Seismic hazard map around Taiwan through a catalog-based deterministic approach

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SUMMARY:
This study developed a national seismic hazard map around Taiwan through a deterministic manner. The essential of this approach is to treat every historic event as a potential point source, then with the seismic hazard taken as the maximum ground motion resulted from the series of earthquake events. A program developed in-house was used to carry out mass computation and map-making. The results show that East and Central Taiwan is subject to high seismic hazards, with 50^{th} percentile peak ground acceleration close to 0.9 g, indicating that current local structure design code is lack of conservatism.

Keywords: Deterministic seismic hazard analysis (DSHA), ground motion, Taiwan

1. INTRODUCTION

Taiwan is in a highly seismically active region, and structures are required to be designed and constructed to withstand earthquakes. Because earthquakes are unpredictable given our current knowledge, the best method is seismic hazard analysis to estimate probable earthquake ground motions, and to mitigate earthquake hazard and associated risks (Geller et al., 1997). DSHA (Deterministic seismic hazard analysis) and PSHA (Probabilistic seismic hazard analysis) are two standard approaches in seismic hazard analysis. Implicitly, DSHA uses "deterministic" information during analysis in which the largest single earthquake defined as Maximum Credible Earthquake (MCE) are accounted for, while PSHA combines the "probabilistic" characteristics (i.e. location, magnitude, attenuation relationship) of a suite of earthquakes (Cornell, 1968).

With regard to time, DSHA is a time-independent method in which the effects from the expected largest earthquake (known as MCE) are its primary focus. It is rational for two reasons: first, because the use of Maximum Credible Earthquake ensures that effects from all other earthquakes are explicitly considered, by designing a structure to withstand the MCE, it will reasonably withstand all other (smaller) earthquakes. Second, the timing of earthquake occurrence is by no means predictable, thus the time-dependent hazard estimate approach such as PSHA is inherently illogical. It is worth noting that the earthquake prediction on the Parkfield section of the San Andreas fault in California (Mualchin, 2005). The earthquake originally expected occurred in September 2004 did not even appear until the prediction time window was closed.

Although disputed (Krinitzsky, 1993a,b; Bommer, 2002; Castanos and Lomnitz, 2002; Krinitzsky, 2002; Bommer, 2003), the two methods are widely applied in regional seismic hazard assessments around the world (Orozova and Suhadolc, 1999; Mualchin, 2005; Cheng et al., 2007; Moratto et al., 2007; Pailoplee et al., 2009; Sokolov et al., 2009). As for Taiwan, a few comprehensive PSHA studies have been conducted (Tsai, 1986; Loh et al., 1991; Cheng et al., 2007), but not a single DSHA application is yet available in this region. As a result, a comprehensive seismic hazard assessment of Taiwan through a deterministic approach was performed in this study. The development of a national seismic hazard map was also included in this paper.

2. DETERMINISTIC SEISMIC HAZARD ANALYSIS

2.1. Overviews

DSHA provides a straightforward framework in which the worst-case ground motion was selected. Fig. 2.1 is a schematic diagram showing essentials of DSHA from a benchmark example (Kramer, 1996). Three source zones (line source, areal source and point source) can produce maximum magnitudes of 7.3, 7.7, and 5.0, respectively. Their corresponding peak ground accelerations can be determined by Eqn. 2.1, referred to as the attenuation relationship:

$$\ln(PGA) = 6.74 + 0.859 \times M - 1.8 \times (R + 25) \quad (2.1)$$

where M and R denote magnitude and distance, respectively. The resultant ground motions are 0.42 g, 0.57 g, 0.02 g, for line source, areal source and point source, respectively. On this basis, the event of areal source (producing a PGA equal to 0.57 g) was selected as controlling earthquake.

