12th National Conference
on Earthquake Engineering
Salt Lake City, Utah
27 June - 1 July 2022
Hosted by the Earthquake Engineering Research Institute

Performance and Comparison of Non-linear Dynamic Analyses for Fragility Derivation when using hazard-consistent CS ground motion selection

M. C. Hoyos[1] and A. F. Hernández[2]

ABSTRACT

A comparison between different non-linear dynamic analyses for fragility derivation is conducted, using previously selected hazard-consistent Conditional Spectrum (CS) ground motion records. An unreinforced masonry structure in Medellin, Colombia, is used as the case study. Four methods are included for comparison: 1) Adapted Incremental Dynamic Analysis (AIDA), 2) censored cloud analysis, 3) cloud to IDA and 4) Multi-Stripe Analysis (MSA), with some adaptations to account for the CS-based selected records. Among the different methods, MSA gives the most reliable results, but an efficient targeted AIDA or Cloud to IDA may render comparable results with consistent hazard, bypassing some of the IDA and Cloud Analysis limitations. However, these results are conditioned to the case study, and thus additional comparisons among methods including the uncertainty on the definition of damage states and different pools or samples for the record selection should be conducted, together with bootstrapping or other techniques to ensure robustness.

Introduction

In the last years, there has been an area within the probabilistic seismic risk assessment (PSRA) that has gained much attention: the derivation of hazard-consistent structure-specific fragility functions, which has been demonstrated to have particular importance in seismic urban risk assessment [1]. However, the common practice in many places is still the use of simpler non-linear dynamic analytical methods for fragility derivations such as the Incremental Dynamic Analysis (IDA) [2], which are known to present shortcomings in accounting for the differing characteristics of low-intensity and high-intensity shaking within the scaling procedure; and the Cloud Analysis (CA) [3], [4] and its variations [5]–[7], that have limitations in assuming a constant dispersion of the regression with respect to the intensity measure (IM) over all ranges [8]; but they tend to give reasonable results when compared to more resource and time-consuming methodologies such as the Multi Stripe Analyses [3], [9], [10] in some contexts. There is a need for more studies comparing the different methods to understand the variability and bias when using each of them.

There has been a considerable number of studies reviewing the different analytical non-linear dynamic methods of fragility derivation, comparing their performance [1], [4], [6], [11]–[13], identifying their strengths and shortcomings in specific cases, and adapting or improving some of the methods to solve part of their limitations. This is the case of the hazard-compatible ground motion selection Adapted IDA (AIDA) [14] and the multi-level record selection method (CSML) [15], that try to solve the issue in the bias of randomly selecting and scaling record sets for IDA, ensuring hazard-consistent fragilities; and the cloud to IDA [6] that uses the strengths of both methods to improve its accuracy.

[1] Independent Seismic Risk Consultant, Bogotá, Colombia (email: mc.hoyos.ramirez@gmail.com)
[2] ISTerre, Université Grenoble Alpes, Grenoble, France

Hoyos, M.C., Hernández, A.F. Performance and comparison of non-linear dynamic analyses for fragility derivation when using hazard-consistent CS ground motion selection. *Proceedings of the 12th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Salt Lake City, UT. 2022.

Acknowledgments: A.F. Hernandez has been funded by the EU Horizon 2020 program under Grant Agreement Number 813137, ITN-MSCA New challenges for Urban Engineering Seismology (URBASIS) project work

As stated in [16], there is still a need to fill the gap of the epistemic uncertainties in the fragility models, which has not been given as much attention in PSRA as its hazard counterpart. These comparisons can be the way to start quantifying and propagating the uncertainties while identifying the biases when considering the trade-off between simple and more resource and time-consuming analyses. In this way, considering the hazard-consistent Conditional Spectrum (CS) record selection in [16] for the specific case of the 2-story unreinforced masonry structure, the variability of the resultant fragility functions using different analytical methods is analyzed. Four methods from the literature that can be used in parallel with CS are considered: censored cloud analysis [17], Cloud to IDA [6], AIDA [14], and MSA [11]. The fragility curves are compared among them, and the major strengths and shortcomings of each method are reported.

