INTRODUCING ADAPTIVE INCREMENTAL DYNAMIC ANALYSIS: A NEW TOOL FOR LINKING GROUND MOTION SELECTION AND STRUCTURAL RESPONSE ASSESSMENT

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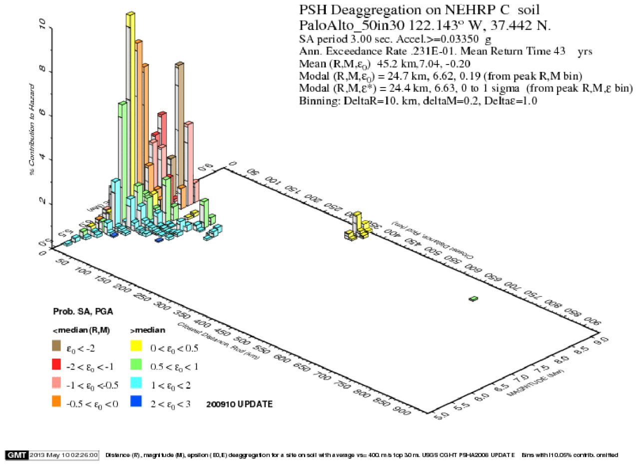
ABSTRACT: Adaptive Incremental Dynamic Analysis (AIDA) is a novel ground motion selection scheme that adaptively changes the ground motion suites at different ground motion intensity levels to match hazard-consistent properties for structural response assessment. Incremental Dynamic Analysis (IDA), a current dynamic response history analysis practice in Performance-Based Earthquake Engineering (PBEE), uses the same suite of ground motions at all Intensity Measure (IM) levels to estimate structural response. Probabilistic Seismic Hazard Analysis (PSHA) deaggregation tells us, however, that the target distributions of important ground motion properties change as the IM levels change. To match hazard-consistent ground motion properties, ground motions can be re-selected at each IM level, but ground motion continuity is lost when using such "stripes" (i.e., individual analysis points at each IM level). Alternatively, the data from the same ground motions in IDA can be re-weighted at various IM levels to match their respective target distributions of properties, but this implies potential omission of data and curse of dimensionality. Adaptive Incremental Dynamic Analysis, in contrast, gradually changes ground motion records to match ground motion properties as the IM level changes, while also partially maintaining ground motion continuity without the omission of useful data. AIDA requires careful record selection across IM levels. Potential record selection criteria include ground motion properties from deaggregation, or target spectrum such as the Conditional Spectrum. Steps to perform AIDA are listed as follows: (1) obtain target ground motion properties for each IM level; (2) determine "bin sizes" (i.e., tolerance for acceptable ground motion properties) and identify all candidate ground motions that fall within target bins; (3) keep ground motions that are usable at multiple IM levels, to maintain continuity; (4) use each ground motion for IDA within its allowable IM range. As a result, if we keep increasing the "bin sizes", AIDA will approach IDA asymptotically; on the other hand, if we decrease the "bin sizes", AIDA will approach the other end of "stripes". This paper addresses the challenges of changing records across various IM levels. Different ground motion selection schemes are compared with AIDA to demonstrate the advantages of using AIDA. Example structural analyses are used to illustrate the impact of AIDA on the estimation of structural response in PBEE. By combining the benefits of IDA and PSHA without the omission of useful data, AIDA is a promising new tool for linking ground motion selection and structural response assessment.

