MULTI-LEVEL CONDITIONAL SPECTRUM-BASED RECORD SELECTION FOR IDA

M. Kohrangi\textsuperscript{1}, D. Vamvatsikos\textsuperscript{2} and P. Bazzurro\textsuperscript{3}

ABSTRACT

Incremental Dynamic Analysis (IDA) is a widespread approach to evaluate the seismic response of structures by means of nonlinear dynamic analysis. It employs a single set of ground motion records and scales them up until dynamic instability is reached. The objective of IDA is to obtain the statistics for different Engineering Demand Parameters (EDPs) that gauge the response of the structure. It is well known, however, that the earthquake scenarios dominating the site hazard differ with the intensity of the ground motion and, therefore, the spectral shape of the expected records should reflect this change. Hence, the response of the structure, in general, would be better estimated in a multiple stripe analysis (MSA) framework by multiple sets of records selected to be hazard consistent to different intensity levels via, for example, the conditional spectrum (CS) method. Despite this issue, IDA is still a standard tool in seismic design and assessment. This study tries to quantify the level of bias that derives from using a single set of randomly selected records in IDA versus a multiple set of CS-based hazard consistent records in a MSA setting. We further explore different alternatives of CS for record selection to implement in IDA including a ‘multi-level’ approach, which combines the seismic properties of multiple intensity levels in a single record set. This proposed approach provides a trade-off between the more accurate but more complex method of MSA versus the conceptually and practically simpler IDA.

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Incremental Dynamic Analysis (IDA) is a widespread approach to evaluate the seismic response of structures by means of nonlinear dynamic analysis. It employs a single set of ground motion records and scales them up until dynamic instability is reached. The objective of IDA is to obtain the statistics for different Engineering Demand Parameters (EDPs) that gauge the response of the structure. It is well known, however, that the earthquake scenarios dominating the site hazard differ with the intensity of the ground motion and, therefore, the spectral shape of the expected records should reflect this change. Hence, the response of the structure, in general, would be better estimated in a multiple stripe analysis (MSA) framework by multiple sets of records selected to be hazard consistent to different intensity levels via, for example, the conditional spectrum (CS) method. Despite this issue, IDA is still a standard tool in seismic design and assessment. This study tries to quantify the level of bias that derives from using a single set of randomly selected records in IDA versus a multiple set of CS-based hazard consistent records in a MSA setting. We further explore different alternatives of CS for record selection to implement in IDA including a ‘multi-level’ approach, which combines the seismic properties of multiple intensity levels in a single record set. This proposed approach provides a trade-off between the more accurate but more complex method of MSA versus the conceptually and practically simpler IDA.

Introduction

Incremental Dynamic Analysis (IDA) \textsuperscript{1} is a widely used approach for evaluating the seismic response of structures using nonlinear dynamic analysis. This approach, which has been in use since the late 80s and early 90s was codified by Vamvatsikos and Cornell \textsuperscript{1} and presented as a sort of ‘dynamic pushover’ where the structure is subject to increasing seismic loads until it reaches dynamic instability. The dynamic loads are a set of earthquake ground motions that are singularly scaled from low- to high-intensity levels. The output of IDA is the response statistics of different Engineering Demand Parameters (EDPs) appropriate for monitoring the overall structural performance. These statistics are usually utilized in a probabilistic performance based earthquake engineering (PBEE) framework \textsuperscript{2} to quantify the occurrence rate of damage or loss of different severity. The selected set of ground motions, thus, is the seismic input that links the

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structural seismic response to the hazard. The connection between EDP and hazard in IDA is assigned to a single intensity measure (IM) of the ground motion that can be any scalable parameter, such as spectral acceleration at single oscillator period, $SA_T$, or spectral acceleration averaged over a specific period range, $AvgSA$ [3].

In PBEE, the rate of exceedance of an IM level (or occurrence of an IM range) of choice at the site of interest is evaluated using probabilistic seismic hazard analysis (PSHA) [4, 5]. Then hazard disaggregation analysis [6], a by-product of PSHA, identifies the contributing scenarios (e.g., magnitude, distance from rupture, fault type, tectonic regimes) at each IM level. Figure 1 shows the disaggregation plots for a low and a high IM level for $SA_T$ at $T=1.6$ s for Ankara. The large differences between the scenarios that most contribute to the hazard at the two selected IM levels are apparent. These differences suggest that, to be faithful to the site hazard, the set of records to be used in structural response estimation should change as the hazard level changes. Conventional IDA, however, utilizes a single set of records for all IM levels.

