Evaluation of Bias in Simulated Ground Motions for Moderate Magnitude Earthquakes in Southern California: A Study Using the Graves-Pitarka Method

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Abstract

This study uses the Graves-Pitarka broadband ground motion simulation method, integrated within the SCEC Broadband Platform (BBP), to simulate 51 moderate magnitude earthquakes (M 3.95 to 5.55) in Southern California. The aim is to assess bias in simulated ground motions compared to observed data, focusing on Effective Amplitude Spectra (EAS) and Pseudo Spectral Acceleration (PSA). Building on Nweke et al. (2022) [1], which identified systematic underprediction of low-frequency (long period) spectral accelerations, this study incorporates data from recent events recorded by standard networks and the Community Seismic Network (CSN). Results show persistent underprediction below 1 Hz, with PSA discrepancies of 10% to 50% and EAS discrepancies of 10% to 80%.

Residual analysis indicates that while site-specific and path-related biases are minor, significant bias remains unaccounted for. We hypothesize that this is linked to earthquake source characteristics, particularly the empirical magnitude-rupture area scaling relationship, as suggested by Leonard (2010) [2], which appears less accurate for smaller magnitude events. The 2008 M 5.39 Chino Hills earthquake supports this, but broader validation is limited by the lack of detailed finite fault models.

Ongoing research focuses on the effects of fault rupture area, stress drop, and average slip on the bias, with further sensitivity analysis of source parameters like rupture speed. These efforts aim to improve simulation accuracy and contribute to better seismic hazard assessment and earthquake engineering design.

Introduction/Background

Validation of simulated ground motions for engineering application involves looking for misfits and refining models to remove bias, often using well-documented earthquake data. Nweke et al. (2022) [1] recently conducted physics-based simulations for 13 moderate magnitude earthquakes (M3.99 to M5.39) in southern California, considering 3D and 1D crustal velocities. Community Velocity Models (CVMs) used for 3D crustal representations were CVM-H15.1 and CVM-S4.26.M01 (hereafter CVM-H and CVM-S4 respectively), and for 1D Northridge Region 1D was used. The authors discovered a significant underprediction in simulated ground motion levels compared to observed data while the simulations matched the overall pattern of amplification within the sedimentary basins (Figure 1).

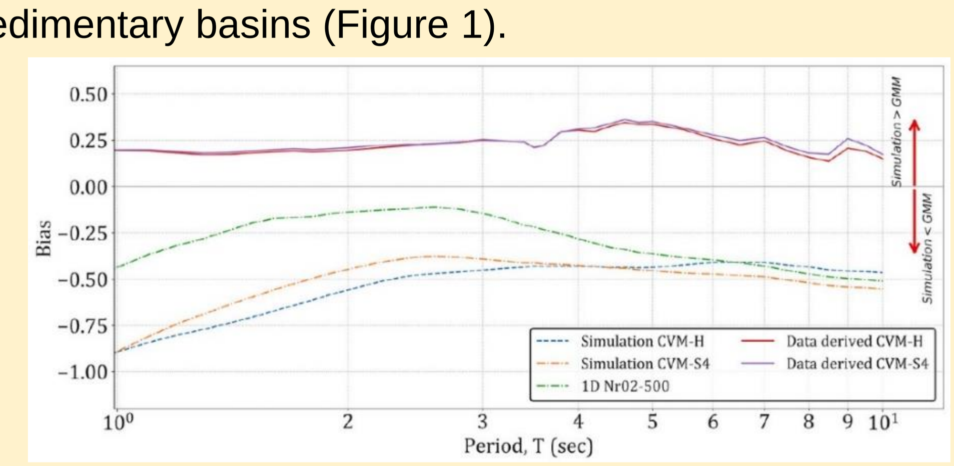

Figure 1: *Bias terms as a function of oscillator period for 3D simulations using CVM-H, CVM-S4 and 1D crustal representation. (From Nweke et al. (2022) [1])*

This current study extends that work and focuses on a systematic investigation to determine and understand the source(s) of the bias. The extended work is focused on performing 1D simulations using SCEC Broadband Platform v22.4.0.

Study Region

The study focuses on Southern California, where we queried the moderate-magnitude earthquakes (**M**3.95–5.5). We selected well-recorded events with at least 24 recordings within 50 km of the hypocenter. From 266 recorded earthquakes, 51 were selected, comprising a total of 8,908 recordings. The study area and the spatial distribution of selected and rejected events are shown in Figure 2.