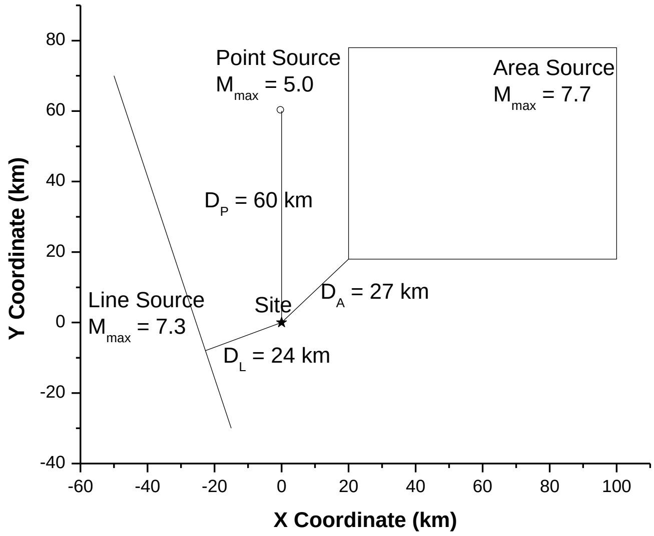

Figure 2.1 Seismic source setup of the benchmark DSHA example (after Kramer, 1996)

2.2. Selection of attenuation relationship

A number of attenuation relationships for estimating peak ground accelerations are available for use in Taiwan (i.e. Cheng et al. 2007, Wu et al., 2001). When Cheng's ground motion model was compared with that of Wu's, the difference of predicted PGAs is not significant at moderate to long distance. But when it comes to a near-source situation (say source-to-site distance < 10 km), the results are quite different from each other (see Fig. 2.2). The difference around 0.5 g under a near-source condition cannot be overlooked. Take Cheng's model as an example, the predicted PGAs remain constant as magnitudes range from 5 to 9 in the near-source region (say source-to-site distance < 1km). As users, we cannot put our hand in choosing one model over another. For conservatism, this study adopted the practice that using the upper bound of attenuation curves (Mualchin, 2005).

2.3. Catalog-based DSHA

It is worth noting that DSHA involves subjective judgements, particularly regarding seismogenic sources and MCE magnitudes (Kramer, 1996). However, within our current understanding and limited data sets, an overly refined analysis combining gigantic logic tree, expertise and expert opinions does not necessarily result in precise estimates (Krinitzsky, 1993a, b).

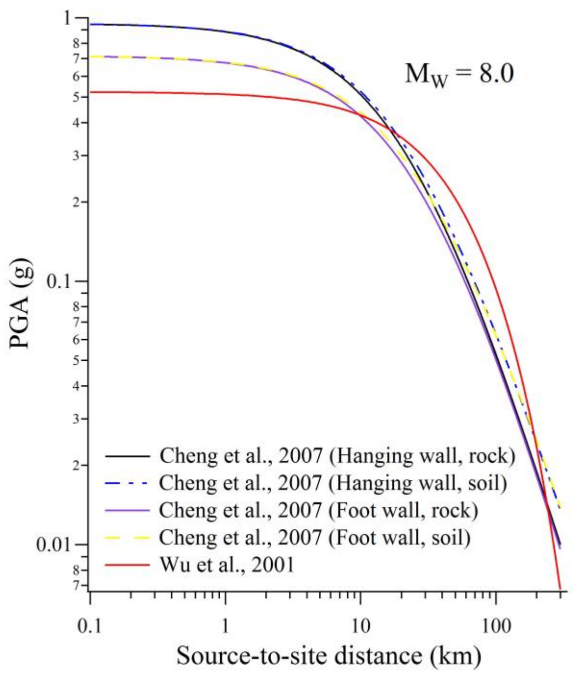

Figure 2.2 The comparison of PGA attenuation relationships from different studies

To avoid the uncertainties in earthquake potential assessments, this study adopted a catalog-based method in a deterministic framework to evaluate seismic hazard in Taiwan. More explicitly, by using the earthquake catalog with more than 57,000 events since 1900 around Taiwan, each historic event was treated as a point source in a DSHA perspective, and the seismic hazard would be taken as the maximum ground motion resulted from the series of earthquake events.

