Smart Geotechnics for Smart Societies – Zhussupbekov, Sarsembayeva & Kaliakin (Eds)

Optimal earthquake intensity measures for probabilistic seismic demand models of rectangular tunnels

Van-Quang Nguyen
Department of Civil and Environmental Engineering, Hanyang University, Seoul, Korea
Department of Civil Engineering, Vinh University, Vietnam

Hyeondong Roh & Duhee Park
Department of Civil and Environmental Engineering, Hanyang University, Seoul, Korea

ABSTRACT: This study aims to identify optimal intensity measures (*IMs*) for use in probabilistic seismic demand models (PSDMs) for rectangular tunnels in three soil deposits. To this end, we performed an extended numerical parametricstudy involving two-dimensional time history analyses of selected soil-tunnel configurations to evaluate the response of the selected tunnels under transverse seismic shaking. A series of 23 *IMs* were selected and tested from motions at tunnel level deoth. The selected *IMs* were tested on several metrics, such as correlation, efficiency, practicality, and proficiency, based on an extended number of regression analyses between the IMs and the damage measure (*DM*), for the studied tunnels. The results indicate that the velocity spectrum intensity (VSI) at the ground tunnel level depth can be considered as the optimal *IM*, whereas the peak ground displacement (PGD) has the less efficient.

1 INTRODUCTION

Underground facilities are a crucial component of contemporary urban infrastructure. In the past, seismic design of tunnel structures received less attention than above-ground structures and most of them were designed and built without considering seismic effects. However, strong earthquakes have shown that even underground structures can be damaged significantly under severe seismic excitation (Hashash et al., 2001). An accurate evaluation of the seismic performance of underground structures is inevitable.

So far, several studies have investigated the correlation between *IMs* and the seismic response of the rectangular tunnel. Zhang et al. (2022) explore the optimum *IMs* for probabilistic seismic demand model (PSDM) of a three-story three-span subway station with different burial depths. Zhang et al. (2021) investigate optimum *IMs* for the performance assessment of a two-storey three-span subway station considering the effects of near-fault seismic excitations with velocity pulses, and then establish the fragility curves of subway stations using the optimum *IMs*. However, neither of the numerical models were validated against recordings. The literature review demonstrated that a study using a validated or verified numerical model to calculate the response of the rectangular tunnel has not yet been performed. Also, the more *IMs* is needed to deeply investigate the optimum *IMs* for PSDM.

The aim of this paper was to develop PSDMs for the rectangular tunnel. For that, 23 earthquake IMs are considered in developing PSDMs. The nonlinear numerical modeling of soil-tunnel configurations is constructed using FLAC^{2D} program (Itasca Consulting Group, 2011). A set of 85 ground motion records, which contain a wide range of amplitudes, magnitudes, epicentral distances, significant durations, and predominant periods, are utilized to perform nonlinear time-history analyses. Three different soil deposits are used in this study. Optimal *IMs* are recognized based on statistical indicators of PSDMs, which are the coefficient of determination, dispersion, practicality, and proficiency.

DOI: 10.1201/9781003299127-231

2 NUMERICAL MODEL AND ANALYSES

2.1 *Tunnel model*

The cross-section size is 12 m × 6 m (center-to-center width and height) and located 6 m below the ground. The thickness of side wall, top, and bottom slabs is 1 m. The center column with the cross-section of 0.4 m × 1.0 m is placed at every 3 m.

The tunnel structure was modeled using beam elements with an element size of 0.25 m. Table 1 and Figure 1 presents the properties and cross-section of the tunnel.

Table 1. Properties of the tunnel structure.

Parameters	Value
Density (kg/m^3)	2400
Young's modulus (Pa)	2.5×10^7
Poission's ratio	0.2

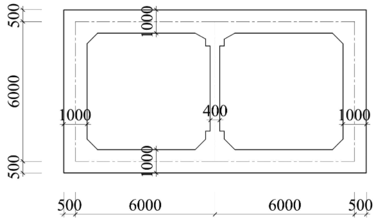

Figure 1. Cross-section of rectangular tunnels (unit: mm).

