estimate the direct and indirect economic loss from tsunami events (e.g. Chen et al. 2018) including interdependencies between different communities.

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Appendix

Figure A1: Extended schematic logic tree model for CSZ.
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