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ON INTENSITY MEASURE SELECTION FOR NONLINEAR DYNAMIC ANALYSIS OF SOIL-MDOF STRUCTURE INTERACTING SYSTEMS

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Abstract. *A major source of variability in seismic responses of structures arises from selecting the earthquake Intensity Measure (IM), for conducting nonlinear dynamic analysis, relative to the damaging effects of earthquakes on structures. In this paper, the capability of the six most common IMs on estimation of Engineering Demand Parameters (EDPs) of Soil-MDOF Structure Interacting (SMSI) systems is investigated. Two-dimensional structural models of 5, 10 and 20 stories shear buildings are studied, using elasto-plastic MDOF stick models, whereas the underlying soil is considered as a homogeneous elastic half space and is modeled using the cone model concept. Then, the systems are subjected to 60 representative ground motions. The analyses are done directly in time domain using direct step-by-step integration method. This paper attempts to elucidate the accuracy and efficiency of considered methods for the evaluation of EDPs, in SMSI systems, and to find the most effective IM. For this purpose, two criteria are examined: (a) the median of EDPs in comparison with the predicted values, obtained from regression analyses, and (b) coefficient of variations of EDPs. The results show that a suitable IM for an EDP may differ from one to another in terms of accuracy and efficiency. Finally, the appropriate IM is proposed for each of the considered EDPs.*

1 INTRODUCTION

The selection of the measure of ground motion intensity challenges researchers, since an appropriate intensity measure (IM), can significantly decrease the runtime of the estimation of engineering demand parameter (EDP). This may lead to more reliable evaluations of the seismic performance of the facilities. Researchers have suggested various measure of ground motion intensity. Shome et al. (1998) [1] recommended that scaling of ground motions to a given level of spectral ordinate at the fundamental period of vibration significantly decrease the variability in the maximum demand observed in the structural system. In another study, Cordova et al.(2000) [2] proposed an intensity measure that accounts for period softening to reduce variability at large levels of maximum interstory drift ratio, drift demands larger than 5%, for composite structures. Luco and Cornell (2001) [3] investigated the effects of six different intensity measures on the estimation of the maximum interstory drift ratio for moderate-to-long period buildings using the concepts of efficiency and sufficiency for an intensity measure. Baker and Cornell (2005) [4] proposed a vector IM containing two or three parameters as opposed to the scalar IMs that contain only a single parameter.

Almost all previous studies on IM selection have either dealt only with the response of fixed base SDOF or MDOF structures. The objective in this study is to evaluate six different measures of ground motion intensity using the results of response history analyses in the context of Soil-MDOF Structure Interaction (SMSI) problem. Two types of structural responses are investigated; maximum roof drift ratio (MRDR) and peak floor acceleration, (PFA), may occur anywhere in the height of structure.

2 SOIL-MDOF STRUCTURE NUMERICAL MODEL

As shown in Figure 1, the system under consideration consists of an N-story building and a foundation resting on a soil medium. The structure is modeled as a shear building with equivalent circular plan. Let m_i , I_i , r_i and H_i denote the mass, the mass moment of inertia around its geometric center, the radius of the equivalent circular plan and the height of the mass in the $\mathbf{i}^{th}$ story from the foundation surface, respectively.

This research assumes that the characteristics of all stories are the same. The foundation is treated as a circular rigid disk and the flexibility of the foundation is not taken into account. The mass and mass moment of inertia of foundation are expressed by m_0 and I_0 , respectively. The mass of foundation is considered so that foundation uplift does not occur due to design earthquake load, and with considering the empirical relationship between the ratio of m_0 and total mass of structure for typical buildings. In this case, $0.05 \le (m_0/M) \le 0.5$ is selected for the considered structures, where M is the total mass of the superstructure.

In order to model soil beneath the structure, a lumped-parameter model is adopted to represent the soil and the interaction mechanisms. The soil beneath the foundation is assumed a homogenous half-space and replaced by a simplified 3DOF system based on the concept of Cone Models. Cone model was proposed by Meek and Wolf (1993) [5] and Wolf (1994) [6] for evaluating the dynamic stiffness and the effective input motion of a foundation on the ground.

