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New intensity measure parameter based on record's velocity characteristics

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Abstract. Hazard analysis is the prominent stage in performance-based earthquake engineering, and proper intensity measure selection is its significant phase. Despite diversity in recently proposed intensity measures, there are still significant variations in the magnitude of structural responses used to assess performance, especially according to the records with pulse-like characteristics. In this study, several intensity measures for two groups of records, far-field and near-field, were evaluated in six scaling levels. In addition, a new scalar intensity measure, accounting for pulse-like characteristics of near-field records, have been generated based on spectral velocity at first-mode period of a structure and maximum amount of velocity. Utilized structural models are steel moment frames with different heights accounting for the effects of wave propagation. It is discovered that this new velocity-based intensity measure is the most convenient IM factor, especially for the stories under pulse propagation associated with near-field records, considering both efficiency and sufficiency aspects. Furthermore, it is found that utilizing nonlinear spectral values does not significantly amplify assessment precision in the moderate range of intensity measures, and considering their unavoidably complicating and time consuming required analyses; elastic spectral values can be adequately substituted.

1. Introduction

1.1. *Performance Based Earthquake Engineering (PBEE)*

Performance-Based Earthquake Engineering (PBEE) has received much attention in recent years as the new proficient method that can provide a quantitative basis in assessment of the seismic performance of structures and aims at the design of structures achieving expected acceptable performance levels during probable future earthquakes. Deficiencies in qualitative approaches in PBEE motivate efforts to develop quantitative measures of structural performance during seismic events and improve methodologies to estimate seismic performance [1]. PBEE comprises a significant number of researches that quantifies performance in metric that is more relevant to stakeholders, namely, deaths (loss of life), dollars (economic losses) and downtime (temporary loss of applications). Proposed fully probabilistic methodology of Pacific Earthquake Engineering Research (PEER) Center [2] (one of the very frequently used performance assessment procedures) is divided into four basic stages accounting for the following: ground motion hazard of the site, structural response of the building, damage of building components and repair costs. The first stage uses probabilistic seismic hazard analysis to generate a seismic hazard curve, which quantifies the frequency of exceeding a ground motion Intensity Measure (IM) from a certain value for the specific site. The second stage involves using structural response analysis to Estimate engineering

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Demand Parameters (EDPs), such as inter-story drift and peak floor accelerations, and the collapse capacity of the structure. The third stage produces Damage Measures (DMs) using fragility functions, which are cumulative distribution functions relating EDPs to the probability of being or exceeding particular levels of damage. The fourth and final stage sets up Decision Variables (DVs), such as economic loses, which stakeholders can use to make more informed design decisions [3]. The outcomes of each stage serve as input to the next stage.

The first step of PEER approach is the main area under discussion in this paper. In this step according to previous history of occurred earthquakes, rate of return for each earthquake and other seismological condition of the site, the hazard's curves were figured out by the help of hazard analysis of the site and corresponding to the selected intensity measure of the records.

The confidence of PBEE implementation depends strongly on the ability to estimate the probability of incurred EDPs; so to decouple the seismological and structural uncertainties (stages 1 and 2 of the PEER approach), an intermediate variable, called Intensity Measure (IM), is typically used in the seismic performance assessment of structures [4-6]. The results of the hazard analysis and the structural analysis can finally be re-coupled by integration over all levels of the selected IM in accordance with the total probability theorem [7]. Manipulating this approach, the probability of exceeding a specific level of EDP estimate, $V(\mathrm{EDP} > edp)$, is expressed in the following equation:

$$v\left(\mathrm{EDP} > edp\right) = \int_0^\infty \left[1 - p(\mathrm{EDP} \ < edp|\mathrm{IM})\right. \left|\frac{dv(\mathrm{IM})}{\mathrm{IM}}\right|\Bigg] d\mathrm{IM}, \quad (1)$$

where the $p(\mathrm{EDP} < edp|\mathrm{IM})$ is the probability that the structural response parameter is smaller than a certain level of edp at the ground motion intensity, IM, and the term of $v(\mathrm{IM})$ denotes the mean annual rate of exceedance of ground motion intensity measure, IM, from a certain value. $p(\mathrm{EDP}<edp|\mathrm{IM})$ is customarily estimated through Incremental Dynamic Analyses (IDA) under a set of ground motions.

As it could be concluded from Eq. (1), appropriate selection of IM parameter plays significant role in evaluating the value of EDPs and their mean annual rates as well as it challenges both researchers and practitioners, since an appropriate IM can significantly decrease the runtime of estimating probability parameters and it can lead to more reliable evaluations of the seismic performance as it strongly influences structural responses.

Record's Peak Ground Acceleration (PGA) was a commonly preliminary employed IM, moreover elastic spectral ordinates calculated at the structure's first period of vibration were assumed to be the selected IM in the significant body of recent works without discussing other alternatives.

Another important aspect in evaluation of structure-specific IM is the dependency of structural response parameters on the other seismological aspects, such as its magnitude and source-to-site distance. This feature can significantly affect the level of complexity of the structural response estimations and eventually impacts the runtime. The responses of structures are greatly more against near-field records than ordinary or far-field ones. This is the fact that motivates more comprehend investigation about IM selection for near-field records. In near-fault regions records influenced by forward directivity or filing step phenomena and most of the seismic rupture energy appears as a single coherent pulse-type motion. Some vector-type IMs have been introduced lately for near-field records [8]. It is obvious from Eq. (1) that for the purpose of computing the mean annual rate of exceedance of edp for a certain value, slope of the seismic hazard curve has to be evaluated at an anticipated intensity level of IM, and when IM is a vector-type parameter, calculating derivation of $v(\mathrm{IM})$ according to this type of IM is too complicated and time-consuming. Besides, we are searching for a unique suitable IM associated with both near and far-field records to get information for aggregating seismic hazard of several sources in a specific site. Nevertheless, pulse-like motions cannot be adequately characterized by the vector of $\Delta_{de}(T_1)$, and ε, because their response spectra usually exhibit a sharp change, making it difficult to simply estimate spectral shape using $\Delta_{de}(T_1)$, and local spectral shape at T_1 via ε [9]. By all the above discussions, utilizing scalar IM has been preferred by PBEE codes like ACT-58 [10] and almost all evaluators and researchers. In this research, some common used scalar IM factors were evaluated accompanied by a new introduced scalar one.

2. Description of the incorporated structural systems

Most of the previous studies on IM selection have either dealt only with the response of SDOF systems or have concentrated on the peak inter-story drift that tends to occur in multi-degree-of-freedom, MDOF, however, estimation of economic losses or loss functionality in buildings requires evaluation of intensity measures based on inter-story drift ratio, IDR_i, and peak floor acceleration, PFA_i, at all floor levels. Whereas the period-specific $\Delta_{de}(T_1)$ requires only an estimate of T_1 typically done from an Eigen value analysis and an SDOF earthquake time-history analysis, where T_1 is the first fundamental period of vibration of the model which is a very common used factor in modal and spectral simulation of structural responses. it is equal to natural period of undamped one degree of freedom systems; however, taking in to account damping ratio for real systems, the first fundamental period of structures becomes a little less than the natural period. The IMs, detailed here, are more structure-specific in that they also make use of EDP values gained from time-history analysis based on MDOF consideration of the models, higher-mode periods, modal damping ratios, and modal participation factors.

In this research, 3D models with 3, 5, 8 and 15 numbers of stories with special steel moment frame (SMRF) system have been utilized to be representative of typical structures with different heights and fundamental periods and time history nonlinear dynamic analyses were performed considering P-Δ effects. The height of each story is deemed equal to 3 m. Loading and complete designing of each model were carried out according to Iran's seismic code (2800), [11], much similar to UBC97 [12], and Iran's steel design code [13], much similar to AISC2005 [14], by the means of the program of SAP2000 [15].

On account of the need for generality of the results, the structural models are not intended to represent a specific structure. For this purpose, very general plans were assumed containing similar and regular plans in all stories with four longitudinal spans and three spans in the other side. Each span has 4 m length and accidental torsion was considered equal to 5% and the earthquake probabilistic hazard level is considered to be very high.

Plastic hinges definition, assignment and nonlinear static analyses were done according to FEMA273 [16], and P-Δ effects were considered in all analyses. All the nonlinear dynamic analyses are conducted as Direct Integration Transient time history analyses using Direct Integration in Hilber, Hughes and Taylor's method by consideration of damping ratio for all modes equal to 5%.

The selected EDPs in performance-based assessment are usually Inter-story Drift Ratios (IDR) and Peak Floor Acceleration (PFA) as well as in this paper.

3. Records

Near-field ground motions containing strong velocity pulses, which generally arise at the beginning of the seismograms, are of interest in the fields of seismology and earthquake engineering because of tending to increase long-period portion of the accelerograms. Based on the previous studies, the maximum demand of structure under this type of motion is affected by the ratio of the period of the near-fault Pulse to the fundamental period of the structure [17]. One approach for detecting these ground motions has been identified as imposing extreme demands on structures to an extent not predicted by typical measures such as response spectra [18-27]. Theoretical considerations also provide an indication of seismological conditions that may result in occurrence of velocity pulses due to, for example, directivity effects [28-30]. Therefore, another way for detecting near-field ground motions is distinguishing velocity pulses in view of these seismological effects. While the effects are relatively well studied, deficiency of a quantitative method for identifying these velocity pulses is a hindrance to incorporating these effects in probabilistic seismic hazard analysis and engineering building codes.

