Toward a Framework for Ground Motion Simulation Validation using Attenuation Relationships. Part 1: Calibration Between NGA-West2 Predictions, Physics-Based Synthetics, and Data

Report for SCEC Award #15177
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Investigators: Ricardo Taborda (UMemphis)

I. Project Overview

A. Abstract

In the box below, describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the abstract. (Maximum 250 words.)

This project aimed to develop the basis for a new framework for validation of ground motion simulations in the absence of data. Since this goes against the implication of validation referring to comparisons with records, the new framework should be such that it can be used to assess the level of (expected) accuracy for a given simulation even if records do not exist. The project's primary objective was to propose and test a metric that could lend itself for comparing simulations against a well-accepted proxy for ground motion prediction (e.g., GMPEs) as a replacement to data. The project plan consisted of (I) proposing the validation formulation, (II) testing the formulation using simulations for which data do exist, and (III) correlating the comparisons with data against that of the proposed formulation when used with the chosen proxy (GMPEs). We completed steps I and II, and are in the process of completing step III. The outcomes of the project include the formulation of our new validation metric, which is based on the slope and amplitude misfit of a given intensity parameter (e.g., decay of PGV with distance); and results from initial tests using data from recorded earthquakes. While tests against GMPEs are still underway, our initial results indicate that the new metric has the potential to serve as a good predictor of the goodness-of-fit of simulations in the absence of data. This will help advance simulations, especially for validation of scenario earthquakes such as those used in physics-based PSHA models.

B. SCEC Annual Science Highlights

Each year, the Science Planning Committee reviews and summarizes SCEC research accomplishments, and presents the results to the SCEC community and funding agencies. Rank (in order of preference) the sections in which you would like your project results to appear. Choose up to 3 working groups from below and re-order them according to your preference ranking.

1. **Ground Motion Simulation Validation (GMSV)**
2. **Ground Motion Prediction (GMP)**
3. **Community Modeling Environment (CME)**

Seismology
Tectonic Geodesy
Earthquake Geology
Computational Science
Unified Structural Representation (USR)
Fault and Rupture Mechanics (FARM)
Earthquake Forecasting and Predictability (EFP)
Southern San Andreas Fault Evaluation (SoSAFE)
Stress and Deformation Through Time (SDOT)
Working Group on California Earthquake Probabilities (WGCEP)
Collaboratory for the Study of Earthquake Predictability (CSEP)
Central California Seismic Project (CCSP)
Aseismic Transient Detection
Source Inversion Validation (SIV)
Dynamic Rupture Code Validation
Earthquake Simulators
Communication, Education, and Outreach

C. Exemplary Figure

Select one figure from your project report that best exemplifies the significance of the results. The figure may be used in the SCEC Annual Science Highlights and chosen for the cover of the Annual Meeting Proceedings Volume. In the box below, enter the figure number from the project report, figure caption and figure credits.

