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Evaluation of 1D Nonlinear Total-stress Site Response Model Performance at 114 KiK-net Downhole Array Sites

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ABSTRACT

A comprehensive assessment of one-dimensional (1D) total-stress nonlinear site response predictions is performed using an unprecedented number of sites and ground motions. Nonlinear site response model predictions for 5626 ground motions at 114 sites in the Kiban-Kyoshin network (KiK-net) of vertical seismometer arrays in Japan are calculated using the program DEEPSOIL and compared to observed ground motions and predictions from simpler models (i.e., linear and equivalent-linear analyses in SHAKE). Statistical analyses of the model residuals indicate that the equivalent-linear and nonlinear site response models generally do not deviate from each other significantly until maximum shear strains of 0.05–0.1% are achieved at certain sites. Although the nonlinear site response model offers a slight improvement over the equivalent-linear model, the remaining trends in the residuals suggest that other factors—such as breakdowns in the 1D site response assumptions and/or poorly characterized soil properties—have significant impacts on site response behavior.

Introduction

It is well-known that nonlinear soil behavior exhibits a strong influence on surficial ground motions at large strains. However, the application of fully nonlinear time-domain site response analyses remains limited in practice, with the equivalent-linear site response approximation to nonlinear soil behavior still the most common approach, using programs such as SHAKE (Schnabel et al., 1972). For a particular project, engineering practitioners are therefore faced with the challenge of selecting the appropriate level of model complexity (e.g., equivalent-linear vs. nonlinear). While previous validation studies have attempted to quantify the levels of ground motion for which nonlinear site response analyses are necessary (e.g., Assimaki et al., 2008; Kwok et al., 2008; Kim and Hashash, 2013; Kaklamanos et al., 2015), the assessment of fully nonlinear site response models is often limited to a relatively small number of sites and ground motions.

In the present work, a comprehensive assessment of one-dimensional (1D) total-stress nonlinear site response predictions is performed using an unprecedented number of sites and ground motions. Nonlinear site response model predictions for 5626 ground motions at 114 vertical seismometer arrays of Japan's Kiban-Kyoshin network (KiK-net) are calculated using the program DEEPSOIL (Hashash et al., 2014) and compared to observed ground motions and

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predictions from linear and equivalent-linear analyses in SHAKE (Schnabel et al., 1972). Although DEEPSOIL also has the capability to perform linear and equivalent-linear analyses, we have chosen SHAKE because it is the most commonly used site response program in engineering practice, and it allows for a direct comparison to the results of Kaklamanos et al. (2013). This study builds upon prior work (Kaklamanos et al., 2013) in which linear and equivalent-linear site response analyses (but not nonlinear analyses) were performed using SHAKE at 100 KiK-net sites using 3720 ground motions. With this large database of nonlinear site response model predictions, statistically significant conclusions are drawn on the predictive capabilities of fully nonlinear site response models over linear and equivalent-linear models.

Data

Vertical seismometer arrays, which contain both surface and downhole recordings, are extremely well-suited for 1D site response validation studies. The downhole recordings are used as input motions at the base of the profile, are propagated though the 1D soil profile to predict the surface ground motions, which are then compared to observed motions. This study utilizes 114 vertical seismometer arrays in Japan's Kiban-Kyoshin network (Aoi et al., 2000). These arrays were selected because they each have recorded at least one strong ground motion with peak ground acceleration (PGA) greater than 0.3*g* at the ground surface, and are thus of engineering interest. Site response analyses for a total of 5626 ground motions, representing 1670 earthquakes from the early 2000s through mid-2014, are analyzed at these sites. The selected ground-motion records span a large range of site characteristics and ground-motion amplitudes, with 239 records having PGA > 0.3*g*.

Methods

Site Response Models

Site response predictions are calculated using the time-domain program DEEPSOIL (Hashash et al., 2014) for the nonlinear analyses, and the frequency-domain program SHAKE (Schnabel et al., 1972) for the linear and equivalent-linear analyses. The soil profiles are based upon the soil types and P- and S-wave velocity profiles provided in the KiK-net database. The Zhang et al. (2005) modulus-reduction and damping curves are used directly in the equivalent-linear analyses and as the target relations for the nonlinear analyses. In DEEPSOIL, the MRDF pressure-dependent hyperbolic model procedure (Phillips and Hashash, 2009) is used to obtain the fitted nonlinear curves from specified modulus-reduction and damping curves.

