SOLVING NEAR-FAULT DATA SCARCITY USING EARTHQUAKE SIMULATIONS TO IMPROVE SEISMIC HAZARD ANALYSIS OF NORMAL FAULTS

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Normal-faulting earthquakes are a regular occurrence in the Intermountain West region of the United States. Ground motion models like the 2023 National Seismic Hazard Model (NSHM) characterize the seismic hazards of all U.S. regions, including the Intermountain West. However, the ground motion observations that inform the current NSHM, such as the NGA-West2 ground motion database, are scarce in normal-slip earthquake data, especially near-fault recordings. Numerical simulations are sometimes used to provide complementary information for NSHM ground motion models, but to date have neglected normal-faulting events. This means that seismic hazard in populations within close ranges of normal faults may at present be mischaracterized. In this study, we use SeisSol, a dynamic rupture simulation and wave propagation software tool based on the discontinuous Galerkin method, to study the near-fault ground motion behaviors of normal-faulting earthquakes. We focus on analyzing ground velocity data in the near-source region from simulations, testing variable fault and environmental characteristics, such as dip, frictional parameters, initial stresses, ground velocity, and topography. These tests will help determine the most influential factors in normal-slip earthquake hazard. With these results, we aim to reveal the potential effects of data scarcity on the reliability of seismic hazard models, which would strongly benefit from additional data for normal-slip ground motion. This understanding will create a stronger physical basis for seismic hazard analysis in areas where normal-faulting events pose a significant risk to nearby communities.

BACKGROUND

- Normal faults under populated areas are known to have high damage potential
  - 2009 L'Aquila, 2016 Amatrice and Norcia earthquakes
- Basin and Range seismicity dominated by normal faulting earthquakes
  - Scarce record due to sparse instrumentation at the time of largest normal-slip events (1915, 1954)
- 2023 NSHM active crustal models derived from scarce normal-slip strong motion data
  - ASK14 dip-slip fault hanging wall term generalized from kinematic simulations of thrust faults [1]
- Data scarcity may cause mischaracterization of seismic hazard in populations close to normal faults (e.g. see Figure 1), including cities like Reno, Salt Lake City, etc.

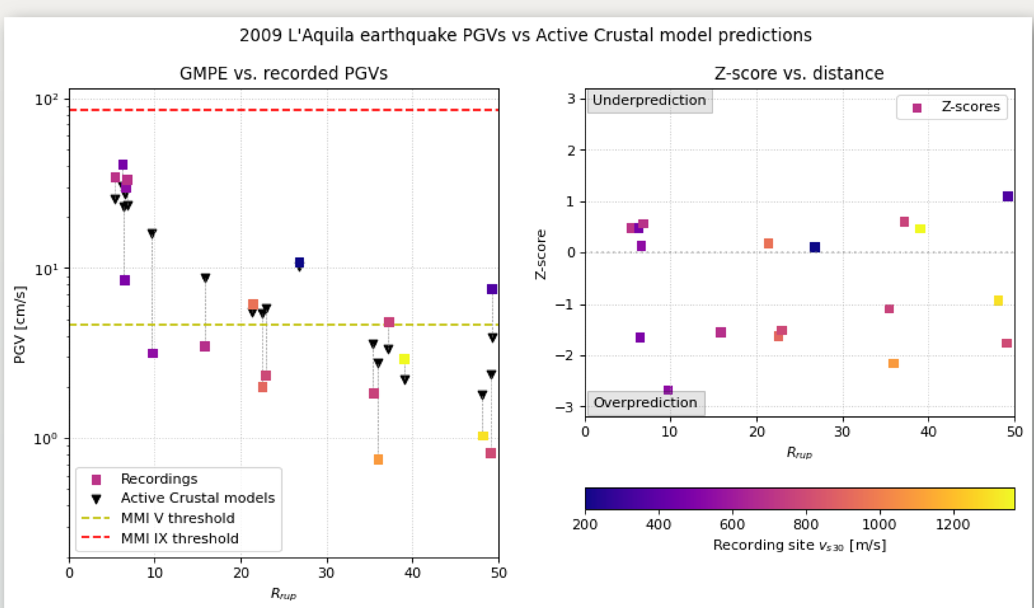


Figure 1: Comparison of recorded PGVs and GM predictions for the M6.3 2009 L'Aquila earthquake. Models use station-specific distance and site parameters. Left plot shows GMDB [2] vs. predicted PGVs. Right plot shows z-scores. Data plotted against R_{rup} (distance from rupture plane). Stations color coded by V_{S30}. Modified Mercalli Intensity (MMI) thresholds for intensities V and IX are plotted as yellow and red dotted lines, respectively.