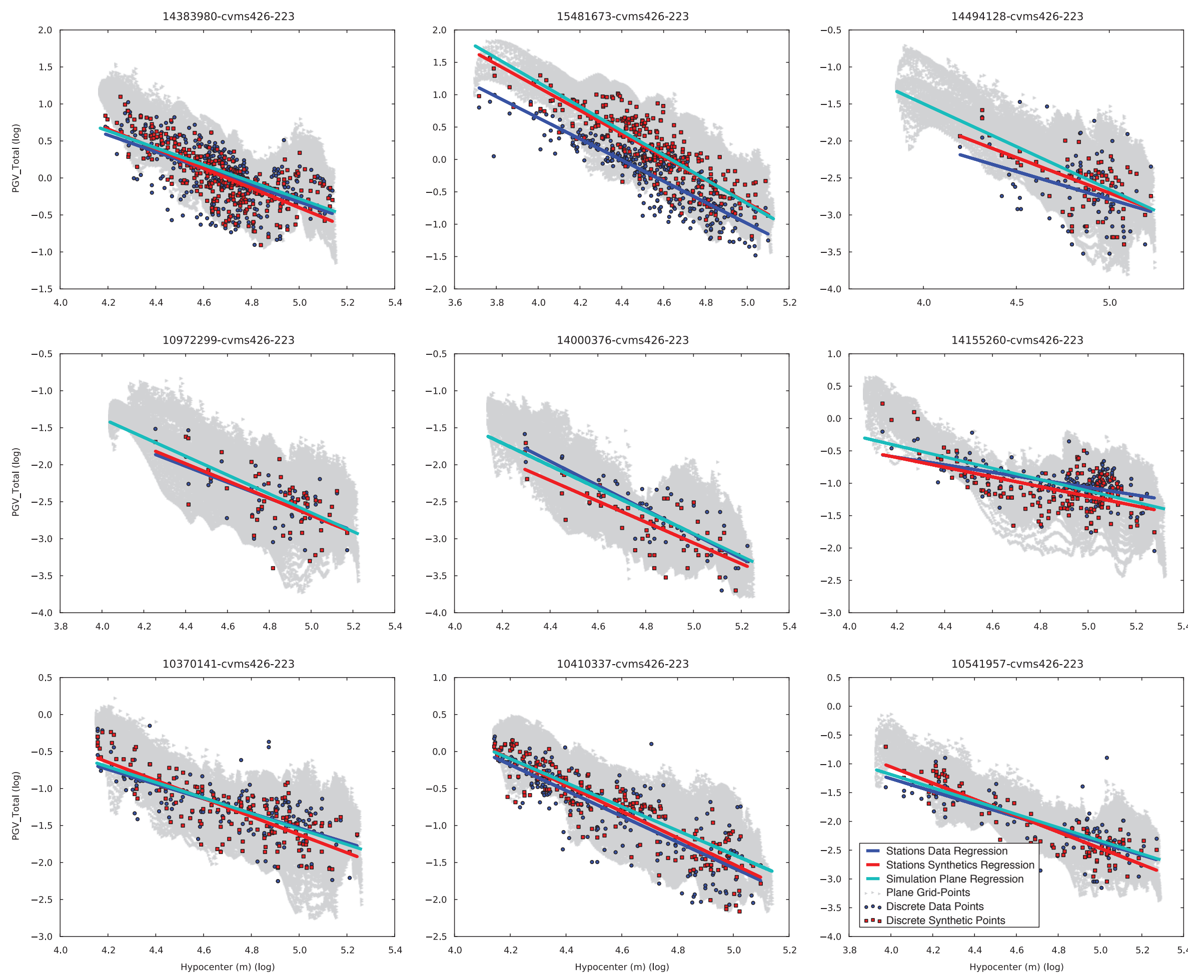


Figure 1. PGV attenuation regressions (solid lines) as functions of distance (in log-log scale) for multiple events comparing results derived from data-points corresponding to stations for which there exist records (blue) and the synthetic data-points obtained at the same locations (red), contrasted with the regressions obtained from using the full simulation-domain gridded surface data-points (green line and gray dots). Validation metrics obtained from comparing station data and synthetic stations is to be used to calibrate validation the new validation metric for when comparing full simulation-domain results to GMPE predictions as if there were no records available.

D. SCEC Science Priorities

In the box below, please list (in rank order) the SCEC priorities this project has achieved. See *https://www.scec.org/research/priorities* for list of SCEC research priorities. *For example: 6a, 6b, 6c*

6e, 6c, 6a

E. Intellectual Merit

How does the project contribute to the overall intellectual merit of SCEC? *For example: How does the research contribute to advancing knowledge and understanding in the field and, more specifically, SCEC research objectives? To what extent has the activity developed creative and original concepts?*

The research idea promoted by this project creates the foundation for a framework aimed to provide a validation alternative to current goodness-of-fit criteria and other ad-hoc validation methods, for validating simulations for which there is limited or no recorded data available. The intellectual merit of the project and the framework being developed resides precisely in that the new validation scheme will not depend on the existence of data, as opposed to current validation methods centered on comparisons with records from past earthquakes. The method will instead use well-accepted ground motion prediction equations as a proxy for the assessment of the accuracy of simulations. This concept will also help maximize the use of synthetic results over the full surface area of a simulation domain as opposed to being limited to the reduced number of locations (stations) for which there are observations. This is accomplished through the novel idea of treating single simulation datasets as rich sets of observations (data-points sample) and assume that these can be consider analog to observations from many events at a reduced number of stations (which is the concept at the core of developing GMPEs). The expectation is that the further development of this framework will lead to a methodology usable for validating scenario earthquakes. This will significantly contribute to SCEC projects promoted and helped by the GMSV activity group initiatives and contribute to the efforts of the UGMS committee, which in turn helps advance simulation initiatives important to SCEC scientists and engineers. A potential future implementation of the framework being developed by this work may also help the in other projects such as CyberShake and the Broadband Platform.

