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METHODOLOGY ON PROGRESSIVE CLIMATE CHANGE-RELATED HAZARD EVALUATION OF TSUNAMIS IN THE SEA OF JAPAN

Cuneyt Yavuz [1,2], Tatsuya Itoi[3]

[1] Asst. Prof., Technical Sciences Vocational School, Dumlupinar University, TURKEY (cuneyt.yavuz@dpu.edu.tr)
[2] Visiting Researcher, Graduate School of Engineering, The University of Tokyo, JAPAN
[3] Assoc. Prof., Graduate School of Engineering, The University of Tokyo, JAPAN

ABSTRACT

Earthquake-triggered Tsunami (EtT) has been threatened the coastlines of the globe. The impact of the EtT is expected to be worsening due to the contribution of climate change related Sea Level Rise (SLR). Estimation of the probable hazard levels for the future years is extremely significant for the countries that are frequently exposed to earthquake hazards. The aim of this study is to reveal clustering and importance sampling methods along with Monte Carlo simulations for stochastic tsunami hazard analysis. These methods help to reliably determine the representative hypothetical earthquake events among a large number of Monte Carlo Simulations for the projected years (i.e. 2020, 2050, and 2100).

INTRODUCTION

Global warming has been one of the main concerns among the scientists due to its remarkably adverse effects on natural hazards (Landsea, 2005; Raper and Braithwaite, 2006; Mousavi et al., 2011; Alfonso et al., 2021). Drastic increase of carbon emissions after the industrial revolution causes climate change that is resulted in glacier melting around the poles and thermal expansion of the oceans (Kont et al., 2003; Solomon et al., 2009; Hurlimann et al., 2021). Therefore, next generations are heavily expose the SLR due to rapid climate change all around the globe.

Tsunamis, on the other hand, have been causing destructive economic, social, and environmental damages along the densely populated coastlines of the countries (Srinivas and Nakagawa, 2008; Mori et al., 2011; IAEA, 2015; Itoi and Sekimura, 2017; Drápela et al., 2021; Lane et al., 2021) that includes an accident at the Fukushima Daiichi Nuclear Power Plant occurred on March 11, 2011. Nonetheless, significant improvement on tsunami disaster mitigation systems has been developed by the scientists and the authorities (Gonzalez et al., 1998; Osti et al., 2009; Imamura et al., 2012; Yamazaki et al., 2013).

Despite the several scientific investigations on SLR and tsunami hazards, combined hazard evaluation of these two natural hazards should be investigated in more depth (Dall'Osso et al., 2014; Li et al., 2018; Yavuz et al., 2020; Nagai et al., 2020). In this study, two methodologies on progressive climate change impact on tsunami hazard evaluation is presented considering the nuclear power plants and the area along the Sea of Japan. Monte Carlo (MC) simulations are applied to generate random earthquake parameters considering historical earthquake records along the study area. Epistemic uncertainty is also taken into consideration for SRL predictions. MC simulations are conducted to get probabilistic hazard curves of the EtTs for the projected years. Finally, clustering and importance sampling methods are implemented to determine the representative earthquake sources along the Sea of Japan.

METHODOLOGY

Two approaches are revealed to combine SLR and EtT hazards for the 21st century. Previously, 100000 MC simulations are performed by validating the assigned distribution on moment magnitude (M_w) of the historical earthquakes. 113 years of historical earthquake records are acquired from ISC-GEM ver. 8.0 catalogue (Di Giacomo et al., 2018). 1000 locations of the historical earthquakes are compiled from Japan University Network Earthquake Catalogue (JUNEC) as shown in Figure 1. Earthquake Data Set (EDS) is generated for probabilistic hazard analysis of SLR and EtT combinations using MC simulations. Using the source parameters given in ISC-GEM catalogue, MC samples for moment magnitude are generated and randomly assigned to the locations retrieved from JUNEC.