METHODS

- Run a suite of dynamic rupture simulations in SeisSol
- Normal-slip simulations based on TPV10 benchmark test [3]
  - Fault dimensions: 30x15 km
  - Dip: 60°
  - Nucleation patch: 3x3 km
  - Hypocenter: 12 km down-dip from midpoint of surface fault trace
  - Fault ruptures the surface
  - Embedded in 100x100x42-km domain
  - Depth-dependent stress parameters

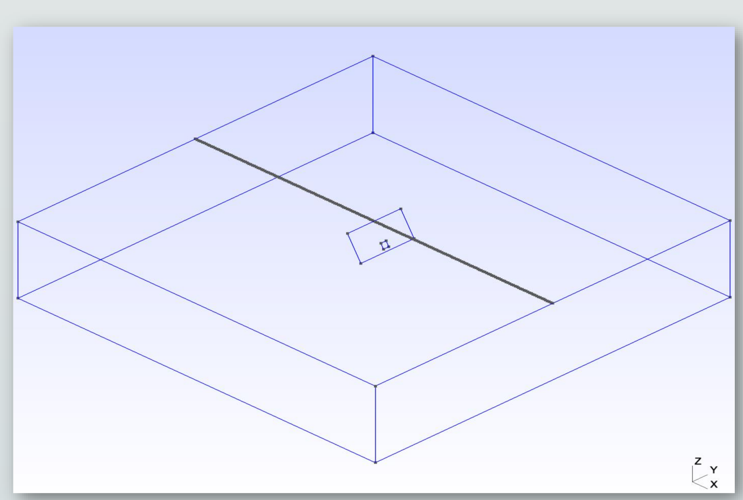


Figure 2: Example of 3D mesh used as SeisSol input for simulations. This is the case of a 60°-dipping fault in a 100x100x42-km domain. Also shown is the line along which PGV is calculated for GMPE comparisons. This line is perpendicular to the surface fault trace and crosses its midpoint.

- Variations in fault parameters for simulations
  - Dip: 25-75° (5° increment)
  - Reverse vs. normal slip
- Compare dynamic rupture simulation data to ground motion models
  - SeisSol data read from mesh output
    - RotD50 velocities computed from V_x and V_y data
  - Ground motion prediction data obtained via OpenQuake Python library [4]
  - Average of four Active Crustal models used in 2023 NSHM:
    - Boore et al., 2014 (BSSA14)
    - Abrahamson et al., 2014 (ASK14)
    - Campbell & Bozorgnia, 2014 (CB14)
    - Chiou & Youngs, 2014 (CY14)

RESULTS

- Base case (60° dip) SeisSol simulations return distribution patterns consistent with previous literature [5]
  - Stronger ground motions on hanging wall ($R_x > 0$) side
- Observed discrepancies:
  - Simulation returns ground motions lower than 1σ (standard deviation) below the GMPE median values
  - Dip angle in normal slip has strong effects on ground motion distributions not encapsulated by GMPEs
- GMPE vs. simulation data discrepancy increases with more extreme high/low-angle faulting
  - Near-fault ($R_x < 10$ km) PGVs over 1σ off from GMPEs in several cases
  - Strongest PGVs migrate to hanging wall ($R_x < 0$) in low-angle faulting cases, not seen in GMPEs
  - Reverse-slip PGVs significantly higher on footwall side than in normal-slip