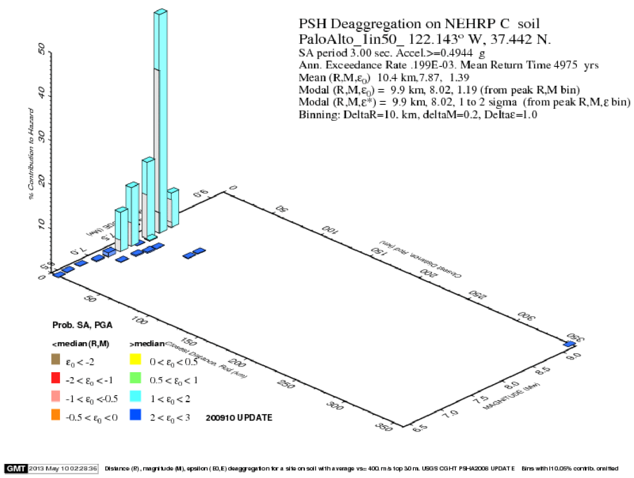
1 INTRODUCTION

Structural response assessment can be categorized as static or dynamic, linear or nonlinear. The complexity in the static regime increases from linear to nonlinear to pushover, where incremental static load is applied to the structure, leading to component by component failure and eventually system failure. Similarly, there is a parallel in the dynamic regime from linear to nonlinear, with a dynamic analysis termed incremental dynamic analysis (IDA) by Vamvatsikos & Cornell (2002) used widely in the last decade. Vamvatsikos & Cornell (2002) vividly described IDA as a "dynamic pushover", where incremental dynamic load is applied to the structure until it reaches dynamic instability. IDA was specifically developed for seismic assessment: the dynamic load is earthquake ground motion, often scaled from lower to higher intensity; a suite of ground motions are typically applied to the structure, to obtain statistics about the structure's performance, characterized by displacement and eventually collapse, under a range of earthquake excitation. The concept of IDA involves ground motions at multiple intensity levels.

Ground motion selection provides the seismic input for structural response assessment. Ground motion intensity is often characterized by spectral acceleration (Sa) at the period of vibration of interest (T^*). Probabilistic seismic hazard analysis (PSHA) incorporates uncertainty from earthquake sources and



(a)



(b)

Figure 1: USGS deaggregation of Sa(3s) corresponding to (a) 50% probability of exceedance in 30 years and (b) 1% probability of exceedance in 50 years in Palo Alto, California.

ground motion predictions using total probability theorem (Cornell 1968, Kramer 1996, McGuire 2004). Its reverse process, deaggregation, identifies the specific contributing scenario(s) for the given ground motion intensity level using Bayes' Rule (McGuire 1995, Bazzurro & Cornell 1999). Petersen et al. (2008) developed the United States national seismic hazard map using the concept of PSHA. The corresponding online deaggregation feature by the US Geological Survey (https://geohazards.usgs.gov/deaggint/2008/) provides plots such as Figure 1. As illustrated by this deaggregation of causal earthquakes for two different return periods, ground motion properties vary as intensity level changes. Careful ground motion selection needs to reflect such variation of ground motion properties with intensity levels.

To match ground motion properties, PSHA-consistent ground motions can be re-selected at each intensity level. This is often termed "stripes" or multiple stripe analysis (MSA). Alternatively, the data from the same ground motions in IDA can be re-weighted at various intensity levels to match their respective target distributions of properties (Jalayer 2003). Recent progress in hazard-consistent ground motion selection utilizes the Conditional Spectrum (CS), a target response spectrum to select ground motions for nonlinear dynamic analysis. Computation of the CS can be refined by incorporating multiple causal earthquakes and ground motion prediction models (Lin, Harmsen, Baker, & Luco 2013). Algorithms to match the mean and variance of the target spectrum are developed as a basis for selecting ground motions (Jayaram, Lin, & Baker 2011). The use of the CS in ground motion selection for risk-based and intensity-based assessments is investigated and compared with alternative target spectra (Lin, Haselton, & Baker 2013a, 2013b). Alternatively, a generalized conditional intensity measure approach that considers intensity measures other than Sa can be used if non-spectral ground motion parameters are also deemed important for predicting the structural response of interest (Bradley 2010, 2012a, 2012b).

The performance-based earthquake engineering (PBEE) framework starts with an intensity measure (IM), to estimate engineering demand parameter (EDP), in order to quantify damage measure (DM) and subsequently, decision variable (DV) (Cornell & Krawinkler 2000, Deierlein 2004). Ground motion selection can be viewed as the bridge between IM and EDP, whereas structural response assessment is linked to EDP. PSHA-consistent ground motion selection involves MSA and potentially the CS as the target spectrum, whereas IDA is still frequently used in structural response assessment despite its lack of hazard consistency. To combine the best of both worlds, we propose a PSHA-consistent IDA, adaptive incremental dynamic analysis (AIDA).

This paper introduces AIDA, a new tool for linking ground motion selection and structural response assessment. Section 2 answers the question "What is AIDA?"; Section 3, "What are the challenges of AIDA"; Section 4, "How good or bad is AIDA?". The last section then concludes with an overview of AIDA.

2 METHODOLOGY

2.1 *AIDA compared to alternative methods*

AIDA adaptively changes the ground motion suites at different ground motion intensity levels to match hazard-consistent properties. AIDA evolves from the ideas of IDA and multiple stripe analysis, as illustrated in Figure 2. In this figure, EDP is plotted against IM, where Sa at the first-mode period of vibration (T_1) is chosen as the IM to represent the level of shaking experienced by the structure. When a ground motion corresponding to each $Sa(T_1)$ is used as an seismic input to the structural model, EDP can then be obtained by running a nonlinear dynamic (response history) analysis. This EDP is typically associated with displacement, but can also be acceleration, member

Table 1: Comparison of ground motion selection methods.

