# Correlation Analysis Between Seismic Response of Primary Auxiliary Building and Ground Motion Intensity Measures

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## 1 Introduction

Peak ground acceleration ($PGA$) and spectral acceleration ($S_a$) have been commonly used as earthquake intensity measures (IMs). Nevertheless, numerous studies pointed out that those IMs were not the most efficient parameters for seismic performance evaluations of structures [1–5]. Correlation analyses between earthquake IMs and damage of reinforced concrete (RC) buildings were extensively investigated [5, 6]. Additionally, various studies evaluated the correlation between seismic IMs and responses of underground structures [2, 7], storage tanks [8], and bridges [9–13].

Previously, the correlation analysis between ground motion IMs and structural performances of civil engineering structures was systematically investigated. However, for nuclear power plant (NPP) structures, it is still limited. Nguyen et al. [14] studied the interrelationship between seismic performance of APR-1400 NPP structures and earthquake IMs considering low- and high-frequency ground motions. Recently, Nguyen et al. [15] identified the optimal earthquake IMs for fragility analysis of the reactor containment building in APR-1400 NPPs. It was emphasized that $S_a$, $S_v$, and $S_d$ at the fundamental period were the efficient IMs. A similar trend was observed in the study of Nguyen et al. [16], in which the base isolated APR-1400 NPP structures were used for numerical model and 90 ground motions were used for time-history analyses. However, a correlation analysis between seismic responses of the primary auxiliary building (AB) in Korean Standard NPPs and earthquake IMs has not been conducted yet.

This study analyzes the correlation between seismic performances of the AB structure and 21 ground motion IMs. 90 nonlinear time-history analyses are performed. As a result, the relationship between engineering parameters (EDPs) of the structure and earthquake IMs is developed. Finally, the strongly correlated IMs are identified.

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## 2 Earthquake Intensity Measures and Ground Motion Records

Selection of optimal earthquake IMs is very important for evaluating seismic responses of structures. There are numerous studies that have proposed IMs previously. However, each type of structure contains specific characteristics that affect its responses under earthquakes. This study considers 21 typical earthquake IMs for evaluating performances of the AB structure. The selected earthquake IMs are summarized in Table 1.

In this study, we employed 90 seismic records from historic earthquakes that are available in the PEER center database. The magnitude of the earthquakes ranged from 5.0 to 7.8 Mw. Figure 1 describes all 90 response spectra of the used records.

