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Damage potential of earthquake records for RC building stock

Hayri Baytan Ozmen[*1] and Mehmet Inel[2a]

[1]Department of Civil Engineering, Usak University, 64200 Usak, Turkey
[2]Department Department of Civil Engineering, Pamukkale University, 20070 Denizli, Turkey

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Abstract. This study investigates ground motion parameters and their damage potential for building type structures. It focuses on low and mid-rise reinforced concrete buildings that are important portion of the existing building stock under seismic risk in many countries. Correlations of 19 parameters of 466 earthquake records with nonlinear displacement demands of 1056 Single Degree of Freedom (SDOF) systems are investigated. Properties of SDOF systems are established to represent RC building construction practice. The correlation of damage and ground motion characteristics is examined with respect to number of story and site classes. Equations for average nonlinear displacement demands of considered RC buildings are given for some of the ground motion parameters. Velocity related parameters are generally found to have better results than the acceleration, displacement and frequency related ones. Correlation of the parameters may be expected to decrease with increasing intensity of seismic event. Velocity Spectrum Intensity and Peak Ground Velocity have been found to have the highest correlation values for almost all site classes and number of story groups. Common parameter of Peak Ground Acceleration has lower correlation with damage when compared to them and some other parameters like Effective Design Acceleration and Characteristic Intensity.

Keywords: destructiveness; seismic evaluation; peak ground velocity; record characteristics; reinforced concrete

1. Introduction

Seismic loadings are among the critical load cases accounted in design of new buildings or evaluation of existing ones. Earthquake induced loading on a building may vary significantly depending on the characteristics of the earthquake and building (Uang ve Bertero 1988, Kramer 1996, Ozmen *et al*. 2013). Earthquakes of higher magnitude and/or peak ground acceleration may have lesser effect on a building depending on the other features of the ground motion. Thus, selection of earthquake records for assessment of buildings or evaluation of damages after an earthquake requires some level of understanding this complex relationship (Ozmen *et al*. 2014). Earthquake records with different characteristics may significantly affect the results of analyses (Özdemir and Bayhan 2015).

*Corresponding author, Associate Professor, E-mail: baytan.ozmen@usak.edu.tr
[a]Professor, E-mail: minel@pau.edu.tr

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Search for a parameter that reflects the damage potential of an earthquake is an ongoing issue in earthquake engineering. It is known that, the damage of earthquakes on structures depends on the intensity, frequency and energy content of the records (Villaverde 2007, Elnashai and Sarno 2008, Moustafa and Takewaki 2012). One of the most common parameters regarding the damage potential of an earthquake record is PGA (Peak Ground Acceleration). Even earthquake forces in seismic codes are commonly based on this parameter. However, concerns about the inefficiency of this parameter are present for quite some time (Takizawa and Jennings 1980).

1.1 Previous studies

There are number of studies in literature that investigates relation between certain characteristics of ground motions and imposed damages on structures. Kramer (1996) and Kramer and Mitchell (2006) claimed that the Cumulative Absolute Velocity (CAV) has a good correlation with structural damage. CAV is also observed to be proportional to the seismic intensity by Hu *et al*. (2013). The correlation between 10 seismic parameters and demands of 20 acceleration records on a reinforced concrete frame building was investigated by Elenas *et al*. (1995), Elenas (1997, 2000), and Elenas and Meskouris (2001). The considered demand parameters are maximum floor acceleration, maximum inter-storey drift and overall structural damage index. These authors concluded that PGA exhibits a poor correlation while energy and spectral parameters have a good correlation with damage indices. However, it is stated that further studies based on larger number of seismic records should be conducted to confirm these results.

Cabanas *et al*. (1997), in the light of damage data obtained after real earthquakes, have stated that Arias Intensity (AI) and CAV have an exponential relationship with damage. However, Sucuoglu (1997) in the discussion he wrote against this article has argued that PGA and Peak Ground Velocity (PGV) have higher correlation with damage than these parameters. Travasarou *et al*. (2003) have also stated that Arias Intensity (AI) correlates well with several commonly used demand measures of structural performance. Wald *et al*. (1999) have examined the correlations of the PGA and PGV values with Modified Mercalli Intensity Scale results after 8 California earthquakes. For large intensity values PGV is observed to have higher correlation.

Liao *et al*. (2001), have noted that the maximum relative story drift increases with increasing PGV/PGA ratio, Spectral Velocity (Sv) and energy content of ground motion records. Wu *et al*. (2003) have reached similar conclusions using the data after 1999 Chi Chi earthquake. Additionally, they have argued that PGV has a higher correlation with the earthquake magnitude than PGA. Wu *et al*. (2004) have stated that PGA and Spectral Acceleration (S_a) at 1.0 seconds have highest correlation with earthquake damage. However, since the value of PGA is more open to change, as it is affected by a single wave with great amplitude, they suggested use of PGV instead. Akkar and Ozen (2005), in a study based on Single Degree of Freedom (SDOF) systems using 60 ground motion records, concluded that PGV correlates better with the deformation demands with respect to other ground motion intensity measures.