	Traditional IDA	Multiple Stripes	Adaptive IDA
Matching properties	No	Yes	Yes
Adaptive records	No	Yes	Yes*
Continuity in records	Yes	No	Yes*

* Adaptive IDA gradually changes records to maintain partial continuity.

force, or any response of interest. Each color line in Figure 2(a) and (c) corresponds to a ground motion that is used across a number of IM levels. For traditional IDA shown as Figure 2(a), every color line spans the whole IM range, illustrating that the same suite of ground motions are used across all IM levels, simply by scaling their $Sa(T_1)$ up and down. IDA is intuitively attractive, yet PSHA deaggregation tells us that the target distributions of important ground motion properties change as the IM levels change. Figure 2(b) shows multiple stripe analysis, where PSHA-consistent ground motions are re-selected at each IM level to match the changing properties. Each dot in Figure 2(b) corresponds to a nonlinear dynamic analysis with EDP as a function of IM. However, ground motion continuity is lost when using such stripes, regardless of the number of stripes. Alternatively, the data from the same ground motions in IDA can be reweighted at various IM levels to match their respective target distributions of properties (Jalayer 2003), but this implies potential omission of data and curse of dimensionality (Baker 2007).

By combining the benefits of IDA and stripes, AIDA makes adaptive changes to ground motions for IDA, as illustrated in Figure 2(c). This allows us to vary stripes-like ground motions to match the changing properties as the IM level changes, while partially maintaining IDA-like ground motion continuity. Figure 2(c) shows color lines that cross various numbers of IM levels, illustrating PSHA-consistent ground motions that are shared among some IM levels but not across the entire range. The evolution of response history analyses with various ground motion selection strategies is also compared in Table 1.

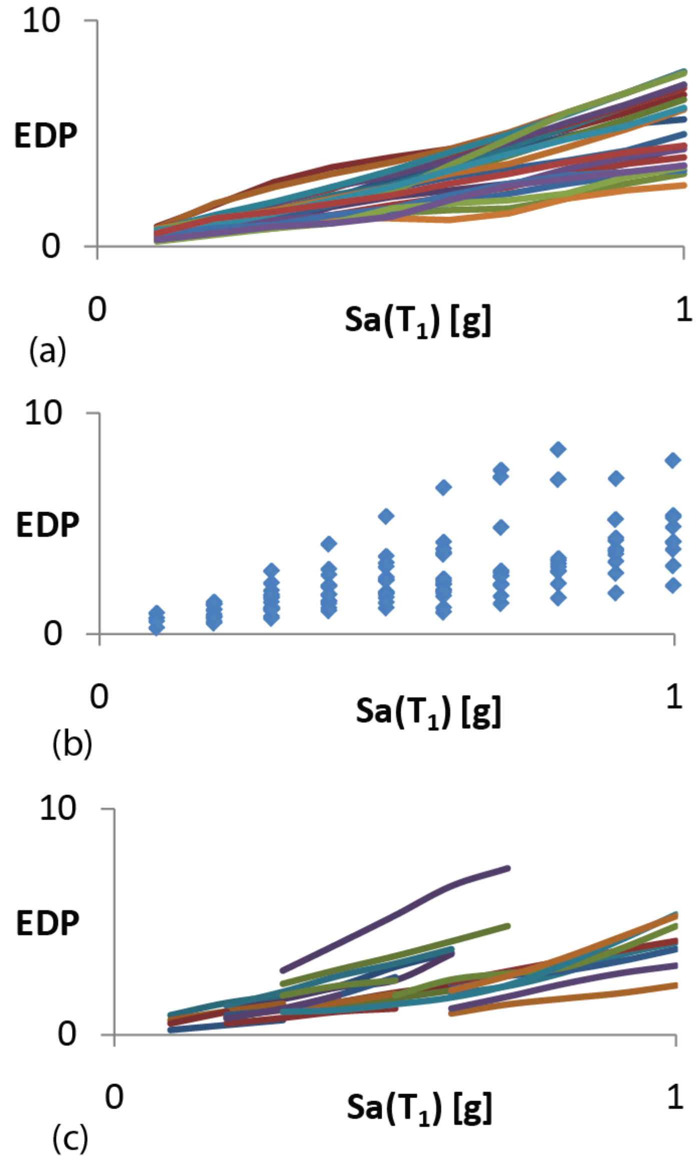


Figure 2: (a) Incremental dynamic analysis (IDA); (b) multiple stripe analysis (MSA); (c) adaptive incremental dynamic analysis (AIDA).