2.2 *Soil model*

The dimension of the computational model was set to 120 × 30 m (width × height) as presented in Figure 2. Three soil profiles P1, P2, and P3 corresponding to soil classes B, C, and D, according to Eurocode 8 (CEN, 2005). The density and Poisson's ratio of the soil were 1800 kg/m^3 and 0.3, respectively. The shear wave velocity profile of soil is presented in Figure 3. The soil medium was modeled using plane-strain quadrilateral elements. The element size, Δl = 0.5 m, was selected based on the following recommendation of Kuhlemeyer and Lysmer (1973). The *Sig3* model, which is available in FLAC^{2D} program, was employed to simulate the nonlinear behavior of soil.

2.3 *Soil-tunnel interface and boundary conditions*

The soil-structure interaction was simulated using the interface elements. The interface option *UNBONED* in the FLAC^{2D} program was used in this study. This contact interface can model a realistic partial-slip condition considering the gapping and the slipping phenomena between soil and tunnel under loading.

The free-field boundary was applied for lateral boundaries to absorb reflected waves. The bottom boundary was fixed to simulate the rigid boundary. The acceleration time history of the input motion was defined at the base of the numerical model.

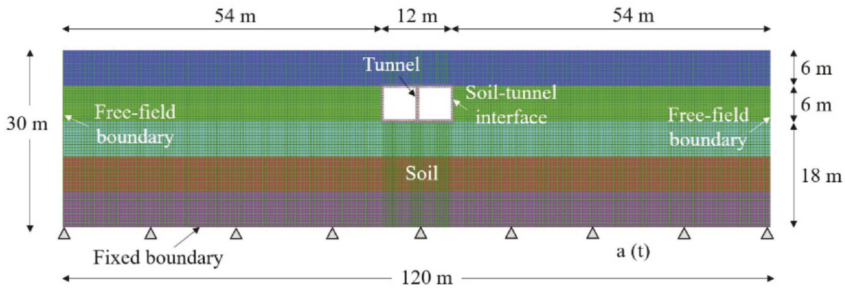

Figure 2. Soil-tunnel numerical configuration in FLAC^{2D}.

2.4 *Ground motions*

A set of 85 ground motion records are selected from historical earthquakes, which are available in the PEER center database (https://ngawest2.berkeley.edu). A wide range of earthquake amplitudes, magnitudes, epicentral distances, significant durations, and predominant periods is considered in used ground motions whose response spectra are shown in Figure 4.

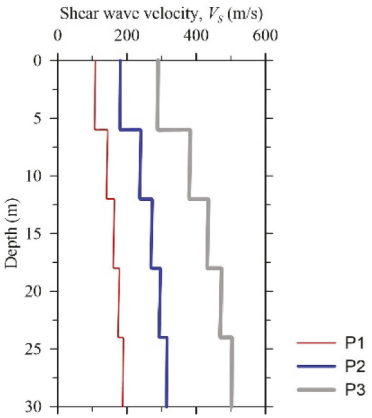

Figure 3. Shear wave velocity profiles.

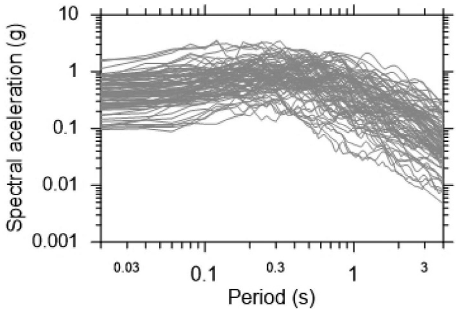

Figure 4. Input ground motions.

2.5 *The numerical validation*

The numerical model in this study was validated against the centrifuge test by (Gillis, 2015). Detail of the centrifuge test and comparison between numerical and experimental results were reported in Nguyen et al. (2022b). The compared results demonstrate that the numerical model was reliable for carrying out parametric research.

3 SELECTION OF OPTIMAL INTENSITY MEASURES

3.1 *Representative numerical results*

This study adopts the results proposed by Nguyen et al. (2022a). The representative numerical result is bending moment at the base of the center column, which is a critical section.

