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# INVESTIGATING THE EFFICIENCY AND THE SUFFICIENCY OF IMs FOR THE PROBABILISTIC SEISMIC ASSESSMENT OF THE POUNDING EFFECT BETWEEN ADJACENT RC STRUCTURES

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## Abstract

*The objective of this study is to identify appropriate intensity measures (IMs) for use in the probabilistic seismic assessment of the pounding effect between adjacent reinforced concrete (RC) structures. For this purpose, the efficiency and the sufficiency of twenty-three seismic IMs of forty-nine 2-component ground motions, are investigated. The structural pounding between multistory RC structures is examined taking into account three different separation gap distances. 294 nonlinear dynamic analyses are performed in the concept of the Cloud Analysis method to define the seismic demand parameters of an eight-story RC structure due to the pounding effect. Structural demands in terms of a) maximum displacement at the top of the contact point $\delta_{max}$, b) maximum interstory drifts, $IDR_{max}$, and c) maximum curvature ductility demand $\mu_{\varphi,max}$ of the most critical column, are estimated. Thereafter, the efficiency and the sufficiency of each IM are evaluated. The results of this study indicate; (a) the structural dependent IMs are more efficient in predicting the seismic demands of the RC structure, (b) an optimal IM that satisfies simultaneously the criteria of efficiency and sufficiency is difficult to be identified, (c) the efficiency of an IM is usually accompanied with lack of its sufficiency and vice versa, (d) the local demands of the critical column that suffers the pounding effect alter the results of the IMs' sufficiency, and (e) the superiority of the $S_{a,T1}$ compared to the structural independent IMs is justified when the relative sufficiency between IMs and seismic demands is evaluated.*

**Keywords:** structural pounding, ground motion IMs, efficiency property, sufficiency property, nonlinear dynamic analyses, reinforced concrete structure, Eurocodes 2 & 8

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## 1 INTRODUCTION

In the last three decades, several research has been undertaken to address the seismic performance of structures through probabilistic procedures. The vulnerability of the structures to seismic damage is assessed as the probability of an engineering demand parameter (EDP) to exceed the capacity for a given intensity measure (IM). For this purpose, nonlinear dynamic analysis methods should be performed to generate samples of EDPs|IMs, where the EDP represents the seismic performance of the structure, and the IM describes the ground motion characteristics [1].

The reliability of the overall probabilistic assessment depends on the IM that has been selected to be used. In order to quantify the suitability of an IM, different criteria such as efficiency [2], sufficiency [3], proficiency, practicality [4], hazard computability [5] have been proposed. Among them the efficiency and sufficiency criteria are the most commonly examined properties of IMs in the earthquake structural engineering. An IM is characterized as an efficient one if it predicts the structural response with small variability. Therefore, the uncertainties of record-to-record variability are reduced, and a small number of records can be used for performing nonlinear dynamic analyses. The sufficiency property indicates that the IM is independent of ground motion characteristics and that the vulnerability assessment is not affected by other parameters such as the magnitude $M_w$, the source-to-site distance $R_{rup}$, and the ground motion parameter epsilon ε.

Scalar and vector IMs are evaluated to improve the prediction of the structural response. Scalar IMs are divided into two categories: the structural independent and the structural dependent IMs. The first category of IMs may capture information on the ground motion such as frequency content, duration, and amplitude [e.g., 6-15], while the structural dependent IMs are related to the structure's dynamic characteristics [6, 16, 17]. On the other hand, the vector IMs incorporate different scalar IMs to improve the predictive capability with respect to the examined EDPs [18]. Also, several IMs that constitute modifications of $S_{a,T1}$ and incorporate spectral values of other periods have been proposed to capture the contribution of the higher modes and the period elongation effects [19, 20]. However, the modified IMs are rarely used due to the lack of attenuation relationship, which is needed to compute seismic hazard in terms of IM that is also required for the probabilistic seismic demand analysis [20]. The most widely used IMs for the probabilistic assessment of the structural seismic performance are the peak ground acceleration (PGA), and the spectral acceleration at the fundamental period of the structure ($S_{a,T1}$).

Literature provides research studies that quantify the efficiency and the sufficiency of an IM and evaluate the correlation between IMs and EDPs [21-25] However, only a few studies have focused on the verification of an appropriate IM when considering the earthquake-induced structural pounding phenomenon. Tubaldi et al [26] examined three different IMs regarding efficiency and sufficiency properties to develop an accurate probabilistic seismic demand model for the pounding risk assessment. The examined IMs arise as a modification of the spectral displacement IM, while the examined structural models were single-degree-of-freedom (SDOF) and multi-degree-of-freedom (MDOF) systems. In 2016, Tubaldi et al [27] examined the sufficiency of three different IMs based on the relative sufficiency measure (RSM) in order to develop different types of regression models. For the probabilistic seismic assessment of the pounding effect between reinforced concrete (RC) structures, Flenga and Favvata [28-31] examined the adequacy of the PGA and the $S_{a,T1}$ measures. Finally, Langlade et al [32] examined the efficiency and the sufficiency of six different IMs in the structural pounding framework between two SDOF systems.

The objective of this study is to identify the appropriate IMs for use in the probabilistic seismic assessment of the pounding effect between adjacent RC structures. For this purpose, the efficiency, and the sufficiency of twenty-three seismic IMs of forty-nine 2-component ground motions, are investigated. The structural pounding between an eight-story RC frame structure and a three-story stiffer structure for three different separation gap distances is examined. Nonlinear dynamic analyses are performed and the seismic demand parameters of the eight-story RC structure due to the pounding effect are estimated. Thereafter, the efficiency and the sufficiency of each IM are evaluated. In this study, Pearson's and Spearman's rank correlation coefficients are also incorporated.

## 2 KEY ASSUMPTIONS

### 2.1 Ground motions and intensity measures

For the needs of this study, both horizontal components of forty-nine strong ground motions extracted from PEER's and ESM's databases are used. All ground motions have magnitude $M_w$ greater than 5.5, source-to-site distance $R_{rup}$ greater than 15km, and they have been recorded on soils with average shear wave velocity in the upper 30 m of soil ($v_{s,30}$) that is up to 813.5 m/s (soil class A in EC8). The main characteristics of the seismic excitations are presented in Table 1. For each seismic record, twenty-three intensity measures (IMs) are considered and numerically estimated. The seismic IMs are either structural independent (PGA, PGV e.tc.) or structural dependent ($S_{a,T1}$, $S_{v,T1}$ e.tc.). The structural independent IMs are calculated directly from the time-history of the examined ground motions and describe characteristics such as amplitude, duration, and frequency in terms of acceleration, velocity or displacement. On the other hand, the structural dependent IMs are evaluated by the response spectra of the ground motions and are classified as spectral, integral, and multi-parameter measures [22]. The examined IMs are presented in Table 2.

### 2.2 Examined case of structural pounding

In this work, the seismic performance of an 8-story RC frame structure against pounding with an adjacent three-story rigid structure, is examined (Fig.1). The story levels of the adjacent structures have the same height so that the collisions may occur between the story diaphragms and consequently between the story masses (floor-to-floor interaction). The separation gap distance ($d_g$) between the adjacent structures is considered equal to $d_g$ = 0.0 cm (structures are in contact from the beginning), and $d_g$ = 2.0 cm. The seismic performance of the 8-story structure without the pounding effect is also addressed. The 8-story RC frame structure has been designed according to Eurocode 2 and 8, and the computer program Drain-2dx has been used to perform the structural modelling and the nonlinear dynamic analyses [34]. More details about the design and the overall modelling assumptions can be found in Flenga and Favvata [29].

Thereafter, two hundred ninety-four (294) nonlinear time history analyses have been performed in the concept of the Cloud Analysis method [1] to define the samples of the EDPs as a function of the IMs. For the correlation process three different EDPs of the 8-story RC frame are considered: (a) the maximum displacement ($\delta_{max}$) at the top level of the contact point of the adjacent structures (4th floor level), (b) the maximum interstory drift ($IDR_{max}$) of the structure as a function of the story height ($\%h_{st}$), and (c) the maximum curvature ductility demand ($\mu_{\varphi,max}$) of the most critical column.

The generated pairs of EDP|IM depict the seismic performance in the case of free vibration of the 8-story RC frame (without pounding) as well as the corresponding responses in the case where the separation gap distance between the adjacent structures is equal to: (a) $d_g$ = 0.0 cm and (b) $d_g$ = 2.0 cm.

