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An Intensity Measure for Seismic Input Energy Demand of Multi-Degree-of-Freedom Systems

Ganjavi, B.[1*] and Rezagholilou, A.R.[2]

[1] Assistant Professor, Department of Civil Engineering, University of Mazandaran, Babolsar, Iran.
[2] Assistant Professor, Faculty of Science and Engineering, Curtin University, Perth, Australia.

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ABSTRACT: Nonlinear dynamic analyses are performed to compute the maximum relative input energy per unit mass for 21 multi-degree-of-freedom systems (MDOF) with preselected target fundamental periods of vibration ranging from 0.2 to 4.0 s and 6 target inter-story ductility demands of 1, 2, 3, 4, 6, 8 subjected to 40 the earthquake ground motions. The efficiency of the several intensity measures as an index for damage potential of ground motion in MDOF systems are examined parametrically. To this end, the dispersion of normalized input energy by different intensity measures have been evaluated and compared. Results of this study show that using all intensity measures will result in a significant discrepancy in input energy spectra of MDOF systems, which are in most cases larger than 0.5 and even can take the value of 1.9 for some cases. This signifies that the evaluated intensity measures may not suitable for MDOF systems. A dimensionless intensity measure as a normalized energy index is proposed for MDOF systems subjected to far-fault earthquakes. It was demonstrated that the proposed normalized input energy values have smaller dispersion compared to those of the other indices for MDOF systems with all ranges of period and ductility ratio used.

Keywords: Intensity Measures, MDOF Systems, Nonlinear Dynamic Analysis, Parametric Study, Seismic Input Energy.

INTRODUCTION

The severity of earthquakes can be stated in terms of a magnitude and an intensity which are both related to the amount of energy released by the earthquake-induced ground motion. This energy, if not appropriately dissipated, could lead to severe damage to or even collapse of structures. However, when structures are properly designed against earthquakes, the property damages and related facilities could be substantially reduced. Currently, seismic design procedures stipulated in earthquake design codes such as ASCE-7-16 (2016) and IBC-2015 (2015) are widely used by practicing engineers to design structures that can resist earthquake forces with an acceptable damage, which is referred to as damage levels in Performance-based design codes such as FEMA 356 (2000).

Forced-based and displacement-based

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* Corresponding author E-mail: b.ganjavi@umz.ac.ir

design approaches are two of the widely used conventional performance-based design procedures in the world. The fundamental concept of these procedures are based on nonlinear static (pushover) approaches. For the case of force-based seismic design (FBSD) method, a design lateral force for a given structure is computed based on an elastic design acceleration response spectrum, which is called the design base shear. To consider the inelastic behavior, the design shear force of a given structural system obtained from the elastic acceleration response spectrum is reduced by a strength-reduction factor or so-called response modification parameter. The building is then redesigned for the decreased shear strength, and the displacement or inter-story drift can be controlled so that the code-compliant limits are coped with. However, many limitations and drawbacks have been reported by researchers on the FBSD procedure. In one of the detailed investigations, Smith and Tso (2002) through studying on a large family of (Reinforced concrete) RC elements such as flexural walls, piers and ductile concrete moment fames asserted that force-based seismic design procedure is inconsistent. They concluded that the assumption of the independency of the shear strength and shear stiffness of a lateral load resisting system is essentially inconsistent since they are indeed related and proportional.

Instead of using design base shear as in the case for FBSD, the displacement-based seismic design (DBSD) method, in general considered to be a better substitute for the FBSD approach, takes inter-story drift or displacement in the design process. Consequently, the key task in a DBSD method is to approximately compute the peak displacement demand value in a given structure with rational accuracy and simplicity as a function of its local mechanical properties including element deformation and strain limits. One of the currently available DBSD methods is the Displacement-Based Coefficient Method (DBCM) provided by FEMA 440 (2005). In this method the linear elastic response of an equivalent SDOF (E-SDF) system is modified by multiplying it by a series of coefficients to compute a target (global) displacement. This approach utilizes an idealized pushover curve corresponding to a given damping ratio of base shear strength with respect to roof displacement developed for a real MDOF structure. The adequacy of the DBSD procedure is greatly subjected to how closely the E-SDOF model and its MDOF counterpart have relationship using the idealized pushover curve. Recently, researchers have diagnosed some drawbacks in the use of roof displacement-based pushover curve. As an instance, Hernandez-Montes et al. (2004) pointed out that the use of roof displacement in producing the capacity curve would be confusing since the capacity curve occasionally tends to exhibit the structure as a source of energy rather than absorbing energy. It was proposed that instead an energy-based pushover analysis be used whereby the lateral force is provided versus a displacement that is a function of energy. Following the research carried out by Hernandez-Montes et al. (2004), Manoukas et al. (2011) developed an energy-based pushover method for estimating structural performance subject to strong ground motion excitations. Through numerical examples, they demonstrated that the proposed approach can provide better results compared to those produced by other similar approaches. Meanwhile, neither the FBSD procedure, using base shear strength as a design parameter, nor the DBD method, using displacement as a design parameter, can directly account for the cumulative damage influence that result from several inelastic cycles of the earthquake ground motion due to strength and stiffness deterioration of the structural hysteretic behavior. As a result, the effect of earthquake excitation on structural systems should be interpreted not only just as a force or displacement quantity, but also as a product of both aforementioned parameters which can be described in terms of input energy. This is the latent notion for the inception of the EBS) approach, which is suggested by many researchers to be considered as the next generation of seismic design procedures. Research is being continuously performed in order to develop a more reliable seismic design procedure taking into account the energy imparted by an earthquake onto a structure. It is in this area that the present study attempts to make a contribution. In this study, several intensity measures already proposed by researchers for damage potential of earthquake ground motions based on energy concepts for SDOF systems are investigated for MDOF systems subject to 40 earthquake records. Finally, an optimum intensity measure as a normalized energy index is proposed for MDOF systems subjected to far-fault earthquakes.

