Title
Lessons Learned from a Decade of Ground Motion Simulation Validation (GMSV) Exercises and a Path Forward

Authors
Rezaeian, Sanaz
Stewart, Jonathan
Luco, Nico
et al.

Publication Date
2022-01-07

Peer reviewed

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

Lessons Learned from a Decade of Ground Motion Simulation Validation (GMSV) Exercises and a Path Forward

S. Rezaeian[1], J.P. Stewart[2], N. Luco[3] and C.A. Goulet[4]

ABSTRACT

Simulated ground motions can advance seismic hazard and structural response analyses, particularly for conditions with limited recorded ground motions, such as large magnitude earthquakes at short source-to-site distances. Rigorous validation of simulated ground motions is required before regulatory bodies, practicing engineers, or hazard analysts can be confident in their use. A decade ago, validation exercises were mainly limited to comparisons of simulated to observed waveforms and median values of spectral accelerations. The Southern California Earthquake Center (SCEC) Ground Motion Simulation Validation (GMSV) group was formed to increase coordination among simulation modelers and research engineers with the aim of devising and applying effective methods for simulation validation. Here, we categorize alternate validation methods according to their approach and the metrics considered. Two general validation approaches are to compare various metrics from simulations to their counterparts from historical records or to their estimated values from existing empirical models. Validation metrics consist of ground motion characteristics and structural responses. We describe this categorization, provide examples that have been valuable in the past decade, and provide potential research directions. Key lessons learned by our GMSV group are that validation is application specific, our outreach and communication warrants improvement, and much research remains unexplored.

Introduction and Background

The Southern California Earthquake Center (SCEC) Ground Motion Simulation Validation (GMSV) group was established in 2011. The objective of this group has been to develop and implement, via collaboration between ground motion modelers and engineering users, testing and rating methodologies for the use of ground motion simulations in engineering applications. The focus of this group has been on validation (consistency with observations) of simulation methodologies and not on verification (e.g., code debugging), nor on evaluation of individually simulated ground motions. Although initial research was focused on validation of SCEC Broadband Platform (BBP) simulations [1] in terms of median pseudo-spectral acceleration (Sa), research quickly expanded to other validation metrics beyond median Sa, and other simulations such as those from the SCEC CyberShake platform were validated [2]. In later years, GMSV-related research topics that work towards achieving the group's objectives were divided into two categories: (1) GMSV-related needs for ground motion characterization (e.g., using simulations in developing empirical ground motion models), and (2) GMSV-related needs for assessing structural responses (e.g., using simulations in performing response history analysis of buildings).

[1] Research Civil Engineer, U.S. Geological Survey (USGS), Golden, CO (srezaeian@usgs.gov)
[2] Professor, Civil & Environmental Engineering Dept, UCLA, Los Angeles, CA (jstewart@seas.ucla.edu)
[3] Research Civil Engineer, U.S. Geological Survey (USGS), Golden, CO (nluco@usgs.gov)
[4] Executive Director for Applied Science, SCEC, University of Southern California, Los Angeles, CA (cgoulet@usc.edu)

Rezaeian S, Stewart J, Luco N, Goulet C. Lessons learned from a decade of ground motion simulation validation (GMSV) exercises and a path forward. *Proceedings of the 12th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Salt Lake City, UT. 2022.

The SCEC GMSV group was designed to provide a collaborative framework and facilitate the coordination of independently funded SCEC GMSV-related projects by individual researchers. The projects are coordinated through periodic web-conferences, meetings, and workshops. Most researchers in this group have been research engineers (engineers in academia or from agencies such as the U.S. Geological Survey). After the first few years, collaborative projects were designed by the group to (1) take advantage of the findings from previous individual projects, and (2) expand the reach of the GMSV group to SCEC ground motion simulation modelers and potential engineering users of simulations outside of SCEC. One such project was initiated in 2015 and led to the implementation of various validation metrics (parameters) on the SCEC BBP for use by ground motion simulation modelers and research engineers. Another collaborative project, which was initiated in 2016, aimed to demonstrate the effectiveness of some of the implemented validation metrics on the BBP for two specific engineering applications related to building response analysis (i.e., American Society of Civil Engineers, ASCE 7-16, building code analysis, and collapse fragility analysis). Although this project did not determine the efficacy of all the validation metrics as originally intended due to the realization that validation is very application-specific, this project led to the development of a set of scenario-based simulations from the SCEC BBP vetted as appropriate for consideration by practicing engineers. This effort initiated more focused conversations with a group of practicing engineers and helped to expand the reach of the group outside of SCEC.

