UTILIZATION OF ALTERNATIVE INTENSITY MEASURES IN THE FORMATION OF GROUND MOTION RECORD SETS FOR SEISMIC DEMAND ANALYSES

K. Kadaş[1] and A. Yakut[2]

[1] *Graduate Student, Civil Eng. Department, Middle East Technical University, Ankara*
[2] *Professor, Civil Eng. Department, Middle East Technical University, Ankara*
Email: koraykadas@yahoo.com

ABSTRACT:

This study concentrates on utilization of alternative intensity measures (IMs) in the formation of ground motion record (GM) sets that could be used for nonlinear time history based seismic demand analyses. To recommend suitable IMs that will be taken as basis in ground motion database formation, correlation of several IMs with top drift demands of single-degree-of-freedom (SDOF) systems has been evaluated as the first step for different levels of strength reduction factor (R) and ductility (μ) utilizing records from PEER's NGA ground motion database. From the results of SDOF-based study, alternative ground motion record sets have been formed considering candidate IMs and following a stratified random sampling approach. As the next step, seven reinforced concrete frames having different structural properties were dynamically analyzed utilizing these record sets and major engineering demand parameters (EDPs) were extracted from the nonlinear time history analysis results to investigate the correlation performance of the selected IMs designating their suitability in the use of ground motion selection.

KEYWORDS: Ground motion, intensity measure, seismic demand analysis, reinforced concrete frames.

1. INTRODUCTION

In the formation of ground motion (GM) record sets for seismic performance assessment of structures, either records seismologically compatible with seismic hazard conditions of the site (i.e., magnitude, distance, faulting style, soil classification etc… of the records are consistent with the probable seismic hazard) are chosen or records, regardless of seismological characteristics, but consistent with specific intensity levels are selected. In the second alternative, the common approach is to choose an intensity measure (IM) which is assumed to correlate relatively well with various engineering demand parameters (EDPs) and then, to form a set of GM records in such a way that each record will individually satisfy a certain level of the selected IM. After completing the task of GM record set formation, it is straightforward to continue with any type of seismic demand analysis (i.e., seismic performance assessment of a structure through nonlinear time history analyses, investigation on correlation of seismic demands with specific intensity measures or performance of a fragility analysis).

Inclined to intensity-based GM selection instead of following a hazard specific selection approach, this study investigates the candidate IMs that could be considered in the formation of GM record sets which will be utilized in the nonlinear time history based seismic demand analyses. To accomplish this, a large set of GM records has been processed to extract the characteristics in terms of IMs available in the literature and all records have been employed in a SDOF-based study to evaluate the variation of correlation (of IMs with maximum top drift) with fundamental period for different strength reduction factor (R) and ductility (μ) levels. Using the SDOF-based study, candidate IMs have been shortlisted and alternative GM record subsets have been formed considering the

shortlisted IMs and following a stratified random sampling approach. These subsets have been further utilized in the nonlinear time history analyses of seven reinforced concrete moment-resisting frames with different structural properties. The results of the multi-degree-of-freedom (MDOF) system based study in terms of correlation statistics (i.e., correlation of candidate IMs with major EDPs namely maximum top drift, TD, maximum inter-story drift ratio, MIDR, and maximum base shear, V) facilitated the marking of most suitable IMs among the alternatives examined.