LITERATURE REVIEW FOR INPUT ENERGY DEMAND

Earthquake input energy is defined as the imparted amount of earthquake energy to a structure. The EBSD method started from the work carried out by Housner (1956) who computed the input energy per unit mass of a SDOF system as proportional to the square of the pseudo spectral velocity. After that during the past six decades, many studies have been conducted on different aspects of energy method. In this regard, a number of researchers have recommended empirical formula to estimate earthquake input energy.

Zahrah and Hall (1985) conducted nonlinear dynamic analyses of buildings subject to eight earthquake ground motions, and concluded that the effects of damping model, ductility ratio, and post-yield stiffness on the imparted and hysteretic energy are insignificant. Utilizing Japanese design earthquakes, Akiyama (1984) recommended the input energy normalized by total structural mass of an elastic SDOF systems under a given earthquake ground motion as a function of the square of the structural period or the ground motion predominant period, whichever is smaller. Following to this study, Kuwamura and Galambos (1989) developed the expressions proposed by Akiyama and incorporated the effects of the earthquake severity and duration.

Fajfar et al. (1989) examined the structures falling within the constant velocity region of the response spectra subjected to 40 ground motions and proposed an input energy expression as a function of the strong motion duration and the PGV of the ground motions. Using 5 ground motion records and the absolute input energy, Uang and Bertero (1990) concluded that the input energy expression proposed by Housner (1956) reflects the peak elastic energy accumulated in the structures but does not account for the damping energy. Following the study carried out by Fajfar et al. (1989), Uang and Bertero (1990), suggested an equation for the absolute input energy normalized by total structural mass as a function of the strong ground motion duration and the PGV of the ground motion.

In another study, Manfredi (2001) using 244 ground motions suggested an input energy equation that was appropriate for SDOF systems having period within the velocity sensitive region of the spectra. His proposed expression consists of parameters such as pseudo spectral velocity, ground motion intensity, PGV, PGA, and cyclic ductility. Khashaee (2004) proposed an expression to estimate seismic input energy as functions of Park and Ang’s earthquake intensity index (1985), the natural period and ductility of the SDOF system. Many other studies conducted on SDOF input energy spectra are those carried out by Benavent-

Climent et al. (2010), Lopez-Almansa et al. (2013), Cheng et al. (2014, 2015) and Mezgebo and Lui (2016).

Since different assumptions and methodologies have been used to quantify the amount of earthquake input energy, large changes and deviations could be found. In addition, because most researchers used SDOF models with bilinear elasto-plastic hysteretic behavior in their investigation, the adequacy of the estimates could drop for building structures that represent different kinds of structural model such as MDOF systems. This is the case that in the present study is to be considered and discussed parametrically.

ENERGY BALANCE EQUATION FOR MDOF SYSTEMS

The basic differential equation of an MDOF system undergone to an earthquake ground motion acceleration can be presented as below:

$$M\ddot{v}(t)+C\dot{v}(t)+Kv(t)=-Ml\ddot{v}_g(t) \qquad (1)$$

in which M: is total structural mass matrix, C: is damping matrix, and K: is also lateral stiffness matrix of the system. $\ddot{v}(t)$, $\dot{v}(t)$ and $v(t)$: are respectively the relative acceleration and relative velocity and vector of N story displacements relative to the ground with t representing time. $\ddot{v}_g(t)$: is defined as time history of ground motion acceleration, and each element of vector L is equal to unity (Amiri et al., 2008, Shayanfar et al., 2016; Chopra, 2016).

The energy expression of an MDOF system can be calculated by integrating the Eq. (1):

$$\int_0^t M\ddot{v}(t)dv+\int_0^t C\dot{v}(t)dv+ \int_0^t Kv(t)dv=-\int_0^t M\ddot{v}_g(t)dv \qquad (2)$$

Eq. (2) can be written as:

$$\int_0^t M\ddot{v}_t(t)dv+\int_0^t C\dot{v}(t)dv+\int_0^t Kv(t)dv=0 \qquad (3)$$

where $\ddot{v}_t=\ddot{v}+\ddot{v}_g$. If the matrix M is assumed to be a diagonal matrix, then Eq. (3) can be expressed as:

$$E_K(t)+E_D(t)+E_A(t)=E_I(t) \qquad (4)$$

where

$$E_K(t)=\frac{1}{2}\sum_{i=1}^{n}m_{ii}\dot{v}_{ti}^{2}(t) \qquad (5)$$

$$E_D(t)=\int_0^t[\sum_{i=1}^{n}\sum_{j=1}^{n}c_{ij}\dot{v}_i(t)\dot{v}_j(t)]dt \qquad (6)$$

$$E_A(t)=\int_0^t[\sum_{i=1}^{n}\sum_{j=1}^{n}k_{ij}v_i(t)\dot{v}_j(t)]dt \qquad (7)$$

$$E_I(t)=\int_0^t[\sum_{i=1}^{n}m_{ii}\ddot{v}_{ti}(t)]dv_g \qquad (8)$$

where $E_K(t)$, $E_D(t)$ and $E_A(t)$: are respectively absolute kinetic energy (KE), damping energy, retrievable absorbed energy only resulting from elastic strain and dissimilar to hysteretic energy $E_h(t)$ that is unrecoverable and is directly dependent on the yielding of the structural elements. $E_I(t)$ is the total absolute input energy imparted to a MDOF system in which m, c, and k represent the components of matrices M, C, and K, respectively.

Considering the fact that $\dot{v}_g(t) = dv_g / dt$, hence, the Eq. (8) can be expressed as:

$$E_I(t) = \int_0^t \sum_{i=1}^{n} m_{ii} \ddot{v}_{ti}(t) \dot{v}_g(t) dt \qquad (9)$$

The above equations are used to compute the seismic input amount imparted to the MDOF structures under 40 earthquake ground motions.

SELECTION OF GROUND MOTION ENSEMBLE

In this investigation, a set of 40 earthquakes ground motions (i.e., two components of 20 ground motions) is compiled from five strong earthquakes and utilized for nonlinear dynamic analyses. All the selected earthquakes were obtained from strong ground motion database of the Pacific Earthquake Engineering Center (PEER, http://ngawest2.berkeley.edu/). These earthquake ground motions have been selected based on the following assumptions: a) They exclude the near-fault ground motion characteristic such as pulse type and forward directivity effects, b) they are not located on soft soil profiles; hence the effect of soil-structure interaction has not been considered in this study, c) They have no long duration characteristics. The selected earthquake ground motions have moment magnitude between 6.5 and 6.9, and closest distance to the fault rupture between 14 km and 40 km. These ground motions are recorded on soils that correspond to IBC-2015 site class D, which is approximately similar to the soil type III of the Iranian seismic code of practice, Standard No. 2800 (BHRC, 2013).