Methodology

The assumptions taken for the different methodologies that will be compared are reported in this section. For all cloud analyses, only the unscaled records were used. For the censored cloud analysis, the increase in the standard deviation to deal with structural uncertainty was omitted to make a one-to-one comparison. In the case of the cloud to IDA, the EDP was kept the same as in the other cases, and the first scaling to the target spectral acceleration (SA* cloud) was not performed as the already scaled closest records from the MSA were used to calculate the IDA lines. For the AIDA a wide binned analysis was performed using only the ground motions [GMs] that were present in more than one bin.

Description of the case study

For the analysis, the two-story unreinforced masonry from [16] located in Medellin, Colombia was considered. The main characteristics of the structure are reported in Table 1.

Table 1. Main characteristics of the unreinforced masonry structure.

Inter Storey Height [m]	**Period Eq.**	**Period [s] Ts**	**Γ**	**Yield Drift [%]**	**Ultimate Drift [%]**	**Reference study**	**Capacity Curve Sd**	**Capacity Curve Sa**
2.4	0.062H^0.9*	0.25	1.2	0.1	0.5	[18]	0.0037 0.0185	0.2296 0.2296

The record selection from [16] for Sa (Ts) was used. For the selection, the conditional-spectrum (CS) method [19] was followed, computing the mean scenario (i.e., mean magnitude, M, distance, R, and epsilon, ε) that best represented the site of analysis [20]. An approximate CS target spectrum using the weights per each branch of the logic tree from the GEM-SGC hazard model [21] was calculated using the mean values of M, R, ε [22]. Correlation models for the tectonic regimes were also considered respectively [23]–[25] The CS selected records for IM = Sa (0.25 s) and 4975-year return period are shown in Figure 1 for both tectonic regimes. To ensure a good number of records in each intensity bin, some of them were scaled with a factor of up to 4. Using the parameters in Table 1, a median capacity curve is determined, and nonlinear time history analysis is performed on the equivalent single degree of freedom (SDOF) model for the 360 records selected, 12 different intensity measure levels (IML) between 73 to 100,000 years return period, 30 records per IML. Next, the fragility functions are derived for the four Damage States [DS] in [17].

Hoyos, M.C., Hernández, A.F. Performance and comparison of non-linear dynamic analyses for fragility derivation when using hazard-consistent CS ground motion selection. *Proceedings of the 12th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Salt Lake City, UT. 2022.

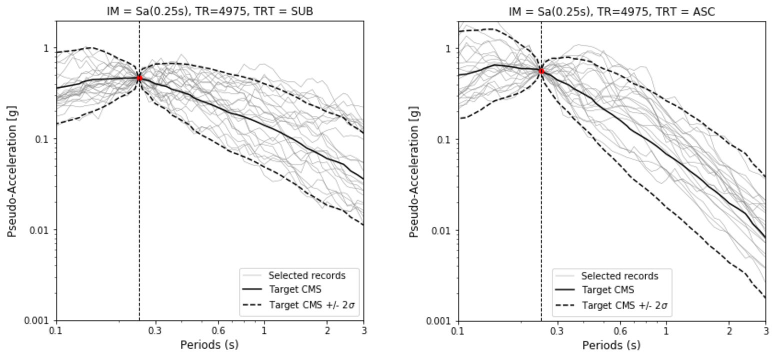

Figure 1. CS record selection for IM = Sa (0.25 s), TR = 4975-year return period for the 2.5th, 50th, and 97.5th target percentiles of Sa. Left: subduction interface (SUB). Right: active shallow crust (ASC).

Results

Figure 2 depicts the treatment of the same IM-EDP data for three of the methodologies while Table 2 and Figure 3 report the fragility curve parameters and visual comparison for the different methods of the fragility curve derivation.