Fig. 2.3 shows the spatial distribution of more than 57,000 earthquakes around Taiwan since 1900. Note that the intense seismicity within the study region is the premise of the catalog-based DSHA approach. The catalog has been used in an earthquake study, analyzing statistical attributes of annual maximum magnitudes around Taiwan (Wang et al., 2011). As a general practice, magnitudes are scaled up quarter magnitude for each earthquake event, ensuring conservatism required by seismic hazard estimates.

2.4. In-house program development

The computer-aided analysis was assisted with an in-house program developed by Igor Pro. Fig. 2.4 shows the flowchart in the development of the computational tool in repeatedly calculating a series of ground motions. The input of the analysis is the aforementioned earthquake catalog including more than 57,000 events around Taiwan, with regard to their corresponding magnitudes and location (using latitude and longitude coordinates). A couple of functions are needed in advance for computing the shortest distance and discretizing the study region. They are, a function to calculate the great-circle distance between a point source and the given site using Haversine formula, and a function to discretize the study region around Taiwan (21.5^0-25.5^0N, 119.5^0-123.5^0E) into 4,800 reference sites with an increment of 0.5 degree.

The first step was to sequently calculate more than 57,000 PGAs from the catalog for the first reference site S1, and then the maximum PGA of the series was selected as the hazard of S1. With repeating (looping) the procedure for 4,800 reference sites, the seismic hazard contour map can be developed.

Note that in a deterministic framework, the PGAs estimated by a attenuation relationship is associated with 50% exceedance probability owing to the aleatory uncertainties of ground motion models. To be more exact, there is a 50-to-50 probability that the actual motion is going to be either greater or less

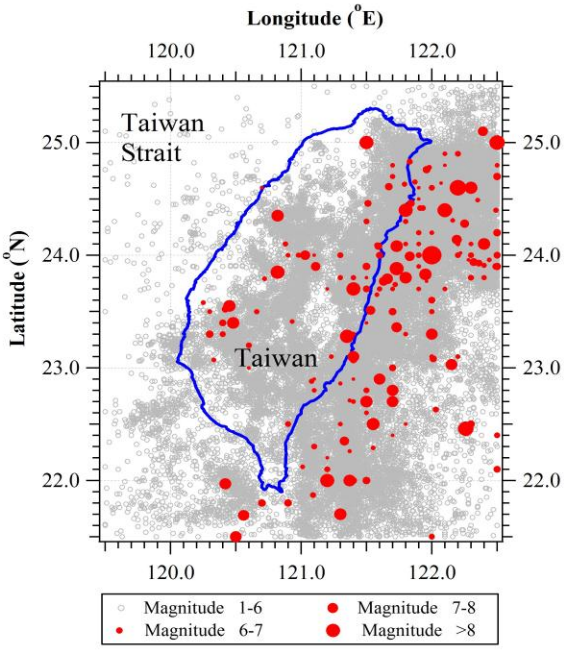

Figure 2.3 Spatial distribution of more than 57,000 earthquakes around Taiwan since 1900

than the mean motion. For conservatism, some deterministic seismic hazard analyses utilize the mean-plus-one-deviation motion in design (Lee et al., 2003). Because the PGAs estimated by the ground motion models are known to follow a lognormal distribution, the exceedance probability for such a motion decreases to 16%. As a result, two contour maps are provided in this study, with 50-percentile and 84-percentile PGA, respectively.