Additional criteria such as magnitude of earthquake, site distance to source, and ground motion characteristics have been used to further refine the data of earthquake records to be used in the study. A description of these additional criteria is presented in Table 1. These ground motions, which are scaled to 0.4 g, have characteristics consistent with those that dominate the design level seismic hazard (i.e., 10/50) in Iranian code of practice-2800 and the western U.S.

STRUCTURAL MODELING AND ANALYSIS ASSUMPTIONS

In a process of initial seismic design of structures based on current seismic codes, buildings are usually idealized to equivalent MDOF systems such as shear-type building structures. This model is one of the most frequently used models that have been widely used to evaluate the seismic response of multi-story building structures.

In spite of some deficiencies, shear-type building structure, is considered in this study due to its capability of incorporating both nonlinear behavior and higher mode effects without making a deal of the time consuming computational analyses. It is worth mentioning that only a single pushover analysis is necessary for determining the required parameters to model the shear-building model equivalent to a full MDOF frame model (Hajirasouliha and Pilakoutas, 2012). Many researchers utilized this model for conducting a parametric study under earthquake excitations (Hajirasouliha and Pilakoutas, 2012; Ganjavi and Hao, 2012, 2013; Ganjavi et al., 2016; Amiri et al., 2017).

A typical shear-type building prototype is shown in Figure 1 where each story is idealized as a lumped mass connected by springs that only experience shear deformations when subjected to lateral forces. In the simplified prototypes, the story shear strength and story shear stiffness are supposed to be proportional to the corresponding story shear strength that can be determined by utilizing force equilibrium with an applied equivalent lateral shear strength profile.

Table 1. Earthquake ground motions used in this study

Event	$M_{w.}$	Station Name	Soil Type	R (Km)	PGA (g)	PGV (cm/s)
Loma Prieta	6.9	Agnews State Hospital	D	28.2	0.172	26
Loma Prieta	6.9	Capitola	D	14.5	0.443	29.3
Loma Prieta	6.9	Gilroy Array #3	D	14.4	0.367	44.7
Loma Prieta	6.9	Gilroy Array #4	D	16.1	0.212	37.9
Loma Prieta	6.9	Gilroy Array #7	D	24.7	0.226	16.4
Loma Prieta	6.9	Hollister City Hall	D	28.2	0.247	38.5
Loma Prieta	6.9	Sunnyvale—Colton Ave.	D	28.8	0.207	37.3
San Fernando	6.6	LA—Hollywood Stor Lot	D	21.2	0.174	14.9
Superstition Hills	6.7	Brawley	D	14	0.156	13.9
Superstition Hills	6.7	El Centro Imp. Co. Cent	D	21	0.358	46.4
Superstition Hills	6.7	Plaster City	D	17.2	0.186	20.6
Northridge	6.7	LA—Centinela St.	D	30.9	0.322	22.9
Northridge	6.7	Canoga Park—Topanga Can.	D	15.8	0.42	60.8
Northridge	6.7	LA—N Faring Rd.	D	23.9	0.273	15.8
Northridge	6.7	LA—Fletcher Dr.	D	29.5	0.24	26.2
Northridge	6.7	LA—Hollywood Stor FF	D	25.5	0.231	18.3
Northridge	6.7	Lake Hughes #1	D	36.3	0.087	9.4
Northridge	6.7	Leona Valley #2	D	37.7	0.063	7.2
Imperial Valley	6.5	El Centro Array #1	D	15.5	0.139	38.1
Imperial Valley	6.5	El Centro Array #12	D	18.2	0.116	16
Imperial Valley	6.5	El Centro Array #13	D	21.9	0.139	21.8
Imperial Valley	6.5	Chihuahua	D	28.7	0.27	13

The lateral seismic shear strength distribution considered in this study is based on IBC-2015 (2015) pattern which is similar to that of the Iranian code of practice, Standard No. 2800 (BHRC, 2013). Other assumptions are described as follows. A family of 21 MDOF systems with fundamental periods of 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.3, 2.5, 2.7, 3.0, 3.3, 3.6 and 4.0 s are adopted based on IBC-2015 lateral force pattern. It should be noted that the 5-story building provided in figure 1 is only a typical model.

In this study to capture the effect of fundamental period of vibration, 21 MDOF models from 3 to 20 stories are considered Each building with a specific number of stories can take 2 or 3 different target fundamental periods. As indicated by the Ganjavi et al. (2016), the presented results will not be significantly affected by changing the number of stories. Hence, one can easily use a given building model with different fundamental periods of vibration for parametric studies.

Generally, the design of earthquake-resistant structures is based on soil site class dependent on the elastic response spectra generated using a damping ratio of 5%. It is also common to consider 5% of critical damping to incorporate the damping behavior of structures that account for inelastic behavior under dynamic loading. Thus, a damping value of 5% was used in this study for dynamic analyses. To this end, structural damping is modelled based on Rayleigh damping model with 5% of critical damping assigned to the first mode as well as to the mode where the cumulative mass participation is at least 95%.

Ductility demand is a substantial parameter in response of structures to earthquake loading. As a rule of thumb, the more ductile a structure is, the less it will experience catastrophic damage during a major seismic event. Constant ductility spectra are used more often for seismic design. In this paper target inter-story ductility ratios of 1, 2, 3, 4, 6 and 8 are taken into account for nonlinear dynamic analyses. The shear story strength of the structure is tuned such that the maximum inter-story ductility demand among all stories is equal to the target value with 0.5% error. This can be achieved through a iteration analysis already proposed by Ganjavi and Hao (2012) and Hajirasouliha and Pilakoutas (2012) for shear-building structures.

