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A COMBINATION-TYPE EARTHQUAKE INTENSITY MEASURE FOR SUPER HIGH-RISE BUILDING

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Abstract

As the superior performance of spectral characteristic of spectral velocity over that of spectral acceleration and spectral displacement in the long period range, a new combination-type ground motion intensity measure considering higher modes based on spectral velocity is developed for super high-rise building structures. The proposed IM multiplies the corresponding spectral velocity of some modes. For a super high-rise building with fundamental period more than 9s, the lower three modes are adequate to get an optimal result. The proposed IM and several other IMs are analyzed from the perspective of efficiency, sufficiency and scaling robustness. The proposed IM is proved to be more superior to other IMs. For a super tall building, the IM which considers higher modes is more practical compared to the one considering period elongation.

Keywords: ground motion intensity measure; super high-rise building; spectral velocity; higher mode

1. Introduction

Super high-rise building, characterized with its big sizes and complex functions, plays an important role in urban area, resulting in the significance of a precise and effective analysis of seismic performance of a super high-rise building. Ground motion intensity measure (IM called hereafter) is a bridge linking the seismic hazard with structures demand, and plays an important role in the framework of performance-based assessment of structures [1].The applicability of different seismic intensity measures varies with the increase of structural height [2,3]. Some widely employed IMs, such as first-mode spectral acceleration $S_a(T_1)$ and peak ground acceleration PGA, are not appropriate for the seismic analyses of tall building [4]. In recent years, some novel IMs are proposed one after another. Those IMs could be divided into two types: acceleration-related IM or displacement-related IM. Most of acceleration-related IMs are the modification form of $S_a(T_1)$. And these improvements are divided into three groups: the first group is the combination-type IM based on $S_a(T_1)$ [4,5,6,7,8,9]; the second is vector-type IM [10,11,12]; the third is the integral type of spectral acceleration [13,14,15]. And aslo displacement-related IMs are the modification form of first-mode spectral displacement $S_d(T_1)$ [16,17].

In order to predict seismic response of super high-rise building accurately, it is necessary to propose suitable IM for super high-rise building. Analyzed is the correlation between seismic response of super high-rise building and different spectral values, i.e. spectral acceleration S_a, spectral velocity S_v and spectral displacement S_d, to determine the best spectral values for super high-rise building. And then a new combination-type ground motion intensity measure considering higher modes based on spectral velocity is proposed. Further, the efficiency, sufficiency and scaling robustness of this proposed IM and several other IMs are evaluated.

2. Structure models used for evaluation

The evaluation of ground motion intensity measures is carried out via two super high-rise building as shown in Fig. 1, i.e. a 61-storey RC frame core-tube (S1 hereafter) and a 118-storey “mega-column/core-tube/outrigger-truss” super tall building (S4 hereafter) designed based on current Chinese code [18,19]. Some unidirectional lower vibration modes and modal mass participation factors of both two buildings are listed in Table 1. Total heights of the two building is 258m and 660m, respectively. All the structural components of S1, e.g. beams, columns and structural walls, are modeled by nonlinear fiber beam-column elements and multi-layer shell elements in the program OpenSEES developed by the Pacific Earthquake Engineering Research Center [20]. And S4 is modeled with the same elements used in OpenSEES in a finite element program proposed by [21], where shared memory parallel computing procedures are used to reduce computational cost. In the analysis of all structures, the P-Δ effect is considered and the linear Rayleigh damping matrix is assumed with the same modal damping ratio of 5%. The dynamic response is computed by the acceleration proportional inertial forces at the foundation.