**Table 1** Selected earthquake IMs

| No. | Seismic IMs | Definition | Unit | References |
|---|---|---|---|---|
| 1 | Peak ground acceleration | $\text{PGA} = \max\lvert a(t)\rvert$ | g | – |
| 2 | Peak ground velocity | $\text{PGV} = \max\lvert v(t)\rvert$ | m/s | – |
| 3 | Peak ground displacement | $\text{PGD} = \max\lvert d(t)\rvert$ | m | – |
| 4 | Ratio of PGV/PGA | PGV/PGA | s | [17] |
| 5 | Root-mean-square of acceleration | $A_{rms} = \sqrt{\frac{1}{t_{\text{tot}}}\int_0^{t_{\text{tot}}} a(t)^2 \mathrm{d}t}$ | g | [18] |
| 6 | Root-mean-square of velocity | $V_{rms} = \sqrt{\frac{1}{t_{\text{tot}}}\int_0^{t_{\text{tot}}} v(t)^2 \mathrm{d}t}$ | m/s | [17] |
| 7 | Root-mean-square of displacement | $D_{rms} = \sqrt{\frac{1}{t_{\text{tot}}}\int_0^{t_{\text{tot}}} \mathrm{d}(t)^2 \mathrm{d}t}$ | m | [17] |
| 8 | Arias intensity | $I_a = \frac{\pi}{2g}\int_0^{t_{\text{tot}}} a(t)^2 \mathrm{d}t$ | m/s | [19] |
| 9 | Characteristic intensity | $I_c = (A_{rms})^{2/3}\sqrt{t_{\text{tot}}}$ | – | [20] |
| 10 | Specific energy density | $\text{SED} = \int_0^{t_{\text{tot}}} v(t)^2 \mathrm{d}t$ | $\text{m}^2/\text{s}$ | – |
| 11 | Cumulative absolute velocity | $\text{CAV} = \int_0^{t_{tot}} \lvert a(t)\rvert \mathrm{d}t$ | m/s | [21] |
| 12 | Acceleration spectrum intensity | $\text{ASI} = \int_{0.1}^{0.5} S_a(\xi = 0.05, T)dT$ | g*s | [22] |
| 13 | Velocity spectrum intensity | $\text{VSI} = \int_{0.1}^{2.5} S_v(\xi = 0.05, T)dT$ | m | [23] |
| 14 | Housner spectrum intensity | $\text{HI} = \int_{0.1}^{2.5} PS_v(\xi = 0.05, T)dT$ | m | [24] |
| 15 | Sustained maximum acceleration | SMA =the 3rd of PGA | g | [25] |
| 16 | Sustained maximum velocity | SMV =the 3rd of PGV | m/s | [25] |
| 17 | Effective peak acceleration | $\text{EPA} = \frac{\text{mean}(s_a^{0.1-0.5}(\xi=0.05))}{2.5}$ | g | [22] |
| 18 | Spectral acceleration at $T_1$ | $S_a\ (T_1)$ | g | [26] |
| 19 | Spectral velocity at $T_1$ | $S_v\ (T_1)$ | m/s | – |
| 20 | Spectral displacement at $T_1$ | $S_d\ (T_1)$ | m | – |
| 21 | A95 parameter | $\text{A}_{95} = 0.764\ I_a^{0.438}$ | g | [27] |

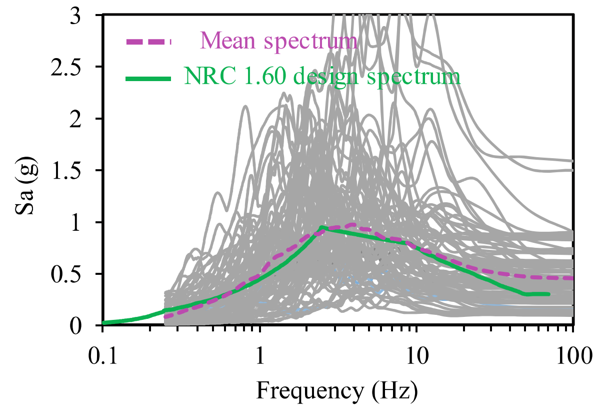


**Fig. 1** Response spectra of 90 ground motion records

## 3 Numerical Modeling of AB Structure

The primary AB is a six-storey RC building with a unique shape, as shown in Fig. 2. It should be noted that AB surrounds the reactor containment building, which has a circular plan with a radius of 24.4 m. A structural system combines RC columns and shear walls, in which shear walls are located along the perimeter and at the center, meanwhile, the columns are inner. Moreover, this building is 37.5 m height and 73.15 × 66.4 m width and length. Additional detailed dimensions can be found in Fig. 2.

A numerical model of the structure is developed in SAP2000, a finite element analysis software. A series of shell elements is used for modeling shear walls, whereas line elements are employed to model the beams and columns. Figure 3 represents the 3D finite element model of the AB structure and a scheme of multi-layer shell element. Additionally, nonlinear material models of concrete and reinforcing bars are considered, as presented in Fig. 4. It should be noted that the building is placed on a base-mat, and therefore, the boundary condition is assumed to be fixed at the base of the structure. The eigenvalue analysis results are shown in Fig. 5.