For a given earthquake ground motion and structure, the inter-story ductility demand is defined as the maximum inter-story drift normalized to the yield drift. The force-displacement diagram or so-called hysteretic behavior of a structure can significantly affects the seismic behavior and response of a structure and also the energy parameters spectra. Therefore, it is mandatory that the force-displacement relationship of a structural elements under seismic design loads is specified and taken into account for in the determination of the energy amount imparted to the structure. In this study bilinear elsto-plastic model with 3% strain hardening is selected to model a non-deteriorating steel structure under earthquake excitation (Figure 1).

EVALUATION OF DIFFERENT ENERGY INTENSITY MEASURES FOR MDOF SYSTEMS

Once the representative ground motion records were complied, a family of MDOF systems are adopted and linear and nonlinear time history analyses were then performed using computer program specifically developed for this study. The already described MDOF building structures with the stiffness degrading hysteretic model were subjected to the 40 far-fault strong round motion records selected for site class D based on IBC-2015. The results of these analyses are discussed for different ground motion intensity measures (GMIMs) for input energy spectra.

It is always desirable to develop intensity dependent spectra through normalizing the energy spectra using seismic damage indices that are generally utilized for estimating the intensity of seismic events. In this study, different damage indices of earthquake ground motion that were already proposed for SDOF systems by researchers are investigated here for MDOF systems in order to find the most appropriate intensity measure parameter. In this investigation, the following earthquake ground motion indices are used for input energy spectra of MDOF systems.

Arias Intensity (*I*a)

Arias Intensity, as defined by Arias (1970), is the total energy normalized total structural weight accumulated by a set of un-damped simple oscillators at the end of ground motion duration. The Arias Intensity for ground motion in any direction is calculated as follows:

$$I_a = \frac{\pi}{2g} \int_0^t [\ddot{u}_g(\mathrm{t})]^2 \mathrm{dt} \qquad (10)$$

where $\ddot{u}_g(t)$: is the corresponding acceleration time history and t is the total duration of the earthquake ground motion record. I_a: is an earthquake parameter incorporating the damaging potential of a ground motion acceleration as the integral of the square of the acceleration-time history. Previous study showed that it is well correlated with most of frequently used demand indices of structural performance, liquefaction, and seismic slope stability.

Cumulative Absolute Velocity (CAV)

(CAV), defined as the integral of the absolute amount of the ground motion acceleration time histories, is defined mathematically through the Eq. (11) (EPRI, 1988):

$$CAV = \int_0^t \left|\ddot{u}_g(t)\right| \mathrm{dt} \qquad (11)$$

While called the cumulative absolute

velocity, CAV is not directly dependent on the velocity time history of a given ground motion. $\dot{u}_g(t)$ has unit of velocity. Cumulative absolute velocity (CAV) introduced by Campbell and Bozorgnia (2012) is defined as an instrumental index to measure the possible earthquake damage imparted to structures. They also scrutinized this concept more by expanding a relationship between the standardized version of CAV and the Japan Meteorological Agency (JMA) and modified Mercalli seismic intensities for correlating the standardized CAV with the qualitative descriptions of damage in the intensity scales counterparts.

Seismic Damage Index (Id)

Using 244 earthquake ground motions, recorded in South America, Europe and Canada, Manfredi (2001) scrutinized the relationship among the equivalent number of yield cycles proposed by Zahrah and Hall (1984), the response modification factor, and a non-dimensional seismic index (intensity measure) I_d *as follows:*

$$I_d = \frac{I_e}{PGA\ .\ PGV}, \quad I_e = \int_0^t [\ddot{u}_g(t)]^2 \mathrm{dt} \tag{12}$$

where *PGA* and *PGV*: respectively represent the peak ground acceleration and velocity. Manfredi (2001) utilized the above intensity measure to estimate the earthquake input energy spectra of SDOF systems for cyclic ductility ratios equal or greater than 2 by using a correlation between an equivalent number of yield cycles and the proposed seismic intensity measure I_d. However, his proposed equation did not incorporate elastic structures as they do not experience yielding.

In this section, nonlinear dynamic analyses were performed to compute the maximum relative input energy per unit mass (E_I/M) for each MDOF building with preselected target fundamental period of vibration (T_1) and target inter-story ductility demand (μ) subject to a the earthquake ground motions listed in Table 1. Then, the mean spectra of input energy per unit mass are computed and plotted for different values of target ductility demands. To examine the efficiency of the above-mentioned intensity measures as an index for damage potential of ground motion in MDOF systems, all the defined indices in Eqs. (10-12) are utilized as normalization parameters and then the resulted spectra are compared to those of the original spectra of input energy per unit mass (i.e., E_I/M).

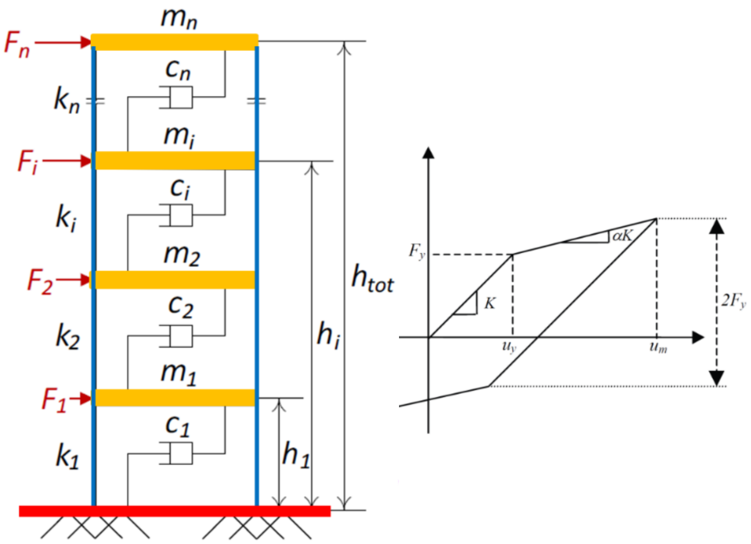


Fig. 1. Typical MDOF and system with bilinear elsto-plastic hinge model used in this study