To consider the frequency dependency of the rotational spring and dashpot coefficients, the additional internal rotational degree of freedom θ, is assigned to a polar mass moment of inertia, M_θ , and connected to the foundation node using a rotational dashpot, with the high frequency limit of the radiation damping. For the motions in the case of nearly incompressible and incompressible soil, corresponding modifications are performed for the soil with Poisson's ratio greater than 0.3, Wolf (2004) [7].

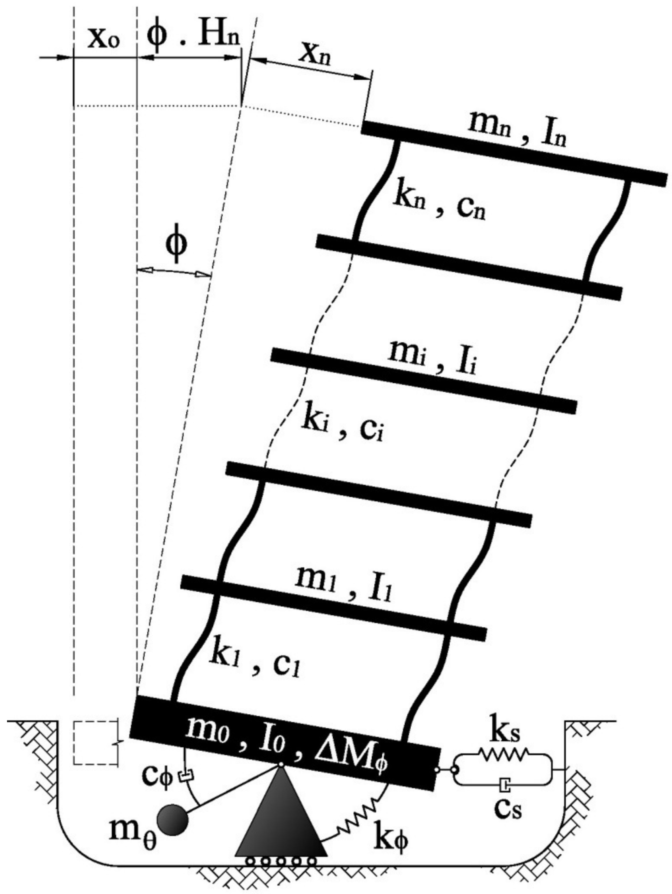

Figure 1: Soil-MDOF structure interacting system and displacement components

3 SOIL-MDOF STRUCTURE SYSTEMS CONSIDERED

Table 1 briefly summarizes the interacting system models evaluated in this paper. These specific three buildings are chosen to capture some variation in number of stories and first-mode period of system. The story shear force-interstory drift relationship is modeled by a normal bilinear hysteretic rule with 5% strain hardening ratio. All of the considered structures have the same value of aspect ratio, $H_n/r = 3$, and viscous damping coefficient $\xi_{str} = 5\%$.

For the superstructure, nonuniform distribution of lateral stiffness and yielding strength along the height of the structure are considered. For this purpose, the vertical distribution coefficient in accordance with ASCE7 (2010) [9] method is calculated. The yield strength of structure is determined in basis of the response modification coefficient and the overstrength factor equal to 8 and 2, respectively ($R = 8$ and $\Omega_0 = 2$).

In order to comparison of soil flexibility condition in the studied systems, dimensionless frequency parameter, a_0 , is introduced as an index for the Structure-to-Soil stiffness ratio:

$$a_0 = \frac{\omega_{fix} H_n}{V_s} \quad (1)$$

Where, ω_{fix} is the circular frequency of the fixed base structure.

It should be noted that two different base fixity conditions are considered base on values of dimensionless frequency. $a_0 = 0$ and $a_0 = 3$ which are representative of the fixed base structure and predominant SSI effect, respectively.

Stories	Fundamental Period	
	Interacting System ($a_0 = 3$)	Fixed Base Structure ($a_0 = 0$)
5	0.75	0.55
10	1.20	0.90
20	2.00	1.50

Table 1: Period of systems in flexible and fixed base conditions

4 REGRESSION ANALYSIS AND POINT OF COMPARISON

To evaluate the prediction accuracy of the various IM methods, it may be helpful to establish an estimate of the true response limit. Because of uncertainty in knowledge of ground motion behavior, this prediction is termed the Point of Comparison (POC) [10].

