Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 198 (2017) 1058 – 1069
Procedia Engineering
www.elsevier.com/locate/procedia

Urban Transitions Conference, Shanghai, September 2016

Probabilistic Earthquake-Tsunami Hazard Assessment: The First Step Towards Resilient Coastal Communities

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Abstract

As more population migrates to coastal regions worldwide, earthquake-triggered tsunamis pose a greater threat than ever before. Stakeholders, decision makers, and emergency managers face an urgent need for operational decision-support tools that provide robust and accurate hazard assessments, when human lives and built environment are at risk. To meet this need, this study presents a new probabilistic procedure for estimating the likelihood that seismic intensity and tsunami inundation will exceed given respective hazard levels. The novelty of the procedure is that a common physical rupture process for shaking and tsunami is explicitly taken into account. The procedure consists of generating numerous stochastic slip distributions of earthquakes with different magnitudes using scaling relationships of source parameters for subduction zones and then using a stochastic synthesis method of earthquake slip distribution. Coupled estimation of earthquake and tsunami intensity parameters is carried out by evaluating spatially correlated strong motion intensity through the adoption of ground motion prediction equations and by solving nonlinear shallow water equations for tsunami wave propagation and inundation. The main output of the proposed procedure is the earthquake-tsunami hazard curves, representing the one-to-one mapping between mean annual rate of occurrence and seismic and inundation tsunami intensity measures. Results are particularly useful for coupled multi-hazard mapping purposes. The developed framework can be further extended to probabilistic seismic and tsunami risk assessment.

Peer-review under responsibility of the organizing committee of the Urban Transitions Conference

Keywords: Mega-thrust subduction earthquake; Tsunami; Probabilistic hazard analysis; Stochastic rupture models; Scaling relationships of earthquake source parameters.

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Peer-review under responsibility of the organizing committee of the Urban Transitions Conference
doi:10.1016/j.proeng.2017.07.150

1. -Introduction

Cascading natural hazards are urgent global issues and may cause catastrophic losses, affecting urban communities from economic, social, and environmental point of view. Earthquake and tsunami can be concurrent threat to coastal cities. In active subduction zones (Japan, Chile, Indonesia, etc.), exposure to these hazards is high because more population migrates to and lives in coastal regions for economic reasons. Probabilistic hazard analysis is the fundamental prerequisite for rigorous risk assessment and thus for decision-making of mitigation strategies addressing the performance of individual facilities and resilience of the entire urban system. Moreover, enhancing preparedness and resilience against future earthquake-tsunami disasters is critical for sustainable development of coastal areas. However, currently, a unified and robust probabilistic cascading hazard assessment approach that is capable of taking into account the main uncertainties of the two hazards in a coupled manner and giving a temporal dimension to the problem is lacking.

Probabilistic hazard analysis involves numerous uncertain parameters. For earthquakes, they are related to geophysical processes and geological characteristics (slip rate, slip distribution, dip, strike, soil condition, etc.), while for tsunamis, sea conditions (e.g. tidal level) and inundation processes (e.g. roughness and topography) are important. Conventional probabilistic seismic hazard analysis [1,2] can incorporate all major uncertain parameters in a comprehensive manner, with a potentially high computational effort. The computation becomes prohibitive when a logic tree with numerous branches (to capture full extent of epistemic uncertainty) is adopted for the assessment. In order to reduce this effort, a simulation-based probabilistic procedure can be implemented [3,4]. Conversely, in current probabilistic tsunami hazard analysis, a comprehensive treatment of these uncertainties is rarely considered due to the lack of high-resolution/accuracy data and the great computational effort involved in tsunami simulation [5,6].

In this study, a novel simulation-based procedure to estimate the likelihood that seismic intensity and tsunami inundation at particular locations will exceed given levels within a certain time interval is presented. Key features of existing hazard assessment methodologies are combined to develop a new procedure for cascading earthquake-tsunami probabilistic hazard assessment. A common physical rupture process for earthquake and tsunami is explicitly taken into account; thus dependency between shaking and tsunami hazard parameters can be investigated probabilistically.

To demonstrate the developed methodology, Sendai City in Miyagi prefecture of Japan is considered as a case study, where large offshore subduction events are the dominant earthquake-tsunami hazards in the future. The obtained results are particularly useful for coupled multi-hazard mapping purposes and the developed framework can be further extended for probabilistic risk analysis by using specific fragility models. Moreover, a potential application of the developed earthquake-tsunami hazard analysis tool will be discussed. It is noteworthy that the procedure is generic and thus can be adapted to other subduction zones.

Nomenclature

$f(\cdot)$	Probability density function
$G(\cdot)$	Complementary cumulative distribution function
h	Tsunami inundation depth
$\mathbf{IM}$	Intensity measures ($\mathbf{im}$ indicates the specific values of $\mathbf{IM}$)
λ	Mean annual rate
M	Moment magnitude (m indicate the specific value of M)
$P(\cdot)$	Probability
PGA	Peck ground acceleration
$\boldsymbol{\theta}$	Earthquake source parameters
t	Reference time in years
V_{S30}	Shear wave velocity in the uppermost 30 meters of soil column