To this end, the coefficients of variation for 21 MDOF models having various periods and 6 ductility ratios computed for the ensemble of 40 earthquake records provided in Table 1 are plotted in Figure 2. The coefficient of variation of maximum input energy, $COV\,(EI_{max})$, is defined as the ratio of the standard deviation of maximum input energy (EI_{max}) to the mean value of them $(EI_{max})_{ave}$ as follows:

$$COV\ (EI_{\max}) = \frac{\sqrt{\dfrac{\sum_{i=1}^{n}[(EI_{\max})_i - (EI_{\max})_{ave})]}{n-1}}}{(EI_{\max})_{ave}} \tag{13}$$

It shows the extent of variability in relation to the mean of the data. The least value of the COV represents the most efficient intensity measure for damage potential of ground motion in MDOF systems. In order to better capturing the effect of different GMIMs the mean results are separately plotted for acceleration sensitive region (i.e., period equal to or less than 0.6 sec) and velocity region (period between 0.6 and 4 sec) for different values of target ductility demand ratios. Effect of fundamental period and ductility ratio can be observed in this figure. As can be seen in the constant acceleration region (left side), except for the case of I_a, generally COV decreases as fundamental period increases. The spectra normalized by I_a are not sensitive to the variation of the period and approximately could be considered as constant. However, for the constant velocity region (right side), the COV of all the selected intensity measures nearly increases with period.

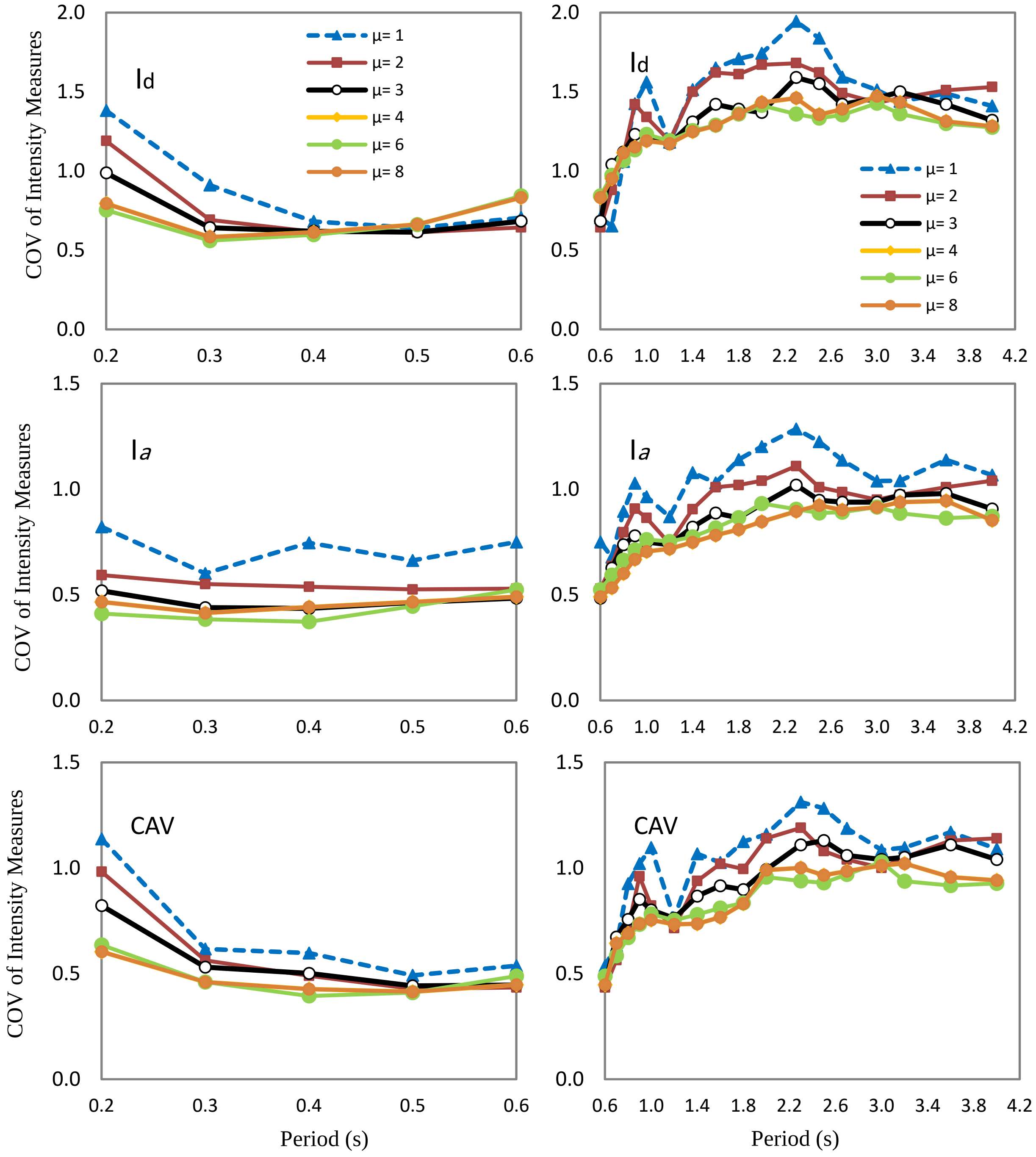
For elastic and low inelastic level ($\mu = 2$), the values of COV have relatively larger peaks and valleys (i.e., jagged shape), and tend to be more uniform as ductility ratio increases. Moreover, in general, for most of the periods used, the dispersion reduces as the ductility demand increases. Results of this figure show that using all types of intensity measures including E_I/M, I_a, I_d and CAV will result in a significant discrepancy in input energy spectra of MDOF systems, which is in most cases larger than 0.5 and even can take the value of 1.9 for the case of input energy spectra normalized by I_d. This signifies that the evaluated intensity measures are not suitable for MDOF systems. Therefore more efficient intensity measure should be used to reduce the discrepancy of the results obtained from different ground motion having various amplitudes, significant durations and frequency contents, which is examined in the upcoming section.