Table 1 – Dynamic properties of two buildings

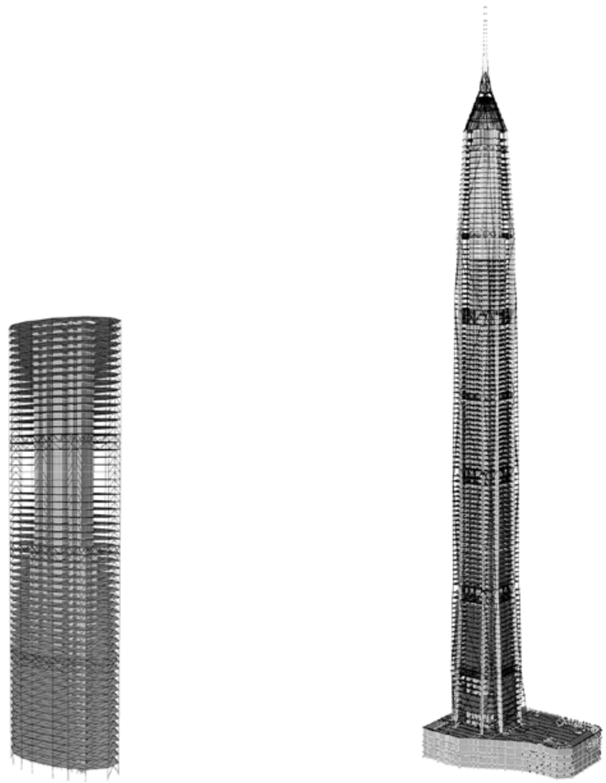
Mode	No.1		No.2		No.3		No.4		No.5	
Parameters	T_1(s)	α_1	T_2(s)	α_2	T_3(s)	α_3	T_4(s)	α_4	T_5(s)	α_5
S1	5.30	0.72	1.48	0.15	0.82	0.06	0.53	0.03	0.36	0.02
S4	9.17	0.56	2.86	0.24	1.40	0.07	0.93	0.05	0.83	0.02

3. Ground motion records

22 far-field strong ground motions, selected from large-magnitude events in the PEER ground motion database, as recommended in FEMA P695 [22] are adopted herein. For each record, Table 2 summarizes the name of the station, file names, magnitude M, site-to-source distance R, as well as the peak ground acceleration, PGA, peak ground velocity, PGV and peak ground displacement, PGD.

Table 2 – Ground motions of the far-field record set [22]

ID No.	Station	File Names	M	R(km)	PGA(g)	PGV(cm/s)	PGD(m)
1	Beverly Hills - Mulhol	NORTHR/MUL009	6.7	13.3	0.42	59	0.13
2	Canyon Country-WLC	NORTHR/LOS000	6.7	26.5	0.41	43	0.12
3	Bolu	DUZCE/BOL000	7.1	41.3	0.73	56	0.23
4	Hector	HECTOR/HEC000	7.1	26.5	0.27	29	0.23
5	Delta	IMPVALL/H-DLT262	6.5	33.7	0.24	26	0.12
6	El Centro Array #11	IMPVALL/H-E11140	6.5	29.4	0.36	34	0.16
7	Nishi-Akashi	KOBE/NIS000	6.9	8.7	0.51	37	0.10
8	Shin-Osaka	KOBE/SHI000	6.9	46	0.24	38	0.09
9	Duzce	KOCAELI/DZC180	7.5	98.2	0.31	59	0.44
10	Arcelik	KOCAELI/ARC000	7.5	53.7	0.22	18	0.14
11	Yermo Fire Station	LANDERS/YER270	7.3	86	0.25	51	0.44
12	Coolwater	LANDERS/CLW-LN	7.3	82.1	0.28	26	0.14
13	Capitola	LOMAP/CAP000	6.9	9.8	0.53	35	0.09
14	Gilroy Array #3	LOMAP/G03000	6.9	31.4	0.56	36	0.08
15	Abbar	MANJIL/ABBAR--L	7.4	40.4	0.52	42	0.15
16	El Centro Imp. Co.	SUPERST/B-ICC000	6.5	35.8	0.36	46	0.18
17	Poe Road (temp)	SUPERST/B-POE270	6.5	11.2	0.45	36	0.09
18	Rio Dell Overpass	CAPEMEND/RIO270	7.0	22.7	0.39	44	0.22
19	CHY101	CHICHI/CHY101-E	7.6	32	0.35	71	0.45
20	TCU045	CHICHI/TCU045-E	7.6	77.5	0.47	50	0.39
21	LA - Hollywood Stor	SFERN/PEL090	6.6	39.5	0.21	19	0.12
22	Tolmezzo	FRIULI/A-TMZ000	6.5	20.2	0.35	22	0.04



(a) 61-story structure (S1) (b) 118-story structure(S4)