## 4 Correlation Between Seismic Responses and Earthquake IMs

To evaluate the interrelationship between structural responses of AB and ground motion IMs, 90 nonlinear time-history analyses were conducted. All ground motion records were applied on the horizontal directions and the structural responses of the building were monitored for each record. It should be noted that 8 vibration modes were considered in dynamic analyses to make sure over 90% mass participation. For primary structures of NPPs, the floor acceleration is one of the important engineering demand parameters (EDPs) since it affects the secondary systems' responses under earthquakes. Moreover, lateral displacement is also the considered demand parameter in this study. Figure 6 depicts seismic responses of the building subjected to the

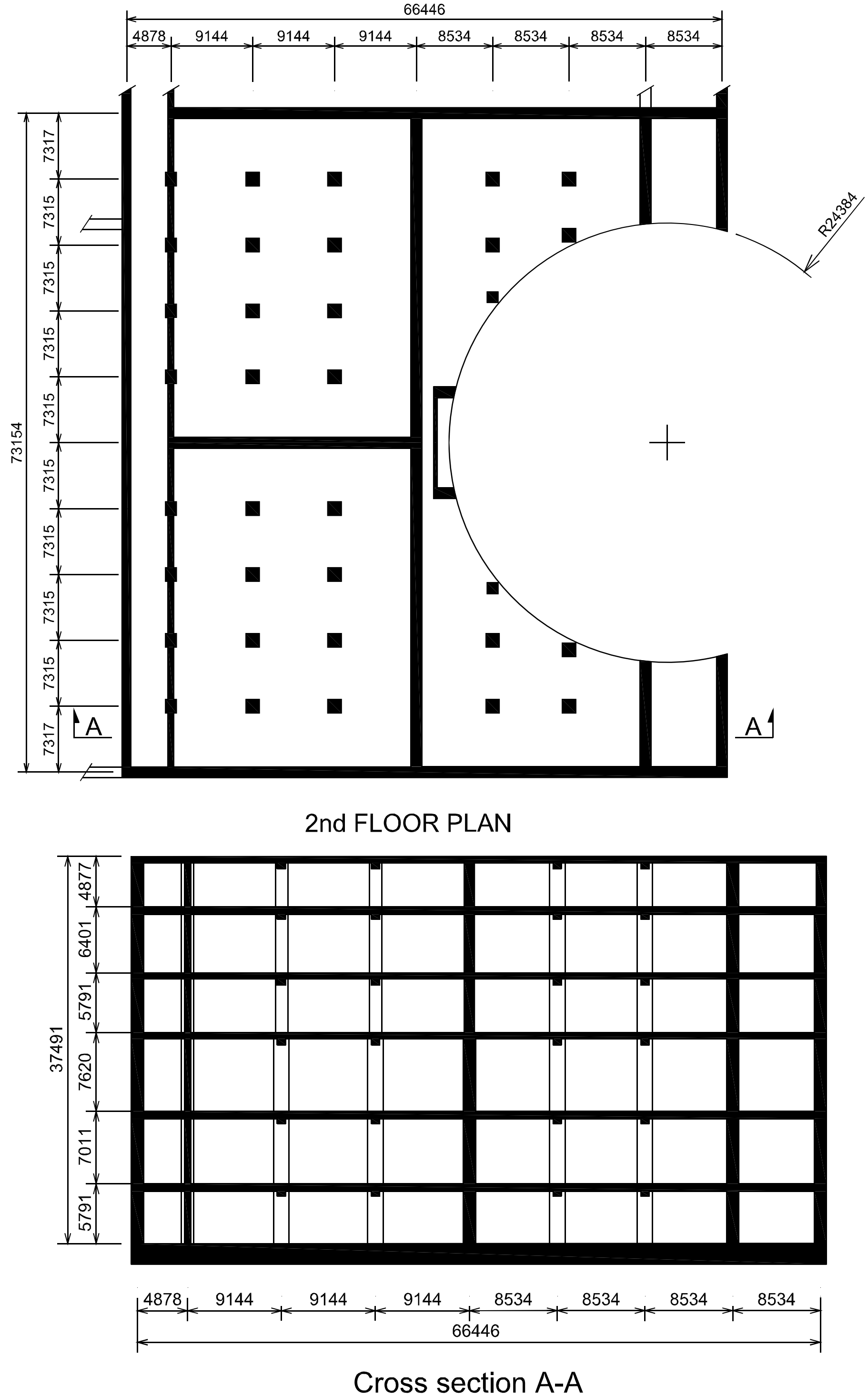


**Fig. 2** Configurations of the AB structure

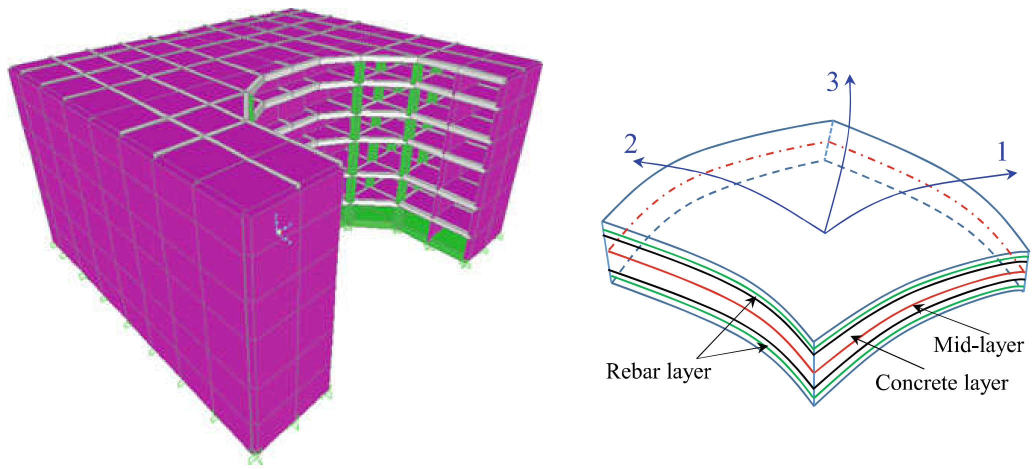


**Fig. 3** Numerical modeling of AB using multi-layer shell elements

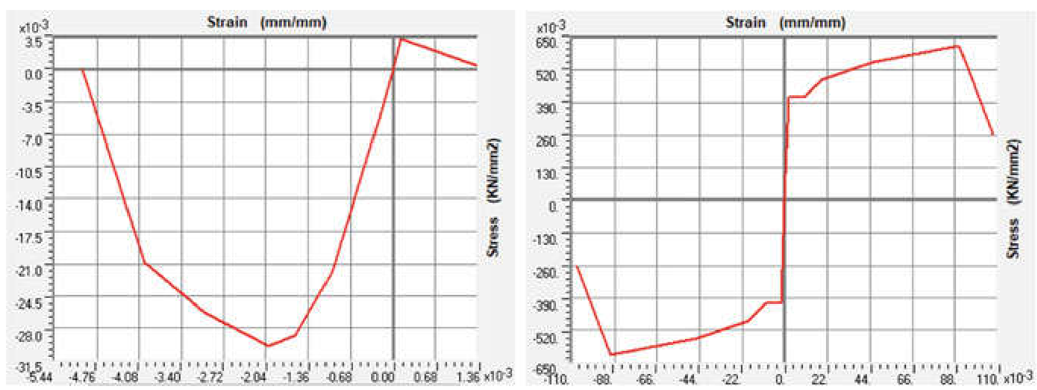


**Fig. 4** Nonlinear concrete (left) and reinforcement (right) material models

1940 El Centro earthquake, in which the floor accelerations and displacements are obtained. The structural responses of AB are monitored for all 90 earthquake records. As a result, we developed the relationship between EDPs and 21 earthquake IMs for evaluating the correlation level. This relationship is also called the probabilistic seismic demand model (PSDM).