In this research, estimation of the new proposed IM does not need to recognize record's pulse explicitly and only has dealt with the maximum amount of velocity considering pulse of velocity record implicitly and records will only be classified in terms of source-to-site distance.

Despite the high variability in ground motions, earthquake engineers would ideally like to select as few representative ground motions as possible for design purposes, having critical ground motion properties that are likely to exhibit a certain response within a given structure. This is mainly because the non-linear modeling and dynamic analysis are computationally expensive, while still being inevitable in earthquake prone areas. It is true that by increasing the number of records, the variability related to record by record variation will be reduced, but each percent of reduction expenses too much with respect to nonlinear dynamic analysis. When used in nonlinear response history analysis, each pair of ground motions will result in a somewhat different prediction of the magnitude of response quantities used to assess performance. The intent is not to reduce the response dispersion by applying great quantities of records; the intent is to obtain an unbiased estimate of the structural response with limited error.

A suit of eleven pairs of ground motions is the minimum recommended by the ATC-58. Such a suite will provide a 75% confidence that the predicted median response from will be with $\pm 20\%$ of the true median value of response for an assumed dispersion of 0.5 [10].

With respect to the considerable effects of pulse motions on dynamic responses of structures, the database in this study comprises nine near-fault earthquake records identified as containing distinct velocity pulses and enclosing source-to-site distances less than 10 km and all of them were recorded on soil type D (stiff soil, very dense soil and rock) based on NEHRP site classification, equal to Zone 4 of UBC [12], and soil type II according to Iran Seismic Code (2800) [11], or adjusted for this type of soil. Records were derived from PEER Strong Motion Database [31] and Iran Strong Motion Network Data Bank [32]. Moreover, three far-

Table 1. Specifications of ground motions.

Near-field ground motions					
Earthquake	**Year**	**Station**	**Distance (km)**	M_W	**Duration (sec)**
Tabas	1978	Tabas	1.2	7.4	32.84
Bam	2003	Bam	1.0	6.8	66.56
Loma Prieta	1989	Los Gate	3.5	7.0	24.96
Mendocino	1992	Petrolia	8.5	7.1	35.98
Erzincan	1992	Erzincan	2.0	6.7	20.78
Landerz	1992	Lucerne	1.1	7.3	48.12
Northridge	1994	Olive View	6.4	6.7	39.98
Kobe	1995	JMA	0.6	6.9	47.98
Chichi	1995	TCU068	1.09	7.6	90.00
Far-field ground motions					
Earthquake	**Year**	**Station**	**Distance (km)**	M_W	**Duration (sec)**
Tabas	1978	Ferdoos	94.40	7.4	40.00
Morgan Hill	2003	Morgan	76.25	6.8	36.00
Landerz	1992	12026 Indio	55.70	7.3	60.00

field records were supplemented to comprehend the comparison. All far-field records have distances above 50 km and do not include any pulse-like wave. The complete specifications of the selected near-field and far-field records have been presented in Table 1 [31-34].

The two horizontal components of records were convert into fault parallel and fault normal directions and the effects of horizontal shaking are considered by applying the earthquake shaking effects simultaneously along each of the two principal orthogonal building axes. The east-west components of the records have been implemented along the x direction of buildings and north-west component along the y direction.

4. Intensity measures

4.1. Considered ground motion intensity measures

Several alternative IMs have been proposed in recent studies with respect to the seismological characteristics of records and structural configurations of models. Some frequently used IMs that were recently worked on in many researches are briefly introduced in this section.

1. Δ_{pga}: is a non-structure-specific IM defined as the normalized peak ground acceleration of the ground motion by the scalar value of $(4\pi^2/T_1^2)$. Since calculation of this IM is very straightforward and does not require computation of the structural response, it is manipulated widely in preliminary studies. N on-structure-specific IMs is preferred for near-field ground motions from a seismology standpoint. However, they do not incorporate spectral characteristics of the structures.

2. Δ_{de}: is the elastic displacement spectral ordinate evaluated at the first fundamental period of vibration of the model, T_1. This intensity measure is the mainly facilitated IM both in practice and research. In part, this IM choice is driven by convenience, as seismic hazard curves in terms of spectral acceleration at the fundamental period of structure are either readily available (e.g., from the U.S. Geological Survey at http:/geohazards.cr.usgs.gov/eq/) or commonly computed.

   As cited earlier, the maximum demand of EDP in structures under near-field records is affected by the ratio of near-fault pulse period to the fundamental period of the structure; so, Δ_{de} cannot adequately predict the seismic demands of structure under near-field pulse-like records. Another important shortcoming of the Δ_{de} is its inability in describing the effective frequency content of earthquakes at a period not equal to the fundamental period of the structure. This dominates higher mode effects and period elongation effects due to nonlinearity [7]. This weakness is more pronounced when pulse motions dominate the structural responses. These inadequacies could be approximately improved by using vector-type IMs [35,36]. Nevertheless, pulse like motions cannot be adequately characterized by the means of the vector type parameter of Δ_{de} because their response spectra usually exhibit a sharp change, making it difficult to simply estimate spectral shape by this type of IM [37].

3. Δ_{ve}: is the elastic velocity spectral ordinate evaluated at the fundamental period of vibration of the structural model, T_1, and normalized by the factor of $(2\pi/T_1)$. Velocity response spectrums in the fault-normal component of the near-field records contain at least one predominate peak, which provides a good estimation of the period of the pulse contained in the near-field record [38]. In some cases the period of these pulses and the structural predominate period match to each other that help us to take into account the velocity pulse effects through implementing Δ_{ve} as the IM parameter; but in most of the cases this matching does not take place and therefore this IM includes some deficiencies to consider pulse effects. This feature is one of the points that motivate us to introduce a new IM factor based on velocity characteristics liberated from deficiencies of the previous velocity-based IMs.

4. Δ_{di}: is the inelastic spectral displacement considered in some studies in order to reflect the period shift effect in near-field ground motions [27,37]. This IM is calculated using the SDOF system with an elastic perfectly plastic hysteresis behavior evaluated at T_1, and with a yield displacement of $\Delta_{y\mathrm{SDOF}}$ calculated as:

$$\Delta_{y\mathrm{SDOF}} = \frac{\Delta_{yr}}{\Gamma_1 \phi_{1,r}}, \tag{2}$$

where Δ_{yr} is the roof displacement for MDOF model at yielding, estimated from static pushover analysis applying the first mode lateral load pattern; Γ_1 is the modal participation factor of the first mode and $\phi_{1,r}$ is the amplitude of the first mode at the roof level [39,40]. While this IM is generally more accurate and is able to describe the period elongation effects, one drawback of the nonlinear spectral values is that they imply a coupling between the earthquake hazard definition and the inelastic structural properties that it requires inelastic SDOF time history analyses and complicates development of seismic hazard maps for general use.

5. Δ_{cdc}: is the combination of the spectral displacement evaluated at two periods of vibration incorporating both period softening and higher mode effects and thereby reducing record-to-record variability [41]. This intensity parameter could be calculated as:

$$\Delta_{cdc} = \Delta_e(T_1)\left(\frac{\Delta_e(cT_1)}{\Delta_e(T_1)}\right)^{\alpha}, \tag{3}$$

where c and α are constant parameters that can be tailored to achieve a certain level of preciseness for a specific structural model. Cordova et al. suggest a pair of $c = 2$ and $\alpha = 0.5$. Δ_{cdc} is equal to the geometric mean of $\Delta_e(T_1)$ and $\Delta_e(2T_1)$ through application of these suggested amounts in our research. By the proposed factors of c and α, the natural period of a model locates between T_1 and $2T_1$.

The IMs of Δ_{di} and Δ_{cdc} are generally more accurate but they complicate the computational efforts needed in characterizing the strength of ground motions.

4.2. Development of an improved velocity-based intensity measure

Recent works describe the significance of the velocity pulses in seismological and earthquake engineering applications, also defining some of their properties, i.e. pulse period, pulse amplitude and their influence to the structures and soils. While some of these studies focus on the effects of these pulses on engineering structures [17,22,42], others proposed scaling relations of the velocity pulses with earthquake magnitude [43-45]. The most widely used description of velocity pulse considers the largest velocity cycle. The pulse starts and ends at the zero crossing times or at the times at which the velocity is equal to 10% of the peak velocity for this pulse [45]. Both of these approaches successfully pick the largest velocity cycle in the recording. Many researchers also illustrate occurrence of near-fault velocity pulses in the periods less than 1.2 sec in most of the cases, which is in the range of fundamental period for a common mid-rise building [17,22,45].

Distinguishing the magnitude of velocity pulses and corresponding occurring period are concepts under discussion, as well as they are very expensive computationally works. Hence, to describe the peculiar spectral shape of pulse-like records that has been observed chiefly in near-field records through applying a simple index, this paper introduces a new IM factor that aggregates both non-structure-specific and structure-specific terms which is defined as the geometric mean of spectral velocity evaluated at the structure's first period of vibration and maximum amount of velocity record, along with normalizing scalar value of $(2\pi/T_1)$. This intensity measure parameter can be calculated as:

$$\Delta_{v_e v_{\max}} = (\Delta_{ev}(T_1).V_{\max})^{0.5}. \tag{4}$$

This IM merges the amount of maximum velocity that is correlated strongly to the pulse intense and the amount of velocity spectrum at the structural fundamental period which implicitly represents the distance of the pulse by the amplitude of spectral velocity in fundamental period.

The efficiency and sufficiency of the new velocity-based IM associated with multiple near-field and far-field earthquake records are investigated according to the evaluation of structural responses with respect to some recently proposed IMs.

