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GROUND MOTION INTENSITY MEASURES FOR PROBABILISTIC SEISMIC ANALYSIS OF THE RC HIGH-RISE BUILDINGS

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Abstract

The construction of high-rise buildings in seismically active areas has become an everyday design trend, which is mainly due to growing urbanisation, rapid growth of cities, and concentration of material resources in urban environments. A similar trend is also emerging in the South-European Mediterranean zone. As the entire Mediterranean belt is a seismically active area, detailed seismic analyses have to be undertaken for this category of buildings. This paper is a part of an extensive research work focusing on the probabilistic seismic analysis and estimation of vulnerability of RC high-rise buildings to seismic excitation typical for the South-European Mediterranean zone. The theme of this paper is the analysis of relationship between the ground motion intensity measure, IM, and the seismic response parameter, EDP, in order to identify and define the most efficient EDP-IM dependencies for RC high-rise buildings that could also be useful in practical terms. The EDP-IM dependency is efficient if it provides the lowest dissipation of EDP results for given IM values. The EDP-IM dependence is practical if the relationship can be established through intensity measures that enable a clear physical interpretation, and that can easily be calculated from seismic records and seismic responses from the non-linear time-history analysis.

As a prototype buildings, 20-story, 30-story and 40-story RC high-rise buildings with core wall structural system were selected. The analysis and design of the prototype RC buildings were conducted according to the Eurocode 2 and Eurocode 8. In order to determine the most efficient EDP-IM model, 720 nonlinear time-history analyses were conducted for 60 ground motion records with a wide range of magnitudes and distances to source, and for various soil types, thus taking into account uncertainties during ground motion selection. Ground motion selection was done within the South-European Mediterranean seismic zone. Due to the lack of ground motions in the Southern Euro-Meditteranean zone, which may be selected without being previously scaled and with mean spectrum to be in accordance with Eurocode spectrum, it was necessary to scale the ground motions. The mean squared error method (MSE) was chosen as a mode of scaling of ground motions. For the purpose of conducting nonlinear time-history analyses, non-linear 3D models of the buildings were designed using the PERFORM-3D software. A detailed analysis and statistical processing of results were performed, and appropriate EDP-IM relationships were derived. Analyzing a large number of results it were adopted conclusions on the efficiency of individual ground motion intensity measures for the case of RC high-rise building.

Keywords: high-rise building, intensity measure, engineering demand parameter, nonlinear time-history analysis, regression analysis