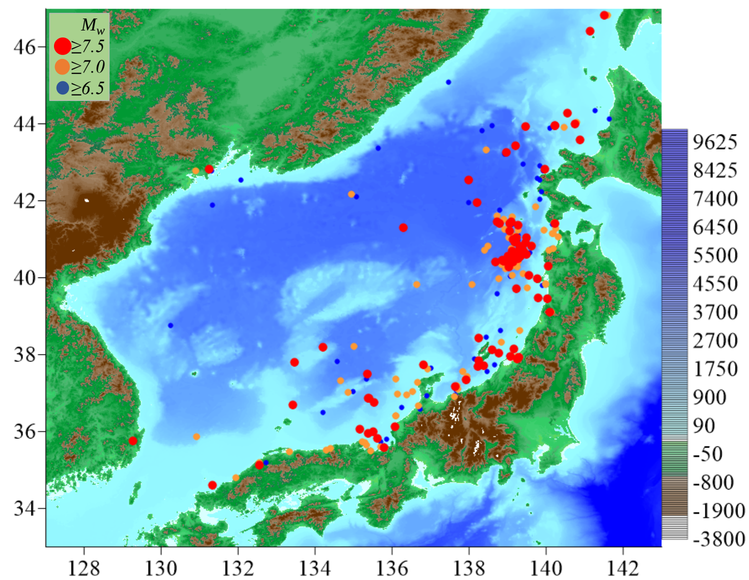

Figure 1. Locations of the historical earthquakes are compiled from JUNEC

Tsunami wave heights are empirically calculated by considering aleatory variabilities which is significant to determine the exceedance probabilities of hypothetical tsunami wave heights along the coastline. The empirical equations previously proposed and applied by Cornell (1968), Aida (1978), Burton (1978), Ishikawa and Kameda (1988), McGuire (1995), Fukutani et al. (2018), Papadopoulos et al. (2020), and Katsumata et al. (2021) are used to determine tsunami hazard curves for the selected regions. Since MC simulation method can only be implemented for the independent parameters, dependent parameters of the earthquake source (i.e. fault length (L) and fault width (W)) are calculated using the empirical equations given by Irikura & Miyake (2001), Otake (2002), and Tajima et al. (2013). Generation mechanism of EDS using MC simulations is shown in Figure 2.

