17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

Global Risk-Targeted Ground Motions

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Abstract

Seismic design in most of the countries around the world is based on uniform hazard for a specific return period. The uncertainty in structural capacity, combined with site to site variability of the shapes of ground motion hazard curves, leads to lack of consistency in building collapse risk. Therefore, seismic design maps driven only by uniform ground motion may not reflect uniform probability of collapse of the buildings.

In order to resolve this issue, ASCE 7-10 started to adopt seismic design maps for the U.S. in the form of Risk-Targeted Ground Motions (RTGM), providing ground motion values that would cause 1% probability of collapse in 50 years. The RTGM calculations require an iterative process in which each iteration involves derivation of the fragility curves, followed by integration of the product of the hazard curve and the derivative of fragility curves. The iterative process is completed when a 1% probability of collapse in 50 years is achieved.

Here, the RTGM methodology adopted by ASCE 7-16 is applied to hazard curves generated for the entire world, based on hazard models collated and developed by the Global Earthquake Model (GEM) foundation. The resulting RTGM values illustrate a uniform view of the risk of collapse for buildings located around the world. In addition, the calculated RTGM values are compared with the seismic design code parameters of major earthquake-prone countries to understand the impact if the RTGM values were implemented instead.

Keywords: risk-targeted, ground-motion, probabilistic, seismic hazard, collapse fragility.

1. Introduction

One of the main parameters required for design of a new structure or evaluation of an existing one in seismic regions is the ground motion intensity at the location. Different uniform hazard parameters (e.g., peak ground acceleration or spectral acceleration that would have 10% probability of being exceeded in 50 years) have been used for seismic design and evaluation around the world. In the United States, ASCE 7-98 [1], in contrast with previous editions, was the first edition to provide seismic design ground motions based on 2/3 of spectral acceleration that would have 2% probability of being exceeded in 50 years (i.e., 2475-year return period). The reason for this change was that, even though ground motions with 475-year return periods seemed sufficient to capture most events that might occur in the western U.S., they would not be large enough to capture ground shaking events in the eastern U.S. such as the 1811-1812 New Madrid earthquakes or the 1886 Charleston earthquake. Although ASCE 7-98 [1] used ground motions with 2475-year return period, the values that were deemed excessively high in regions close to major active faults were capped by deterministic estimates of maximum likely ground shaking.

By using uniform hazard parameters and assuming no uncertainty in the structural capacity, the probability of damage or collapse of a structure would then also be considered uniform. However, since there is a significant uncertainty in the structural capacity and site to site variability in the shape of the hazard curves, the design ground motion would not result in a uniform probability of damage/collapse of structures. In 2007, Luco et al. [2] used a probability distribution for collapse capacity along with hazard curves to generate Risk-Targeted Ground Motion (RTGM) values. This methodology was used to generate seismic design maps of ASCE 7-10 [3] for periods of 0.2 s and 1 s, providing a uniform risk in contrast with the uniform hazard maps in the previous editions of the code. The same methodology with minor adjustments was used by ASCE 7-16 [4] to generate seismic design maps. It should be noted that ASCE 7-16 seismic design values are still subject to the deterministic caps in regions close to major faults, similar to ASCE 7-98, which would disrupt the uniform risk concept of the developed RTGM maps. RTGM maps also have been developed for other regions. For example, Silva et al. [5] for Europe and Petersen et al. [6] for South America used similar approaches. However, there is a need to develop a global RTGM map, which is the focus of this study.

2. Risk-Targeted Ground Motion

Figure 1 shows the iterative process to calculate the RTGM values summarizing the approach by Luco et al. [2]. The process starts by selecting the ground motion with 2475-year return period (GM) at the specific location. A generic fragility curve (i.e., a lognormal function representing the probability of exceeding collapse damage state as a function of spectral acceleration), shown in Figure 1, is then constructed by considering the uncertainty in the collapse capacity that determines the GM that would cause 10% probability of collapse. Integration of the fragility function with the hazard curve of the location through risk integral (see [2] for details) determines the probability of collapse. By choosing 1% probability of collapse in 50 years (based on the 2003 NEHRP Provisions [7] recommendation as applied in ASCE 7) as a target, the RTGM value can be calculated by iteration.

