Development of Machine Learning-Based Ground Motion Models for South Korea Using Stochastic Simulations with Quaternary Fault Scenarios

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1. Introduction

Probabilistic seismic hazard analysis (PSHA), a key component of seismic probabilistic safety assessment for nuclear power plants (NPPs), requires reliable ground motion models (GMMs) that cover a wide range of earthquake magnitudes. The 2016 Gyeongju and 2017 Pohang earthquakes, the largest instrumentally recorded events in South Korea with a moment magnitude (**M**) of 5.5, raised significant concerns regarding the seismic safety of NPPs. These events emphasized the necessity of evaluating safety against all potential scenarios that a site may experience, including larger magnitude earthquakes exceeding **M**5.5. However, since South Korea is located in a stable continental region (SCR), the scarcity of observational data for such events restricts the development of GMMs applicable to moderate-to-large magnitude events. To address this limitation, this study utilizes Quaternary fault information identified by the Korea Active Fault Research Group, which has been conducting nationwide surveys since 2017. The fault data identified in the southeastern Korean Peninsula enable the construction of earthquake scenarios beyond the observed magnitude range. In this study, 27 scenario earthquakes (**M**5.52–7.19) are considered based on the identified Quaternary faults. Ground motions are estimated using the stochastic extended finite-fault ground-motion simulation (EXSIM), incorporating the correction model proposed by Seo et al. [1]. The simulated ground motions are then combined with instrumental records (**M** ≥ 3.0) observed in South Korea to develop machine learning-based GMMs covering **M** ranging from 3 to 7, which can be directly applied to PSHA for NPPs in South Korea.

2. Earthquake Scenario Construction

In this study, Quaternary fault data identified through field investigation in southeastern Korea from 2017 to 2022 were utilized to construct earthquake scenarios [2]. The moment magnitude of the inferred earthquake on each fault was estimated using the empirical relationships proposed by Wells and Coppersmith [3], based on the near-surface displacement of the most recent earthquake event. To account for the uncertainty in the relationships, three **M** values were assigned to each fault corresponding to the mean and mean ± one standard deviation. The appropriate equation was selected according to the fault type (i.e., normal, reverse, strike-slip, or all fault types). The fault plane dimensions (length and width) were also determined using the equations of Wells and Coppersmith [3] for the estimated moment magnitude and fault type. Since Quaternary faults were identified near the surface, the top of the fault plane was set at a depth of 0 km, and the focal depth was set at the center of the fault plane. A total of 27 scenario earthquakes ranging from **M**5.52 to **M**7.19 were generated, and their fault type, strike, and dip are summarized in Table 1.

Table I: Fault parameters of the 27 scenario earthquakes.

No	Fault type	Strike/Dip (°)	**M**
1	Reverse	334/50NE	6.07, 6.59, 7.11
2	Reverse	181/48NW	6.15, 6.67, 7.19
3	Reverse-oblique dextral strike-slip fault	191/72W	6.32, 6.72, 7.12
4	Strike slip	1/69SE	6.05, 6.66, 6.63
5	Reverse-oblique dextral strike-slip fault	74/74SE	5.52, 5.92, 6.32
6	Reverse-oblique dextral strike-slip fault	85/46SE	6.39, 6.79, 7.19
7	Reverse-oblique dextral strike-slip fault	53/31SE	6.38, 6.78, 7.18
8	Reverse-oblique dextral strike-slip fault	2/50SE	6.21, 6.61, 7.01
9	Reverse-oblique dextral strike-slip fault	15/62SE	6.11, 6.51, 6.91

Stress drop ($\Delta\sigma$) is also a critical parameter for EXSIM simulations. However, estimating $\Delta\sigma$ values for events with **M** > 5.5 is challenging in South Korea due to the scarcity of observational data. Moreover, applying stress drop values from active crustal regions such as Japan or the United States would be inappropriate, as stress drop tends to be higher in SCRs than in active crustal regions [4]. Therefore, $\Delta\sigma$ values from the 27 earthquakes (**M** ≥ 4.0) occurred in SCRs were collected, and an empirical relationship was derived as a function of moment magnitude and focal depth (Eq. 1). The estimated stress drops were then applied to the corresponding scenario earthquakes.

$$\ln(\Delta\sigma) = 2.5423 + 0.8640\ln(\mathbf{M}) + 0.3431\ln(h) \quad (1)$$

where h is the focal depth and the units of $\Delta\sigma$ and h are bar and km, respectively.