MORE ADEQUATE ENERGY INTENSITY MEASURE FOR MDOF SYSTEMS

It was demonstrated in the previous section that the evaluated intensity measures are not suitable for MDOF systems. Hence, introducing a more efficient intensity measure to reduce the discrepancy of the results seems to be necessary. As stated in the literature, the parameter CAV has a superiority over other peak ground motion and response-spectral parameters such that it can incorporate the cumulative influence of the total and significant duration of the selected earthquake ground motion through integration of the absolute value of the ground acceleration. Based on the study carried out by EPRI (1988), among the various investigated ground motion parameters, CAV best correlates with structural damage. However, its main drawback is that despite having the unit of velocity, it is not directly related to the ground motion velocity, resulting some important characteristics of the ground motion be ignored. To overcome this shortcoming, by merging both CAV and PGV into a single parameter, Mezgebo and Lui (2016) proposed a new intensity index for SDOF systems defined as *VI= CAV.PGV* and showed that their proposed velocity index (VI) could be used as the normalization parameter for input energy as follows:

$$NE = \sqrt{\frac{E_I / m}{CAV\ .\ PGV}} \qquad (14)$$

where the unit of VI is distance^2/time^2, which equals to that of energy per unit mass.



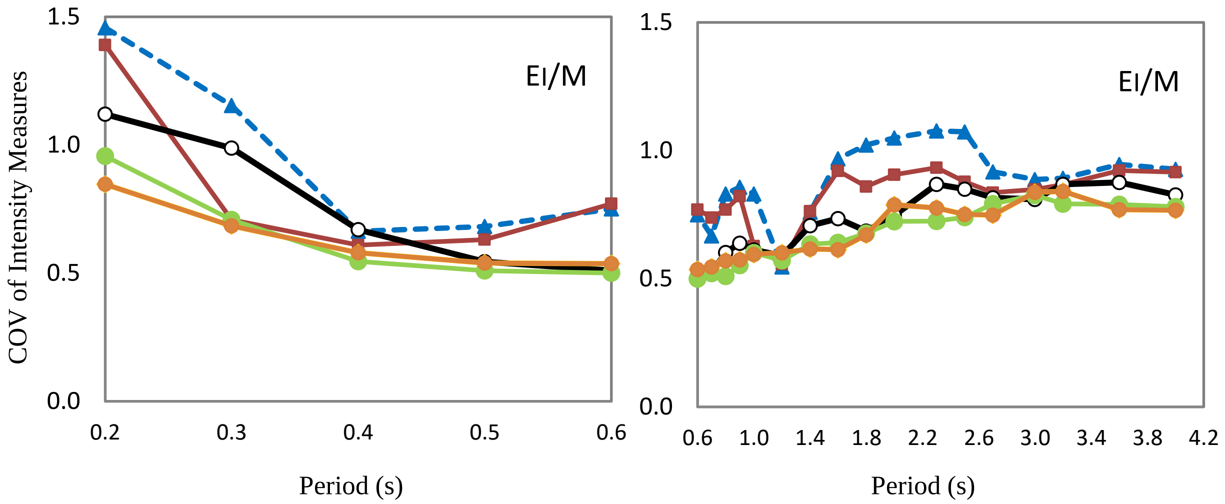


Fig. 2. Coefficient of variation of input energy per unit mass normalized by different intensity measures

As a result, by normalizing the input energy per unit mass by VI, leads to a dimensionless energy spectrum. The dimensionless spectrum allows engineers to utilize any arbitrary unit in the design process. In addition, for a given seismic site and soil class, the two quantities PGV and CAV required to calculate the velocity index can be easily computed from the empirical equations developed by researches such as Campbell and Bozorgnia (2012), and Bradley (2012). Results of this study showed using square root to define *VI* cannot appropriately exhibit the variation of the ductility demands in energy spectra of MDOF systems. Therefore, Eq. (14) can be revised as:

$$NE_{MDOF} = \left(\frac{E_I / m}{\int_0^t \left| \ddot{u}_g(t) \right| \mathrm{dt} \quad .\, PGV} \right) *100 \qquad (15)$$

where NE_{MDOF}: is dimensionless normalized input energy for MDOF systems. Figures 3 and 4 show the mean actual input energy spectra (E_I/M) and dimensionless normalized input energy (NE_{MDOF}) for target ductility ratios of μ = 1,2,3,4,6 subjected to the 40 selected earthquake ground motions. As seen, the proposed dimensionless normalized input energy gives values which have relatively smaller peaks and valleys when compared with E_I/M spectra shown in Figure 3. Similar to Figure 2, the COV spectra for 21 MDOF models having various periods and 6 values of ductility ratios are computed and the results are plotted in Figure 5. As seen, except for very short-period structure with fundamental period of 0.2 s, the COV values are less than 0.4 for the entire range of periods and ductility ratios. The figure clearly shows that when the input energy is normalized by the velocity index, the peaks and valleys of the spectra are less pronounced, leading to reduction of the dispersion of the spectral values.

Consequently, the resulting standard deviation will more examine the efficiency of the proposed intensity measure as an index for damage potential of ground motion in MDOF systems. The results obtained from Eq. (15) are compared with those computed from in Eqs. (10-12) for 3 levels of ductility demand (μ = 1,2,8) as shown in Figure 6 for both acceleration and constant velocity regions. It can be observed that, irrespective the value of ductility ratio, the proposed normalized input energy values have smaller COV values compared to those of the other indices for MDOF systems with all ranges of periods and ductility ratios used. Moreover, the proposed intensity measure takes smaller and more uniform values for the COV spectra compared to others, demonstrating the efficiency of the *NE_{MDOF}* intensity measures for damage potential of ground motions. In order to quantitatively show the efficiency of the proposed index in reducing the dispersion of input energy, the average error, defined as the differences between the dispersion of the proposed index and the corresponding values in other indices, is computed. The results indicate that the proposed index can reduce, on average 63%, the dispersion of input energy compared to the best measure of other indices with lowest dispersion, demonstrating the efficiency of the proposed index as a damage index.