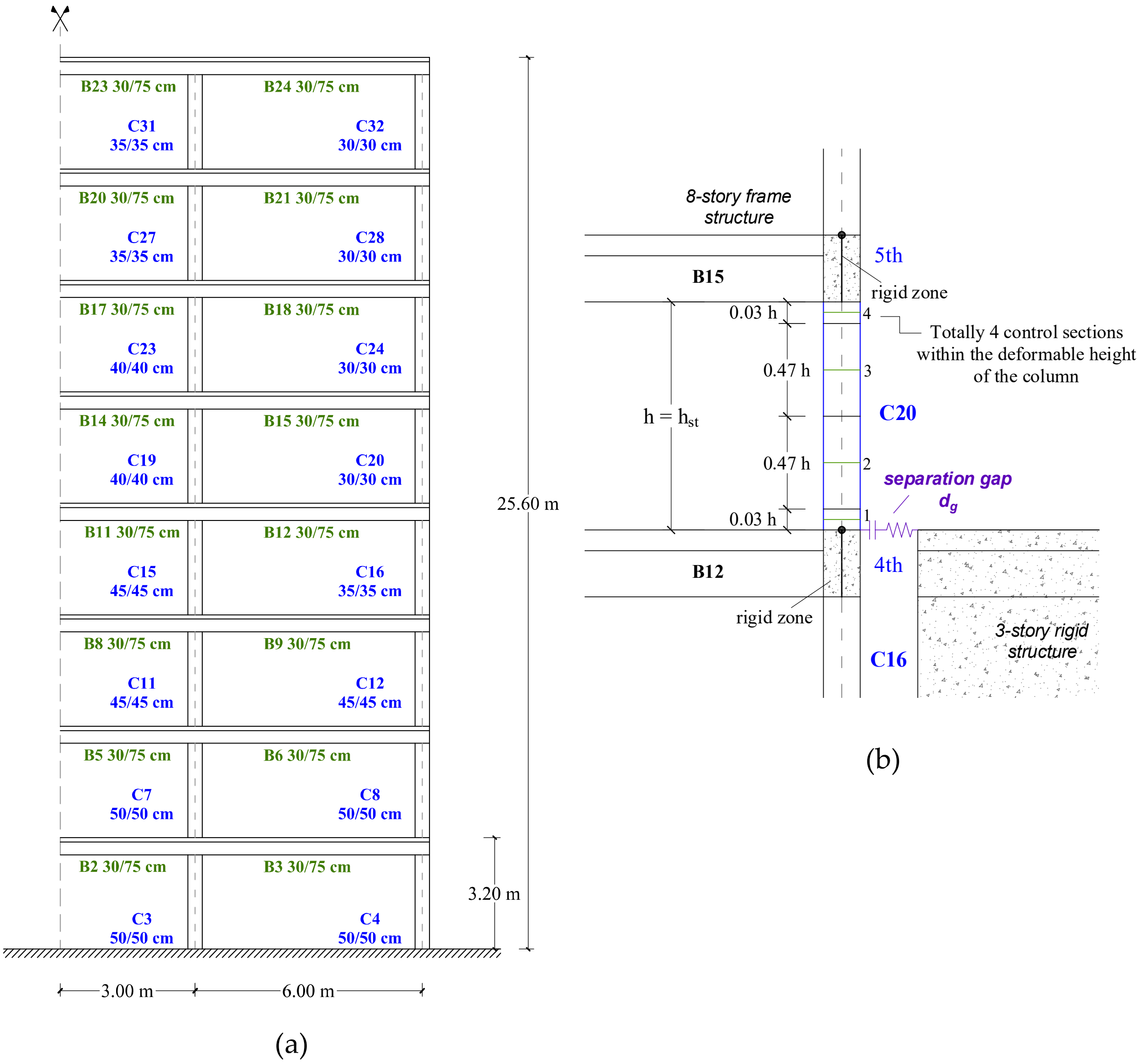



**Figure 1.** (a) Eight-story RC frame structure and (b) idealization of the contact area [29].

## 3 EVALUATION OF THE EXAMINED IMs

The seismic probabilistic assessement of a structure involves the use of an adequate IM that verifies specific criteria of efficiency and sufficiency. An efficient IM denotes small variation in the estimation of the structural demand for a given value of IM, while a sufficient IM indicates that it is independent of ground motion characteristics such as $M_w$, and $R_{rup}$. In the next sections, the adequacy of the examined IMs as indicators of the structural demand against pounding between adjacent structures for three different separation gap distances is addressed and discussesed.

**Table 1:** Ground motions' characteristics

| No | Earthquake ID | Earthquake Name | Station Name | Magnitude ($M_w$) | Closest distance ($R_{rup}$) (km) | Duration (sec) | No. | Earthquake ID | Earthquake Name | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | RSN 643 | Whittier Narrows-01 | LA - Wonderland Ave | 5.99 | 27.64 | 18.14 | 26 | EMSC-20161030_0000029 | Central Italy | Terar |
| 2 | RSN 4312 | Umbria-03, Italy | Gubbio | 5.60 | 15.72 | 17.99 | 27 | ME-1979-0003 | Northwestern Balkan Peninsula | Herce O.S.D Schoo |
| 3 | IT-2009-0009 | L' Aquila | Montereale | 6.10 | 17.11 | 99.99 | 28 | RSN 5618 | Iwate, Japan | IWT0 |
| 4 | EMSC-20160824_0000006 | Central Italy | Teramo | 6.00 | 22.12 | 78.61 | 29 | RSN 1091 | Northridge-01 | Vasq |
| 5 | IT-1984-0004 | Lazio Abruzzo | Atina | 5.90 | 16.32 | 30.68 | 30 | RSN 3954 | Tottori, Japan | SMN |
| 6 | RSN 680 | Whittier Narrows-01 | Pasadena - CIT Kresge Lab | 5.99 | 18.12 | 39.99 | 31 | EMSC-20161030_0000029 | Central Italy | Regg |
| 7 | GR-1999-0001 | Greece | -(ATH4) | 5.90 | 16.79 | 42.35 | 32 | ME-1979-0003 | Northwestern Balkan Peninsula | Dubr Pomo |
| 8 | IT-2009-0009 | L' Aquila | Antrodoco | 6.10 | 23.18 | 120.00 | 33 | RSN 284 | Iprinia, Italy | Aulet |
| 9 | EMSC-20170118_0000034 | Central Italy | Leonessa | 5.50 | 22.40 | 59.90 | 34 | RSN 5006 | Chuetsu-oki, Japan | FKSI |
| 10 | IT-1997-0006 | Umbria March | Monte Fiegni | 6.00 | 21.98 | 34.75 | 35 | RSN 5993 | El Mayor-Cucapah | El Mo Park |
| 11 | RSN 4438 | Molise-02, Italy | Sannicandro | 5.70 | 51.32 | 36.28 | 36 | RSN 3799 | Hector Mine | LA - Obse |
| 12 | RSN 1649 | Sierra Madre | Vasquez Rocks Park | 5.61 | 39.81 | 39.98 | 37 | RSN 788 | Loma Prieta | Piedr Schoo |
| 13 | IT-2012-0008 | Emilia 1st shock | S Zeno Di Montagna | 6.10 | 77.86 | 200.00 | 38 | RSN 4167 | Niigata, Japan | FKSI |
| 14 | EMSC-20161026_0000095 | Central Italy | Monte Murano | 5.90 | 48.95 | 124.81 | 39 | RSN 804 | Loma Prieta | So. S Sierra |
| 15 | RSN 2805 | Chi-Chi Taiwan-04 | KAU003 | 6.20 | 116.20 | 60.00 | 40 | RSN 59 | San Fernando | Ceda Ranc |
| 16 | ME-1979-0012 | Northwestern Balkan Peninsula | Hercegnovi Novi-O.S.D. Pavicic School | 6.20 | 30.7 | 24.58 | 41 | RSN 283 | Iprinia, Italy | Arien |
| 17 | RSN8168 | Parkfield-02, CA | Diablo Canyon Power Plant | 6.00 | 78.32 | 39.67 | 42 | RSN 5363 | Chuetsu-oki, Japan | TCGI |
| 18 | GR-1997-0019 | Ionean Sea | Kyparissia | 6.40 | 104.34 | 27.80 | 43 | RSN 6041 | El Mayor-Cucapah | San D Dept |
| 19 | IT-2012-0008 | Emilia 1st shock | Tregnago | 6.10 | 63.89 | 160.18 | 44 | RSN 5483 | Iwate, Japan | AKT |
| 20 | EMSC-20161026_0000095 | Central Italy | Teramo | 5.90 | 41.70 | 187.49 | 45 | RSN 8167 | San Simeon, CA | Diabl Powe |
| 21 | RSN 3479 | Chi-Chi Taiwan-06 | TCU085 | 6.30 | 83.40 | 42.00 | 46 | RSN 4248 | Niigata, Japan | TCGI |
| 22 | RSN 2508 | Chi-Chi Taiwan-03 | CHY102 | 6.20 | 60.36 | 60.99 | 47 | RSN 1245 | Chi-Chi, Taiwan | CHY |
| 23 | RSN 80 | San Fernando | Pasadena - Old Seismo Lab | 6.61 | 21.50 | 101.10 | 48 | RSN 1257 | Chi-Chi, Taiwan | HWA |
| 24 | RSN 1011 | Northridge-01 | LA - Wonderland Ave | 6.69 | 20.29 | 29.98 | 49 | RSN 2107 | Denali, Alaska | Carlo |
| 25 | RSN 3925 | Tottori, Japan | OKYH07 | 6.61 | 15.23 | 299.99 | | | | |