Some recent studies (e.g. [7]) showed that using randomly selected record sets for IDA without consideration to hazard consistency, can generate biased risk estimates. Hence, to limit the bias, state-of-the-art literature proposed PSHA-based record selection methods, such as the Conditional Mean Spectrum (CMS), the Conditional Spectrum (CS) and the Generalized Conditional Intensity Measure approaches (GCIM) [8-11], which account for the variation of ground motion properties with intensity levels. These methods provide multiple sets of records that are best used within a multiple stripe analysis (MSA) [12] approach.

Despite the fact that MSA is more flexible than IDA in accommodating PSHA-based record selections and, therefore, arguably it is a “superior” method in terms of accuracy of the results, IDA is still frequently utilized in building-specific seismic risk assessment. The question, therefore, remains if it is possible to include a PSHA-based record selection in IDA that resolves, at least partially, this inconsistency. To answer this question, Lin and Baker [14] proposed an ‘adaptive incremental dynamic analysis’ (AIDA) approach by combining the benefits of IDA to those of MSA. AIDA utilizes stripes-like ground motions to match the changing causal properties of the earthquakes as the IM level changes, while partially maintaining IDA-like ground motion continuity. Other researchers tried to work indirectly around this limitation by post-processing IDA results or by applying IMs more advanced than the commonly used $SA_T$. For instance, Haselton et al. [15] proposed a simplified method to adjust the IDA estimate of
collapse capacity for a set of buildings by approximately accounting for ground motion spectral shape. Kazantzì and Vamvatsikos [16] proposed the use of averaged spectral acceleration (AvgSA) in IDA as a common, first-mode-period independent IM to assess the vulnerability of a class of buildings that is also less dependent on the site characteristics.

In this paper we alternatively propose a multi-level record selection method (hereafter referred to as CSML), which combines disaggregation data from multiple IM levels to determine a single CS target spectrum that approximately accounts for spectral shape across all levels. In the following, we describe the details of this alternative methodology and attempt to quantify the bias that one might introduce to IDA-based building response estimates vis-à-vis the arguably unbiased hazard consistent MSA-based response estimates.

Multi-level Conditional Spectrum (CSML)

The conventional conditional spectrum-based record selection, CS(\(IM^*\)), provides a set of records that is compatible with each specific intensity level of the conditioning IM (i.e. \(IM^*\)). In this approach, the selected spectra are commonly conditioned at different values of the single spectral quantity that is considered the best predictor of the demand parameter of interest [17]. \(IM^*\) is often the spectral acceleration at the first mode period of vibration of the structure, \(SAT_1\). Many studies, however, showed inadequacy of this IM for estimating the response of complex buildings [18,19] especially when both local and global response metrics are of interest for detailed building-specific loss assessment purposes [20]. To resolve the limitations of \(SAT_1\), several studies suggested the use of AvgSA as the conditioning IM when performing IDA, e.g. [16,21,22] to take advantage of its higher efficiency and sufficiency vis-à-vis \(SAT_1\). To further take advantage of AvgSA by offering hazard-consistent record selection, Kohrangi et al. [20] extended the CS(SAT) approach to CS(AvgSA).

Our proposed method simplifies the more rigorous CS approach as follows. Based on the hazard disaggregation analysis results, the CS method provides a target for the mean and variability of the spectral shape of records that are consistent with a target \(IM^*\) level at the site. When generating such a target spectrum, Lin et al. [14] used the law of total variance to incorporate multiple causal earthquakes and to account for multiple ground motion prediction equations (GMPEs) used in PSHA. Herein, we utilize the same concept to incorporate multiple target spectra from multiple IM levels into a single, compound target spectrum. This method involves the following steps: 1) conduct PSHA and disaggregation for \(IM^*\) at all considered intensity levels at the site of interest; 2) generate a CS target spectrum for each of the selected IM levels; 3) normalize all target spectra to a common value of \(IM^*\); 4) incorporate all target spectra into single target spectrum; 5) employ a record selection algorithm [8] to select and scale a set of records that collectively match the compound target spectrum. Combining individual targets of logarithmic mean and standard deviation of spectral acceleration at period \(Ti\) when conditioned on \(IM^*\) weighing all the IM levels (numbered by \(iml\)) to estimate the overall target can be achieved as follows:

\[
\mu_{\ln SAT_i, \ln IM^*} = \sum_{iml} p_{iml} \cdot \mu_{\ln SAT_i, iml}^{ln IM^*}
\]

\[
\sigma_{\ln SAT_i, \ln IM^*} = \sqrt{\sum_{iml} p_{iml} \cdot \left[ \sigma_{\ln SAT_i, iml}^{\ln IM^*} + \left( \mu_{\ln SAT_i, iml}^{\ln IM^*} - \mu_{\ln SAT_i, \ln IM^*} \right)^2 \right]}
\]
The quantities $\mu_{\ln SAT_i|ln IM^*}$ and $\mu_{\ln SAT_i,iml|ln IM^*}$ are the $i$-th element of the logarithmic mean vector of the multi-site and $iml$-th intensity measure level, respectively. The quantities $\sigma_{\ln SAT_i|ln IM^*}$ and $\sigma_{\ln SAT_i,iml|ln IM^*}$ are the $i$-th diagonal element of the co-variance matrix of the multi-level and $iml$-th intensity measure level, respectively. The quantity $p_{iml}$ is the weight for $iml$-th intensity measure level, as it applies on the logarithmic mean value of the conditional spectral accelerations.

Illustrative example

A plan-symmetric 7 story reinforced concrete frame building will serve as a case study. This is a modern structure built to post-1980 seismic design provisions for high-seismicity regions in Turkey. A 2D centerline idealization of the building was modeled using OpenSees [23]. Further details on the building properties and modeling approach appear in [16]. The first and second modal periods of the building are $T_1 = 1.60$ sec and $T_2 = 0.52$ sec. We considered a site located in Ankara with latitude and longitude of [32.76°N, 32.76°E] on a soil with $Vs_{30}$=620 m/s. We used OpenQuake [12] to perform the seismic hazard and disaggregation computations for this study. The analysis is based on the SHARE Project [13] area source model and the GMPE proposed by Boore and Atkinson (BA08) [24]. We adopted two conditioning IMs of $SAT_1$ and $AvgSA$, the latter defined over the range of $[T_2:1.5T_1]$.

To compare and contrast the results of the application of the three approaches, namely MSA, conventional IDA and IDA with approximate CS-based record selection, we performed multiple sets of nonlinear dynamic analyses. The results that we seek to compare are the response distributions of global EDPs (here MIDR) and local EDPs (IDR and PFA at all stories) and the corresponding global fragility curves for four limit states of increasing severity. Conceptually, we carried out three distinct batches of nonlinear dynamic analyses, each one comprising multiple variants as explained below.

The first batch includes two variants of MSA with site-specific hazard-consistent record selection comprising 44 accelerograms for each of the 10 IM levels. One variant uses the conventional CS($SAT_1$) approach for setting the target for record selection at each IM level, and the second variant uses the newer CS($AvgSA$) approach for the same purpose. The output of this first batch is two sets of EDP’s distributions, one for the $SAT_1$ variant and one for the $AvgSA$ variant. MSA is arguably the most refined method, whose building response estimates are considered here as the benchmark. The second batch comprises two variants of the conventional IDA method, which utilizes a single set of records that is not site-hazard-consistent for any of the 10 IM levels. For this exercise we used the 22 pairs of motions of the FEMA P695 (ATC-63) [13] far-field ground motion set and, as before, we scaled them to 10 increasing IM levels, the first time with IM=$SAT_1$ and the second time with IM=$AvgSA$. Again, the output of this second batch is two sets of EDP’s distributions, one for the $SAT_1$ variant and one for the $AvgSA$ variant. This is the least refined method, which is known to provide, in general, biased response estimates for high scale factors.