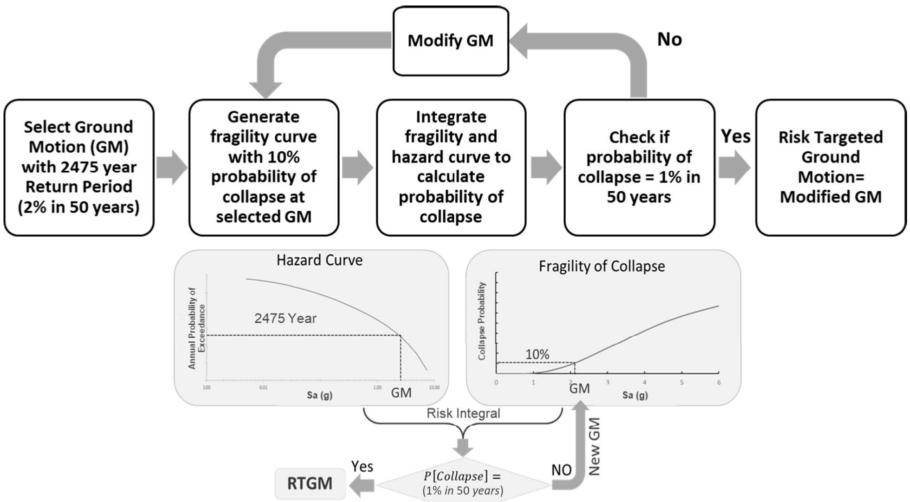

Figure 1. Methodology to obtain Risk-Targeted Ground Motion values from hazard curves, with left graph representing the conditions used for the first iteration.

3. Maximum Direction Ground Motion Factor

The probabilistic hazard models predict the median spectral acceleration of a ground motion when rotated over all horizontal orientations. However, most engineers recommend that the maximum spectral acceleration over all orientations be considered more meaningful than the median value for structural design (e.g., NEHRP [8]). Figure 2 shows an example of a ground motion in two directions. The figure indicates that the maximum ground motion can occur in a direction other than the orientation of the sensors recording the ground motions. In 2008, Huang et al. [9] proposed maximum direction factors for different periods to amplify median ground motions to account for the directionality of the motion. The two recent editions of ASCE 7 (ASCE 7-10 [3] and ASCE 7-16 [4]) used maximum direction factors of 1.1 for 0.2-s and 1.3 for 1-s ground motions to amplify the median RTGM values. However, Shahi et al. [10] in 2014 studied over 3000 ground motions from the expanded NGA-West2 database and built empirical models to calculate these factors, which resulted in NEHRP recommendations [11] of 1.2 and 1.25 for 0.2-s and 1-s ground motions, respectively.

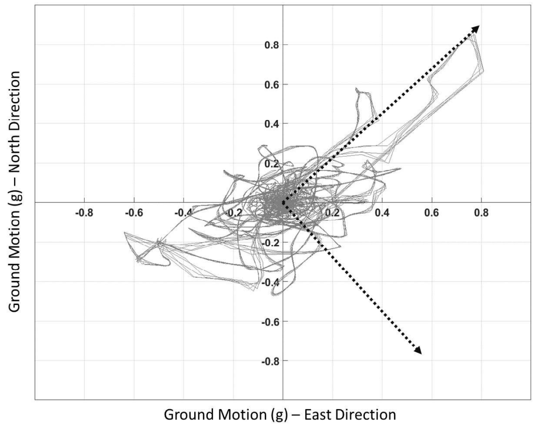

Figure 2. An example of a ground motion (Chi-Chi earthquake, 1999) in two directions showing the maximum direction effect.

4. Global Seismic Hazard Curves

To develop a global RTGM map, global seismic hazard curves are required. Recently, the Global Earthquake Model (GEM) foundation released OpenQuake [12] input files of global earthquake models [13] as a mosaic of regional (Arabian Peninsula, Europe, Caribbean and Central America, Sub-Saharan Africa, Central Asia, Northwest Asia, Northeast Asia, Pacific Islands, Middle East, North Africa, South Africa, Western Africa, Southeast Asia, South America) and national/local (Alaska, Australia, Canada, China, India, Hawaii, Indonesia, Japan, Korea, Mexico, New Zealand, Philippines, Papua New Guinea, South Africa, Taiwan) earthquake hazard models. A minor fraction of the GEM mosaic contains models that are not necessarily recognized by the government entities but are available in the literature or have been developed by GEM researchers. Therefore, the mosaic incorporates openly available probabilistic seismic hazard assessment (PSHA) models. In this study, all those models are used to generate seismic hazard curves around the globe using OpenQuake software developed by GEM. In addition, a more recent detailed model of mainland China [14] and the 2018 US Geological Survey (USGS) national seismic hazard map for the conterminous United States [15] are used here.