Riddel (2007) conducted a comprehensive study for 23 ground motion parameters. He concluded that no index is found to be satisfactory over the entire frequency range. Indices related to ground acceleration found to rank better in the acceleration-sensitive region of the spectrum; indices based on ground velocity are better in the velocity-sensitive region and, same generally for the displacement-controlled region. He stated that despite frequent criticism, the peak ground motion parameters passed the test successfully and choice for the most appropriate one depends on the frequency range of interest. PGA and Housner intensity (HI) ranked as the best indices in the acceleration and velocity sensitive regions, respectively.

Nanos *et al*. (2008) examined the relation between overall damage indices of a 6-storey reinforced concrete (RC) frame and the characteristics of 450 artificial ground motion records. They concluded that PGA and Arias Intensity (AI) have good correlation with the damage indices. Yakut and Yılmaz (2008) have investigated the correlation between maximum interstory drift demand of frame structures and ground motion intensity parameters. They have used 16 RC frames and 80 ground motion records. They concluded that spectrum intensity parameters are superior to other parameters such as PGV, PGA and S_a. For a period range of 0.1-2.5 s; HI, Velocity Spectrum Intensity (VSI) and Acceleration Spectrum Intensity (ASI) are the best correlated parameters. For period range of 0.2-0.5 s; PGA followed by VSI and Characteristic Intensity (CI); for period range of 0.5-1.1 s, VSI, HI and S_a are the best parameters, respectively.

Kadas *et al*. (2011) proposed an intensity parameter that relies on the expected elongated period of the structure under seismic forces. Cao and Ronagh (2014) have investigated the correlation of some parameters of strong ground motion records with interstory drift and damage indices of a 3 story RC frame. The number of records was 1040. However, all records are from 4 different earthquakes and 1999 Chi Chi earthquake constitute nearly half of them. They stated that VSI has the best correlation followed by HI and S_a while PGA has low correlation.

1.2 Features of this study

In the light of these present studies in literature, a study with distinctive features is aimed. When the present literature is examined, it may be seen that no solid conclusion on a parameter reflecting the intensity of ground motion has been reached. In past studies, the number of used building models are seems to be limited. Some studies are based on a single building. On the other hand, the number of earthquake records are either in limited numbers (around 20-60) or use of limited events constitute a great portion in the sets.

In this study correlation of 19 parameters of 466 earthquake records with nonlinear displacement demands of 1056 SDOF systems are investigated. Earthquake records are selected from 28 different seismic events. Properties of SDOF systems are established to represent existing low and mid-rise RC building stock. Conclusions are based on approximately half a million analyses results.

No study in literature (in authors' knowledge) has the diversity of the proposed study in terms of the number of ground motion records and building models. Additionally, this study focuses on RC building stock and has the perspective of examining damage potential for stock of buildings. This may be seen as a distinctive quality when the present literature is considered. The correlation of damage and ground motion characteristics is examined with respect to building feature (number of story) and site class which is limited in the literature.

2. Ground motion parameters

Brief introduction for the considered parameters are given in this section. Further information may be found in any geotechnical engineering book such as (Kramer 1996). The values of the parameters used in the study are determined using the software SeismoSignal (SeismoSignal 2011).

Peak ground values of acceleration (PGA), velocity (PGV) and displacement (PGD) is the maximum values of the mentioned parameters throughout the earthquake record. Effective Design Acceleration (EDA) is defined as the peak acceleration value found after low-pass filtering the input time history with a cut-off frequency of 9 Hz. (Benjamin 1988). A95 parameter is defined as the acceleration level below which 95% of the total Arias intensity is contained (Sarma and Yang 1987). Sustained Maximum Acceleration (SMA) and Velocity (SMV) are defined as the third highest absolute value of acceleration and velocity in the time history (Nuttli 1979). Predominant Period (Tp) is the period value at which the maximum spectral acceleration occurs at a 5% damped acceleration response spectrum. Peak velocity and acceleration ratio (V_{max}/A_{max}) is the ratio of peak velocity over peak acceleration and gives a value in time unit. It is assumed to be an indicator for the frequency content of the record.

Root Mean Square (RMS) of the acceleration, velocity and displacement is calculated as follows

$$f_{rms} = \sqrt{\frac{1}{t_r}\int_0^t [f(t)]^2 dt} \tag{1}$$

t refers time and t_r is the duration of the record. Arias Intensity (Ia), Characteristic Intensity (Ic), and Cumulative Absolute Velocity (CAV) and Specific Energy Density (SED) parameters are determined as follows

$$I_a = \frac{\pi}{2g}\int_0^\infty [a(t)]^2 dt\,,\quad I_c = (a_{rms})^{3/2}\sqrt{t_r}\,,\quad CAV = \int_0^t |a(t)| dt\,,\quad SED = \int_0^t [v(t)]^2 dt \qquad (2, 3, 4, 5)$$

Acceleration (ASI) and Velocity (VSI) Spectrum Intensity are provided in Eqs. (6), (7). ξ is the damping ratio in the equation (Von Thun *et al*. 1988)

$$ASI = \int_{0.1}^{0.5} S_a(t)dt \;\; (\xi = 0.05)\,,\quad VSI = \int_{0.1}^{2.5} S_v(t)dt \;\; (\xi = 0.05) \qquad (6, 7)$$

