Complex Site Response: Does One-Dimensional Site Response Work?

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ABSTRACT

Blind prediction experiments have consistently shown that dynamic soil models rarely reproduce observed behavior. We hypothesize that a common reason for the poor performance of existing site response models is that the standard assumptions (one-dimensional vertically-propagating plane shear waves in layered media (SH1D)) do not adequately represent the complexity of site response behavior in many cases. We use weak motions from vertical seismic arrays to characterize sites in terms of the complexity of the site response. We compare empirical and theoretical SH1D transfer functions at sites from a broad range of geologic environments. We identify complexity from inter-event variability and misfit to the SH1D response. For simple SH1D sites, we examine nonlinear soil behavior. For complex sites, we illustrate how site complexities such as soil profile uncertainty, spatial heterogeneity, and soil nonlinearity can explain the observed deviations from the SH1D model. Through examples drawn from the Kiban-Kyoshin network (KiK-net) in Japan, we identify sites that follow the SH1D assumptions and are therefore ideal for calibrating nonlinear constitutive models in a SH1D framework, as well as sites that are better for investigating complex site effects.

INTRODUCTION

Site effects have been recognized as an important component of earthquake hazard studies for several decades (Borcherdt, 1970). Early observations of site effects were related to correlations of observed damage patterns to mapped surficial geology (Borcherdt and Gibbs, 1976; Boatwright et al., 1991; Hanks and Brady, 1991). Subsequent quantitative studies of site response used reference rock and soil sites to identify site effects and validate site response models (Johnson and Silva, 1981; Seale and Archuleta, 1989; Archuleta et al., 1992), but only a few strong-motion station rock/soil pairs were available. Reference rock sites were then shown to be problematic as the surface rock site often exhibited site response of its own and did not adequately represent the incoming wavefield for the soil (Steidl et al., 1996; Boore and Joyner, 1997; Abercrombie, 1998; Baise et al., 2003a,b). Vertical seismic arrays and subsequent occurrences of large earthquakes have substantially increased the observations that are available to constrain the seismic response of the near surface materials because the incident wavefield is more directly observed.

Our research has focused on using observed ground motion records in vertical seismic arrays to study site effects. Our approach has been to focus on the weak motions first in order to constrain the linear behavior so as not to confound complexities in the wave propagation (e.g., basin waves, heterogeneity, path effects) with the nonlinear soil behavior. Once the linear site response is constrained (by identifying whether the site can be modeled by the common SH1D assumptions), we address the more complex effects such as nonlinear soil behavior. If the SH1D assumption does not hold, we must model site response by broadening the theoretical formulation to account for additional effects (e.g., soil heterogeneity, basin effects, poorly constrained soil properties). In this paper, we provide an overview of our recent work using vertical seismic arrays to identify site effects through observation. We develop a classification system to determine when site response is simple or complex. Using the simple sites (those that are well-modeled by SH1D and have low inter-event variability), we examine the effect of soil nonlinearity and the SH1D formulation on prediction accuracy. Using the complex sites, we begin to look at causes of site response complexity, including non-vertical incidence of the incoming wave, soil property uncertainty, and soil heterogeneity. Further details of this work can be found in Thompson et al. (2009), Kaklamanos et al. (2011), Thompson et al. (2011), and Kaklamanos et al. (2012).

DATA

This work takes advantage of the large network of vertical seismic arrays developed by Japan after the 1995 Hyogo-ken Nanbu earthquake. The KiK-Net strong-motion network in Japan provides numerous surface-downhole station pairs that have recorded many earthquakes over a wide range of magnitudes and peak ground accelerations (Aoi et al., 2000; Okada et al., 2004). The KiK-Net web site provides the velocity structure measured from downhole logging at each site in the KiK-Net network. While other vertical seismic arrays may be better characterized (e.g. Lotung, Garner Valley, Wildlife), the KiK-Net network allows us to evaluate site response over a larger range of site conditions and therefore draw conclusions about site response more broadly.

METHODS

Site response is a relative quantity and thus requires a pair of ground motions, one of which contains the effects of the near-surface soils and one that does not. The record without the effects of the soil is termed the "input" time series, and the receiver is either located at some depth below the free surface (i.e., a "downhole" receiver), or on outcropping bedrock. The "output" motion includes the effects of soil, so it is located either above a downhole input motion, or on soil near the outcrop motion. Site response is often represented as an input/output transfer function, and we refer to estimates of the site response transfer function derived from recordings of ground motions as the empirical transfer function (ETF). The ETF can be compared to theoretical predictions of the transfer function (TTF) based on in situ estimates of the seismic properties of the soil and a physical/mechanical model for wave propagation between the two points. The transfer function (empirical or theoretical) shows how the soil amplifies and attenuates seismic waves as a function of the frequency of the loading, f. Thus, it is convenient to visualize the transfer function in the frequency domain.