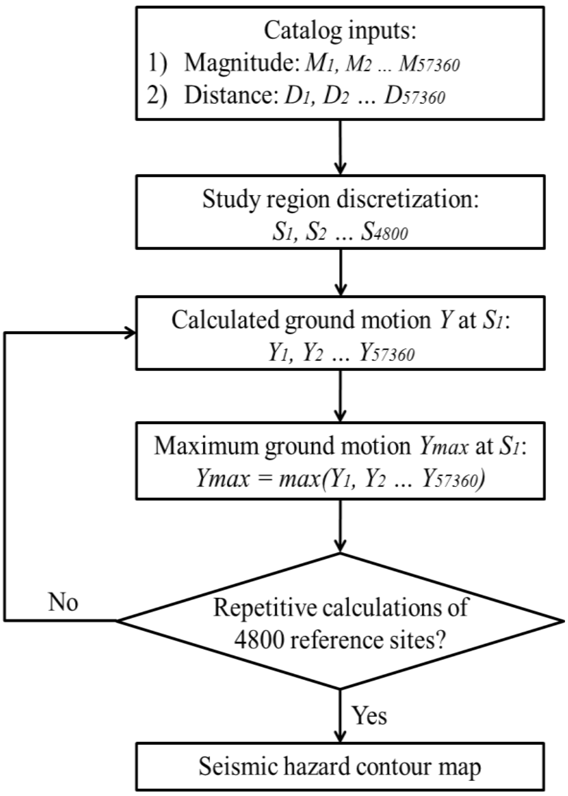

Figure 2.4 Flowchart for the development of the in-house program

2.5. Program updates

The DSHA in-house program is adaptable to new information and inputs, such as different earthquake catalog and ground motion models. In Igor Pro, the algorithm for calculating PGAs with the use of attenuation relationships was coded in the subroutine "Calculate_motion_attenuation". As a result, when different ground motion models are adopted in the analysis, users simply re-compile this module, and keep all other subroutines being unchanged.

3. RESULTS AND DISCUSSIONS

Fig. 3.1(left) shows the 50-percentile PGA contour map around Taiwan through this deterministic approach. The greatest value of PGA is 0.9 g. Eastern Taiwan and offshore regions are associated with significantly high seismic hazards, which is related to the two active subduction zones located offshore. For inland areas, Central Taiwan suffers high seismic hazard as well, where the Western Foothill Thrust Belt is located. Fig. 3.1(right) shows the 84-percentile PGA contour map, in which the highest PGA value is equal to 1.6 g, owing to the mean-plus-one-deviation motion.

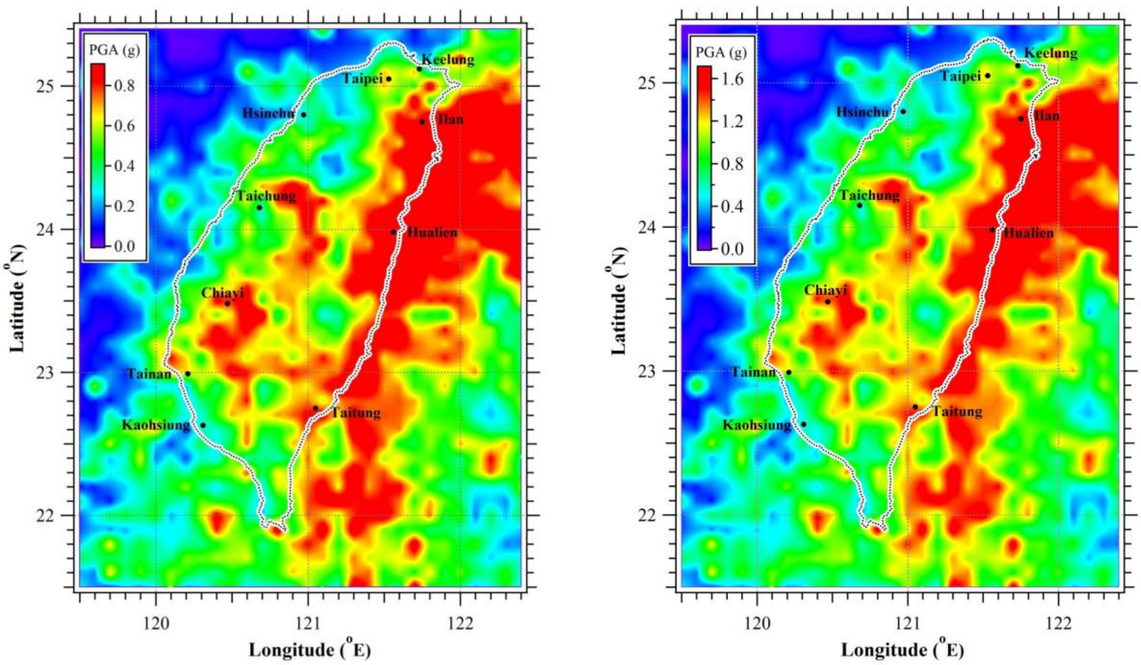

Figure 3.1 Seismic hazard map around Taiwan of 50-percentile PGA (left), and 84-percentile PGA (right)