**Table 2:** Examined Intensity Measures [6 - 17]

| | IMs | Units | Name | Formula | Ref. |
|---|---|---|---|---|---|
| ***Structural Independent IM*** | | | | | |
| *Acceleration – based IMs* | PGA | [m/sec²] | Peak Ground Acceleration | $PGA=\max\lvert a(t)\rvert$ | [6] |
| | $RMS_a$ | [m/sec²] | Root-mean-square of acceleration | $RMS_a=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(a(t))^2}$ | [9] |
| | Ia | [m/sec] | Arias Intensity | $I_a=\int_0^{T_d}(a(t))^2dt$ | [10] |
| | Ic | | Characteristic Intensity | $I_c={a_{rms}}^{1.5}T_d^{0.5}$ | [11] |
| | CAV | [m/sec] | Cumulative Absolute Velocity | $CAV=\int_0^{t_{tot}}\lvert a(t)\rvert\, dt$ | [7] |
| | SMA | [m/sec²] | Sustained Maximum Acceleration | 3rd largest peak in acceleration time history | [8] |
| | EDA | [m/sec²] | Effective Design Acceleration | Peak acceleration value after filtering out time history above 9Hz | [7] |
| | $A_{95}$ | [m/sec²] | $A_{95}$ parameter | The acceleration level below which 95% of the total Arias intensity is contained | [13] |
| *Velocity – based IMs* | PGV | [m/sec] | Peak Ground Velocity | $PGV=\max\lvert v(t)\rvert$ | [6] |
| | $RMS_v$ | [m/sec] | Root-mean-square of velocity | $RMS_v=\sqrt{\frac{1}{T_d}\int_0^{T_d}(v(t))^2dt}$ | [9] |
| | SED | [m/sec²] | Specific Energy Density | $SED=\int_0^{T_d}(v(t))^2dt$ | [6] |
| | SMV | [m/sec] | Sustained Maximum Velocity | 3rd largest peak in velocity time history | [8] |
| | MIV | [m/sec] | Maximum Incremental Velocity | Maximum area under the acceleration curve between two zero crossings of the accelerogram | [12] |
| *Displacement – based IMs* | PGD | [m] | Peak Ground Displacement | $PGD=\max\lvert d(t)\rvert$ | [6] |
| | $RMS_d$ | [m] | Root-mean-square of displacement | $RMS_d=\sqrt{\frac{1}{T_d}\int_0^{T_d}(d(t))^2dt}$ | [9] |
| | PGV/PGA | [sec] | Peak velocity and acceleration ratio | $PGV/PGA=\max\lvert v(t)\rvert/\max\lvert a(t)\rvert$ | [6] |
| ***Structural Dependent IM*** | | | | | |
| *Spectral IMs* | $S_{a,T1}$ | [m/sec²] | Spectral Acceleration | Spectral Acceleration at the fundamental period of the structure | [6] |
| | $S_{v,T1}$ | [m/sec] | Spectral Velocity | Spectral velocity at the fundamental period of the structure | [6] |
| | $S_{d,T1}$ | [m] | Spectral Displacement | Spectral displacement at the fundamental period of the structure | [6] |
| *Integral IMs* | ASI | [m/sec] | Acceleration Spectrum Intensity | $ASI=\int_{0.1}^{0.5}S_a(0.05,T)\, dT$ | [14] |
| | VSI | [m] | Velocity Spectrum Intensity | $VSI=\int_{0.1}^{2.5}S_v(0.05,T)\, dT$ | [14] |
| | HI | [m] | Housner Intensity | $HI=\int_{0.1}^{2.5}PSV(\xi,T)\, dT$ | [16] |
| *Multi-Parameter IMs* | $S_{a,avg}$ | [m/sec²] | Average Spectral Acceleration | $S_{a(T1....TN)}=\left(\prod_{i=1}^{n}S_a(T_i)\right)^{1/n}$ | [17] |

### 3.1 Verification of IMs' Efficiency

The most common method to evaluate the variability of an IM is through the logarithm standard deviation, $\beta_{EDP|IM}$. For this purpose, the EDP|IM pairs are generated through the nonlinear dynamic analyses and linear regression of the EDP|IM pairs in log-log space is performed. Assuming that the structural response demand is following lognormal distribution [2] the logarithm standard deviation $\beta_{EDP|IM}$ is calculated as:

$$\beta_{EDP|IM}=\sqrt{\frac{\sum_{i=1}^{n}\left(\ln EDP_i|IM_i - \ln \widehat{EDP}|IM\right)^2}{n-2}} \tag{1}$$

where, n is the number of the nonlinear dynamic analyses, and $\widehat{EDP}$ is the median structural demand.

Based on Malaioli et al [23] values of dispersion lower than 0.30 indicate ideal efficiency of the seismic intensity measure, however a logarithm standard error in the range of 0.30-0.40 is also acceptable to characterize an IM efficient.

Furthermore, Pearson's and Spearman's rank correlation coefficients could also be used to justify the adequacy of an IM. The Pearson's rank correlation coefficient evaluates the linear relationship between the EDP-IM pairs and can be calculated by the following expression:

$$\rho_{pearson}=\frac{\sum_{i=1}^{n}(X_i-\bar{X})(Y_i-\bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i-\bar{X})^2\sum_{i=1}^{n}(Y_i-\bar{Y})^2}} \tag{2}$$

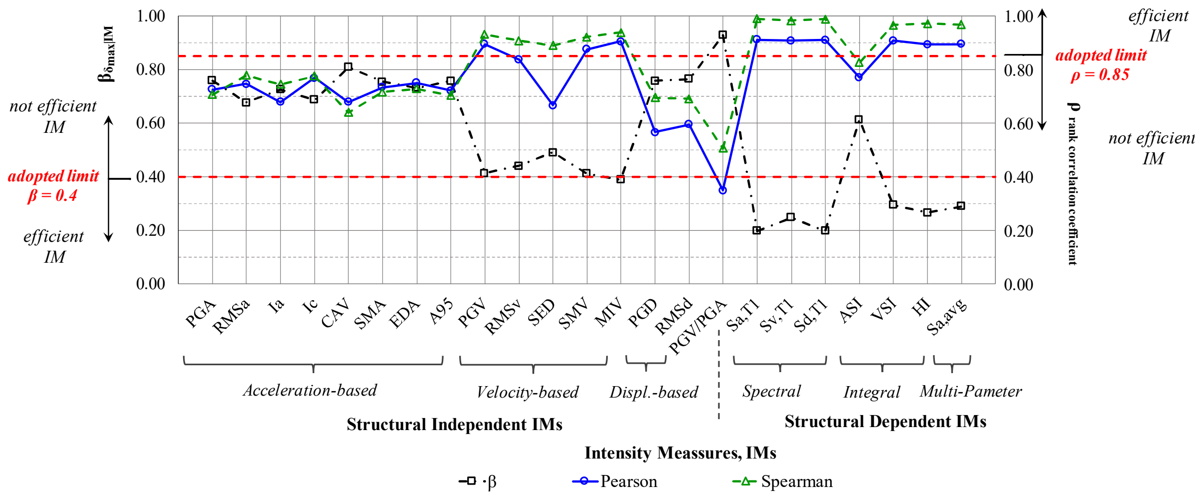
where, $X_i$, $Y_i$ are the IM, EDP of the ith pair of data, $\bar{X}_i$, $\bar{Y}_i$ are the mean values of the IMs, EDPs data, and n is the number of the seismic excitations.

