Coastal Engineering 117 (2016) 79–96

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Probabilistic assessment of near-field tsunami hazards: Inundation depth, velocity, momentum flux, arrival time, and duration applied to Seaside, Oregon

Hyoungsu Park *, Daniel T. Cox

School of Civil and Construction Engineering, Oregon State University, Corvallis, OR 97331-2302, USA

ARTICLE INFO

Article history:
Received 22 April 2016
Received in revised form 29 June 2016
Accepted 28 July 2016
Available online xxxx

Keywords:
Cascadia Subduction Zone
Near-field tsunami
Aleatory uncertainty
Resilience
Intensity measures
Probabilistic tsunami hazard assessment

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 1000-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 shorter inundation duration, T_h (<10 min) is observed at the higher ground level (z > 3 m) while a longer T_h (~100 min) is observed near the river and creek.

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; Rossetto 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, 1987). 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 min. 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 1000 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).

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

http://dx.doi.org/10.1016/j.coastaleng.2016.07.011
0378-3839/

(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 tsunami. 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; González 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 (e.g., Wang et al., 2015), 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 modelling 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.

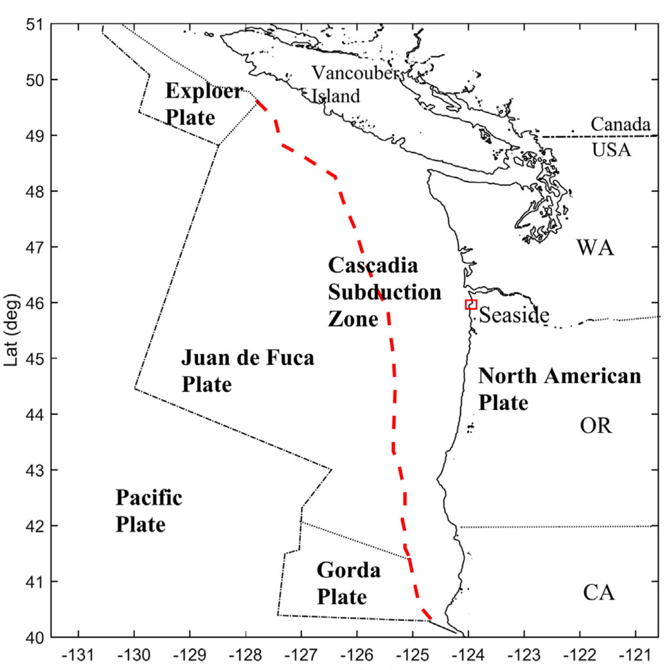

Fig. 1. Regional map of Cascadia Subduction Zone (CSZ) and study area, Seaside, Oregon.

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 and Baptista, 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