Fig. 3.2 shows a PGA contour map of a recent PSHA study in a 2475-year return period (Cheng et al., 2007). The PSHA map was found comparable to the 50-percentile DSHA map developed in this study. Both demonstrated that eastern and central Taiwan is subjected to high seismic hazards, with PGA equal to 0.9 g. The hazards distribution patterns are similar owing to the underlying tectonic setting around the study region: subduction zones and Luzon Volcanic Arc, and the Western Foothill Thrust Belt inland (Campbell et al., 2002). It is worth noting that both analyses indicate high seismic hazard around Taiwan, which is expectable as a result of the aforementioned tectonic setting of the study region. However, currently local design code prescribes structures be designed to withstand earthquake-induced PGA up to 0.33 g (CPA, 2005). Given the seismic hazard estimated, the level of conservatism in seismic design is not adequate. Revisions based on more earthquake studies are recommended to local authorities.

Depending on the nature of structural analysis being carried out, seismic inputs from different hazard analysis approaches are expected to present. The decision makers should understand the fundamental differences between the two approaches before they deliver a decision in seismic hazard evaluation and earthquake-resistant design.

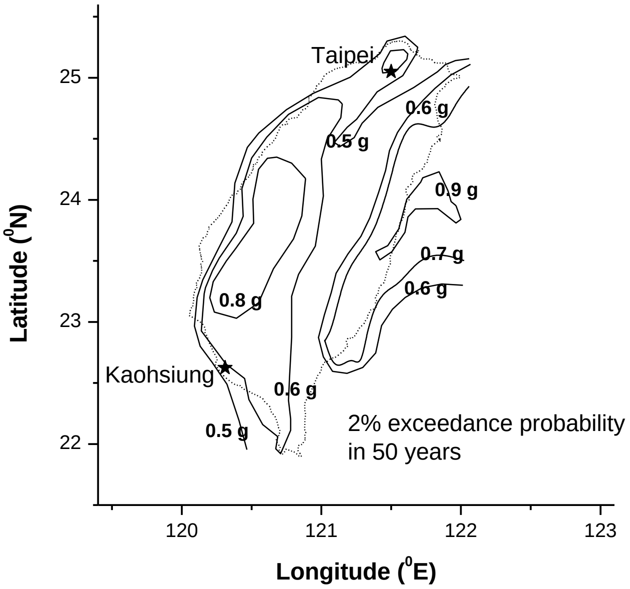

Figure 3.2 PSHA hazard map in a 2475-year return period (after Cheng et al., 2007)

4. CONCLUSIONS

This paper provides a PGA hazard map for Taiwan through a catalog-based deterministic manner. The essential of this approach utilizing intense seismicity is to treat every historic event as a potential point source. The results show that East and Central Taiwan is subject to high seismic hazard compared to the rest regions, and such a seismic hazard distribution is in a good agreement with a recent PSHA study. More exactly, the 50-percentile PGA in this study is found close to the PGA estimate with 2% exceedance probability within 50 years in the PSHA study, both indicating 0.9 g in East and Central Taiwan.

It is worth noting that seismic hazards estimated in this study indicate the unconservatism of local design code, particularly in terms of the PGAs for earthquake-resistant design. Potential needs in revision based on more earthquake studies are recommended to local authorities. Regarding to the two approaches, the designers and decision makers should understand their fundamental differences before they deliver a decision in seismic hazard evaluation and earthquake-resistant design.

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