On the other hand, the Spearman's rank correlation coefficient evaluates the monotonic relationship of the EDP-IM pairs and can be calculated by the following expression:

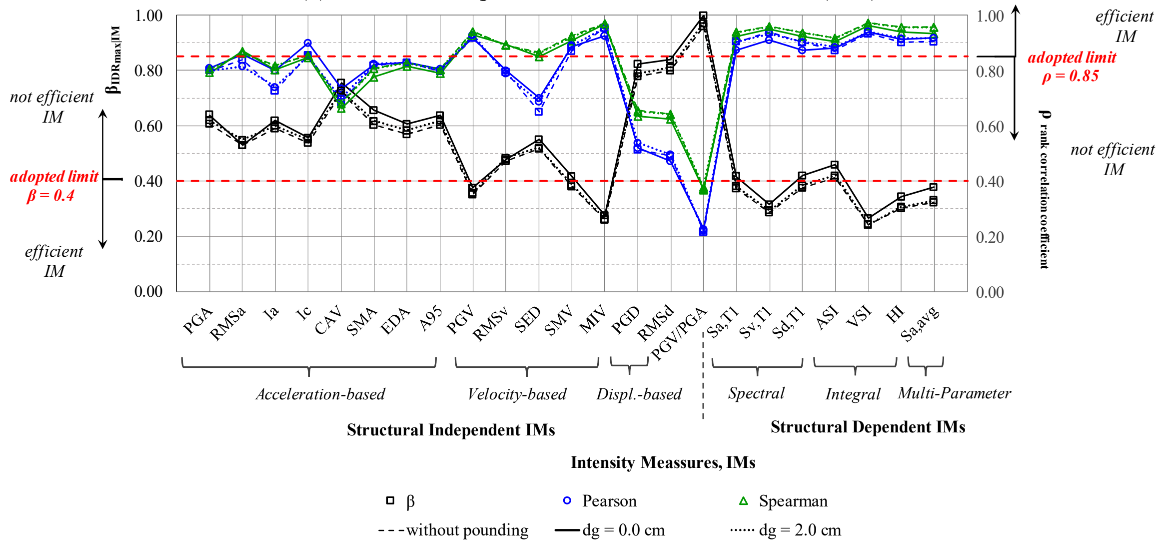
$$\rho_{spearman}=1-\frac{6\sum_{i=1}^{n}{d_i}^2}{n\,(n^2-1)} \tag{3}$$

where, $d_i$ denotes the differences between the ranks of corresponding values of $X_i$, $Y_i$ and n is the number of the seismic excitations.

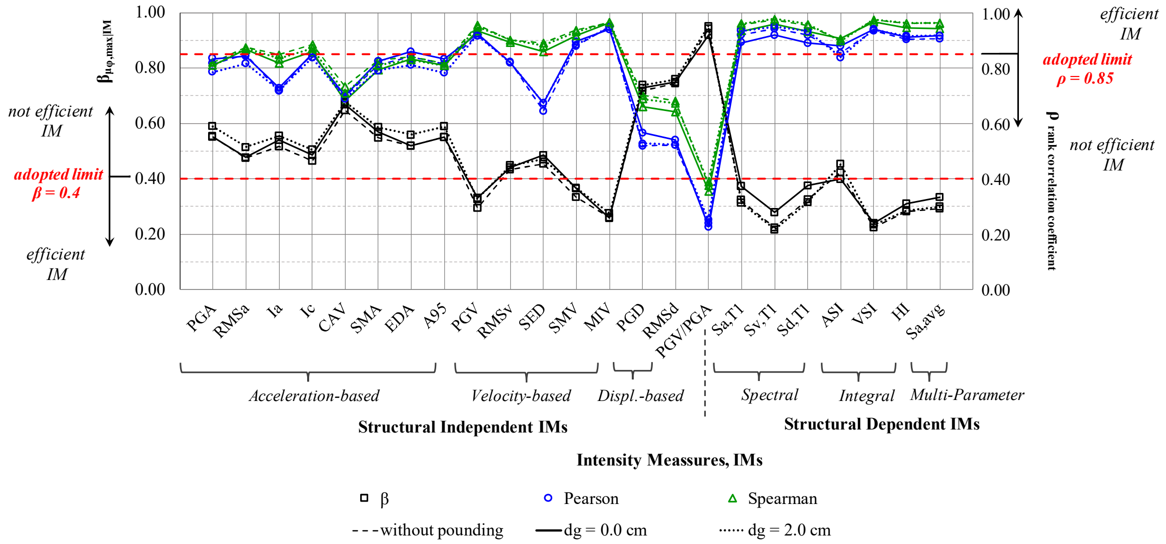
Values of Pearson's and Spearman's correlation coefficients equal to $\pm 1$ indicate perfect linear relationship between the EDP and the IM. For comparison reasons, absolute values of the correlation between the intensity measures and the demands of the structures are presented. In this study, a value of correlation greater than 0.85 is considered adequate to verify the IMs' efficiency. So, Figure 2 shows values of the logarithm standard deviation $\beta_{EDP|IM}$, the Pearson's rank correlation coefficient, and the Spearman's rank correlation coefficient, when the IMs are evaluated as indicators of the 8-story RC frame demands: (a) maximum displacement demand of at the 4th floor level ($\delta_{max}$), (b) maximum interstory drift ($IDR_{max}$ - $\%h_{st}$), and (c) maximum curvature ductility of the column at the 4th floor level ($\mu_{\varphi,max}$). As it can be observed, with exception the ASI all the other structural dependent IMs are generally more efficient in evaluating the demands in terms of $\delta_{max}$, $IDR_{max}$, and $\mu_{\varphi,max}$ of the RC frame. In general, the values of $\beta_{EDP|IM}$ are lower than 0.40 indicating the superiority of the structural dependent IMs to predict the EDPs with reduced variation. Similarly, Pearson's and Spearman's correlation coefficients are ranged between 0.85-1.00 in the case of structural dependent IMs (blue and green lines in Fig. 2) that indicates an almost linear relationship between IM and EDP.




(a) maximum displacement at the 4th floor level ($\delta_{max}$)




(b) maximum interstory drift ($IDR_{max}$ - $\%h_{st}$)




(c) maximum curvature ductility of the column at the 4th floor level ($\mu_{\varphi,max}$)

**Figure 2.** Evaluation of the IMs' efficiency with the EDPs of 8-story RC frame based on the logarithm standard deviation $\beta_{EDP|IM}$, the Pearson's, and the Spearman's rank correlation coefficients.

On the contrary, the structural independent IMs show an increased variation in the prediction of the EDPs. In these cases, the structural independent IMs have values of $\beta_{EDP|IM}$ greater than 0.4, while the values of Pearson's and Spearman's rank correlation coefficients are lower than 0.85. Nevertheless, among all the structural independent IMs, PGV and MIV have shown better predictive capability to EDPs. The least effective structural independent IMs are the acceleration-based and the displacement-based, with the IM of PGV/PGA to be the most invalid indicator to describe the demands of the structure.

The evaluation of the IMs' efficiency seems not to be affected when the structural pounding problem is involved. For example, the estimated values of $\beta_{IDRmax|IM}$ are slightly increased when $d_g$ = 0.0 cm compared to the cases of $d_g$ = 2.0 cm and without pounding. Generally, the dispersion remains within the acceptable range ($\beta_{IDRmax|IM}$ <0.4) for the structural dependent IMs. Also, the estimation of the rank correlation coefficients shows that the interdependence of the IMs with the examined EDPs is slightly changed when structures are in contact from the beginning. The velocity-based IMs remain more efficient for predicting the demands of the 8-story RC frame structure subjected to pounding. The displacement-based IMs indicate no interdependence with EDPs. In Figure 3, indicative results of the relationship between the $IDR_{max}$ and the IMs of PGV, PGD, $S_{a,T1}$, and $S_{v,T1}$ are presented. The results are in log-log space, and the examined case is for separation gap distance $d_g$ = 0.0 cm. As can be observed, the linear regression model is adequate to capture the median $IDR_{max}$ demands of the 8-story RC frame through the IMs of PGV, $S_{v,T1}$ and $S_{a,T1}$, while PGD fails to describe the median structural demands.

