STRUCTURE SPECIFIC GROUND MOTION SELECTION: PROS, CONS AND FUTURE DIRECTIONS

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Keywords: Time-history analysis, Ground motion selection, Pros and Cons

ABSTRACT

Following recent development in the probabilistic approaches for seismic design and evaluation of structures in earthquake engineering; use of Nonlinear Time-History Analysis (NLTHA) is common and is increasing. One important step in NLTHA is to select and prepare a set of Strong Ground Motions (SGMs) as the input of analysis such that they represent a predefined level of seismic intensity. This paper reviews the most common ground motion selection and modification methods in the literature, highlights the pros of targeted selection of SGMs and discusses potential problems with the quantification of selection criteria. After a glimpse on the unresolved problems and controversies related to the structure-specific SGM selection, future research directions are proposed.

Increase in the reliability of the estimated responses in term of statistical dispersion, reduction in the computational cost without losing the accuracy and the prevention of bias in the results are on the “pro” side of the ledger, while the “con” side includes the challenges on involving new selection criteria and intensity measures in the traditional code-based design process, difficulties in the alleviation of uncertainties from ground motion such as near-fault characteristics, frequency content and vertical component of motion and obstacles for the introduction of an integrated selection scheme due to the large variation in the structural systems and details.

After a comprehensive qualitative comparison among the features of most common approaches which have been proposed in recent years; some methods are applied to predict the dynamic response of a 2-D steel frame which represents a typical case of vertically irregular system. Results confirm the superiority of structure-specific selection against the blind selection from preliminary refined SGMs based on seismological requirements.

INTRODUCTION

An important step for the Nonlinear Time History Analysis (NLTHA) of structures is to select a reliable set of ground motions (Ghafory-Ashtiany et al., 2012). In probabilistic seismic demand analysis of structures based on the Pacific Earthquake Engineering Research (PEER) centre framework, described in FEMA-350 (2000), one of the key points to ensure the reliability of results is to reduce the dispersion in calculated Engineering Demand Parameters (EDPs). The Mean Annual Frequency (MAF) of exceedance of a particular Limit State (LS) (e.g. FEMA-350 2000) is expressed mathematically in Eq.1 (Ghafory-Ashtiany et al., 2012):

$$MAF(LS) = \int_{IM} \int_{EDP} G(LS|EDP).|dG(EDP|IM)|.|d\lambda(IM)| \qquad (1)$$

where IM is the intensity measure e.g. Spectral acceleration (Sa) at the first period of structure and a given damping ratio; G (LS|EDP) denotes the probability of exceeding LS conditioned on the value of EDP e.g. Inter-Story Drift Ratio (IDR) and G (EDP|IM) denotes the probability of exceeding EDP conditioned on the value of IM. One of the key points in calculation of Eq.1 is the inherent assumption on the dependency of EDP only on the chosen IM. If there is dependency of EDP on any other indicator, then, equation results in a biased estimate of the MAF. Hence the sufficient IM must represent the EDP without any dependency on other variables e.g. magnitude, distance and etc. On the other hand, the spectral acceleration at the first period of structure, Sa (T1), has been commonly used as the traditional IM in earthquake engineering. Design codes use a Sa-based target spectrum to facilitate ground motion selection approach as the input to dynamic analysis such as Iranian Code of Practice for Seismic Resistant Design of Buildings, standard no. 2800.

Besides using Sa-based elastic spectrum, other approaches have been emerged to predict the response of a structure more precisely. It is proved that Sa (T1) is not sufficient enough specially when applied to the long-period buildings, the structures with high levels of nonlinearity or in the near source regions. To deal with this problem, some researchers attempted to introduce new IMs which are more sufficient than Sa (T1). Despite of the IM sufficiency, the attenuation model availability plays an important role in this subject which makes many of the new proposed IMs inapplicable (Ghafory-Ashtiany et al., 2012).