4.3. Requirements of selected intensity measures

Common to most studies of improved intensity measures, the goal is to characterize ground motion hazards in a statistically meaningful way for predicting structural performance. This implies that the best intensity measures are those that result in the least record-to-record variability, measured with respect to a common intensity index, when evaluating structural performance to multiple earthquake records. Of course, even with the best ground motion characterization, uncertainties will persist in characterizing the geologic earthquake hazard and in simulating inelastic structural performance.

Desirably the point estimators for EDPs evaluated by the certain intensity measure should have three properties: consistency, efficiency and sufficiency.

A point estimator is consistent if its error asymptotically decreases with the enlargement in the sample size. On the basis of the law of large numbers, it could be demonstrated that for different intensity measures the point estimators of various types of structural response, EDPs, are consistent. Hence, the consistency of EDPs is not going to be discussed further in this study [39,46,47].

An intensity parameter is considered more efficient than the other if it leads to a smaller dispersion of the point estimator of the same seismic performance parameter [39]. In this study, the standard deviation of natural logarithm of EDP parameters was utilized to compare dispersion around the median values for each EDP parameter associated with the six alternative IMs introduced here, and have been assessed for each of four different building models subjected to a suite of far-field and near-field earthquake records.

An estimator is considered sufficient if it utilizes all the information in the sample that is relevant to the estimation of the seismic performance parameter [39]. In this study, the records are divided into two groups, near and far-field, to evaluate the sufficiency of EDPs under each intensity parameter more precisely. A sufficient IM produces the same distribution of demands and capacities independently of the record selection, e.g. there is no bias in the fractile IM-capacities if we select records with low rather than high magnitudes or if the records do or do not contain directivity pulses [6]. The goals of efficiency and sufficiency are not necessarily tied together as the former aims at reducing the variability in the IDA results while the latter at reducing (or eliminating) their dependence on record characteristics other than the IM. Still, using a more efficient IM will bring the results from all records closer, and similarly bring close the IDA curves of records coming from different magnitudes or containing different directivity pulses, thus reducing the importance of any magnitude or directivity dependence [48].

5. Scaling ground motions

Probabilistic seismic demands are typically obtained through Incremental Dynamic Analyses (IDA) of a building subjected to a suite of ground motions. In IDA, the intensity of each record is incremented after each inelastic dynamic analysis, using IM as the seismic intensity scaling index. Taking into account the prevalence of linear spectral terms in codes and practice, all of the IMs considered in this paper can be thought of as (multiplicative) modifications of Δ_{de}, which serve as a basis for comparison. Most of the modifications are intended to reflect the contributions of higher modes or the effects of Inelasticity and multiple analyses should be done to get standard deviations for EDP parameters. In this research, the ground motions were scaled in some levels of demand according to scale factors gained from scaled displacement response spectra of each record in the fundamental period of models (T_1) to six levels of Δ_{de}: 2.5, 5, 10, 20, 35 and 50 cm.

Having eighteen accelerograms for near-field and six for far-field ones, median values of the other IM factors were estimated for each of the scaling level of Δ_{de} to illustrate scaling factors of the other IM factors. These equivalent scaling factors for the other IM parameters help us to scale the ground motion corresponding to the assumed IM factors. For example, these scaling relations for 3- and 15-story models subjected to near and far-field records were tabulated in Figure 1. It is captured from this figure that the differences between intensity measures for near-field records are prominently more than far-field ones, emphasizing the key role of choosing IM factor associated to near-field records. Good compatibility between Δ_{ve} and Δ_{de} was denoted in all models under both of the record groups, alighting in the mind the sparkler of utilizing velocity based IM factors. Also, It could be seen that Δ_{pga} and $\Delta_{v_e v_{\max}}$ enclose dissimilar trend in comparison with the other intensity measures, in both low and high-rise and both near and far-field records, especially in 15-story building under far-field records. Moreover, the figures demonstrate that by raising the number of stories, the relation between Δ_{de} and Δ_{di} become more nonlinear and the differences between them turn out to be larger. Hence, it could be understood that the model configurations could play a significant role in choosing the appropriate IM factor for the assessment, the fact that has been ignored in most of the previous works. The amplification in

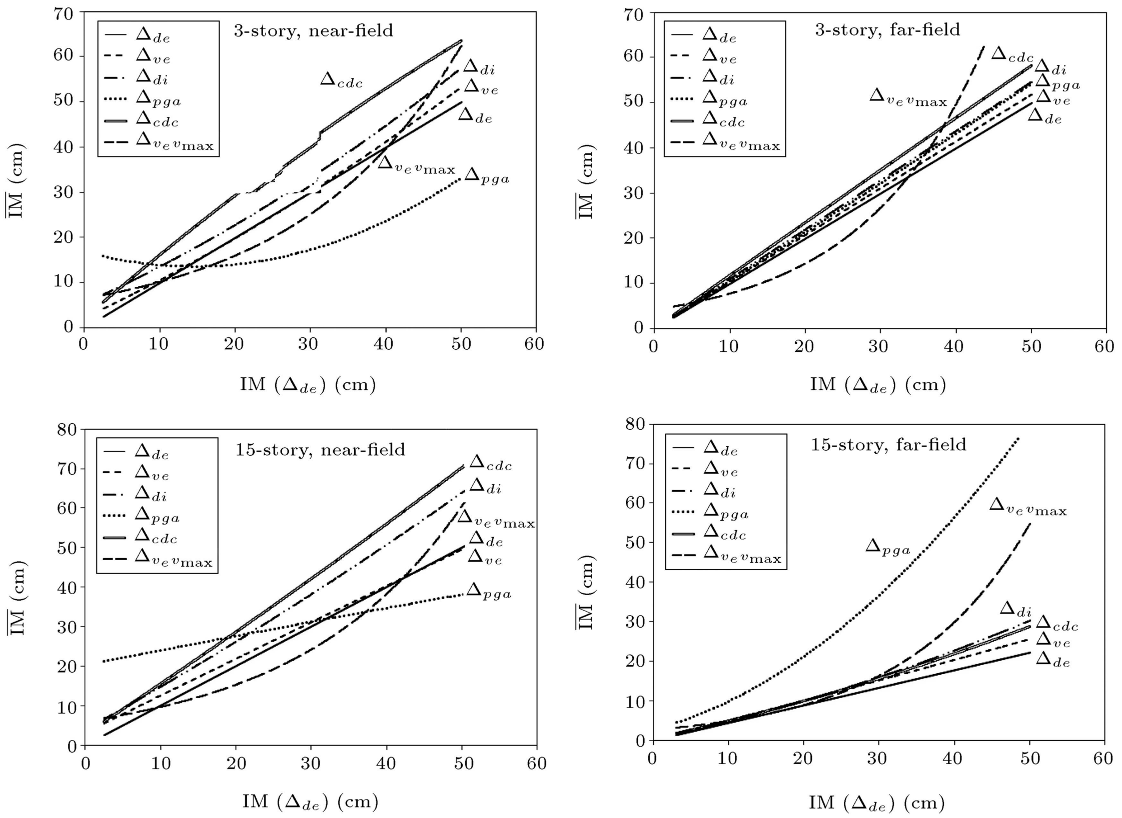

Figure 1. Scaling factors for the intensity measures based on Δ_{de} subjected to near and far-field ground motions.

nonlinearity and amount of differences between Δ_{de} and Δ_{di} also has been experienced by switching from far-field to near-field records. Δ_{cdc} is the IM parameter that accounts intensity in two periods and considers period softening and higher mode participation; however, it is seen that there are great differences between scale factors of this IM and Δ_{de}, especially for high-rise models subjected to near-field records.

Scaling factors for all the assumed models are presented in Table 2. As the models are not specific and the IM factors are the common ones, these factors could be directly used by the other researchers to commute a scaling factor from one IM to the other considering models' fundamental periods. Covering the relations between IMs, scaling procedure according to the other IMs could be done corresponding to the compatible scaling levels.

6. Evaluation of the structural responses

By means of the scaling approach detailed in the previous section and regarding system modeling requirements, analyses were performed under the selected records and the efficiency and sufficiency (as well as the median values) for each of the IMs are quantified and investigated in the following.

The results could be compared in a pair-wise manner or could be all mentioned in a graph. Although comparison, in pair-wise manner, illustrates predominantly the outstanding superior characteristics of a new established IM factor in this study, $\Delta_{v_e v_{\max}}$, one graph for all of the six investigated IM has been preferred to avoid elongation of the paper for assessing median values and efficiency of the results. However, given the prevalence of linear spectral acceleration or displacement in codes and practice, for assessing sufficiency, pair-wise comparison has been merely accomplished between Δ_{de} and $\Delta_{v_e v_{\max}}$; for the other IMs one could refer to lots of previous references in this field (e.g. [39,47]).

6.1. Statistical parameters of the structural responses

In this research, the median and standard deviation of the natural logarithm of EDP parameters were reported as the statistical parameters and the probability distribution of EDPs were assumed lognormal with the median and standard deviations gained from the outcomes of nonlinear dynamic analyses.

6.2. Median of EDPs and their distribution in height

The median of the EDPs plays a key role in evaluation of structural response and it is the input data to stage three of (PBEE); therefore, its precise estimation conducts to accurate evaluation of the building

Table 2. Scaling factors for different intensity measures.