Table 1. Mean magnitude and distance from rupture obtained from disaggregation analysis

<table>
<thead>
<tr>
<th>IM level</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>IM Value</td>
<td>0.05</td>
<td>0.05</td>
<td>0.08</td>
<td>0.15</td>
<td>0.25</td>
<td>0.35</td>
<td>0.5</td>
<td>0.65</td>
<td>0.8</td>
<td>0.95</td>
</tr>
<tr>
<td>Weights</td>
<td>W1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1/21</td>
<td>2/21</td>
<td>3/21</td>
<td>4/21</td>
<td>5/21</td>
</tr>
</tbody>
</table>
The third batch also contains two variants of the IDA method with CS selection, again one time based on SAT1 and the other time based on AvgSA. Here IDA still uses a single set of accelerograms for all IM levels but this single set is now assembled to be consistent, to the extent possible and in the different ways discussed below, with the site hazard. The consistency for record selection is sought via the CS paradigm, either the original CS(SAT1) or the newer CS(AvgSA). Six cases for selecting records for each of the two variants were considered here. In the first three cases record selection is performed at a single IM level, here corresponding to hazard levels of 30%, 10% and 2% in 50 years. The identified record set is then scaled to all the 10 IM levels employed. In these first three cases the record selection was carried out using the computationally efficient algorithm of [8] for CS(SAT1) and its modified version available in [26] for CS(AvgSA). In the latter three cases, we implemented instead our CSML proposed method for record selection that probabilistically combines the target spectra of multiple IM levels into a single, compound target spectrum. What differentiates each one of these three cases is the suite of the $p_{ml}$ weights (see Equations (1) and (2)) assigned to each one of the 10 IM levels (see Table 1). In the first case we assigned equal weights to all 10 IM levels while in the second and third cases we increasingly gave more weight to the higher IM levels. The output of this third batch of analyses comprises 12 sets of EDP’s distributions, six for the SAT1 variant (three of which are based on the CSML method) and six for the AvgSA variant (again, three of which are based on the CSML method).

Figure 2. Conditional median (left) and dispersion (right) of the target spectral shapes for CS(SAT1) (top) and CS(AvgSA) (bottom) at IM level 5. The green dashed lines show the corresponding values for the FEMA P695 far-field set. The vertical dashed line in the top panels refers to $T_1$ while the two vertical lines in the bottom panels at $T_2$ and $1.5T_1$ delimit the boundaries of the range averaging for the computation of AvgSA.
Overall, for each IM, one MSA and seven different IDA realizations are employed. The question is whether one of the different record selection approaches can approximate well enough the benchmark MSA results. Figure 2 illustrates the median (left column) and dispersion (right column) of the target median spectra employed for CS record selection, all scaled to IM level 5. For comparison Figure 2 also shows in dashed green lines the median of the FEMA P695 record set. Note that the target conditional dispersion of CS at different IM levels corresponding to 30%, 10% and 2% in 50yrs (with different governing scenarios to generate the target spectra) coincide in the right column of Figure 2 because the standard deviations obtained from the adopted GMPE (i.e., BA08) and the correlation coefficient model [27] are independent of magnitude and distance.

Response distributions and fragility curves

Response profiles

Figure 3 shows the 8 median IDA curves for Maximum Interstory Drift Ratio (MIDR) and also the data points on the stripes produced by the MSA. A more local overview of the results is provided in Figure 4, which displays the median Interstory Drift Ratio (IDR) and the median Peak Floor Acceleration (PFA) response profiles along the height of the building obtained for the moderately intense IM level 7 records (of \( SAT_1 \) value equal to 0.5g) selected by all the different approaches. The median response profiles conditioned on \( SAT_1 \) appears in Figure 4a and Figure 4b while Figure 4c and Figure 4d show their counterpart response profiles conditioned on \( AvgSA \).

Figure 3. IDA curves in terms of MIDR for the 7-story building using the two different conditioning IMs, \( SAT_1 \) (left) and \( AvgSA \) (right).

The first comment that is apparent from an inspection of Figures 3 and 4 is that the family of curves is considerably tighter, especially for PFA, for different record selection approaches that utilize \( AvgSA \) instead of \( SAT_1 \) as the conditioning IM. This is a direct consequence of the higher sufficiency of \( AvgSA \). The main practical implication of this behavior is that when one uses \( AvgSA \) in IDA analyses (either only for scaling, as in the conventional IDA of the second batch, or to inform the CS method for record selection) the response estimates are much closer to those
of the MSA method. In other words, being religiously hazard-consistent in the selection of records is much less important when \( \text{AvgSA} \) is used than when \( SAT_1 \) is utilized. Even the FEMA P695 records that carry no information of site hazard give results that are closer to the reference ones because of the improved sufficiency of \( \text{AvgSA} \). Similar findings where already shown previously in [7,16]. Even when \( \text{AvgSA} \) is used, this ensemble of results seems to suggest that being more hazard-consistent in the record selection via the CSML method pays off. The three CSML-based median IDA curves for MIDR, IDR and PFA are slightly closer to the MSA benchmark than are the median IDAs that are consistent with the hazard only at single hazard levels. The FEMA P695 record set also happens to be quite close to the CS-based results although larger bias can be expected in other situations. Still the amount of bias becomes significant mostly when \( SAT_1 \) is the IM of choice.