Quantification of Uncertainty

To quantify the goodness-of-fit of the site response models, we compare observations and predictions of multiple ground-motion intensity measures (IMs), including PGA, Arias intensity (I_a), and 5%-damped pseudo-acceleration response spectra (PSA) at various spectral periods (T). The model residuals for a given ground-motion intensity measure, $\mathrm{IM_{resid}}$, are calculated in natural logarithmic space as $\mathrm{IM_{resid}} = \ln(\mathrm{IM_{obs}}) - \ln(\mathrm{IM_{pred}})$, where $\mathrm{IM_{obs}}$ is the observed intensity measure at the ground surface, and $\mathrm{IM_{pred}}$ is the predicted intensity measure at the ground surface from the site response model.

Mixed effects regression (Pinheiro et al., 2008) is used to account for the dependence between multiple recordings at a single site. Let $y_{i,j}$ denote the model residual, IM_{resid}, of an intensity measure for the i^{th} site and the j^{th} ground motion. Following the notation of Kaklamanos et al. (2013), the residuals are represented by the mixed effects regression equation $y_{i,j} = a + \eta_{Si} + \varepsilon_{i,j}$, where a is the fixed effect, which represents the average bias in the predicted intensity measure across all sites and ground motions; η_{Si} is the inter-site residual, which gives the average deviation from the population mean for the i^{th} site; and $\varepsilon_{i,j}$ is the intra-site residual, which represents the deviation after all repeatable site effects have been removed. The three regression parameters are the fixed effect a, inter-site standard deviation τ_S (the standard deviation of the inter-site residuals), and intra-site standard deviation σ_o (the standard deviation of the intra-site residuals). Therefore, the mean and variance of the normal random variable $Y = IM_{resid}$ are given by $\mu_Y = a$ and $\sigma_Y = \sqrt{\tau_S^2 + \sigma_o^2}$, respectively.

Results and Discussion

Example Site Response Observations and Predictions

Before conducting a rigorous statistical analysis on a large dataset, it is instructive to study an example ground-motion record to provide a physical context for the statistical results. Figure 1 presents the observed and predicted acceleration time series, response spectra, and amplification spectra for the M_w 8.0 earthquake of 26 September 2003 recorded at station TKCH07, with an observed PGA of 0.412g. This site consists of 85 m of soil (clay, sand, and silt) over bedrock, and has an average shear-wave velocity (V_{S30}) of 140 m/s in the upper 30 m. In general, all predictions are poor at short to moderate spectral periods. This record illustrates some common trends observed across many sites and ground motions: the linear model tends to overpredict the ground response, as observed in both the response spectra and the amplification spectra. The equivalent-linear model often underpredicts short-period (high-frequency) ground motions at large strains, as observed in Figure 1(d-e). For this particular record, as observed in Figure 1(d), the nonlinear site response model offers a slight improvement over the equivalent-linear model at short periods (less than 0.5 s), the equivalent-linear model more closely matches the observations at moderate periods (0.5–2 s), and the differences between the models are less significant at longer spectral periods, where the effects of nonlinear soil behavior are less pronounced.

Analysis of Site Response Residuals

The uncertainties of each model can be assessed by statistically analyzing the site response model residuals using the full dataset. Kaklamanos et al. (2013) identified the maximum shear strain in the soil profile (γ_{max}) as the explanatory variable that most efficiently characterizes site response model uncertainty. The trends in the model residuals can be used to quantify the bias and precision of each site response model as a function of γ_{max}. Figure 2 presents plots of the intra-site residuals versus γ_{max}; columns correspond to different site response models (linear, equivalent-linear, and nonlinear), and rows correspond to different ground-motion intensity measures (PGA, PSA at several vibration periods, and Arias intensity).

