Quantification of uncertainty in nonlinear soil models at a representative seismic array

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ABSTRACT: Vertical seismometer arrays represent a unique interaction between observed and predicted ground motions, and they are especially helpful for validating and comparing soil models for earthquake site response. In this study, we take advantage of the extensive database of ground motions recorded by the Kiban-Kyoshin network (KiK-net) of vertical seismometer arrays in Japan. We perform comprehensive linear-elastic, equivalent-linear, and nonlinear site response analyses of 18 ground motions recorded at a representative site in the KiK-net database (station IWTH08). To model the dynamic ground response, we use the equivalent-linear program SHAKE, the nonlinear program DEEPSOIL, and an overlay-type material model in the finite element software Abaqus/Explicit. We quantify the uncertainties of the alternative site response models, measure the strain levels at which various models break down, and provide recommendations for modeling complex site response and performing site response analyses in engineering practice.

1 INTRODUCTION

For many engineering design projects, a site-specific analysis of earthquake ground-motion amplification is necessary to quantify the seismic hazard. Site response models, which are used to estimate the ground motion at the surface of a site (as a function of the soil profile and the input ground motion), are associated with large uncertainties and have often been found to poorly replicate observed ground motions. During earthquakes, the greatest damage often occurs during large ground motions, which are associated with nonlinear soil behavior. However, the area affected by nonlinear soil behavior for a given earthquake is generally small, thus limiting the number of observations of nonlinear soil behavior for validation of site response models. Recent earthquakes in Japan, including the M9.0 Tohoku earthquake of 11 March 2011, have substantially increased the observations of strong-motion records that can be used to compare alternative site response models at large strains, and these records can subsequently provide insight into the accuracy and precision of site response models.

Vertical seismometer arrays represent a unique interaction between observed and predicted ground motions, and they are especially helpful for validating and comparing site response models. In this study, we take advantage of the extensive database of ground motions recorded by the Kiban-Kyoshin network (KiK-net) of vertical seismometer arrays in Japan. In prior work (Kaklamanos et al. 2013a), we performed linear and equivalent-linear site response analyses at 100 KiK-net sites using 3720 ground motions ranging from weak to strong in amplitude. We analyzed the accuracy (bias) and variability (precision) resulting from common site response modeling assumptions, and we identified critical parameters that significantly contribute to the uncertainty in site response analyses. We focused on linear and equivalent-linear site response analyses because our goal was to identify trends in model performance of widely used site response models using a large database; an assessment of nonlinear time-domain site response models is more computationally intensive and therefore must often focus on a smaller subset of records.

In the present work, we perform comprehensive site response analyses of the weak and strong ground motions recorded at a representative site in the KiK-net database, IWTH08. Using linear-elastic, equivalent-linear, and nonlinear site response codes, we perform analyses of 18 ground motions at this site. The reader is referred to Kaklamanos et al. (2013b) for similar analyses at five additional KiK-net stations. Station IWTH08 was selected because it strongly meets the assumptions of one-dimensional (1D) wave propagation (per the classification scheme of Thompson et al. (2012)), and is therefore ideal for validating and calibrating 1D site response models. We use the equivalent-linear site response program SHAKE, the nonlinear site response program DEEPSOIL, and the finite element software Abaqus/Explicit, which involves explicit time integration and is ideally suited to simulate wave propagation in solid continua. Within Abaqus, we employ an overlay-type material model (Kaklamanos et al. 2013c) that conveniently leads to a multilinear approximation of the stress-strain curve. In this paper, we quantify the prediction accuracies of the alternative site response models, measure the strain levels at which various models break down, and provide recommendations for modeling complex site response and performing site response analyses in engineering practice.

2 DATA

This study focuses on KiK-net site IWTH08, which is a vertical seismic array maintained by the National Research Institute for Earth Science and Disaster Prevention (NIED) in Japan. KiK-net stations have two seismometers: one located at some depth below the ground surface (a "downhole" receiver) and one located at the ground surface. The downhole recording may be used as the "bedrock" input motion to the site-response model, and the surface ground motion is then predicted by the site-response model. The observed surface ground motion can be compared to the predicted surface ground motion to quantify the predictive capability of the site-response model.