**Figure 4.** Median IDR and PFA response profiles for IM level 7 based on the different record selection approaches and two different conditioning IMS: (a) EDP = IDR and IM = \( SAT_1 \); (b) EDP = PFA, IM = \( SAT_1 \); (c) EDP = IDR, IM = \( \text{AvgSA} \); (d) EDP = PFA, IM = \( \text{AvgSA} \).

**Analytical fragility functions**

In order to provide another comparison between the response estimates obtained using the different record selection approaches, we employed the results obtained from MSA and IDA with and without CS record selection to derive analytical fragility functions. For illustrative purposes only and for the sake of simplicity, we have limited our consideration to one EDP: the maximum IDR along the building height (MIDR) as this EDP is routinely used to monitor the overall structural performance up to global collapse. For generating fragility curves based on MIDR, we selected four different limit states, LS1 through LS4, ranging from low to extensive damage levels that we associated to MIDR values of 0.75, 1.2, 2.0 and 4.0%. We computed the parameters of the analytical fragility curves corresponding to each limit state (i.e. the logarithmic mean, \( \mu_{\ln IM} \), and standard deviation, \( \sigma_{\ln IM} \), of the log-normal distribution) using the maximum likelihood method for MSA and the method of moments for IDA [28]. Figure 5 shows the fragility curves in terms of MIDR for LS1 and LS4 using \( SAT_1 \) and \( \text{AvgSA} \) as the conditioning IMs. By inspecting Figure 5, we observe the following:

- Building fragility curves are dependent on the record selection approach used for the structural analysis. Blindly using sets of records that are not representative of the site to perform IDA can produce biased estimates of the response.
• At lower limit states the estimates of fragility parameters are generally very close regardless of the adopted record selection approach. Nevertheless, for higher limit states especially at collapse (i.e., LS4 here), the differences between IDA-based and MSA-based fragility curves become larger. Again this difference is large when SAT1 is used and less so when AvgSA is adopted given its sufficiency that makes hazard-specific record selection for IDA less important.

• Based on additional results to what is show herein, we have observed that IDA supported by some form of hazard-consistent record selection (e.g., one of the CSML cases used herein) provides more robust results than IDA when records are selected with no regards to the seismicity around the site. Among different alternatives, we express some preference toward CSML-W1 with uniformly weighting low, moderate and high IM levels when conducting CSML based record selection. This method besides providing in this particular case reasonably close estimates to those of the benchmark MSA method, seems to be more balanced when assessing response in both the near linear and severely nonlinear ranges. It also does not require the analyst to guess the importance of spectral accelerations above and below the fundamental period, judgment that would be reflected in different weights, when estimating the building response. More investigations on different building models, sites and weights are required to provide additional stronger recommendations on the choice of the weighting in the proposed CSML approach.

Figure 5. MIDR fragility curves obtained for LS1 (left panel) and LS4 (right panel) based on SAT1 and AvgSA using different record sets. The onset of LS1 and LS4 correspond to MIDR values of 0.75% and 4.0%, respectively.
Conclusions

The conventional IDA as originally conceived does not require any specific record selection. Thus, IDA may produce biased structural responses since the records used may not be compatible with those that may be experienced at the site hazard. A possible solution for the selection of a single set of records that is consistent with the hazard and that can be utilized to perform IDA is presented in this study. This method, which is called the multi-level conditional spectrum (CSML) approach, uses a variation of the conditional spectrum for record selection (CS). The CSML method probabilistically incorporates the spectral shape information of multiple IM levels into one single target. Three cases of CSML were tested here on response prediction for a 7-story building. The results showed that considerable improvements in accuracy are achieved when CSML based sets of records are used in IDA compared to application of a random set of records. This improvement is more prominent when SAT1 instead of average spectral acceleration (AvgSA) was used as the conditioning IM. The superior sufficiency of AvgSA makes the details of record selection less critical.

References