5. Global RTGM Maps

A consistent global RTGM map is based on uniform risk of collapse. Therefore, it could provide a good perspective of the design ground motion at a location. In this study, the global seismic hazard curves were generated for all around the world, as explained in Section 4, and the RTGM calculation process (Figure 1) was performed. The RTGM values were generated for periods of 0.2 s and 1 s globally. In addition, to account for maximum direction amplification, based on NEHRP recommendations [11], the generated RTGM values were amplified by 1.2 and 1.25 for 0.2 s and 1 s, respectively. Figure 3 shows the global RTGM maps on bedrock (soil type B/C) for 0.2 s and 1 s periods. As mentioned earlier, deterministic ground motion caps were used by recent ASCE 7 seismic design maps to reduce the RTGM values in regions close to faults, accepting more risk of collapse in these regions. Since applying such caps on RTGM values would disturb the uniform risk concept of the RTGM maps (which is the main objective of this process), deterministic caps were not applied to the RTGM values in this study.

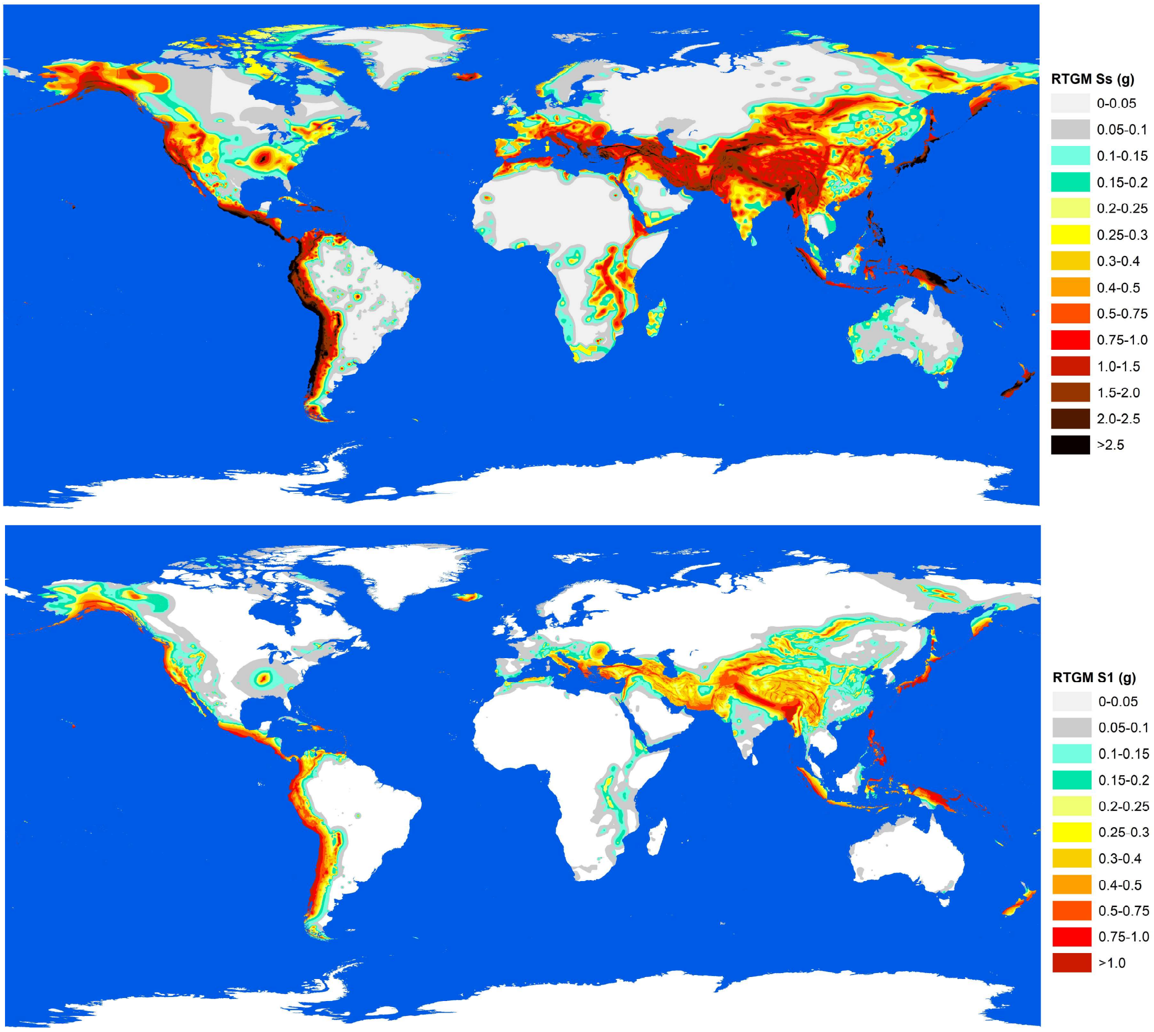

Figure 3. Global RTGM maps on bedrock, top: Ss (0.2 s period), bottom: S1 (1 s period).

6. Comparison of RTGM values with National Building Codes

To have a better sense of the calculated RTGM values, we compare them with the design ground motions of major cities in different countries. Seismic design codes of 40 different countries were reviewed, based on the latest design code provided by IAEE [16]. The design code-level ground motions (i.e., PGA values with 475-year return period on bedrock) for 134 major cities in these 40 countries were obtained. Then, the city with the maximum ground motion in each country was selected and their PGAs were compared with the corresponding generated RTGM values. Figure 4 shows the comparison