Station IWTH08 (Latitude: 40.2658°, Longitude: 141.7867°) is located in Kuji, in Iwate prefecture on northeastern Honshu island. The site consists of 83 m of weathered granite over competent granite, has an average shear-wave velocity of 305 m/s in the upper 30 m, and is a Class D site (stiff soil) according to the National Earthquake Hazards Reduction Program guidelines (BSSC 1998). Due to the low V_S values in the upper 20 m ($V_S \leq 280$ m/s), we assume that the upper 20 m is composed of residual soil. For the bottom 80 m of the profile ($V_S \geq 680$ m/s), the rock material is assumed to exhibit linear stress-strain behavior for all analyses. Figure 1 shows a full shear-wave velocity (V_S) profile for IWTH08, which was obtained from the KiK-net website (NIED 2012). The profile extends to 100 m depth, which is the install depth of the downhole seismometer (where the input motion is applied).

The 18 ground motions used in this study represent the catalog of recordings from 2001 (when the station went online) through mid-2011. As described in Thompson et al. (2012), we require that each record have a minimum signal-to-noise ratio that is greater than five for the 0.5 to 20 Hz passband. This data filtering scheme leaves us with 18 ground motions at IWTH08. Figure 2 is a map of IWTH08 and the 18 earthquake epicenters, which represent a wide range of sources and paths. Further information about the ground motions is available in Kaklamanos et al. (2013b) and Kaklamanos (2012).

3 SITE-RESPONSE METHODS

3.1 *Linear site response*

Linear site response analyses assume a viscoelastic formulation that allows for strain- and frequency-independent damping, while the material response follows the linear-elastic stress-strain curve. The slope of the stress-strain curve is given by the small-strain shear modulus G_{max}, which is related to the layer density and shear-wave velocity by the equation $G_{max} = \rho V_S^2$, where ρ is the density and V_S is the shear-wave velocity of the layer. The viscoelastic damping ratio (ξ) is assumed to be constant throughout the profile, and selected to fit the recorded motions at the site, as explained by Thompson et al. (2012); the assumed value of ξ at IWTH08 is 2.0%.

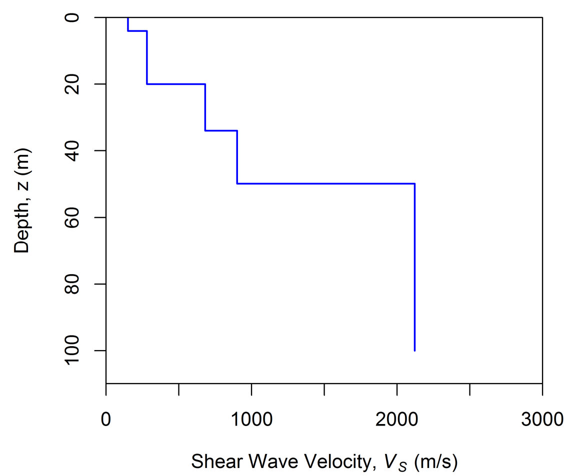

Figure 1. Shear-wave velocity profile at KiK-net station IWTH08.

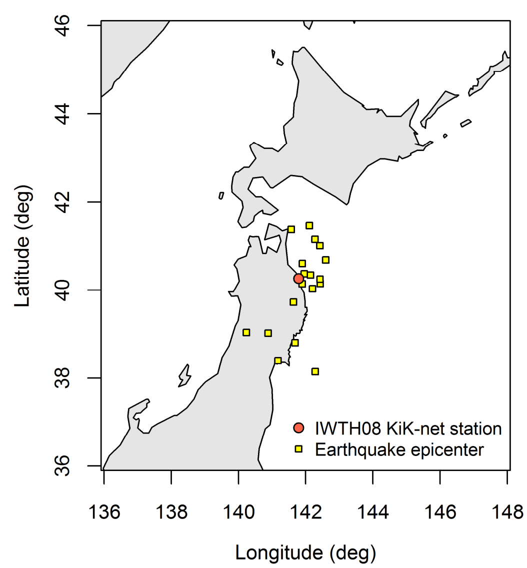

Figure 2. Map of northern Japan, illustrating the location of station IWTH08 and the 18 earthquake epicenters used in this study.

3.2 *Equivalent-linear site response*

To improve site response predictions, the nonlinear strain-dependent behavior of soil should be taken into account. The most frequently employed site response model in engineering practice is the equivalent-linear model, which is coded in the computer program SHAKE (Schnabel et al. 1972, Idriss & Sun 1992, Ordóñez 2010) and offers an approximation of nonlinear behavior. In addition to the basic soil properties required by the linear model (ρ and V_S), SHAKE requires strain-dependent modulus-reduction (G/G_{max}) and damping (ξ) curves. A number of modulus-reduction and damping relationships are available for use in engineering practice; in this study, we use the relationships of Darendeli (2001) and Zhang et al. (2005), and we compare the prediction accuracies of these two models.