2.2 *Basic Algorithm*

AIDA requires careful record selection across IM levels. Steps to perform AIDA are listed as follows: (1) obtain target ground motion properties for each IM level; (2) determine "bin sizes" (i.e., tolerance for acceptable ground motion properties) and identify all candidate ground motions that fall within target bins; (3) keep ground motions that are usable at multiple IM levels, to maintain continuity; (4) use each ground motion for IDA within its allowable IM range.

2.3 *Ground motion selection criteria*

Potential ground motion selection criteria include seismological properties such as magnitude (M) and distance (R) from deaggregation associated with

$Sa(T_1)$ (McGuire 1995, Bazzurro & Cornell 1999, Lin & Baker 2011), and/or spectral content similar to a target spectrum such as the Conditional Mean Spectrum (CMS) (Baker & Cornell 2006, Baker 2011, Gulerce & Abrahamson 2011) or more recently the Conditional Spectrum (CS) (Abrahamson & Al Atik 2010, Lin, Harmsen, Baker, & Luco 2013). The reader is referred to these documents for relevant computation procedures related to deaggregation and target spectrum as record selection criteria. Although the first-mode period T_1 is often used to obtain corresponding Sa, any period of vibration of interest T^* can be applied instead. Deaggregation of M and R, along with computation of the CMS, for sites in the US, can be obtained directly from the USGS hazard mapping tool or commercial seismic hazard analysis software.

Other effects such as duration (e.g., Iervolino, Manfredi, & Cosenza 2006) and directivity (e.g., Shahi & Baker 2011) can also be used as ground motion selection criteria. A generalized conditional IM that is extended from the concept of the CMS (Bradley 2010) can be an alternative criterion for the engineering application of interest. In principle any IM that is used for typical ground motion selection (e.g., Shome et al. 1998, Luco and Cornell 2007, Haselton et al. 2009, Katsanos et al. 2010) can be used as the selection criterion for AIDA. The basic algorithm is then applied to the IM of interest.

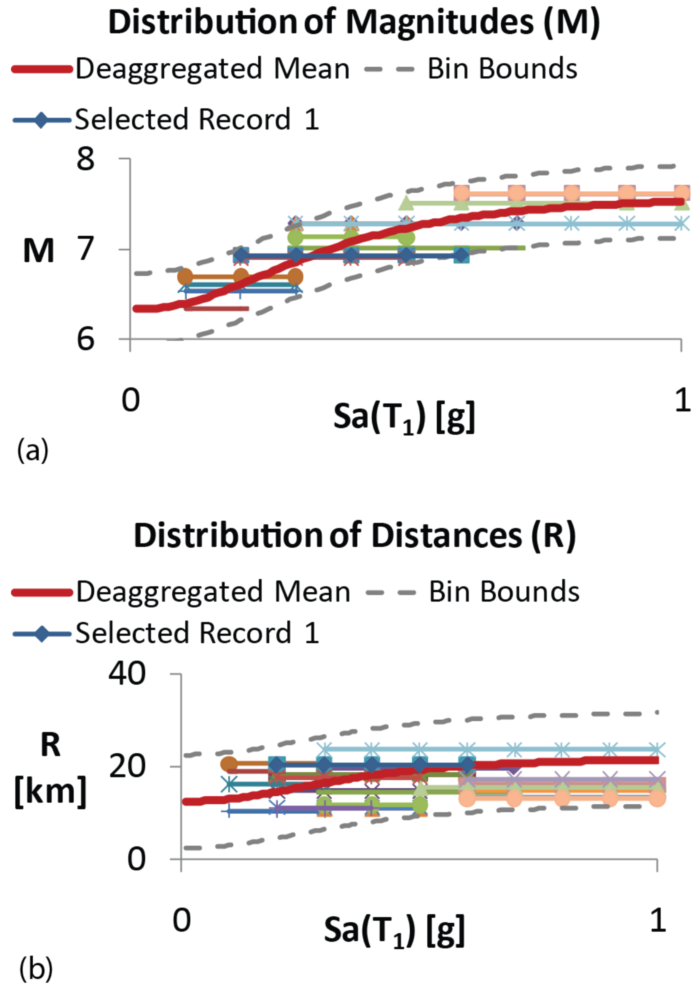


Figure 3: (a) Magnitude and (b) distance distributions across IM levels.