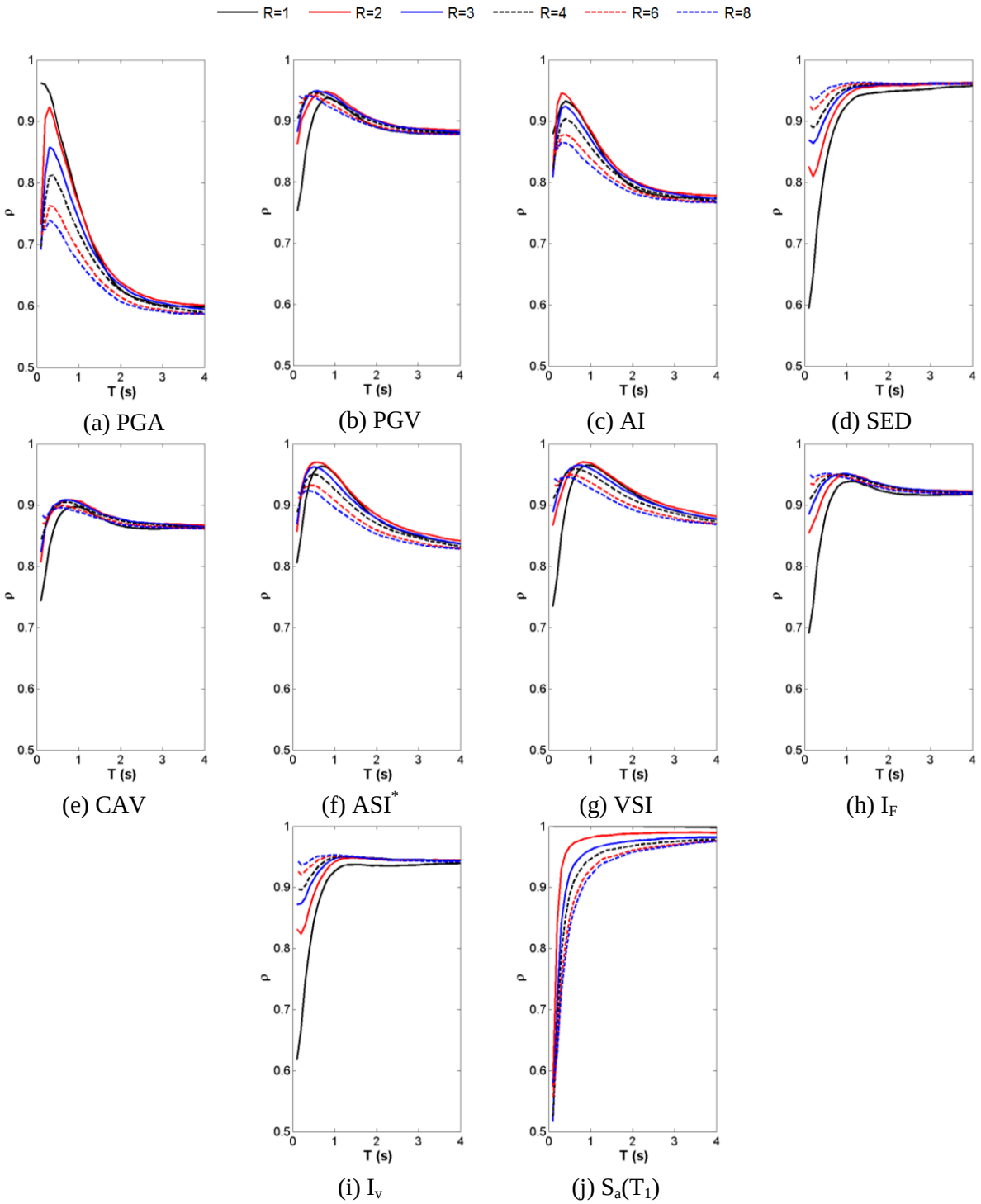
2. MAIN GROUND MOTION DATABASE AND INTENSITY MEASURES CONSIDERED

In order to incorporate as many records with wide range of strong ground motion characteristics as possible, Pacific Earthquake Engineering Research Center's (PEER) 2005 Ground Motion database have been utilized as the main ground motion library and totally 6'883 horizontal records compiled from over 100 earthquakes have been processed via SeismoSignal (Seismosoft, 2010) software in order to obtain the GM intensity parameters (mainly non-structure specific IMs that are provided by SeismoSignal) and acceleration, velocity and displacement spectra (for periods in between 0.02 and 10.0 seconds) of each record. Along with the IMs provided by SeismoSignal software (**PGA**-Peak ground acceleration, **PGV**-Peak ground velocity, **PGD**-Peak ground displacement, **PGV/PGA** ratio, $\mathbf{a_{rms}}$-Root-mean-square of acceleration, $\mathbf{v_{rms}}$-Root-mean-square of velocity, $\mathbf{d_{rms}}$-Root-mean-square of displacement, **AI**-Arias Intensity, $\mathbf{I_C}$-Characteristic Intensity, **SED**-Specific Energy Density, **CAV**-Cumulative Absolute Velocity, **ASI**-Acceleration Spectrum Intensity, **VSI**-Velocity Spectrum Intensity, **SMA**-Sustained Maximum Acceleration, **SMV**-Sustained Maximum Velocity, **EDA**-Effective Design Acceleration, $\mathbf{A_{95}}$ parameter, $\mathbf{T_p}$-Predominant Period, $\mathbf{T_m}$-Mean Period, $\mathbf{t_r}$-Significant Duration, $\mathbf{S_a(T_1)}$, $\mathbf{S_v(T_1)}$, $\mathbf{S_d(T_1)}$-Spectral Acceleration, Velocity and Displacement at the fundamental period, respectively), additional IMs ($\mathbf{I_F}$-Fajfar Index, $\mathbf{I_a}$, $\mathbf{I_v}$, $\mathbf{I_d}$ –Riddell and Garcia Indices for Acceleration, Velocity and Displacement regions, respectively, $\mathbf{ASI^*}$-a modified version of Acceleration Spectrum Intensity (Yakut and Yilmaz, 2008), **EPA**-Effective Peak Acceleration, **EPV**-Effective Peak Velocity) have also been computed yielding almost 30 IMs for consideration. The reader may refer to Kadaş and Yakut (2012) for the major statistical features of the GM database and is advised to refer to SeismoSignal software manual and Ye et al. (2013) for the explicit explanation of the IMs examined.