A transfer function $H(f)$ may be written in simple mathematical form by

$$H(f) = \frac{U_{surface}(f)}{U_{downhole}(f)},$$ (1)

where $U_{surface}(f)$ is the Fourier series representation of the ground motion time series at the surface, and $U_{downhole}(f)$ is the Fourier series representation of the downhole ground motion time series. The transfer function $H(f)$ may be written for various ground response parameters, such as displacement, velocity, acceleration, or shear stress. We estimate the ETF from two acceleration time histories at the same site: one recorded at the surface, and the other recorded downhole. We use recordings from multiple earthquakes, and as the number of surface/downhole pairs of records at a site increases, we can obtain stable estimates of the median empirical transfer function and its confidence intervals (Aki and Richards, 2002). We use a minimum of 10 earthquakes to estimate the ETF at a site.

At a particular site, we evaluate the accuracy of site response models by comparing the theoretical amplifications of the TTF to the empirically-derived ETF. The most common assumptions for computing a theoretical transfer function include: (1) the medium is assumed to consist of laterally-constant layers overlying a non-attenuating halfspace; (2) wavefronts are assumed to be planar; and (3) only the horizontally-polarized component of the S wave (the SH wave) is modeled. We refer to these collective assumptions as the SH1D site response model. We compute the SH1D site response transfer function for linear wave propagation with the Thomson-Haskell matrix method (Thomson, 1950; Haskell, 1953). The SH1D input parameters are the S-wave velocity (V_S), density (ρ), and the intrinsic attenuation of S waves ($^iQ_s^{-1}$). Since we do not have in situ estimates of ρ, we use the procedure recommended by Boore (2007) for estimating ρ from the P-wave velocity (V_P), where V_P is reported by the surface-source downhole-receiver survey. In implementing the SH1D model, we assign V_S and ρ of the non-attenuating halfspace to be the values of the deepest measured layer to avoid spurious amplifications from an arbitrary impedance contrast at the bottom of the borehole.

When the SH1D assumptions are appropriate, we investigate the accuracy of equivalent linear and nonlinear site response formulations using the one-dimensional site response programs SHAKE (Schnabel et al., 1972; Idriss and Sun, 1992), DEEPSOIL (Hashash and Park, 2001, 2002; Park and Hashash, 2004), and D-MOD (Matasovic, 2006). The details of our methodology can be found in Kaklamanos et al., 2012.

RESULTS

When studying site response, there are many different issues that lead to complexities in the observed site response (e.g., precision of soil properties, non-vertical incidence, soil heterogeneity, surface waves and basin effects, and topographic effects). In order to study these effects individually, we need to be able to identify which sites are affected by which effects. We have developed a site classification taxonomy that uses inter-event variability and SH1D goodness-of-fit to group sites into four categories. Once grouped, the sites can be used to study individual and/or confounding site effects.

<u>Site classification taxonomy</u>

To develop our preliminary classification system, we started with 78 KiK-net stations having at least one ground-motion record for which the peak ground acceleration (*PGA*) exceeds 0.3*g*. Using these 78 stations, we found 2,551 total ground-motion records from 1,038 total earthquakes, illustrated in Fig. 1. From these 78 stations, we selected 74 stations that meet the following data selection criteria:

- The station must have 10 or more "linear events" to develop the empirical transfer function (ETF). We define "linear events" as events having an input *PGA* less than 0.1*g*. In addition, the signal-to-noise ratio must be at least 5, for the *f* = 0.5 to 20 Hz frequency passband.
- The station must have a geophysical survey in order to develop the theoretical transfer function (TTF).

Using these 74 stations and the suite of ground-motion records, we develop a methodology using two key criteria: (1) *inter-event variability* and (2) *goodness-of-fit between the ETF and TTF*.
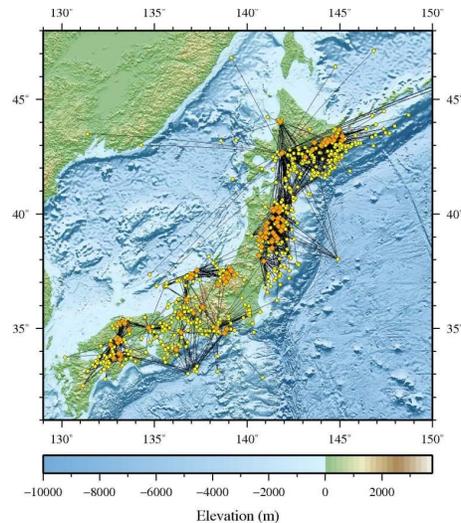
Fig. 1. Map of stations and earthquakes used to develop site classification taxonomy.