Most of studies in this field are focused on the first mode dominated structures. Moreover, some controversial issues such as the selection and scaling of vertical components, selection of a horizontal pair of components in case of bidirectional analysis, near-fault characteristics and the influence of applying increasing amplitude scale factors on a record while the frequency content is constant are still unresolved.

SGM RECORD SELECTION APPROCHES

In this section, a brief review on the SGM selection methodologies is presented. The most common approaches can be classified in 11 categories:

1- SITE-SPECIFIC RECORD SELECTION:

Site specific selection of SGMs, also known as “scenario-based” selection, is, probably, the first engineering approach to refine a general dataset and introduce the best possible SGMs which can represent the level of seismic hazard at a site. The method aims to achieve a good agreement of magnitude, distance and soil conditions with the target values. However, the selected SGMs must be scaled to the target spectral acceleration to be consistent with the required hazard level. The influence of each component of scenario in the target scenario i.e. magnitude, distance and soil type on the estimated structural responses have been studied (Bommer and Acevedo, 2004). Althogh the simplicity of method would be an advantage in practical cases, there is no concrete evidence showing its more efficiency. İn other words, when the selected records must be scaled to the predefined spectral values before NLTHA, site-specific selection showes no superiority compared with the structure-specific selection(Bommer and Acevedo, 2004).

2- CODE-BASED RECORD SELECTION:

Almost all seismic codes and guidelines provide a scaling and selection process for SGMs used in NLTHA. The method can be considered as a conservative generalization of scenario-based approach, while mean response spectra corresponding to the selected SGMs cannot fall below the target (design) spectra in a range of periods covering possible contribution of higher modes of vibration and structural softening due to the nonlinear behaviour. The method often results in the scaled SGMs with high energy content when the uniform hazard spectrum (UHS) is defined as the target (Baker, 2011). When a relatively large dataset of SGMs is available, there are different optimization methods to minimize the applied scale factors and, consequently, select SGMs with the best spectral agreement with the target (Iervolino et al., 2010).

3- DISPLACEMENT-BASED RECORD SELECTION:

As a response to the increasing development of performance based earthquake engineering and the highlited role of displacement-based representation of seismic actions, new definition of hazard-consistensy in term of displacement-spectrum compatibility is introduced (Smerzini et al. 2012). Also, it is mandatory to ensure high qulity spectrum, especially, at longer periods where the presense of noise can affect the reliability of spectral values. Subsequently, a selection scheme can be designed to find sets of unscaled, or lightly scaled accelerograms while the record to record and record to target spectral variability is in a tolerable range. Similar process may be proposed by using a nonlinear design spectra as a target, although, the PSHA-based generation of such spectra would be another challenge (Ghafory-Ashtiany et al., 2012).

4- PRECEDENCE LİST OF SGM RECORDS:

The goal of methods in this category is to rank SGMs from a large dataset in a way that the best SGMs which can predict the dynamic capacity of a target structure is refined. Dynamic capacity of structure may be obtained from median IDA curve or any summarized IDA curve(i.e. 16th, 50th and 84th fractiles). Use of simplified models of structures in conjunction with modern optimization techniques result in a computationally efficient method for seismic evaluation of structures usng IDA(Azarbakht and Dolsek, 2011). Also, it is possible to select a small number of SGMs for accurate prediction of nonlinear response of a particular group of structures with a typical behaviour range(Ghafory-Ashtiany et al., 2011).

5- SPECTRAL SHAPE-BASED RECORD SELECTION:

The method requires scaling of records such that an acceptable match between epsilon values corresponding to each record and the target epsilon as an output of PSHA disaggregation can be acieved (Ghafory-Ashtiany et al., 2012). The epsilon is usually calculated at the first modal period of structure. Epsilon measures the deviation of Sa(T1,5%) for a ground motion from the geometric mean Sa(T1,5%) computed from a Ground Motion Prediction Equation (GMPE):

$$\varepsilon = \frac{\ln Sa_{Mean} - \ln Sa}{\sigma_{\ln Sa}} \tag{2}$$

Correlation of spectral shape measured by ε with the inelastic structural response is used for structure-specific ground motion selection by introducing Conditional Mean Spectrum (CMS) (Baker, 2011). The CMS provides the expected response spectrum, conditioned on occurrence of a target spectral acceleration value at the period of interest which is a less conservative alternative for UHS.