3. SDOF-BASED STUDY

3.1. SDOF Analyses and Correlation Studies

The suitability of an IM in use of GM database formation is generally evaluated through its correlation with certain EDPs. As the number of IMs in the initial list is beyond manageable limit for a comprehensive evaluation, preliminary screening has been done through SDOF-based nonlinear time history analyses. To achieve this goal, maximum top drift demands of SDOF systems with periods 0.1, 0.2, …, 4.0 s have been calculated utilizing SA4NOR, analysis module of USDP (2008) software, for different strength reduction factor, R=1, 2, 3, 4, 6 and 8 and ductility, μ=1, 2, 3, 4, 6, 8 levels. Throughout the analyses performed under 6'883 records of the main GM library, two different hysteretic cases have been considered: (i) elastic-perfectly-plastic (i.e., α=0%), (ii) bi-linear hardening (i.e., α=5%). As the next step, Pearson correlation coefficient (on ln-transformed IM and EDP - TD for SDOF case- data) values (the reader may refer to Riddell, 2007 and Kadaş and Yakut, 2012 for correlation coefficient calculation) have been computed for all IMs for each fundamental period and R or μ level. In the final step of the SDOF-based study, variation of Pearson statistics for each IM with fundamental period has been depicted for elastic and various inelastic levels. Figure 1 and Figure 2 represent the variation of Pearson statistics with period for the elastic-perfectly-plastic case for different R and μ levels, respectively. It is important to note here that both figures only contain graphical outcomes for candidate IMs (PGA, PGV, AI, SED, CAV, ASI^*, VSI, I_F, I_v and $S_a(T_1)$) due to their relatively better performance with respect to remaining IMs in the initial list.



(a) PGA (b) PGV (c) AI (d) SED

(e) CAV (f) ASI* (g) VSI (h) I_F

(i) I_v (j) $S_a(T_1)$

Figure 1. Variation of Pearson correlation coefficient values with period for different R levels