Fig. 1 – Geometric configuration of two structures

4. S_a, S_v or S_d: Which one is better for super high-rise building?

The relationship between the structural seismic response demand measure (DM) and the ground motion intensity measure (IM) can be estimated using the power-function model presented in Eq. (1):

$$DM = a \cdot IM^{b} \tag{1}$$

where a and b are the regression coefficients. The equation can be rearranged in a linear form as shown in Eq. (2):

$$\ln(DM) = \ln a + b\ln(IM) \tag{2}$$

The correlation coefficient ρ between IM and DM can be obtained through carrying out linear regression analysis of the discrete data points ($\ln(DM_i)$,$\ln(IM_i)$) in time-history analysis. The value of correlation coefficient ρ is calculated from Eq. (3) below. The correlation coefficient ρ ranges between -1 and 1. The closer to 1 the $|\rho|$ is, the better the correlation between the between IM and DM.

$$\rho = \frac{m\sum_{i=1}^{m} x_i \cdot y_i - \sum_{i=1}^{m} x_i \cdot \sum_{i=1}^{m} y_i}{\sqrt{m\sum_{i=1}^{m} x_i^2 - \left(\sum_{i=1}^{m} x_i\right)^2} \cdot \sqrt{m\sum_{i=1}^{m} y_i^2 - \left(\sum_{i=1}^{m} y_i\right)^2}} \tag{3}$$

where, x_i=$\ln(DM_i)$, y_i=$\ln(IM_i)$; DM_i and IM_i represent the structural seismic response demand measure and the ground motion intensity measure under i-th ground motion; m is the total number of ground motion. As one of performance indexes, the maximum inter-story drift ratio, $\theta_{\max}$, has a good correlation with structural damage [23], as adopted herein.

Time history analyses are carried out for the two structures excited by the selected 22 original ground motions as listed in Table 2 without scaling. Figure 2 shows the logarithmic correlation coefficients, ρ, of two models between the maximum inter-story drift (DM) and spectral values at any vibration period, $S_a(\tau)$, $S_a(\tau)$ and $S_a(\tau)$. The coefficients are determined in the same way as described in Eq. (3). As can be seen from Fig. 2, there is significant consistency between the correlation of S_a and S_d to $\theta_{\max}$, while the correlation between S_v and $\theta_{\max}$ is distinctly different from the other two. In the short and intermediate period range, S_a and S_d presents a higher correlation to $\theta_{\max}$ than S_v[17], however in the long period range the correlation of S_v is significant higher than the other two. In terms of Duhamel integral, when the damping radio is small, the first order term containing damping ratio ξ can be ignored and the structural natural frequencies $\omega_d=\omega\sqrt{1-\xi^2}$ can also be simplified as ω. So:

$$S_d=\frac{1}{\omega_d}\left|\int_0^t \ddot{u}_g(\tau)e^{-\xi\omega(t-\tau)}\sin\omega(t-\tau)\,d\tau\right|_{max} \tag{4}$$

$$S_v=\left|\int_0^t \ddot{u}_g(\tau)e^{-\xi\omega(t-\tau)}\cos\omega(t-\tau)\,d\tau\right|_{max} \tag{5}$$

$$S_a=\omega_d\left|\int_0^t \ddot{u}_g(\tau)e^{-\varsigma\omega(t-\tau)}\sin\omega(t-\tau)\,d\tau\right|_{max} \tag{6}$$

As can be seen from Eq. (4) and (6), when the damping ratio is very small, there is a linear relationship between S_a and S_d, i.e. $S_a=\omega^2 S_d$. Thus they has the nearly the same correlation coefficient. While as shown in Eq. (5) and (6), there is a phase difference between S_v and S_a, which are not proportional, hence their correlation coefficients are different.