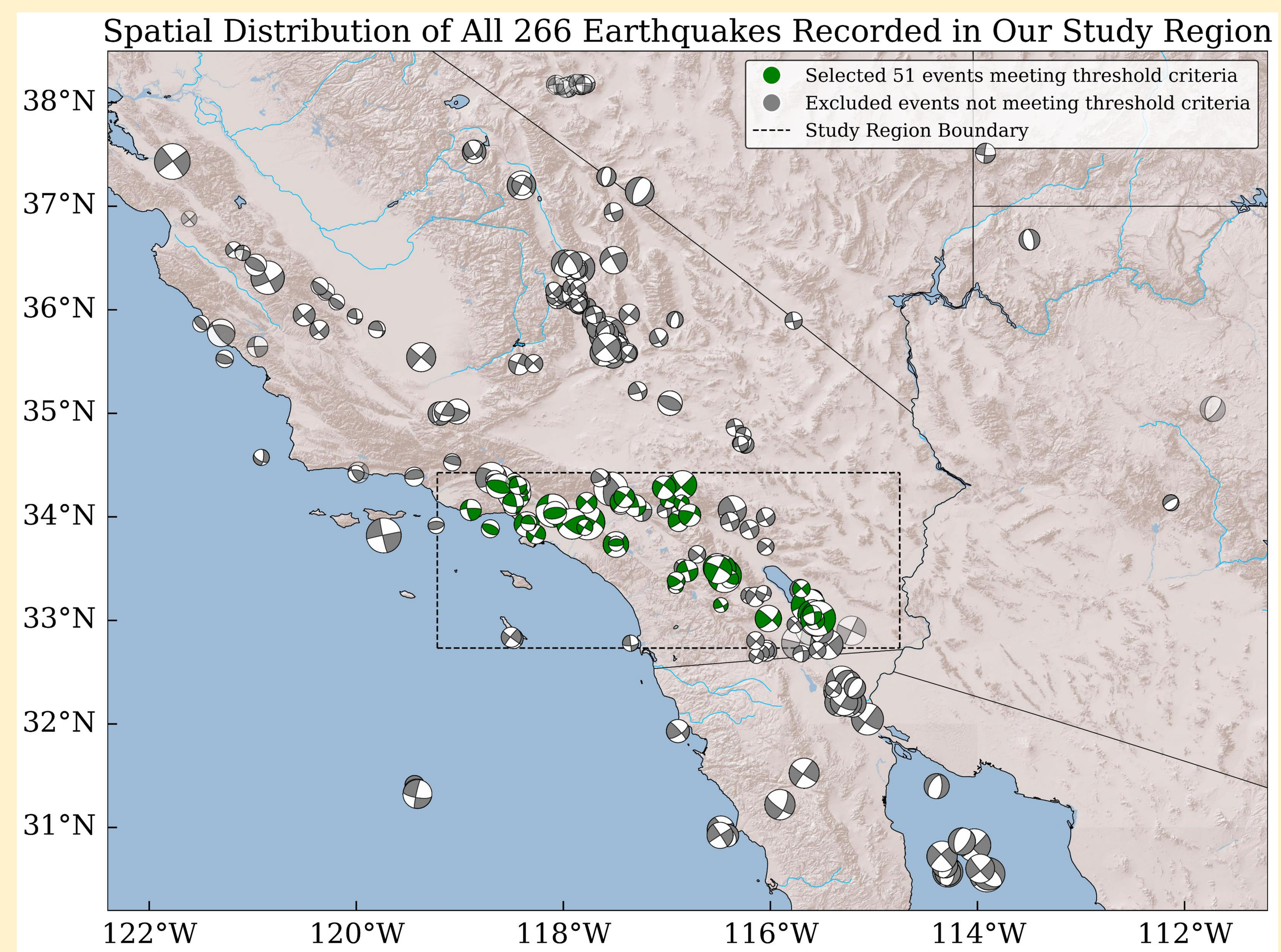

Figure 2: *Spatial distribution of 51 selected earthquakes (green beachballs) meeting the selection criteria. Rejected events are shown in grey.*