3.3 *Nonlinear site response*

By performing fully nonlinear analyses in the time domain, the shear modulus (G) and damping ratio (ξ) are more realistically allowed to vary throughout the duration of loading. In this study, we compare the linear and equivalent-linear model predictions with two nonlinear site response models: (1) the 1D nonlinear site response program DEEPSOIL (Hashash et al. 2011), and (2) a site response overlay model within the general finite element program Abaqus/Explicit (Dassault Systèmes 2009), introduced by Kaklamanos et al. (2013c). Details of the two nonlinear site response models are described in the following subsections.

3.3.1 *DEEPSOIL*

Hashash & Park (2001) and Park & Hashash (2005) found that conventional equivalent-linear models for estimating site response at deep soil profiles were often inaccurate, and they developed the equivalent-linear and nonlinear soil model DEEPSOIL to simulate wave propagation through deep soil deposits. The stress-strain relation used in DEEPSOIL is given by the hyperbolic equation

$$\tau(\gamma) = \frac{G_{\max}\gamma}{1+\beta\left(\frac{\gamma}{\gamma_r}\right)^s}, \tag{1}$$

where τ = shear stress, γ = shear strain, G_{max} = initial shear modulus, γ_r = reference shear strain, and β and s are the model parameters found from calibrations with experimental stress-strain data or specified modulus-reduction curves. In this study, the Zhang et al. (2005) modulus-reduction and damping curves are used as the target curves.

3.3.2 *Overlay model in Abaqus*

Kaklamanos et al. (2013c) presented a methodology for modeling earthquake site response within a general finite element framework, using an overlay model (Nelson and Dorfmann 1995) to represent nonlinear soil behavior. Using parallel load-carrying elements with varying stiffness and yield stress, the behavior of any given backbone stress-strain relation can be replicated. The behavior is consistent with the material model of Iwan (1967) and Mroz (1967), which represented the stress-strain response of a material by using set of elastoplastic springs connected in parallel. Specifically, each element is composed of a linear spring with shear modulus G_i and a Coulomb friction element with yield stress τ_{Yi}, as illustrated in Figure 3. The stress-strain behavior is given by the sum of an elastic and plastic component:

$$\tau(\gamma) = \sum_{i=1}^{n} G_i\gamma + \sum_{i=n+1}^{N}\tau_{Yi}, \tag{2}$$

where the parameters G_i and τ_{Yi} are defined above, n is the number of elements that remain elastic up to a strain level of γ, and N is the total number of elements. In this study, N = 20 overlay elements are used, and the backbone curves corresponding to the Zhang et al. (2005) modulus-reduction curves are used to derive the individual G_i and τ_{Yi}. Further details are provided in Kaklamanos et al. (2013c) and Kaklamanos (2012).

4 RESULTS

4.1 *Quantification of uncertainty*

To quantify the goodness-of-fit of the site response models, we compare the response spectra of the observed surface ground motion, $PSA_{obs}(T)$, to the response spectra of the predicted surface ground motion using the site response model, $PSA_{pred}(T)$, where PSA is the 5%-damped pseudo-acceleration response spectra as a function of spectral period (T). We compute the residual between the observed and

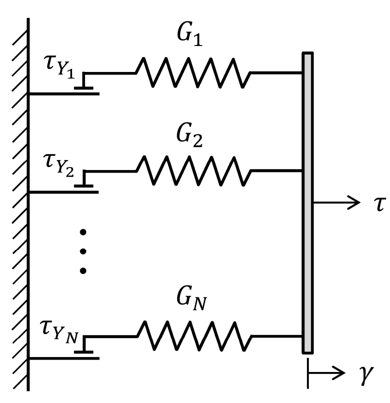

Figure 3. Schematic of the Iwan (1967) and Mroz (1967) material model composed of elastoplastic springs in parallel.

predicted PSA values in natural logarithmic space as

$$PSA_{resid}(T) = \ln[PSA_{obs}(T)] - \ln[PSA_{pred}(T)], \quad (3)$$

where the geometric mean is used to combine the two orthogonal horizontal components of recorded ground motion. At a given site, the individual residuals are represented as

$$PSA_{resid}(T)_i = a + \varepsilon_i, \quad (4)$$

where a is the population mean of $PSA_{resid}(T)$ across all ground motions (the "fixed effect"), and ε_i is the intra-site residual, which represents the deviation for ground-motion observation i from the mean residual at station IWTH08. If multiple sites were to be considered, then Equation 4 could be generalized using a mixed-effects regression model.