Model specification	Scaling factors											
	Near-field						Far-field					
	Δ_{pga}	Δ_{de}	Δ_{ve}	Δ_{di}	Δ_{cdc}	$\Delta_{v_e v_{\max}}$	Δ_{pga}	Δ_{de}	Δ_{ve}	Δ_{di}	Δ_{cdc}	$\Delta_{v_e v_{\max}}$
3-story	13.8	10	10.6	13.1	17.2	10.1	11.3	10	10.7	11.9	12.3	8.1
	12.6	20	20.1	22.4	29.7	16.7	22.7	20	21.9	23.9	25.7	12.5
	18.7	30	30.9	32.5	42.7	27.1	32.7	30	31.6	33.1	35.1	24.6
	22.2	40	42.1	41.9	53.1	40.9	42.1	40	41.7	43.6	46.1	45.7
	33.1	50	52.7	55.2	62.4	58.9	52.6	50	46.8	53.1	58.1	70.1
5-story	16.5	10	11.7	11.4	15.8	12.8	9.8	10	8.1	7.9	9.3	6.4
	18.9	20	19.8	18.6	28.7	19.6	22.9	20	16.7	17.9	19.1	11.2
	22.7	30	29.4	28.6	41.9	30.4	33.1	30	25.9	28.7	20.6	19.8
	26.5	40	41.5	40.5	52.8	43.9	46.9	40	33.9	33.2	30.7	35.4
	33.9	50	51.6	56.7	64.8	59.9	58.9	50	40.2	42.9	45.7	63.7
8-story	18.4	10	12.5	9.9	16.3	14.8	10.5	10	6.4	4.5	6.8	4.2
	24.3	20	18.5	16.3	30.1	22.3	24.7	20	10.9	12.5	11.9	9.7
	28.9	30	29.3	26.5	42.3	32.1	34.8	30	18.9	20.5	17.6	10.5
	30.7	40	40.6	38.9	51.6	48.3	49.8	40	24.9	24.9	26.9	30.9
	34.3	50	50.3	57.9	66.9	62.6	67.3	50	33.9	34.6	37.9	57.6
15-story	22.7	10	13.1	8.7	17.3	16.5	11.0	10	4.1	3.9	4.2	3.8
	28.4	20	18.2	14.1	29.6	24.7	23.1	20	8.2	9.0	8.9	8.3
	31.6	30	28.7	24.4	40.6	37.3	35.7	30	13.1	13.9	13.7	14.2
	32.9	40	39.1	33.7	52.4	52.6	52.8	40	16.1	19.1	18.8	28.6
	35.7	50	49.1	58.6	68.9	63.3	76.1	50	24.3	26.0	25.2	52.8

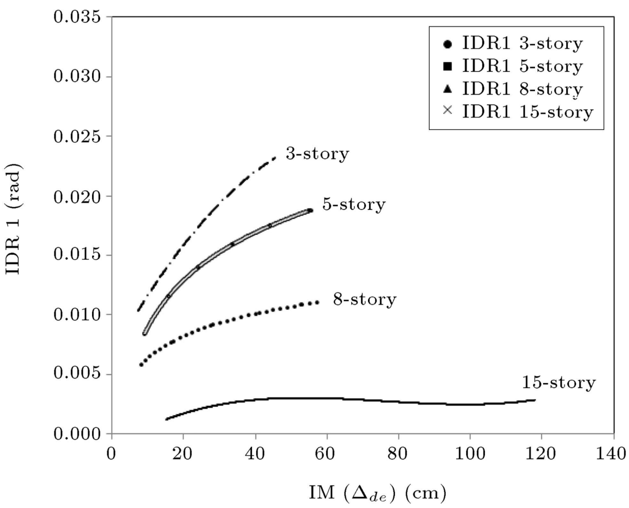

Figure 2. Median inter-story drift ratios for the first story of the models with different number of stories when the IM is Δ_{de}.

performance. The median inter-story drift ratios for the first story of the models with different number of stories were demonstrated in the case of Δ_{de} as IM factor in Figure 2. As it is expected, the rate of changes in median values of IDRs are more in low-rise than high-rise models. Also, the median values of IDR in the roof story for different IM factors under near and far-field records are presented in Figure 3. It is considered that the trends of diagrams in median values for different IMs are similar except for Δ_{pga}. As the presumed values of Δ_{de} served as the scaling levels in scaling procedure of this study, and PGA amounts of the applied ground motions are in the amplitudes ranging in magnitude from 0.462 g to 0.852 g, so the results of Δ_{pga} are in a narrow domain. Considering the fact of situating PGA amounts of the common earthquakes in this domain, the conclusion could be expanded that Δ_{pga} covers more limited domain of IM than the other IMs. Also, it could be inferred from the diagrams of this figure that the differences between IDRs increase by raising the number of stories.

For far-field records fewer EDP, differences have been derived by different IMs. Also it could be inferred that in the case of far-field records, the amplification in median values of IDR are perceived more than near-field ones by raising the number of stories. It is due to higher mode effects and transferring location of maximum inter-story drift from the roof story to the middle stories in the structures under near-field ones.

The median values of peak floor acceleration of the models' roof stories are seen in Figure 4. The maximum medians for PFA have been seen in view of

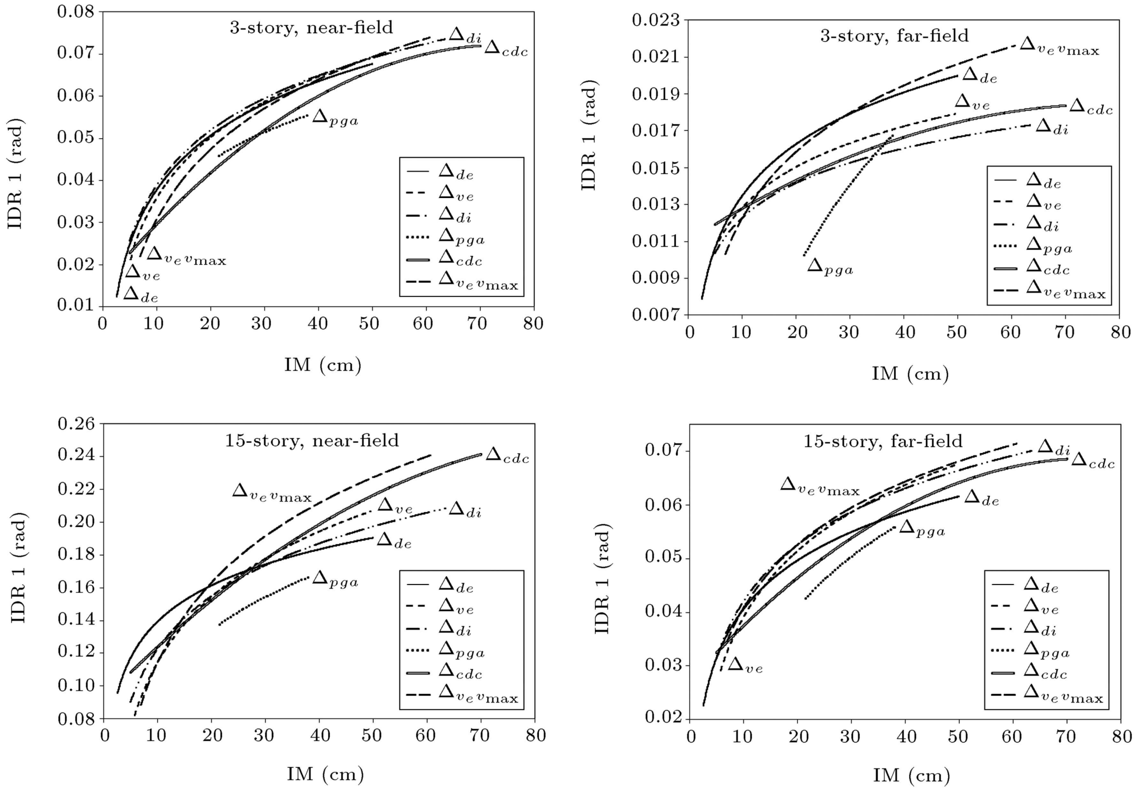

Figure 3. The median values of IDR in roof story for different IM factors under near and far-field records.

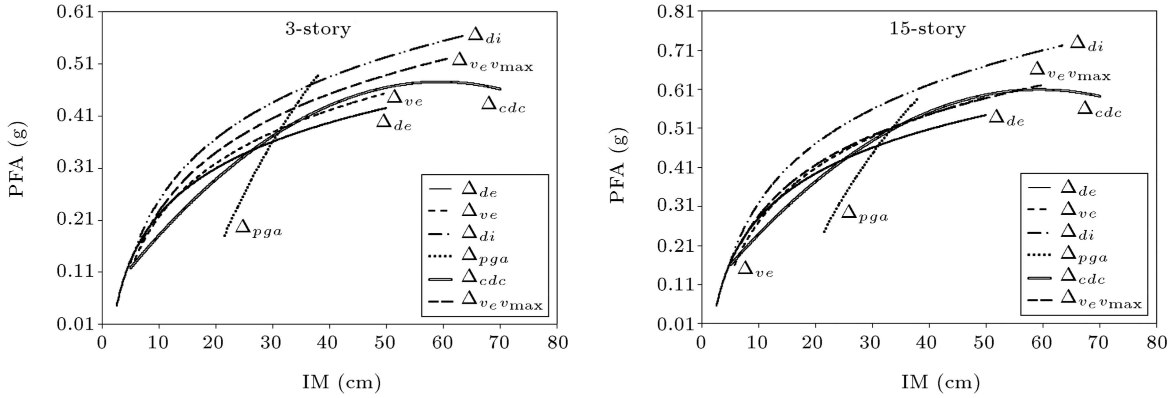

Figure 4. The median values of PFA in roof story for different IM factors under near-field records.