Mean Period (Tm) is defined according to Eq. (8) (Rathje *et al*. 1998). In Eq. (8), C_i is the fourier amplitudes, fi is the discrete fourier transform frequencies between 0.25 and 20 Hz

$$T_m = \frac{\sum C_i^2 / f_i}{\sum C_i^2} \tag{8}$$

3. Ground motion records

Ground motion records from 28 different seismic events are used for the study. All earthquake records are taken from PEER website (PEER Database 2011). Information about ground motion records of earthquakes used in the study and range of PGA and PGV values (as most familiar for civil engineers) are listed in Table 1. The values in the table are given as grouped for the seismic events, since individual information for all records covers tens of pages. The PGA and PGV values of the used records may be seen in Fig. 1.

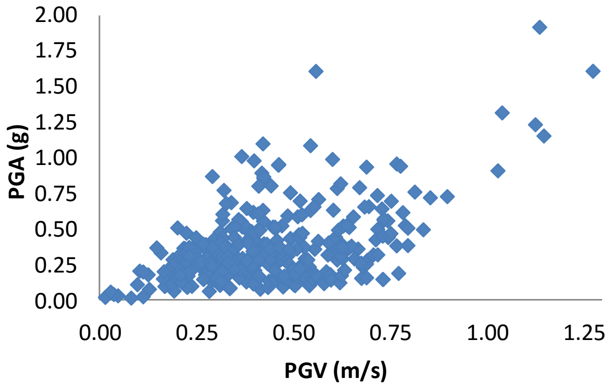


Fig. 1 PGA and PGV values of the used ground motion records

Table 1 Earthquakes and PGA and PGV ranges of the records used in the study

Event	# of Records	PGA Range (g)		PGV Range (m/s)	
		Min.	Max.	Min.	Max.
Cape Mendocino 1992/04/25	10	0.114	1.612	0.220	1.274
Chi-Chi, Taiwan 1999/09/20	108	0.069	1.158	0.130	1.150
Coalinga 1983/05/02	11	0.038	0.984	0.045	0.440
Coyote Lake 1979/08/06	5	0.266	0.435	0.190	0.492
Duzce, Turkey 1999/11/12	9	0.022	1.014	0.080	0.840
Erzincan, Turkey 1992/03/13	1	0.517	0.517	0.643	0.643
Friuli, Italy 1976/05/06	2	0.300	0.338	0.220	0.308
Gazli, USSR 1976/05/17	2	0.591	0.741	0.654	0.716
Imperial Valley 1940/05/19	48	0.113	0.758	0.190	0.766
Irpinia, Italy 1980/11/23	17	0.104	0.377	0.236	0.527
Kobe 1995/01/16	13	0.232	0.765	0.190	0.850
Kocaeli, Turkey 1999/08/17	23	0.097	0.390	0.160	0.795
Landers 1992/06/28	10	0.148	0.777	0.180	0.515
Livermore 1980/01/24 19:00	1	0.212	0.212	0.205	0.205
Loma Prieta 1989/10/18	52	0.133	0.661	0.209	0.624
Mammoth Lakes 1980/05/27	5	0.027	0.874	0.012	0.339
Morgan Hill 1984/04/24	6	0.047	0.702	0.034	0.516
N. Palm Springs 1986/07/08	8	0.210	0.691	0.295	0.733
Nahanni, Canada 1985/12/23	5	0.953	0.985	0.460	0.641
Northridge 1994/01/17	70	0.116	1.920	0.095	1.140
Parkfield 1966/06/28	8	0.369	0.474	0.215	0.751
San Fernando 1971/02/09	10	0.064	1.237	0.026	1.130
Spitak, Armenia 1988/12/07	1	0.187	0.187	0.286	0.286
Superstition Hills(B) 1987/11/24	18	0.139	0.871	0.206	0.464
Tabas, Iran 1978/09/16	2	0.328	0.401	0.206	0.265
Victoria, Mexico 1980/06/09	2	0.514	0.609	0.199	0.316

Table 1 Continued

Event	# of Records	PGA Range (g)		PGA Range (m/s)	
		Min.	Min.	Min.	Max.
Westmorland 1981/04/26	9	0.152	0.363	0.120	0.487
Whittier Narrows 1987/10/01	10	0.205	0.407	0.110	0.381
Total	466	0.022	1.920	0.012	1.274

4. Building models

Important portion of the existing building stock that is under seismic risk in many countries consists of low and mid-rise reinforced concrete buildings (Ozmen *et al*. 2015). Therefore, low and mid-rise reinforced concrete buildings are focused in the study.

Proper modelling of the buildings as they are built by the practitioners is important for consistence of results. For this reason, an inventory study including 475 real residential RC buildings, 40351 column and 3123 beam elements is conducted prior to the establishment of building models (Ozmen *et al*. 2015). Values of more than 30 key parameters like plan dimensions, story height, total column area per unit area, total load carrying infill-wall area per unit area, overhang area per floor area ratio, floor story height over regular story height for building level and section dimensions and reinforcement detailing for member level are examined. Results of this inventory are taken into account for determination of building model features.