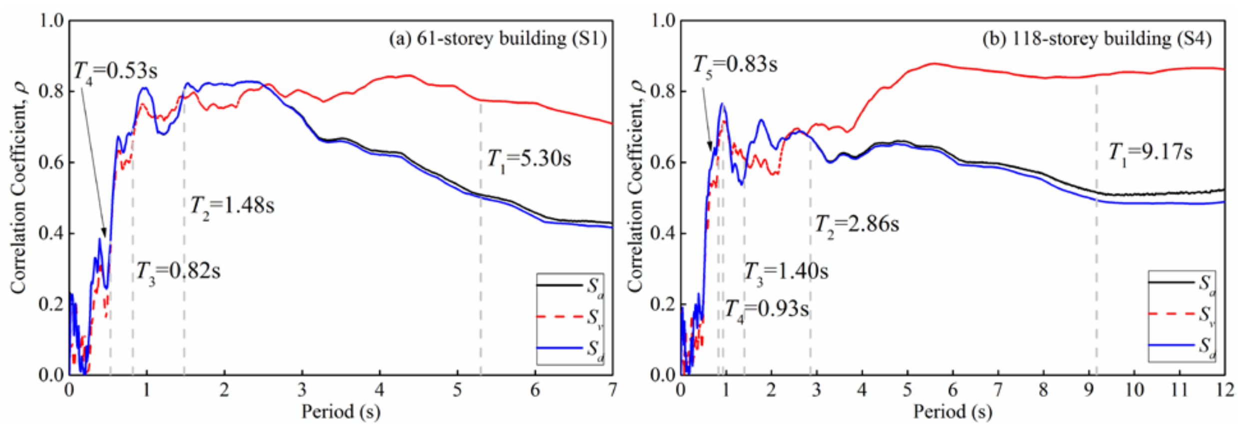


Fig. 2 – The correlation of S_a, S_v and S_d to $\theta_{\max}$ of the two buildings

5. New combination-type ground motion IM

In the improvement process of $S_a(T_1)$, literature [6,7,8,9] pointed that it is advisable to consider the effect of high modes in IMs for tall building. And all of these IMs are multiplication-type of corresponding spectral acceleration of higher modes. Inspired by the above researches the authors try to propose a new combination-type intensity measure for super high-rise building, while the term combined is corresponding spectral velocities of higher modes. As shown in Eq. (7), the combination coefficient of exponent is 1/n:

$$S_v^*=\sqrt[n]{\prod_{i=1}^{n}(S_v(T_i))} \tag{7}$$

where $S_v(T_i)$ is the spectral velocity of i-th mode; n is the number of combination term. When n=1, $S_v(T_1)$ can be used directly as this IM. When n=2 and n=3, the Eq. (7) can be simplified into Eq. (8) and Eq. (9), respectively.

$$S^{*}_{v12} = \left(S_v\left(T_1\right)\right)^{1/2}\left(S_v\left(T_2\right)\right)^{1/2} \tag{8}$$

$$S^{*}_{v123} = \left(S_v\left(T_1\right)\right)^{1/3}\left(S_v\left(T_2\right)\right)^{1/3}\left(S_v\left(T_3\right)\right)^{1/3} \tag{9}$$

Fig. 3 shows the correlation coefficient between the $\theta_{\max}$ and the proposed IM S^{*}_{v} considering different combinatorial terms for structure model S1 and S4. Shown in Fig. 3, model S1 arrives at a maximum correlation coefficient when the IM S^{*}_{v} needs the first two modes. And for model S4 the maximum coefficient of correlation is attained when all the first three modes are considered in the IM S^{*}_{v}.

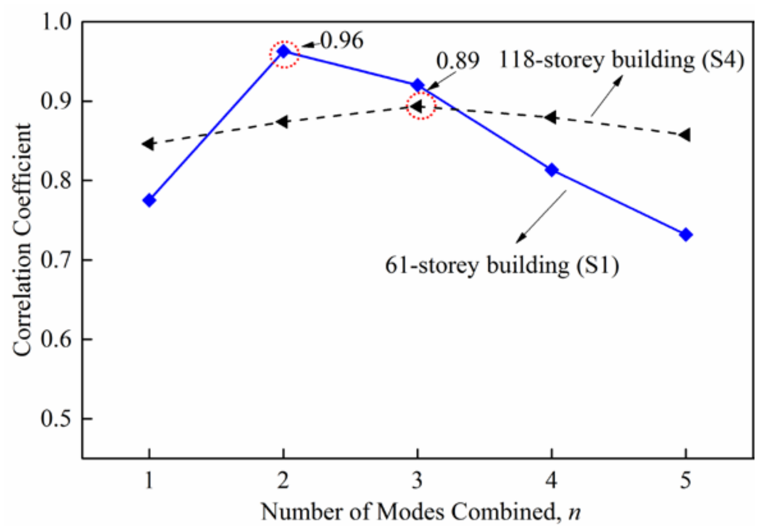


Fig.3 – Correlation coefficients between $\theta_{\max}$ and S^{*}_{v} with different combinatorial terms