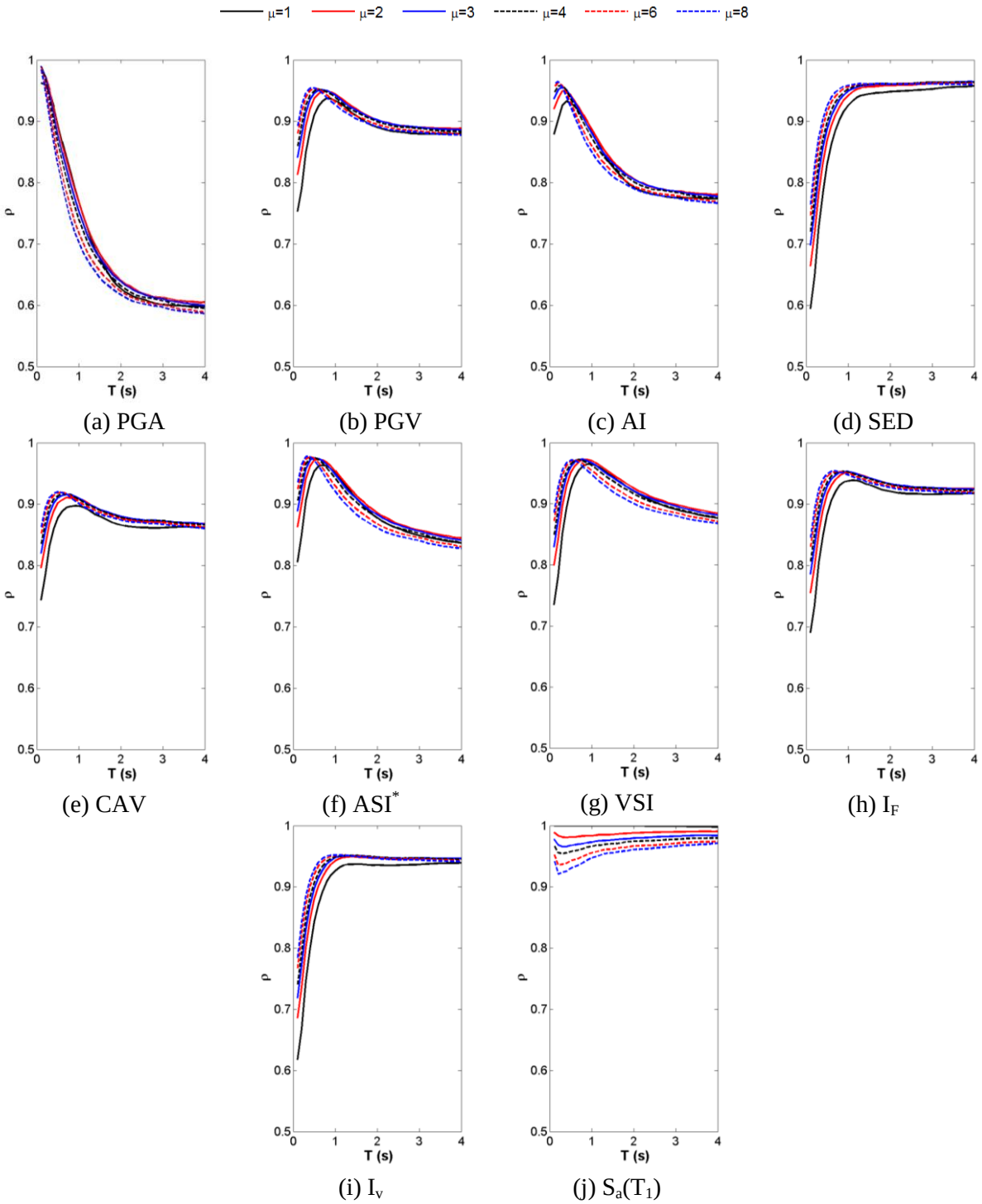


Figure 2. Variation of Pearson correlation coefficient values with period for different μ levels

3.2. Discussion Based on SDOF Results

Eliminating the insignificant IMs due to their low correlation performance or their high cross-correlation with major IMs, a total of 10 IMs (PGA, PGV, AI, SED, CAV, ASI^*, VSI, I_F, I_v and $S_a(T_1)$) has been selected and examined in detail. Period versus Pearson's correlation relationships for selected IMs reveal that PGA correlates well with the deformation demands of short period systems. However, as the fundamental period enters into the medium and long period range, the performance rapidly diminishes. Additionally, when the level of nonlinearity of short period systems increases, for constant values of R PGA's high correlation performance at short periods also disappears, unlike the case for different μ levels. PGV's significant performance over intermediate and long periods meets the deficit of its drawback at short periods for elastic systems. This observation is fully in agreement with the outcomes of Akkar and Özen (2005). VSI shows similar performance for the entire period range. AI and ASI^* show resembling correlation variation as PGA, but they perform better at long periods, ASI being superior with respect to AI. SED reveals a good correlation with SDOF drift demands at medium-to-long periods. Results for different R levels show that correlation performance improves as the degree of inelasticity increases. CAV also shows a stable performance at medium-to-long periods. I_F and I_v show a stable and good correlation with the deformation demand at a wide period range. $S_a(T_1)$ shows perfect correlation with drift demands for elastic case and reveal good correlation for different μ levels. However, for different R levels, the performance of $S_a(T_1)$ is very low for short-to-medium periods. It has been observed throughout the study that outcomes for the bi-linear hardening case do not differ significantly from the findings of the elastic-perfectly-plastic case. SDOF-based observations suggest that acceleration-based IMs such as PGA, AI and ASI^* could be considered as candidate IMs in GM selection for short period systems and IMs that exhibit good and stable correlation performance at medium-to-long periods (such as PGV, SED, CAV, VSI, I_F and I_v) could be used in GM selection for medium-to-long period systems and for structural systems that are expected to undergo various degrees of inelasticity.