The GMSV group also interfaces closely with several other SCEC groups, including the BBP and CyberShake simulation groups, and the committee for Utilization of Ground Motion Simulations (UGMS). These interfaces along with workshops and seminars organized in collaboration with these groups have contributed to larger and beneficial projects such as (1) the SCEC BBP Validation Project, initiated in 2012, (2) the GMSV component of SCEC's Software Environment for Integrated Seismic Modeling (SEISM) Project, initiated in 2013, and (3) a 2019 project that selected a subset of CyberShake time-series for use by practicing engineers, in support of the UGMS committee [3]. As a decade of GMSV-related research draws to a close, here we examine the work completed to date by proposing a framework for categorizing different validation methods. This examination provides a useful perspective on the body of knowledge in this field for planning future work that meets important user needs. Subsequent sections introduce the framework and provide a few examples.

Proposed Framework for Categorizing GMSV Methods

Validation methods can be categorized according to their approach and the metrics considered (Table 1).

Validation Approaches

Validation "approaches," which appear as columns in Table 1, pertain to the manner in which "reality" is represented for the purpose of comparisons to simulations. Reality in this context can be represented by observations (i.e., recorded ground motions). However, a dilemma is that validation exercises are of best quality when and where recorded ground motions are available, whereas simulations are needed when and where recorded ground motions are lacking. A practical approach is to validate simulations using the scanty number of available recorded motions and then assume, considering the physical basis of the simulation methods, that the conclusions hold for unobserved scenarios (e.g., validate for moderate magnitude earthquakes at moderate distances, then assume conclusions hold for large magnitude earthquake at small distances). For some validation metrics, empirical models are also available that represent general global trends of ground motions for various parameterized scenarios. As these empirical models also suffer from lack of data, they are best utilized for validation in the range in which they are constrained by data. Beyond these ranges, although they are not strictly a validation tool, they can still provide valuable estimates for comparisons of simulations to "reality." As a result, validation approaches may represent observations in two ways: (1) comparing simulations to historical records, and (2) comparing simulations to empirical models.

Validation by comparing simulations to historical earthquake records can be done in several ways. The most obvious is to directly compare a ground motion waveform for a recorded and a corresponding simulated motion. This approach is typically qualitative and is usually done only by simulation modelers to see if their methods can reproduce a realistic time-series. A more quantitative approach is to compare statistics (e.g., median, dispersion, correlation) of a scalar validation metric (e.g., an intensity measure, IM, or an engineering demand parameter, EDP) for a suite of historical earthquake records and for a comparable suite of simulations. Such suites of recorded and simulated motions can be selected based on a historical earthquake at specific locations, a hypothetical earthquake scenario at hypothetical sites (e.g., a given magnitude, distance, and site condition) to generalize the validation, or even based on various motions that are conditioned on certain similarities (e.g., similar Sa values or similar duration of motion) for consistency with typical building code applications.

Validation by comparing simulations to empirical models will typically have one or both of the following objectives: (1) compare scaling trends of a scalar ground motion validation metric (e.g., Sa) with earthquake parameters such as magnitude, distance, and site conditions, and (2) compare statistics of that metric for a suite of simulated records, such as mean misfit (bias), dispersion (aleatory variability), and various correlations (spatial or inter-periods), to the corresponding values from empirical models.

Table 1. Categorizing various GMSV approaches (columns) and metrics (rows). Checkmarks correspond to combinations covered by the GMSV activities over the years.