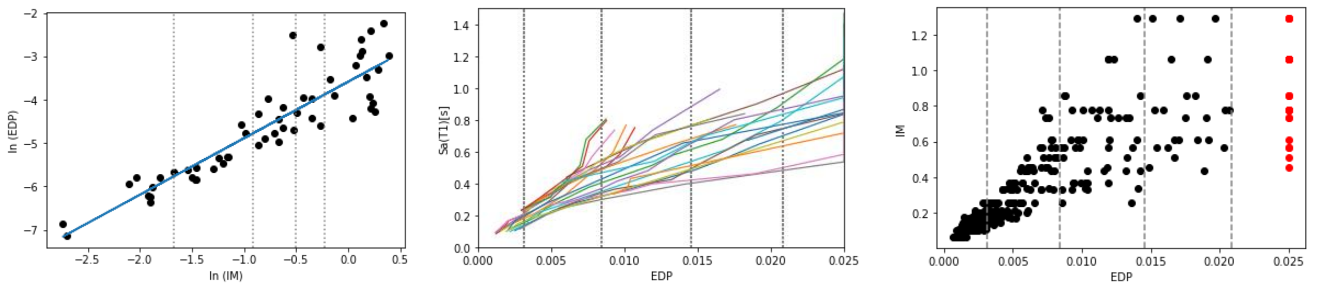

Figure 2. IM-EDP data for three of the methods: Censored cloud (left) AIDA (centre) and Cloud to IDA (right)

Table 1. Fragility curve parameters and the number of records used to derive each analysis.

Non-linear analysis	Slight		Moderate		Extensive		Collapse		N records	N scaled records	Comments
	θ	β	θ	β	θ	Β	θ	β			
MSA	0.19	0.26	0.46	0.36	0.75	0.41	1.06	0.49	76	288	CS-based
AIDA	0.18	0.20	0.44	0.25	0.72	0.34	0.85	0.35	62	286	Collapse underestimated
Censored cloud	0.19	0.30	0.43	0.30	0.69	0.30	0.92	0.30	76	-	Same std dev
Cloud to IDA	0.18	0.20	0.46	0.25	0.74	0.41	0.89	0.42	62	124	Collapse underestimated

Hoyos, M.C., Hernández, A.F. Performance and comparison of non-linear dynamic analyses for fragility derivation when using hazard-consistent CS ground motion selection. *Proceedings of the 12th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Salt Lake City, UT. 2022.

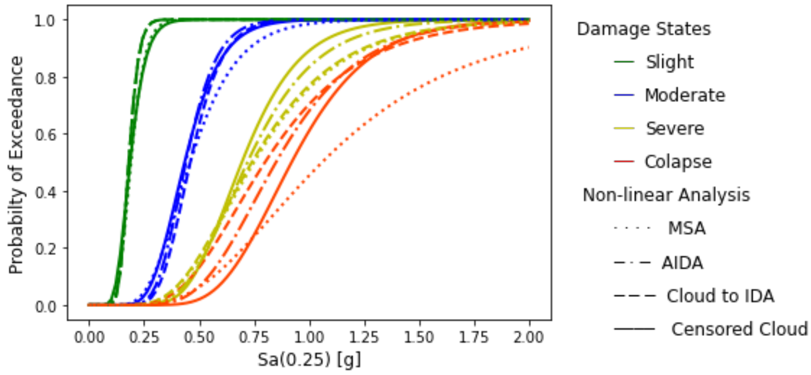

Figure 3. Comparison of fragilities derived with the four methods.

Overall, the results for the first three DS agree with each other, with a minor variation for the severe case. Regarding the collapse DS, except for the MSA, the accuracy for all methods seems to be low. This could be conditioned by the number and type of records selected in the high return period range, given scaling factors of up to 4 were used to ensure a good number of records for these high IMLs. Additionally, the treatment of the collapse cases varies from one method to the other, so it is possible that these discrepancies can also influence the large dispersion of the fragilities for the collapse DS. Regarding the computational and time efficiency of the methods, an analysis on the number of records needed for the derivation of the fragility curves in the different cases suggests that there is indeed a reduction in the needed number of records for the cloud procedures; however, there can be an unexpected bias introduced in the results if records for high IMLs are not well conditioned or are not sufficient and do not generate enough collapses.