4. MDOF-BASED STUDY

4.1. Formation of Alternative Ground Motion Sets for MDOF Analyses and Correlation Studies

Considering the overall correlation performance of the IMs supported by the comprehensive SDOF-based evaluation and availability of ground motion prediction equations (GMPEs) for some of the selected IMs, a total of 10 IMs **(PGA, PGV, AI, SED, CAV, ASI^*, VSI, I_F, I_v** and **$S_a(T_1)$)** were shortlisted to develop alternative GM record sets taking these IMs as basis. For each IM, the main GM database was stratified into 10 bins (strata) between 0 and upper bound of the IM considered (PGA_{max}: 1.7794 g, PGV_{max}: 263.23 cm/s, AI_{max}: 22.75 m/s, SED_{max}: 20504.29 cm^2/s, CAV_{max}: 4813.88 cm/s, ASI^*_{max}: 4.02 g*s, VSI_{max}: 717.04 cm, $I_{F,max}$: 500.92, $I_{v,max}$: 96.86). Using stratified random sampling approach, 11 records (as advised in ATC-58-1 75% Draft [ATC, 2011]) from each bin (stratum) were tried to be selected, theoretically yielding 110 records in total for each IM. However, the skewed distribution of the GM parameters resulted in less number of records at high intensities which may affect the results at these levels. These alternative sets of GM records were used for MDOF-based evaluation. Utilizing seven reinforced concrete moment-resisting frames (Kadaş, 2006) which are dominated by the first mode behavior and had been previously modeled in OpenSees software, nonlinear time history analyses under 10 different GM record sets were performed and major EDPs such as maximum top displacement (TD), maximum inter-story drift ratio (MIDR) and maximum base shear (V) values have been recorded. Following this step, correlation statistics on ln-transformed values of shortlisted IMs and selected EDPs have been performed. Along with the scatter diagrams prepared for each IM and frame case (Figure 3 exemplifies the cases for frame F2S2B), Pearson correlation coefficient values, as summarized in Table 1, served to elaborate evaluation of the candidate IMs.