Methodology

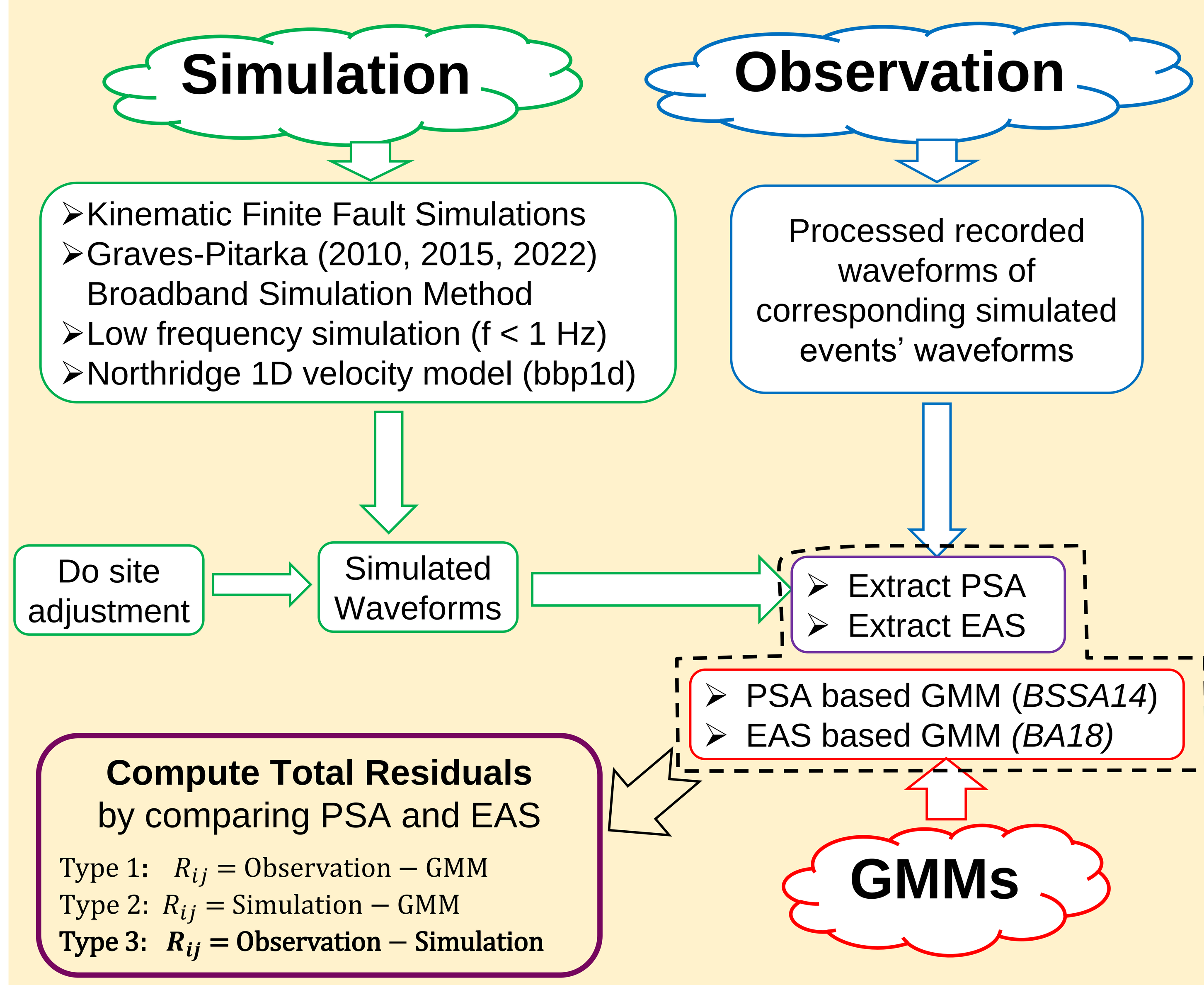

Figure 3: *Schematic diagram showing workflow of calculating total residuals (R_{ij}) for residual analysis among Simulation, Observation and GMMs.*

Figure 3 illustrates the systematic approach employed in this study. The process begins with 1D kinematic finite fault simulations of the selected earthquakes using the Graves-Pitarka (2010, 2015) [4] broadband simulation method. Simulated waveforms are then subjected to site adjustments using various approaches, followed by the calculation of PSA and EAS, which are compared against their corresponding observed waveforms. The BSSA14 [5] ground motion model (GMM) is used for PSA comparison, while BA18 [6] is utilized for EAS-based comparisons. Although three types of residuals are computed, the focus of this study is on reconciling type 3 bias (Observation - Simulation).