In order to estimate the POC values of response parameters of interest (MRDR and PFA), a large number of SMSI systems analyses are performed. For this purpose, 60 representative ground motions are scaled by 16 incremental scale factor (a total of 5760 independent nonlinear analyses for SMSI systems) and MRDRs and PFAs are recorded for each analysis, along with spectral acceleration at periods of interest, $S_a(\beta_i T_1)$.

To create a predictive equation that relates the spectral accelerations to the observed structural response, regression analysis is used. For this study, the following functional form is selected to model the EDPs of interest.

$$\mathrm{Ln(EDP)} = a_0 + \sum_{i=1}^{11} \left[a_i \left(\mathrm{Ln}\, S_a(\beta_i T_1) \right) + b_i \left(\mathrm{Ln}\, S_a(\beta_i T_1) \right)^2 \right] \tag{2}$$

Where β_i coefficients are selected in eleven different levels to consider the spectral shape of each record, including $\beta = \{0, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 2.5, 3.0\}$. Then, a_i and b_i coefficients are determined using least-squares regression.

The values of POC and coefficients of determination, R^2, of predictive equation obtained from this procedure are shown in Table 2. In general, the selected regression model has good predictive ability as indicated by its R^2 values greater than 90% in the most cases, which indicates that the predictive equation explains more than 90% of variance in $\mathrm{Ln(EDP)}$ observed in the raw data.

	MRDR		**PFA**	
Structure / System	**POC**	$\mathbf{R^2}$	**POC**	$\mathbf{R^2}$
5-Story / SSI	0.023	0.945	14.60	0.907
10-Story / SSI	0.016	0.921	17.96	0.903
20-Story / SSI	0.011	0.921	19.85	0.881
5-Story / Fixed	0.020	0.877	16.00	0.932
10-Story / Fixed	0.018	0.906	17.32	0.918
20-Story / Fixed	0.010	0.922	18.70	0.897

Table 2: Values of point of comparison and R^2 of predictive equation

5 EVALUATION OF INTENSITY MEASURE METHODS

The objective in this study is to evaluate capability of six common Intensity Measures (IMs) on estimation of EDPs of SMSI systems. As expressed in introduction, Maximum Roof Drift Ratio (MRDR) and peak floor acceleration (PFA), occurring anywhere in the structure, are the focuses on this current paper as EDPs.

Many different methods for scaling to specified severity are proposed in the literature. In this study, the following methods are explored:

IM-1: Scaling the ground motions to a constant peak ground acceleration, PGA.

$$\mathrm{IM_1} = \mathrm{S_a}(\mathrm{T} = 0) \tag{3}$$

IM-2: Scaling the ground motions to the spectral acceleration measured at the fundamental period of vibration.

$$\mathrm{IM_2} = \mathrm{S_a}(\mathrm{T_1}) \tag{4}$$

IM-3: Scaling the ground motions to a two-parameter intensity index proposed by Cordova et. al (2000) [2].

$$\mathrm{IM_3} = \sqrt{\mathrm{S_a}(\mathrm{T_1})\mathrm{S_a}(2\mathrm{T_1})} \tag{5}$$

IM-4: Scaling the ground motions to the intensity measure proposed by Cornell and Luco (2001) [3], base on the ratio of inelastic spectral displacement to the corresponding elastic spectral displacement and participation factors.

$$\mathrm{IM_4} = \frac{\mathrm{S_d^I}(\mathrm{T_1}, \xi_1, \mathrm{d_y})}{\mathrm{S_d}(\mathrm{T_1}, \xi_1)} \sqrt{\left[\mathrm{PF_1^{[2]}}\mathrm{S_d}(\mathrm{T_1}, \xi_1)\right]^2 + \left[\mathrm{PF_2^{[2]}}\mathrm{S_d}(\mathrm{T_2}, \xi_2)\right]^2} \tag{6}$$

IM-5: Scaling the ground motions to three-parameter intensity measure proposed by Vamvatsikos and Cornell (2005) [11].

$$\mathrm{IM_5} = \sqrt[3]{\mathrm{S_a}(\tau_a)\mathrm{S_a}(\tau_b)\mathrm{S_a}(\tau_c)} \tag{7}$$

IM-6: Scaling the ground motions in accordance with the provisions of seismic codes such as NEHRP 2003 [12]. In this case, the ground motions are scaled such that for each period between $0.2\mathrm{T_1}$ and $1.5\mathrm{T_1}$ the avarega of the five-percent damped response spectra for the suit of ground motion is not less than the corresponding ordinate of the target response spectrum.