This project falls within proposal category B: theory and integration; it addresses SCEC's fundamental problem 6: seismic wave generation and scattering: prediction of strong ground motions; and focuses on research priority 6e: collaboration with the engineering community in validation of ground motion simulations.

F. Broader Impacts

How does the project contribute to the broader impacts of SCEC as a whole? *For example: How well has the activity promoted or supported teaching, training, and learning at your institution or across SCEC? If your project included a SCEC intern, what was his/her contribution? How has your project broadened the participation of underrepresented groups? To what extent has the project enhanced the infrastructure for research and education (e.g., facilities, instrumentation, networks, and partnerships)? What are some possible benefits of the activity to society?*

The validation framework put forward by this project will help evaluate the expected accuracy of scenario ground motion simulations, which provides a basis for validating simulations such as those used in physics-based probabilistic seismic hazard analysis. Furthermore, because the framework being developed by seed funding from this project is based on concepts deeply regarded by the earthquake engineering community, completion of the project plan will translate into closer integration and acceptance of simulations for engineering applications (e.g., building code provisions as intended by the SCEC UGMS committee).

On an educational front, this project has provided direct funds and a research opportunity for Shima Azizzadeh-Roodpish, a research assistant in the Center for Earthquake Research and Information (CERI) and Ph.D. candidate in doctoral program in Civil Engineering at The University of Memphis. Support from the project allowed Azizzadeh-Roodpish to attend the 2015 SCEC Annual Meeting, where she presented preliminary work leading to the development of the project activities.

Both PI Ricardo Taborda (Hispanic) and graduate student Azizzadeh-Roodpish (woman) belong to underrepresented groups in STEM fields.

G. Project Publications

All publications and presentations of the work funded must be entered in the SCEC Publications database. Log in at *http://www.scec.org/user/login* and select the Publications button to enter the SCEC Publications System. Please either (a) update a publication record you previously submitted or (b) add new publication record(s) as needed. If you have any problems, please email *web@scec.org* for assistance.

Our publications list is up-to-date. This project has not yet been directly linked to any particular publication but we expect the seed support provided with this project toward the validation framework being developed here will soon produce a conference and journal publication which we will include in SCEC's publications database at due time.

II. Technical Report

A. Summary

During the course of this project we took the first two of three planned steps to develop a new framework for validation of ground motion simulations in the absence of data for direct comparisons with synthetics. The validation framework put forward in this project is based on the idea that regressions derived from the full set of synthetics obtained during a physics-based three-dimensional (3D) ground motion simulation for a given set of intensity measures are comparable to the relationships from ground motion prediction equations (GMPEs), which are conversely derived from a smaller number of records but over a large number of events. Based on this assumption, we identified and formulated two basic and simple parameters for comparing the trends observed on the synthetics with a given reference relationship. The two parameters chosen are the slope of the attenuation observed in intensity (e.g., PGV) with respect to distance (e.g., R_{hyp}), and the average misfit in the amplitude of the simulation-derived function with respect to a reference function. As a first step to calibrate this formulation we tested the chosen parameters in comparisons between synthetics and data from past earthquakes at both selected locations (for which there are observations) and using the regression functions obtained from the simulations using the results at regular grid points on the surface area of the simulation-domain. In total, we used a database of 30 simulations done a low frequencies ($f \leq 1$ Hz) and obtained the proposed validation metrics and compared them to other goodness-of-fit validation results on the same datasets. Our results indicate that the formulation put forward in this project is a promising predictor of more complete validation results and thus has the potential to be used for validation of scenario earthquakes where there is no available records for comparisons, or past earthquakes for which available data is limited in number. Unfortunately, we could not complete the last part of the planned proposal because the narrow bandwidth of the simulations impeded us from testing the formulation against GMPEs (e.g., NGA-West2) results due to the discrepancy in the amplitude of the narrow-banded synthetics with respect to the relationships derived from the broadband data. We expect to correct this by adjusting the GMPEs with an amplitude correction factor, but this will require additional time and resources. We will continue to work on this and other aspects of the problem and expect to submit a second proposal for the first cycle of SCEC5, once we have completed analysis on the results presented in this report.