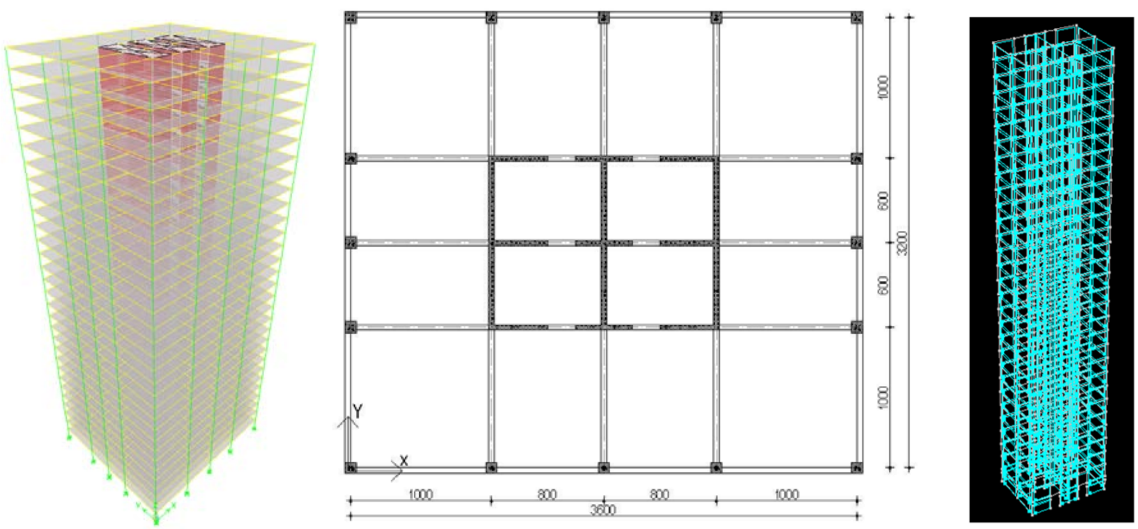
1. Introduction

The theme of this paper is the analysis of relationship between the ground motion intensity measure, IM, and the engineering demand parameter, EDP, in order to identify and define the most efficient EDP-IM dependencies for RC high-rise buildings that could also be useful in practical terms. The EDP-IM dependency is efficient if it provides the lowest dissipation of EDP results for given IM values. The EDP-IM dependence is practical if the relationship can be established through intensity measures that enable a clear physical interpretation, and that can easily be calculated from seismic records and seismic responses directly resulting from the non-linear time-history analysis. This dependence is indispensable for obtaining the probability of exceeding P [EDP/IM] of an appropriate measure of seismic response EDP, as related to the seismic intensity measure IM, in the process of probabilistic seismic analysis according to the performance-based design [1].

As a prototype buildings, 20-story, 30-story and 40-story RC high-rise buildings with core wall structural system were selected. In order to determine the most efficient EDP-IM model, 720 nonlinear time-history analyses were conducted for 60 ground motion records with a wide range of magnitudes and distances to source, and for various soil types, thus taking into account uncertainties during ground motion selection. A detailed analysis and statistical processing of results were performed, and appropriate EDP-IM relationships were derived.

2. Description of prototype RC high–rise buildings

As a prototype buildings, 20-story, 30-story and 40-story RC high-rise buildings with core wall structural system that assumes the entire seismic force, and with RC frames along the periphery that assume the gravity load only [2] were selected. The typical plan view of the storey, the ETABS model [3] and PERFORM-3D model [4] of prototype RC high-rise buildings are presented in Fig. 1.



(a) (b) (c)

Fig. 1 (a) Etabs model of reference building, (b) typical plan view of the storey, and (c) Perform3D model of a reference building

Basic properties of a reference building are shown in Table 1.

Table 1 - Main features of the prototype RC high-rise buildings

Features	20-story building	30-story building	40-story building
Total height (m)	60	90	120
Storey height (m)	3	3	3
Floor RC slab thickness	20cm	20cm	20cm
RC beams	40x65cm	40x65cm	40x65cm
RC columns	80x80cm	80x80cm	90x90cm
Core walls thickness	1-5 storey: 30cm	1-5 storey: 40cm	1-10 storey: 55cm
	6-20 storey: 20cm	6-30 storey: 30cm	11-40 storey: 45cm
Coupling beams in X direction	20x80cm and 30x80cm	30x80cm and 40x80cm	45x80cm and 55x80cm
Concrete f_{ck} (f_{cm}) (MPa)	35(43)	45(53)	55(63)
Reinforcement f_{yk} (f_{ym}) (MPa)	500(575)	500(575)	500(575)
Modulus of elasticity E_{cm} (MPa)	34000	36000	38000

Seismic design of the prototype RC buildings was done in accordance with Eurocode 2 [5] and Eurocode 8-1 [6]. Seismic linear analysis of buildings was done using a multi-modal response spectrum analysis, which is quite appropriate due to higher-mode effects in high-rise RC buildings. The modal periods of buildings and mass participation factors of first four modes are shown in the table 2. For linear analysis and seismic design of buildings, ETABS spatial models of buildings [3] were used. Seismic forces are dominantly accepted by RC core walls. For this reason, RC core walls were subject to further detailed seismic design in accordance with relevant provisions of Eurocodes and thereafter nonlinear time-history analyses.

Table 2 Modal periods and mass participation factors for the prototype RC high-rise buildings

Prototype buildings			20-story building	30-story building	40-story building
Period in Y direction (sec)	Mode	1	1.652	2.880	4.097
		2	0.389	0.623	0.858
		3	0.181	0.270	0.355
		4	0.117	0.164	0.207
Period in X direction (sec)	Mode	1	1.641	2.597	3.511
		2	0.480	0.702	0.880
		3	0.250	0.347	0.423
		4	0.164	0.228	0.275
Mass participation factors in Y direction (%)	Mode	1	64.26	63.53	63.24
		2	20.32	19.43	18.94
		3	7.04	7.05	7.05
		4	3.23	3.57	3.65
Sum of mass part.factors in Y direction (%)			94.85	93.58	92.88
Mass participation factors in X direction (%)	Mode	1	69.36	67.70	66.08
		2	15.96	17.40	18.78
		3	5.49	5.23	5.68
		4	2.83	2.78	2.64
Sum of mass part.factors in X direction (%)			93.64	93.11	93.18