3.2 *Selection of examined seismic intensity measures*

This study accounts for 23 common ground motion *IMs*and these parameters are calculated for every motion record using SeismoSignal (Seismosoft, 2012). The used *IMs* are described in Nguyen et al. (2022b).

3.3 *Overview of PSDM*

PSDM, which contains the relationship between structural demand and an earthquake *IM*, needs to be appropriately established in the probabilistic performance-based seismic design. The most common expression of the relationship between seismic demand and earthquake *IMs* is the power form in Eq. (1) (Nguyen et al., 2021, Cornell et al., 2002):

$$S_D = a \times (IM)^b \tag{1}$$

where S_D is the median value of structural demand; a and b are the regression coefficients; IM is the earthquake intensity measure considered. This equation can be rewritten in forms of linear regression as follows:

$$ln(S_D) = \ln(a) + b \times ln(IM) \quad (2)$$

The conditional failure probability that the structural demand (D) exceeds its capacity for a given *IM* in the fragility analysis can be expressed as:

$$P_f = P[D \geq d|IM] \quad (3)$$

where *d* is the specified value, normally it is based on the structural capacity. Assuming that the structural demand and capacity follow lognormal distributions, Eq. (3) can be rewritten as:

$$P[D \geq d|IM] = 1 - \Phi\left[\frac{\ln(d) - \ln(S_D)}{\sigma_{D|IM}}\right] \quad (4)$$

The uncertainty in the seismic demand $\sigma_{D|IM}$ is approximated as the dispersion of the simulated demand with respect to the regression fit for the calculated damage data obtained from the non-linear time history analyses, as shown in Eq. (5):

$$\sigma_{D|IM} = \sqrt{\frac{\sum(\ln(d_i) - \ln(a \times IM^b))^2}{n-2}}$$

3.4 *Results of PSDM study*

3.4.1 *Correlation testing*

Figure 5 presents the regression analyses between four representative seismic *IMs* and *DM*. Notably, the *IMs* is determined from the motions at tunnel level depth. It can be observed that VSI has the strongest correlation with the *DM*, followed by PGV and HI. The correlation coefficients R^2 for the three most correlated *IMs* are 0.762, 0.754, and 0.747, respectively. Furthermore, the weakest correlation between *IMs* and *DM* is T_p with a correlation coefficient of 0.118, followed by CAV and PGV/PGA (i.e. correlation coefficients of 0.315 and 0.380, respectively).

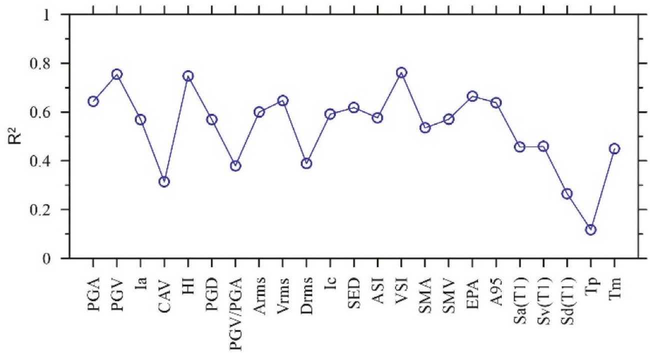

Figure 5. Regression parameter R^2 between four representative seismic *IMs* and *DM*.

3.4.2 *Efficiency testing*

The results of the efficiency analyses are depicted in Figure 6. VSI, PGV, and HI are considered more efficient measures since they have smaller standard deviations $\sigma_{D|IM}$. Among them, VSI is the most efficient *IMs* with the lowest standard deviation $\sigma_{D|IM}$, i.e. 0.194. The corresponding $\sigma_{D|IM}$ for the next two most efficient *IMs* are 0.195 and 0.197, respectively, which are slightly higher than that for VSI. The maximum standard deviation $\sigma_{D|IM}$ is observed for A_{rms}, i.e. 0.714, indicating that this measure is the least efficient. This is followed by PGA and S_d(T1). Their corresponding standard deviations $\sigma_{D|IM}$ are 0.426 and 0.404, respectively, which are lower than that for A_{rms}.

