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Comparison of inundation depth and momentum flux based fragilities for probabilistic tsunami damage assessment and uncertainty analysis

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A B S T R A C T

Annual exceedance probabilities of the maximum tsunami inundation depth, h_{Max}, and momentum flux, M_{Max}, conditional on a full-rupture event of the Cascadia Subduction Zone (CSZ) were used to estimate the probability of building damage using a fragility analysis at Seaside, Oregon. Tax lot data, Google Street View, and field reconnaissance surveys were used to classify the buildings in Seaside and to correlate building typologies with existing fragility curves according to the construction material, number of stories, and building seismic design level based on the date of construction. A fragility analysis was used to estimate the damage probability of buildings for 500-, 1000-, and 2500-year exceedance probabilities conditioned on a full-rupture CSZ event. Finally, the sensitivity of building damage was estimated for both the aleatory and epistemic uncertainties involved in the process of damage estimation. Probable damage estimates from the fragility curves based on h_{Max} and on M_{Max} both generally show higher damage probability for structures that are wooden and closer to the shoreline than those that are reinforced concrete (RC) and further landward of the shoreline. However, a relatively high and somewhat unrealistic damage probability was found at the river and creek region from the fragility curve analysis using h_{Max}. Within 500 m from the shoreline, wood structure damage shows significant sensitivity to the aleatory uncertainty of the tsunami generation from the CSZ event. On the other hand, RC structure damage showed equal sensitivity to the aleatory uncertainty of the tsunami generation as well as the epistemic uncertainties due to the numerical modeling of the tsunami inundation (friction), the building classification (material and date of construction), and the type of fragility curves (depth or momentum flux type curves). Further from the shoreline, the wood structures showed similar aleatory and epistemic uncertainties, qualitatively similar to the RC structure sensitivity closer to the shoreline.

1. Introduction

Over the past two decades, megathrust earthquakes and resulting tsunamis, such as the 2004 Indian Ocean tsunami, the 2010 Chile tsunami, and the 2011 Tohoku tsunami have generated catastrophic casualties and damage to the built and natural environments. Post-disaster surveys of damage to the built environment [24,27] highlight the need for strategies to increase the resilience of communities to prepare for future tsunami events and to minimize structural damage and losses. For the study of tsunami resilience, it is necessary to understand the hazard, to estimate how the systems in the built environment will respond, and to predict the recovery processes of infrastructure systems such as buildings, transportation networks (bridges and roads, harbors, railways, and airports), water and waste-water networks, energy networks (electric power and fuel) and communication networks (radio, landlines and wireless). Although the five civil infrastructure systems contain multiple inter-dependencies, building damage assessment is often studied in isolation for evacuation planning to minimize casualties or estimate the need for sheltering. Moreover, building damages are utilized to estimate direct and indirect economic and social impacts on the community [48,6]. In addition, damage assessment of critical facilities such as hospitals, schools, fire stations, and city halls is important because such facilities play significant roles in community management, rescue, and recovery at the moment of a tsunami strike and after the event (e.g., [19]).

Tsunami damage assessments of buildings can be analyzed using either deterministic or probabilistic approaches. Deterministic approaches typically consider a small number of scenarios and then choose the largest “reasonable” tsunami for analysis. Probabilistic approaches, on the other hand, typically consider a wide range of possible scenarios and the associated annual rates of occurrence of each scenario. Both deterministic and probabilistic approaches deal with uncertainties in several steps of tsunami vulnerability assessment, including the estimation of both the tsunami intensity and the tsunami-

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Nomenclature

Symbol	Descriptions	Unit
B	Width of a building	L
C_d	Drag coefficient	-
F_{TS}	Lateral tsunami flow force	MLT^{-2}
h	Inundation depth	L
K_d	Coefficient for the shielding or debris impact	-
M	Momentum flux	L^3T^{-2}
M'	Mean momentum flux	L^3T^{-2}
n	Manning number	$TL^{-1/3}$
P	Probability	-
P_{mean}	Mean probability of damage	-
P_{RC}	Probability damage of RC buildings	-
P_{Wood}	Probability damage of wood buildings	-
x'	Distance to shore-normal direction	L
y'	Distance to shore-parallel direction	L
z	Ground elevation from referenced level	L
β_M	Total logarithmic standard deviation for M	L^3T^{-2}
μ	Mean	L or L^3T^{-2}
μ'	Lognormal mean	L or L^3T^{-2}
ρ_s	Density of water	ML^{-3}
σ	Standard deviation	L
σ'	Lognormal standard deviation	L
Φ	Standardized normal distribution function	-

induced damage on the community. In the deterministic damage assessment of buildings from tsunami inundation, several attempts have been made to estimate the direct tsunami-induced forces on buildings based on the tsunami inundation depth, velocity, and building shape (e.g. [51,28]). FEMA P-646 [11] describes seven tsunami-induced forces on a building, namely the hydrostatic force, buoyancy force, hydrodynamic force, impulsive force, debris impact force, debris damming force, and uplift force. Although it might be possible to estimate these forces for an individual building to determine the design considerations to enable it to withstand the tsunami inundation, it is difficult to apply these forces on the scale of an entire city comprised of thousands of buildings. In addition, estimation of the capacity of individual structures is an overwhelming task as there are a wide range of possibilities for failure including foundation failure, structural failure of columns or beams, failure of infilled walls, or the sliding and overturning of buildings [24,34,43,52,53].