3. Nonlinear time-history analysis of prototype RC high-rise buildings

The PERFORM-3D software [4] was used for the nonlinear time-history analysis. The nonlinear spatial model of the RC core walls was made. The mathematical model used for elastic analysis is extended to include the strength of structural elements and their post-elastic behaviour. In order to present as realistically as possible the real behaviour of the structure during nonlinear analyses, the properties of elements were based on mean values of material properties in accordance with recommendations given in Eurocode 8 – Part 1 [6], which differs from the design analysis phase where typical values of material properties are adopted (values with the fractile of 5%) so as to remain on the side of safety. Stress-strain relationship for unconfined concrete, confined concrete, and reinforcement, compliant with recommendations given in Eurocode 8 – Part 2 [7], were adopted.

The core walls were modeled using non-linear vertical fiber elements representing the expected behavior of the concrete and reinforcing steel [8]. The area and location of reinforcement within the cross-section, as well as concrete properties, were defined using individual fibers forming the cross-section of the wall. The shear behavior was modeled as elastic.

The data of the Seismological Institute of Montenegro and the European strong-motion database [9] were used as database of ground motions. Sixty seismic records were selected. Out of these records 25 were recorded in rock, which corresponds to the type A soil according to Eurocode 8. The remaining 35 records were recorded on stiff soil, which corresponds to the type B soil according to Eurocode 8. Magnitude values for selected records range between 5.1 and 7.0, while distances to source vary from 5 to 70 km. The basic criterion used in this paper for the selection of ground motions is that the mean value of their response spectra be compatible with the corresponding target spectrum in a wider range of periods. The elastic spectrum from Eurocode 8 was selected as the target spectrum for the return period of 475 years, with the design ground acceleration amounting to 0.37g. The mean squared error method (MSE) was chosen as a mode of scaling of ground motions [10]. By this method ground motions are scaled in a way where the mean squared error is minimized over the whole range of periods. Besides earthquakes corresponding to a 475-year return period (earthquake with a 10% chance of exceedance in 50 years), the prototype buildings were also tested for seismic action with a 2475-year return period (earthquake with a 2% chance of exceedance in 50 years).

Fig. 2 and 3 show: response spectra of selected ground motions scaled by MSE method for the intensity level of 10%/50, the mean spectrum and relevant target spectra (Eurocodes 8 elastic spectra) for the intensity level of 10%/50 and the mean spectrum for the intensity level of 2%/50, for certain soil types.

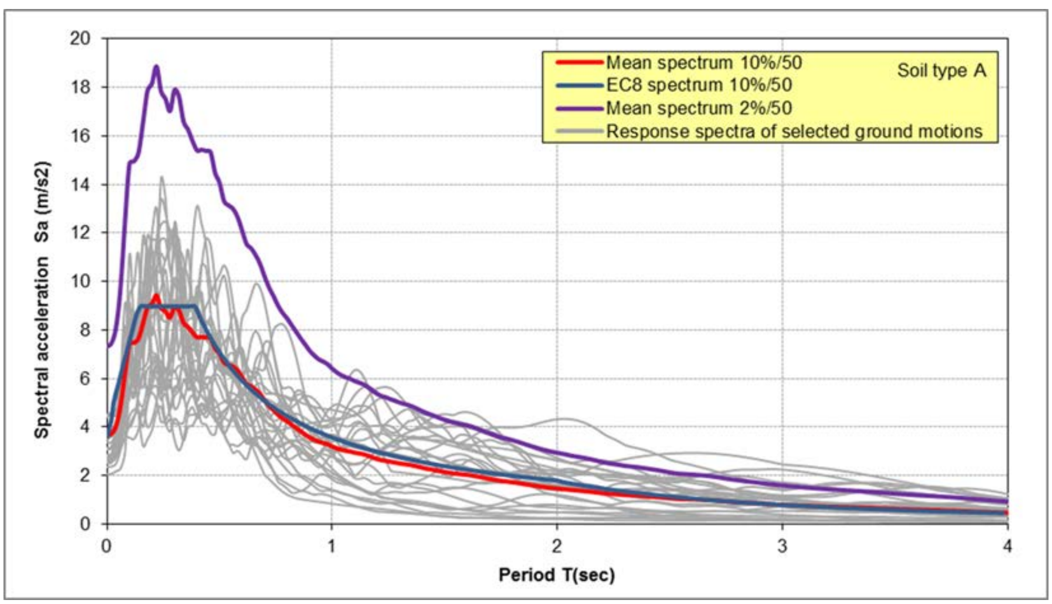


Fig. 2 Response spectra of the selected ground motions for soil type A, mean spectra of the selected ground motions for intensity levels 10%/50 and 2%/50 and elastic EC8 spectrum for soil type A for intensity level 10%/50