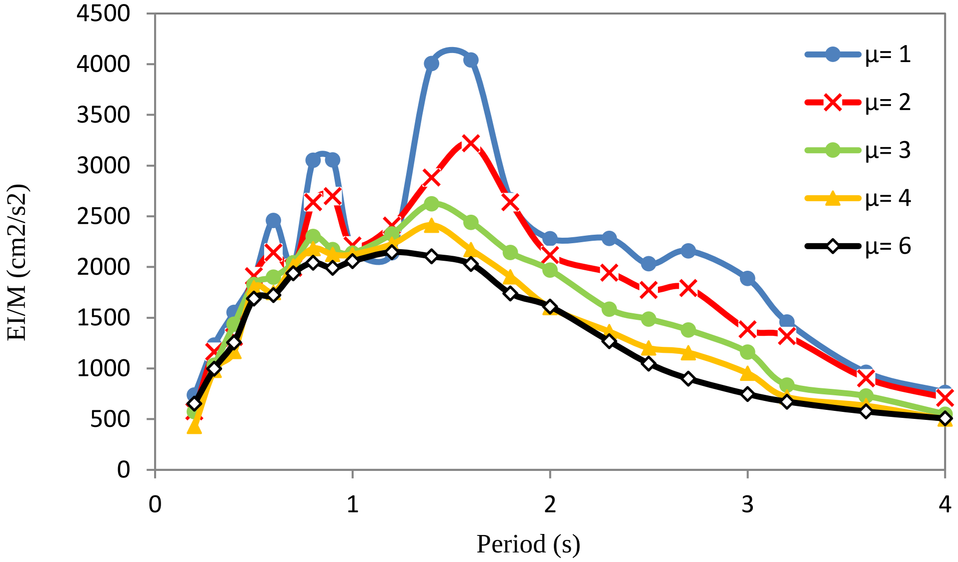


Fig. 3. Mean actual input energy spectra (E_I/M) of MDOF systems for target ductility ratios of μ = 1,2,3,4,6 subjected to the 40 ground motions

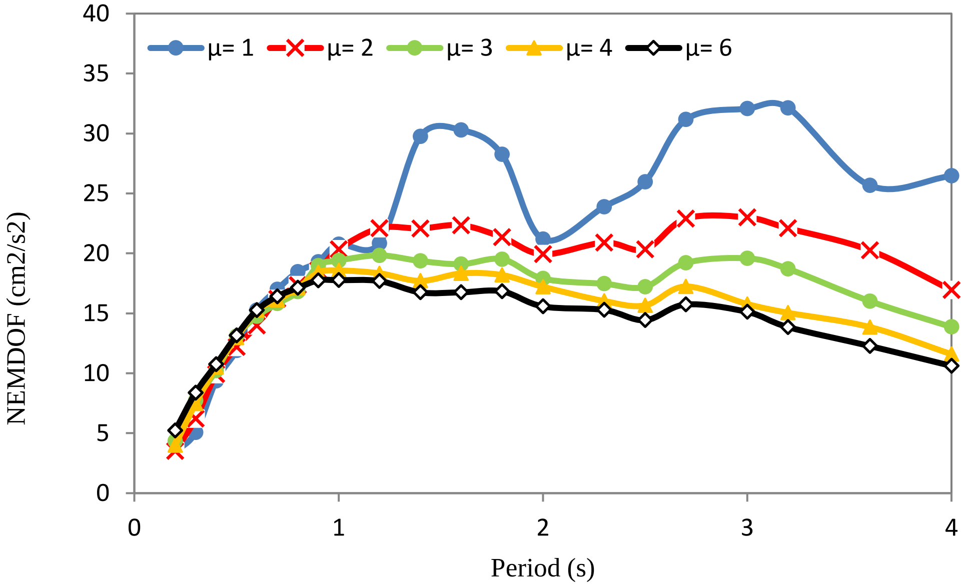


Fig. 4. Mean dimensionless normalized input energy (NE_{MDOF}) for target ductility ratios of μ = 1,2,3,4,6 subjected to 40 ground motions

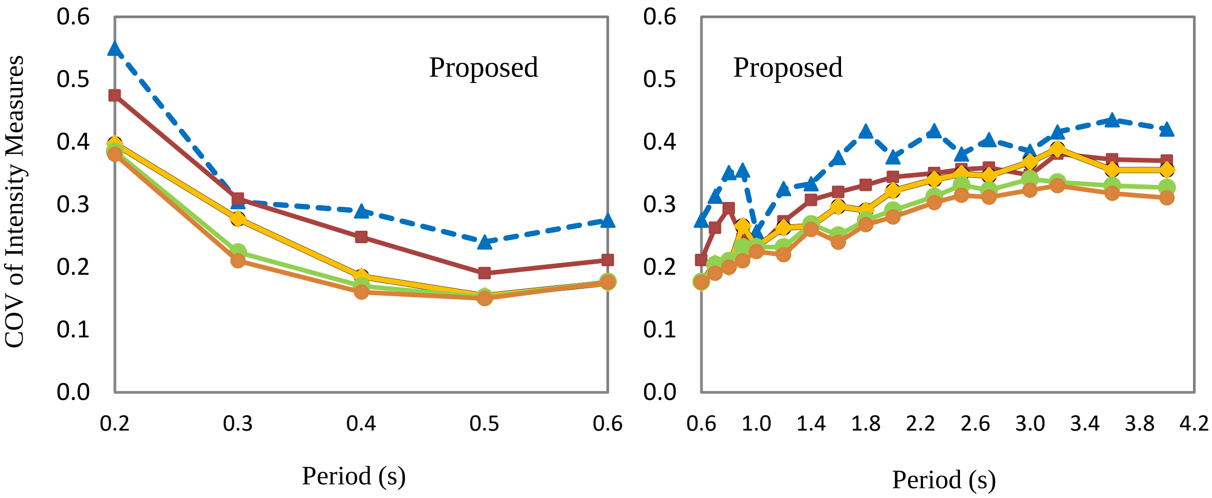


Fig. 5. Coefficient of variation of input energy per unit mass normalized by proposed intensity measures

CONCLUSIONS

In this study, several intensity measures already proposed by researchers for damage potential of earthquake ground motions based on energy concepts for SDOF systems are investigated for MDOF systems. Nonlinear dynamic analyses were performed to compute the maximum relative input energy per unit mass (E_I/M) for 21 MDOF systems with preselected target fundamental period of vibration ranging from 0.2 to 4.0 s and 6 target inter-story ductility demands of 1, 2, 3, 4, 6, 8 subjected to 40 the earthquake ground motions. The coefficient of variation (COV) has been used to compare the degree of uncertainty involved in normalizing the input energies by different indices. To examine the efficiency of the already proposed intensity measures as an index for damage potential of ground motion in MDOF systems, all the defined indices were utilized as normalization parameters and then the resulted spectra are compared to those of the original spectra of input energy per unit mass (i.e., E_I/M). In this regard, the COV for 21 MDOF models having various periods and ductility ratios were computed for the ensemble of 40 earthquake records used in this study.