For the linear site response model, shown in the first column of Figure 2, the residuals exhibit noticeable downward slopes at large shear strains (at least 0.01% for short spectral periods). This downward-sloping pattern occurs because the linear model overpredicts large-strain ground motions. The trends are most apparent for short spectral periods and for Arias intensity, which tends to emphasize high-frequency motion (since I_a is calculated from the square of the acceleration time history). For the equivalent-linear site response model, shown in the second column of Figure 2, the residuals exhibit noticeable upward slopes at large shear strains (at least 0.1–0.4%). This upward-sloping pattern occurs because the equivalent-linear model tends to 'overdamp' (and hence underpredict) high frequency response for large-strain ground motions. At spectral periods greater than 0.5 s (not shown in Figure 2), we find that the effects of nonlinear surficial soil behavior are less pronounced, and that all site response models are generally unbiased, even for sites with relatively high fundamental periods. This can be explained by the fact that longer spectral periods are associated with longer wavelengths, and therefore longer-period waves are less affected by shallow soil layers that typically experience the greatest nonlinear effects. The bias in the linear and equivalent-linear models is strongest at spectral periods in the 0.1–0.2 s range, close to the fundamental periods of many sites.

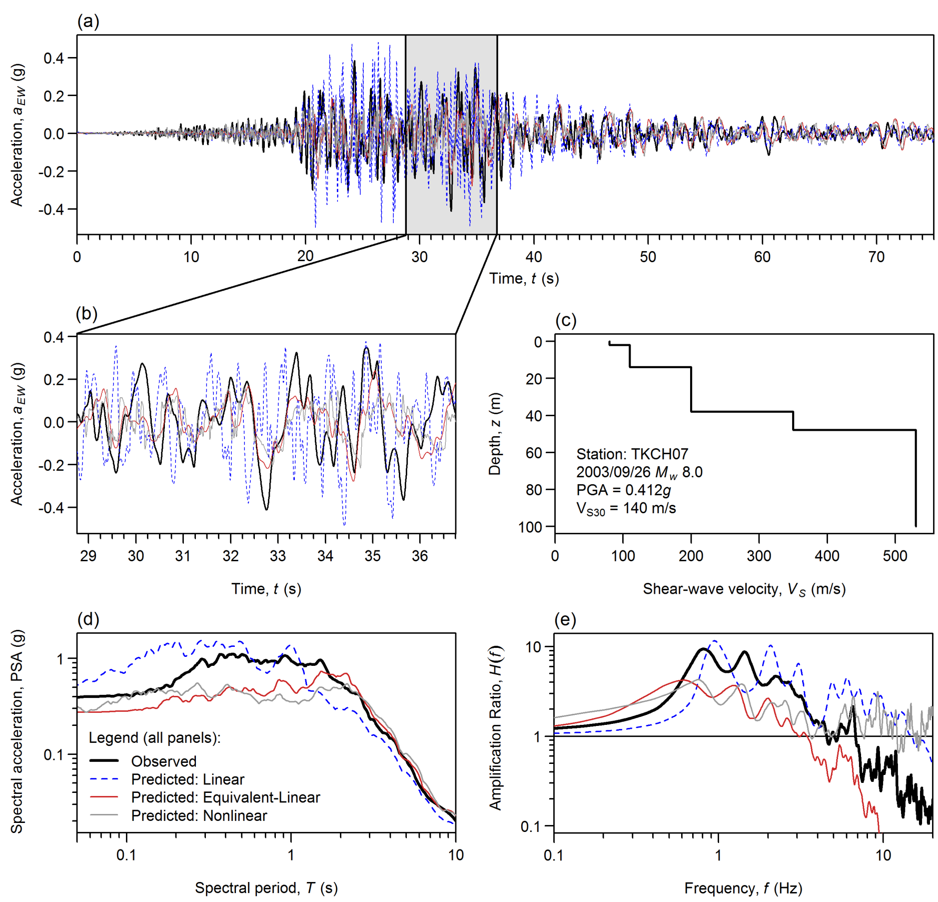

Figure 1. Example site response observations and predictions for the M_w 8.0 earthquake of 26 September 2003 recorded at station TKCH07: (a) acceleration time histories, (b) acceleration time histories centered at maximum acceleration, (c) shear-wave velocity profile, (d) pseudo-acceleration response spectra, and (e) surface/downhole amplification ratios.