3. Machine Learning-Based GMMs Development

Ground motions for the 27 scenario earthquakes were simulated using EXSIM with a correction model developed to improve the prediction accuracy of EXSIM for South Korea [1]. The key simulation parameters, including geometrical spreading, anelastic attenuation, path duration, and site amplification, are summarized in Table 2. Parameters were primarily sourced from studies conducted on South Korea. However, in the absence of region-specific values, parameters proposed for SCR were adopted, given the tectonic similarity of the Korean Peninsula to SCR environments. Simulated records within a hypocentral distance (R_{hypo}) of 250 km were included, resulting in 414 records. These were combined with 1,570 instrumental records ($\mathbf{M} \geq 3.0$) observed in South Korea to construct a ground motion database. The **M** and R_{hypo} distribution of the database is shown in Fig. 1. The orientation-independent median (RotD50) peak ground acceleration (PGA) and R_{hypo} range from 4.78×10^{-6} to 0.926 g and from 6.99 to 508 km, respectively.

Table II: Key parameters used in EXSIM.

Parameter	Value (Reference)
Geometrical spreading	R^{-1} for $R \leq 40$ km; $R^{-1.3}$ for $40 < R \leq 60$ km; $R^{-0.1}$ for $60 < R \leq 250$ km; $R^{-0.5}$ for $R > 250$ km ([5])
Anelastic attenuation	Gyeonggi Massif: $330f^{0.4}$ ([5])
	Okcheon Belt: $201.4f^{0.751}$ ([6])
	Yeongnam Massif: $893f^{0.32}$ ([7])
	Gyeongsang Basin: $250f^{0.88}$ ([8])
	Yeonil Basin: $893f^{0.32}$ ([7])
Path duration	0.173R for $R \leq 15$ km; 0.745R – 8.585 for $15 < R \leq 35$ km; 0.507R + 9.755 for $35 < R \leq 50$ km; 25.1 for $50 < R \leq 125$ km; 0.045R + 19.475 for $125 < R \leq 200$ km; 0.091R + 10.3 for $200 < R \leq 392$ km; 0.111R + 25.588 for $R > 392$ km ([9])
Site amplification	Site amplification factors for V_{S30} = 760 m/s ([7])

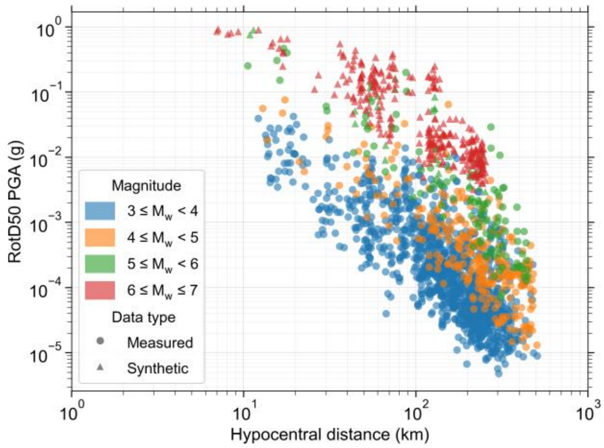

Fig. 1. Distribution of orientation-independent median (RotD50) peak ground acceleration (PGA) and hypocentral distance for the ground motion database used in this study.

The database was randomly split into training (80%) and test (20%) sets. Using **M**, R_{hypo}, average shear wave velocity up to 30 m depth (V_{S30}) as input variables, machine learning-based GMMs were developed with a neural network to predict RotD50 PGA and response spectra at frequencies ranging from 0.1 to 100 Hz.

The predicted RotD50 PGA values for **M**7.0 and a V_{S30} of 970 m/s, which represents the average V_{S30} values of the 39 surface stations used in this study, were compared with those for existing GMMs for South Korea [10-12], as shown in Fig. 2. The proposed model predicted larger PGA within R_{hypo} of 300 km compared to the existing models, and the predicted ground motions remain nearly constant at R_{hypo} less than 10 km. It should be noted that the existing models were developed using the geometric mean of horizontal ground motions (EW and NS), whereas the proposed models utilized RotD50.

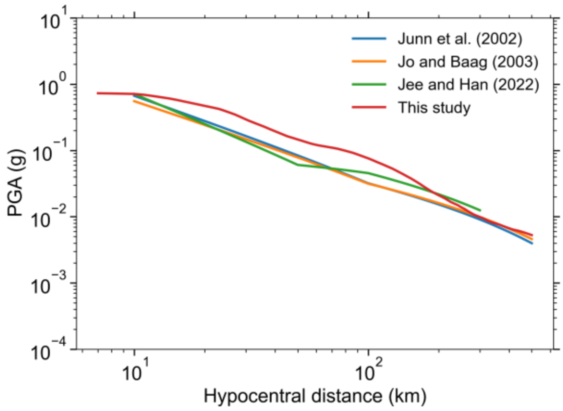

Fig. 2. Comparison of predicted PGA as a function of R_{hypo} for M7.0 between this study and existing GMMs for South Korea.

4. Conclusions

Machine learning-based GMMs for South Korea were developed using a ground motion database combining stochastic simulations and measured records. The scenario earthquakes were constructed based on Quaternary fault data identified in southeastern Korea. The proposed models cover a magnitude range of **M**3–7 and can be directly applied to PSHA in South Korea.

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