Results of this study show that using all types of intensity measures including E_I/M, I_a, I_d and *CAV* will result in a significant discrepancy in input energy spectra of MDOF systems, which is in most cases larger than 0.5 and even can take the value of 1.9 for the case of input energy spectra normalized by I_d. This signifies that the evaluated intensity measures are not suitable for MDOF systems.

An optimum dimensionless intensity measure as a normalized energy index is proposed for MDOF systems subjected to far-fault earthquakes. The dimensionless energy intensity index allows engineers to utilize any arbitrary unit in the design process. In addition, for a specified seismic zone and soil type, the two parameters of PGV and CAV required to compute the velocity index can be easily computed from the empirical equations developed by researches. It was demonstrated that the proposed normalized input energy values have smaller dispersion compared to those of the other indices for MDOF systems with all ranges of periods and ductility ratios used. The results indicate that the proposed index can reduce, on average 63%, the dispersion of input energy compared to the best measure of other indices with lowest dispersion, demonstrating the efficiency of the proposed index as a damage index.

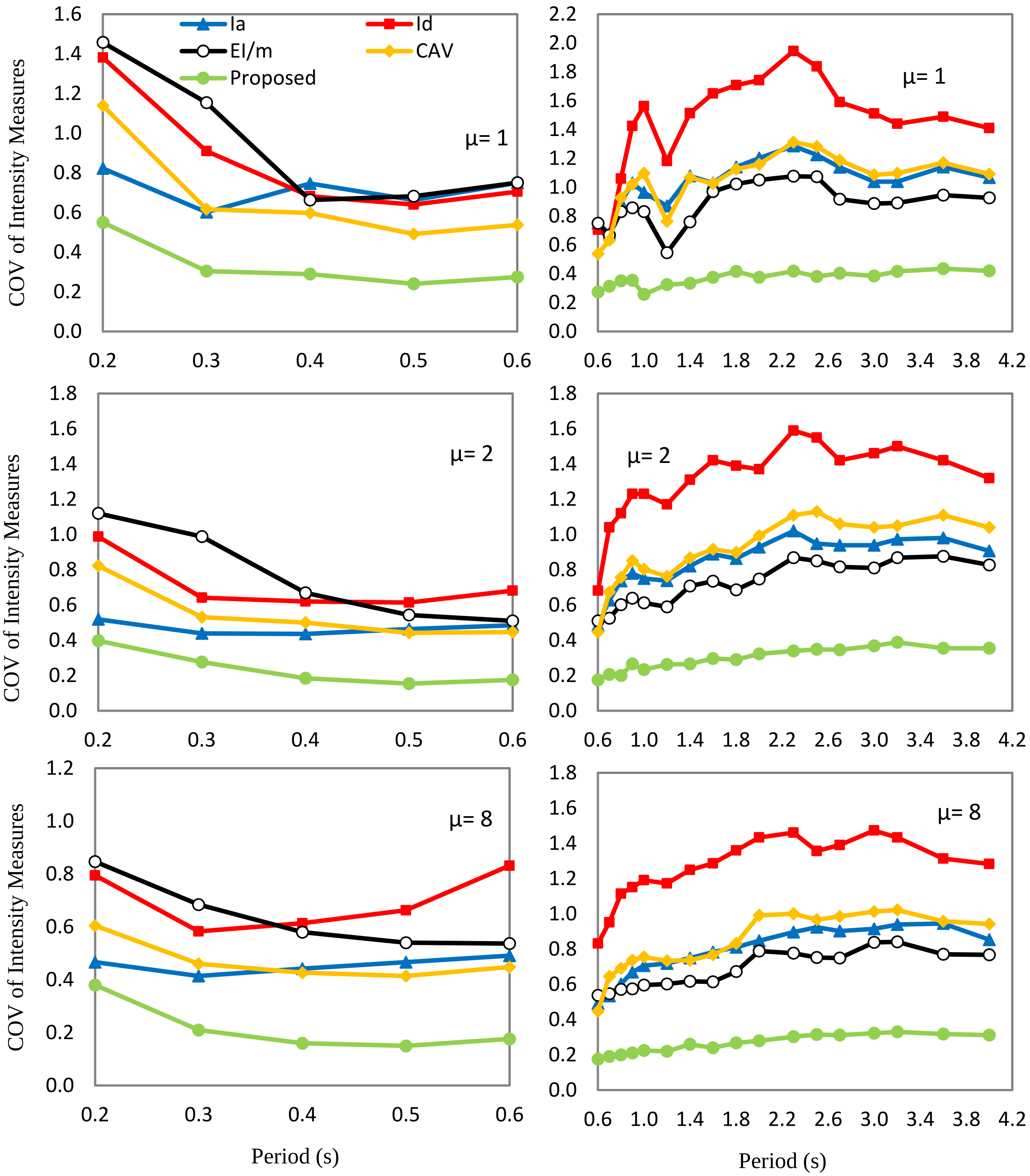


Fig. 6. Comparison of dispersion of input energy per unit mass normalized by different intensity measures

Considering the fact that the energy parameters are basically dependent on the displacement, velocity and acceleration of the structure as well as the given ground motion, therefore, the proposed intensity measure can be easily used for other types of building structures such as steel-moment frames, reinforced concrete buildings, steel braced-frames, and etc. However, for pulse-type near-fault ground motion with forward directivity effect further studies need to be conducted to investigate the correlation between the pulse period of the ground motion and the proposed intensity measure.

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