First, the inter-event variability quantifies the consistency of a site's empirical transfer function from event to event. Since we only use the linear events to estimate the inter-event variability, this measure is independent of the nonlinear soil behavior, and high inter-event variability most likely results from source or path effects. Our measure is the standard deviation (σ_i) of the ETF in natural logarithmic space ($\sigma_{\ln}$). Here, we only consider the ETF in the *f* = 0.5 to 5 Hz passband. The passband used for computing σ_i is refined in Thompson et al. (2011).

To classify the stations in terms of inter-event variability, we need a threshold value. In this study, we have selected a threshold of σ_i = 0.15 for differentiating between sites with high and low inter-event variability. In Thompson et al. (2011), we have increased this threshold after changing the passband considered for σ_i and also adding additional sites that recorded large ground motions from the Tohoku earthquake. Figure 2 compares the empirical transfer functions for two sites, (a) one with high inter-event variability, and (b) one with low inter-event variability. The median ETF and the 95% confidence band are shown for each site. Our hypothesis is that when the site ETF is consistent over several sources and paths (low σ_i), the site is well-behaved and the site response is dependent on the local soil profile. When the inter-event variability is high, the ETF is changing depending on variations in the source and/or path, or there is a source of noise that is leading to inaccurate estimates of the ETF. When the focus is on the local site response behavior, low inter-event variability is preferred, as it signifies consistent behavior from earthquake to earthquake.

Second, the goodness-of-fit between the ETF and the TTF (using the SH1D formulation) is quantified using Pearson's correlation coefficient (*r*). The primary concern is the alignment of the resonances, particularly the peaks of the first few fundamental modes. We use logarithmically-spaced samples from the first to last peak in the *f* = 0 to 20 Hz passband. To differentiate between sites with good and poor fit between the ETF and TTF, we currently use a threshold of *r* = 0.6. Figure 3 compares the transfer functions for two sites, (a) one with good fit between the ETF and TTF, and (b) one with poor fit between the ETF and TTF. In this example, the ETF and TTF at site IWTH04 share the same peaks, and the TTF is almost entirely within the 95% confidence band for the ETF. On the other hand, the TTF at site IWTH12 has a clear first peak below 2 Hz that is not evident in the ETF. Using the results presented in

Thompson et al. (2009), our preliminary interpretation of the misfit at IWTH12 is that spatial heterogeneity in the subsurface may be causing scattering of the downgoing wave, which smoothes the ETF.
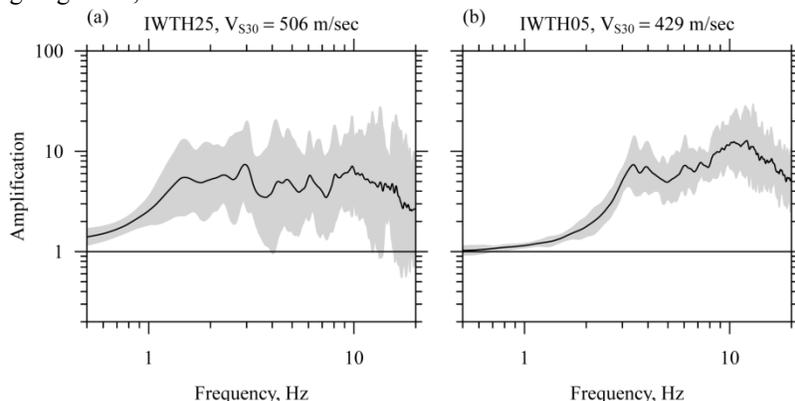
Fig. 2. The ETF at two stations, illustrating inter-event variability: (a) IWTH25 is characteristic of a site with a large degree of inter-event variability, and (b) IWTH05 is characteristic of a site with low inter-event variability. The median prediction of the ETF is shown as a black line, and the 95% confidence band is shown in gray.
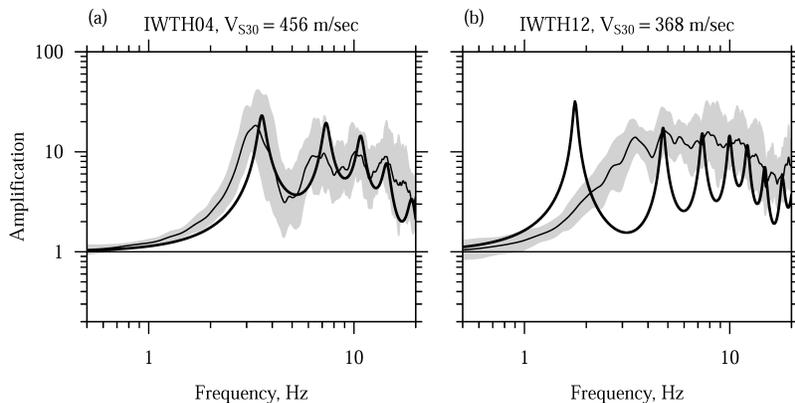
Fig. 3. The ETF and TTF at two stations, illustrating goodness-of-fit: (a) IWTH04 is characteristic of a site where the SH1D model accurately predicts the ETF, and (b) IWTH12 is characteristic of a site where the SH1D model poorly predicts the ETF.