3 CHALLENGES

3.1 *Effect of bin size*

One major step in the AIDA algorithm is to determine bin sizes. This is required to identify all candidate ground motions that fall within target bins, so as to keep ground motions that are usable at multiple IM levels. To maintain continuity, each ground motion is then used for IDA within its allowable IM range.

PSHA deaggregation, as previously illustrated in Figure 1, implies that causal earthquake magnitudes (M) and distances (R) change as IM levels change. Figure 3 shows the distribution of M and R conditional on $Sa(T_1)$. First, mean M and R values are obtained from deaggregation for the range of $Sa(T_1)$ considered. Next, bin bounds are applied to the deaggregated mean M and R respectively, in this case, M+/-0.5 and R+/-10km. Using these M and R ranges as the selection criteria, ground motions that match both criteria can be identified. The corresponding selected records are marked as color lines in Figure 3, with each distinct color illustrating a unique ground motion. Many of these ground motions are usable across multiple IM levels (up to 8 IM levels in this example), and their respective allowable IM range is indicated by the length of the corresponding color line. For instance, Selected Record 1, marked as a blue line with diamonds at IM levels, spans the length of IM 2 (second lowest IM level) to IM 6. It is expected that the extent of ground motion overlaps varies depending on the selection criteria.

Bin size determines the degree of overlapping of ground motions. To illustrate, take the deaggregated mean magnitudes in Figure 3 and vary their bin sizes in Figure 4. Assume a bin with magnitude bounds of +/-0.5 is considered wide (Figure 4(a)), AIDA selects ground motions that fall within this target bin, with resultant ground motion overlaps that span many IM levels (Figure 4(b)). Altenatively, take a narrow bin with magnitude bounds of +/-0.2 (Figure 4(c)), and the resultant AIDA motions then overlap fewer IM levels (Figure 4(d)). If we keep increasing the bin sizes, the relaxed selection criteria allow for more ground motion overlaps, and AIDA will approach IDA asymptotically. On the other hand, if we decrease the bin sizes, the stringent selection criteria limit ground motions to be usable across IM levels, and AIDA will approach the other end of multiple stripes.

3.2 *Benefit of CS as the target spectrum*

Using the Conditional Spectrum as the target spectrum for AIDA application allows more sharing of ground motions across different IM levels without arbitrarily defining bin sizes. The CS removes the con-