Figure 7 shows the PSDM of AB for 21 earthquake IMs using peak floor acceleration. It can be found that PSDMs using $S_a(T_1)$, $S_v(T_1)$, $S_d(T_1)$ had the highest $R^2$ values, followed by $ASI$, $SMA$, $EPA$, and $PGA$. Additionally, the scatter of PSDMs with these IMs was significantly lesser than that of other IMs. Thus, these IMs were strongly correlated to the seismic response of AB. This tendency was also observed for lateral displacements. Meanwhile, $PGA/PGV$, $PGV$, $PGD$, $V_{RMS}$, and $D_{RMS}$ are shown to be weak correlation with EDPs. Overall, the strong IMs were directly correlated with acceleration. This can be attributed that the seismic response of a rigid structure like AB is sensitive to acceleration rather than velocity or displacement [12]. Moreover, $S_a(T_1)$, $S_v(T_1)$, and $S_d(T_1)$ were the efficient IMs because those IMs are combined the ground motion and structural characteristics.

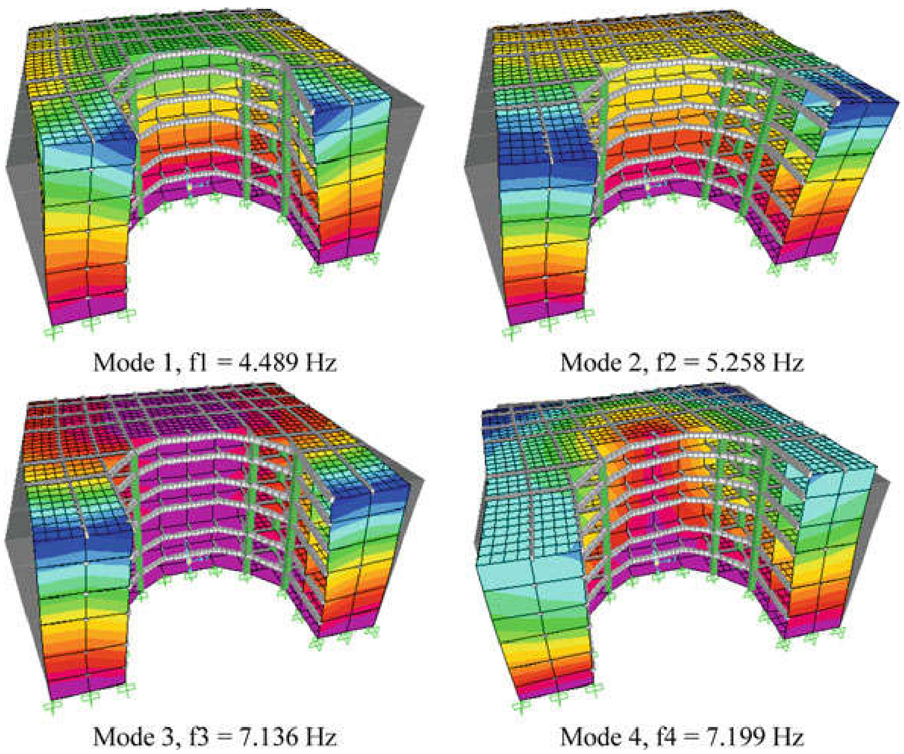


**Fig. 5** Eigenvalue analysis results

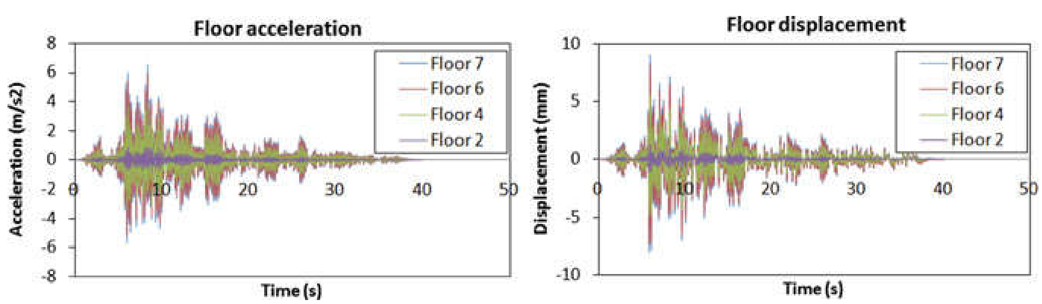


**Fig. 6** Example of seismic responses of AB under the 1940 El Centro earthquake

In this study, three statistical indicators are employed to evaluate the correlation between EDPs and earthquake IMs, in which goodness of fit ($R^2$), standard deviation ($\sigma_{D|IM}$), and practicality are considered. Figure 8 shows the calculated values of the indicators. Again, it can be found that $S_a(T_1)$, $S_v(T_1)$, and $S_d(T_1)$ had a lower standard deviation and higher practicality compared to other IMs. In other words, these IMs are strongly correlated to EDPs of the AB structure.

