Modelling Nonlinear Site Effects in Physics-Based Ground Motion Simulation

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1. Background

This study examines the performance of site response analysis via nonlinear total-stress 1D wave-propagation for modelling site effects in physics-based ground motion simulations of the 2010-2011 Canterbury, New Zealand earthquake sequence. This approach allows for explicit modeling of 3D ground motion phenomena at the regional scale, as well as detailed nonlinear site effects at the local scale. The approach is compared to a more commonly used empirical V_{S30} (30 m time-averaged shear wave velocity)-based method for computing site amplification as proposed by Graves and Pitarka (2010, 2015), and to empirical ground motion prediction via a ground motion model (GMM).

2. Site Response Analysis Methodologies

Empirical V_{S30}-Based Method: Figure 1a shows period-dependent nonlinear site amplification factors from the empirical ground motion model (GMM) by Campbell and Bozorgnia (2014). This function is then truncated, as recommended by Graves and Pitarka (2010), for two different reasons: 1) long periods are truncated because the 3D long period component of the simulation should account for deep site response which would influence very long periods, and 2) short periods are truncated because this amplification function is meant to be applied to response spectra, but in this context it is applied to Fourier spectra in the frequency domain.

Physics-Based Wave Propagation Analysis: Figure 1b illustrates physics-based site response via wave propagation, in which simulated ground motions are extracted from the 3D model, deconvolved, and used as input to a nonlinear 1D site response analysis in OpenSees. Because the simulations are viscoelastic, they can be deconvolved in the frequency domain using a transfer function for damped soil over an elastic halfspace.