4.2 *Analysis of model residuals*

In Figure 4, we display plots of the 18 intra-site residuals (ε_i) for PSA at a spectral period of $T = 0.1$ s, versus the maximum shear strain in the soil profile (γ_{max}) calculated from the site response analyses. In Kaklamanos et al. (2013a), we found that γ_{max} was the most informative critical parameter for site response (having the strongest residual trends), and therefore the model residuals are plotted against γ_{max}. The results are shown for each of the 18 ground motions using seven different site response models: linear analyses in (a) SHAKE, (b) DEEPSOIL, and (c) Abaqus; equivalent-linear analyses in SHAKE using the modulus-reduction and damping curves of (d) Zhang et al. (2005) and (e) Darendeli (2001); and nonlinear analyses in (f) DEEPSOIL and (g) Abaqus with backbone curves derived from the

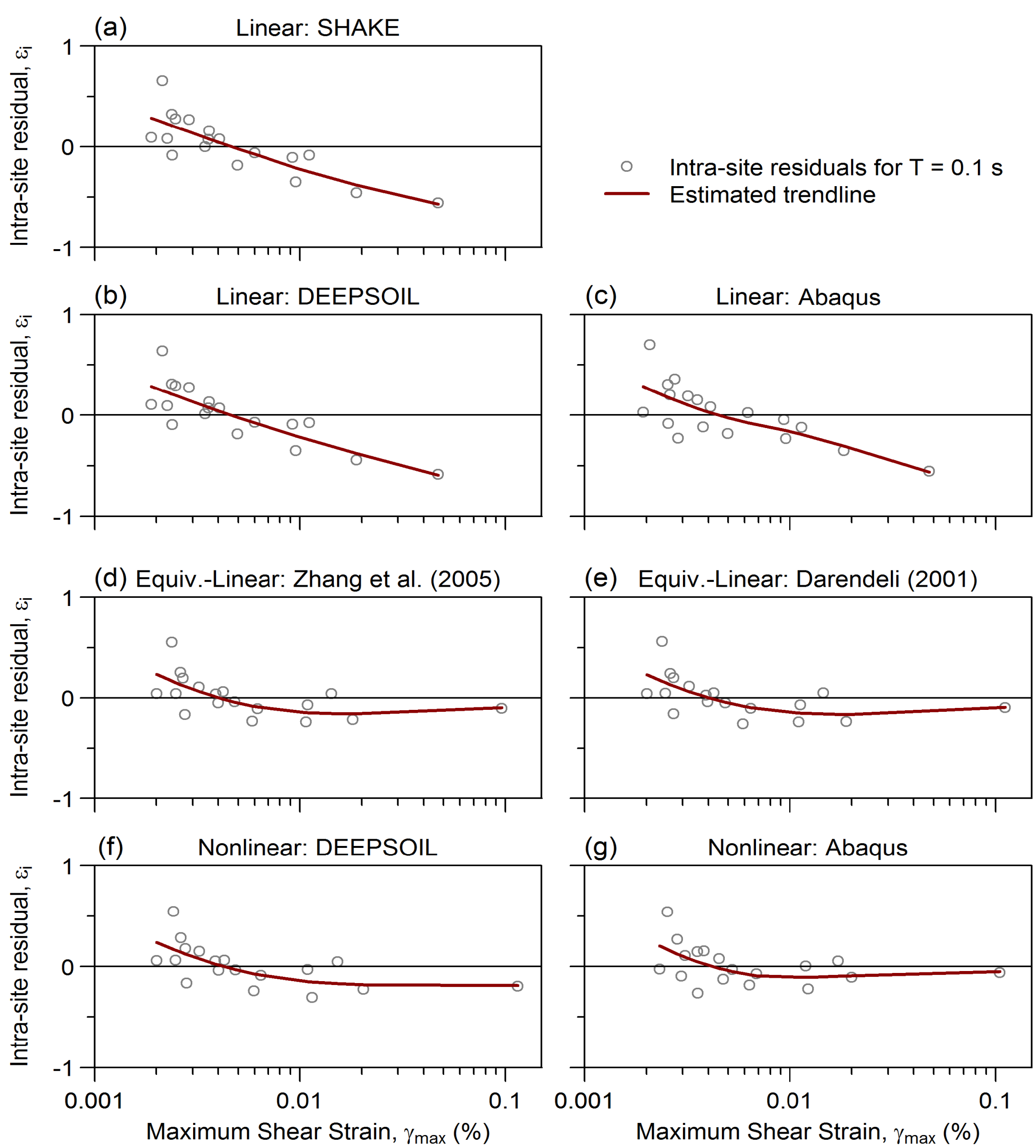

Figure 4. Plots of the intra-site residuals (ε_i) for PSA at a spectral period of $T = 0.1$ s, versus the maximum calculated shear strain in the soil profile (γ_{max}). The results are shown for each of the 18 ground motions using seven different site response models (a-g): linear analyses in (a) SHAKE, (b) DEEPSOIL, and (c) Abaqus; equivalent-linear analyses in SHAKE using the modulus-reduction and damping curves of (d) Zhang et al. (2005) and (e) Darendeli (2001); and nonlinear analyses in (f) DEEPSOIL and (g) Abaqus using backbone curves derived from the Zhang et al. (2005) model.