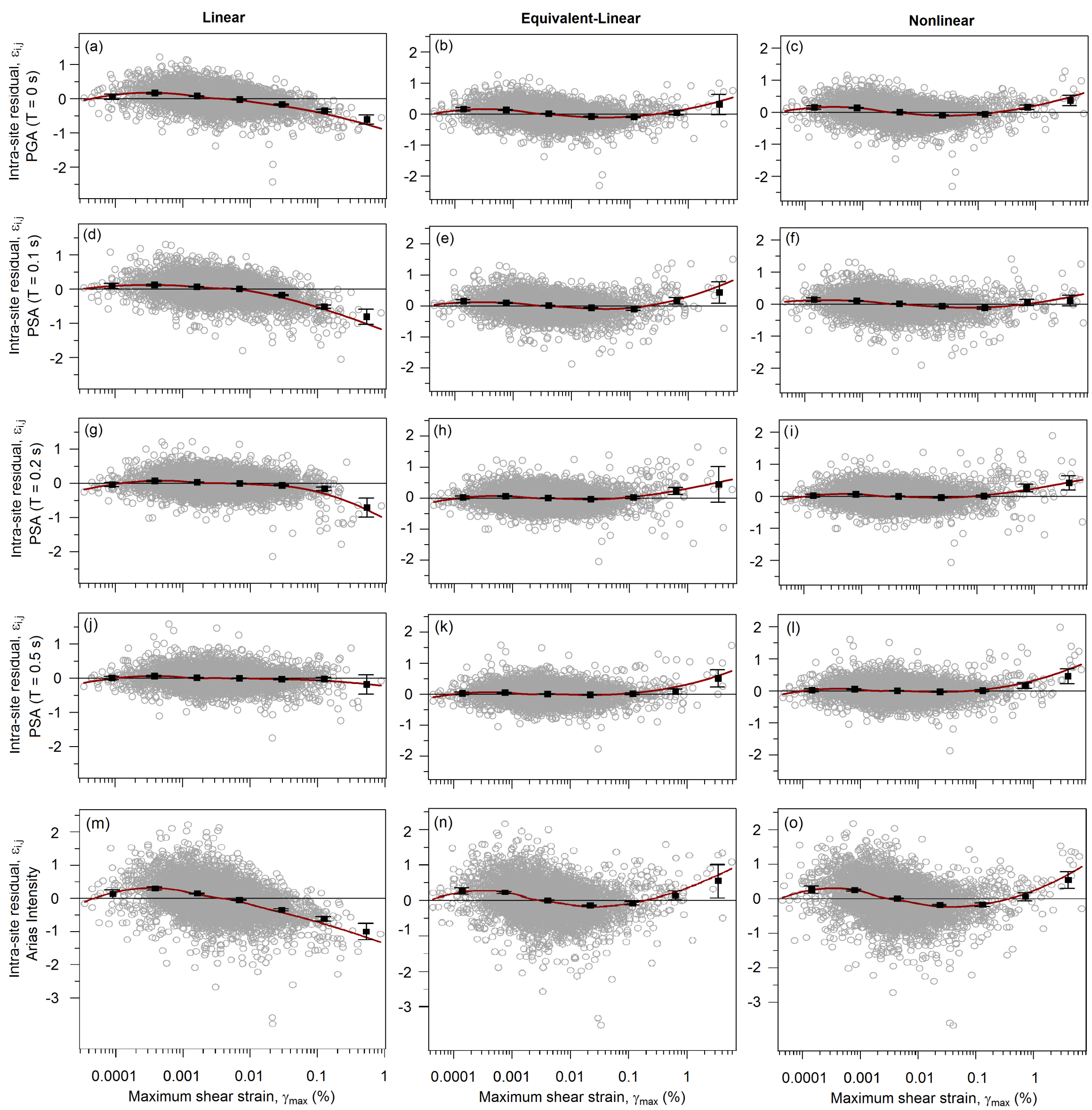

Figure 2. Plots of the intra-site residuals ($\varepsilon_{i,j}$) versus maximum shear strain in the soil profile (γ_{max}); each column corresponds to a different model (linear, equivalent-linear, and nonlinear, respectively), and each row corresponds to a different intensity measure: (a-c) PGA, (d-f) PSA at T = 0.1 s, (g-i) PSA at T = 0.2 s, (j-l) PSA at T = 0.5 s, and (m-o) Arias intensity. For each panel, we also display an estimate of the trend line (a locally weighted polynomial regression line; in maroon color) and the binned means and error bars (representing +/- two standard errors).