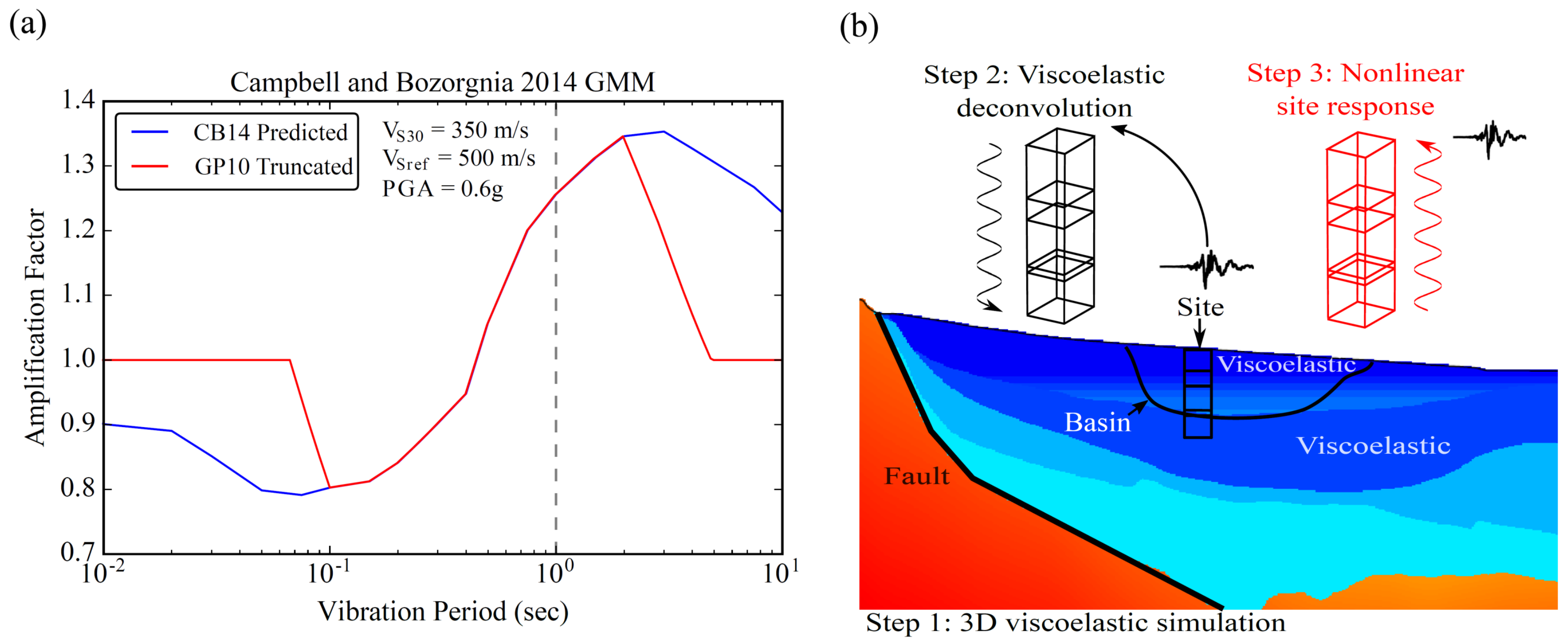

Figure 1: Two methods compared in this study for modelling nonlinear site effects: (a) Empirical V_{S30}-based nonlinear site amplification factors from Campbell and Bozorgnia (2014) GMM, applied to simulated ground motions in the frequency domain, and (b) Simulated ground motions extracted from 3D model, deconvolved, and input to OpenSees for wave-propagation site response analysis.

3. Sites and Earthquakes Considered

Eleven events from the 2010-2011 Canterbury earthquake sequence with $4.8 \leq M_w \leq 7.1$ were simulated by Razafindrakoto et al (2016). A detailed wave propagation site response analysis was performed at 20 strong motion stations in Christchurch using these simulations as input. Figure 2 shows the rupture models for all events and the locations of strong motion stations relative to the Christchurch urban area.

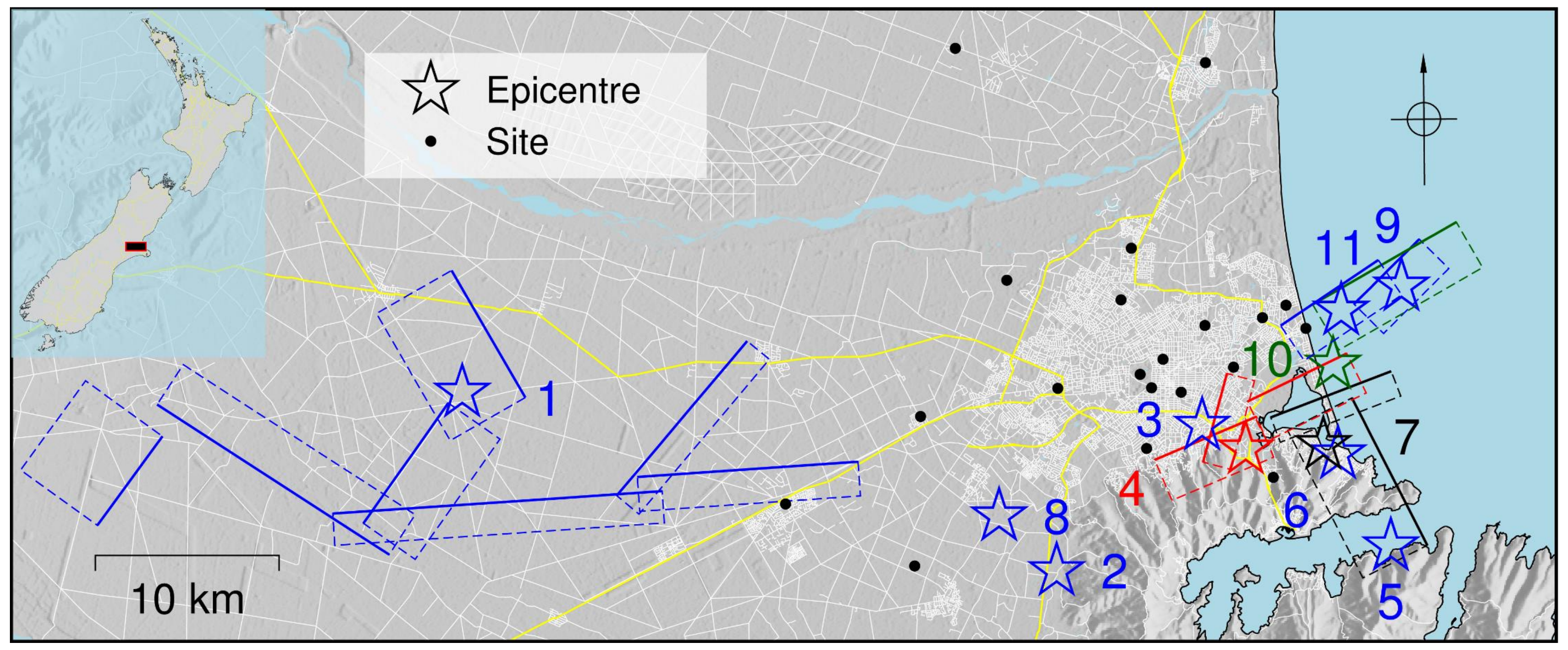

Figure 2: Earthquake rupture models for the 11 simulated earthquakes and locations of 20 strong motion stations analyzed.