To clearly and succinctly communicate the classification of a site, our preliminary classification scheme involves two letters: the first letter indicates the inter-event variability class (H for "high" and L for "low"), while the second letter indicates the fit to the SH1D model (G for "good" and P for "poor"). Thus, all sites are separated into four distinct categories: LG, LP, HG, and HP.

- LG sites have low σ_i and good fit to SH1D. These sites are ideal for calibration and validation of one-dimensional constitutive models where the focus can be on modeling the soil nonlinearity.
- LP sites have low σ_i and poor fit to SH1D. These sites are appropriate for evaluating site effects where the focus is on determining the cause of misfit to SH1D (i.e., precision of soil properties, non-vertical incidence, soil heterogeneity).
- HG sites have a high σ_i and a good fit to SH1D. These sites can be used with SH1D formulations but care should be taken to determine if the high inter-event variability (e.g., noise at the site; path effects) significantly influence the results.
- HP sites have high σ_i and a poor fit to the SH1D. These sites are the most complex as they exhibit high inter-event variability (i.e. site noise, source and/or path effects) and poor fit to the SH1D formulation. These should be left to the most ambitious site response modeler.

In order to demonstrate the variation of site conditions represented in this dataset, Fig. 4 shows the inter-event variability (a) and the goodness-of-fit (b) plotted against V_{S30}. Out of 74 sites used in this study, only six are LG sites, five are HG sites, and the majority is split between LP (26) and HP (37). This classification alone begins to explain why site response has been so difficult to predict historically. Only 15% appear to adequately follow the SH1D assumption. As we will show, the site response at many LP sites can be predicted with minor changes to the SH1D assumptions. It is also important to remember that these results use only weak motions and are not confounded by nonlinear effects. Table 1 provides a summary of the LG sites identified in this study. The site conditions for the LG sites vary from deep soil sites (e.g., station NMRH04 [V_{S30} = 168 m/s], with 185 m of Quaternary sand and gravel), to rock sites such as IWTH27 (V_{S30} = 670 m/s) and MYGH11 (V_{S30} = 859 m/s), which are composed of less than 10 m of granular fill

overlying bedrock. The five HG sites are also worth examining in future work, as they are all from soil sites ($V_{S30} < 500$ m/s) and the high inter-event variability may not confound the site response.
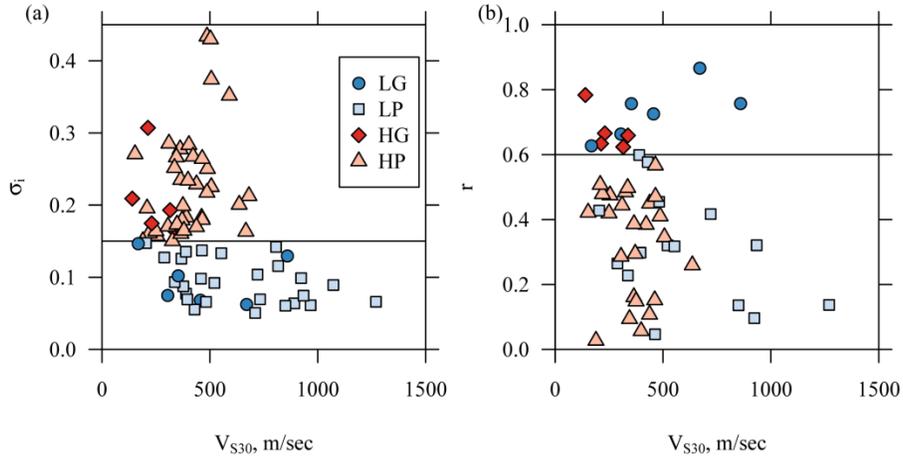
Fig. 4. *Summary plot of site classification versus V_{S30}, showing (a) the inter-event variability (σ_i), and (b) the fit to SH1D (r).*

Table 1. LG sites in the KiK-Net Array

Station	V_{S30} (m/s)	Characteristics of nonlinear event					
		Date	Time	Magnitude	Depth (km)	PGA^D (g)	PGA^S (g)
IWTH04	456	2003/05/26	18:24:00	7.0	71	0.154	1.305
IWTH08	305	2008/07/24	00:26:00	6.8	108	0.059	0.392
IWTH27	670	2003/05/26	18:24:00	7.0	71	0.170	0.905
MYGH11	859	2005/08/16	11:46:00	7.2	42	0.105	0.471
NMRH04	168	2003/09/26	04:50:00	8.0	42	0.156	0.446
TKCH08	353	2003/09/26	04:50:00	8.0	42	0.130	0.509