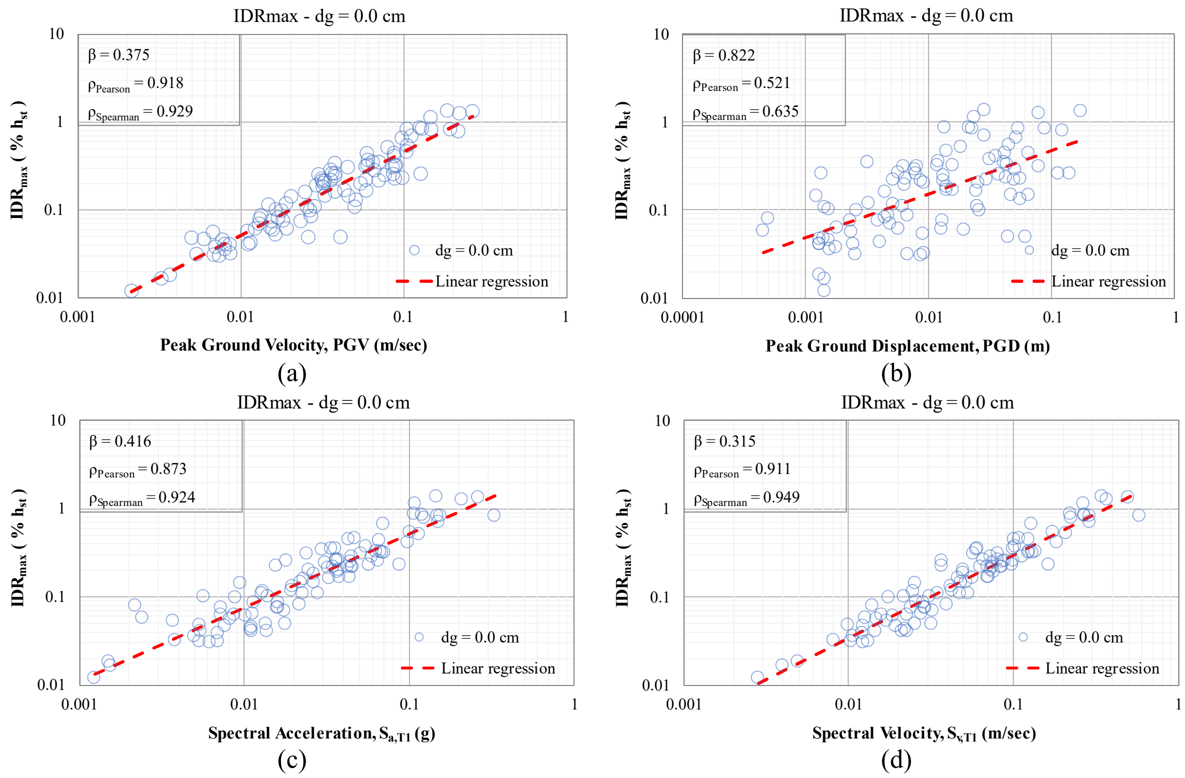



**Figure 3.** Relationship in log-log space between (a) PGV-$IDR_{max}$, (b) PGD-$IDR_{max}$, (c) $S_{a,T1}$-$IDR_{max}$, and (d) $S_{v,T1}$-$IDR_{max}$ . Results for separation gap distance $d_g$ = 0.0 cm.

## 3.2 Verification of IMs' Sufficiency

The criterion of sufficiency is also an important measure for the evaluation of the IM's adequacy. The most common way to evaluate the sufficiency of an IM is through the p-value between the residuals ε|IM of the regression analysis and the examined characteristic of the ground motion ($M_w$ or $R_{rup}$). In general, p-value represents the probability of rejecting the null hypothesis ($H_o = 0$) which states that the regression coefficient is zero. A small p-value (less than a cut-off value of 0.05 for 95% confidence level) indicates that the regression coefficient is statistically significant, and the IM is insufficient.

The sufficiency of an IM could also be classified based on the Spearman's rank correlation coefficient. In this case, the Spearman method examines the interdependency between residuals ε|IM and the ground motion characteristic ($M_w$ or $R_{rup}$). Coefficient values equal to ±1 indicate the monotonic (linear or nonlinear) relationship between the examined variables and the insufficiency of the IM. For comparison reasons, absolute values of the correlation are presented. De Biaso [35] adopted an arbitrary upper limit of 0.20 as a cut-off value to assess the IM's sufficiency.

The above methodologies evaluate the criterion of sufficiency in an absolute sense. However, it is difficult to satisfy the sufficiency measure of a scalar IM since that requires the independence of all possible values of IM from the examined ground motion characteristics [36]. Jalayer et al [36] introduced the concept of relative sufficiency measure (RSM) to quantify the prediction capability of an IM instead of the reference IM for a certain EDP. The evaluation of RSM is based on relative entropy and measures the similarity of two probability density functions (PDF) (e.g., $p(EDP|IM_i)$, and $p(EDP|IM_j)$) [37]. The RSM can be approximately calculated for a suite of n ground motion by the following expression:

$$I(EDP|IM_2|IM_1) \approx \frac{1}{n}\sum_{i=1}^{n}\log_2\left(\frac{\beta_{EDP|IM_1}\,\Phi\left(\frac{\ln EDP_i - \ln \widehat{EDP}|IM_{2,i}}{\beta_{EDP|IM_2}}\right)}{\beta_{EDP|IM_2}\left(\frac{\ln EDP_i - \ln \widehat{EDP}|IM_{1,i}}{\beta_{EDP|IM_1}}\right)}\right) \tag{4}$$

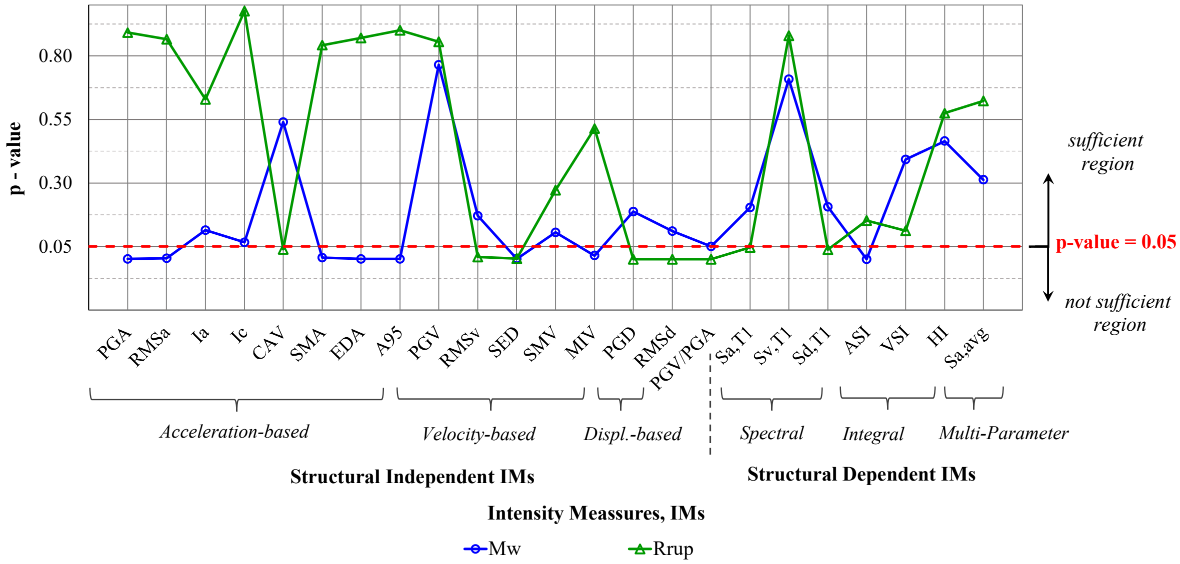
where, $IM_1$ is the reference and $IM_2$ is the candidate IM.