4. Observed and Simulated Response Spectra

Acceleration response spectra are compared for each ground motion at all sites, as illustrated for two examples in Figure 3. Simulations that model site response via the empirical V_{S30}-based and the wave propagation methods, and viscoelastic simulations with a minimum Vs of 500 m/s that neglect site effects are compared to observed ground motions. The observed-to-simulated residual of spectral accelerations is then computed.

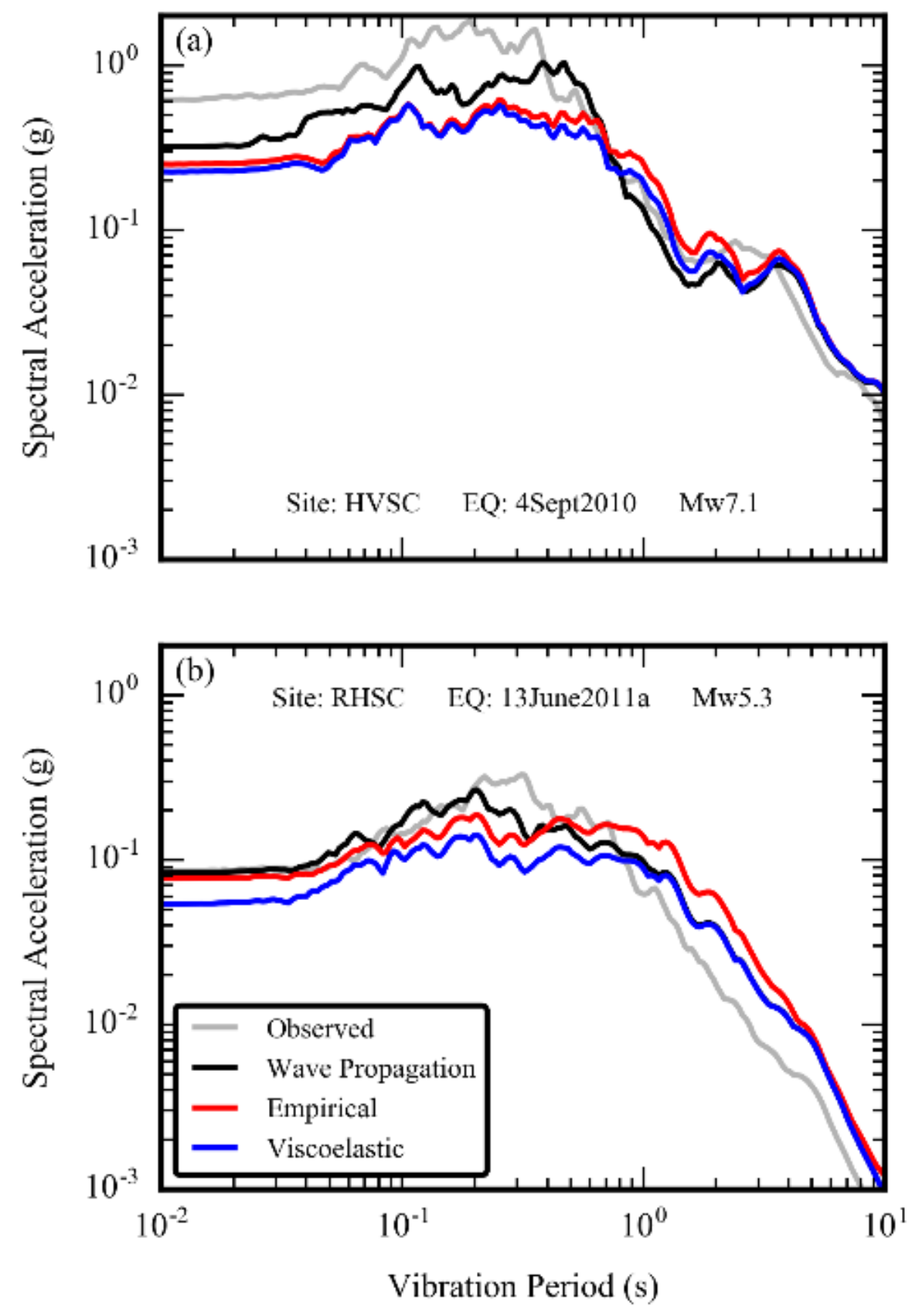

Figure 3: Comparison between observed and simulated acceleration response spectra for the empirical V_{S30}-based method, wave propagation site response analysis, and reference viscoelastic simulations.