Figure 5 shows an example LG site (TKCH05) that we will use to compare SH1D formulations for nonlinear soil behavior, and two LP sites that illustrate different types of misfit to the SH1D TTF. In Fig. 5, the misfit at ISKH02 results from a misalignment of the peaks (but the general shape of the ETF is correct), and the misfit at TKCH05 results from an absence of the initial peak in the ETF.
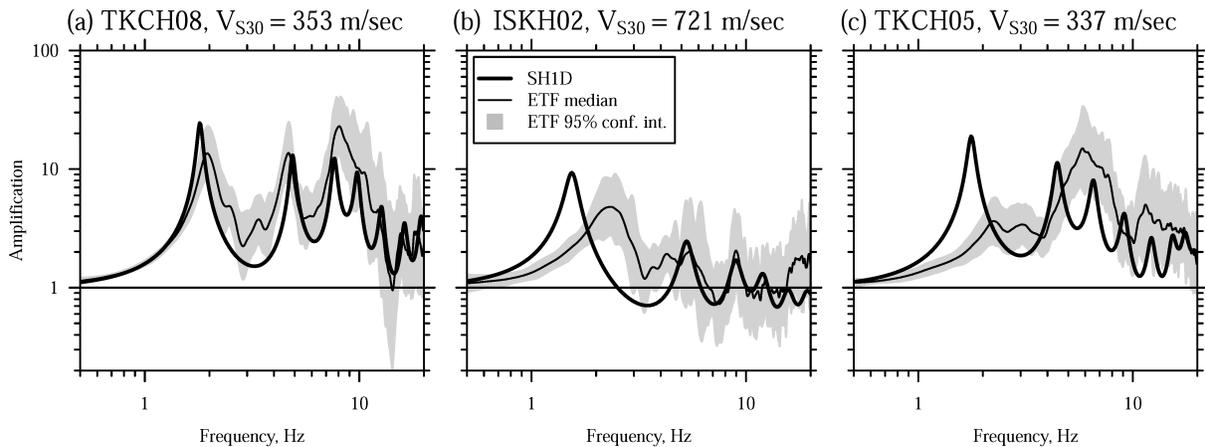
Fig. 5. *Example the ETF and SH1D amplifications at LG and LP sites: a) TKCH08, an LG site; b) ISKH02, an LP site where the misfit is in the alignment of the peaks; and c) TKCH05, an LP site where the misfit is in the absence of the first peak.*

Using sites that are categorized as LG (sites where the SH1D assumptions hold), we can take a closer look at the dependence on the SH1D formulation including various assumptions on soil properties, and the effect of soil nonlinearity on the observed site effect (ETF).