Three sets of RC buildings with 2, 4 and 7 stories are selected to represent low and mid-rise residential buildings. 176 buildings with different features for each number of story group is modelled. 1056 SDOF system properties are determined for total 528 3-D building models. All of the considered buildings are typical beam-column RC frame buildings with no shear walls. More information about the building models can be found in Ozmen *et al*. (2015).

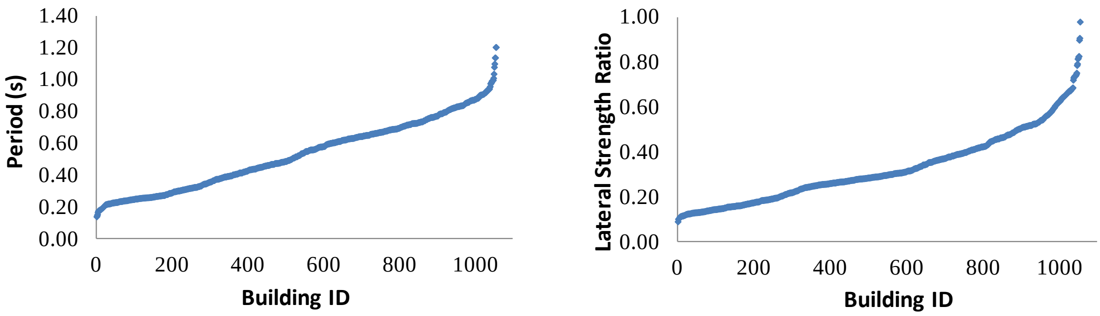
4.1 Modelling approach

Nonlinear static analyses have been performed using SAP2000 Nonlinear that is a general-purpose structural analysis program (SAP2000). Three-dimensional model of each structure is created in SAP2000 to carry out nonlinear static analysis. Beam and column elements are modelled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of beams and columns. The definition of hinge properties requires moment-curvature analysis of each element. Moment-curvature analyses of the RC members are carried out according to Turkish Earthquake Code-2007 (TEC-2007, 2007) by using software called SEMAp (Inel *et al*. 2008) that is developed by a team which the authors are a part of. Cracked section stiffness is used for members. The effective stiffness values as per TEC-2007 (TEC-2007, 2007), 0.4EI for $N/(A_c \times f_c) \leq 0.1$ and 0.8EI for $N/(A_c \times f_c) \geq 0.4$. f_c is concrete compressive strength, N is axial load, A_c is area of section. For the $N/(A_c \times f_c)$ values between 0.1 and 0.4 linear interpolation is made.

Effect of infill walls are modelled through diagonal struts as suggested in TEC-2007 and FEMA-356. Nonlinear behaviour of infill walls is reflected by assigned axial load hinges on diagonal struts whose characteristics are determined as given in FEMA-356. Material properties are taken from TEC-2007 to reflect characteristics of infill walls in Turkey; 1000 MPa, 1 MPa and 0.15 MPa were assumed as modulus of elasticity, compressive strength and shear strength values,

Table 2 Range of some important properties of the building models

Parameter	Minimum	Maximum	Mean
Seismic Weight (kN)	2504	22498	10004
Period (s)	0.139	1.204	0.529
Lateral Strength Ratio	0.09	0.98	0.34



(a) Building period distribution (b) Building lateral strength ratio distribution

Fig. 2 Distribution of period and lateral strength ratio of building models

respectively. Range of some important properties of the building models is listed in Table 2. “Seismic weight” values in the table correspond to the dead loads plus 30% of the live loads. “Lateral strength ratio” is the ratio of yield strength to the seismic weight. High lateral strength ratios up to seismic weight are for the two story buildings and attributable to higher overstrength ratio because of minimum requirements of code and significant infill-wall contributions.

Distribution of some key parameters, like period and lateral strength ratio, which greatly affect building displacement demands are important in a model set. Distributions of these parameters are given in Fig. 2. Please note that this is a “dot” graph rather than a “line” graph. Due to the high density of the models in the considered ranges, the graphs look like a line graph for most points. As seen in figures parameters seem to be evenly distributed in the considered range.

4.2 Nonlinear static and response history analyses

Capacity curves of 528 buildings are obtained by nonlinear static analyses using SAP2000 in two principal directions. The lateral forces applied at mass centre were proportional to the product of mass and the first mode shape amplitude at each story level under consideration. P-Delta effects were taken into account. The capacity curves of each building obtained from pushover analysis was approximated with bilinear curves using TEC-2007 (TEC-2007, 2007) and reduced to equivalent SDOF systems according to guidelines given in ATC-40 and FEMA-440 (ATC-40 1996, FEMA-440 2005). Then these SDOF systems are subjected to nonlinear response history analysis by using ground motion records with the software BiSpec (BiSpec 2011).