Conclusions

The different methods should continue to be studied to ensure the selection of the most appropriate one given the available information in each specific case. For hazard-consistent fragilities, the unavailability of a good number of records in global databases that match the hazard characteristics of specific sites or urban settings, especially for the high IMLs, may add unintended biases to the results given the needed scaling. Methods such as MSA have as their strength the easiness and appropriateness for the derivation of hazard consistent fragilities and can be efficient for CS selected records. Regarding the other methods, AIDA is also straightforward in accounting for the hazard-consistency, while maintaining the continuity of the GM within multiple IMLs, which was a major limitation of IDA.

On the other hand, Cloud Analysis should only be used when ensuring a very sufficient IM or just focusing on a specific DS, as having the same dispersion across all damage states is not realistic in practice, given the additional uncertainties encountered for the near-collapse damage states. Cloud to IDA is also considered an efficient method, with its strength being probably the analysis for one damage state. When trying to derive the fragilities of multiple DS, it may need considerable time (like that of IDA or MSA). Additionally, results are extremely sensitive to the used pool of records, as different tries showed. For this reason, as a future trend, the inclusion of uncertainty in the DS, treating it as a random variable, should be studied, as well as a robustness analysis considering the random sampling for GMs.

Hoyos, M.C., Hernández, A.F. Performance and comparison of non-linear dynamic analyses for fragility derivation when using hazard-consistent CS ground motion selection. *Proceedings of the 12th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Salt Lake City, UT. 2022.

References

[1] M. Kohrangi, D. Vamvatsikos, and P. Bazzurro, "Site dependence and record selection schemes for building fragility and regional loss assessment," *Earthq. Eng. Struct. Dyn.*, vol. 46, no. 10, pp. 1625–1643, 2017.

[2] D. Vamvatsikos and C. Allin Cornell, "Incremental dynamic analysis," *Earthq. Eng. Struct. Dyn.*, vol. 31, no. 3, pp. 491–514, 2002.

[3] P. Bazzurro, C. A. Cornell, N. Shome, and J. E. Carballo, "Three Proposals for Characterizing MDOF Nonlinear Seismic Response," *J. Struct. Eng.*, vol. 124, no. 11, pp. 1281–1289, Nov. 1998.

[4] F. Jalayer, "Direct Probabilistic Seismic Analysis: Implementing Non-Linear Dynamic Assessments," Stanford University, 2003.

[5] F. Jalayer, H. Ebrahimian, A. Miano, G. Manfredi, and H. Sezen, "Analytical fragility assessment using unscaled ground motion records," *Earthq. Eng. Struct. Dyn.*, vol. 46, no. 15, pp. 2639–2663, 2017.

[6] A. Miano, F. Jalayer, H. Ebrahimian, and A. Prota, "Cloud to IDA: Efficient fragility assessment with limited scaling," *Earthq. Eng. Struct. Dyn.*, vol. 47, no. 5, pp. 1124–1147, 2018.

[7] L. Zhuang, "Enhanced Cloud Method (E-Cloud) for Efficient Seismic Fragility Assessment of Structures," *Res. Sq.*, pp. 1–23, 2021.

[8] M. T. Giugliano, A. Longo, R. Montuori, and V. Piluso, "Influence of homoschedasticity hypothesis of structural response parameters on seismic reliability of CB-frames," *Georisk*, vol. 5, no. 2, pp. 120–131, 2011.

[9] J. W. Baker, "Measuring bias in structural response caused by ground motion scaling," *Pacific Conf. Earthq. Eng.*, no. 056, pp. 1–6, 2007.