Dependence on SH1D formulation. For six LG sites shown in Table 1, we performed one-dimensional site response analyses using a suite of linear and nonlinear earthquake records, including the events shown in Table 1. We performed the calculations using the "pure linear" SH1D approach; equivalent-linear analyses in SHAKE; and nonlinear time-domain analyses using the programs D-MOD and DEEPSOIL. Within SHAKE, we tested several modulus reduction and damping curves to represent the nonlinearity of the soil: Seed and Idriss, 1970 (SI70); Vucetic and Dobry, 1991 (VD91); EPRI, 1993 (EPRI93); Ishibashi and Zhang, 1993 (IZ93); Darendeli, 2001 (D01); and Zhang et al., 2005 (ZAJ05). The results for the nonlinear event at TKCH08 are illustrated as an example in Fig. 6, where we plot (a) observed versus predicted surface/downhole amplification, and (b) logarithmic residuals of 5%-damped pseudo-absolute response spectral acceleration (PSA), as a function of loading frequency. The Zhang et al. (2005) curves have the strongest goodness-of-fit over the frequency range of interest, and thus we select these relationships for further equivalent-linear analyses in SHAKE. In Fig. 7, we compare the amplification functions and ratios of observed spectral acceleration to predicted acceleration at site TKCH08 for the three site response programs and the linear SH1D formulation. At TKCH08, the nonlinear and equivalent linear programs better capture the shape of the site response amplification program than the linear SH1D. Next, we do a more thorough calculation with events at all six LG sites.
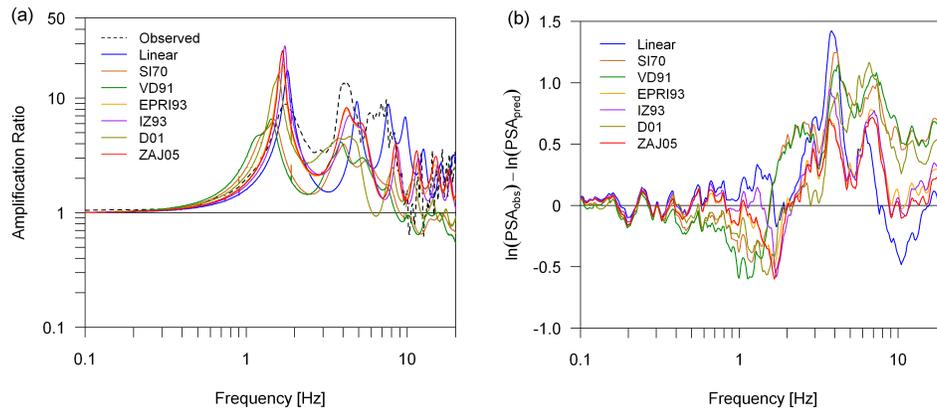
Fig. 6. Effect of modulus reduction and damping relationship on the goodness-of-fit of ground-motion predictions using the equivalent-linear site response program SHAKE: (a) observed versus predicted surface/downhole amplification, and (b) logarithmic residuals of 5%-damped pseudo-absolute response spectral acceleration (PSA), as a function of loading frequency.
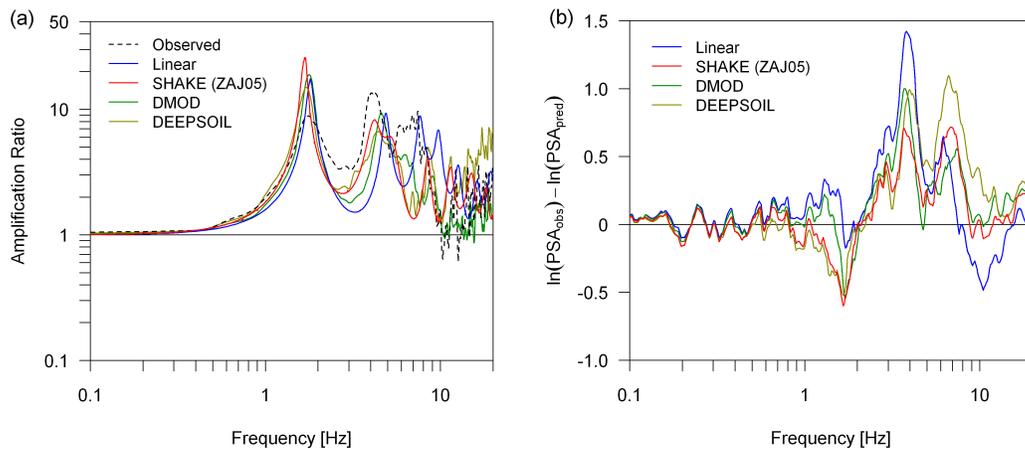
Fig. 7. Effect of site response code on the goodness-of-fit of ground-motion predictions using a pure linear analysis, equivalent-linear analysis in SHAKE, and nonlinear time-domain analyses in D-MOD and DEEPSOIL: (a) observed versus predicted surface/downhole amplification, and (b) logarithmic residuals of PSA, as a function of loading frequency.
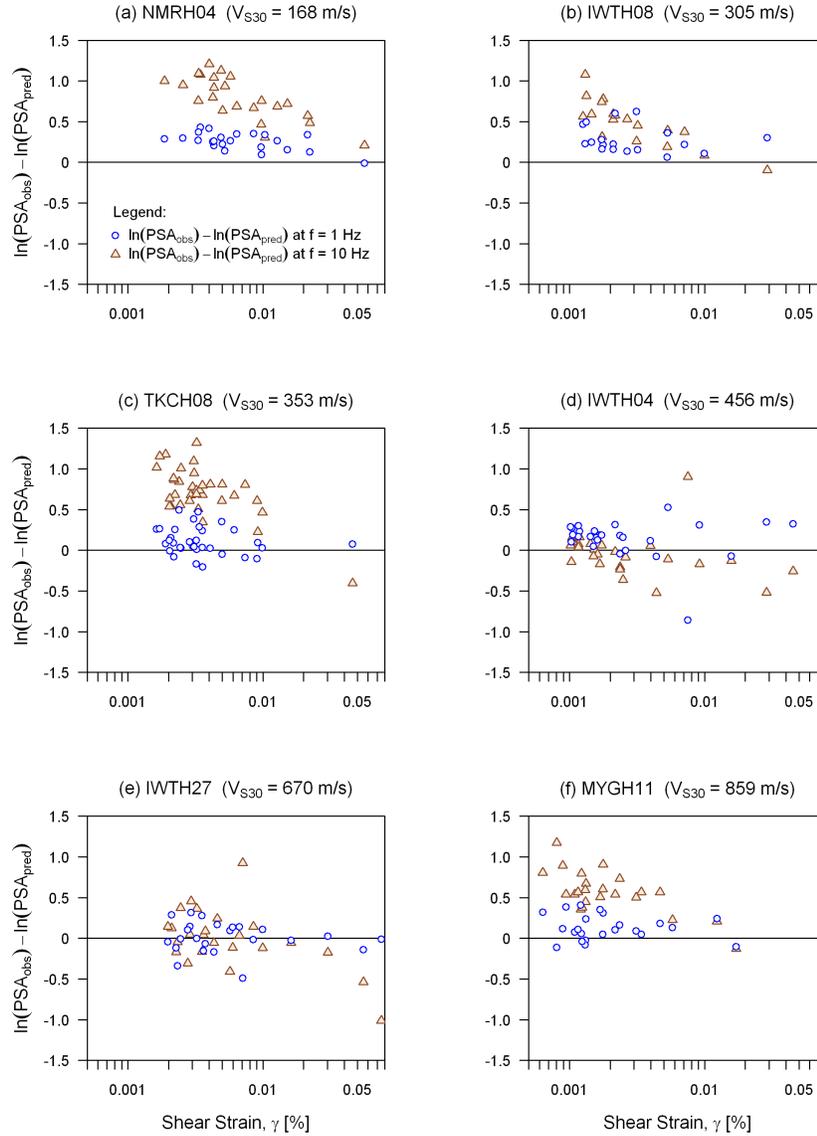
Fig. 8. *Goodness-of-fit of* <u>*linear*</u> *site response analyses for all events at the six LG sites: logarithmic residuals of PSA (at frequencies of 1 and 10 Hz) plotted against the calculated shear strain from the site response analysis. Each event is represented by two data points (one at 1 Hz and the other at 10 Hz).*

