Seismic hazard assessment of South Korea

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ABSTRACT

Korea is located on the eastern margin of the Eurasian Plate. Although it is far from a plate boundary (the closest distance is about 400-500km), the seismicity is affected by the complex interaction of the collision of the Indo-Australian and the Eurasian plates, and the subduction of the Philippine Sea plates beneath the Eurasian plate along the Japan and the Ryukyu trenches respectively.

This paper presents a study on seismic horizontal ground motions for rock sites in South Korea. As part of the study, historical and recent earthquakes have been used. A seismic source model has been developed which incorporates the Korean local tectonic and subduction of the Philippines Sea Plate. Also, recently published empirical and stochastic attenuation relationships have been adopted. The seismic hazard for spectral accelerations at structural periods of short period (0.1s) and 1.0 seconds having a 2% probability of being exceeded in the next 50 years are presented as hazard contour maps across South Korea. De-aggregation plots are also shown for a few major cities to investigate the earthquake magnitude and distance combinations. The results show that the subduction zones near Japan contribute significantly to the seismic hazard in South Korea particularly for the longer structural period ground motion.

Keywords: Seismic hazard, South Korea

1 INTRODUCTION

South Korea is regarded as a Stable Continental Region (SCR) and is far from a tectonic plate boundary. Some global seismic model (e.g. GSHAP) which developed the seismic hazard model for South Korea based on the instrumental records shows the region has relatively low seismicity. However, the modern instrumental record is only available for a very short period of time and it may not be adequate to represent the seismic hazard of Korea.

In addition, the current stress field and internal deformation of Korea is also controlled by far field stresses transmitted from the plate boundaries, which are primarily originated from the collision of the Indo-Australian and the Eurasian plates and from the subduction of the Pacific Sea and the Philippine Sea plates under the Eurasian plate along the Japan and the Ryukyu trenches. Also, although the subduction along Japan is more than 400km away from South Korea, the high seismicity of that region potentially poses significant hazard to South Korea, in particular, for structures with long period.

In this study, a conventional Probabilistic Seismic Hazard Analysis (PSHA) is carried out using historical

and recent earthquake catalogues. The developed seismic source zones extend to the subduction zone in Japan to consider the effect of far field earthquakes. Hazard contour maps for spectral acceleration at short period and 1s having a 2% probability of being exceeded in the next 50 years have been developed. These can be readily incorporated with international standards (e.g. IBC, ASCE, etc) for seismic design.

2 TECTONIC SETTING

The Korean Peninsula is located on the eastern margin of the Eurasian Plate. The nearest plate boundary is ~800 km to the southeast at the Ryukyu and Nankai Trough where the Philippine Sea Plate is subducting beneath the Eurasian Plate in Southern Japan. The current stress field and deformation of the Korean Peninsula is mainly affected by the complex interaction of the collision of the Indo-Australian and the Eurasian plates, and the subduction of the Pacific Sea and the Philippine Sea plates beneath the Eurasian plate along the Japan and the Ryukyu Trenches respectively (Fig. 1). The resultant stress regime is east-northeast to west-southwest compression and north-northwest to south-southwest extension which are

evidenced by earthquake focal mechanism analysis and GPS measurements (Kim & Park, 2010).

Fig. 1 Tectonics of the Korean Peninsula

The Precambrian blocks and fold & thrust belts of the Korean peninsula include (from north to south) the Nangrim Massif-Pyongnam Basin, the Imjingang Fold and Thrust Belt, the Kyonggi Massif, the Okcheon (Okchun) Fold Belt, Taebaeksan Belt, and the Yeongnam Massif (Chough et al., 2000; see Fig. 1). These units are separated by major northeast-southwest trending faults Okcheon Fault, Honam Shear Zone (Taebk-Seogchun Fault), and the Yangsan Fault. The north-south Bongwhajae Fault separates the Okcheon Fold Belt and Taebaeksan Fold Belt.