B. Project Objectives and Summary of Accomplishments

The main goal of the project was to provide an initial version of a new validation framework based on the use of attenuation relationships, as opposed to direct comparisons with data, to assess the accuracy of (physics-based) deterministic 3D earthquake ground motion simulations. Since the development of such a framework was likely to require a multi-year effort, the project was conceived as a first step in which we expected to formulate the methodology and calibrate it using results from a dataset of simulations done for small-to-moderate magnitude events recorded in southern California. A specific objective of the process was to use data as reference to test the formulation and compare the results of the new validation method when used in real events. The project also planned to draw a parallel between validation results obtained with the proposed method and validation results obtained with other commonly used goodness-of-fit (GOF) metrics (e.g., Anderson 2004). This parallel comparison sought to identify if the new method's metrics are good predictors of typical GOF results. A secondary objective of the project was to test the robustness of the methodology for the long term goal of comparisons with attenuation relationships (e.g., NGA-West2 GMPEs) by doing similar parallels but with attenuation curves.

We accomplished the first two objectives (i.e., formulation and testing with data) to a good extent, but will still need to dedicate additional time and effort to accomplish the third objective (i.e., testing with GMPEs). We expect to continue working on this third objective over the course of 2016 and submit a Part II proposal for testing (high frequency) past and scenario earthquake simulations during the first cycle of SCEC5.

C. Background

Recent progress in earthquake ground motion simulations has increased the demand for validation methods that can be used to determine the level of realism of simulations and its applicability in engineering practice. Within this context, validation is understood as the process by means of which one can measure the accuracy of synthetics with respect to actual records. In this sense, the level of realism of a simulation is primarily dictated by its proximity to observations from a given past earthquake.

Following this concept, up until now validation of ground motion simulations has mostly been done by comparing synthetic seismograms against observations from past earthquakes. These comparisons are nowadays done using quantitative metrics in the form of GOF criteria such as those proposed by Anderson (2004) and Olsen and Mayhew (2010), or the more recent validation methods introduced by Burks and Baker (2014) and Rezaeian et al. (2015).

These validation processes, however, depend strongly (if not entirely) on the availability of data. While much is still to be done to make simulations compatible to observations, this dependency has made it difficult to validate scenario earthquake simulations or simulations from past earthquakes with very limited amount of data. Even for recent past earthquakes, it could be argued that the validation efforts done recently (e.g., Taborda and Bielak 2013) may be incomplete at best (if not misleading) because comparisons can only be done at somewhat limited number of locations, i.e., the stations at which a given earthquake was recorded. Especially considering the fact that neither the observation nor the synthetic at any given location can be thought as representative of the spatial variability of a the ground motion at reduced distances. Furthermore, the events for which good validation studies can be conducted (i.e., those with the largest number of records) are usually of moderate magnitudes (e.g., Chino Hills and La Habra). This means it is uncertain at this point how well simulations do when it comes to large magnitude earthquakes, which are the ones that ultimately control hazard.

This project was then conceived to formulate a framework that provides a method for validation of ground motion simulations that is not limited to the availability of data, but that instead uses the cumulative knowledge of other predictors as a reference for validation. The following section describes the formulation a validation method based on metrics that can be used with both data and results from GMPEs as reference. The latter being the key here because it can help reduce the strong dependency of validation on data.

D. Methodology

Ground motion prediction equations often relate intensity measures with respect to parameters such as magnitude (M_w) and distance from the earthquake source, and other parameters such as source mechanism, near surface shear-wave velocity (V_{S30}) rupture depth, and basin depth (Z1.0, Z2.5). Common intensity measures are PGA, PGV, PGD, and Sa. In the end, GMPEs are regressions built based on datasets from observations compiled for a large numbers of earthquakes—despite the observations per individual earthquake not necessarily being many. Regardless of this, the resulting regressions, commonly called attenuation relationships (e.g., Bozorgnia et al. 2014), have proven for many years to be robust predictors and, moreover, they are widely accepted by engineers who have built many design decisions on.