between the equivalent PGA derived from the global RTGM map and the design codes PGAs. The equivalent PGAs are obtained as 40% of 2/3 RTGM values for 0.2 s period (per ASCE 7 seismic design spectrum). The differences between RTGM and the design code in Figure 4 can be due to (1) new hazard models for the country that are not yet reflected in the design code, (2) differences between 2/3 RTGM and the 475-year ground motion typically used for design for some countries, or (3) the seismic design code of the country applying a maximum cap for the design ground motion. The RTGM values could be considered a more useful representative of a ground motion used for design because it shows a uniform risk globally, considering uncertainties in structural collapse as well as ground motions with higher return period.

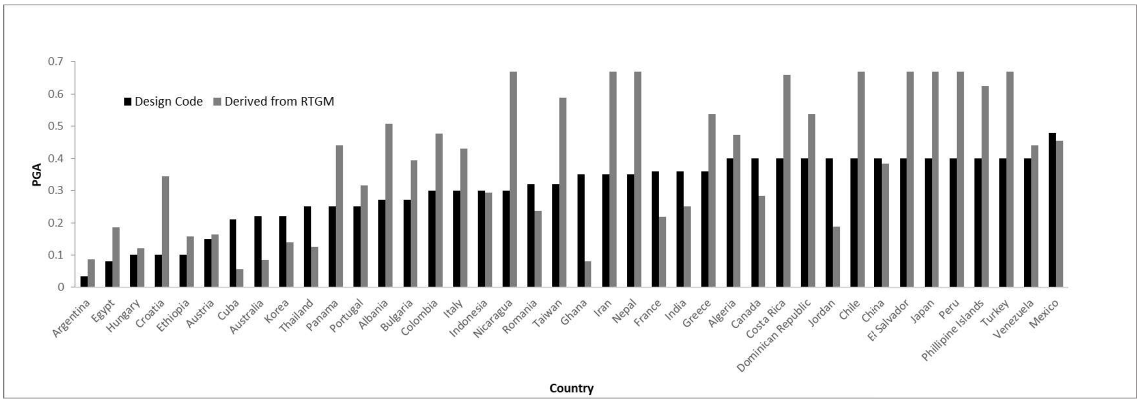

Figure 4. Comparison of design code PGAs with the equivalent PGAs derived from RTGM values for different countries, sorted by design code.

6. Summary

In this study, probabilistic seismic hazard calculations were performed using OpenQuake software developed by GEM to generate seismic hazard curves globally, which were used to calculate risk-targeted ground motions (RTGM) for periods of 0.2 s and 1 s. The generated hazard values were amplified to account for maximum direction effects and were used to generate global RTGM maps, showing the level of ground motion for a uniform risk of 1% probability of collapse in 50 years. The RTGM values were also compared to current building codes of different countries to have a better sense of the generated values and their comparison to the local building codes.

Acknowledgements

The authors would like to thank Hosam Ali for his helpful input and support of this study and Chris Deneff for reviewing this paper and providing comments.

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