6- RECORD SELECTİON BASED ON CONDİTİONAL İNTENSİTY MEASURES:

As a generalization of CMS and following tha same path (Mousavi et al., 2011) the Eta indicator is defined as a combination of the conventional epsilon and the PGV epsilon. The Eta indicator has more correlation with the structural response in comparison with the a conventional Epsilon and can represent the linear spectral shape in a good manner. It can be employed to represent the Eta based conditional mean spectrum (E-CMS). In a more complicated methodology, a Generalised Conditional İntensity Measure (GCIM) can be defined by the construction of the multivariate distribution of any set of ground motion intensity measures conditioned on the occurrence of a specific ground motion intensity measure (Bradley, 2011).

7- MODAL PUSHOVER-BASED RECORD SELECTION:

Modal Pushover-Based Scaling (MPS) procedure uses the peak deformation of the first-"mode" inelastic SDOF system due to the record as the criterion for both scaling and selection of SGMs. The effects of higher modes of vibration is checked in term of the consistency of the elastic spectral displacement response values at higher modal periods of the structure with the target spectrum(Kalkan and Chopra, 2010). After some structural evaluation of proposed method for tall buildings(Kalkan and Chopra, 2012), the method is recently, extended to the multi-story unsymmetric-plan buildings (Reyes et al. 2015).

8- RECORD SELECTION USING DATA REDUCTION TECHNIQUES:
Following the successful use of optimization techniques, such as genetic algorithm and principal component analysis, in earthquake engineering; skyline query as a modern data reduction tool is applied for the efficient selection of SGMs using a more comlicated new vector-valued IM which can prdrict the damage potential of ground motions(Shi et al., 2013). However, more extended structural evaluation is required to prove the success of proposed method in prctical cases.

9- STRUCTURE-SPECIFIC SELECTION BASED ON THE COMBINATION OF SEVERAL MODES OF VIBRATION:
There is a variety of proposed approaches the aim of which is to provide NLTHA users with a scaling and selection process considering several modes of vibration simultaneously in the spectral matching problem. Multimode ground motion scaling methods may apply the square root of the sum of the squares (SRSS) or complete quadratic combination (CQC) rule in computing peak seismic demands such that minimized weighted sum of the square differences between the spectral responses and the target responses is obtaıned(Wang et al., 2010).

10- DAMAGE-BASED RECORD SELECTION
Vulnerability assessment of structures is a frequently used task in today earthquake engineering, the sensitivity of computed fragility curves to the selected set of ground motions has been studied (Cimellaro et al.,2009). It is shown that damage surfaces can play the role of as a generalization of target spectrum when engineering demands are substituted by the damage levels (Nakhaei, 2012).

11- SELECTION OF PULSE-LIKE GROUND MOTIONS
Near-fault ground motions show unique features such that the general patterns for ordinary SGMs cannot be easily generalised for them. High damage potential of near-fault events is a result of intense pulse-like nature in the velocity-time series. Different IMs have been developed to quantify the contribution of pulse-type motions to the target seismic hazard level. Recently, a classification scheme is proposed to answer the question that: How many pulse-like SGMs base on the which criteria should be selected for NLTHA? (Hayden and Bray, 2014)

STRUCTURE-SPECIFIC SELECTION

Considering the NLTHA as a robust method for seismic response estimation of engineering structures; There has been a constant interest on the selection of appropriate SGM set such that represent the level of seismic hazard at the target site. Increasing use of probabilistic approaches to demonstrate the performance of structures is questioning the traditional selection criteria and guidelines. The structure-specific SGM selection has the advantages including but not limited to following points:

- Increased reliability in the results: It is shown that more confident prediction of mean structural responses can be achieved when a minimum control on the spectral shape of the SGMs is done. In a typical code-based scaling procedure, all intention is paid to the introduction of a conservative representative for a given intensity (e.g. 2% probability of exceedance in 50 years); while there is no guarantee that the record to record variability inherent in SGMs is reduced. When one is interested in the estimation of probability of failure in a structural element, both the mean value of demand and its variability become important (Kalkan and Chopra, 2010).
- Reduction in computational cost: There is no concrete scientific evidence supporting common code-based recommendations on the required number (e.g. three or seven) of input SGMs for Response History Analysis (RHA) of engineering structures. It is expected, logically, that more number of randomly selected SGMs leads us to a more accurate estimate of EDPs (Reyes and Kalkan, 2012). The structure-specific targeted selection enables us to reduce the number of required SGMs to ensure the constant level of accuracy (Reyes and Kalkan, 2012).

- Involving structural characteristics as a filter for ground motion uncertainties: Inherent uncertainty in recorded SGMs initiates from different sources such as propagation patterns or faulting styles which can be characterized following seismological approaches. Use of the structure-specific refinement can, implicitly, reduce the uncertainty by focusing on the consequences of variable seismological features on the seismic behaviour of structure. For example, when the ability to predict the median IDA curve is chosen as the selection criteria, there is no need to evaluate the ground motion parameters such as frequency content, duration and number of imposed cycles which are proved to be influencing on the nonlinear capacity of structures (Elnashai and DiSarno, 2008).

CHALLENGES AND CONTROVERSIES

Following the described progress in structure-specific SGM selection, there are still some challenges that need to be addressed:

- **Modern IMs:** As it is explained in the previous sections, many researchers have tried to propose more “efficient” IMs to describe the near true seismic behaviour of structures. Although the inability of the conventional IMs such as peak ground values and spectral accelerations in the reliable estimation of seismic response has been shown, for engineering practices, there is a mandatory need to develop GMPEs to involve modern IMs in the design process. Furthermore, general beliefs about the validation and capability of new selection and scaling tools, among the audience of seismic codes and guidelines, must be improved. For example, the concept of CMS as an alternative for UHS is still controversial, even among structural engineering researchers.
- **Variation in the structural behaviour:** One of the most advantages of conventional IMs, such as Sa(T1,5%), is the potential of IM to easily represent any dynamic system. while, there must be a comprehensive research program to provide us with sufficient evidence on the acceptable performance of new IM for a variety of structural systems or details. However, there are cases such as special structures, lifelines, secondary systems and geotechnical systems for which RHA is prescriptive, but, the structural achievements in selection and scaling cannot easily be generalized to them.
- **Multi-component SGM selection:** For RHA of a 3-D model, especially, when the structure cannot be categorised as “regular” system, bidirectional Analysis is proffered. To capture the full structural consequences of ground shaking, the NLTHA may be performed using vertical component of motion. The target level of scaling (design spectrum) and applied scale factors (e.g. for IDA analysis) are still questionable parameters in such cases.
- **Near-fault ground motions:** Following the brief review of near-fault characteristics in previous section (11th selection method); it should be noted that there is a tough challenge in dealing with this type of SGMs at the probabilistic seismic hazard analysis, prediction of spectral shape, quantification of structural issues related to the pulse-like nature of them and etc.
- **Higher modes of vibration:** Most of the studies in this field assume the first mode dominant dynamic behaviour for structures. There are critical cases such as tall buildings, asymmetric in plan systems and vertically irregular MDOFs, which several modes of vibration can participate in the response, particularly, under excitation by SGMs with rich frequency content (e.g. near-fault SGMs).

QUANTITATIVE COMPARIOSON OF SELECTION METHODS

In this section, a typical 2-D 12-story steel moment frame is selected from a standard database (Dimopoulos et al., 2011) and is modelled. To investigate the efficiency of selection methods, IDA curves is computed and statistical dispersion in term of Coefficient of Variation (COV) is compared. Different patterns to simulate the predefined levels of irregularity are suggested in the literature (Chopra and Chintanapakdee, 2004). It is shown that a simultaneous change in the stiffness and strength of a single story in the frame can affect the seismic behaviour of structure and represent a first mode dominant system with the potential of higher modes contribution (Michalis et al., 2006). Here, reduction factor of 0.5 is applied to the overall stiffness and strength at the 8th story of the frame.