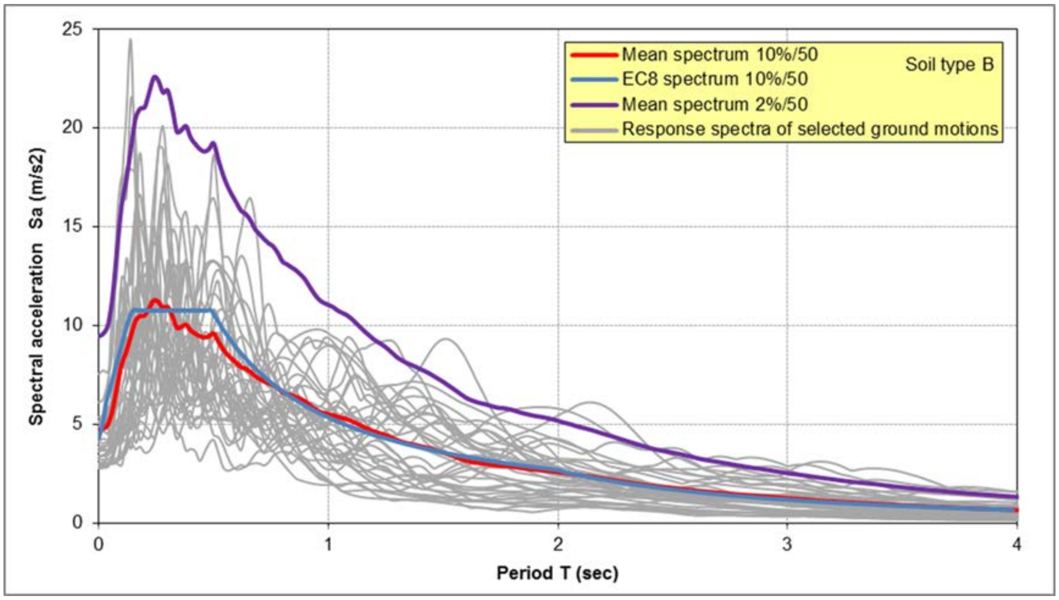


Fig. 3 Response spectra of the selected ground motions for soil type B, mean spectra of the selected ground motions for intensity levels 10%/50 and 2%/50 and elastic EC8 spectrum for soil type B for intensity level 10%/50

4. Selection of earthquake intensity measures and engineering demand parameters

The selection of an appropriate intensity measure is a question that has been studied for a long time in earthquake engineering. The intensity measures should be such that they comprise the greatest possible number of earthquake features such as the amplitude, frequency content, duration of strong part of ground motion, etc. Selected intensity measures representing ground motion amplitudes are: peak ground acceleration (PGA), peak ground velocity (PGV), and peak ground displacement (PGD). The peak ground acceleration (PGA) exerts the greatest influence on the seismic response of structures with higher frequencies (periods of less than 0.5 s), while structures with lower frequencies, i.e. with periods of more than 0.5 s, are more sensitive to peak ground velocity (PGV) and peak ground displacement (PGD) [11]. The intensity measures characterizing the frequency content are: spectral acceleration $S_a(T_1)$, spectral velocity $S_v(T_1)$, spectral displacement $S_d(T_1)$, and pseudo spectral velocity $PSV(T_1)$.

High-rise buildings are specific, due to their response frequency range is much wider than for low-rise or mid-rise buildings. For that reason, intensity measures comprising a wider range of frequency content of response spectra are more appropriate for the case of high-rise buildings. The following intensity measures, comprising a wider frequency range of response spectra, are studied in this paper:

- Matsumura mean spectrum intensity SI_m

The Matsumura mean spectrum intensity SI_m is defined as the area below the velocity spectrum between the periods T_y and $2T_y$, where T_y is the period corresponding to yield of structure [12]:

$$SI_m = \frac{1}{T_y}\int_{T_y}^{2T_y} S_v(T)\,dT \qquad (1)$$

- Martinez-Rueda mean spectrum intensity SI_{yh}

The Martinez-Rueda proposed that the second integration limit in the integral of the Matsumura mean spectrum intensity SI_m should be replaced with the period T_h which represents the new vibration period of the structure in the hardening range after yielding [13]:

$$SI_{yh} = \frac{1}{T_h - T_y} \int_{T_y}^{T_h} S_v(T)dT \tag{2}$$

In the case of RC high-rise buildings, higher-mode effects can not be neglected, and so the MPF (mass participation factor) weighted average value is adopted in this paper for the period corresponding to yield of structure T_y Eq. (3) [11]:

$$T_y = \frac{m_1 \cdot T_1 + m_2 \cdot T_2 + ... + m_n \cdot T_n}{m_1 + m_2 + ... + m_n} \tag{3}$$

where m_1,...m_n are mass participation factors of structural modes.

The value of the period T_h in the hardening range after yielding is determined using the nonlinear static pushover method, as proposed by Martinez-Rueda [13].

- Mean spectral velocity $S_{v,avg1}$:

$$S_{v,avg1} = \frac{m_1 \cdot S_v(T_1) + m_2 \cdot S_v(T_2) + m_3 \cdot S_v(T_3)}{m_1 + m_2 + m_3} \tag{4}$$

- Mean spectral displacement $S_{d,avg1}$:

$$S_{d,avg1} = \frac{m_1 \cdot S_d(T_1) + m_2 \cdot S_d(T_2) + m_3 \cdot S_d(T_3)}{m_1 + m_2 + m_3} \tag{5}$$

- Mean pseudo spectral velocity PSV_{avg1}:

$$PSV_{avg1} = \frac{m_1 \cdot PSV(T_1) + m_2 \cdot PSV(T_2) + m_3 \cdot PSV(T_3)}{m_1 + m_2 + m_3} \tag{6}$$

In analogy to these intensity measures, the values $S_{v,avg2}$, $S_{d,avg2}$ and PSV_{avg2} were defined, which take into account spectral values for the first four structural modes. Two cases were considered for the reference building in order to analyse the influence of higher-mode effects for the computation of intensity measures and yield periods T_y. In the first case, only the structure modes with mass participation factors greater than 5%, which are the first three modes of the reference building, were taken into account. In the second case, in which the first four modes of structure were taken into account, the analysis was made so as to consider the need of taking into account the modes whose mass participation factors are smaller than 5%.

The maximum interstorey drift for the entire structure IDR_{max}, the most frequently used engineering demand parameter, was selected in this paper as a engineering demand parameter.

5. Analysis results

In order to define the EDP-IM relationship for RC high-rise buildings, the prototype buildings were exposed to 60 ground motions with two levels of intensity in both directions of the structure. The total of 720 nonlinear time-history analyses were performed. Performing nonlinear time-history analyses for the selected ground motions scatter diagrams were obtained. The regression analysis was performed for each of these diagrams and, in the scope of these analyses, detailed statistical processing of results was made, and the corresponding EDP-IM relationships were derived. It assumes an exponential relationship between the engineering demand parameter EDP and intensity measure IM ($EDP=aIM^b$). The standard deviation value (deviation of the natural logarithms of the residuals IDR_{max} data obtained (on random sample) from the regression line) is used in this paper for the estimation of the dispersion of results [15].

Derived regression-model parameters *a* and *b*, dispersion results (standard deviations), and variation coefficients, are presented in Table 3. Coefficients of variation are smaller than 0.3 for most EDP-IM relationships considered, which means that a very small variability of results was obtained. This points to a high level of accuracy of calculated EDP-IM relationships, which is due to the great number of selected ground motions, i.e. to a great size of random sample in statistical term.

As to the ground motion amplitude parameters, the peak ground velocity (PGV) provided less dispersion of results, compared to the peak ground acceleration (PGA), and peak ground displacement (PGD). In general terms, all intensity measures related to velocity provided less dispersion, compared to those related to acceleration and displacement, because the reference building has basic modal periods in the tripartite spectrum area that is sensitive to velocity [14].

With respect to amplitude parameters, spectral values (parameters representing concrete points of frequency content) have proven to be more efficient, i.e. the presented smaller dispersion of results. With regard to these measures, the smallest dispersion of results was provided by spectral velocity $S_v(T_1)$, while other spectral values provided greater dispersion (Table 3).