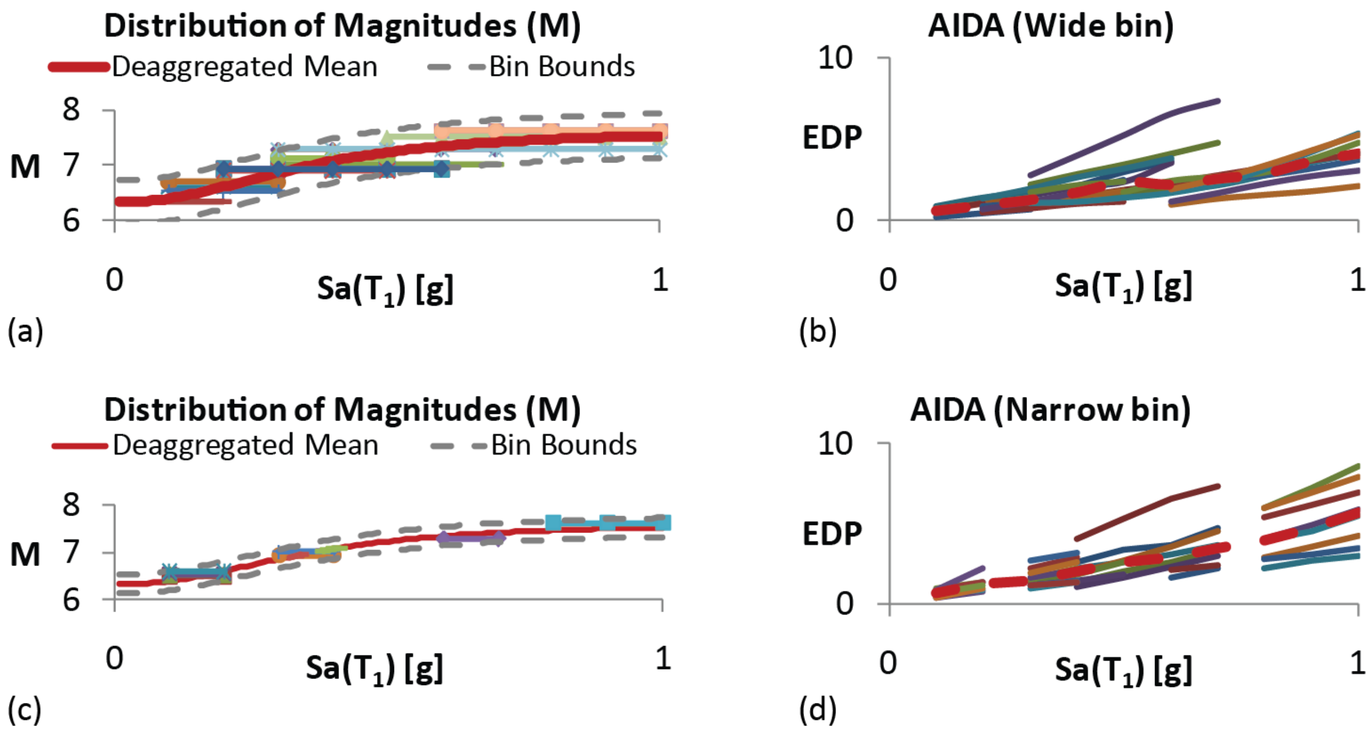


Figure 4: Distribution of wide and narrow magnitude bins (a and c respectively) and their resulting AIDA (b and d).

servatism from the uniform hazard spectrum (UHS), and implicitly considers M and R through Sa. The CS differs from the CMS only in that it additionally accounts for the variability in the spectrum. In this regard, instead of just matching the mean through the CMS (or M and R) and adjusting the bin size with tolerance criteria, the CS automatically sets the bin size with its spectral variability. This is illustrated through plots of CMS (solid lines) vs. CS (solid and dotted lines) at various IM levels (Figure 5). Note that while there are practically no overlaps in the defined CMSs, the CSs will have overlaps naturally. This implies that there may be more ground motions with similar spectral shapes in adjacent IM levels because the goal of the selection is to match both the mean and the variance. To match the variance, one ground motion with a spectral shape that is slightly above the target CS at an IM level may be a suitable candidate for a spectral shape that is slightly below the target CS at another IM level (Figure 5).

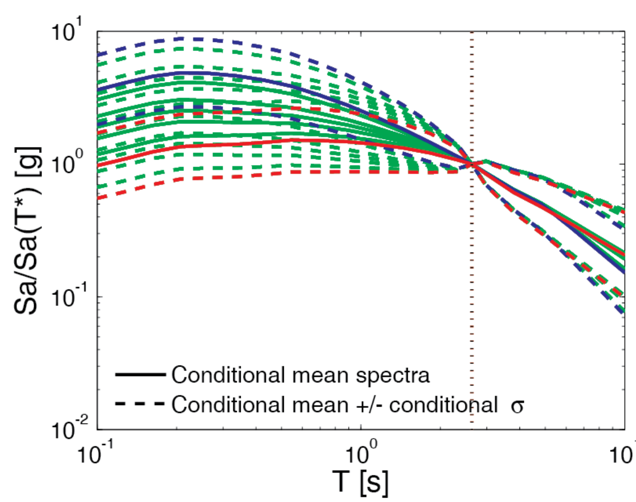


Figure 5: Normalized target response spectra conditional on $Sa(2.6\text{s})$, to illustrate the change of spectral shape across IM levels. The lower-bound IM level (IM 1) corresponds to 50% in 30 years probability of exceedance, and the upper-bound IM level (IM 7) corresponds to 1% in 50 years probability of exceedance.

3.3 *Implementation schemes*

Once the selection criteria are established, ground motions that meet the criteria can be selected from a ground motion database such as the PEER NGA database (Chiou, Darragh, Gregor, & Silva 2008). The common idea with all the selection criteria is to minimize the sum of squared errors (SSE) between the selected ground motions and the target. In addition, there should be a certain extent of ground motion sharing in adjacent IM levels to maintain partial continuity. This requires the optimization of shared ground motions that meet the selection criteria.