In general, the RSM method quantifies the amount of information gained or lost in the case of using $IM_2$ instead of $IM_1$. Positive values of $I(EDP|IM_2|IM_1)$ indicate that $IM_2$ is more sufficient than $IM_1$, while negative values imply that $IM_2$ is less sufficient of $IM_1$.

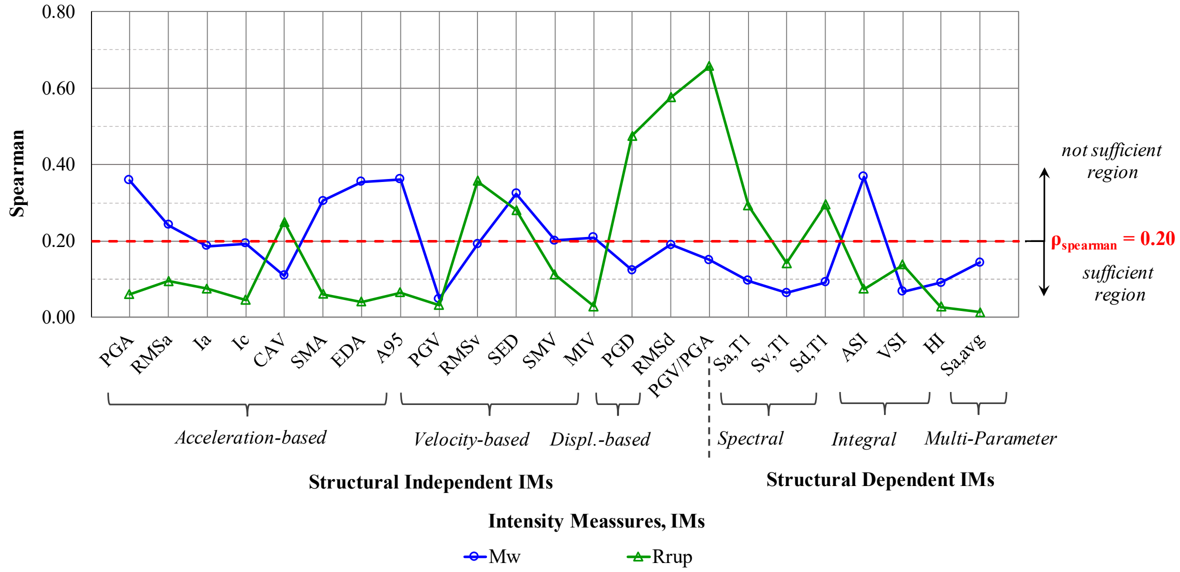
So, in this study, the sufficiency of an IM is evaluated based on a) the p-value of the regression analysis, b) the Spearman's rank correlation coefficient and c) the relative sufficiency measure (RSM). In the case of p-value and Spearman's rank correlation coefficient the IMs' sufficiency is evaluated for the examined ground motion characteristic ($M_w$ and $R_{rup}$), while RSM examines the sufficiency property in a relative sense. The IMs' sufficiency is verified for three separation gap distances between the adjacent structures and incorporates EDPs in terms of $\delta_{max}$, $IDR_{max}$, and $\mu_{\varphi,max}$.

Figure 4 shows the evaluation of the IMs' sufficiency in the case of $\delta_{max}$ with respect to $M_w$ and $R_{rup}$. Results indicate that the structural dependent IMs (except ASI) are independent of $M_w$ (blue line) (p-value>0.05). From the acceleration-based IMs only $I_a$, $I_c$, and CAV satisfy the criterion of sufficiency and that may be attributed to the fact that these IMs are characterized by the duration, the amplitude and the frequency of the ground motion. The velocity-based and the displacement-based independent IMs are also independent of $M_w$ except of MIV and SED. Rating the IMs sufficiency with respect to $R_{rup}$, the structural dependent IMs and the acceleration-based IMs are deduced to be independent (Fig. 4 – green line), since p-values are greater than 0.05. The velocity related IMs (except of $RMS_v$ and SED) result to be more sufficient than the displacement-based IMs. Additionally, the structural independent PGV, SMV, $I_a$ and $I_c$ are simultaneously independent of $M_w$ and $R_{rup}$. Based on Spearman's approach, $I_a$, $I_c$, PGV, SMV, MIV $S_{v,T1}$, VSI, HI, and $S_{a,avg}$ are simultaneously independent of $M_w$ and $R_{rup}$.

In Figure 5, the evaluation of the IMs' sufficiency in terms of $IDR_{max}$ for all the examined structural pounding cases, is presented. As can be observed, the p-values of the structural dependent IMs and the p-values of the velocity-based PGV, $RMS_v$, SED, and SMV are around the limit value of 0.05 both on $M_w$ and $R_{rup}$. However, the acceleration-based IMs of $RMS_a$, $I_a$, and $I_c$, seem to be the most sufficient for predicting $IDR_{max}$ demands of the 8-story structure with respect to the ground motion characteristics. Based on Spearman's rank correlation coefficient approach, the velocity-based PGV, $RMS_v$, SED, and SMV are insufficient IMs to predict the $IDR_{max}$ demands of the 8-story RC structure (Fig. 5). The corresponding evaluation of the structural dependent IMs introduces the $S_{v,T1}$, HI, and $S_{a,avg}$ insufficient on both seismic characteristics $M_w$ and $R_{rup}$ (Fig.5).