5. Correlation analyses

1056 single degree of freedom (SDOF) models are subjected to response history analyses with the mentioned 466 ground motion records. In order to measure the destructiveness of earthquake ground motions, nonlinear displacement demands are taken as an indicator. Displacement demand and interstory drift demand have strong correlation with damage in buildings and have been used by many researchers as damage related parameters (Algan 1982, Moehle 1992, 1994, Miranda 1999, Gulkan and Sozen 1999). Inel *et al*. using the same building set, suggested that global and interstory drift demands are highly correlated with each other (Inel *et al*. 2014). Therefore, mean values of displacement demands of corresponding building models are compared with the aforementioned parameters of the ground motion. Displacement demands are not directly used but they are normalized with building heights and used as global displacement drift demands. This way, it is aimed to reduce the effect of building height in evaluation of buildings with different heights.

In scope of this study, the aim in examining the correlation of the given parameters with drift demands is to understand which parameters have the best information concerning damage potential of the earthquake record. Therefore the correlations are determined by fitting curves to the relation between drift demand and given parameters. The correlation factor of the fitted curve is taken as correlation coefficient of the regarding parameter.

In order to have a more detailed investigation, correlations for different number of story and site classes are examined separately. In this study USGS site classification based on the average shear wave velocity to a depth of 30 m is used (USGS 2015). Site class A is the stiffest type with a shear wave velocity higher than 750 m/s, and D is the weakest site with a shear wave velocity lower than 180 m/s. The site B has a shear wave velocity between 750 m/s and 360 m/s whereas site C has a shear wave velocity between 360 m/s and 180 m/s.

Since this study has the perspective of investigation for stock of buildings, the buildings are grouped for number of story rather than period. Number of story is an obvious and readily available feature of the buildings in the stock. However, building period may significantly change depending on other properties of buildings.

Correlation of the parameters with the displacement demands of models with different number of stories, site classes and all combined are given in Tables 3 and 4. The best three parameters in each column are given in bold and the ones greater than 0.79 are shaded gray in tables to better express the trend. Relation of some of the parameters with strongest correlation or well-known ones such as PGA, PGV, PGD, VSI, SMV and AI with drift demands for all of the buildings and site classes combined are given in Fig. 3.

In grouping of the parameters, given under the column “Type”, it is not intended to do a scientific classification but to help understanding how the parameters are calculated and physical meaning of them. For example, the parameters in the Type frequency are related to the frequency content of the record and distribution of the Fourier amplitudes.

In Table 3 it can be observed that the correlation values may significantly change with respect to site class or number of story. In the same site class, number of story may affect the correlation factor as much as 0.25. Additionally, site class may affect the correlation more than 0.2 for the same number of story group. For example as one of the most common ground motion parameters PGA and PGV of 2 story buildings has a difference of approximately 0.16 and 0.22 for different site classes, respectively. However, there is no clear trend observed for site class and correlation relation.

When Table 3 is examined it is seen that bold and shaded values are all in acceleration and velocity group. This shows that the parameters in acceleration and velocity group have better correlation when compared to the ones in displacement and frequency group. Acceleration group parameters generally have fine results for 2 and 4 story buildings for site class A and C and for all stories for site class D. However, their correlations for site class B and 7 story buildings are poorer.

The correlation values for displacement and frequency group are too low to have any observations and comments.

Velocity related parameters seem to be better related with damage with more bold and shaded values. Especially VSI and PGV have the best results for all site classes and number of story groups with nearly all shaded and many bold values throughout the table. VSI has one step forward with one more shaded and bold value and generally higher results for all columns when compared to PGV.

Being one of the common parameters, PGA's performance is adversely affected by the values for site class B and 7 story buildings.

Table 4 shows the correlation results from a higher level combined for site class and story groups. Like Table 3 values, VSI is the best parameter with fully bold and gray values indicating a superior performance. PGV follows with one less bold value. These two have also the best correlation values of 0.937 and 0.901 (respectively) for all cases regardless of site class and number of story shown in last column of Table 4. The third best value, which is also in the velocity related group, is SMV. However, the correlation factor for SMV is 0.811 and has a great difference when compared to the first two.

AI, EDA and CI have the best values for acceleration related parameters, respectively. They all have correlation factors around 0.8 for all cases combined. Well known parameter PGA follows them with 0.74 correlation factor.

One of the other well known parameter of PGD has a very low correlation factor and seems not to be useful as an indicator of damage for the structures in scope of the study. None of the parameters in displacement and frequency group in Table 4 has promising results, as well.

Fig. 3 illustrates the relation between nonlinear drift demands and selected parameters used in the study. The figure shows that the deviations increase with increasing intensity of the related parameter. As the intensity of the parameters is directly proportional with the intensity of ground motions, correlation of the given parameters may be expected to decrease with increasing intensity of seismic event.

Fig. 3 illustrates that the best parameters are VSI and PGV and the scatter for VSI appears to be smaller compared to PGV. When the standard deviation values from the given curves in the figures are determined, it is seen that VSI has 23% lesser deviation than PGV.