Several methods may be used here. For instance,

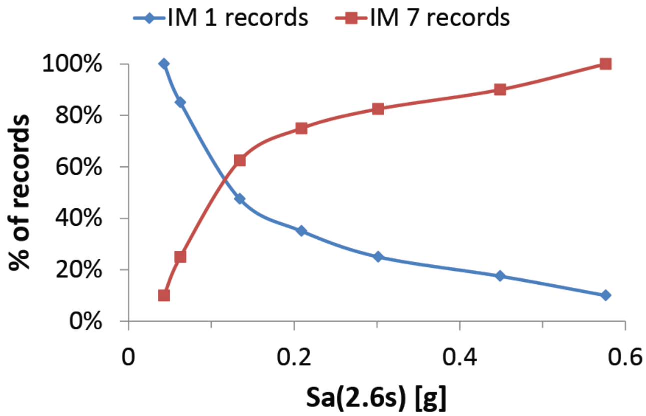


Figure 6: Percentage of records from lower- to upper-bound IM levels (corresponding to 0.04g and 0.58g respectively).

ground motions can be selected using an optimization algorithm at an arbitrary IM level, and this algorithm can then be applied successively to the adjacent IM levels while requiring reuse of some motions from the previous level. Another practical option would be to (1) define the upper and lower IM levels, and select the best-matched ground motions at those IM levels from the database; (2) for an intermediate IM level, use the selected ground motions from the upper and lower IM levels as the new candidate database to select ground motions; (3) repeat (2) with updated upper or lower IM levels until there are no more intermediate IM levels. This way, all IM levels are covered, and there will be common ground motions throughout the entire IM range, while each suite of ground motions meet the selection criteria at a specific IM level.

Using the latter approach with the Conditional Spectra illustrated in Figure 5 as the target spectra, 40 ground motions are selected at each IM level. Figure 6 shows the overlaps of ground motions through percentage changes from the lowest IM 1 to the highest IM 7. At IM 1, all ground motions satisfy the selection criteria and come from IM 1; similarly, at IM 7, all ground motions satisfy the selection criteria and come from IM 7. At intermediate IM levels 2 to 6, the ground motion candidates are those from IM 1 and IM 7, and the selected ground motions are a subset of the candidates expressed in terms of percentage IM 1 and IM 7. For instance, ground motions at IM 4 come from 35% IM 1 and 75% IM 7 motions, with 10% ground motions shared throughout the IM levels. In this example, if 40 ground motions are selected at each IM level, multiple stripe analysis at 7 IM levels would require re-selection of ground motions at each IM level totaling 280 ground motions with minimal overlaps. Compared to the 280 ground motions used in multiple stripes, fewer than 80 ground motions (only 76 in this case because of 10% common ground motions) from IM 1 and IM 7 are used and reused for AIDA. With AIDA, the number of ground motions decreases relative to multiple stripes; yet, ground motion properties are matched and partial continuity maintained.

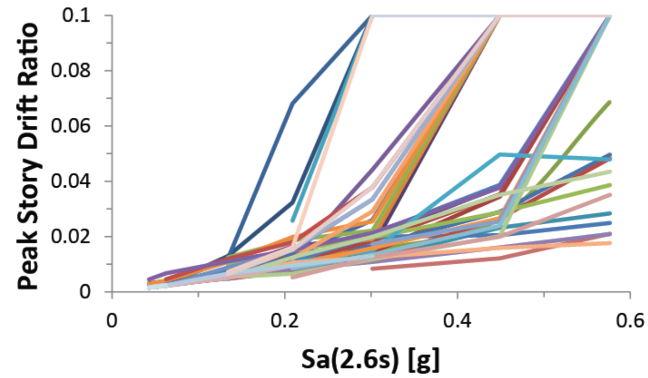


Figure 7: Adaptive Incremental Dynamic Analysis using the Conditional Spectrum as the target spectrum.

4 ILLUSTRATIVE EXAMPLE

To illustrate the methodology of AIDA, we use a 20-story reinforced concrete special moment frame located in Palo Alto, California. This building was designed for the FEMA P695 project (ATC 2009, Haselton & Deierlein 2007), and is denoted Building 1020 in that study. It is a 2-D model in OpenSEES (opensees.berkeley.edu), with strength deterioration (both cyclic and in-cycle) and stiffness deterioration that is believed to reasonably capture the responses up to the point of collapse due to dynamic instability. Its first modal period of vibration is 2.6s. This structure is analyzed using ground motions selected to match (1) the Uniform Hazard Spectra (UHS) with IDA-like characteristics (little change in spectral shape across IM levels resulting in similar ground motions), (2) Conditional Spectra at multiple stripes, and (3) Conditional Spectra using AIDA. The range of IM levels correspond to 50% in 30 years to 1% in 50 years probability of exceedance at $Sa(2.6\text{s})$. The target CS is illustrated in Figure 5 and the corresponding ground motions selected for AIDA in Figure 6. The resulting AIDA with peak story drift ratio of individual ground motions as a function of $Sa(2.6\text{s})$ is plotted in Figure 7. The analysis results for median peak story drift ratio and probability of collapse for the three methods are shown in Figure 8.