As illustration of obtained analyses results the derived relationships between the intensity measure SI_m and interstorey drift IDR_{max} are shown in Fig. 4. Very small dispersion value σ was obtained, corresponding to coefficients of variation less than 0.3, which also points to a very small variability of the obtained data. The derived regression curve represents the mean value of IDR_{max}-SI_m relationships.

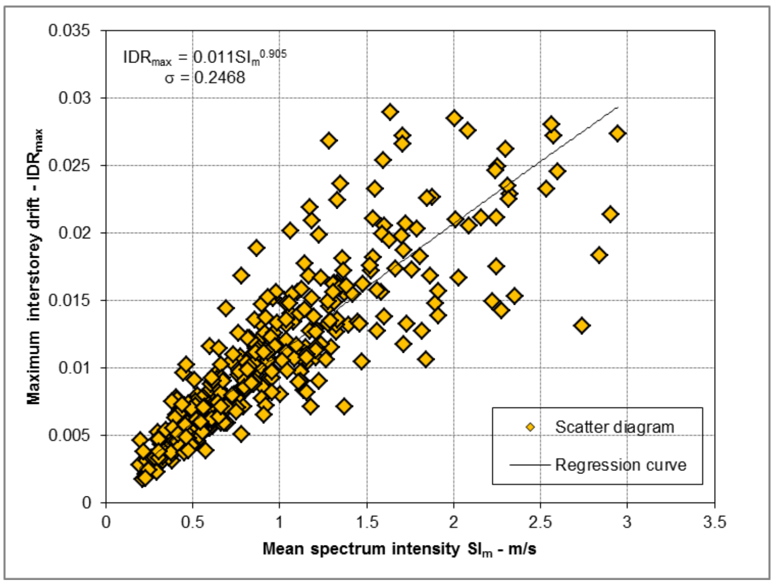


Fig. 4 Derived relationships between the intensity measure SI_m and interstorey drift IDR_{max}

Table 3. Derived regression model parameters, standard deviations and coefficients of variation for the analyzed IDR_{max}-IM_i relationships

Intensity measure IM		Regression model parameters		Coefficient of variation C.O.V	Standard deviation σ
Description	Denotation	a	b		
Ground motion amplitude parameters	PGA	0.0039	0.5280	0.5783	0.5371
	PGV	0.0191	1.1254	0.2914	0.2854
	PGD	0.0093	0.0459	0.6349	0.5819
Parameters representing concrete points of frequency content	$S_a(T_1)$	0.0080	0.4136	0.4156	0.3992
	$S_v(T_1)$	0.0106	0.8320	0.2857	0.2801
	$S_d(T_1)$	0.0202	0.5671	0.3476	0.3377
	$PSV(T_1)$	0.0124	0.5579	0.3346	0.3258
Parameters comprising a wider range of frequency content	SI_m	0.0110	0.9050	0.2506	0.2468
	SI_{yh}	0.0114	0.9230	0.2486	0.2449
	$S_{a,avg1}$	0.0030	0.8108	0.4185	0.4017
	$S_{v,avg1}$	0.0111	1.0468	0.2566	0.2525
	$S_{d,avg1}$	0.0255	0.6350	0.3374	0.3283
	PSV_{avg1}	0.0130	0.8747	0.2607	0.2565
	$S_{a,avg2}$	0.0025	0.8668	0.4207	0.4037
	$S_{v,avg2}$	0.0114	1.0535	0.2585	0.2544
	$S_{d,avg2}$	0.0262	0.6369	0.3379	0.3289
	PSV_{avg2}	0.0132	0.8926	0.2597	0.2555

Intensity measures comprising a wider range of response spectra SI_m and SI_{yh} provided a smaller dispersion of results compared to individual spectral values $S_a(T_1)$, $S_v(T_1)$, $S_d(T_1)$ and $PSV(T_1)$. This is due to the fact that the range of frequency response of high-rise buildings is much wider compared to lower buildings, and hence the intensity measures comprising a wider range of response spectra are more efficient. In the case of mean Matsumura intensity SI_m and mean Martinez-Rueda intensity SI_{yh}, the dispersion is practically the same, because the modal period T_h is approximately equal to $2T_y$ for the case of the reference building.