Four sets of SGMs are selected using different available criteria:

1- Seven random selections among the results of a preliminary site-specific selection using the moment magnitude of 7, closest distance to the rupture equal to 15 km and soil class B based on the Eurocode8 classification. All SGMs are selected from a worldwide database of shallow crustal events SIMBAD (Iervolino et al., 2010).
2- Seven selections based on the best compatibility in the acceleration response spectrum at a range of periods (0.2T to 1.5T) using REXEL software (Iervolino et al., 2010). The target spectrum is the Eurocode8 design spectra for PGA of 0.36g and soil class B.
3- Seven selections based on the best broad band compatibility in the displacement response spectrum at a range of periods using REXEL-Disp software (Smerzini et al. 2012). The software is designed to refine high quality spectral values at long periods. The target spectrum is similar to the previous set.
4- Seven random selections among proposed worldwide pulse-like SGMs based on the first modal period of structure (1.17sec), pulse period ($1 \leq T_P \leq 2$) and soil class B (Hayden and Bray, 2014).

Results are summarized in Fig.1. The variation of dispersion in the estimated capacity with the increase in the maximum inter-story drift ratio is compared in Fig.2.

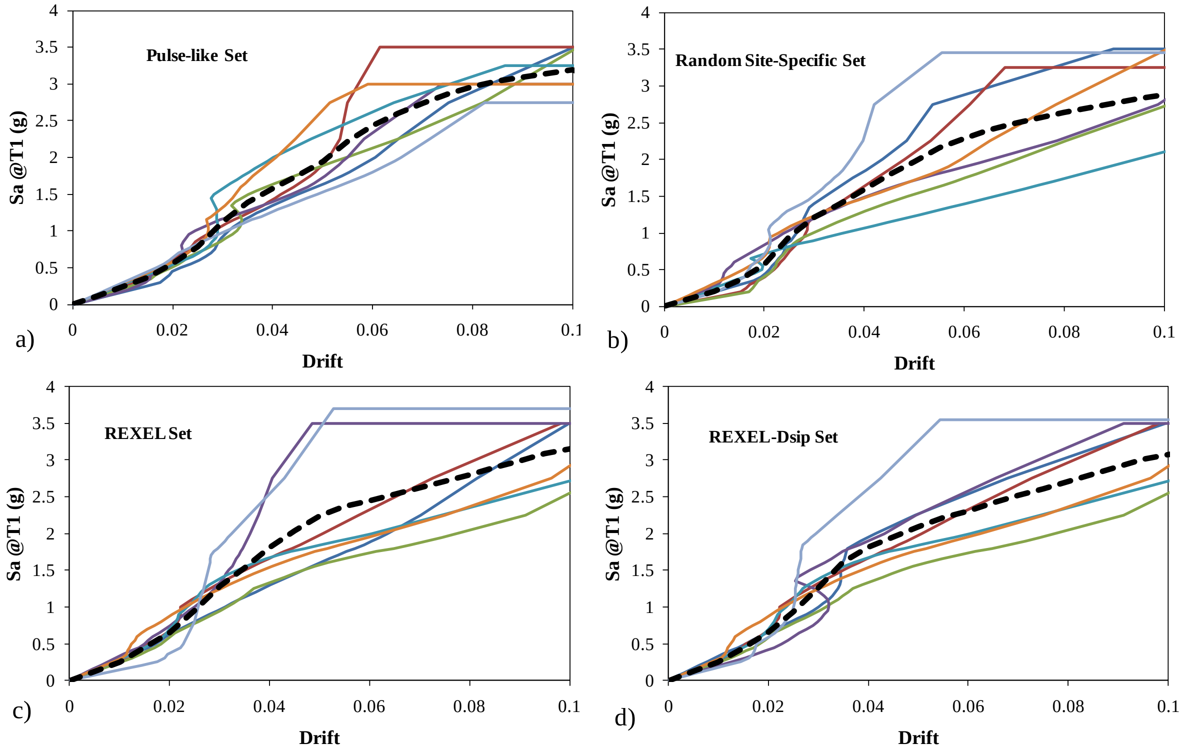

Figure 1. Computed IDA curves using different sets of SGMs: a) Pulse-like, b) Randomly selected site-specific, c) REXEL and d)REXEL-Disp. Colored lines denote the single records while the dashed line is the mean curve