Where

$\mathrm{T_1}$	:	Fundamental period of the Soil-MDOF Structure system
$\mathrm{S_d^I}(\mathrm{T_1}, \xi_1, \mathrm{d_y})$	:	The spectral displacement of an elastic-perfectly-plastic oscillator with period $\mathrm{T_1}$, damping ratio ξ_1, and yield-displacement $\mathrm{d_y}$
$\mathrm{S_d}(\mathrm{T_1}, \xi_1)$	:	Elastic spectral displacement with period $\mathrm{T_1}$ and damping ratio ξ_1
$\mathrm{PF_1^{[2]}}$	:	The first-mode participation factor for the story corresponding to the first-two-mode SRSS estimate of EDP.
τ_a, τ_b and τ_c	:	Arbitrary periods, which are selected in this research equal to $\mathrm{T_2}$, $\mathrm{T_1}$ and $1.5\mathrm{T_1}$

More descriptions and information about the parameters used in the mentioned intensity measure can be reached in the relevant references.

The Maximum Considered Earthquake (MCE) spectrum, introduced in current building code provisions (ASCE 2010 [9]), is selected as target spectrum. For each of applied ground motion records, a scale factor is calculated so that the same values of intensity measure is obtained from target spectrum (MCE) and each of the individual ground motion response spectrum.

Three selected structures are analyzed using 60 ordinary ground motion records in the fixed and flexible base conditions. In each case, the quality of distribution of results, their averages and coefficient of variation (COV) are shown in Figure 2 to 4.

6 CONCLUSIONS

The objective of this study was to gain an insight on capability of the six different methods of scaling earthquake ground motions required for nonlinear dynamic analysis of MDOF structure in context of soil-structure interaction problem. For this purpose, two criteria are examined: (a) the mean value of EDPs in comparison with the predicted values, obtained from regression analyses, and (b) dispersion of the response. As shown in figure 2 and 4, the following conclusions can be drawn from the investigation of MRDR results:

- In most cases, with increasing number of stories, the dispersion of MRDR tendency to decrease and concentration of mean of results around POC values increases .In this regard, as indicated in figure 4, IM-3 and IM-5 indicate the lowest values of dispersion in comparison with other methods.
- IM-1 and IM-6 can lead to conservative mean for 5-story and all building considered in comparison with POC value, respectively. The values of COV are between about 50% and 65% for IM-1 and between about 30% and 70% for IM-6, in the considered systems, which may not be desirable.
- Mean of the results obtained through IM-4 represents the least values of response. Accordingly, IM-4 might be taken as an unsafe method in accordance with POC values.
- In comparison with the other methods, e.g. IM-2, 3 and 5, for the case of maximum roof drift ratio (MRDR), IM-3 may be better measure of intensity in terms of estimating the dispersion and mean of the responses, both at fixed and flexible base conditions.

As indicated in figure 3 and 4, for the case of PFA response, the conclusion may be summarized as follows:

- Except for IM-1, in the other cases, along with increasing number of stories, the dispersion of PFA is increasing.
- In general, for the case of the peak floor acceleration, PFA, the dispersion of results due to IM-1 has the lowest values. Therefore, PGA is the best measure of intensity in terms of estimating the dispersion and mean of the response, both at fixed and flexible base structures. Similar conclusion had been presented by Aslani and Miranda (2005) [13] for fixed base structures.

Finally, it can be noted that base on engineering demand parameter of interest, the type of the appropriate measure of ground motion intensity (IM) may be changed. It should be recall that the results presented here are based on a suite of soil-structure models and these models are by no means representative of all classes of systems in existence. It is believed that further work is needed to consider more different types of EDPs and IMs.