The Honam Shear Zone located in the Okcheon Fold Belt is an aggregate of ductile shear zones of various scale 0.5 to 10 km in width and 10 to 100 km in length, sub-parallel to each other intervening non- or weakly deformed zones (Yanai et al., 1985; Kim, 1996). Crustal movement of the Honam Shear Zone was estimated by using GPS to resolved average velocity in this area less than 2.4 mm/year. The results demonstrate the presence of relative movement between the Okcheon Belt and its surrounding blocks, Yeongnam Massif and Kyonggi Massif, along the Honam Shear Zone. The Okcheon Belt is moving to the northeast relative to the adjacent blocks. It is also noted that the northeastern part of Okcheon Belt with high seismic energy released based on historical earthquake suggesting that a possible active fault may exist (Chiu and Kim, 2004).

The Yangsan Fault Zone, located at the southeastern

margin of the Yeongnam massif is considered to be active in the Quaternary (past 2.5 Ma) and has an extremely well developed topographic expression. Paleoseismic studies show the fault displacing Quaternary deposits. Electron Spin Resonance (ESR) dating of the fault gouge show activity in the Quaternary between 2,700 to 140,000 years and slip estimates range from 0.001 to 0.07 mm/year (Seo et al., 2009). The smaller Ulsan Fault Zone and Hupo Fault are considered to have a similar tectonic setting.

Off the southeast Korean Peninsula the crust transitions from rifted continental to oceanic crust. Two north-northeast faults, the Uleung and Tsushima Faults are located offshore. Kang & Shin (2006) indicate these faults are possibly active. The 2004 M_W 5.1 event, offshore the southeast coast of Korea, is associated with these faults.

3 EARTHQUAKE CATALOGIE

3.1 Data sources

As part of the study, an earthquake catalogue was compiled for the region instrumental and historical records. The study area extends from 120.0°E to 135.5°E and 29.0°N to 43.0°N.

Historical events before 1900 were compiled from Lee & Young (2006), the Chinese Earthquake Catalogue (Wu et al., 1992 and DMP, 2005) and the National Oceanic and Atmospheric Administration (NOAA).

Instrumental records from 1900 were compiled from the International Seismological Centre (ISC), the EHB Bulletin in ISC, the ISC-GEM Global Instrumental Earthquake Catalogue (ISC-GEM; Storchak et al., 2012) and National Earthquake Information Centre (NEIC, 2013).

3.2 Aftershock removal and magnitude conversion

To carry out a probabilistic analysis for seismic hazard ideally all earthquake events should be statistically independent, the foreshocks and aftershocks should be removed from the catalogue. Gardner & Knopoff (1974) have proposed a windowing procedure to remove aftershocks. The moment magnitude scale (M_W) was chosen and the body-wave magnitude (m_b), surface-wave magnitude (M_S) values were converted to M_W using Scordilis (2006). Heaton et al. (1986) was adopted to convert from M_L (Local magnitude) to M_W .

3.3 Earthquake Completeness

The compilation of the different seismicity catalogues across the study area, suggests that there are 3 different completeness intervals corresponding to historic monitoring regimes. These regions are within the Korean Peninsula, outside Korea excluding Japan and the Japan region. The completeness thresholds have been calculated for each of the 3 regions.

4 SEISMOTECTONIC SOURCE MODEL

Seismotectonic sources delineate areas with a consistent distribution of earthquake activity and associated tectonic setting. Two types of source zones have been identified as follows:

- Shallow Crustal Source Zones (0 to 50 km deep) including areal source zones and linear active fault sources; and
- Subduction Zone Sources including subduction interface (0-50 km) and subduction intraslab (50 to 300 km deep).

4.2 Crustal areal source zones

Crustal areal sources were delineated based on the observed spatial density or activity of seismicity and corresponding tectonic parameters including depth of seismicity, focal mechanism of observed earthquakes, orientation of structures, type of faulting, age of crust and type of crust.

A summary of the areal sources zones is presented as follows (Fig. 2):

- Zone 1: Relatively high seismicity in the northeastern part of the study area related to the tectonic source related to the active Tanlu Fault in East China.
- Zone 2: Relatively high seismicity in the western part of the study area related to the eastern China.
- Zone 3: Yellow Sea - Stable continental-shelf marginal sea.

Fig. 2 Shallow source zones with complete earthquake catalogue

- Zone 4: Captures a concentration of increased seismicity related to east northeast – west northwest striking normal faults resolved from focal mechanisms of recent earthquakes.