3.4.3 *Practicality testing*

Figure 7. summarises the b values calculated from the regression models for each *IM-DM* pair. The comparisons in Figure 7 suggest that T_m is the most practical *IMs* among others, because it has the maximum slope b of 0.859. ASI and EPA proved to be the second and third most practical *IMs*, with the corresponding slope b equal to 0.841 and 0.798, respectively. In contrast, SED is found to be the least practical *IM* among the other tested *IMs*, as it exhibits the minimum slope b of 0.233 for the examined cases. D_{rms} and PGD prove to be the other two least practical *IMs*, with slightly higher slope values b, i.e. 0.282 and 0.343, respectively.

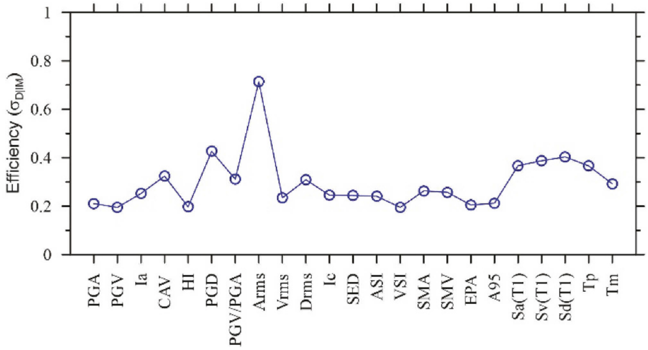

Figure 6. Regression parameter $\sigma_{D|IM}$ between four representative seismic *IMs* and *DM*.

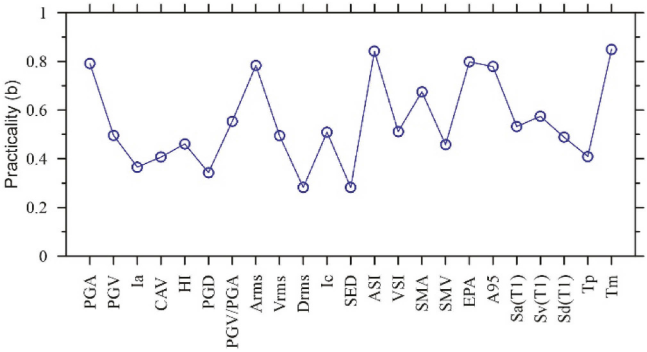

Figure 7. Regression parameter b between four representative seismic *IMs* and *DM*.

3.4.4 *Proficiency testing*

Padgett et al. (2008) proposed an indicator, namely proficiency, which can balance the selections between efficiency and practicality. The proficiency is defined by the ratio of dispersion ($\sigma_{D|IM}$) to the practicality (b), as shown in Eq. (6). The smaller value of ξ is, the more proficient is.

$$\xi = \frac{\sigma_{D|IM}}{b} \tag{6}$$

Figure 8 compares the computed ξ for the considered *DM* with regard to the 23 tested *IMs*. EPA is the most proficient *IM* due to the corresponding smallest ξ of 0.256, followed by PGA and A_{95}, which have ξ values of 0.266 and 0.273, respectively, which are quite close to the value for EPA. PGD is the less proficient measure, as it has the maximum ξ, i.e. 1.243. The next two least proficient *IMs* are D_{rms} and A_{rms}. Their corresponding values of ξ are 1.095 and 0.911, respectively, which are considerably lower than the value for PGD.

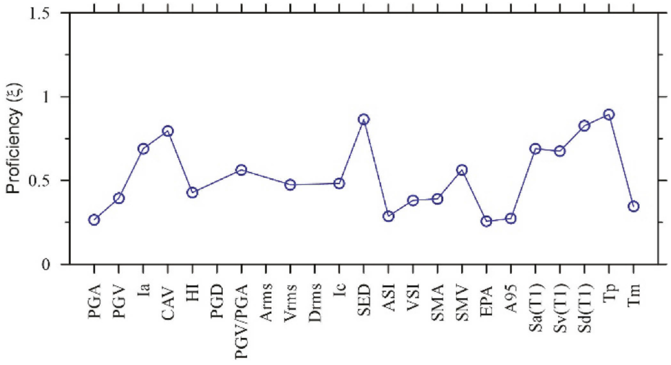

Figure 8. Regression parameter between four representative seismic *IMs* and *DM*.

