Soil Dynamics and Earthquake Engineering 109 (2018) 339–353

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Ground motion prediction equations for distant subduction interface earthquakes based on empirical data in the Malay Peninsula and Japan

Abdollah Vaez Shoushtari[a], Azlan Bin Adnan[a,*], Mehdi Zare[b]

[a] Department of Structure and Materials, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Bahru, Malaysia

[b] Department of Engineering Seismology, International Institute of Earthquake Engineering and Seismology (IIEES), 26 Arghavan St., 19395/3913 Tehran, Iran

ARTICLE INFO

Keywords:
Ground motion prediction equations
Distant subduction interface earthquakes
Peninsular Malaysia
Sumatra
Japan
Seismic hazard analysis

ABSTRACT

Ground motion prediction equations (GMPEs) for earthquakes that occur in subduction zones, including both interface and slab parts, have a major impact on seismic hazard analysis in many parts of the world. For example, in the Sumatran subduction region, there could be a remarkable hazard for the Malay Peninsula due to the large megathrust earthquakes that occur far from the region along the subduction interface. This study has developed new empirical spectral GMPEs for long-distance subduction interface earthquakes based on the recorded ground motion data in the Malay Peninsula and Japan. The compiled ground motion database is from hundreds of ground motion recordings due to twenty five reliably identified subduction interface events with moment magnitude [**M**] of 5.0–9.1 and hypocentral distance (R_{hyp}) up to 1300 km. The data from the large megathrust earthquakes with **M** ≥ 7.0 such as 2011 **M** 9.1 Tohoku-Japan, the 2007 **M** 8.5 earthquake near Bengkulu in Sumatra Island, 2005 **M** 8.6 Nias-Sumatra, and 2004 **M** 9.0 Aceh-Sumatra earthquakes were included in the database. The proposed GMPEs are able to predict peak ground acceleration (PGA), peak ground velocity (PGV), and 5% damped pseudo-spectral acceleration (PSA) for four different site classes based on the National Earthquake Hazards Reduction Program (NEHRP) site classification. The results of this study could be applied to develop logic tree frameworks for seismic hazard analyses of Peninsular Malaysia as well as the regions affected by large and distant subduction interface earthquake events.

1. Introduction

Generally, earthquake design has not been taken into account for the structures of Southeast Asia regions with low to moderate seismicity, as these areas have not as yet experienced disasters caused by earthquakes. The Malay Peninsula is a good example of these regions. Although the main cities of the region (i.e., Kuala Lumpur-capital of Malaysia, Johor Bahru, Penang, and etc.), are located in a low seismicity region, they could be vulnerable to distant Sumatran earthquakes with long epicentral distance (R_{epi}) of more than 300 km away. The large magnitude earthquakes generated by the Sumatran seismic sources have caused shaking in medium to high rise buildings in Kuala Lumpur and Singapore and have raised concern through the region. The rapid construction of medium to high rise buildings in the region has caused the increase of the number of felt events [33]. The 2011 Tohoku earthquake in Japan with moment magnitude [**M**] 9.1 could be a good example of gigantic megathrust earthquakes with significant influences on sites far from the epicenter. It was reported that most of the high rise buildings of Osaka and Tokyo cities of Japan were seriously shaken by the earthquake-induced long-period ground motions with R_{epi} of about 760 and 385 km away, respectively [44]. Soil site effect as another criterion is able to cause serious damage by amplifying the long-period, low amplitude ground motions. For example, in 1985, Mexico City experienced serious damage by the Michoacán earthquake with a moment magnitude of about 8.2 and R_{epi} of about 400 km away from the city. The disaster was due to the amplified incoming earthquake waves by the soft soil layers on the ground surface [39].