Probabilistic damage assessments using a fragility curve analysis have been widely used to estimate damage to buildings and other infrastructure from diverse hazards such as earthquake, flood, hurricane, and tsunami [14,17,18,29,47]. The fragility curve describes the probability of reaching or exceeding damage levels for a given intensity measure. The damage levels are often described as slight, moderate, extensive, and complete damage. Slight damage is considered as easily reparable and often does not affect the functionality of the building. Complete damage, on the other hand, implies structural failure of buildings, which can no longer provide for life safety to building occupants. For tsunamis, a higher damage state, “collapse or washed away,” can also be considered [39], which is similar to collapse fragility curves derived for other hazards. The intensity measures (IMs) parameterize the hazard and can include peak ground acceleration (PGA) for earthquakes [25], inundation depth for floods [36], maximum wind speed for hurricanes [44,7], and maximum inundation depth, flow velocity, or momentum flux for tsunamis [12,18,39]. Different fragility curves are required to differentiate building typologies: for example, construction material (e.g. wood, steel, reinforced concrete, etc.), number of stories, and the age of construction. Therefore, it is necessary to construct a large number of fragility curves to apply this type of analysis to a community with possibly hundreds of different structural typologies. Fragility curves can be derived empirically based on field or laboratory observations of known intensity measures and resulting damage, by numerical simulations, or, in some cases, through expert opinion (e.g., [10]).

Because of the use of fragility curves for estimating tsunami damage is still relatively new, there are several outstanding questions. First, there is some question about the appropriate intensity measure (IM) to use, particularly whether depth, h, or momentum flux, M, of the flow is more appropriate. On the one hand, flow depth can be more easily estimated from field surveys after large tsunamis, while it is more difficult to estimate velocity. On the other hand, the actual damage to the building may be due to the fluid forces (momentum flux) arising from the tsunami velocity and its spatial distribution. Second, there is also a question about other sources of uncertainty such as the characterization of the building stock. Third, there are questions about the time dependent nature of damage and how the propagation of failure of one building can influence the failure of other buildings either through changes to the flow field or through debris forces from the damaged or destroyed building. While it is difficult to answer all of these questions simultaneously, this paper develops a general framework for the probabilistic tsunami damage assessment (PTDA) on buildings at a community scale (Section 2) using the City of Seaside, Oregon, as a testbed community, and it provides a brief review of the work of [31]; hereafter PC16) to characterize the tsunami hazard

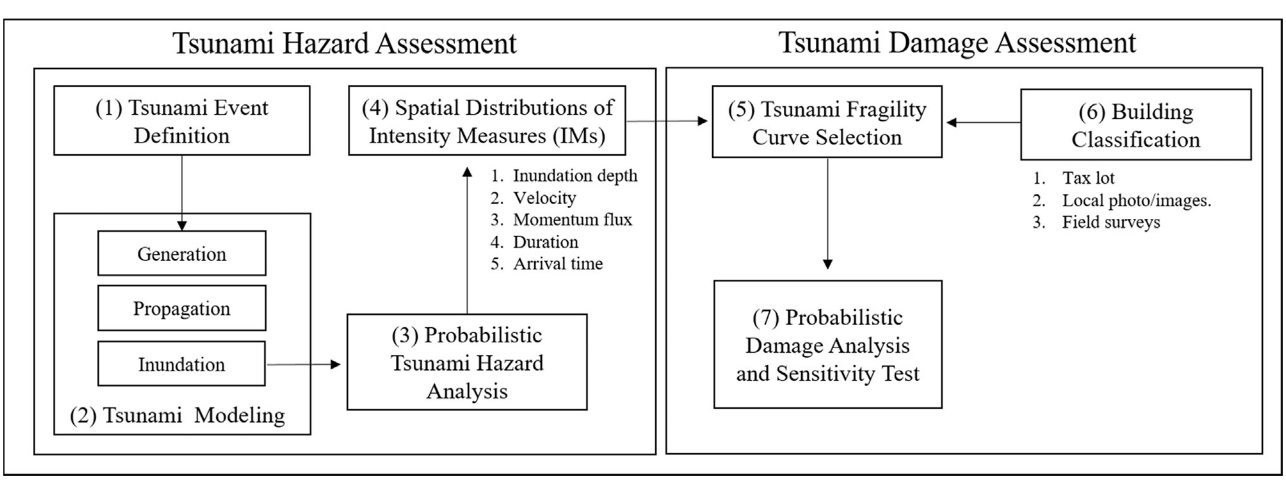

Fig. 1. Flow chart of the probabilistic tsunami damage assessment (PTDA) process.