4 CONCLUSIONS

This study developed PSDMs for various *IMs* and identified optimal *IMs* for the seismic performance of the rectangular tunnel structure embedded in three soil deposits. A group of 85 ground motion records and 23 different *IMs* were used in nonlinear time-history analyses. The selected *IMs* were tested using the correlation, efficiency, practicality, and proficiency metrics, with the aim of identifying the optimal *IMs* from the selected ones for the examined soil-tunnel systems. The following conclusions are drawn.

The optimal *IMs* for PSDMs of the rectangular tunnel structure are VSI followed by PGV and HI. The PSDMs with respect to these *IMs* contain higher values of R^2, lower standard deviations and proficiency values, and larger practicalities than those of others.

The less efficient *IMs* for PSDMs of the rectangular tunnel structure are PGD, D_{rms}, and A_{rms}. These *IMs* are displacement- and acceleration-based parameters.

REFERENCES

Cen 2005. Eurocode 8: Design of structures for earthquake resistance-part 1: general rules, seismic actions and rules for buildings. *Brussels: European Committee for Standardization*.

Cornell, C. A., Jalayer, F., Hamburger, R. O. & Foutch, D. A. 2002. Probabilistic basis for 2000 SAC federal emergency management agency steel moment frame guidelines. *Journal of structural engineering*, 128, 526–533.

Gillis, K. M. 2015. *Seismic Response of Shallow Underground Structures in Dense Urban Environments*. Ph.-D. dissertation, University of Colorado at Boulder.

Hashash, Y. M., Hook, J. J., Schmidt, B., John, I. & Yao, C. 2001. Seismic design and analysis of underground structures. *Tunnelling and underground space technology*, 16, 247–293.

Itasca Consulting Group 2011. *FLAC - Fast Lagrange Analysis of Continua; Version7.0. In: User Manual*.

Kuhlemeyer, R. L. & Lysmer, J. 1973. Finite element method accuracy for wave propagation problems. *Journal of Soil Mechanics & Foundations Div*, 99.

Nguyen, D.-D., Thusa, B., Azad, M. S., Tran, V.-L. & Lee, T.-H. 2021. Optimal earthquake intensity measures for probabilistic seismic demand models of ARP1400 reactor containment building. *Nuclear Engineering and Technology*, 53, 4179–4188.

Nguyen, V.-Q., Lee, Y.-G. & Park, D. 2022a. Seismic damage evaluation of double box metro tunnel using three-dimensional finite element analysis. *Structures (submitted for publication)*.

Nguyen, V.-Q., Tran, V.-L., Nguyen, D.-D., Sadiq, S. & Park, D. 2022b. Novel hybrid MFO-XGBoost model for predicting the racking ratio of the rectangular tunnels subjected to seismic loading. *Transportation Geotechnics*, 100878.

Padgett, J. E., Nielson, B. G. & Desroches, R. 2008. Selection of optimal intensity measures in probabilistic seismic demand models of highway bridge portfolios. *Earthquake engineering & structural dynamics*, 37, 711–725.

Seismosoft, L. 2012. Seismosignal. *Pavia*, Italy.

Zhang, C., Zhao, M., Zhong, Z. & Du, X. 2021. Seismic Intensity Measures and Fragility Analysis for Subway Stations Subjected to Near-fault Ground Motions with Velocity Pulses. *Journal of Earthquake Engineering*, 1–27.

Zhang, C., Zhao, M., Zhong, Z. & Du, X. 2022. Optimum intensity measures for probabilistic seismic demand model of subway stations with different burial depths. *Soil Dynamics and Earthquake Engineering*, 154, 107138.