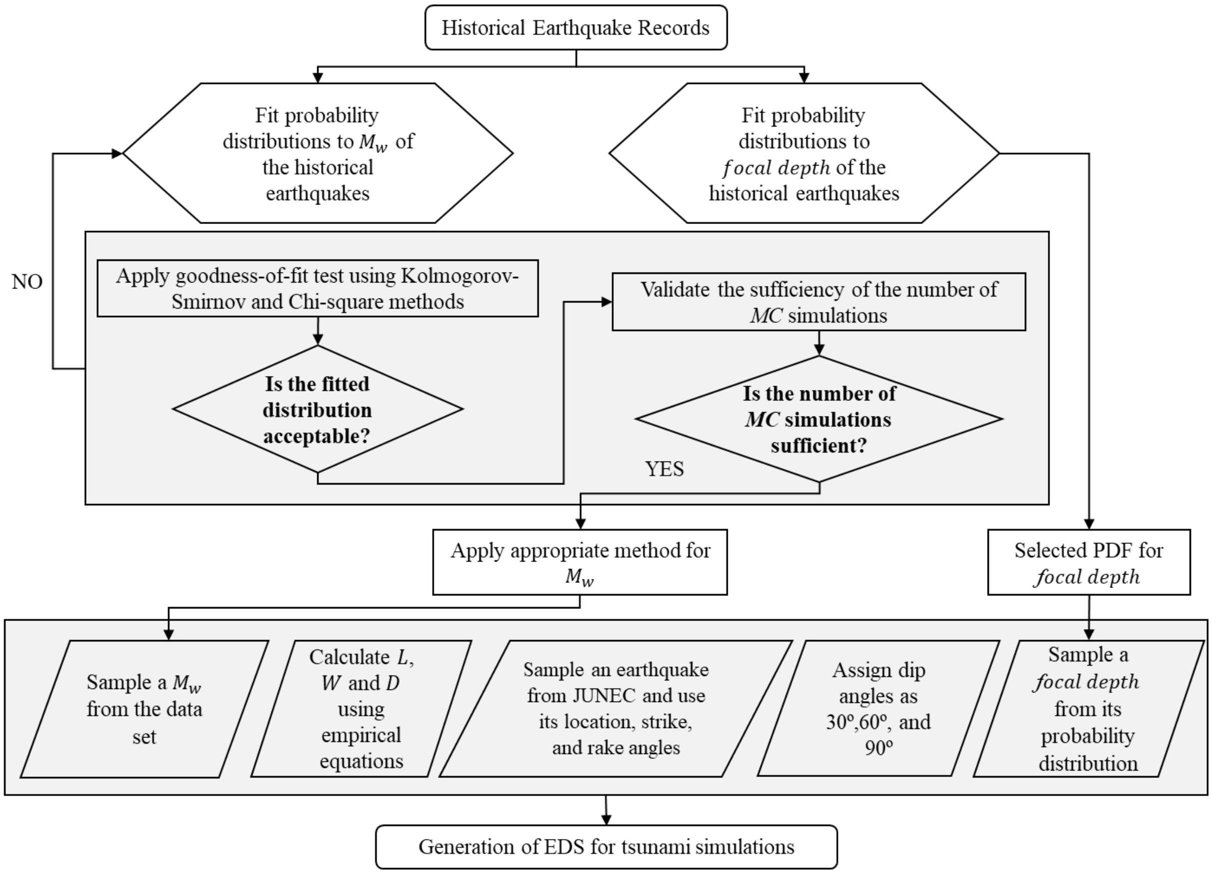

Figure 2. Generation mechanism of the EDS by MC simulations

SLR Estimations

Currently, the most comprehensive investigation on climate change has been performed by the International Panel on Climate Change (IPCC). In this study, epistemic uncertainty in sea level rise predictions is considered based on the different IPCC scenarios. NASA (2022) developed a SLR prediction tool based on the Shared Socioeconomic Pathway (SSP) scenarios released in the IPCC 6th assessment report (AR6). The tool developed by NASA is used in this study to estimate the SLR levels from 9 different locations (i.e. Izuhara, Tonoura, Sakai, Maizuru, Wajima, Kashiwazaki, Nezugaseki, Oshoro and Wakkanai) along the Sea of Japan for the optimistic, medium, and extreme SSP scenarios given in IPCC AR6. The average SLR estimations of 3 different SSP scenarios are illustrated in Figure 3.

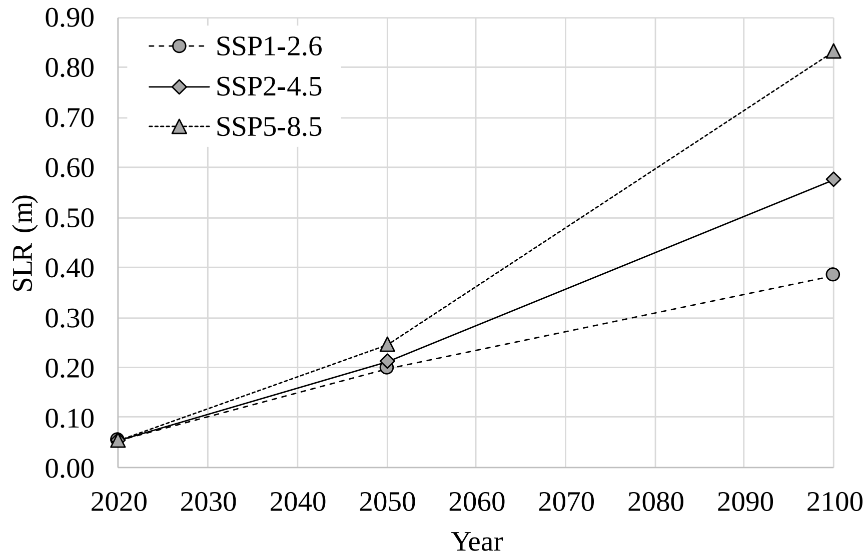

Figure 3. (a) Locations and (b) SLR predictions for the different SSP scenarios throughout the 21st century

By determining the SLR predictions for the projected years, bathymetric levels can be revised accordingly. Tsunami simulations can be conducted using the revised bathymetries for each projected year considering the SLR predictions.

Tsunami Hazard Curves

In advance of the determination of representative earthquakes from MC simulations, the accuracy of the tsunami model has to be satisfied for a reliable probabilistic tsunami hazard evaluation. To achieve a reliable tsunami hazard curve from the generated hypothetical earthquake sources using MC simulations depending on the commonly used methods proposed in the literature (Aida, 1978; McGuire, 1995; Fukutani et al., 2015, 2018). In this study, several tsunami hazard curves are generated by referencing the location of Niigata, Japan using the earthquake magnitudes obtained from MC simulations (see Figure 4). As clearly shown in Figure 4 that tsunami hazard analysis is reliable up to 10^{-4}/year according to the coincidence of the hazard curves. The following combined hazard analyses are proposed according to the coincidence of the hazard curves for the selected region.