For the nonlinear site response model, shown in the third column of Figure 2, the residuals generally display similar behavior to the equivalent-linear site response model residuals at large shear strains (at least 0.1–0.4%). The nonlinear site response model residuals also slope upwards, indicating the tendency to underpredict large-strain ground motions. Some general similarities between the equivalent-linear and nonlinear site response models are expected because the stress-strain behavior for both models is based upon Zhang et al. (2005) modulus-reduction and damping curves. However, the nonlinear model residuals do not slope upward as significantly as the equivalent-linear model residuals at some spectral periods (especially at T = 0.1 s). Furthermore, the scatter in the equivalent-linear model residuals is greater than that of the nonlinear model residuals at large shear strains, suggesting that the equivalent-linear site response model is also less precise at large shear strains. However, all models (linear, equivalent-linear, and nonlinear) systematically exhibit less precision at large strains (indicated by the wider error bars) than they do at smaller strains, perhaps due to the lesser amount of large-strain data. It is also interesting to note that all models tend to underpredict I_a for small ground motions. For large ground motions, the trends in I_a are more consistent with the trends for the short-period PSA values.

To further decipher the differences between the equivalent-linear and nonlinear models, 1-to-1 plots of the equivalent-linear versus the nonlinear model residuals for PSA at T = 0.1 s are presented in Figure 3. The predictions are binned by: (a) site classification according to the Thompson et al. (2012) taxonomy (which uses weak ground motions to identify sites where the 1D assumption is valid), and (b) the maximum level of shear strain encountered in the soil profile. The distribution of residuals generally follows the 1-to-1 line, indicating that the models usually offer similar predictions. However, there are a group of observations for which the equivalent-linear models more severely underpredicts the surface ground motion than the nonlinear models. Figure 3(a) indicates that most of these 'problem' sites are classified as LP, indicating that they have poor fits for the 1D site response transfer function and low inter-event variability. Figure 3(b) indicates that the ground motions corresponding to the equivalent-linear/nonlinear mismatch have maximum shear strains greater than 0.05–0.1%; that is, the mismatch is generally limited to the largest categories of maximum shear strain, as expected.

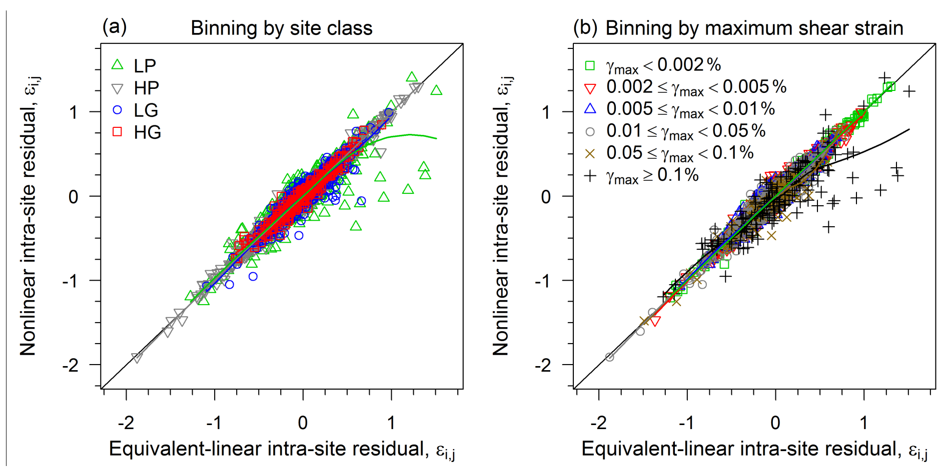

Figure 3. Plots of the nonlinear intra-site residuals versus the equivalent-linear intra-site residuals for pseudo-acceleration response spectra at a vibration period of T = 0.1 s. Records are binned by (a) each site's classification according to the Thompson et al. (2012) taxonomy, and (b) the maximum level of shear strain encountered in the soil profile.

Comparisons of Site Response Model Uncertainties

The output from the mixed-effects regression calculations allows for the quantification of the linear, equivalent-linear, and nonlinear model biases and precisions across all sites and ground motions. Figure 4 displays the each model's bias (μ_Y) and standard deviation (σ_Y) for the pseudo-acceleration response spectra as a function of spectral period T.