6. Estimation of ground motion parameters prior to a seismic event

In earthquake engineering, evaluation of the damage may be done for two different cases: prior to and after a seismic event. If it is the latter case, the ground motion recording will be at hand and the parameter selection may only involve the one with greater correlation. However, if it is the former case, the predictability of the ground motion parameter prior to a seismic event is also important. For the sake of the completeness of the subject, prediction of ground motion parameters that are observed to be highly correlated is examined.

Even if VSI has greater correlation and lesser deviation than PGV, PGV comes to the forefront because of its simpler nature and available literature with attenuation relations for damage estimation studies.

There are numerous studies about attenuation relations based on PGV values in literature, some of which are Theodulidis and Papazachos (1992), Sabetta and Pugliese (1996), Tromans and Bommer (2002), Pankow and Pechmann (2004), Akkar and Bommer (2007), Gandomi *et al*. (2011), Mohammadnejad (2012), Bindi *et al*. (2014), Boore *et al*. (2014).

PGV and PGA are among the ground motion parameters that are used for development of attenuation relations for Next Generation Attenuation of Ground Motions (NGA) project (Akkar and Bommer 2007, Kaklamanos and Baise 2011, Boore *et al*. 2014).

For the comparison of predictability of PGV with a commonly used parameter PGA, two studies may be examined. Gandomi *et al*. (2011) and Mohammadnejad *et al*. (2012) developed attenuations relations for PGA, PGV and PGD. The correlation values of both studies give higher results for PGV than PGA.

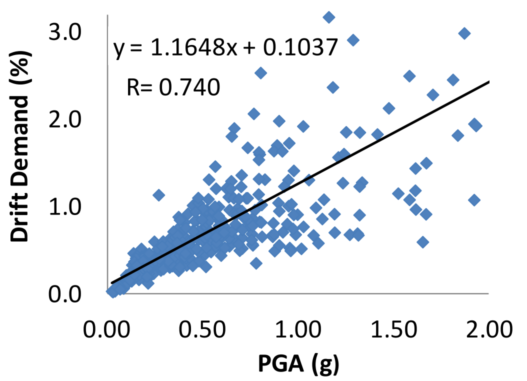
Table 3 Correlation of the parameters with the displacement demands of models with different number of stories and site class

			Site Class A			Site Class B			Site Class C			Site Class D		
		Story	2 st.	4 st.	7 st.	2 st.	4 st.	7 st.	2 st.	4 st.	7 st.	2 st.	4 st.	7 st.
Type	Parameter	Unit	R	R	R	R	R	R	R	R	R	R	R	R
Acceleration	Characteristic		**0.867**	**0.901**	0.702	**0.815**	0.723	0.680	0.792	0.815	0.782	0.768	0.723	0.717
	Eff. Design Acc. (EDA)	g	**0.868**	0.841	0.606	0.786	0.683	0.656	**0.846**	0.833	0.784	0.871	0.826	0.816
	Arias Intensity	m/s	0.860	0.897	0.699	**0.863**	0.788	0.728	0.795	0.819	0.789	0.775	0.730	0.726
	Peak Ground Acc. (PGA)	g	0.859	0.850	0.618	0.706	0.604	0.585	0.802	0.784	0.741	**0.872**	**0.828**	**0.819**
	A95 Parameter	g	0.859	0.850	0.618	0.704	0.603	0.584	0.800	0.783	0.740	0.871	0.827	0.818
	Acc. RMS	g	**0.868**	0.898	0.697	0.633	0.567	0.562	0.762	0.779	0.739	0.748	0.702	0.692
	Sustained Max. Acc. (SMA)	g	0.708	0.775	0.601	0.672	0.598	0.571	0.740	0.740	0.699	0.869	0.798	0.778
	Acc. Spec. Int. (ASI)	g.s	0.838	0.796	0.573	0.691	0.582	0.554	0.757	0.734	0.672	0.765	0.708	0.700
Velocity	Velocity Spec. Int. (VSI)	m	0.811	**0.956**	0.794	**0.903**	**0.969**	**0.951**	**0.875**	**0.960**	**0.923**	**0.948**	**0.935**	**0.923**
	Peak Ground Velo. (PGV)	m/s	0.754	**0.930**	0.798	0.804	**0.795**	**0.801**	**0.864**	**0.923**	**0.891**	**0.974**	**0.959**	**0.951**
	Sustained Max. Vel. (SMV)	m/s	0.598	0.825	**0.838**	0.782	**0.800**	**0.740**	0.751	**0.856**	**0.841**	0.827	0.788	0.781
	Cum. Abs. Vel. (CAV)	m/s	0.748	0.859	0.756	0.751	0.699	0.665	0.631	0.666	0.675	0.613	0.587	0.606
	Velocity RMS	m/s	0.443	0.707	**0.811**	0.755	0.737	0.689	0.708	0.800	0.803	0.810	0.770	0.771
	Specific Energy Density	m^2/s	0.474	0.734	**0.836**	0.706	0.679	0.632	0.545	0.647	0.690	0.780	0.732	0.744
Disp.	Displacement RMS	m	-0.09	0.347	0.465	-0.18	-0.21	-0.26	0.156	0.247	0.325	0.393	0.391	0.414
	Peak Ground Disp. (PGD)	m	-0.319	0.543	0.683	-0.146	-0.229	-0.312	0.321	0.426	0.435	0.715	0.678	0.694
Freq.	V_{max}/A_{max}	s	0.567	0.421	0.202	0.349	0.252	0.184	0.328	0.289	0.244	-0.19	-0.21	-0.20
	Mean Period	s	0.416	0.202	-0.17	0.198	-0.13	-0.13	-0.18	-0.16	-0.13	-0.19	-0.20	-0.19
	Predominant Period	s	0.542	0.409	0.210	0.067	0.197	-0.25	-0.08	-0.08	-0.20	-0.20	-0.21	-0.24