Total Residual (R_{ij}) is subsequently partitioned using mixed-effect analysis:

$$R_{ij} = c_k + \eta_{E,i} + \eta_{S,j} + \varepsilon_{ij}$$

- c_k is the mean bias of the chosen model (fixed effect)
- $\eta_{E,i}$ is the earthquake-source-related random effect
- $\eta_{S,j}$ is the site-related random effect, and
- ε_{ij} is the remaining residual

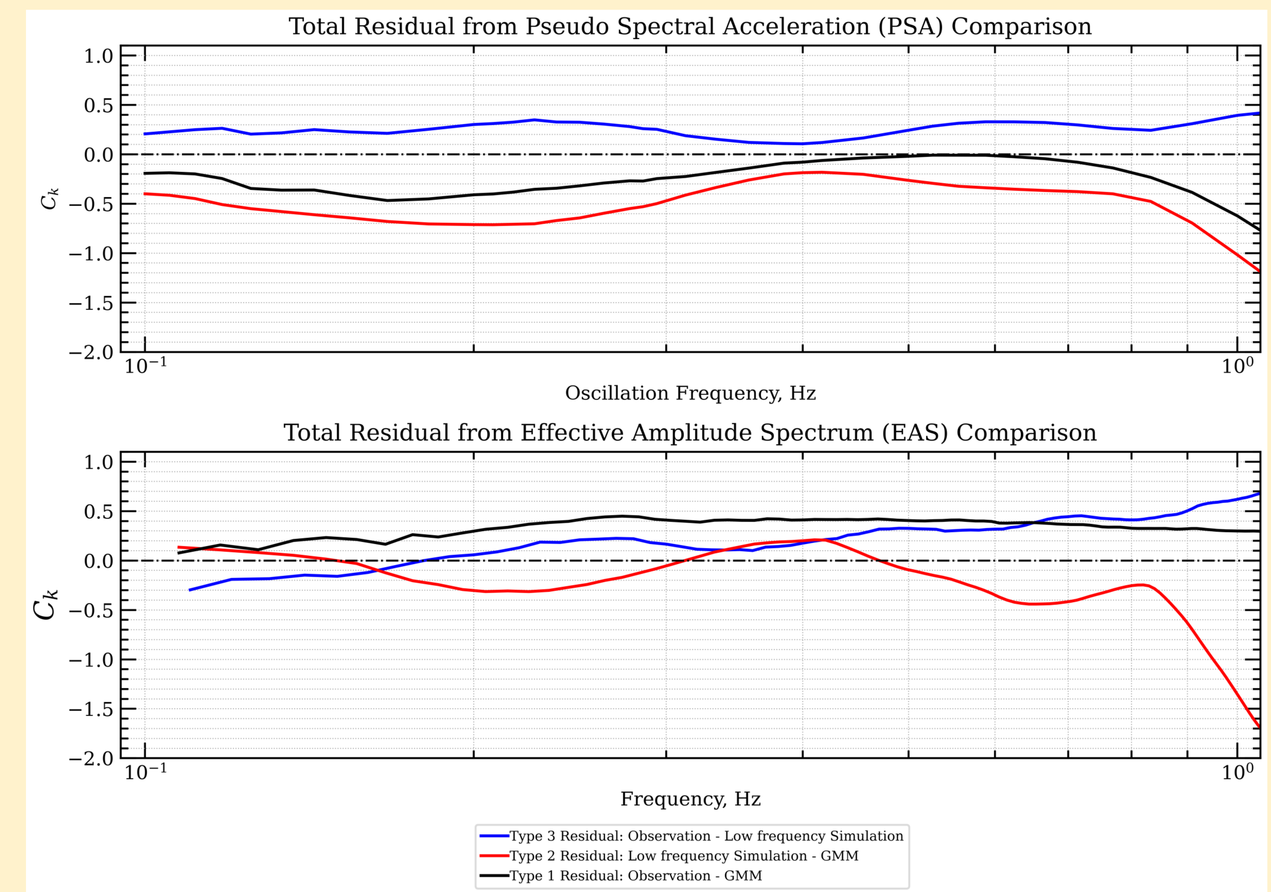

Figure 4: *Comparison of mean model bias (c_k) for different types of residuals for the 8908 recordings from 51 Southern California events.*

Results

The present study has found that ***GMMs*** are overpredicting ***Observation*** in response spectra domain and underpredicting in Fourier domain. **GMMs** are overpredicting **Simulations** in response spectra domain whereas closely matching for f < 0.45 Hz but overpredicting for f > 0.45 Hz in Fourier domain. The **Simulations** are underpredicting **observations** in response spectra domain whereas they exhibit a linear trend of residual in Fourier domain although almost completely underpredicting. There is still a significant bias of simulations against observations, and it needs to be reconciled.

Future Works

We want to focus on understanding the effects of fault rupture area, stress drop, and average slip on the overall bias, and includes a sensitivity study of other earthquake source attributes, such as average rupture speed, on a case-by-case basis to explore potential solutions for the observed bias.

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