Zone 5: Northern part of the Korean Peninsula characterised by relatively low seismicity in the Nangrim Massif and Pyongnam Basin

Zone 6: Pyongnam Basin bounded by the Imjingang fold and thrust belt to the south. Dominate structure is north-south. Relatively higher seismicity is observed in this zone.

Zone 7: Imjingang fold and thrust belt and the western part of Kyonggi massif.

Zone 8: Represents the southwestern Okcheon fold belt. This zone contains the Honam Shear Zone an aggregate of ductile shear zones. Crustal movement of the Honam Shear Zone was estimated by using GPS to resolved average velocity in this area less than 2.4 mm/year.

Zone 9: Represents the northeastern Okcheon fold belt. This zone is separated from the southwestern Okcheon fold belt by a deep north-south trending crustal fault. This is also the zone elevated with high seismic energy released from historical seismicity.

Zone 10: The Youngnam massif comprising northeast striking faults.

Zone 11: Zone 10 captures the Yangsan Fault Zone, Ulsan Fault zone and Hupo fault within the Youngnam massif. These faults are considered to be Quaternary active faults. There is an observed increase in seismic activity.

Zone 12: Transitional zone of rifted continental to oceanic crust. Includes the active Uleung and Tsushima Faults

Zone 13: Japan Sea. The sea opened in the end of Oligocene (~24 Ma) and the opening ceased in the middle Miocene (~13 Ma) and the oceanic crust is therefore relatively young. This zone is tectonically stable at the present time.

Zone 14 and 15: Zone 14 and Zone 15 are the shallow crustal seismic actively regions influenced by the oblique subduction of the Philippine Sea plate along the Rukyu Trench and Nankai Trough. Zone 15 is part of the oblique subduction induces a partitioning of string of dextral motion along the Median tectonic line and faults around and within Japan. Zone 14 is considered a transition zone from the subduction to stable continent as it is slightly further to the trench and the seismicity is relatively lower than Zone 15.

4.3 Crustal fault source zones

The Yangsan Fault Zone is ~200 km long on southeast of Korea. The average slip rate is inferred to be about 0.02 to 0.07 mm/yr based on Paleoseismic studies (Seo et al., 2009).

The Median Tectonic Line in Japan is about 500 km long large fault zone across Japan. The slip rate is estimated to be about 5 to 10 mm/yr.

Note that the seismic activity of the fault sources is

subtracted from their encompassing areal source zone to account for double counting.

4.2 Subduction source zone

Subducting Philippine Sea Plate beneath the Eurasian Plate along the Nankai Trench southeast of the Korean Peninsula is modeled as subduction interface and subducting slab. The upper 50 km of the subduction interface is modelled as a fault source. Two areal sources captures the seismicity associated with the intermediate, Zone 16, (50-100km) and deep, Zone 17 (100-300km) subducting intraslab. The source zones for the subduction are shown in Fig. 3.

Fig. 3 Source zones for subduction zone

5 SEISMIC SOURCE PARAMETERS

5.1 Earthquake recurrence of areal sources

The rate of occurrence of earthquakes in each area zone is described in terms of magnitude recurrence relationships in the form of the ‘Gutenberg-Richter’ relationship (Gutenberg and Richter, 1965):

$$\log_{10} N = a - b(M - 4)$$

where N is the annual number of earthquakes greater than magnitude M , a is the activity rate defined as the annual number of earthquakes greater than magnitude 4.0 and b is the slope of the recurrence relationship.

The complete part of the earthquake catalogue together with the equation above are used to compute a value (activity rate) and b value for each source zone through application of Weichert’s maximum likelihood

approach (Weichert, 1980). The best estimate a value and b value are applied with 60% weighting and values at one standard deviation above and below each applied with a weighting of 20%.

5.2 Earthquake recurrence of fault sources

Earthquake recurrence curves for fault sources with slip rates specified have been based on the procedure recommended by Youngs & Coppersmith (1985). The maximum magnitude is the magnitude corresponding to the maximum fault rupture area assigned to the fault (Wells & Coppersmith, 1994). The b - value of smaller events is assumed to be 0.9.

5.3 Limiting magnitudes

A minimum magnitude of M_w 5 has been adopted for the seismic hazard assessment. This is because the likelihood of an earthquake of smaller magnitude causing damage to engineered structures can be discounted, and using a lower minimum magnitude will unrealistically increase the low-period ground motions.