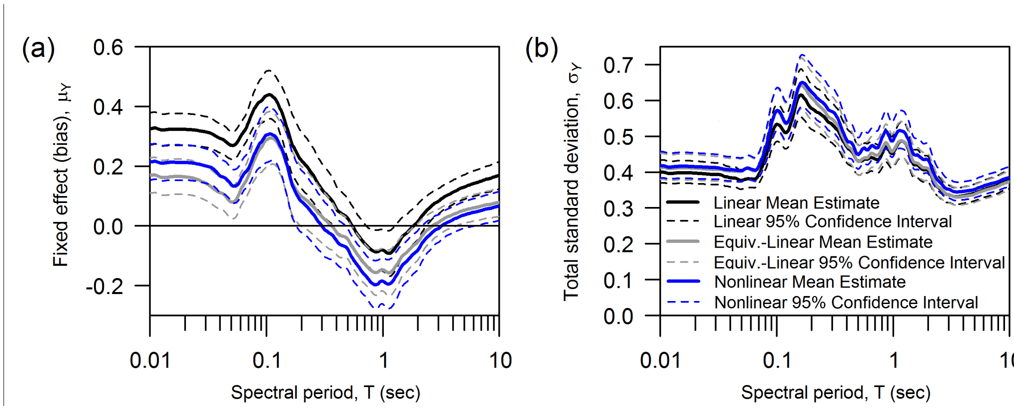

Figure 4. Period dependence of the mixed-effects regression model parameters: (a) bias (fixed effect) $\mu_Y = a$, and (b) total standard deviation $\sigma_Y = \sqrt{\tau_S^2 + \sigma_o^2}$.

As observed in Figure 4, there are more significant differences for the model biases than the model standard deviations (the differences in the model standard deviations shown in Figure 4(b) are not significant between the models). Comparisons of the model biases in Figure 4(a) indicate that all 1D site response models (linear, equivalent-linear, and nonlinear) are biased towards underprediction of ground motions at short spectral periods, where nonlinear effects have the most significant impact. However, the equivalent-linear and nonlinear model biases are smaller than the linear model bias. The persistent model biases suggest that: (1) many of these sites may experience a breakdown in the 1D site-response assumptions; and/or (2) the site investigation data provided on KiK-net (i.e. velocity profile discretization and broad soil type) may be over-simplified. These two effects are coupled and difficult to deconvolve. With respect to the first point, in particular, the underlying assumptions of 1D site response may have to be addressed in order to make notable prediction improvements, perhaps by incorporation of three-dimensional soil constitutive response, lateral stratigraphic variability, and incident ground motion effects. With respect to the second point, the oversimplification of the KiK-net velocity profiles may result in bias at short periods, because the thicknesses of thin soil layers (that are perhaps missed by the KiK-net profile) would not be large enough to affect the response at longer periods.

Conclusions

The results of a comprehensive assessment of one-dimensional (1D) total-stress nonlinear site response predictions indicate that the equivalent-linear and nonlinear site response models generally do not deviate from each other significantly until maximum shear strains of 0.05–0.1%. At larger shear strains, the nonlinear site response model residuals have less scatter and offer less severe underpredictions than the equivalent-linear model. Across all sites and ground motions, the model biases at large strains are strongest for PSA in the 0.1-0.2 s range and for Arias intensity. The largest differences between the equivalent-linear and nonlinear model predictions are generally limited to sites that are poorly characterized by 1D site response. Three-dimensional effects (such as lateral variations in subsurface seismic velocities) can scatter the seismic waves, reducing the effects of downgoing wave interference (Thompson et al., 2009). This net effect on observed ground motions is similar to that of nonlinear soil behavior (i.e., modulus reduction and damping), and perhaps this is why the nonlinear model outperforms the equivalent-linear model at these sites. Even though none of the models in this study explicitly account for three-dimensional effects, the nonlinear model may be inadvertently capturing such behavior by reducing the seismic energy that is transmitted to the surface. Although the nonlinear site response model offers a slight improvement over the equivalent-linear model, the remaining trends in the residuals suggest that other factors—such as breakdowns in the 1D site response assumptions and/or poorly characterized soil properties—have significant impacts on site response behavior.

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