			Approach: Compare to	
			Historical Records	**Empirical Models**
Metric	**Ground Motion Characteristics**	Waveforms	√	N/A
		Spectral Response Intensity Measures (IM)*	√	√
		Other Intensity Measures (IM)**	√	√
	Structural Responses* **	Idealized/Simple Structural Systems	√	√
		Realistic/Complex Structural Systems	√	N/A

*Includes median, dispersion, and correlation of the spectral IM (e.g., spectral acceleration, Sa).
**Includes scalar, goodness-of-fit (combination of scalars), and evolutionary (time-varying) parameters.
***Includes engineering demand parameters (EDPs) and failure probabilities from structural analyses.

Validation Metrics

Validation "metrics," which appear as rows in Table 1, pertain to what feature of the ground motion itself, or a derived response quantity from the ground motion, is compared to its corollary from observation. A decade ago, the most common validation metrics were the ground motion waveform (mostly used by modelers) and the median Sa (mostly used by modelers and those who were interested in enhancing empirical ground motion models). The SCEC GMSV group anticipated that validation outcomes could depend on the type of application of simulations (i.e., there is no one-size-fits-all validation method), an assumption that was confirmed over time. Whereas many individual metrics can be considered for various applications, Table 1 groups them into two main categories: (1) metrics that best describe ground motion characteristics, and (2) metrics that best describe structural responses.

Validation metrics that describe ground motion characteristics include waveforms (time-series), spectral response intensity measures (e.g., Sa), and other intensity measures (e.g., duration). Waveform comparisons are usually done by seismologists and simulation modelers, as mentioned above, and are not easy to quantify. Spectral response intensity measures (IMs) such as Sa are the most common validation metrics used by simulation modelers because they are used by both empirical ground motion modelers and engineers as the simplest representation of an idealized structure, i.e., single-degree-of-freedom (SDoF) elastic response. The validations can be performed by comparing the metrics from simulations either to those from historical records or from empirical models. Traditional validation exercises have focused only on the median value of Sa [1], as it was the most efficient way to respond to immediate engineering needs. However, more recently, researchers have recognized the importance of dispersion in spectral IMs (e.g., standard deviation of Sa), inter-period correlations in Sa, and spatial correlations in Sa. These metrics become more important in certain engineering applications such as probabilistic seismic hazard analysis, multi-mode structural responses, and distributed infrastructure risk assessments.

Many new validation metrics other than spectral response IMs that characterize ground motion waveforms have been explored. These are assigned to a separate row in Table 1 and are usually used in combination with Sa for more specialized engineering applications that go beyond looking at the elastic SDoF response without performing analysis that need complex models of structural systems. They include (1) scalar parameters such as Arias intensity (Ia), and various measures of duration, (2) various combinations of scalar parameters such as the goodness-of-fit (GOF) metric used by [4] or Ia/duration used by [5], and (3) non-scalar evolutionary (time-varying) parameters that describe the ground motion waveform characteristics in terms of the evolution of intensity, frequency, and bandwidth with time [5] and can relate complex ground motion characteristics to structural responses in a relatively simple way that enables interactions among simulation modelers and practicing engineers.

Validation metrics that describe structural responses include engineering demand parameters (EDPs), such as story drifts and peak floor accelerations in buildings, and failure probabilities, such as building collapse fragilities. These metrics can be categorized based on the level of complexity of the structural model used for the response history analysis. Idealized or simple structural systems are typically used to validate simulations for wide ranges of structural characteristics, e.g., stiffness and strength. Inelastic Sa is a validation metric that falls under this category, e.g., in [6]. Other simplified building models, e.g., elastic cantilever beams in [7], have also been used to approximate complicated Multi-Degree-of-Freedom (MDoF) structural responses. More realistic but also more complicated structural systems have also been used by research engineers to examine EDPs for buildings and even collapse fragility curves [8]. Finally, a few studies have started to investigate the responses for other types of structures such as bridges and dams.