Δ_{di} for both low-rise and high-rise buildings. Despite the narrow bound and therefore dissimilar diagrams of Δ_{pga}, it could be inferred from Figure 4 that for the values of IMs between 20 cm and 40 cm, the median values of PFA have the least amounts according to Δ_{pga}.

In this step, the question is about the distribution of demands associated with the selected IM parameters in the height of structures. Many researchers have stated that by propagating pulse effects in height of building, the maximum values of IDR transfer from the roof story to the lower stories [22]. Consequently, the maximum drift is conveyed from the roof story to middle stories under near-field records in mid-rise and high-rise buildings. The median values of IDR in various stories of 8-story building under near-field records were reported in Figure 5, in view of Δ_{de} and $\Delta_{v_e v_{\max}}$. It is confirmed by Figure 5, that if IM factor is $\Delta_{v_e v_{\max}}$, the median values of IDR are more in story 4 than the other stories, but when IM is Δ_{de} the results for stories 2 and 4 are very close to each other that illustrates some inaccuracy in evaluation of building responses; therefore, it could be concluded that utilizing $\Delta_{v_e v_{\max}}$ as IM factor could be more compatible with the aspect of demand distribution in the height of building especially under near-field records. For comparing the EDP distribution in height according to $\Delta_{v_e v_{\max}}$ by the other IM factors, similar diagrams could be figured

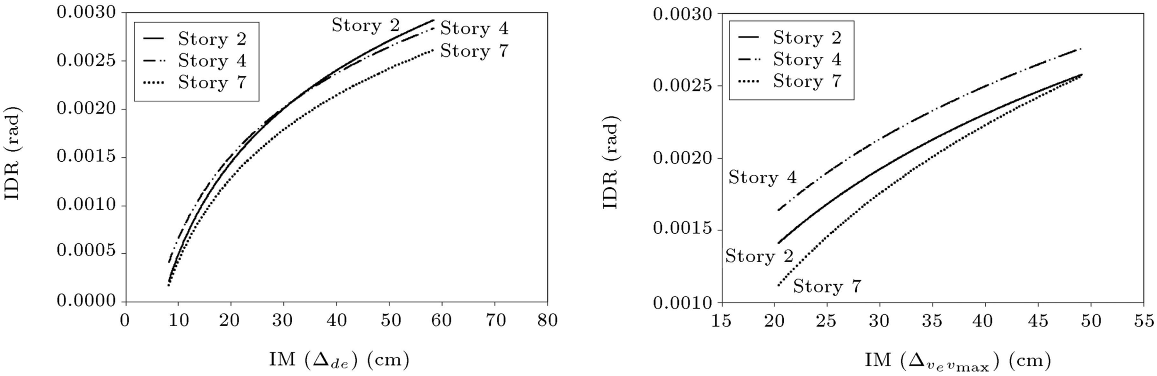

Figure 5. The median values of IDR according to Δ_{de} and $\Delta_{v_e v_{\max}}$ for 8-story model under near-field records.

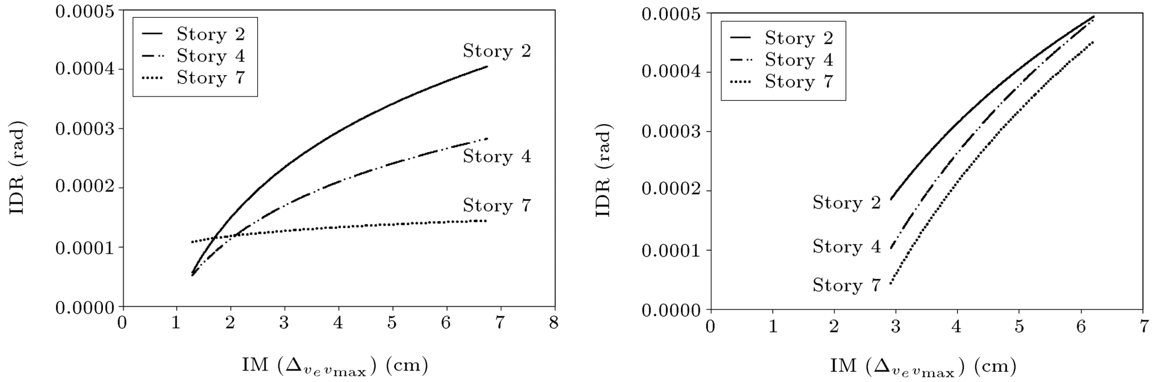

Figure 6. The median values of IDR according to Δ_{de} and $\Delta_{v_e v_{\max}}$ for 8-story model under far-field records.

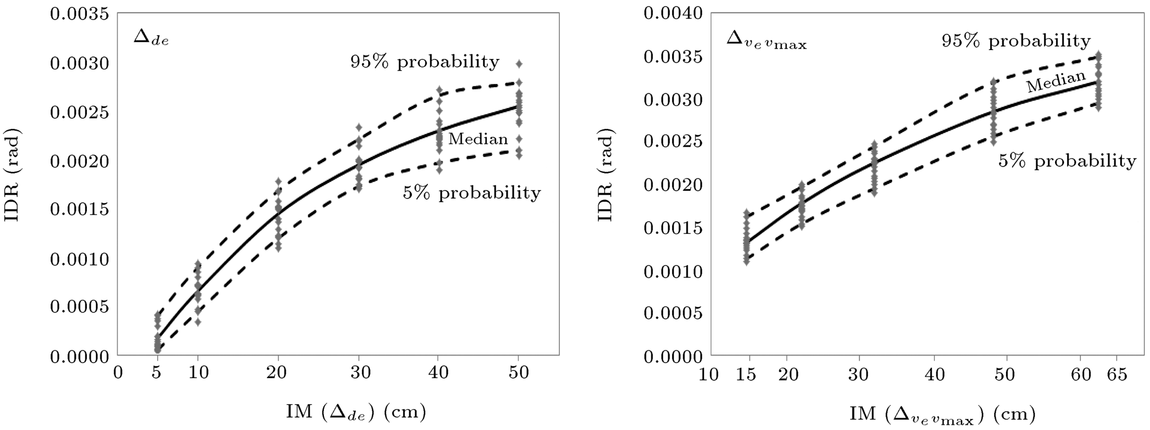

Figure 7. The extreme outliers of 5 and 95th percentile confidence interval and the median values of IDR according to Δ_{de} and $\Delta_{v_e v_{\max}}$ for story 4 of the 8-story model under near-field records.

out leading to similar conclusions as Δ_{de}. Also since the standard deviations, not median values, have been depicted as the decision making parameter of efficiency, diagrams of median values for the other IM factors have not been focused in this paper.

The median values of IDR in terms of Δ_{de} and $\Delta_{v_e v_{\max}}$ for 8-story model under far-field records have been exposed in Figure 6. The median values are more in story 2 than in story 4 and after that in story 7 leading to the same conclusions from median values when the IM is either Δ_{de} or $\Delta_{v_e v_{\max}}$ under far-field records; however, in these diagrams, variations in median values of IDRs are more regular if the IM is $\Delta_{v_e v_{\max}}$ rather than Δ_{de}.

The extreme outliers usually defined by the help of 5 or 95th percentile confidence interval are one of the statistical factors illustrating the degree of confidence of the results. In Figure 7, these outliers in company with the median values and IDR results for story 4 of the 8-story model have been presented based on Δ_{de} or

$\Delta_{v_e v_{\max}}$ under near-field records. Approximately the same trend of outliers' diagrams as median diagram and their close locations to the median ones illustrating that the probability distribution of the IDR results in all of the IM scaling levels are the same. Also the outliers based on $\Delta_{v_e v_{\max}}$ are closer to the median values in comparison with the outliers based on Δ_{de} concluding in fewer amounts of standard deviations based on this IM especially for high level of IM values. For careful assessment, the amounts of EDPs' standard deviation based on different assumed IM factors are going to be assessed in the next section.

6.3. Standard deviation of EDPs (evaluation of the IMs efficiency)

Standard deviation (σ) of Ln(EDP) is the main parameter for distinguishing efficiency of the IM factors. The IM that contributes to the minimum standard deviation is preferred as the most efficient one.

The standard deviation of inter-story drifts for the roof story and their variations are a lot less for far-field records than near-field ones. For instance, in far-field records, the standard deviation for Δ_{de} is a number between 0.13 to 0.2, whereas in near-field ones this number is ranging from 0.21 to 0.45. The amounts of σ for IDR in the roof story, based on different IMs depicted for 15-story model under near and far-field earthquakes could be observed in Figure 8.

Referring to this figure, for the near-field records, the IDRs calculated according to $\Delta_{v_e v_{\max}}$ have the least dispersion, and consequently, this recently established IM index is the most efficient IM parameter for evaluation of IDRs under this type of records. Although for far-field records, Δ_{de} has the minimum standard deviation, the amounts of standard deviation under $\Delta_{v_e v_{\max}}$ are very close to the amounts of standard deviation based on the Δ_{de}. The efficiency of $\Delta_{v_e v_{\max}}$ in comparison to the other IMs is more apparent if we consider the standard deviation of inter-story drift ratios for story 6 of 15-story model which represents significant dissimilarities between the standard deviations according to $\Delta_{v_e v_{\max}}$ with the standard deviations based on Δ_{de}, which is usually used as IM factor. This phenomena caused by pulse propagation of near-field record leading to more inter-story drift demands in the middle stories; therefore, in the discussed condition, application of $\Delta_{v_e v_{\max}}$ instead of the other IM factors is preferable with respect to the efficiency aspect. This fact could be noticed in Figure 9. Considering Figures 8 and 9 simultaneously, it is perceived that because of concentration of inter-story drifts in the middle stories, amplification of intensity measures concludes amplification of standard deviations in these stories; however, in the roof story, standard deviations decrease by increasing the amounts of IMs.