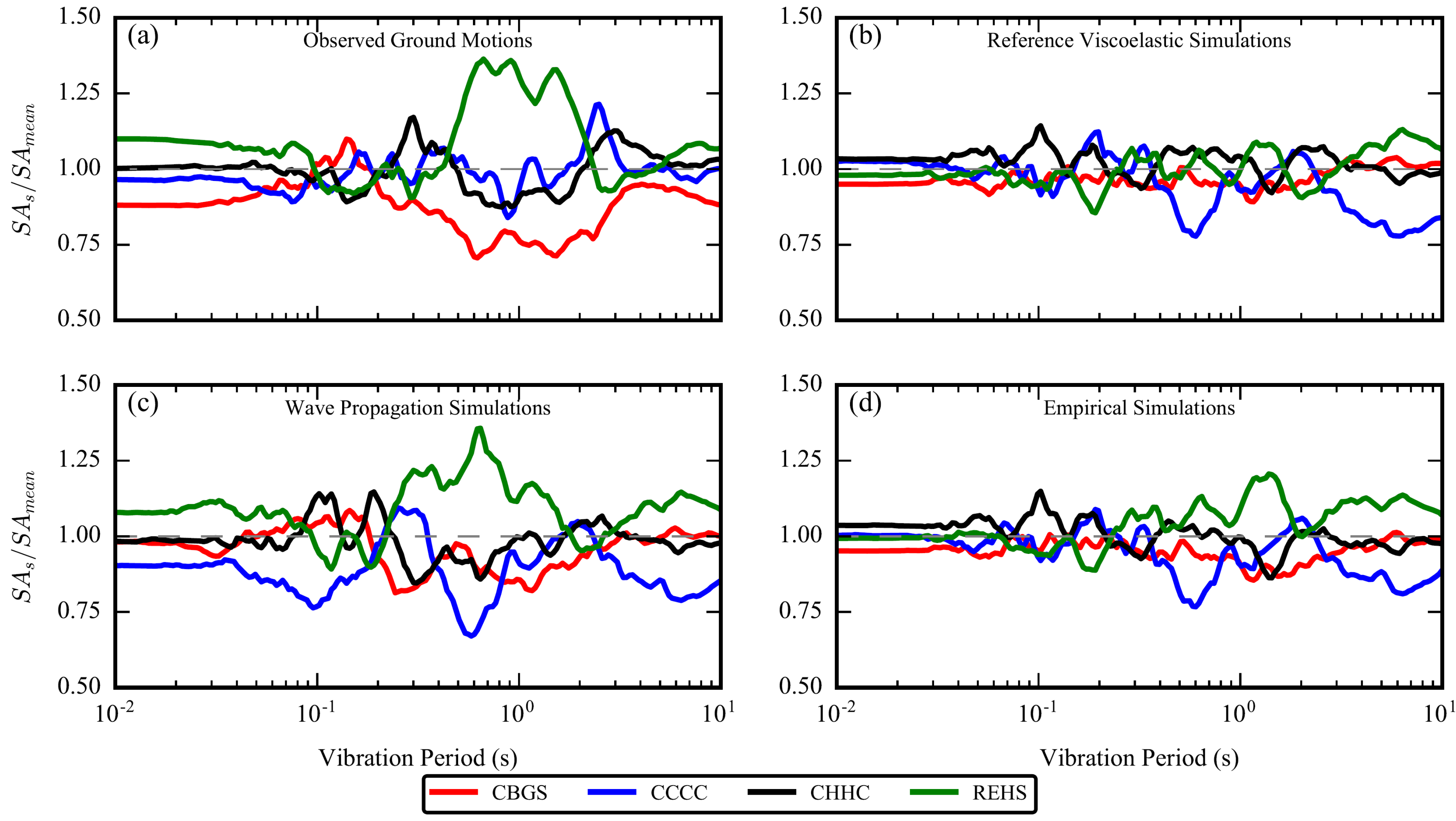

Figure 4: Response spectral ratios for sites in the Christchurch CBD from observed and simulated ground motions. The spectral ratio corresponds to the mean ratio for all 11 events where the ratio for an individual ground motion is the spectral acceleration for a given site over the mean from all sites in the group.

Figure 4 compares the ground surface response of nearby sites within a group from both observed and simulated ground motions to examine if the site response methods can capture local variability in ground motion that is attributed to near-surface site effects. Spectral ratios are computed at every site and for every event as the ratio of the surface response spectrum for each site to the geometric mean response spectrum for the full group of sites.