Zhang et al. (2005) model.

As in Kaklamanos et al. (2013a), the linear site response models are biased at large strains: the residuals display a strong downward slope, characteristic of overprediction of ground motion. This negative trend in the residuals occurs because linear site response models do not capture the deamplification of high-frequency ground motion due to shear stiffness reduction and energy dissipation that occurs when soil deforms nonlinearly (Kaklamanos et al. 2013a). The linear site response residuals begin to deviate from zero at approximately γ_{max} = 0.01%, which is consistent with the results of Kaklamanos et al. (2013a) for T = 0.1 s. Few differences are visible between the three linear site response models (panels a-c). Figures 4d through 4g illustrate that the equivalent-linear and nonlinear site response models are generally better able to accurately predict ground motions at large strains, and they offer a noticeable improvement over the linear site response models. No significant differences between the equivalent-linear residuals and the nonlinear residuals are noticed. Additional plots are necessary in order to decipher the differences between equivalent-linear and nonlinear site response models.

The model performances at additional spectral periods are shown in Figure 5, which displays the intra-site residuals (ε_i) versus γ_{max} for PGA (T = 0), and PSA at spectral periods of 0.1, 0.15, 0.2, 0.3, and 0.5 s, in panels a-f, respectively. Each panel displays the residuals for the linear site response model (from SHAKE), the equivalent-linear site response model (from SHAKE, using the Zhang et al. (2005) modulus-reduction and damping curves), and the nonlinear site response model (from Abaqus); by plotting the alternative models in the same panel, differences between the model predictions are more easily observed. The Zhang et al. (2005) modulus-reduction curves are used to derive the backbone curves and material parameters for the nonlinear site response analyses in this study, because we found the Zhang et al. (2005) curves to be associated with smaller bias than the Darendeli (2001) curves over a broader range of spectral periods. First, for low spectral periods (especially for 0–0.1 s), the linear residuals have a strong downward slope at large strains. The equivalent-linear and nonlinear residuals trend closer to zero at larger strains, indicating an improvement in the model predictions. The spectral period at which the equivalent-linear and nonlinear models show the greatest improvement is 0.3 s, which is near the peak of the site's amplification function (0.36 s). The model performances in this important frequency range are explored further in the next section.

At larger spectral periods (i.e. 0.5 s), the linear, equivalent-linear, and nonlinear site response models do not display significant biases at large strains. This finding is consistent with Kaklamanos et al. (2013a), in which we concluded that site response residuals at spectral periods greater than 0.5 s do not systematically display noticeable effects of nonlinear soil behavior. We expect a decreased effect of nonlinearity at longer periods, because longer-period seismic waves sample a deeper (and stiffer) portion of the profile, and therefore longer-period waves are not as greatly affected by the shallow soft layers that typically experience the greatest nonlinear effects (Kaklamanos et al. 2013a). At spectral periods greater than 0.5 s (not shown in the plots in Figure 5), there was a similar lack of trends in the linear, equivalent-linear, and nonlinear site response models.

4.3 *Detailed study of ground motions*

The residual plots presented thus far are period-specific; each panel represents a slice of the response spectrum at a single spectral period. In such analyses, we lose a large portion of a site's behavior by only considering a single period or a discrete set of periods. In this section, we present figures of detailed results for two ground motions at IWTH08: one weak and one strong ground motion. Due to space limitations, only two ground motions are discussed in detail here; the reader is referred Kaklamanos et al. (2013b) and Kaklamanos (2012) for additional results. Characteristics of the two ground motions are summarized in Table 1. The first record represents a weak ground motion (PGA = 0.04g), and the soil behavior can reasonably be assumed as linear. The stronger second record, with PGA = 0.32g, is characterized by nonlinear soil behavior.

Table 1. Characteristics of ground motions studied at IWTH08.