In recent years, the Malay Peninsula and Singapore have experienced the aforementioned concepts [29,34,35,37]. Thus, the seismic hazard of the region, where there are several metropolises with high concentrations of high rise buildings and large populations, should be assessed comprehensively. Probabilistic seismic hazard analysis (PSHA) is the best method to estimate the seismic hazard level of a region. One of the most important key factors in any PSHA is the selection of applicable ground motion prediction equations (GMPEs). In a recent seismic hazard study conducted by Nabilah and Balendra [29], the peak ground acceleration (PGA) values on rock site in Kuala Lumpur with 10% and 2% probabilities of exceedance over 50-year corresponding to

* Corresponding author.
E-mail addresses: vsabdollah3@live.utm.my (A. Vaez Shoushtari), azlanadnan@utm.my (A.B. Adnan), mzare@iiees.ac.ir (M. Zare).

https://doi.org/10.1016/j.soildyn.2018.03.024
Received 22 June 2017; Received in revised form 25 February 2018; Accepted 20 March 2018
0267-7261/

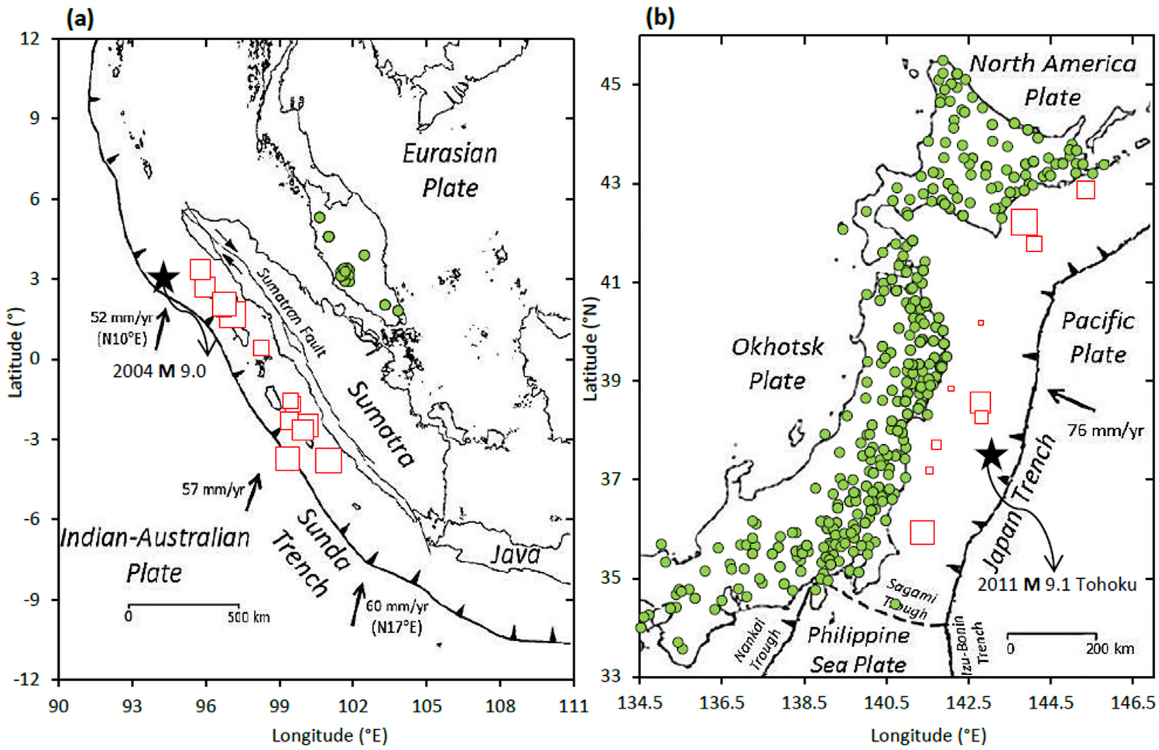

Fig. 1. Ground motion recording stations (illustrated by filled circles) and epicenters (illustrated by open squares) of (a) Sumatran subduction interface earthquakes recorded by Malaysian Meteorological Department (MMD) stations located in the Malay Peninsula. The epicenter of 2004 **M** 9.0 Aceh earthquake is indicated with a large black star - modified figure from Megawati and Pan [28] and (b) Japan subduction interface earthquakes recorded by Kyoshin (K-NET) and Kiban Kyoshin (KiK-net) stations in Japan. The epicenter of 2011 **M** 9.1 Tohoku earthquake is indicated with a large black star - modified figure from Ghofrani and Atkinson [25]. The sizes of the open square symbols are representative of the magnitudes.