The wave propagation site response (Fig 4c) can capture relative features in observed ground response (Fig 4a), such as the large amplification at a soft peat site (REHS), much better than the empirical V_{S30}-based method (Fig 4d).

5. Systematic Prediction Residuals

Figure 5 illustrates the systematic model bias (Fig 5a), and the total standard deviation, σ (Fig 5b), in spectral acceleration prediction, as a function of vibration period, across all sites and earthquakes considered for all three analysis methods. Three average trends are identified in the results:

- Reference viscoelastic simulations which ignore site effects (blue line in Fig 5) significantly underpredict spectral accelerations at periods between 0.2 to 2 seconds.
- The V_{S30}-based approach significantly over-amplifies the long periods (i.e., 1-5 s) and the wave propagation method performs better in this period range, suggesting that the long period component of the simulation is capturing deep site effects reasonably well and that the period range over which the empirical amplification function is truncated (see Figure 1a) needs to be revised.
- The empirical V_{S30}-based method performs slightly better than the wave propagation approach at short periods. This is likely caused by over prediction from the semi-empirical high frequency component of the reference simulation which then causes further overprediction when site response is applied.

Comparison with Empirical Ground Motion Prediction

To benchmark results from simulations against the current standard of practice for ground motion prediction (i.e., empirical GMM), response spectra were computed using the Bradley (2013) GMM. Figure 5 also includes model bias and total standard deviation from the prediction via GMM.

Considering both the magnitude of bias and uncertainty, it can be concluded that for periods less than 5 seconds, the physics-based and purely empirical methods predict ground motion with comparable performance while for periods greater than 5 seconds the physics-based simulation methods perform significantly better.

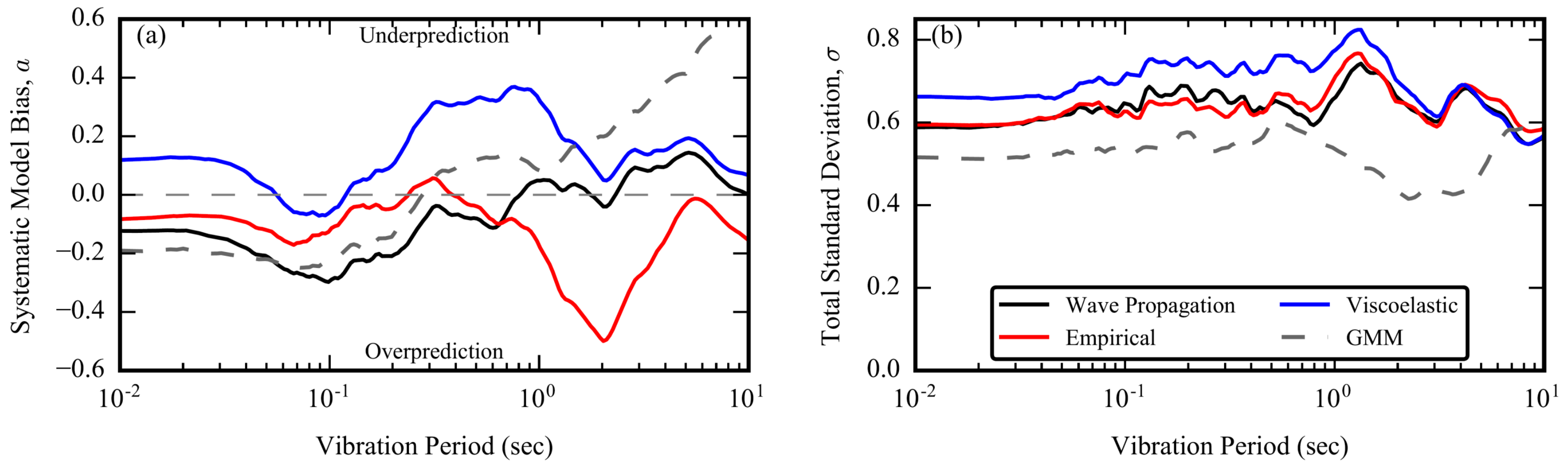

Figure 5: (a) Model bias and (b) total uncertainty from all events and sites considered for simulations that model nonlinear site effects via wave propagation site response and empirical V_{S30}-based site amplification factors, simulations that neglect site effects (i.e., reference viscoelastic condition), and purely empirical ground motion prediction via GMM.