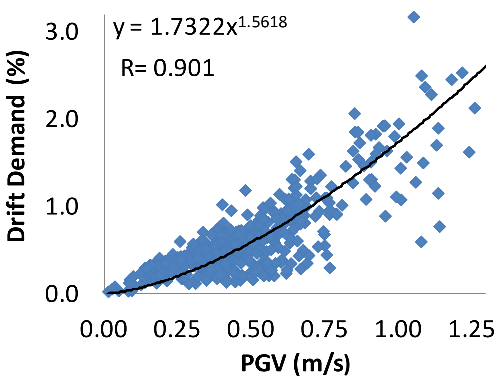
This study shows that PGD has a very low correlation factor for the low and mid-rise RC buildings in scope. One of disadvantages of the PGD is also observed by Boore *et al*. (2008) as being too sensitive to filtering to be a stable measure of ground shaking.

Table 4 Correlation of the parameters with the displacement demands of models combined for different number of stories and site classes and all

Type	Parameter	Unit	A	B	C	D	2 st.	4 st.	7 st.	All
			All Number of Stories				All Site Classes			
Acceleration	Characteristic Intensity		**0.892**	0.768	0.822	0.743	0.798	0.769	0.716	0.790
	Eff. Design Acc. (EDA)	g	0.837	0.737	**0.849**	0.844	**0.825**	0.766	0.699	0.794
	Arias Intensity	m/s	0.887	**0.826**	0.827	0.750	0.807	0.782	0.729	0.802
	Peak Ground Acc. (PGA)	g	0.842	0.656	0.802	**0.847**	0.771	0.712	0.653	0.740
	A95 Parameter	g	0.843	0.655	0.801	0.845	0.769	0.710	0.652	0.739
	Acc. RMS	g	**0.890**	0.606	0.786	0.721	0.742	0.707	0.659	0.730
	Sustained Max. Acc. (SMA)	g	0.750	0.636	0.751	0.824	0.721	0.693	0.641	0.712
	Acc. Spec. Int. (ASI)	g.s	0.798	0.633	0.749	0.730	0.752	0.681	0.616	0.712
Velocity	Velocity Spec. Int. (VSI)	m	**0.919**	**0.969**	**0.945**	**0.943**	**0.877**	**0.947**	**0.896**	**0.937**
	Peak Ground Velo. (PGV)	m/s	0.888	**0.816**	**0.917**	**0.969**	**0.844**	**0.902**	**0.873**	**0.901**
	Sustained Max. Vel. (SMV)	m/s	0.792	0.798	0.838	0.806	0.735	**0.820**	**0.805**	**0.811**
	Cum. Abs. Vel. (CAV)	m/s	0.849	0.727	0.677	0.605	0.639	0.649	0.635	0.663
	Velocity RMS	m/s	0.674	0.745	0.789	0.789	0.662	0.752	0.775	0.747
	Specific Energy Density	m^2/s	0.701	0.673	0.641	0.754	0.561	0.658	0.677	0.649
Disp.	Displacement RMS	m	-0.317	-0.218	0.240	0.400	0.131	0.254	0.331	0.246
	Peak Ground Disp. (PGD)	m	0.504	-0.221	0.416	0.698	0.245	0.363	0.441	0.353
Freq.	V_{max}/A_{max}	s	0.438	0.280	0.295	-0.206	0.330	0.258	0.197	0.274
	Mean Period	s	0.216	-0.147	-0.165	-0.198	0.202	-0.156	-0.118	-0.162
	Predominant Period	s	0.426	-0.215	-0.083	-0.213	-0.071	-0.143	-0.146	-0.109