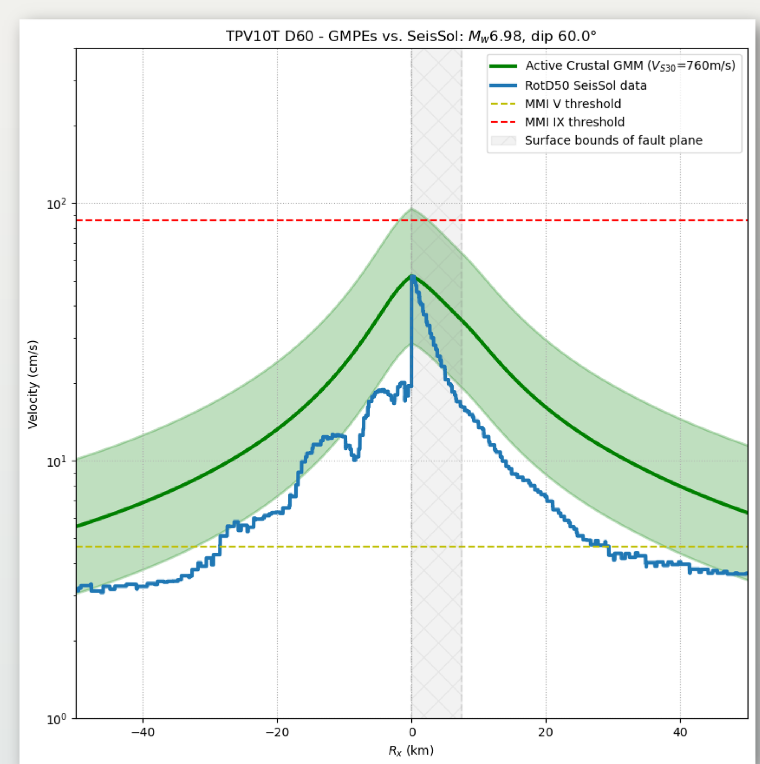


Figure 3: Results from a SeisSol simulation based on TPV10 (60°-dipping, 30x15 km fault rupturing the surface). RotD50 (rotation-independent median of horizontal motion) peak ground velocities (PGVs) computed from SeisSol data are plotted in log-y scale as a blue line. The average of the log-median of the four GMPEs previously listed, using the parameters from the SeisSol simulation, is plotted in log-y scale as a green line. Infill shows one log-standard deviation (1σ).