Examples of such attenuation relationships include functions of PGV with respect to (hypocentral) distance (R_{hyp}). We select this as our testbed case. It turns out that when plotted in log-log scale, the mid-range and long distance (R > ~10 km) portion of this relationship follows a linear regression of the form:

$$y = a + bx + \epsilon, \tag{1}$$

where *x* is the distance, *a* is the intercept, *b* is the slope and *ε* is the error or disturbance term associated with the regression model. In reality, attenuation relationships are not as simple as eq. (1) and the intercept happens at a flatten portion corresponding to close distances from the source. We use eq. (1) for simplicity (i.e., to facilitate the comparisons) and because by concentrating in the mid-range and long distances we avoid other effects that result from near-source large deformations.

The new validation method works as follow. Given two regressions of the form of eq. (1), one corresponding to intensity values obtained from the simulation and a second one corresponding to intensity values obtained from a reference "observation" (either from real data or from an actual attenuation relationship), we compare two parameters: (i) the amplitude difference between the two curves, and (ii) the slopes of the attenuation curves. For the amplitude we use the same scaling GOF criterion defined by Anderston (2004), that is, at different points along the two curves we evaluate the function:

$$\mathrm{S}(\mathrm{p}_1, \mathrm{p}_2) = 10exp\left(-(\frac{p_1 - p_2}{min(p_1, p_2)})^2\right), \tag{2}$$

where p_i is the intensity value (e.g., PGV) at a given point for the i-th dataset (1 and 2 corresponding to the synthetic value and the reference value, respectively.) This scaling has shown to work well in validations and has the advantage of providing a score ranking the comparison in a slcae from 0 to 10. One can either work with eq. (2) for particular scattered values for comparisons at the "stations" or for a uniform distribution of values along the log-log linear regression.

In the case of the slopes we define a GOF score based on the difference between the two slopes using a version of the Student's *t*-test based on the standard error of regression models following Andre and Estevez-Perez (2014). The advantages of using t-test is that this parameter not only considers the different slopes, but also the number of samples used in the comparison and the standard deviation. Generally speaking, when there is a good fit of the slopes, the *t* has lower values. On the other hand, a small number of comparison points and a higher standard deviation increases the value of *t*. The *t* value is defined by:

$$\mathrm{t} = \left(\frac{b_1 - b_2}{s_{b_1 - b_2}}\right), \tag{3}$$

where b_1 and b_2 are the two slopes for the simulation values and the reference case and the denominator term is given by:

$$\mathrm{s}_{\mathrm{b}_1 - \mathrm{b}_2} = \left(s_{Res}\sqrt{\frac{1}{s_{x_1}^2(n_1 - 1)} + \frac{1}{s_{x_2}^2(n_2 - 1)}}\right) \tag{4}$$

and

$$\mathrm{s}_{\mathrm{Res}}^2 = \left(\frac{(n_1 - 2)s_{y,x_1}^2 + (n_2 - 2)s_{y,x_2}^2}{(n_1 - 2) + (n_2 - 2)}\right). \tag{5}$$

In (4) and (5), n_1 and n_2 are the sample sizes for each set and s_{x1} and s_{x2} are the standard deviations. s_{Res} is a unique estimator which is a weighted average of two variances (also known as s_{pool} since by that we can pool the estimates of the error variance. In eq (5), $s_{y,x1}$ and $s_{y,x2}$ are the residual variance (often known as squared standard error of the regression), which estimate the variance of the regression or variance of the model from the experimental (reference) dataset. Using (3–5) we can find the rate score of each pair of regression lines.

There can be different approaches in the way the amplitude and rate scores are combined. We can use simple average or also give weight to each score and calculate a weighted average. In this report, we simply considered the total average as simple average of two calculated scores.