Mean spectral values as the intensity measures that take into account the influence of higher-mode effects, $S_{v,avg1}$, $S_{d,avg1}$ and PSV_{avg1}, provide approximately (10-40)% smaller dispersion of results compared to spectral values $S_v(T_1)$, $S_d(T_1)$ and $PSV(T_1)$, and hence demonstrate that they are better intensity measures for the case of RC high-rise buildings [16]. Relationships derived between mean spectral velocities $S_{v,avg1}$ and $S_{v,avg2}$ and seismic response parameter IDR_{max} are presented in Fig. 5. By comparing two typical cases of mean spectral velocity, the first one in which only the structure modes with mass participation factors greater than 5% are taken into account, which represents only the first three structural modes $S_{v,avg1}$, and the second one where the first four structural modes $S_{v,avg2}$ are taken into account, it can be observed that differences in dispersion are not great, i.e. the dispersion is practically the same. It can therefore be concluded that it would be sufficient, during calculation of mean spectral values, to take into account only the modes that dominantly influence the system's response, i.e. in accordance with Eurocode 8, those vibration modes whose mass participation factors are greater than 5% with the total sum of more than 90%.

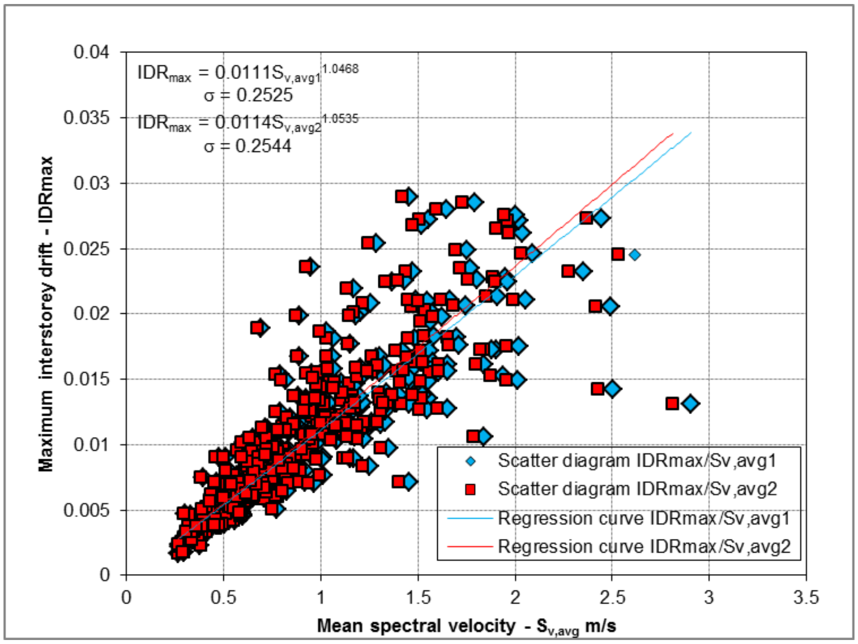


Fig. 5 Derived relationships between mean spectral velocities $S_{v,avg1}$ and $S_{v,avg2}$ and interstorey drift IDR_{max}

6. Conclusions

In the scope of analysis of relationships between the earthquake intensity measure IM and the engineering demand parameter EDP, as conducted on the selected prototype RC high-rise buildings, appropriate conclusions were made regarding the efficiency of individual intensity measures IM, as related to the considered engineering demand parameters IDR_{max}. Appropriate relationships between IDR_{max}-IM_i were derived as a result of a detailed analysis and statistical processing of results. Considering the quality of results obtained, the derived dependencies can be used for defining maximal interstorey drifts (IDR_{max}) for RC high-rise buildings of the structural system corresponding to the reference building and similar systems.

Intensity measures related to velocity provided less dispersion, compared to those related to acceleration and displacement and, by that, they have proven to be more efficient. Intensity measures based on frequency content are more efficient than the measures representing ground motion amplitudes (PGA and PGD). Peak ground velocity PGV, with respect to its efficiency and feasibility proved to be quite satisfactory intensity measure. Mean spectral values that take into account spectral values of modes with mass participation factors greater than 5%, $S_{v,avg}$, $S_{d,avg}$ and PSV_{avg}, have proven to be more efficient for the case of RC high-rise buildings as related to the spectral values $S_v(T_1)$, $S_d(T_1)$, and $PSV(T_1)$. For that reason, they are proposed as the intensity measures appropriate for RC high-rise buildings.

Intensity measures comprising a wider range of response spectra are the intensity measures that provide the most efficient relationships between the engineering demand parameter and the intensity measure, in the case of RC high-rise buildings.

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