475 and 2475 years return period were found to be about 0.017 and 0.024 g, respectively. Adnan et al. [4] and Petersen et al. [38] estimated the rock site PGA values for Kuala Lumpur of about 0.075 and 0.095 g with 475 years return period, respectively. Pan and Megawati [36] predicted the PGA values to be around 0.03 and 0.013 g with the same return period on rock site in Kuala Lumpur and Singapore, respectively. The aforementioned different results could be due to the selection of GMPEs that are not generally compatible with the region.

Sumatran seismic sources include Sumatran fault, Sumatran subduction interface, and Sumatran subduction slab. At the Sumatran subduction region there could be a considerable hazard for Peninsular Malaysia due to the distant large megathrust earthquakes along the subduction interface. Megawati et al. [27] and Megawati and Pan [28] have proposed spectral GMPEs for Sumatran subduction interface earthquakes based on synthetic ground motions obtained using point-source dislocation and finite-fault kinematic models, respectively. However, having referred to [15,16], in the regions such as Peninsular Malaysia where real recordings are very limited, there could be a large degree of uncertainty in the calculation of absolute values of ground motions using theoretical methods. Petersen et al. [38] modified the empirical GMPE of Youngs et al. [45] derived for subduction interface earthquakes using several regional recorded data at long distances for predicting PGA. The GMPE developed by Adnan et al. [3] was also presented to only predict peak ground acceleration using worldwide ground motion recordings due to subduction interface and slab earthquakes. In 2012, a new empirical GMPE to estimate peak ground acceleration was proposed for Peninsular Malaysia by Nabilah and Balendra [29] using 35 local ground motion recordings due to the Sumatran subduction interface earthquakes. Shoushtari et al. [40] proposed a new set of empirical spectral GMPEs for distant subduction slab events and the model for distant interface earthquakes is presented by this study.

Towards the seismic hazard analysis of the region more realistically, this study has attempted to derive new empirical spectral GMPEs based on a response spectra database complied from hundreds of ground motion recorded data due to the reliably identified subduction interface earthquakes with moment magnitude [**M**] of 5.0–9.1 with long hypocentral distance (R_{hyp}) range between 120 and 1300 km. The presented GMPEs are for peak ground acceleration (PGA), peak ground velocity (PGV), and 5% damped pseudo-spectral acceleration (PSA) for four different site classes based on the National Earthquake Hazards Reduction Program (NEHRP) site classification.

2. Ground motion database

The number of recorded ground motion data in the Malay Peninsula due to Sumatran subduction interface earthquakes was limited and sparse. However, based on the limited empirical ground motion data it has been concluded that for a given magnitude and distance there are no significant differences between the earthquake-induced ground motions due to different subduction regions [18,46,6]. On the other hand, in reference to the studies done by Pan and Megawati [36] and Shoushtari et al. [41], the ground-motion relations proposed by Fukushima and Tanaka [24] and Zhao et al. [47] developed for Japanese seismic sources were found to correlate well with the ground motion data recorded in Peninsular Malaysia and Singapore. In addition, as the tectonic setting of the Sumatra-Malay Peninsula is similar to that of the Japan region, it was concluded that the attenuation rate of the two regions is likely to be comparable with each other. Therefore, the new empirical spectral GMPEs for distant subduction interface earthquakes are derived based on the ground motion database compiled from the recorded data in Peninsular Malaysia and Japan due to the Sumatran and Japan subduction interface earthquakes, respectively.

Sumatra Island located on the Eurasian plate rests on top of the subducting Indian-Australian plate. The convergence of the two Indian-Australian and Eurasian tectonic plates has formed the Sunda trench