	Event no. 1	Event no. 2
Date	9/22/2004	7/24/2008
Moment magnitude, M_w	4.8	6.8
Epicentral distance, R (km)	124.6	61.1
Observed downhole PGA (g)	0.0027	0.059
Observed surface PGA (g)	0.0397	0.320
Component	North-South	North-South

In Figure 6, we display comparisons of the predicted ground motions between four site response models: linear frequency-domain (SHAKE), linear time-domain (Abaqus), equivalent-linear (SHAKE), and nonlinear (Abaqus). In Figure 6, the 5%-damped pseudo-acceleration response spectra for the surface ground motions are shown for (a) event 1 and (b) event 2. First, in both panels we see that the linear analyses in the frequency domain (SHAKE) and time domain (Abaqus) display similar predictions, as would be expected, with slight differences due to the frequency-domain and time-domain damping specifications. In Figure 6a, the predicted response spectra for the weak ground motion (event 1) are similar between the four models, because the SHAKE equivalent-linear and Abaqus nonlinear analyses are not predicting a large degree of nonlinear soil behavior. In Figure 6a, all four models slightly underpredict the surface ground motions across most spectral periods. However, for the strong ground motion presented in Figure 6b, there are large differences between the linear, equivalent-linear, and nonlinear site response models. The linear site response models greatly overpredict the level of ground motion, and this overprediction is especially severe at spectral periods in the 0.3–0.4 s range, where the fundamental peak of the linear site response theoretical transfer function is located (0.36 s). At this fundamental peak, the equivalent-linear model is able to improve the prediction (through reduced ground-motion estimates by considering nonlinearity), and the nonlinear overlay model in Abaqus improves the prediction even more. In Figure 6b, the predictions between the equivalent-linear and nonlinear site response models are similar, but the nonlinear overlay model more closely matches the observations. Figure 6 illustrates the importance of considering the period dependence of the results that is not apparent when a single slice of the amplification or response spectrum is analyzed.

5 DISCUSSION

5.1 *Prediction accuracies of site response models*

In this section, we summarize the prediction accuracies of the linear, equivalent-linear, and nonlinear site response models across all 18 ground motions. First, similar to Thompson et al. (2012), Pearson's correlation coefficient (r) is used to compare the observed and predicted amplification spectra. For each site, r is calculated using the pooled amplification spectra from all events, for n = 200 logarithmically spaced frequencies between the first and fourth peak of the site's linear transfer function (which is event-independent). At IWTH08, frequencies between 2.80 and 11.59 Hz are used in the goodness-of-fit calculations; this is the frequency range that will likely dominate the seismic response at this site.

Table 2 displays the correlation coefficients between the observed and predicted amplification spectra using (a) all the ground motions at the site (18 events), and (b) the large ground motions that have a maximum shear strain of at least 0.05% (one event, given as event no. 2 in Table 1). The critical shear strain level is based upon the results of this study, as well as the results of Kaklamanos et al. (2013a), in which we found that linear site response analyses begin to become inaccurate at shear strains between 0.01% and 0.1%; the level of 0.05% is an intermediate value. At first, when all ground