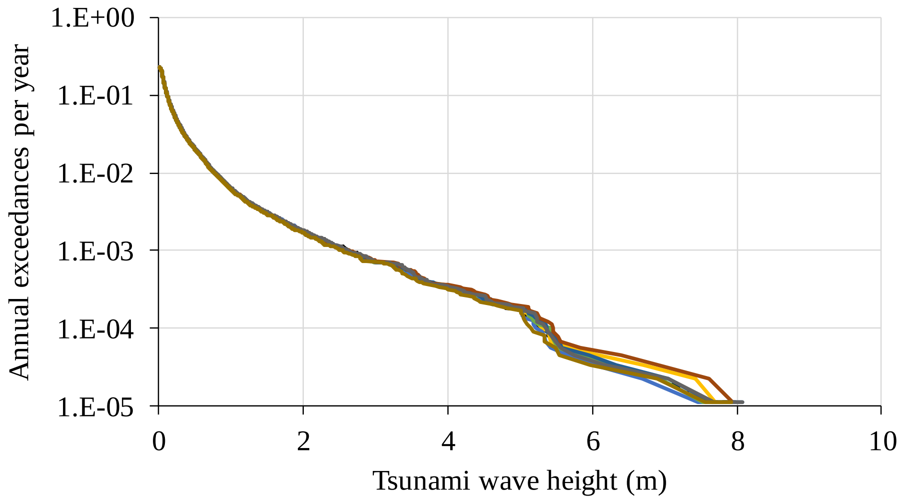

Figure 4. Coincidence of the tsunami hazard curves generated for probabilistic hazard analysis

It is stated by US Geological Survey (USGS, 2022) that earthquakes of 6.5 magnitudes and below this magnitude are unexpected to trigger a tsunami. Therefore, hypothetical earthquakes having $6.5<M_w$ are considered for the tsunami hazard evaluation in this study. Thus, the number of the magnitudes should be considered for tsunami simulations are obtained as 20136 out of 100000 to get a reliable convergence for tsunami hazard evaluation.

Determination of Representative Hypothetical Earthquakes using Clustering Method

The numerical simulation of 20136 hypothetical earthquakes in the study area will be incredibly demanding even for a single location in the study area. Moreover, many of the hypothetically generated earthquake events would result in quite similar inundation levels and patterns. Therefore, clustering the events probably having the same patterns and wisely chosen representative hypothetical earthquakes can be a good solution to reduce the number of numerical simulations and get a tsunami hazard curve for a single site. The framework of the proposed method is given in Figure 5. Clustering of events having a similar pattern can be possible by using box-whisker analysis of the hypothetical earthquakes generated by MC simulations.