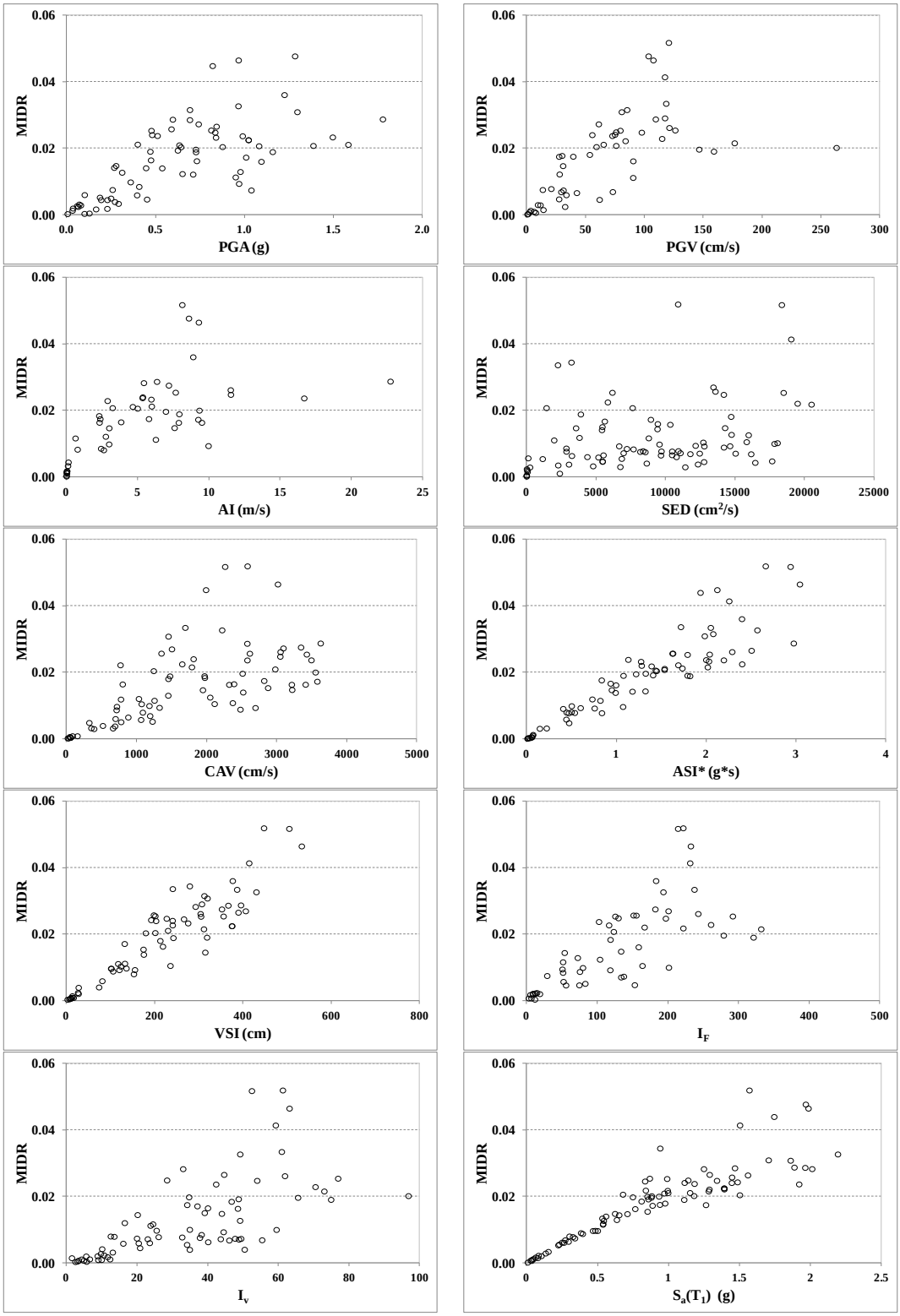


Figure 3. Scatter (IM versus MIDR) diagrams for sample case: F2S2B (T_1=0.59 s)

Table 1. Correlation of major EDPs with selected IMs

IM	F2S2B2 (T_1 = 0.30 s)	F3S2B (T_1 = 0.45 s)	F2S2B (T_1 = 0.59 s)	F5S7B (T_1 = 0.66 s)	F5S2B (T_1 = 0.75 s)	F5S4B (T_1 = 0.95 s)	F8S3B (T_1 = 1.20 s)	EDP
PGA	0.918	0.829	0.812	0.786	0.770	0.773	0.729	**Maximum Top Displacement (TD)**
PGV	0.854	0.885	0.916	0.921	0.908	0.947	0.962	
AI	0.954	0.936	0.924	0.928	0.888	0.894	0.866	
SED	0.552	0.686	0.713	0.814	0.758	0.805	0.842	
CAV	0.895	0.923	0.916	0.948	0.889	0.908	0.897	
ASI*	0.965	0.969	0.982	0.984	0.973	0.977	0.963	
VSI	0.911	0.953	0.977	0.981	0.978	0.984	0.980	
I_F	0.826	0.863	0.882	0.888	0.878	0.918	0.943	
I_v	0.752	0.815	0.859	0.879	0.854	0.895	0.924	
$S_a(T_1)$	0.986	0.986	0.975	0.990	0.987	0.991	0.986	
PGA	0.927	0.847	0.843	0.818	0.797	0.801	0.795	**Maximum Inter-story Drift Ratio (MIDR)**
PGV	0.855	0.886	0.911	0.916	0.920	0.950	0.962	
AI	0.955	0.941	0.933	0.926	0.908	0.915	0.920	
SED	0.548	0.693	0.703	0.797	0.763	0.791	0.784	
CAV	0.897	0.926	0.925	0.946	0.907	0.912	0.909	
ASI*	0.965	0.970	0.984	0.984	0.979	0.983	0.984	
VSI	0.911	0.955	0.977	0.983	0.987	0.984	0.988	
I_F	0.827	0.865	0.880	0.885	0.886	0.917	0.938	
I_v	0.751	0.817	0.856	0.871	0.853	0.895	0.912	
$S_a(T_1)$	0.986	0.985	0.979	0.988	0.989	0.991	0.986	
PGA	0.911	0.876	0.875	0.835	0.822	0.823	0.822	**Maximum Base Shear (V)**
PGV	0.873	0.905	0.919	0.924	0.920	0.947	0.953	
AI	0.962	0.958	0.948	0.943	0.915	0.929	0.929	
SED	0.591	0.739	0.799	0.842	0.866	0.865	0.886	
CAV	0.908	0.940	0.945	0.953	0.939	0.936	0.931	
ASI*	0.971	0.971	0.969	0.973	0.959	0.969	0.971	
VSI	0.934	0.964	0.968	0.968	0.969	0.968	0.967	
I_F	0.860	0.886	0.900	0.887	0.897	0.913	0.943	
I_v	0.775	0.836	0.878	0.882	0.888	0.913	0.930	
$S_a(T_1)$	0.970	0.970	0.956	0.970	0.971	0.970	0.968	