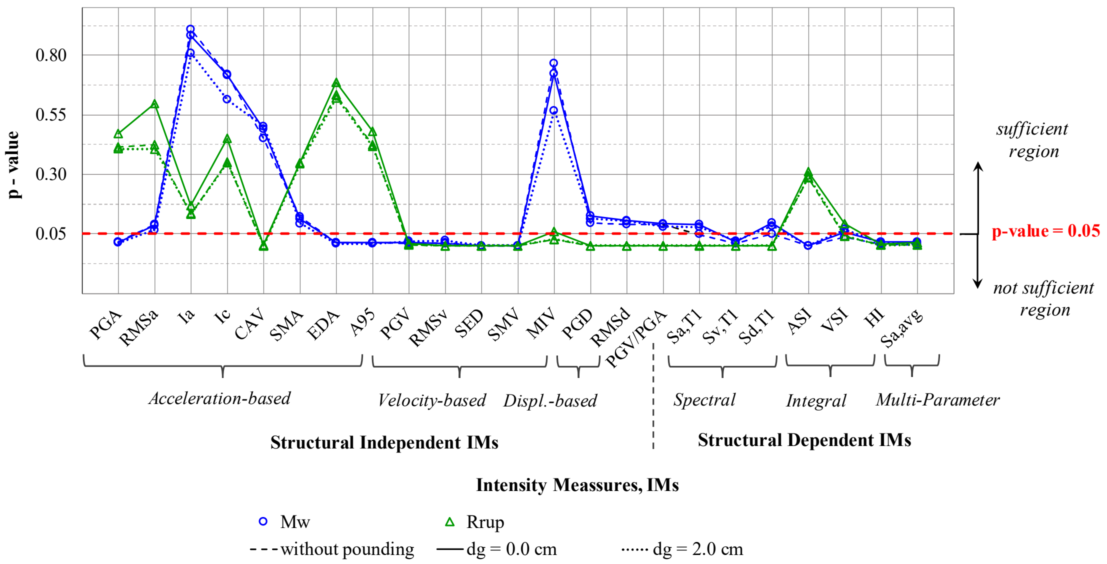



a) p-value

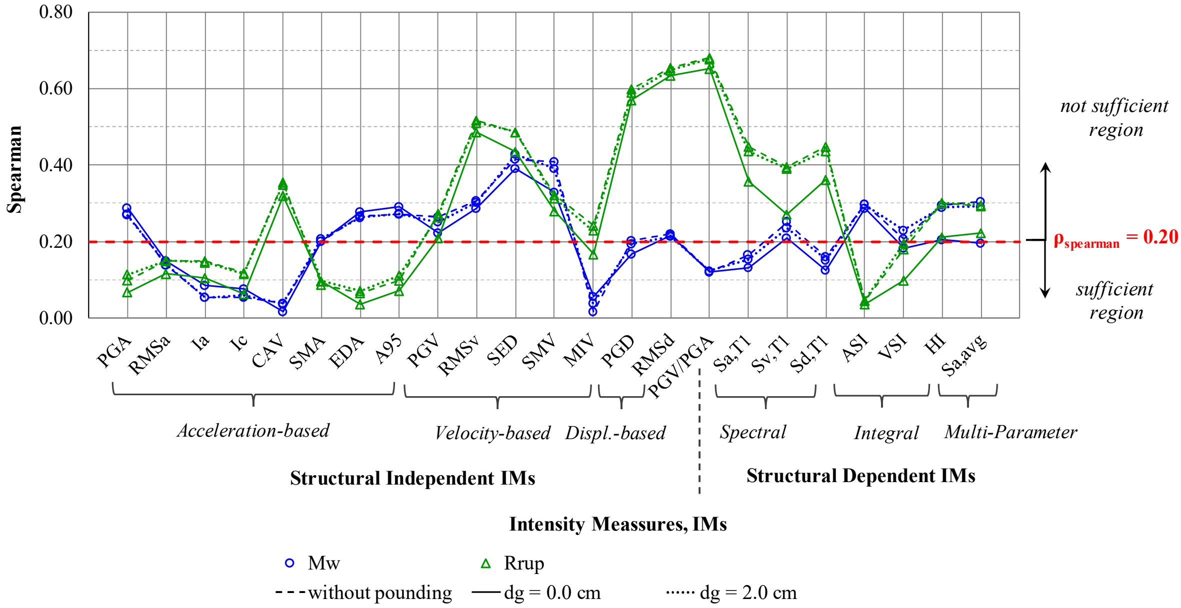



b) Spearman's rank correlation coefficient

**Figure 4.** Evaluation of the IMs' sufficiency with the maximum displacement at the top level of the contact point ($\delta_{max}$) based on a) p-value and b) Spearman's rank correlation coefficient with respect to the magnitude ($M_w$) and to source-to-site distance ($R_{rup}$).



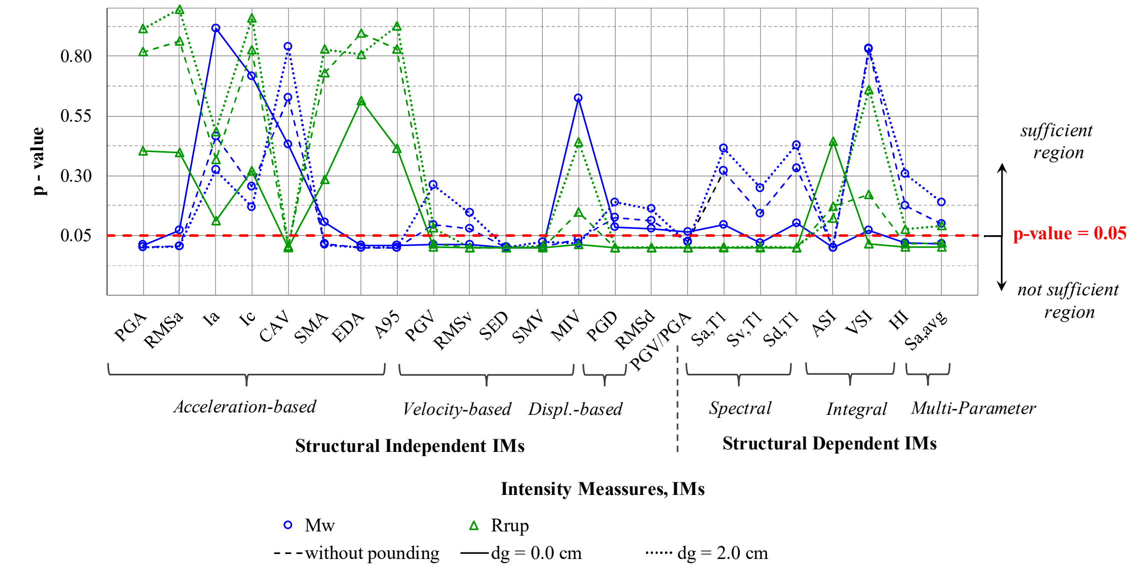

a) p-value



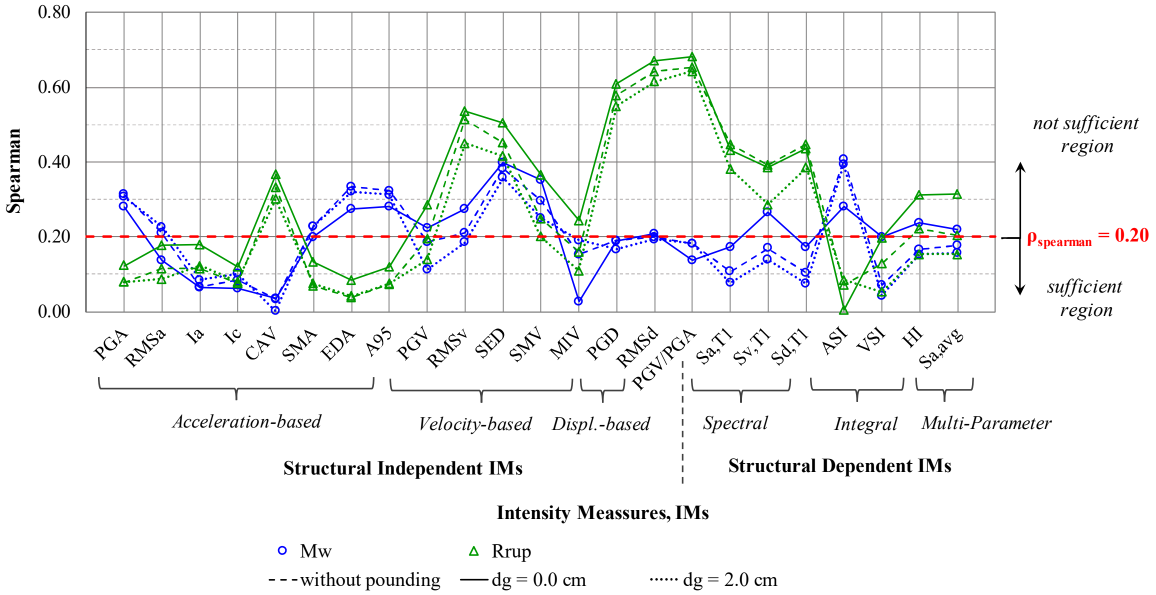

b) Spearman's rank correlation coefficient

**Figure 5.** Evaluation of the IMs' sufficiency with the maximum interstory drift ($IDR_{max}$-$\%h_{st}$) based on a) p-value and b) Spearman' rank correlation coefficient with respect to the magnitude ($M_w$), and the source-to-site distance ($R_{rup}$).

Furthermore, the results of this study show that the pounding effect does not significantly alter the evaluation of the sufficiency property (Fig. 5). In fact, similar values of p-values and Spearman's correlation coefficients have been estimated either with or without considering the structural pounding effect. Only in the case of separation gap distance $d_g$ = 0.0 cm the p-values with respect to $R_{rup}$, (green lines) are slightly shifted to higher values for some IMs, while the separation gap distance $d_g$ = 2.0 cm slightly reduces the interdependency of $I_a$, $I_c$ and MIV in the case of $M_w$ (blue lines in Fig. 5). However, the verification of the IMs' sufficiency for predicting the local demands of the column is altered due to the pounding effect (Fig. 6).




a) p-value




b) Spearman's rank correlation coefficient

**Figure 6.** Evaluation of the IMs' sufficiency with the maximum curvature ductility $\mu_{\varphi,max}$ of the column C20 based on a) p-value and b) Spearman' rank correlation coefficient with respect to the magnitude ($M_w$), and the source-to-site distance ($R_{rup}$).

For example, as can be observed in Figure 6, the p-values of the structural independent IMs with respect to $R_{rup}$ (green lines) are decreased in the case of $d_g$=0.0 cm compared to the corresponding results without the pounding or $d_g$= 2.0 cm. On the other hand, the p-values of $RMS_a$, $I_a$, $I_c$, and MIV with respect to $M_w$ (blue lines) are increased in the case of $d_g$=0.0 cm. Slight differences in the estimated values of Spearman's correlation coefficients between the examined pounding cases are observed based on the results in Fig. 6b. Based on the p-value and Spearman's method only $I_a$ and $I_c$ are sufficient on $M_w$ and $R_{rup}$ for predicting the $\mu_{\varphi,max}$ of the examined column. The above results (Figs. 2-6) indicate that the satisfaction of IM's sufficiency implies lack of IM's efficiency and vice versa. For instance, the seismic measures $I_a$ and $I_c$ which are independent on $M_w$ and $R_{rup}$ do not pass the efficiency requirements since $\beta_{EDP|IM}$ is greater than the acceptable limit. On the contrary, the more efficient IMs ($\beta_{EDP|IM}$ <0.4) result to be insufficient for the examined ground motion characteristics. Thereafter, the IMs' sufficiency is evaluated based on the RSM. As reference IM is considered the first-mode spectral acceleration ($S_{a,T1}$) since it is the most commonly IM used in structural engineering.