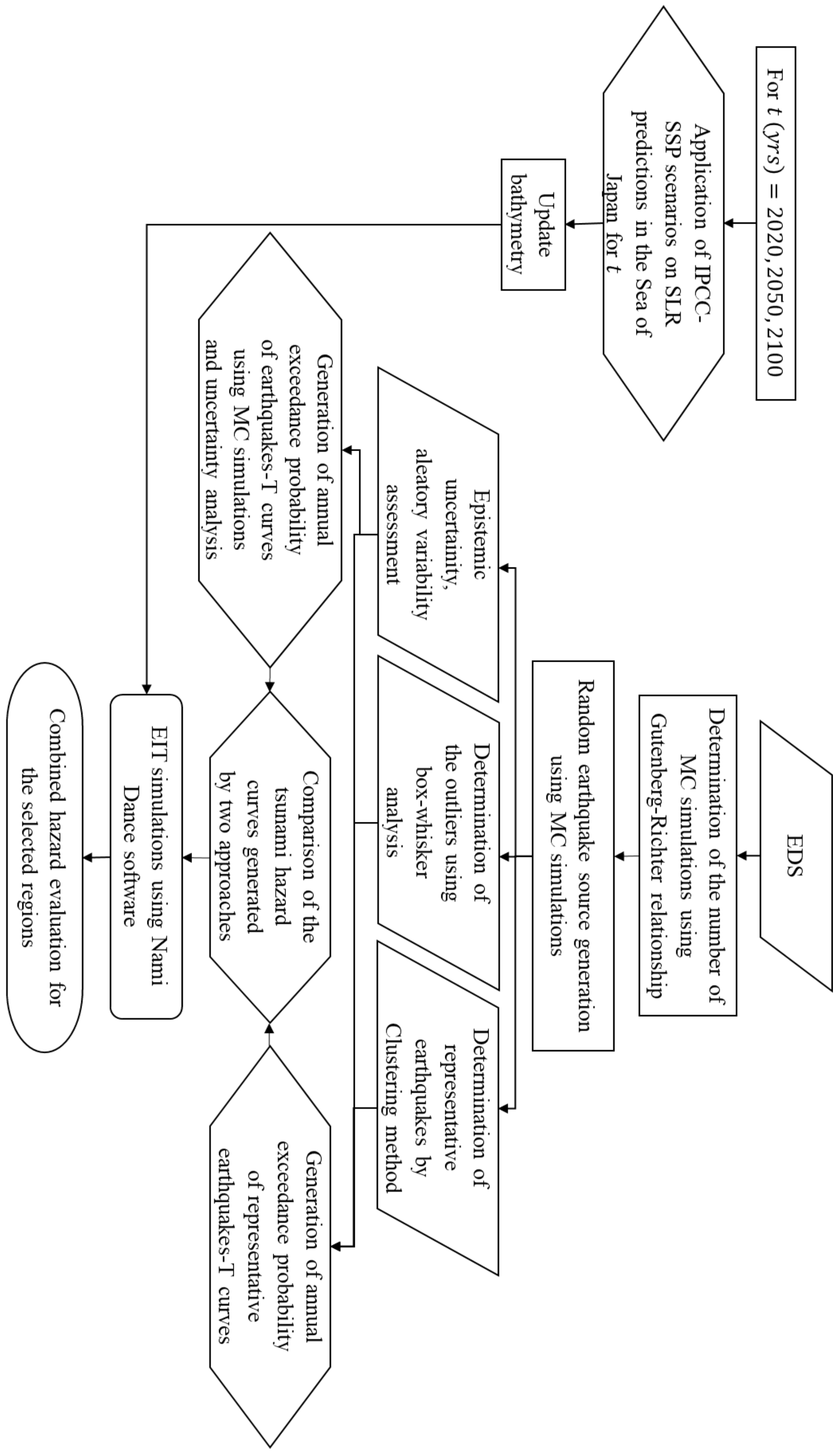

Figure 5. Clustering method to determine the representative earthquake events in the study area

Determination of Representative Hypothetical Earthquakes using Importance Sampling Method

Importance sampling method is widely used in stochastic analysis of natural hazards and also applicable for probabilistic tsunami hazard analysis. The method has some additional advantages like manually determination of representative data number depending on the convergence of the representative tsunami hazard curve to the curve generated from MC simulations. The details about the methodology is given in the flowchart as shown in Figure 6. Thanks to the importance sampling method, a consistent tsunami hazard curve can easily be obtained wıth far fewer numerical simulations.