6. Evaluation of IMs

A desirable IM should possess efficiency, sufficiency and scaling robustness [24]. An efficient IM is defined to be one that could diminish variability in the structural demand measure for a given IM level.And an IM is deemed to be sufficient provided that for a given value it would render the structural response conditionally independent of earthquake magnitude (M) and source-to-site distance (R). Scaling robustness herein is the capability of the IM to result in unbiased structural responses with ground motion records scaled to certain IM value, compared to the analogous responses obtained from as-recorded (un-scaled) ground motions[24]. The evaluation of structural seismic performance tends to use incremental dynamic analysis method with scaling the records, so the scaling robustness of earthquake intensity measure is very important. Therefore, the evaluation of IMs will be discussed in these three aspects.

From the perspective of easy calculation and application, the simply intensity measure $S_a(T_1)$, $S_v(T_1)$, $S_d(T_1)$, PGA, PGV, PGD , the IMs mentioned above S^{*}_{a12} [4], S^{*}_{a123} [4], S^{*} [5], IM_{12}[6], IM_{123}[6], S_{12}[8], S_{123}[8], and the proposed IM S^{*}_{v} are evaluated as shown in Table 3. For S1 and S4, the IM S^{*}_{v} the first two and three modes are considered, respectively, i.e. Eq. (8) and Eq. (9). The maximum inter-story drift ratio, $\theta_{\max}$, is adopted herein.

Table 3 – Some intensity measures (IMs)

Symbol	Description of intensity
$S_a(T_1)$	Spectral acceleration at the period of first mode T_1

$S_v(T_1)$	Spectral velocity at the period of first mode T_1
$S_d(T_1)$	Spectral displacement at the period of first mode T_1
PGA	Peak ground acceleration
PGV	Peak ground velocity
PGD	Peak ground displacement
S^*_{a12} S^*_{a123}	$S^*_{a12}=0.80S_a(T_1)+0.20S_a(T_2)$ $S^*_{a123}=0.80S_a(T_1)+0.15S_a(T_2)+0.05S_a(T_3)$
S^*	$S^*=S_a(T_1)R^{\alpha}_{S_a}=(S_a(T_1))^{1-\alpha}(S_a(T_f))^{\alpha}$ $T_f=2T_1, \alpha=0.5$
IM_{12}, IM_{123}	$IM_{12}=S_a(\tau_a,5\%)^{1-\beta}S_a(\tau_b,5\%)^{\beta}$ $\beta=0.5$ $IM_{123}=S_a(\tau_a,5\%)^{1-\beta-\gamma}S_a(\tau_b,5\%)^{\beta}S_a(\tau_c,5\%)^{\gamma}$ $\beta=\gamma=1/3$ $\tau_a=T_1$, $\tau_b=T_2$, $\tau_c=T_3$
S_{12}, S_{123}	$S_{12}=\left[S_a(T_1,\zeta)\right]^{\alpha}\cdot\left[S_a(T_2,\zeta)\right]^{\beta}$ $\alpha=m_1/(m_1+m_2), \beta=m_2/(m_1+m_2)$ $S_{123}=\left[S_a(T_1,\zeta)\right]^{\alpha}\cdot\left[S_a(T_2,\zeta)\right]^{\beta}\cdot\left[S_a(T_3,\zeta)\right]^{\gamma}$ $\alpha=m_1/(m_1+m_2+m_3)$, $\beta=m_2/(m_1+m_2+m_3)$, $\gamma=m_3/(m_1+m_2+m_3)$ m_1, m_2, m_3=modal mass participation ratio for 1th 2th 3th mode
S^*_v	The IM proposed by the authors

6.1 Efficiency

The efficiency of IMs is evaluated by calculating the correlation coefficient between structural demand and IMs. When the correlation coefficient has a relatively high magnitude, a higher efficiency is pronounced of associated IMs. Time history analyses are implemented for the structures excited by the selected 22 original ground motions without scaling. Fig. 4 shows the correlation efficient between θ_{max} and IMs calculated via Eq. (3). As shown in Fig. 4, the proposed IM S^*_v has highest coefficient compared to other IMs for both structures. As simple-form IMs, PGV and $S_v(T_1)$ can remain a relatively high efficiency, while PGA is rather poor in both cases. And for high-rise building, the IM considering soften period, i.e. S^*, has no advantage comparing with IMs considering higher modes. As illustrated in Fig. 4, for both S1 and S4, some IMs considering higher modes, such as S^*_{a123} and IM_{123}, also behave well. S_{12} （or S_{123}） has a relative poor correlation compared to IM_{12} (or IM_{123}), although only the exponent is different.