<u>Soil nonlinearity.</u> To study the effect of soil nonlinearity, we plot the logarithmic residual of spectral acceleration (PSA) against shear strain for each site using the linear SH1D formulation. The results for loading frequencies of 1 Hz and 10 Hz are shown in Fig. 8. We would expect that goodness-of-fit would decrease when soil nonlinearity starts to cause a misfit between linear TTF and the ETF; i.e., as strain increases, the goodness-of-fit plot should slope downwards. From this analysis, nonlinearity is evident at all six sites at $f = 10$ Hz and to a lesser extent at $f = 1$ Hz. The less stiff sites ($V_{S30} < 400$ m/s) show more pronounced nonlinear behavior, although the shallow soil site (MYGH11) displays a noticeable degree of nonlinearity.

Using the linear SH1D formulation, ground motions tend to be underpredicted at several of the sites (as evidenced by the positive residuals in Fig. 8). This bias can be explained by the nature of the TTF-ETF misfit: for a given site, the peaks of the TTF are often larger and sharper than the peaks of the ETF; however, between the peaks, the TTF often plots below the ETF, resulting in underpredictions across these frequency ranges (for example, consider the TTF and ETF of TKCH08 shown in Fig. 5a, compared to the residuals at $f = 1$ Hz [little bias] and $f = 10$ Hz [large bias] shown in Fig. 8c). However, as nonlinear effects begin to dominate at larger strains, the linear SH1D model tends to overpredict the ground motion, and the net result is a decrease in bias. This demonstrates how these two effects (TTF-ETF misfit versus SH1D model limitations) can be confounding for large ground motions.
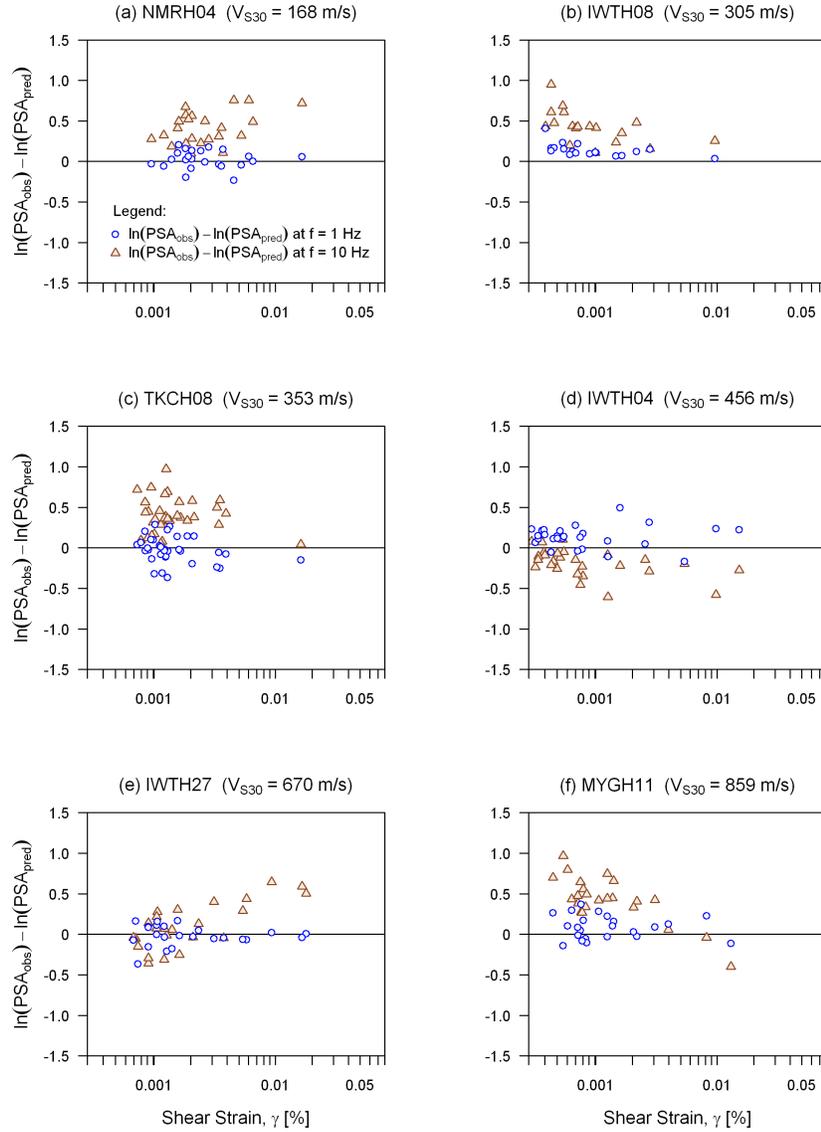
Fig. 9. Goodness-of-fit of <u>equivalent-linear</u> site response analyses for all events at the six LG sites: logarithmic residuals of PSA (at frequencies of 1 and 10 Hz) plotted against the calculated shear strain from the site response analysis. The calculations are performed using SHAKE with the Zhang et al. (2005) modulus reduction and damping relationships.