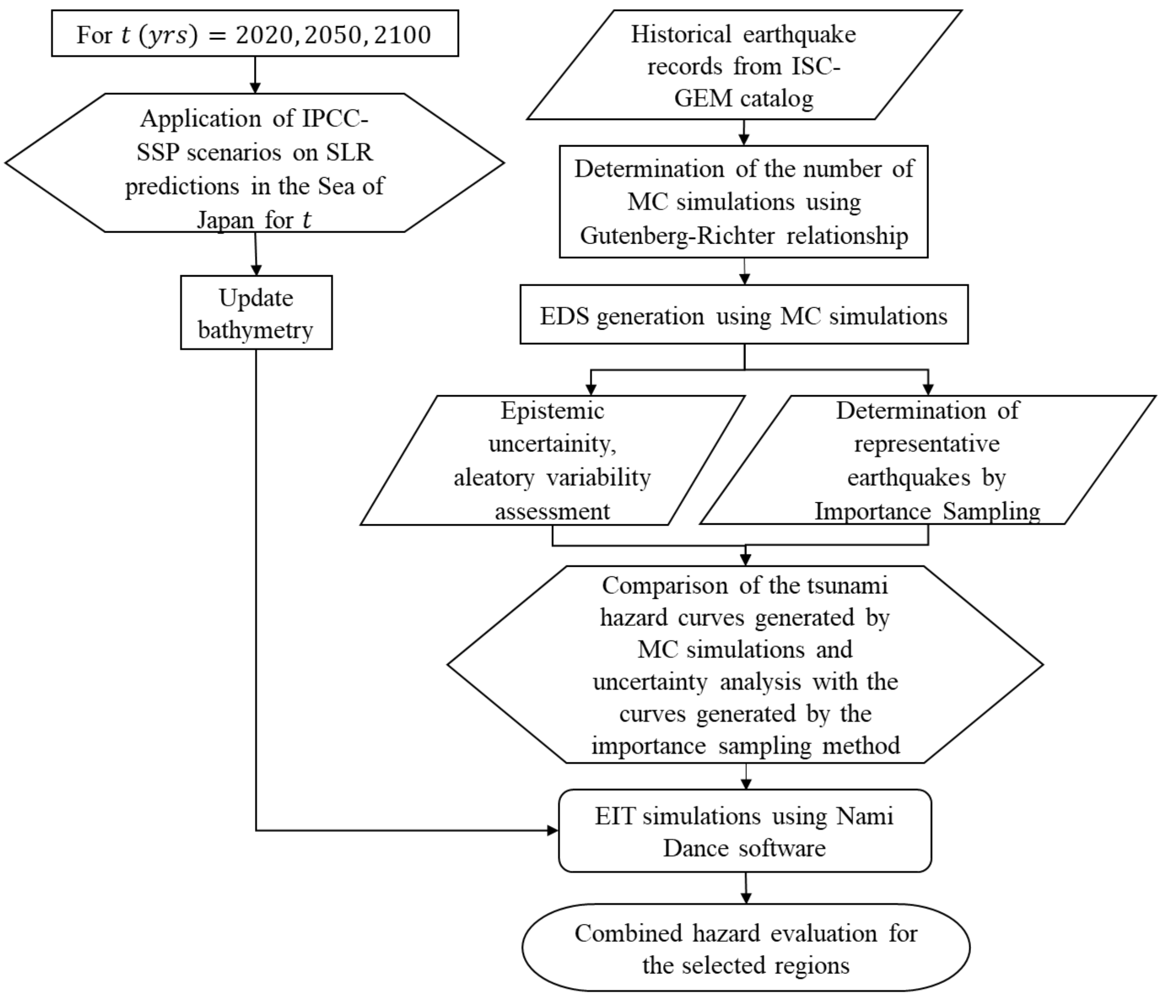

Figure 6. Application procedure of the Importance sampling method in the study area

RESULTS AND DISCUSSIONS

Combined hazard evaluation of SLR and EtT can be conducted for projected years with either clustering or importance sampling method. In clustering method, M_w of the hypothetical earthquake events are clustered using the box-whisker analysis according to empirically calculated tsunami wave heights at Niigata coastline. In Figure 7, the convergence of the M_w values can be seen clearly. By inspecting the convergence of the M_w values, around 1500 event is sufficient to represent a reliable tsunami hazard curve as obtained from 100000 MC simulations.