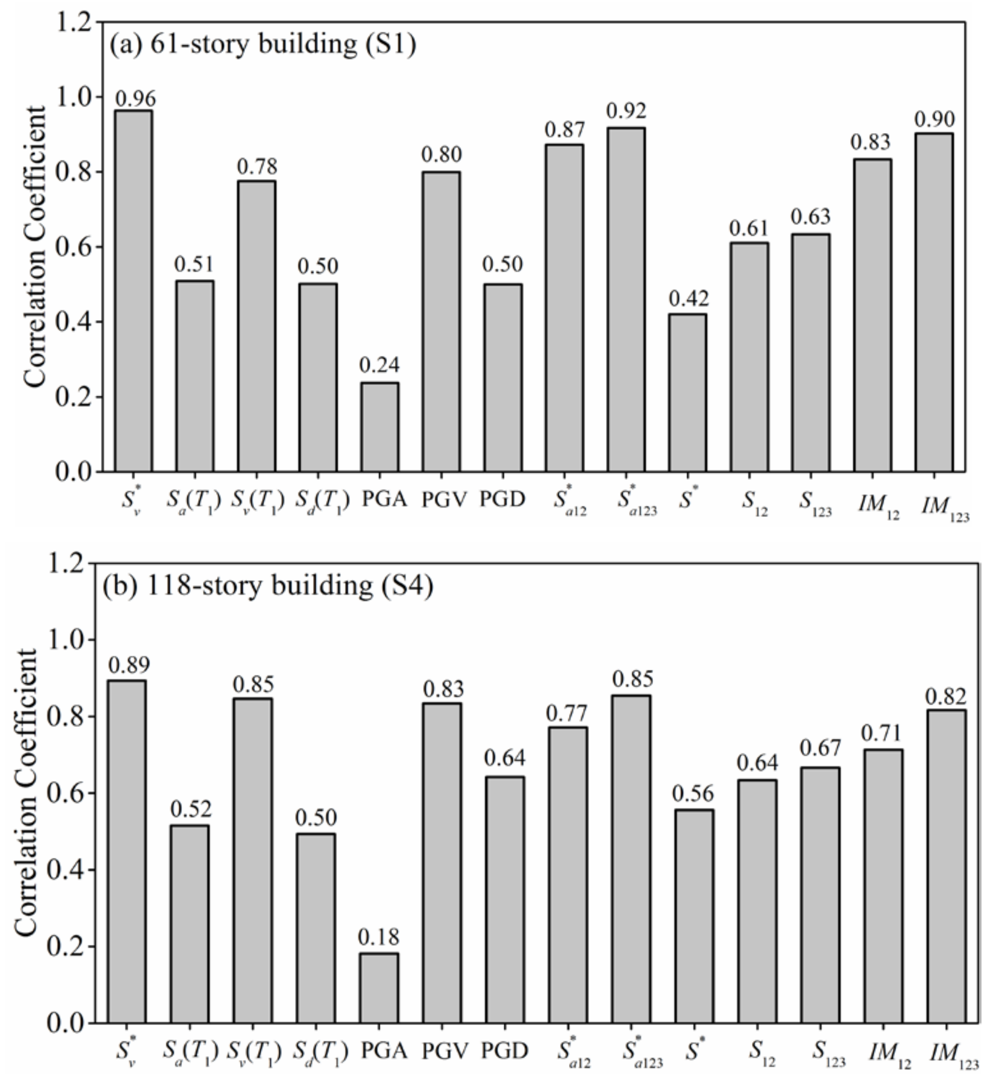


Fig. 4 – The correlation between $\theta_{\max}$ and IMs for efficiency

6.2 Sufficiency

A sufficient IM is defined as one that, for a given value, renders the structural response conditionally independent of earthquake magnitude (M) and source-to-site distance (R). Generally, an IM could be considered as a sufficient one when it has a larger correlation with M and R. The following model is used for regression analysis [4]:

$$\mathrm{DM} = \alpha \cdot \mathrm{IM}^{\beta_1} \cdot e^{\beta_2 \cdot M} \cdot R^{\beta_3} \cdot \varepsilon \tag{10}$$

here, α, β_1, β_2 and β_3 are the regression parameters; ε is random error. As shown in Fig. 5, the sufficiency of IMs is analyzed by adopting the ground motion records in Table 2. As shown in Fig. 5, compared to other IMs S_v^* has very high sufficiency for both structures under the given M and R. And a higher efficiency IM tends to have a higher sufficiency as depicted in Fig. 4 and Fig. 5.

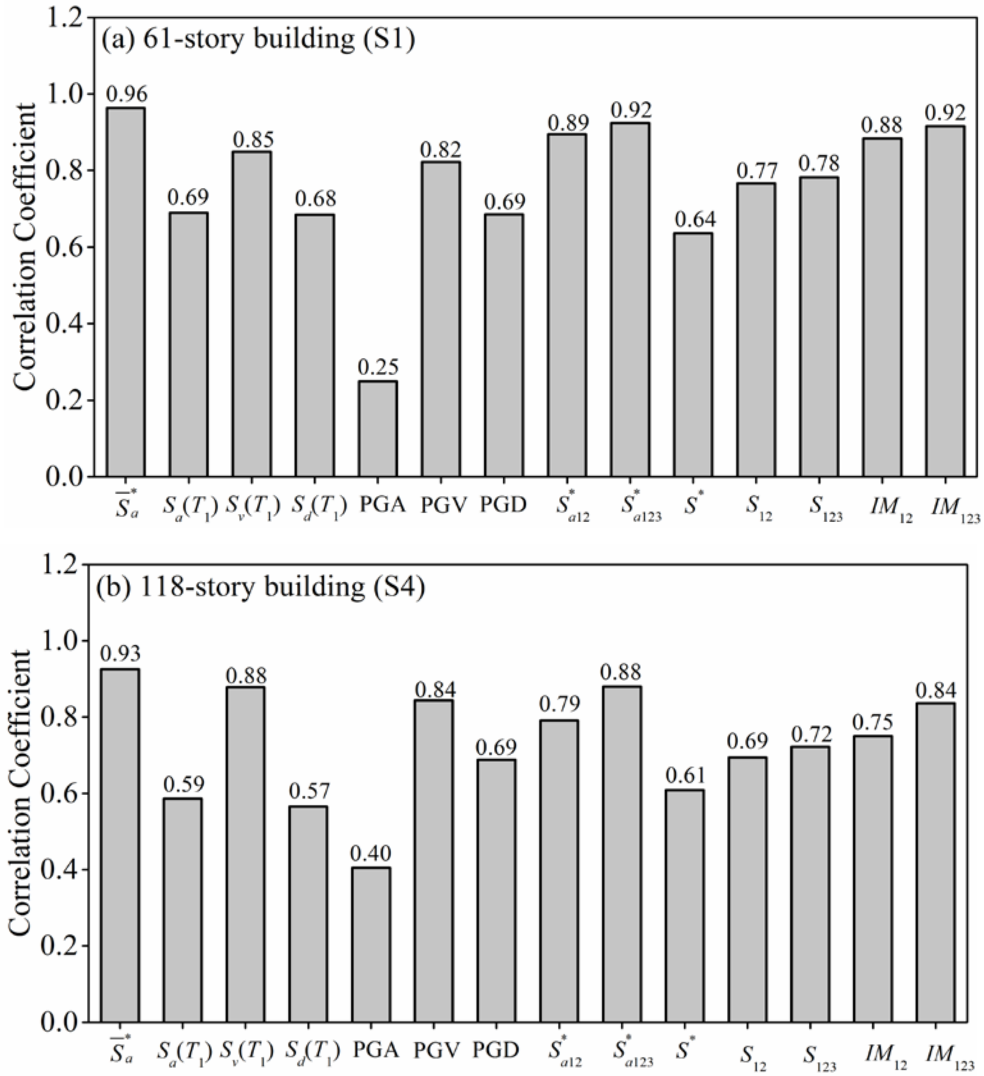


Fig. 5 – The correlation between $\theta_{\max}$ and IMs under given M, R for sufficiency