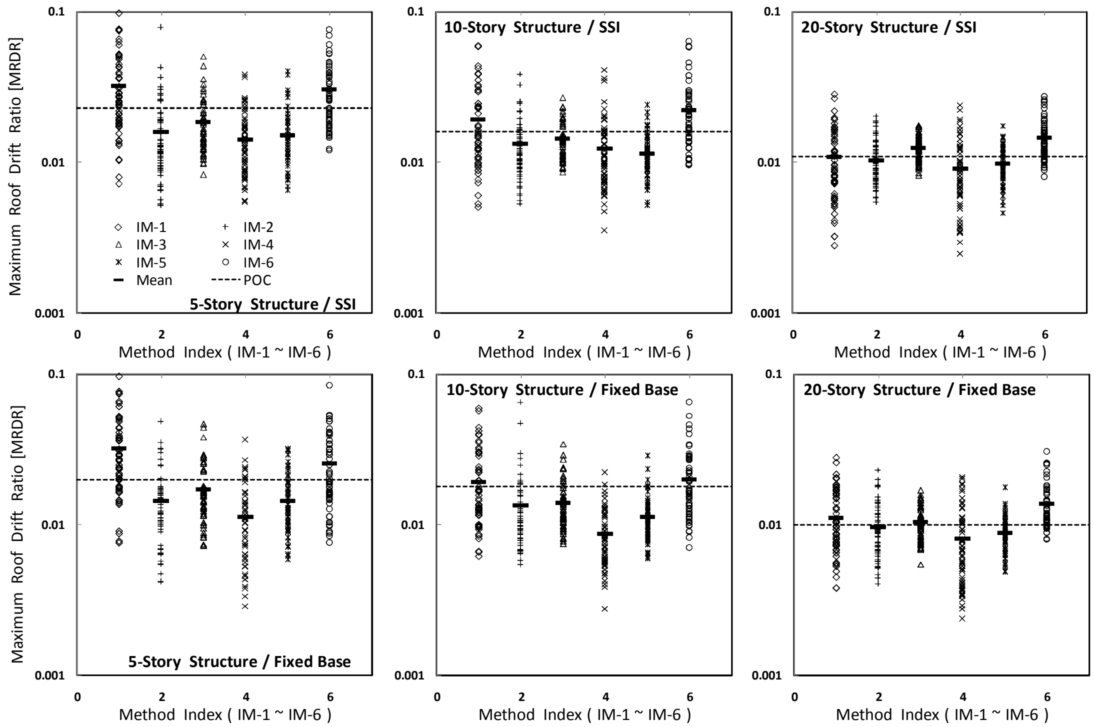

Figure 2: Comparison of Mean of MRDRs from different IM methods and POC values in fixed and flexible base conditions