Also, from slight variations between dispersion of

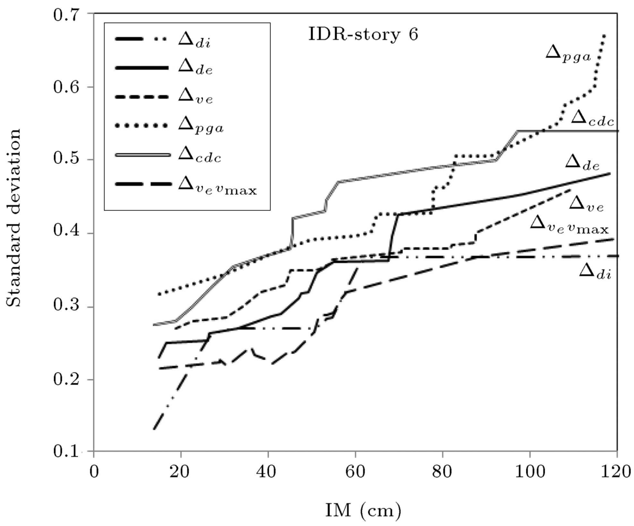

Figure 9. Standard deviations for IDR in story 6 of 15-story model under near-field records subjected to different IMs.

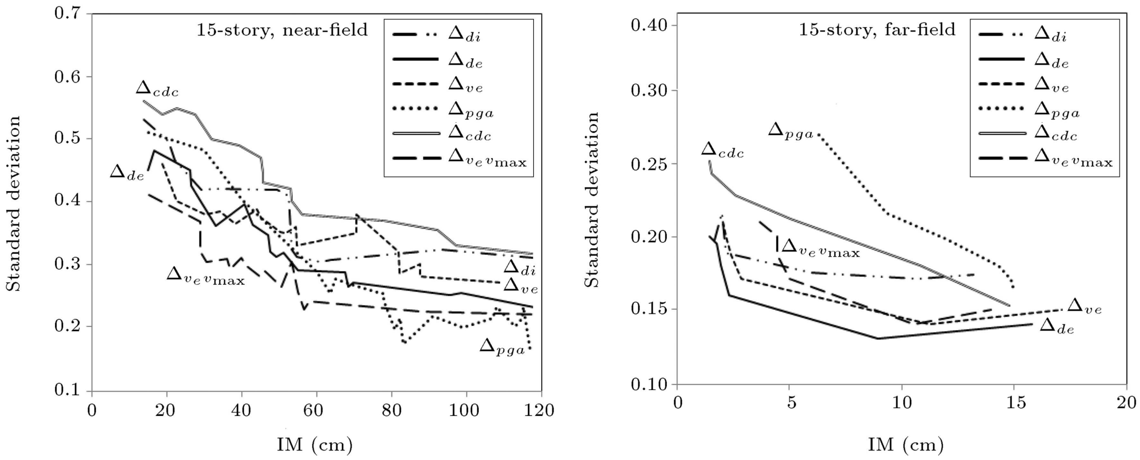

Figure 8. Standard deviations for IDR in roof story according to different IMs for 15-story model under near and far-field records.

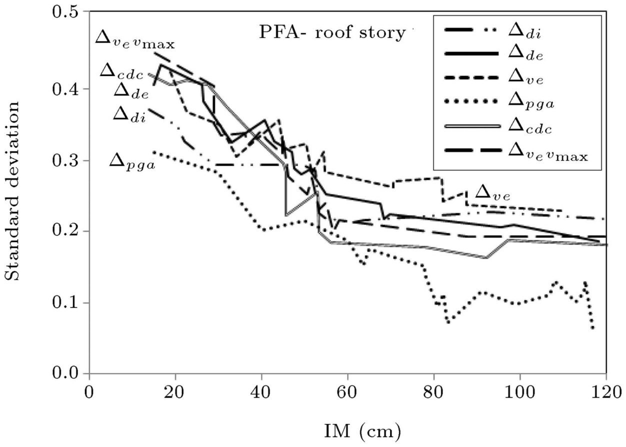

Figure 10. Standard deviations for PFA in roof story of 15-story model under near-field records subjected to different IMs.

IDRs calculated in terms of Δ_{di} and Δ_{de}, especially for IMs smaller than 80 cm, common amounts of IMs, it could be concluded that it is satisfactory to manipulate elastic spectral values rather than inelastic spectral ones considering unavoidably complicating and time-consuming analyses for attaining Δ_{di}.

To assess the IM factors for acceleration sensitive EDPs, standard deviations of PFA in the roof story were computed and tabulated in Figure 10. It is observed that Δ_{pga} is the most efficient IM factor for this EDP. But on the other hand, comprising dissimilar trend for the median values of Δ_{pga} is the significant deficiency for this index. Moreover, employing Δ_{pga} as IM could only donate a narrow range of moderate IMs and for providing other amounts of IM, record scaling has to be done.

The differences between dispersion of PFAs calculated according to Δ_{di} and Δ_{de} is remarkable. There is slight difference between these IMs in the range of 40 cm to 80 cm, but for the IMs out of this range considerable difference between the outcomes corresponding to Δ_{di} and Δ_{de} has been noted. Implementation of inelastic spectral displacement as IM index has more deviation in comparison to Δ_{de} for IMs larger than 80 cm whereas for small amount of IMs Δ_{di} concludes the smaller deviations.

6.4. Evaluation of the IMs sufficiency

The sufficiency of an IM has been identified as a viable measure of its appropriateness for use in PBEE. As defined earlier, an estimator is considered sufficient if it utilizes all the information in the sample that is relevant to the estimation of the seismic performance parameter. This means that the conditional probability distribution of EDP, given IM, does not vary with the other parameters involved in computing the seismic hazard, mainly magnitude (M) and source-to-site distance (R) [37]. Sufficiency, or in other words, independence of the structural responses from the ground motion characteristics except assumed intensity measure is the main assumption in assessing the structural performance according to Eq. (1); otherwise, M and R should appear after the IM in the first integrand in Eq. (1) [49]. Taking into account sufficient IM contributes significantly in decreasing the runtime of the seismic performance assessment procedures [39]. Selecting an efficient and sufficient IM for near-fault ground motions requires more accurate attention for the special characteristics of this type of motions. In near-fault records, most of the seismic rupture energy appears as a single coherent pulse-type motion. Ground motions with these distinct pulse-like characteristics, generally arise at the beginning of the seismogram, and their effects tend to increase the long-period portion of the acceleration response spectrum [11]. Consequently, the spectral acceleration, measured at the first-mode period of vibration, $\Delta_{de}(T_1)$, which is commonly used as IM in the PBEE, cannot adequately predict the seismic demands imposed by the near-fault pulse-like ground motions on structures. To describe the peculiar spectral shape of pulse-like records by using a simple index, in this study, the records are divided to two groups, near and far-field, to evaluate the sufficiency of EDPs under each intensity parameter more precisely. Dependency of EDPs in other seismological factors, namely the earthquake magnitude, M_w, and source to site distance, R, is evaluated by studying the residuals of EDP's estimated using that intensity parameter. The residual of an EDP at a given level of IM are computed as:

$$\varepsilon = \mathrm{Ln}\left(\frac{\mathrm{EDP}}{\overline{\mathrm{EDP}_{est.}}}\right) = \mathrm{Ln}(\mathrm{EDP}) - \mathrm{Ln}(\overline{\mathrm{EDP}_{est.}}), \quad (5)$$

where EDP is the demand parameter estimated from the result of nonlinear dynamic analysis and $\overline{\mathrm{EDP}_{est}}$ is the median of the EDPs estimated from the series of nonlinear dynamic analyses.

Once the residuals are estimated, it is assumed that they vary linearly with earthquake magnitude or distance as follows:

$$\varepsilon = a + bx, \quad (6)$$

where x is any seismological factor that affects the selected IM, a and b are constants estimated by performing linear regression analysis.

Figures 11 and 12 tabulate the variation of IDR's residuals in the roof story with the changes in M_w and R for scale levels of $\Delta_{de} = 5$ cm and $\Delta_{de} = 100$ cm. As it could be confirmed by the plots in both cited figures, the diagram of the residuals according to $\Delta_{v_e v_{\max}}$ is closer to constant line meaning the less dependency on M_w and R in comparison with the common used IM, Δ_{de}. The dependency values of EDPs due to Δ_{de} both

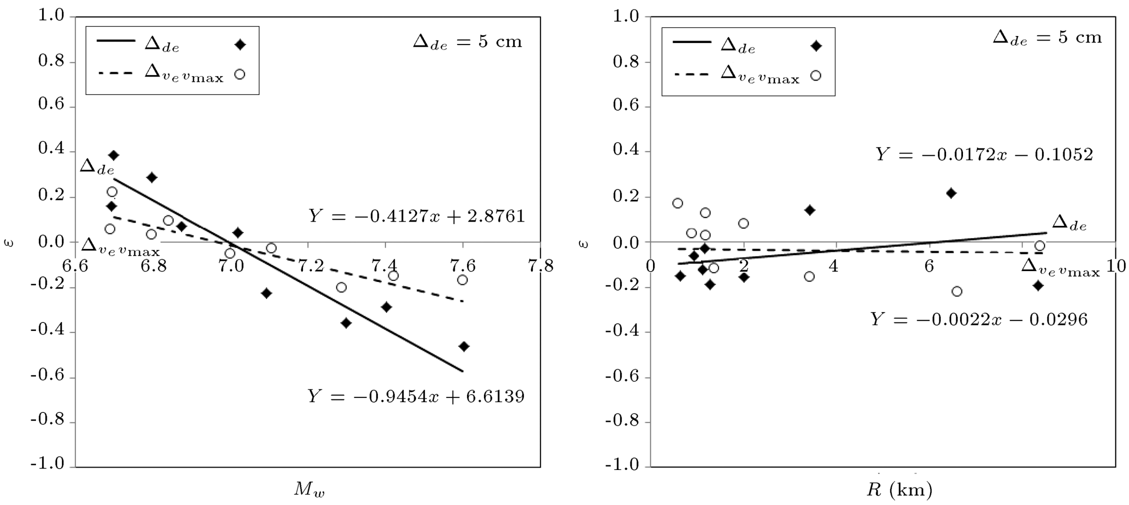

Figure 11. Variation of EDP residuals with earthquake magnitude, M_w, and earthquake closest site to source distance, R, for IDR in roof story for 3-story model under near-field records.