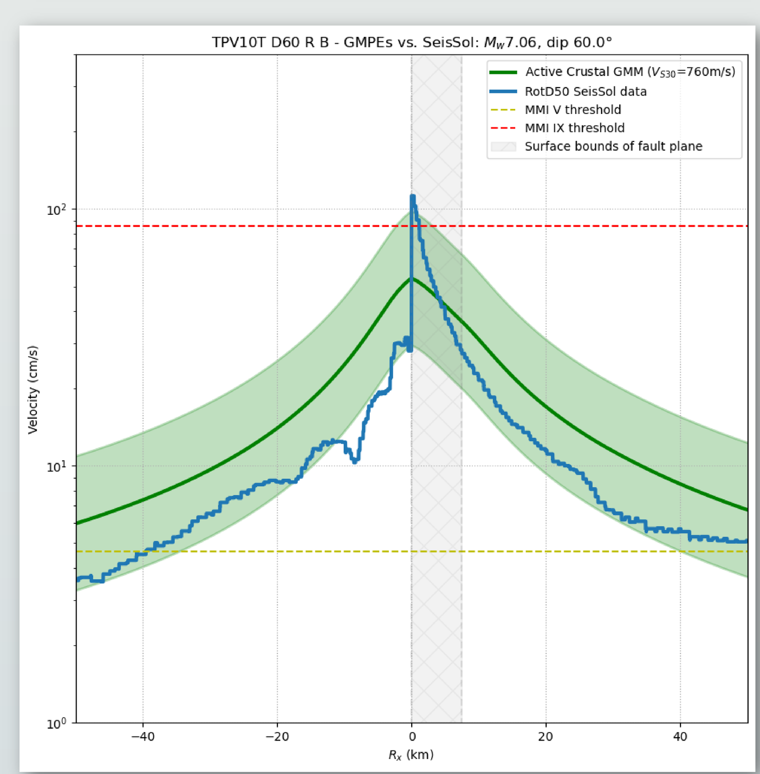
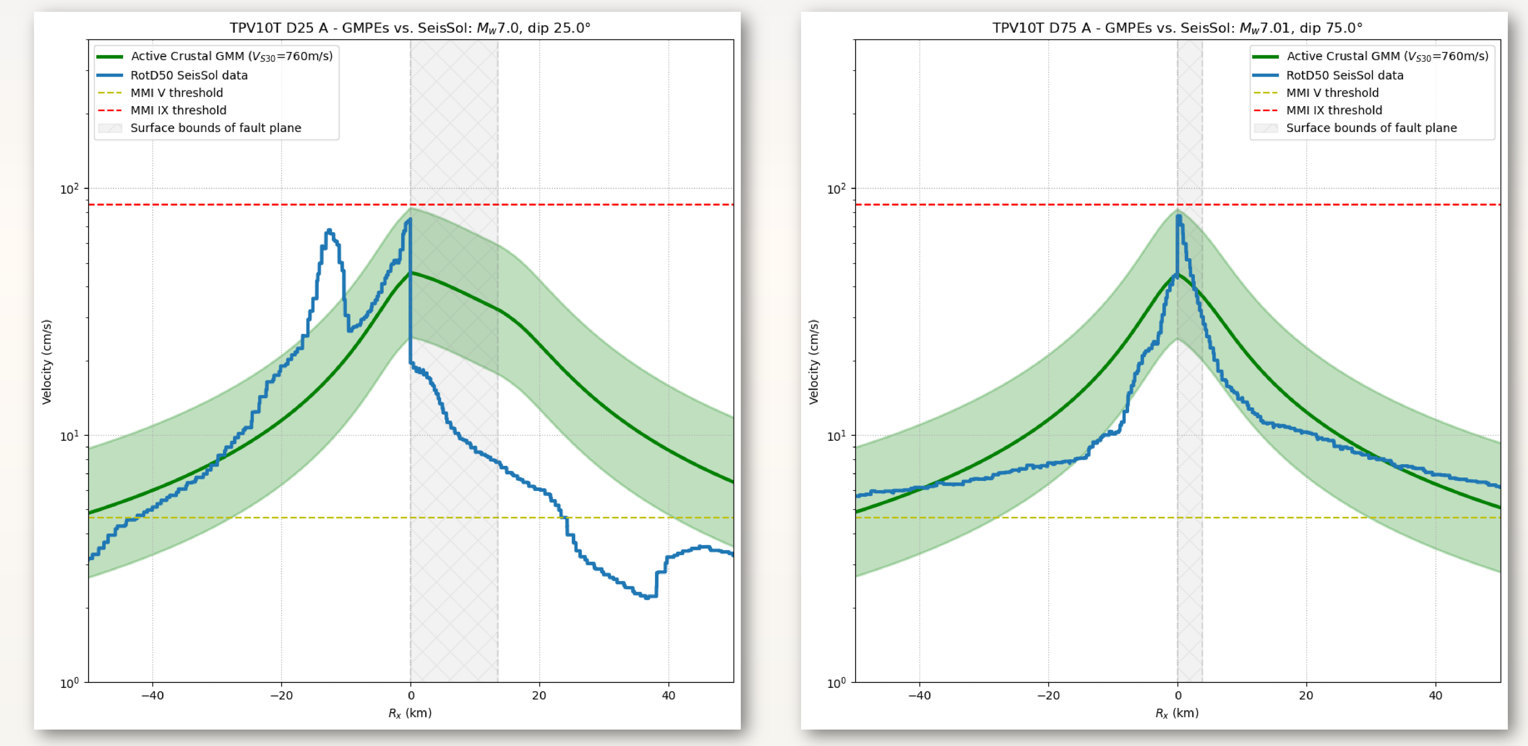
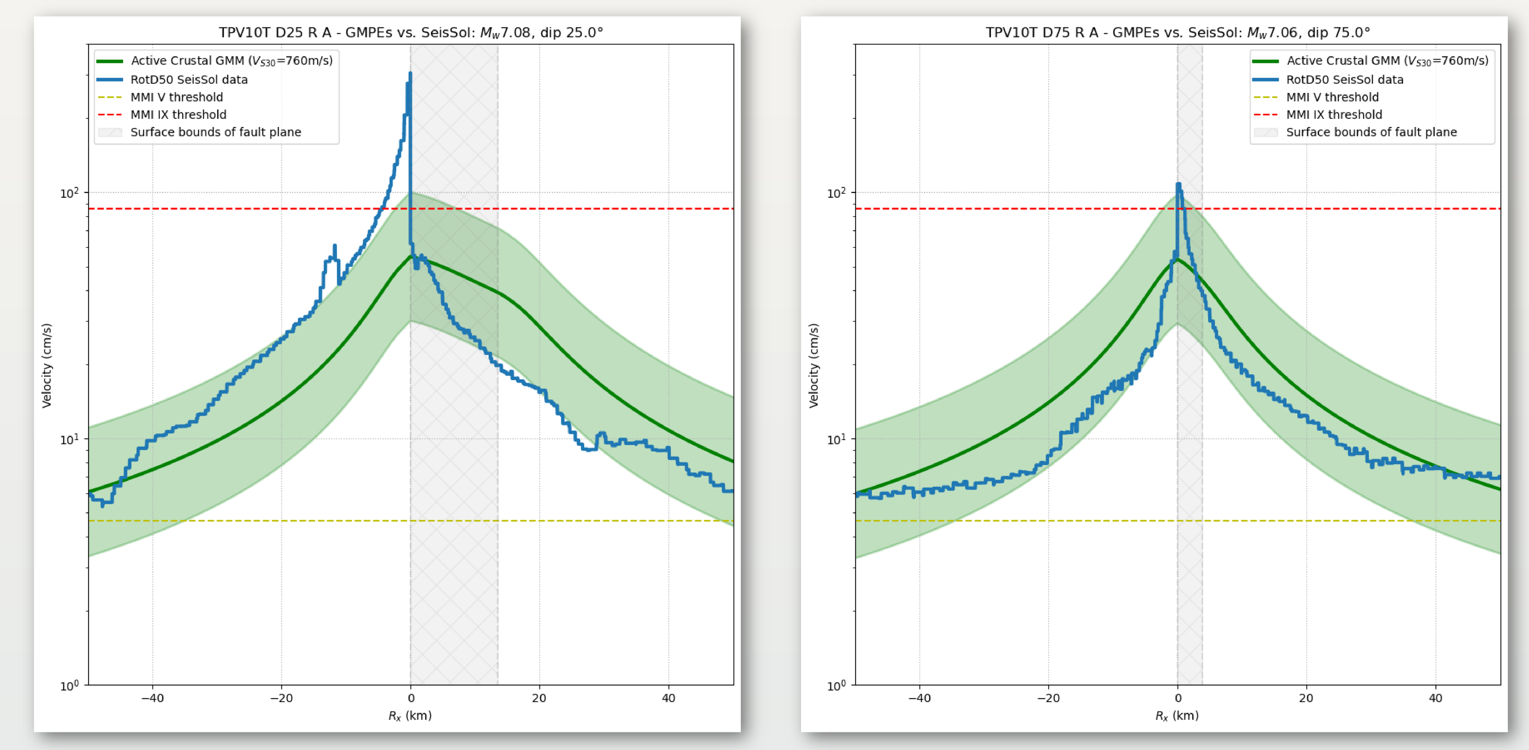