Results from AIDA are comparable to those from multiple stripes, while IDA using UHS produces higher responses. On the other hand, fewer ground motions can be used for the whole range of intensity levels considered in AIDA, compared to changing ground motions at each intensity level in multiple stripes. Because of this, the structural analysis can be further optimized by running the AIDA records at fewer IM levels and interpolating, or by using these analysis results to interpolate further to intermediate IM levels. In addition, compared to the same suite of ground motions used uniformly across all intensity levels in IDA, AIDA changes the ground motions at each intensity level gradually to reflect the change in ground motion properties according to PSHA information.

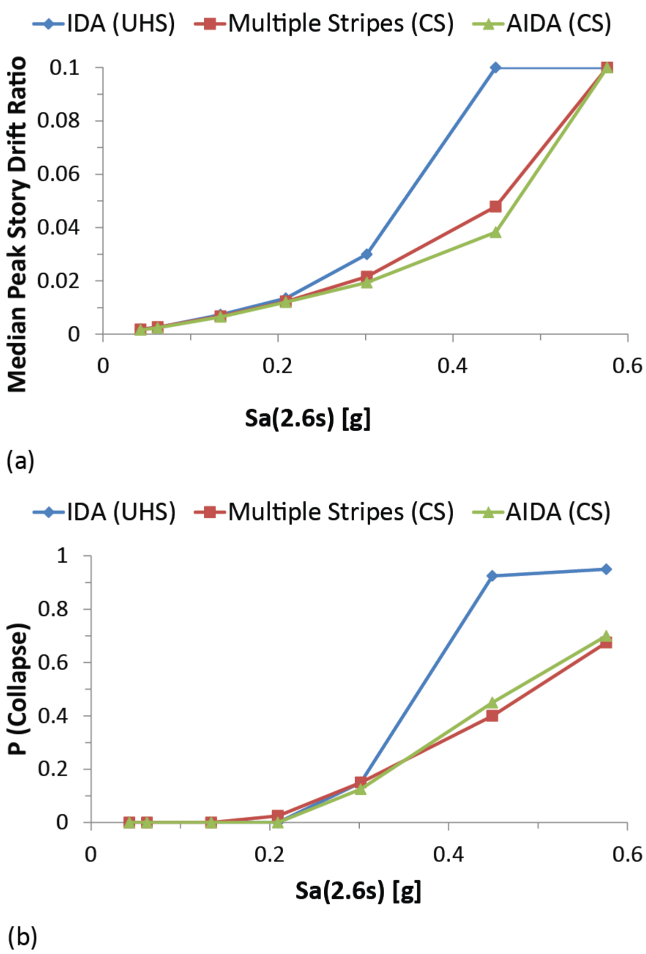


Figure 8: Comparison of (a) median peak story drift ratio and (b) probability of collapse for IDA (UHS), MSA (CS), and AIDA (CS).

5 CONCLUSIONS

Adaptive Incremental Dynamic Analysis matches ground motion properties at various Intensity Measure levels, and maintains continuity by overlapping some ground motions across multiple IM levels. The basic algorithm includes (1) obtain target ground motion properties at each IM level; (2) determine bin sizes, i.e., tolerance for acceptable ground motion properties; (3) identify candidate ground motions usable at multiple IM levels; (4) use each ground motion for Incremental Dynamic Analysis within its allowable IM range. Ground motion selection criteria can vary from causal earthquake properties such as magnitudes and distances to a target response spectrum such as the Conditional Spectrum. The bin size of the selection criteria determines the degree of overlapping of ground motions. As a result, if we keep increasing the bin sizes, AIDA will approach IDA asymptotically; on the other hand, if we decrease the bin sizes, AIDA will approach the other end of Multiple Stripe Analysis. Using the CS as the target spectrum allows natural sharing of ground motions across different IM levels without arbitrarily defining bin sizes. Examples were used to illustrate application of AIDA using various selection criteria and a practical implementation scheme. With a 20-story reinforced concrete frame located in Palo Alto, California, it is shown that AIDA produces similar peak story drift ratio and probability of collapse as its MSA counterpart, while IDA produces higher responses due to discrepancies in the spectral shapes of the IDA ground motions relative to the target spectrum (which changes with spectral acceleration amplitude). In addition to producing comparable results as MSA, AIDA uses fewer ground motions. AIDA combines IDA and Probabilistic Seismic Hazard Analysis without the omission of useful data, and hence an improvement over IDA for ground motion selection. With its advantages over other ground motion selection methods, AIDA is a promising new tool for linking ground motion selection and structural response assessment.

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