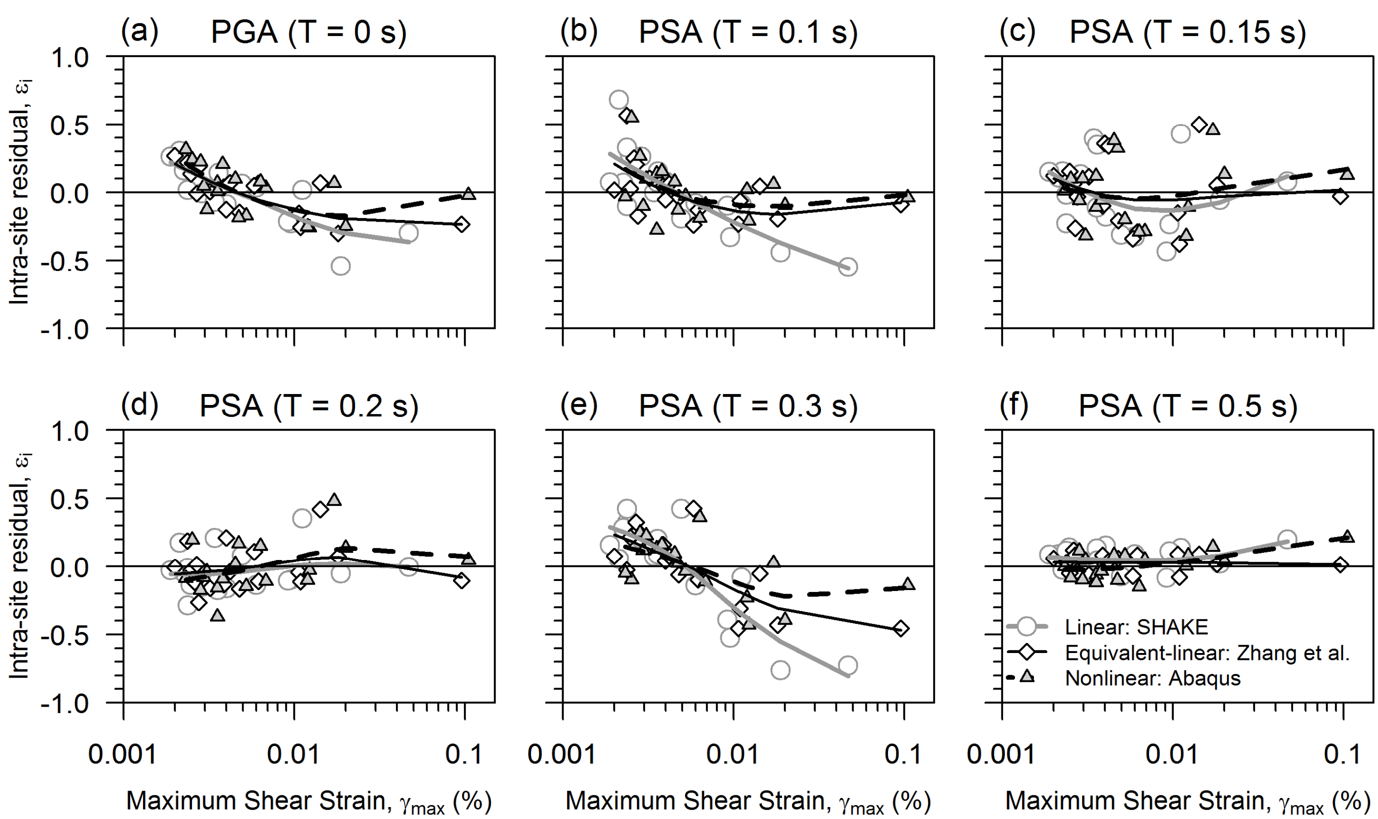

Figure 5. Plots of the intra-site residuals (ε_i) for PSA at six spectral periods (a-f). Each panel displays the residuals for the linear site response model (SHAKE), the equivalent-linear site response model (SHAKE, using the Zhang et al. (2005) modulus-reduction and damping curves), and the nonlinear site response model (Abaqus, using N = 20 overlays and backbone curve derived from Zhang et al. (2005)). The estimated trend line for each residual group is also displayed.

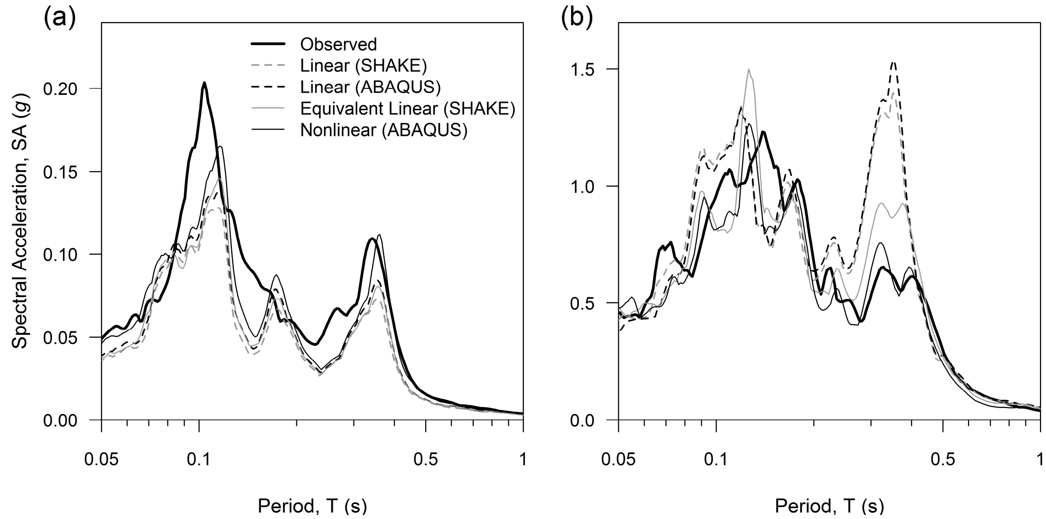

Figure 6. Observed and predicted 5%-damped pseudo-acceleration response spectra for the surface ground motions of (a) event 1 and (b) event 2 at IWTH08; note the differences in scale on the vertical axis.