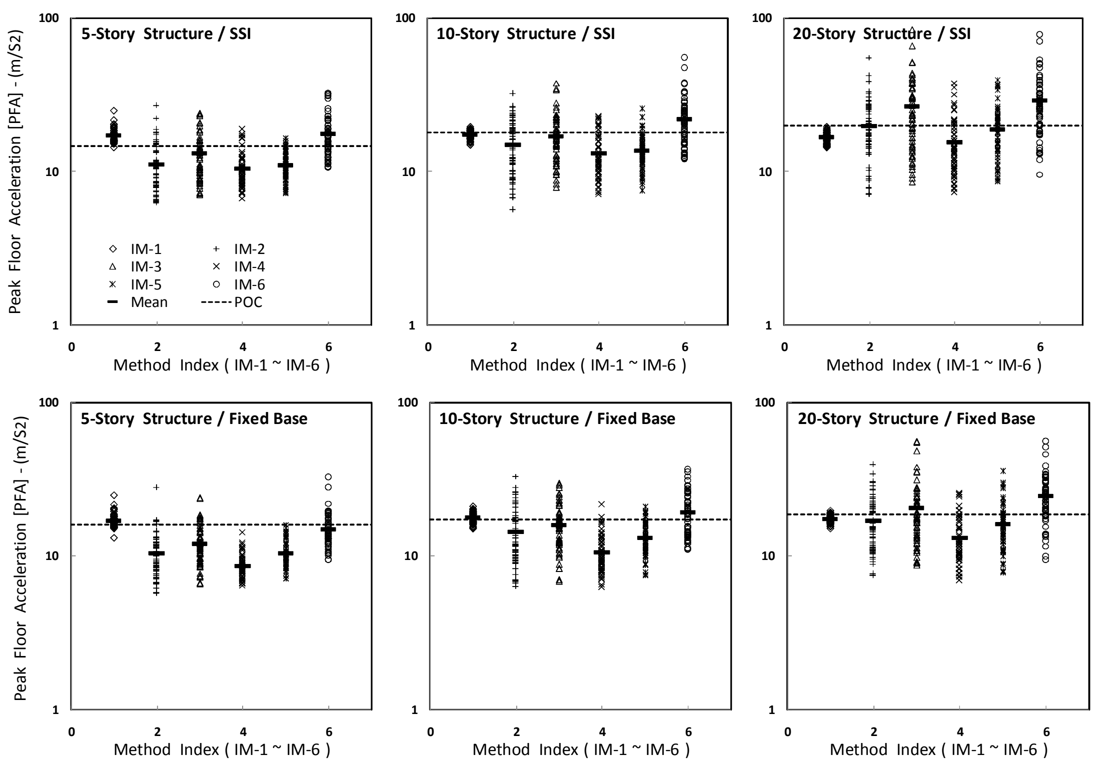

Figure 3: Comparison of Mean of PFAs from different IM methods and POC values in fixed and flexible base conditions

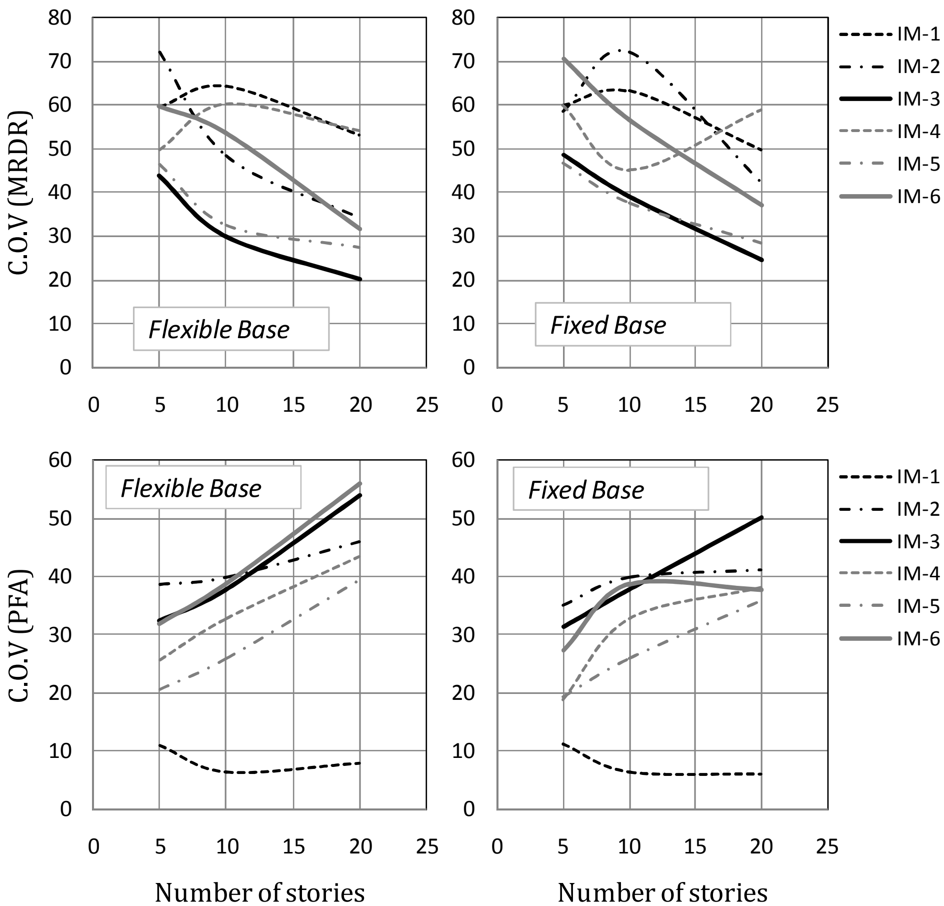

Figure 4: Comparison of COV (EDP) of different IM methods in flexible and fixed base conditions

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