6.3 Scaling robustness

Scaling robustness is one property of an IM, which could guarantee structural responses due to records scaled to the same resulting IM level by different factors should not form a trend in the responses versus scale factors curve. The recorders in Table 2 are scaled to the same S_v^* level or the same $S_a(T_1)$ level of the second ground motion recorder. Linear least-squares regression (applied to the logarithms of the variables, i.e., $\ln(\theta_{\max})$ and ln(scaling factor)) is used to estimate the relationship between maximum inter-story drift ratios and scaling factors. If the regression line has a small slope, the IM is considered robust with respect to scaling factor [25]. And the siginificance of the slopes can be measured by p-value from F-Test. A lower p-value indicates that the observed trend is statistically significant, while a larger p-value indicates there is likely no underlying trend [26]. The Fig. 6 illustrates that the scaling robustness of S_v^* is obvious improved compared to $S_a(T_1)$ scaling in model S4.

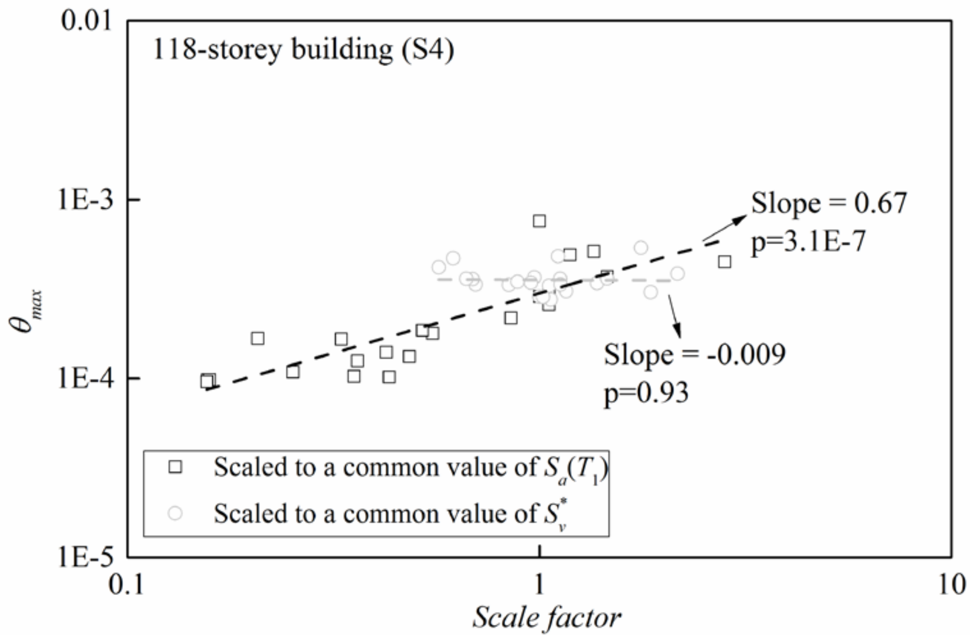


Fig. 6 – θ_{max} versus record scale factor

7. Conclusion

Some conclusions can be reached as follows through the development of a combination-type earthquake intensity measure for super high-rise building,

(1) The correlation between spectral velocity and maximum inter-story drift radio of super high-rise building is higher than that of spectral acceleration and displacement in the long period range. Motivated by above, the multiplication-type IM considering higher modes based on spectral velocity is proposed. For a structure with fundamental period more than 9.0s, the combination of first three modes in the IM could get an adequate performance.

(2) The proposed IM and several other IMs are evaluated from three aspects, i.e. efficiency, sufficiency and scaling robustness. Results show that the proposed IM has better performance. And also found is that the increase of the efficiency could improve the sufficiency. The IM considering high modes is more suitable for super high-rise building compared to the one considering soften period.

(3)The IM is proposed based on the selected far-field ground motions without near-field ground motion. And the development of this IM is based on the limited structural models. More case studies on other super tall building are desirable in further work.

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