When selecting the maximum magnitude for the hazard calculations, it is necessary to take into account the tectonic setting and the time span of the earthquake catalogue, which could be shorter than the return period of large earthquakes. The crustal source in SCR were assigned with M_w 7 and Japan crustal and Intraslab were assigned with M_w 8 (60%), with ± 0.25 (40%)

6 GROUND MOTION PREDICTION EQUATIONS

Ground Motion Prediction Equations (GMPE’s) describe the change in earthquake ground motion with distance. They are often derived based on an analysis of the records available for the specific region and can also take account of theoretically derived components.

The Korea Peninsula and eastern China is considered to be part of a stable continental crust. Atkinson & Boore (2006), Silva et al. (2002) and Pezeshk et al. (2011) have been adopted for the stable continental crust with equal weighting. These two GEMPs are also recommended in Global Earthquake Model (GEM).

The Japan Sea (Zone 12 and 13) is young oceanic crust and GMPE’s from equal weight of NGA relationships, i.e. 25% applied to each GMPE is considered to be appropriate.

For Japan zone (Zone 14 and 15), Zhao et al. (2006) and the four NGA-West 2 GMPEs used in the PSHA were equally weighted for 50% each.

GMPE’s by Atkinson & Boore (2003) and Zhao et al. (2006) have been used weighted 30% and 70% to model interface and intraslab events.

7 RESULTS

7.1 Contour maps

The results of the PSHA are presented as the spectral acceleration for short periods of 0.1 seconds and 1 second for rock site contoured across the South Korea (Fig. 4 and Fig. 5). The contours give the values for ground motions having a 2% probability of being exceeded in the next 50 years. The contours were developed by running the hazard model at 169 locations evenly spaced across the South Korean region.

The contour variation shows the hazard at the eastern and southeastern of South Korea is higher particular for spectral acceleration at 1s which is highly associated with the high seismicity in Japan.

Fig. 4 Contour of spectral acceleration at short period (0.1s) having a 2% probability of being exceeded in the next 50 years

Fig. 5 Contour of spectral acceleration at long period (1s) having a 2% probability of being exceeded in the next 50 years

7.2 De-aggregation of Hazard

The PSHA results of this study have been de-aggregated in terms of magnitude and distance, to

investigate earthquake occurrences that contribute the most to resulting ground-motion hazard, in accordance with the procedure recommended by McGuire (1995). De-aggregation of Seoul and Busan has been carried out for or 5% damped spectral values for structural periods of 0.1 and 1.0 sec for return periods of 2475 years that give rise to the target ground motion hazard value are determined. The short period (0.1s) de-aggregation plots are shown in Fig. 6. The long period (1s) de-aggregation plots are presented in Fig. 7.

The de-aggregation plots show the seismic hazard at 0.1s is mainly from the local source (< 100 km) for Seoul and Busan and slightly contribution from far field source (~200 km which is about the distance to Japan) for Busan.

For the long period (1s), the degradation plot for Seoul the hazard is mainly contributed by the source at 100 km to 200 km with some contribution from > 500 km which is from seismicity in Japan. Regarding to Busan, most of the hazard is contributed by the source at > 200 km, which is from the seismicity in Japan from both crustal and subduction earthquake events.

Fig. 6 De-aggregation of hazard for 0.1s at a 2475 year return period for (a) Seoul and (b) Busan

Fig. 7 De-aggregation of hazard for 1s at a 2475 year return period for (a) Seoul and (b) Busan

8 CONCLUSION AND DISCUSSION

A PSHA has been carried out for South Korea using the historical and instrumental earthquake catalogue. The seismic source zones including subduction in Japan and the recently published GMPE's have also been adopted in the model development.

The result shows that the seismic hazard in the eastern and southeastern South Korea is relatively

higher. The de-aggregation curves indicate that dominant hazard source for short period is from the local source zone. However, the hazard for long period structures has a significant contribution from far field sources in Japan. Therefore, the seismic hazard of South Korea cannot only consider the seismicity within Korea, but also has to include seismic source zone from Japan. This becomes more important to evaluate the spectral acceleration for long period and become more critical for structures with long structural periods such as high rise buildings and long span bridges.

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