Conclusions and Lessons from GMSV Activities in the Past Decade

In the past decade, various validation exercises have been performed by individual researchers and in collaborative projects in our GMSV group. We have also coordinated with other SCEC groups including simulation modelers and convened numerous workshops to interact with practicing engineers. Here, we highlight three high-level key findings. First, validation at this stage is application-specific: for example, in structural analysis, the appropriate validation metric depends on the type of structure and the EDP under consideration, whereas in seismic hazard analysis, the median Sa might be a sufficient validation metric, or it might need to be combined with dispersion or correlation of Sa, depending on the desired output. The ability to validate ground motions for several applications at once could be developed in the future, but there is still too much to learn to expect this in the near future. Second, our outreach and communication warrant improvement for simulations to be used in practice. Many simulation sets have been validated and are ready to be used for engineering applications, such as those that only require reasonable median Sa estimates or are selected and scaled to match a target design spectrum in building code applications; however, the end users are either not aware of the existing simulation and validation resources or are discouraged from utilizing them due to a lack of accessibility or the overwhelming amount of simulation data. Third, despite the expansion of GMSV research in the past decade, much research remains regarding validation and utilization of simulated ground motions for many of the categories shown in Table 1, although we have touched on each of the possible combinations. There is much yet to be achieved, and productive research – and future simulation method improvements – requires coordination and collaboration among research engineers and ground motion modelers.

Acknowledgments

We acknowledge the invaluable participation and continued interactions of the SCEC GMSV technical activity group members, as well as the simulation modelers and practicing engineers who are not officially in this group but have attended our workshops and provided feedback and advice to this group. This research was supported by the SCEC Award #21144. SCEC is funded by the National Science Foundation (NSF) and U.S. Geological Survey (USGS) through cooperative agreements with the University of Southern California, with additional funding for this project provided by the Pacific Gas & Electric Company (PG&E). Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References

1. Dreger DS, Beroza GC, Day SM, Goulet CA, Jordan TH, Spudich PA, Stewart JP. Validation of the SCEC Broadband platform V14.3 simulation methods using pseudospectral acceleration data. *Seismological Research Letters* 2015; **86** (1): 39-47. https://doi.org/10.1785/0220140118

2. Graves R, Jordan TH, Callaghan S, Deelman E, Field E, Juve G, Kesselman C, Maechling P, Mehta G, Milner K, Okaya D, Small P, Vahi K. CyberShake: A physics-based seismic hazard model for southern California. *Pure and Applied Geophysics* 2011; **168** (3–4): 367–81. https://doi.org/10.1007/s00024-010-0161-6

3. Baker JW, Rezaeian S, Goulet CA, Luco N, Teng G. A subset of CyberShake ground-motion time series for response-history analysis. *Earthquake Spectra* 2021; **37** (2): 1162-1176. https://doi.org/10.1177/8755293020981970

4. Anderson J. Quantitative measure of the goodness-of-fit of synthetic seismograms. *13th World Conference on Earthquake Engineering*, 2004, Vancouver, B.C., Canada. Paper No. 243. Available at https://www.iitk.ac.in/nicee/wcee/article/13_243.pdf

5. Rezaeian S, Zhong P, Hartzell S, Zareian T. Validation of simulated earthquake ground motions based on evolution of intensity and frequency content. *Bulletin of the Seismological Society of America* 2015; **105** (6): 3036–3049. https://doi.org/10.1785/0120140210

6. Lynne S. Burks, Jack W. Baker; Validation of ground-motion simulations through simple proxies for the response of engineered systems. *Bulletin of the Seismological Society of America* 2014; **104** (4): 1930–1946. https://doi.org/10.1785/0120130276

7. Galasso, C., Zhong, P., Zareian, F., Iervolino, I., & Graves, R. W. Validation of ground-motion simulations for historical events using MDoF systems. *Earthquake Engineering & Structural Dynamics* 2013; **42** (9), 1395-1412. https://doi.org/10.1002/eqe.2278

8. Zhong, K., Ling, T., Deierlein, G.G., Graves, R.W., Silva, F., & Luco, N. Tall building performance-based seismic design using SCEC Broadband Platform site-specific ground motion simulations. *Earthquake Engineering & Structural Dynamics* 2020; **50** (1): 81–98. https://doi.org/10.1002/eqe.3364