[10] F. Jalayer and C. A. Cornell, "Alternative non-linear demand estimation methods for probability-based seismic assessments," *Earthq. Eng. Struct. Dyn.*, vol. 38, no. 8, pp. 951–972, 2009.

[11] J. W. Baker, "Efficient analytical fragility function fitting using dynamic structural analysis," *Earthq. Spectra*, vol. 31, no. 1, pp. 579–599, 2015.

[12] K. Bakalis and D. Vamvatsikos, "Seismic Fragility Functions via Nonlinear Response History Analysis," *J. Struct. Eng.*, vol. 144, no. 10, p. 04018181, 2018.

[13] L. Di-Sarno and A. S. Elnashai, "Seismic Fragility Relationships for Structures," *Adv. Assess. Model. Earthq. Loss*, pp. 189–221, 2021.

[14] T. Lin and J. W. Baker, "Introducing adaptive incremental dynamic analysis: A new tool for linking ground motion selection and structural response assessment," *Safety, Reliab. Risk Life-Cycle Perform. Struct. Infrastructures - Proc. 11th Int. Conf. Struct. Saf. Reliab. ICOSSAR 2013*, no. Icossar, pp. 805–811, 2013.

[15] M. Kohrangi, D. Vamvatsikos, and P. Bazzurro, "Multi-level conditional spectrum-based record selection for IdA," in *Eleventh U.S. National Conference on Earthquake Engineering*, 2018, no. July.

[16] M. C. Hoyos and A. F. Hernández, "Impact of vulnerability assumptions and input parameters in urban seismic risk assessment," *Bull. Earthq. Eng.*, vol. 19, no. 11, pp. 4407–4434, 2021.

[17] L. Martins and V. Silva, "Development of a fragility and vulnerability model for global seismic risk analyses," *Bull. Earthq. Eng.*, no. 0123456789, 2020.

Hoyos, M.C., Hernández, A.F. Performance and comparison of non-linear dynamic analyses for fragility derivation when using hazard-consistent CS ground motion selection. *Proceedings of the 12th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Salt Lake City, UT. 2022.

[18] A. B. Acevedo, J. D. Jaramillo, C. Yepes, V. Silva, F. A. Osorio, and M. Villar, "Evaluation of the seismic risk of the unreinforced masonry building stock in Antioquia, Colombia," *Nat. Hazards*, vol. 86, pp. 31–54, 2017.

[19] N. Jayaram, T. Lin, and J. W. Baker, "A Computationally Efficient Ground-Motion Selection Algorithm for Matching a Target Response Spectrum Mean and Variance," *Earthq. Spectra*, vol. 27, no. 3, pp. 797–815, Aug. 2011.

[20] S. C. Harmsen, "Mean and Modal in the Deaggregation of Probabilistic Ground Motion," *Bull. Seismol. Soc. Am.*, vol. 91, no. 6, pp. 1537–1552, Dec. 2001.

[21] M. Arcila *et al.*, *Modelo nacional de amenaza sísmica para Colombia*. Servicio Geológico Colombiano, 2020.

[22] T. Lin, S. C. Harmsen, J. W. Baker, and N. Luco, "Conditional Spectrum Computation Incorporating Multiple Causal Earthquakes and Ground-Motion Prediction Models," *Bull. Seismol. Soc. Am.*, vol. 103, no. 2A, pp. 1103–1116, Apr. 2013.

[23] J. W. Baker and N. Jayaram, "Correlation of Spectral Acceleration Values from NGA Ground Motion Models," *Earthq. Spectra*, vol. 24, no. 1, pp. 299–317, Feb. 2008.

[24] N. Jayaram and J. W. Baker, "Correlation model for spatially distributed ground-motion intensities," *Earthq. Eng. Struct. Dyn.*, vol. 38, no. 15, pp. 1687–1708, Dec. 2009.

[25] M. A. Jaimes and G. Candia, "Interperiod Correlation Model for Mexican Interface Earthquakes," *Earthq. Spectra*, vol. 35, no. 3, pp. 1351–1365, Aug. 2019.