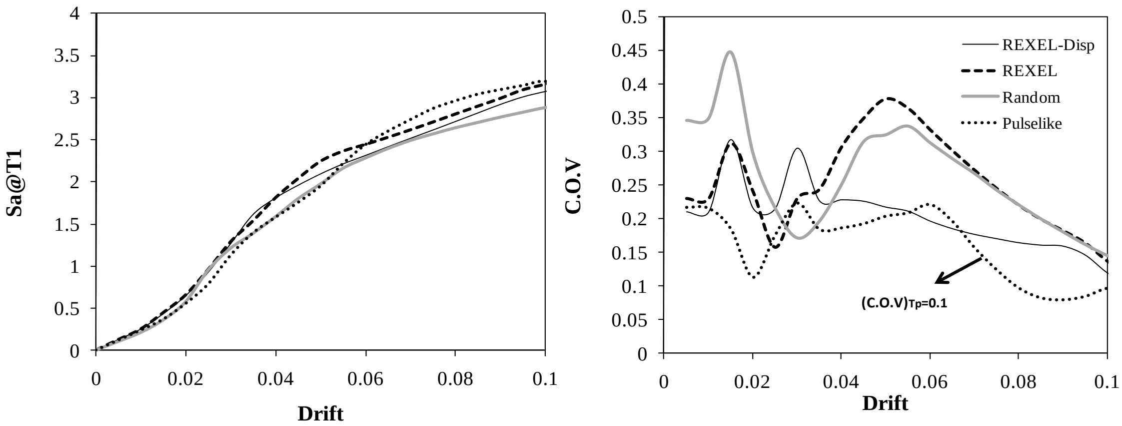

Figure 2. Comparison among mean IDA curve estimated by different methods (left) and variation of dispersion in the results (right)

CONCLUSIONS

A brief review and classification on the available SGM record selection methods is presented. After qualitative comparison of pros and cons of structure-specific methods, the efficiency of 4 selection processes is investigated by the estimation of IDA curves for a 2-D 12-story standard frame which is manipulated such that a vertically irregular case study can be achieved. The most important conclusions can be summarized as:

- Randomly selected site-specific SGMs result in the lowest estimation for the mean IDA capacity curve. Although the 4 methods generate approximately similar mean IDA curve, one cannot relate this to the accuracy of methods, due to the unknown “true” results which must be estimated using a large dataset of SGMs. At the whole range of drifts the highest COV is associated with the results of site-specific selection.
- Pulse-like set of SGMs yields lowest record to record dispersion almost at whole range of drifts. In the nonlinear zone, it can be related to low-frequency nature of pulses which makes same potential of seismic excitation for all pulses. In other words, the COV of pulse periods is small enough (≈ 0.1) to excite similar failure mechanism under all pulse-like SGMs. In the elastic zone, it can be concluded that the narrow band frequency content of SGMs cannot excite higher modes of system (the initial slope of all individual IDA curves matches).
- Interesting trend can be observed by comparing the results of REXEL and REXEL-Disp, where the good efficiency of both methods in the elastic zone is proved and with the increase in the drift ratios and gradual structural softening, the superiority of REXEL-Disp becomes clear. It is completely in agreement with the claimed intention of REXEL-Disp designers i.e. the more reliable estimations when soft systems yield large displacement.
- Assuming that a large dataset of SGMs is available (e.g. SIMBAD), it is possible to refine the whole data using preferred structure specific spectral IMs, if requirements such as GMPEs is provided.

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