Figure 4: Same as Figure 2, but with data from a reverse-slip simulation. The only difference between these simulations is the down-dip fault traction, which has been reoriented to be up-dip. GMPEs rerun accordingly.



Figures 5a and 5b: SeisSol vs. GMPE data plotted as in Figures 2 and 3, showing the differences between low and high-angle normal faulting. Figure 4a (left) plots PGVs for a normal-slip rupture along a fault dipping 25° (low-angle), and 4b shows the same for 75° (high-angle). Limits of x-axis changed to 50 km per side.



Figures 6a and 6b: SeisSol vs. GMPE data plotted as in 4a and 4b, but for reverse faulting. Note the difference in simulated PGVs between reverse and normal-slip earthquakes.

SUMMARY & FUTURE STEPS

- Normal and reverse-slip simulations have starkly different peak PGVs and ground motion distributions
  - Simulated ground motion for dip-slip earthquakes should be distinguished by direction (normal/reverse) when used as substitute for real data
- 2023 NSHM in Basin and Range, if purely based on GM predictions, may mischaracterize hazard
- Future GMPEs would benefit from richer near-fault strong motion data, while dynamic rupture simulations can temporarily substitute for scarce data in current models
- Future work will encompass tests applying basin topography and ground velocity variations and possible earthquake scenarios

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