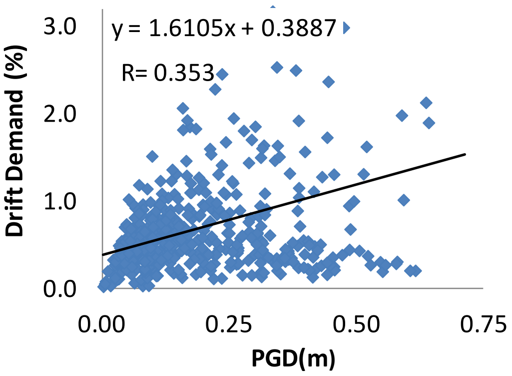


(a) PGA

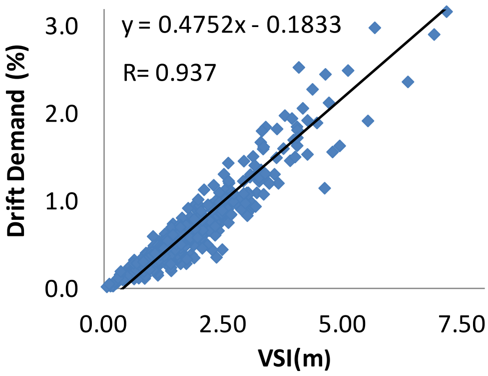


(b) PGV

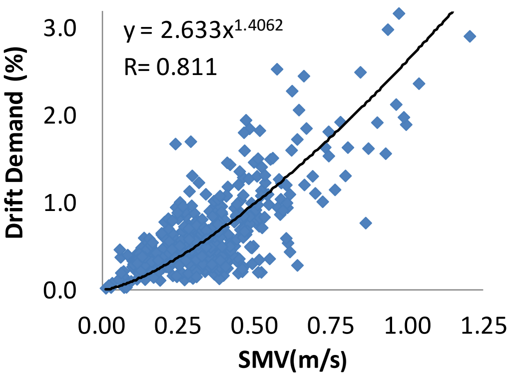
Fig. 3 Relation of some parameters with drift demands for all of the buildings and site classes combined



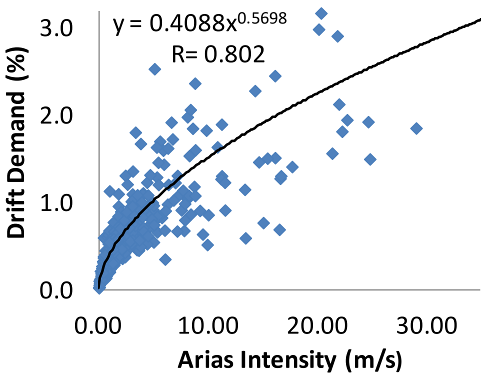
(c) PGD



(d) VSI



(e) SMV



(f) Arias Intensity

Fig. 3 Continued

5. Conclusions

Seismic loadings are among the critical load cases accounted in design of new buildings or evaluation of existing ones. Therefore understanding the nature of this loading type is critical. There are many parameters reflecting the features of a ground motion. This study investigates ground motion parameters and their damage potential for building type structures and focuses on low and mid-rise reinforced concrete buildings that are important portion of the existing building stock under seismic risk in many countries. Properties of SDOF systems are established to represent RC building stock. Correlation of 19 parameters of 466 earthquake records with nonlinear displacement demands of 1056 SDOF systems are investigated. As the literature suggests that displacement demand has strong correlation with damage in buildings, it is assumed to reflect the damage potential of ground motions. Earthquake records are selected from 28 different seismic events. The correlation of nonlinear displacement demands and ground motion characteristics is examined with respect to number of story and site classes. Conclusions are based on approximately half a million analyses. The comparison of the foundings and existing literature are made. For the low and mid-rise reinforced concrete buildings accounted in the study, it is concluded that:

• The correlation values may significantly change with respect to site class or number of story. In the same site class, number of story may affect the correlation factor as much as 0.25. Additionally, site class may affect the correlation more than 0.2 for the same number of story group. However, there is no clear trend observed for site class and correlation relation.

• The parameters in acceleration and velocity group have better correlation when compared to the ones in displacement and frequency group. Also, velocity related parameters seem to be better related with damage.

• Being one of the common parameters, PGA's performance is adversely affected by the values for site class B and high story buildings.

• One of the other well known parameter of PGD has a very low correlation factor and seems not to be useful as an indicator of damage for the structures in scope of the study.

• Acceleration related parameters have better performance for low story buildings which is in the high frequency range due to low periods. Their performance becomes worse for buildings with higher number of story, such as seven. That is also a parallel finding with Riddel (2007).

• PGA has lower correlation with damage when compared to the VSI, PGV and some other parameters like EDA and CI. Lower correlation of PGA has been mentioned before by Elenas *et al*. (1995), Elenas (1997, 2000), and Elenas and Meskouris (2001) and Cao and Ronagh (2014), as well.

• VSI has the best correlation and the least deviation with displacement demands for the considered RC building stock, which makes it the best parameter to express the damage potential of earthquake records. Similar conclusions have also been reached by Yakut and Yılmaz (2008) and Cao and Ronagh (2014a, 2014b) for their cases.

• PGV is also good indicator of the intensity of ground motions and destructiveness of earthquakes. This conclusion is also in agreement with the studies by Sucuoğlu (1997), Wald *et al*. (1999), Wu *et al*. (2003), Worden *et al*. (2012), Bilgin (2015) and Akkar and Ozen (2005).

• Correlation of the ground motion parameters may be expected to decrease with increasing intensity of seismic event.

In the light of these findings VSI and PGV is the best parameters for correlation with damage in low and mid rise RC building stock. Despite somewhat better performance of VSI, PGV may still be preferred due to its simpler nature and available literature for estimation prior to a seismic event. The latter one may be important for fragility studies for probable future events.

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