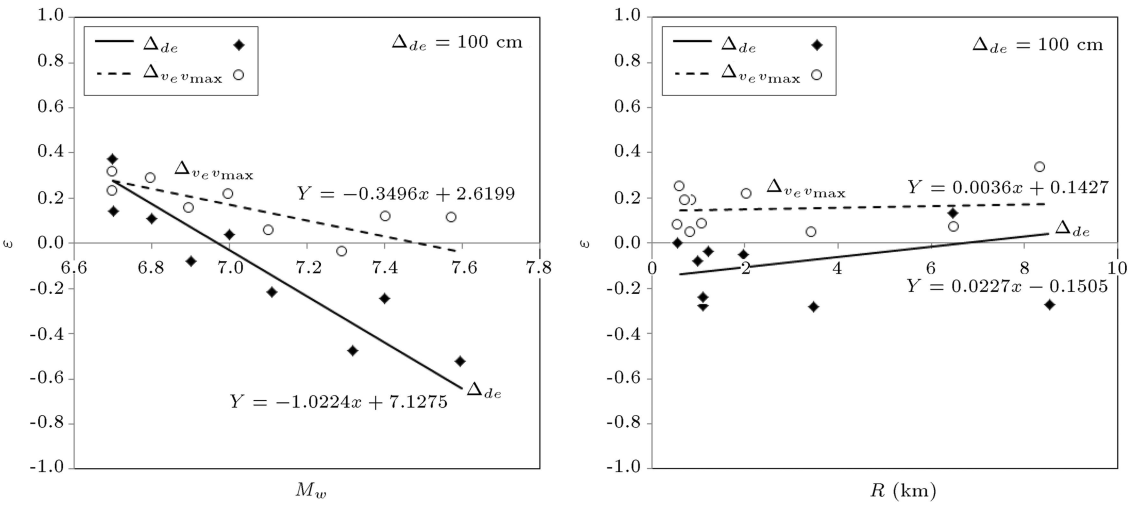

Figure 12. Variation of EDP residuals with earthquake magnitude, M_w, and earthquake closest site to source distance, R, for IDR of roof story for 3-story model under near-field records.

$\Delta_{v_e v_{\max}}$ and in company with the differences between these dependency values increases by raising the scaling levels, whereas it is prominent that the dependency of EDPs to M_w according to $\Delta_{v_e v_{\max}}$ is incredibly less than this value in view of Δ_{de}.

The ratio of b (slope of diagram) according to $\Delta_{v_e v_{\max}}$ to the b according to Δ_{de} when scaling level is $\Delta_{de} = 5$ cm is equal to 2.291, which is derived from dividing -0.9454 by -0.4127. However, this ratio in scaling level of $\Delta_{de} = 100$ cm is equal to 2.92 (-1.0224/-0.3496) presenting the growing trend in dependency of EDPs to M_w by raising the scaling level.

The dependency of EDPs to R (site to source distance), for both $\Delta_{v_e v_{\max}}$ and Δ_{de} are considerably less than the dependency of these parameters to the magnitude of earthquake, M_w. By evaluating EDPs of the model associated with $\Delta_{v_e v_{\max}}$ rather than Δ_{de}, the slope of the residual diagram upon source to site distance declined from 0.0172 to 0.0022 in the scale factor of $\Delta_{de} = 5$ cm that means of 7.82 ratio of reducing. This reduction ratio in scale level of $\Delta_{de} = 100$ cm declined to the amounts of 6.31, derived from dividing 0.0227 by 0.0036. Consequently, it could be concluded that the influence of using $\Delta_{v_e v_{\max}}$ in reduction of dependency of EDPs to site to source distance decrease by raising the scale levels.

For more comprehension comparison of $\Delta_{v_e v_{\max}}$ and Δ_{de}, the residuals of IDR in story 6 for 15-story building were supplemented. It could be observed that in middle stories, in the condition of intense pulse-like effects, using $\Delta_{v_e v_{\max}}$instead of Δ_{de} has more influence on sufficiency of the IM. Diagrams in Figure 13 demonstrate that the reduction ratio in slope of dependency on M_w was equal to 4.75 (0.659/0.1386) and this value in the case of dependency on distance

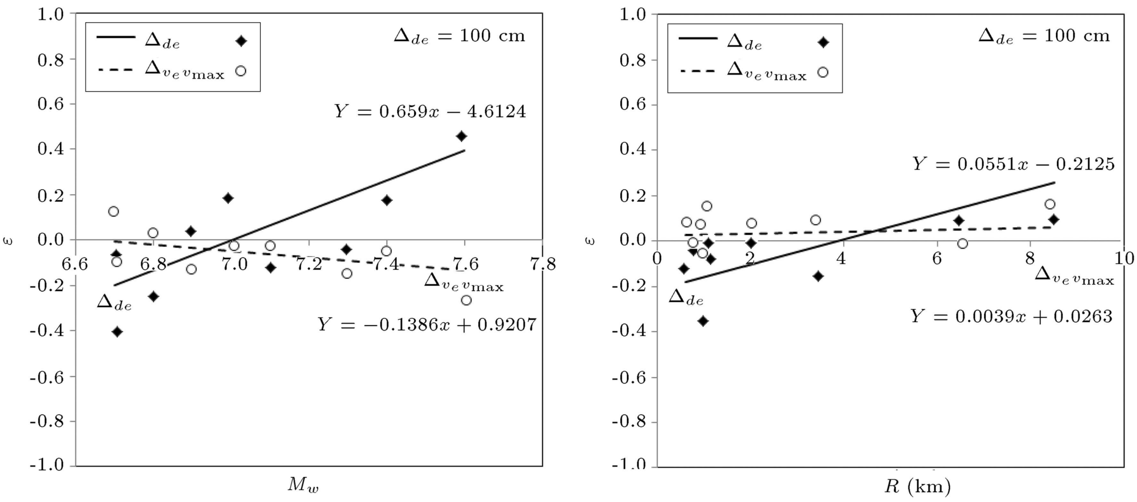

Figure 13. Variation of EDP residuals with earthquake magnitude, M_w, and earthquake closest site to source distance, R, for IDR in 6th story for 8-story model under near-field records.

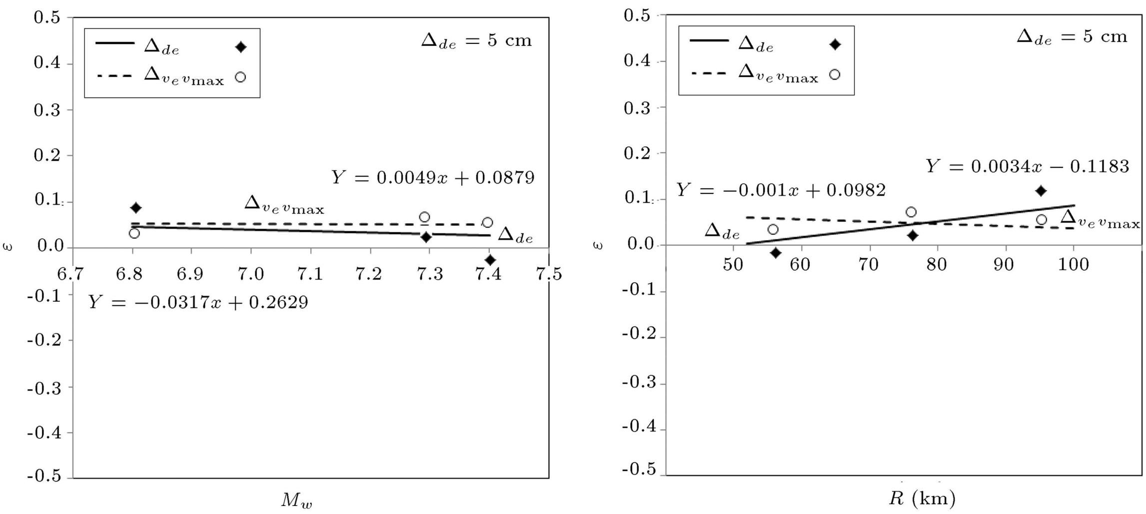

Figure 14. Variation of EDP residuals with earthquake magnitude, M_w, and earthquake closest site to source distance, R, for IDR in roof story for 3-story model under far-field records.

was evaluated equal to 14.128 (0.0551/0.0039), whereas both of them are more than the reduction ratios in the roof story which were pointed above. It could be confirmed that utilizing this new established IM could reduce the dependency of EDPs to M_w and R especially for EDPs in stories under pulse-like effects. For far-field records, using $\Delta_{v_e v_{\max}}$ increases the independency of EDPs on M_w and R too; however, because of smallness of EDP values, the effect is not as evident as near-field records. The residuals for IDR in roof story for 3-story building under far-filed records are seen in Figure 14. Also the residuals for PFA in roof story for 3-story and 15-story building under near-field records are seen in Figures 15 and 16 presenting less dependency on M_w and R, under $\Delta_{v_e v_{\max}}$ than Δ_{de}.