motions are considered, it may seem surprising that the benefits of the equivalent-linear and nonlinear models are not apparent, but this is because goodness-of-fit calculations in this table are performed for *all* ground motions at each site, including weak motions. In many respects, equivalent-linear and nonlinear models have disadvantages compared to linear models with regards to predicting small-strain ground motions. The equivalent-linear iterative algorithm selects values of G and ξ based upon peak strain, leading to potential misfits for small-strain ground motions. The damping in nonlinear site response models is often poorly constrained at small strains (for example, when Rayleigh damping is used), although the damping formulation in DEEPSOIL offers an improvement. However, the true benefit of equivalent-linear and nonlinear site response models is observed when large-strain ground motions are considered separately. At each site, increases in the values of r are observed when the model type is advanced from linear, to equivalent-linear and nonlinear.

Table 2. Correlation coefficients between observed and predicted amplification spectra.

Model:	All ground motions (18)	Large ground motion (1)
Linear: SHAKE	0.415	0.537
Linear: DEEPSOIL	0.396	0.526
Linear: Abaqus	0.404	0.553
Equivalent-linear (SHAKE): Darendeli (2001)	0.378	0.559
Equivalent-linear (SHAKE): Zhang et al. (2005)	0.379	0.592
Nonlinear: DEEPSOIL	0.383	0.715
Nonlinear: Abaqus	0.396	0.719

5.2 *Onset of nonlinearity*

In Kaklamanos et al. (2013a), we concluded that in terms of γ_{max}, the linear site response model begins to break down (by overpredicting the ground motions) at strains in the range of 0.01% to 0.1%. At shear strains greater than these values, and less than $\gamma_{max} \approx$ 0.1% to 0.4%, the equivalent-linear site response formulation improves the accuracy of site response predictions. We based our conclusions on linear and equivalent-linear analyses in SHAKE, using the Zhang et al. (2005) modulus-reduction and damping curves in the equivalent-linear model. In the present study, these conclusions are supported using the results from additional linear site response models (DEEPSOIL and Abaqus) and equivalent-linear site response models (Darendeli 2001). Equivalent-linear and nonlinear site response models perform similarly across most levels of ground motion, but Figure 6b and Table 2 illustrate that the nonlinear site response models offer an improvement upon equivalent-linear analyses for shear strains beyond 0.05%, especially at the spectral periods of greatest response.

5.3 *1D site response modeling limitations*

The site response models considered in this study all share a common trait: they are 1D total stress analyses. Inherent to a 1D site response analysis, it is assumed (1) that the medium consists of laterally-constant layers overlying a non-attenuating half-space; (2) wavefronts are planar; and (3) only the SH-wave (the horizontally-polarized component of the S wave) is modeled. Furthermore, by adding the total stress assumption, the generation of earthquake-induced pore pressures is not considered. These simplifying assumptions are often reasonable enough to accurately represent the surface ground motion, but as seen in this study and a number of others, there is still plenty of room for improvement. Compounding factors such as basin waves, path effects, soil heterogeneity, nonvertical incidence, and poorly constrained soil properties can greatly reduce the accuracies of 1D site response models (Baise et al. 2011). Although the site in this study was selected because it appears to meet the assumption of 1D wave propagation (compared to other sites in the KiK-net database), it is not a perfect site, and some of these factors are likely apparent to some degree. Although the explicit time-domain modeling of nonlinear soil behavior represents an improvement over linear and equivalent-linear site response models, the modeling of material nonlinearity is just one step towards more accurately modeling complex site response.

6 CONCLUSIONS

In this study, we performed linear, equivalent-linear, and nonlinear site response analyses of 18 ground motions at a representative vertical seismic array. Because we focused on a site that is well-modeled by 1D wave propagation, the observed misfit for strong motions can mostly be attributed to the soil model (and not other factors, such as three-dimensional effects, although the results suggest that these factors are still likely apparent to some degree). Across all ground motions, one of the most consistent findings is that the differences in accuracy are largest between the linear model and the other models, and that there are relatively small differences in accuracy between equivalent-linear and nonlinear site response models. The critical level of maximum shear strain (γ_{max}) at which the linear site response model breaks down is 0.01%–0.1% (with a midpoint of approximately 0.05%), confirming the results of Kaklamanos et al. (2013a). When observed and predicted amplification spectra are compared over a range of spectral periods (instead of at a single period or at a set of discrete periods), nonlinear site response models are shown to exhibit a slight improvement over equivalent-linear site response models for shear strains greater than 0.05%. In engineering practice, however, site response model selection will be determined by the ultimate goal of the site-specific ground motion study, and whether the limitations of frequency-domain modeling are adequate for the problem at hand.

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