So, in Figure 7, the verification of the relative sufficiency of the $S_{a,T1}$ with the other IMs, is presented. Demands in terms of $\delta_{max}$, $IDR_{max}$, and $\mu_{\varphi,max}$ are involved for the three examined separation gap distances between the adjacent structures. In the case of $\delta_{max}$, the intensity measure $S_{a,T1}$ provides more information than the other IMs, while is equally sufficient with $S_{d,T1}$. For example, the SMA is insufficient compared to the $S_{a,T1}$ since it provides 1.967 times less information regarding the demand $\delta_{max}$ (Fig. 7a). Evaluating the relative sufficiency in the case of $IDR_{max}$ it can be observed that the structural dependent IMs (except ASI) provide more information than $S_{a,T1}$ (Fig. 7b). Thus, $S_{a,T1}$ is more sufficient in relative sense than the examined independent IMs but it is insufficient with respect to the other structural dependent IMs. Also, it can be observed that considering the pounding effect, the RSM is slightly moved towards higher values for $d_g = 0.0$cm (Fig. 7b). $S_{d,T1}$, HI, $S_{a,avg}$, and MIV are relatively more sufficient than $S_{a,T1}$ for predicting the local demands of the column in terms of $\mu_{\varphi,max}$ (Fig. 7c). On the other hand, $S_{a,T1}$ is equally sufficient with PGV, $S_{v,T1}$, and ASI. Increased values of RSM are observed in the case of $d_g = 0.0$ cm in comparison to the corresponding values without pounding. In the case of $d_g = 2.0$ cm the RSMs are less than the evaluated ones based on the free vibration of the 8-story RC frame structure.

## 4 CONCLUSIONS

In this study, criteria of efficiency and sufficiency are used to identify an adequate IM for the probabilistic assessment of the earthquake-induced pounding between adjacent RC structures. Different methodologies are utilized to estimate the predictive capability of the IMs and their dependence with respect to the ground motion characteristics $M_w$ and $R_{rup}$. Based on the results of this study the following outcomes are noted:

<u>IMs' efficiency</u>

- The structural dependent IMs are more efficient in predicting the examined seismic demands of the 8-story RC frame structure.
- The least effective structural independent IMs are the acceleration-based and the displacement-based, with the PGV/PGA to be the most invalid indicator to describe the demands of the structure.
- IMs' efficiency seems not to be affected when the structural pounding is involved.

<u>IMs' sufficiency</u>

- In the case of $\delta_{max}$ the sufficient IMs (independent of $M_w$ and $R_{rup}$) are; PGV, SMV, $I_a$, $I_c$, $S_{v,T1}$, VSI, HI, and $S_{a,avg}$.
- The acceleration-based $I_a$, $I_c$, and $RMS_a$ seem to be sufficient measures for predicting $IDR_{max}$ demands of the 8-story structure with respect to the ground motion characteristics.
- The acceleration-based $I_a$, and $I_c$ are also sufficient for predicting the $\mu_{\varphi,max}$ of the examined column.
- In all the examined cases, the local demands of the critical column that suffers the pounding effect alter the results of the IMs' sufficiency.

Finally, based on the above notations, it can be concluded that an optimal IM that satisfies simultaneously the criteria of efficiency and sufficiency is difficult to be identified. Usually, the satisfaction of efficiency indicates a lack of sufficiency and vice versa. Nevertheless, the relative sufficiency measure of the IMs indicates the superiority of $S_{a,T1}$ compared to the structural independent IMs.

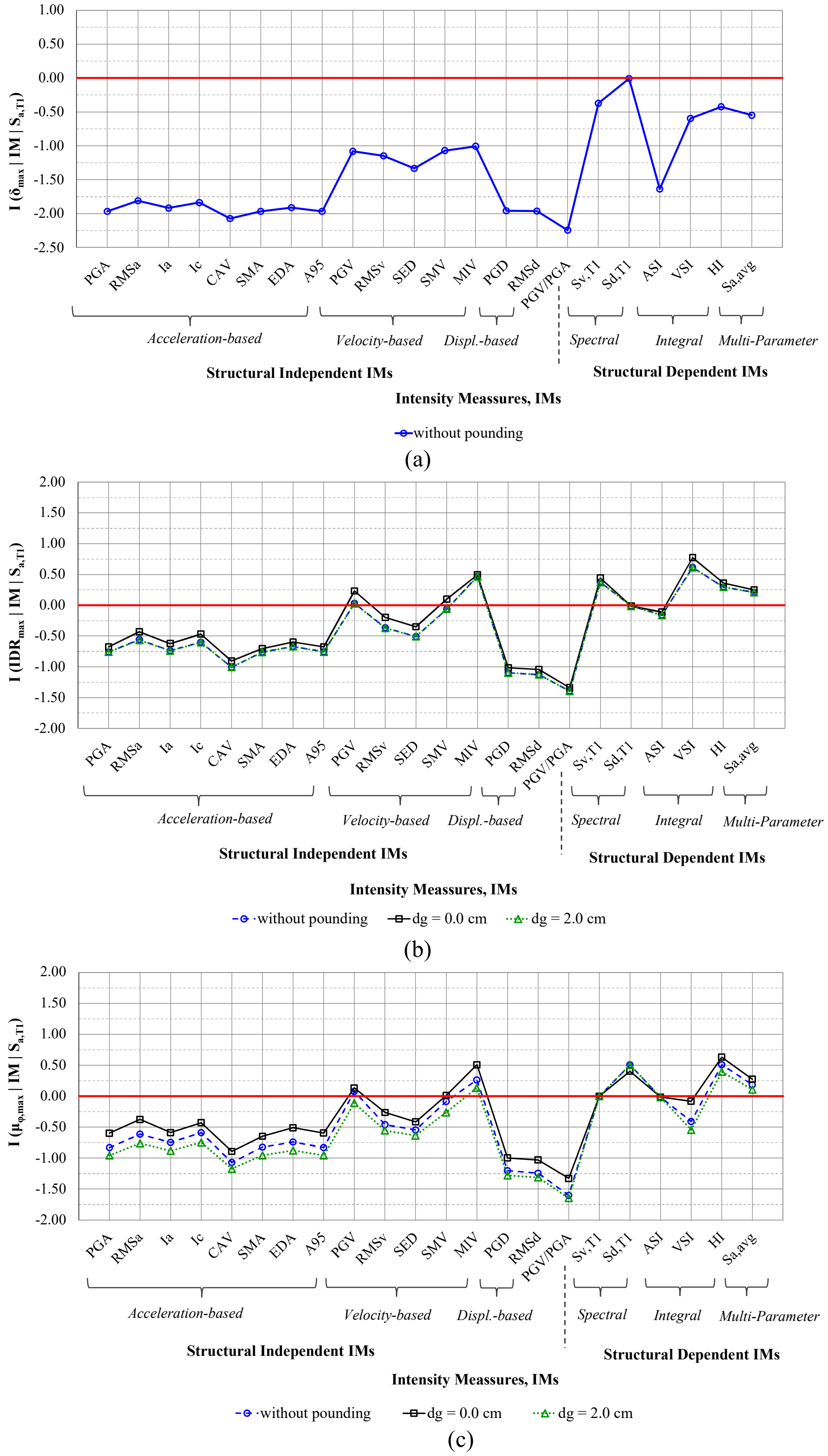



**Figure 7.** Evaluating the relative sufficiency of the $S_{a,T1}$ in the case of (a) maximum interstory drift ($IDR_{max}$-$\%h_{st}$), (b) maximum displacement at the top level of the contact point ($\delta_{max}$), and c) the maximum curvature ductility $\mu_{\varphi,max}$ of the column C20.

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