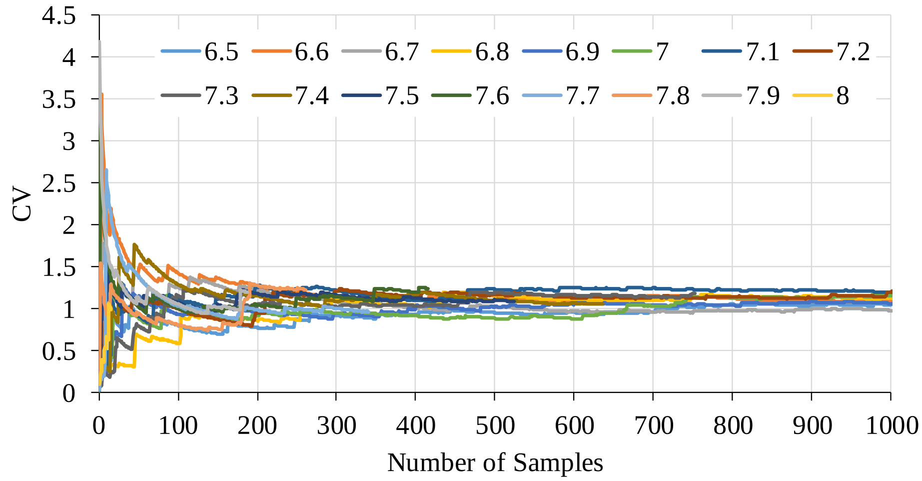

Figure 7. Convergence of the M_w values in clustering method

Tsunami hazard curve obtained from 1500 representative event is compared with the hazard curve obtained from MC simulations and the result of the comparison is shown in Figure 8. As shown in the related figure, there is a perfect match between two tsunami hazard curves of the analyses. Thus, similar hazard values can be obtained with clustering method just by simulating 1500 representative events out of 100000 MC samples.

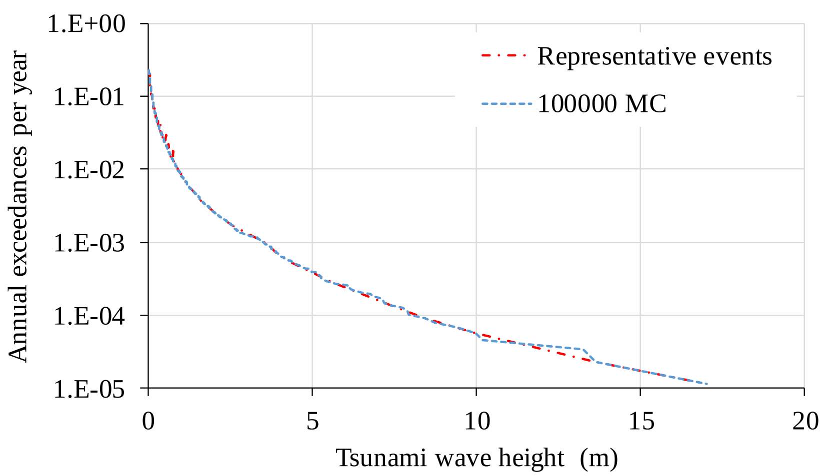

Figure 8. Convergence of the M_w values in clustering method

Importance sampling method is also proposed in this study. As the advantage of this method, the number of samples can be defined manually. In this study, uniform distribution is used to generate 250 hypothetical earthquake magnitude samples that have the identical hypocentre distance and the consistency of the tsunami hazard curve of the samples with the curve obtained from MC simulations can be seen in Figure 9. The convergence of the tsunami hazard curves shows that this method can also be applicable for probabilistic hazard analysis.

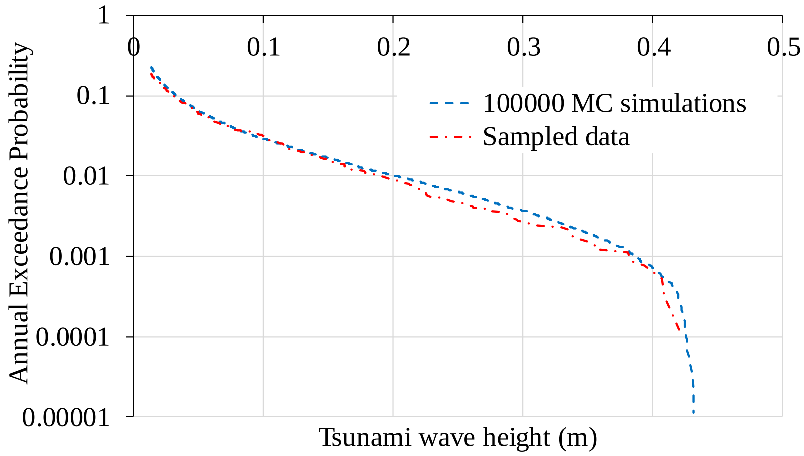

Figure 9. Convergence of the M_w values in importance sampling method

CONCLUSION

This study summarized a methodology for stochastic tsunami hazard analysis based on Monte Carlo simulation. Importance sampling and clustering approaches are proposed to conduct combined hazard analyses in the Sea of Japan. Both methods have a reliable convergence with the MC simulations even with the far fewer simulations. Considering the result of the clustering method, the convergence of the M_w is satisfied with comparatively large number of representative earthquake events. Importance sampling also has a reliable match in hazard curve comparison. Both of the methodologies can be applicable in probabilistic combined hazard analyses.

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