E. Results

We tested the methodology just described in a collection of simulations for 30 earthquakes recorded in southern California (details about the simulations are given in Taborda et al. 2016). The validation method was implemented in a Python script along with other utilities for plotting. A selection of comparisons including the data and synthetic intensity (PGV) values at the stations used for validation, the simulation surface results, the three corresponding regressions are shown in Fig. 1 for selected simulations of the set of 30 used for testing.

We used the results obtained for the *t* parameter for the initial round of comparisons between synthetics and data at the stations locations to learn about the values of *t*, i.e., to understand the range of values within which *t* varies. We found that as a first approximation, the inverse 1/*t* was a good estimate for values ≤ 10, and thus provided a reasonable rate score comparable to the GOF values obtained for the amplitude score. We tested this for regressions of PGA, PGV, and PGD.

Fig. 2 shows the results obtained for PGV for the amplitude, rate and combine scores for the complete set of (30) simulations labeled from A to AD for 4 different velocity models (details in Taborda et al. 2016). While we still have some work to do to correctly interpret and combine the two scores, these initial results seem to indicate that the combined score has a good level of correlation with the GOF scores obtained for these same events using the Anderson (2004) method. This is a significant result because if proven to be consistent it could be said that the method is a good predictor of the GOF score.

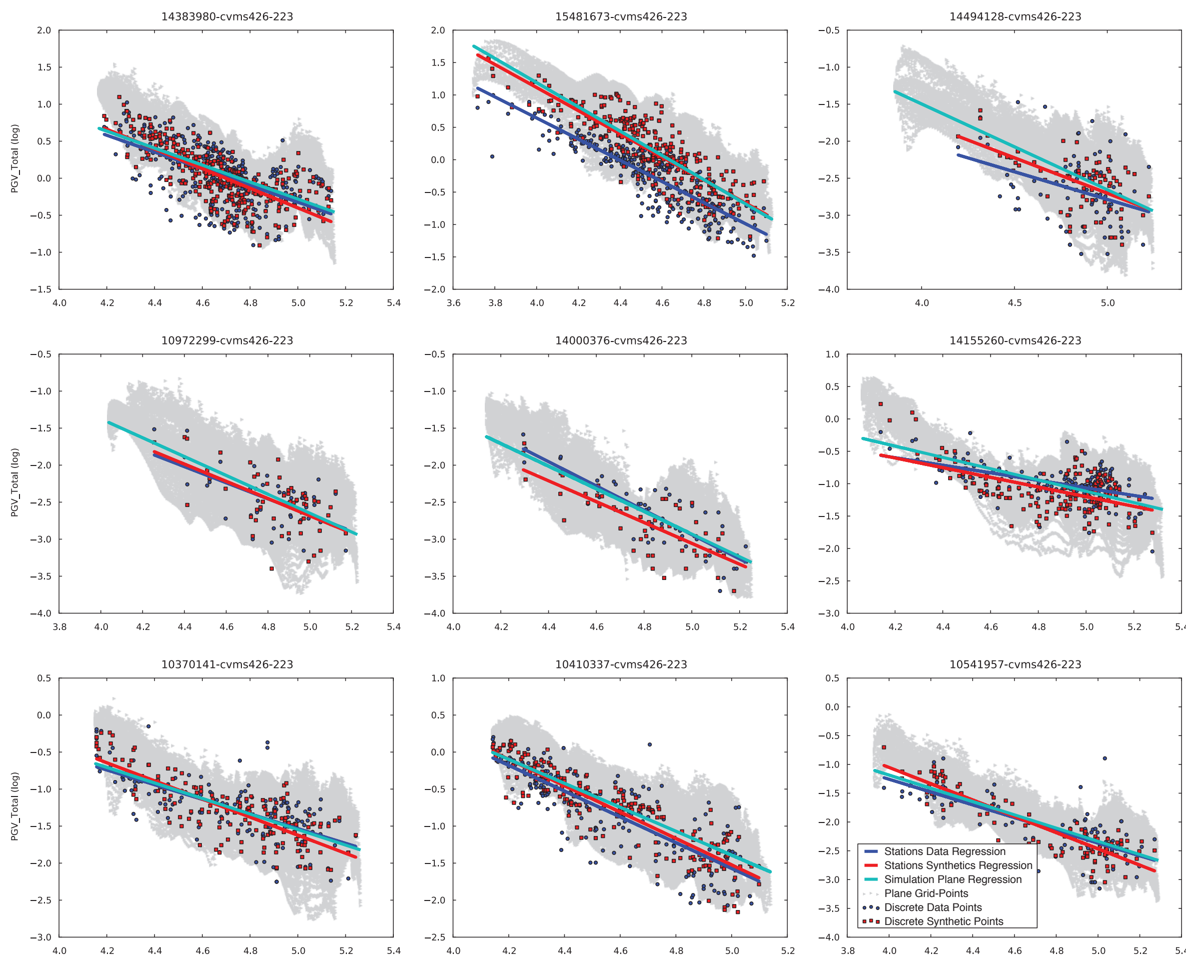
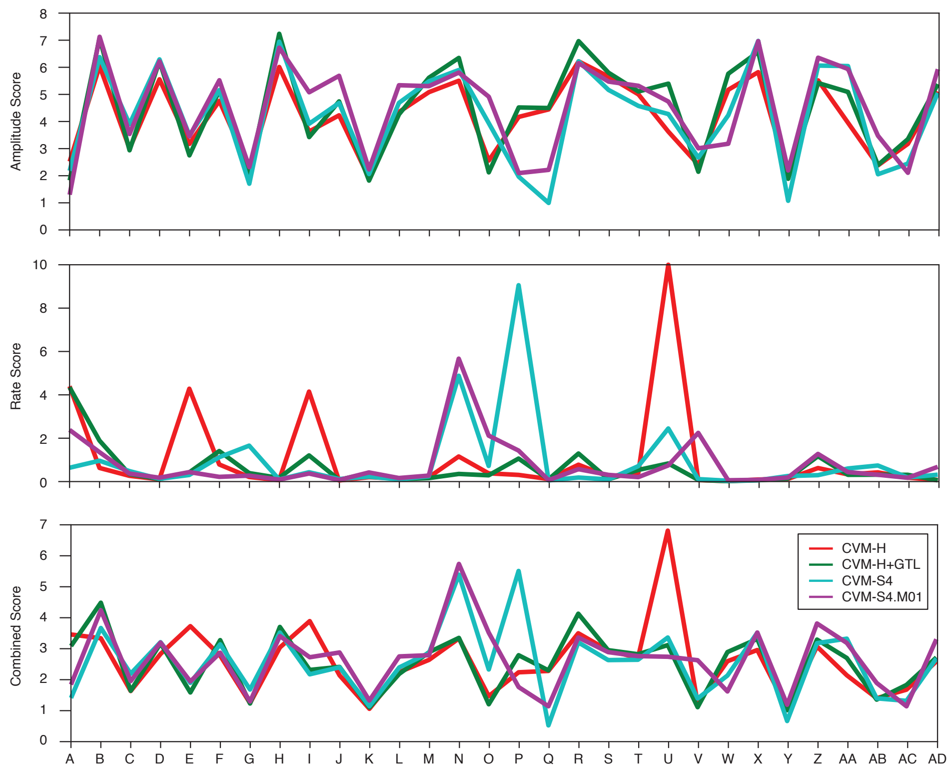


Figure 1. PGV attenuation regressions (solid lines) as functions of distance (in log-log scale) for multiple events comparing results derived from data-points corresponding to stations for which there exist records (blue) and the synthetic data-points obtained at the same locations (red), contrasted with the regressions obtained from using the full simulation-domain gridded surface data-points (green line and gray dots). Validation metrics obtained from comparing station data and synthetic stations is to be used to calibrate validation the new validation metric for when comparing full simulation-domain results to GMPE predictions as if there were no records available.

Another important aspect of the formulation is that it involves statistical information about the regression (e.g., standard deviation). This is relevant because we need to involve the statistics of the regression corresponding to a given GMPE for the validation of scenario earthquakes. In that way, the method can take into consideration the information from the GMPE without depending on data availability for th event being simulatied.



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F. Publications

We have not yet published any work directly linked to this particular project, but we expect to do so in the near future, in the form of both conference abstracts and a journal publication. Once that happens we will make sure to submit these contributions into the SCEC publications database.

G. References

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