4.3. Discussion Based on MDOF Results

In agreement with the observations of past studies (Elenas, 2000; Elenas and Meskouris, 2001; Riddell, 2007; Yakut and Yılmaz, 2008), MDOF-based results reveal that SDOF-based observations for PGA are valid for TD and MIDR; the correlation performance of PGA decreases with increasing period. In contrast, PGV shows more stable performance along the entire period range of 0.30-1.20 s. SED, I_F and I_v showed poor correlation with all EDPs. CAV has moderate correlation with largest dispersion that seems to be affected less with the period range. ASI*, VSI and $S_a(T_1)$ appear to have the best correlation and least dispersion when all EDPs are considered. PGA is better at low periods whereas PGV shows better correlation beyond short period range. Both PGV and PGA have notable dispersion.

5. CONCLUSIONS

A comprehensive research incorporating both SDOF- and MDOF-based evaluation has been undertaken to show the most suitable IMs that could be used as basis for ground motion set formation which will further be utilized for seismic demand analyses. SDOF-based study enabled the elimination of IMs of less importance. Of the shortlisted IMs (PGA, PGV, AI, SED, CAV, ASI^*, VSI, I_F, I_v and $S_a(T_1)$), MDOF-based study revealed that ASI^*, VSI and $S_a(T_1)$ mostly introduce less dispersion and correlate well with major EDPs (TD, MIDR and V) and thus, are recommended to be taken as basis in the compilation of a ground motion record set. Further studies will be carried out to investigate the effect of these IMs on fragility studies for the employed frames.

ACKNOWLEDGEMENT

The first author has been financially supported by The Scientific and Technological Research Council of Turkey (TÜBİTAK) through Domestic Doctoral Scholarship Program.

REFERENCES

Akkar, S. and Özen, Ö. (2005). Effect of peak ground velocity on deformation demands for SDOF systems. *Earthquake Engineering and Structural Dynamics* **34:13**, 151-1571.

Applied Technology Council (ATC) (2011). ATC-58-1 75% Draft, Seismic performance assessment of buildings, Redwood City, CA.

Elenas, A. (2000). Correlation between seismic acceleration parameters and overall structural damage indices of buildings. *Soil Dynamics and Earthquake Engineering* **20:1-4**, 93-100.

Elenas, A. and Meskouris, K. (2001). Correlation study between seismic acceleration parameters and damage indices of structure. *Engineering Structures* **23:6**, 698-704.

Kadaş, K. (2006). Influence of idealized pushover curves on seismic response. Master's Thesis, Department of Civil Eng., Middle East Technical University, Ankara.

Kadaş, K. and Yakut, A. (2012). Re-examination of a Spectral Ground Motion Intensity Measure Based on Predicted Period Elongation. *10th International Congress on Advances in Civil Engineering*, 17-19 October 2012, Middle East Technical University, Ankara, Turkey.

OpenSees 2.3.2. Computer Software, University of California, Berkeley, CA. Retrieved from http://opensees.berkeley.edu

Riddell, R. (2007). On ground motion intensity indices. *Earthquake Spectra* **23:1**, 147-173.

Seismosoft (2010) SeismoSignal Software. Retrieved from http://www.seismosoft.com

Utility Software for Data Processing (USDP), (2008). Department of Civil Engineering, Middle East Technical University, Ankara, Turkey, available on Internet at http://www2.ce.metu.edu.tr/~sakkar/usdp.html.

Yakut, A. and Yilmaz, H. (2008). Correlation of deformation demands with ground motion intensity. *Journal of Structural Engineering* **134:12**, 1818-1828.

Ye, L., Ma, Q., Miao, Z., Guan, H. and Zhuge, Y. (2013). Numerical and comparative study of earthquake intensity indices in seismic analysis. *The Structural Design of Tall and Special Buildings* **22**, 362-381.