It is worth mentioning that there are some quantitative measures for assessing sufficiency of a parameter. By using these measures, a safe domain for b and correlation coefficient of specimen values has been acquired [39]. Many researchers have illustrated that the sufficiency of Δ_{de} always locates in the safe domain and as the gained dependency of EDPs according to $\Delta_{v_e v_{\max}}$ is less than Δ_{de}, therefore, it is not required to discuss the safe domain of sufficiency for $\Delta_{v_e v_{\max}}$. On the other hand, the attempt is to compare the sufficiency of the new proposed IM factor with the common used one that both were located in the safe domain. In all the relevant diagrams, there is less dependency between EDPs and the magnitude of earthquake, M_w, and source to site distance, R, when the IM is $\Delta_{v_e v_{\max}}$ than the case of utilization of Δ_{de} as IM parameter and further discussion about their safe domains are beyond the scope of this study.

For the other IM factors, previously conducted researches have revealed that the residual of EDPs under Δ_{pga} are beyond the safe domain and the residuals of

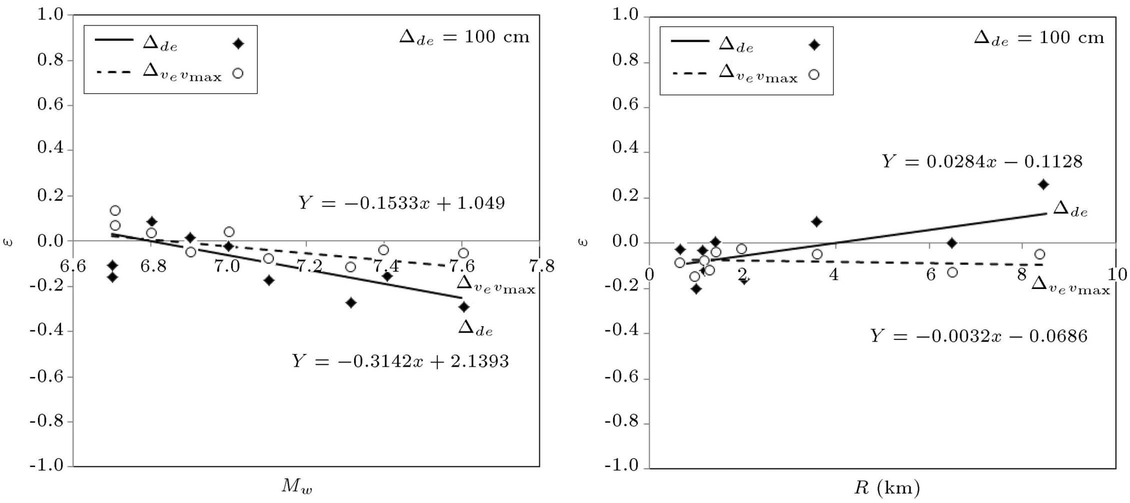

Figure 15. Variation of EDP residuals with earthquake magnitude, M_w, and earthquake closest site to source distance, R, for PFA in roof story for 3-story model under near-field records.

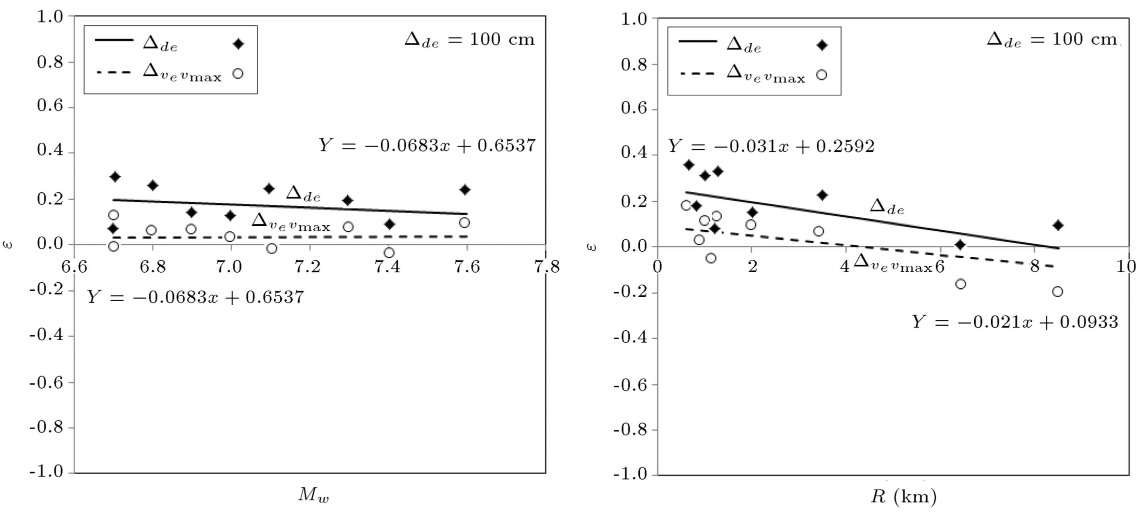

Figure 16. Variation of EDP residuals with earthquake magnitude, M_w, and earthquake closest site to source distance, R for PFA in roof story for 15-story model under near-field records.

EDPs associated with Δ_{cdc} are approximately in the limit lines. The residuals of EDPs under Δ_{di} and Δ_{ve} are close to the amounts of Δ_{de} [39].

By all the discussions, it could be distinguished that the $\Delta_{v_e v_{\max}}$ is the most sufficient IM factor, among the frequently used factors that have been studied in this paper, and since calculation and evaluation of EDPs according to this IM is very straightforward, it could be selected as the utilized IM, especially for near-field records to reduce the dependency of structural responses to magnitude of earthquake, M_w, and source to site distance, R.

7. Conclusion

The central issue of this research is proposing a new intensity measure based on velocity characteristics of ground motions. For this purpose, a new intensity measure $\Delta_{v_e v_{\max}}$ has been introduced and some assessments in view of efficiency and sufficiency were conducted subjected to near and far-field records. Also, evaluation of some common facilitated intensity measures was done and the following results could be presented briefly.

- The trend of median values distribution based on $\Delta_{v_e v_{\max}}$ is similar to the other IMs considering the both IDR and PFA as the EDP parameter, and both near and far-field ground motions except some observations about the limited domain of Δ_{pga} that makes utilizing of this new proposed IM very straightforward, and transmission from this IM to one another is too reliable.
- For the near-field records, the calculated IDRs according to $\Delta_{v_e v_{\max}}$ have the least dispersion, and consequently, this recently established IM index is

the most efficient IM parameter for evaluation of IDRs under this type of records. Although for far-field records Δ_{de} has the minimum standard deviation, the amounts of standard deviation under $\Delta_{v_e v_{\max}}$ are very close to the amounts of standard deviation based on the Δ_{de}. The efficiency of $\Delta_{v_e v_{\max}}$ in comparison to the other IMs is more apparent if we consider the standard deviation of inter-story drift ratios for the middle stories of high and mid-rise models which represents significant dissimilarities between the standard deviations according to $\Delta_{v_e v_{\max}}$ with the standard deviations based on the other IMs. This phenomena were caused by pulse propagation of near-field record leading to more inter-story drift demands in the middle stories; therefore, in the discussed condition, application of $\Delta_{v_e v_{\max}}$ instead of the other IM factors is preferable with respect to the efficiency aspect.

- The diagram of the residuals according to $\Delta_{v_e v_{\max}}$ is closer to constant line, meaning the less dependency on M_w and R in comparison with the common used IM, Δ_{de}. Raising the scaling levels, either the dependency values of EDPs due to both $\Delta_{v_e v_{\max}}$ and Δ_{de} and the differences between these dependency values increase, whereas it is prominent that the dependency of EDPs to M_w according to $\Delta_{v_e v_{\max}}$ is incredibly less than this value in view of Δ_{de}. Also, it could be observed that in middle stories, in the condition of intense pulse-like effects, using $\Delta_{v_e v_{\max}}$ instead of Δ_{de} has more influence on sufficiency. By all the discussions, it could be distinguished that the $\Delta_{v_e v_{\max}}$ is the most sufficient IM factor, among the factors that have been studied in this paper, and since calculation and evaluation of EDPs according to this IM are very straightforward, it could be selected as the utilized IM especially for near-field records to reduce the dependency of structural responses to the magnitude of earthquake, M_w, and source to site distance, R.

- It could be concluded that it is satisfactory to manipulate elastic spectral values rather than inelastic spectral ones from slight variations between dispersion of IDRs calculated in terms of Δ_{di} and Δ_{de}, especially for IMs smaller than 80 cm considering unavoidably complicating and time-consuming analyses for attaining Δ_{di}. However, the differences between dispersion of PFAs calculated according to Δ_{di} and Δ_{de} is remarkable except for the moderate IMs ranging from 40 cm to 80 cm. by all the discussions, it could be concluded that for common amounts of IMs which is in a moderate range, elastic spectral values could be adequately substituted.

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