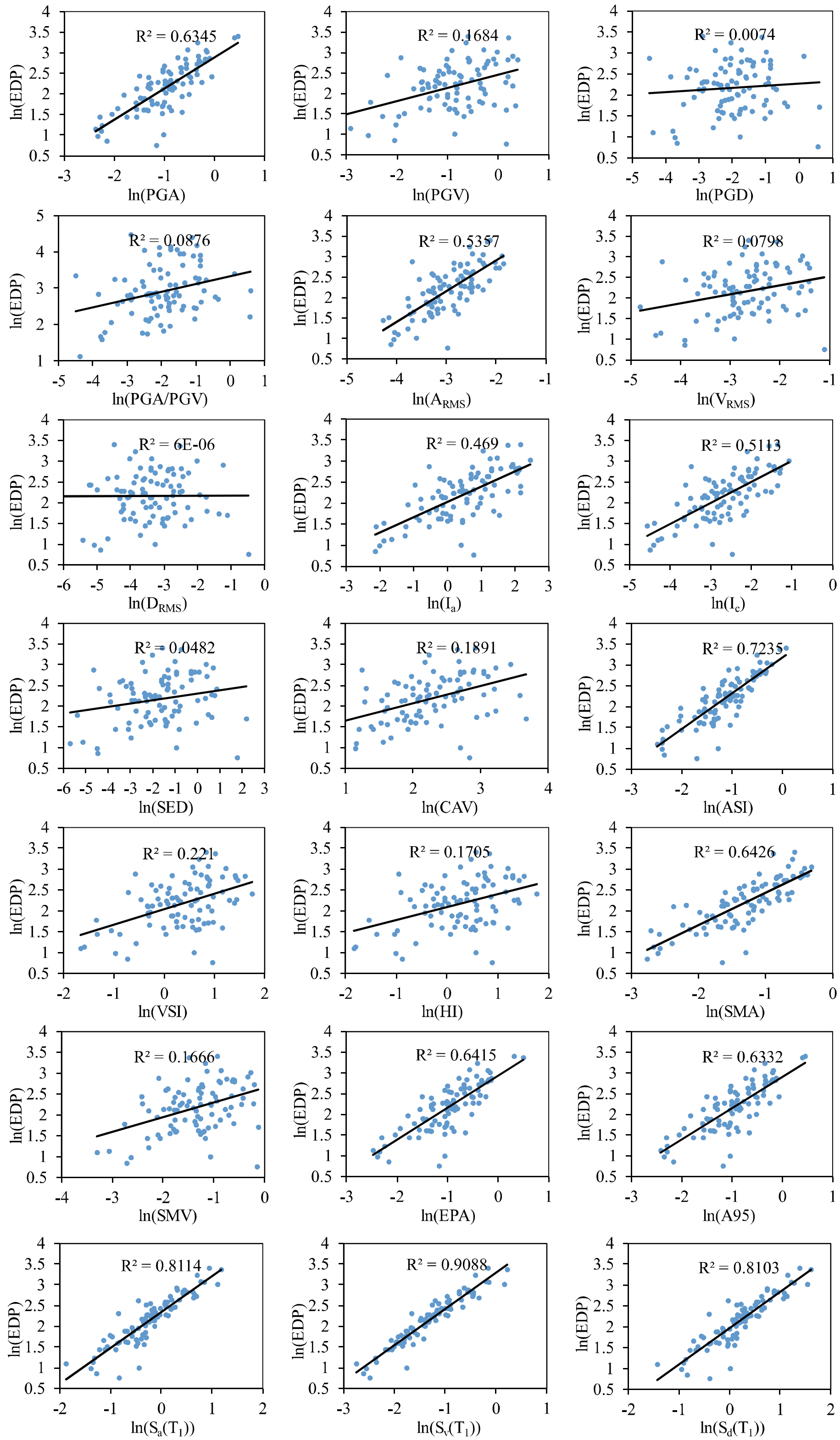


**Fig. 7** Correlation between the floor accelerations and 21 earthquake IMs

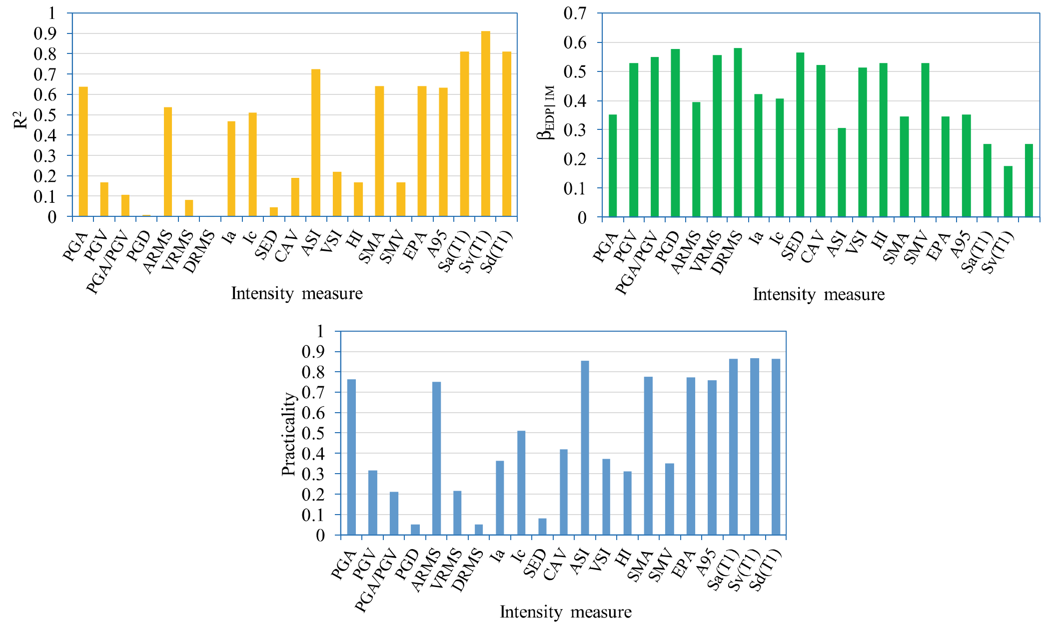


**Fig. 8** Statistical values of 21 PSDMs

# 5 Conclusions

A set of 90 time-history analyses were conducted to analyze the correlation between earthquake intensity measures (IMs) and responses of the primary auxiliary building (AB) in nuclear power plants (NPPs. A total of 21 earthquake IMs were employed. The relationship between engineering demand parameters (EDPs) (floor accelerations and displacements) and 21 IMs was developed. The following conclusions are obtained.

- $S_a(T_1)$, $S_v(T_1)$, $S_d(T_1)$ are strongly correlated with EDPs of AB, followed by $ASI$, $SMA$, $EPA$, and $PGA$.
- $PGA/PGV$, $PGV$, $PGD$, $V_{RMS}$, and $D_{RMS}$ exhibit to be weak correlation with EDPs.
- $PGA$ has a medium correlation with seismic performance of AB structure.

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