In Fig. 9, we make the same plot as in Fig. 8, except using an equivalent-linear analysis in SHAKE with the Zhang et al. (2005) modulus reduction and damping relationships. We notice some significant differences from the previous plot. First, the range of residuals is narrower and is more centered near zero (especially for f = 1 Hz), illustrating a decrease in bias with the equivalent-linear site response formulation. Because these plots are generally flat with increasing strain, the equivalent-linear model of SHAKE is better than the linear SH1D model at capturing the nonlinear behavior at these LG sites. Further results using nonlinear time domain analyses with alternative constitutive models are discussed in Kaklamanos et al. (2012).

One site of interest, however, is MYGH11, which is composed of a 3 m layer of granular fill overlying granite bedrock. Based on the value of V_{S30} alone, we would not expect a large degree of nonlinearity at this site, but the negative slope in the residual patterns indicates that there is some nonlinearity that is not being captured by SH1D or SHAKE. The effects of the resonances of trapped seismic waves within this shallow layer may be underpredicted by the site response models. Further work will allow us to better identify why this stiff site displays such a large degree of nonlinearity.

When SH1D does not hold (LP sites)

Using sites that are categorized as LP sites (sites where inter-event variability is low but SH1D assumptions do not hold), we can take a closer look at the effect of the precision of soil properties, non-vertical incidence, soil heterogeneity, surface waves, basin effects and topographic effects. Because of space constraints and since this is an on-going project, we will only discuss precision of soil properties, non-vertical incidence, and soil heterogeneity in this paper.

Precision of soil properties. For an LP site, the misfit to the SH1D can be caused by a variety of effects. The soil profiles in the KiK-net array are interpreted and may have some level of error or uncertainty. The methodology for creating the velocity profiles posted on the KiK-net website is not well-documented, and previous researchers (e.g., Assimaki et al., 2006) have chosen to vary the soil profiles from the "measured values" to improve fit. In order to address this, we chose an LP site (ISKH02, shown in Fig. 5) that had the correct shape but had a misalignment of the primary peaks. For ISKH02, we vary the profile parameters to evaluate whether an improvement in fit can be made through optimizing the soil parameters alone (within the SH1D framework). In Fig. 10a, we vary the incidence angle from vertical to 31 degrees to improve the fit of the first peak. In Fig. 10b, we vary the velocity and attenuation in the bottom layer only and in Fig. 10c, we allow more variation the velocities across the entire profile. The results, as illustrated in Fig. 10 with the adjusted profiles shown in Fig. 11d, show that the TTF peaks can be shifted by varying the soil profile parameters within realistic ranges (illustrating the nonuniqueness of the problem). In this case, the SH1D formulation holds, with an optimized velocity profile.
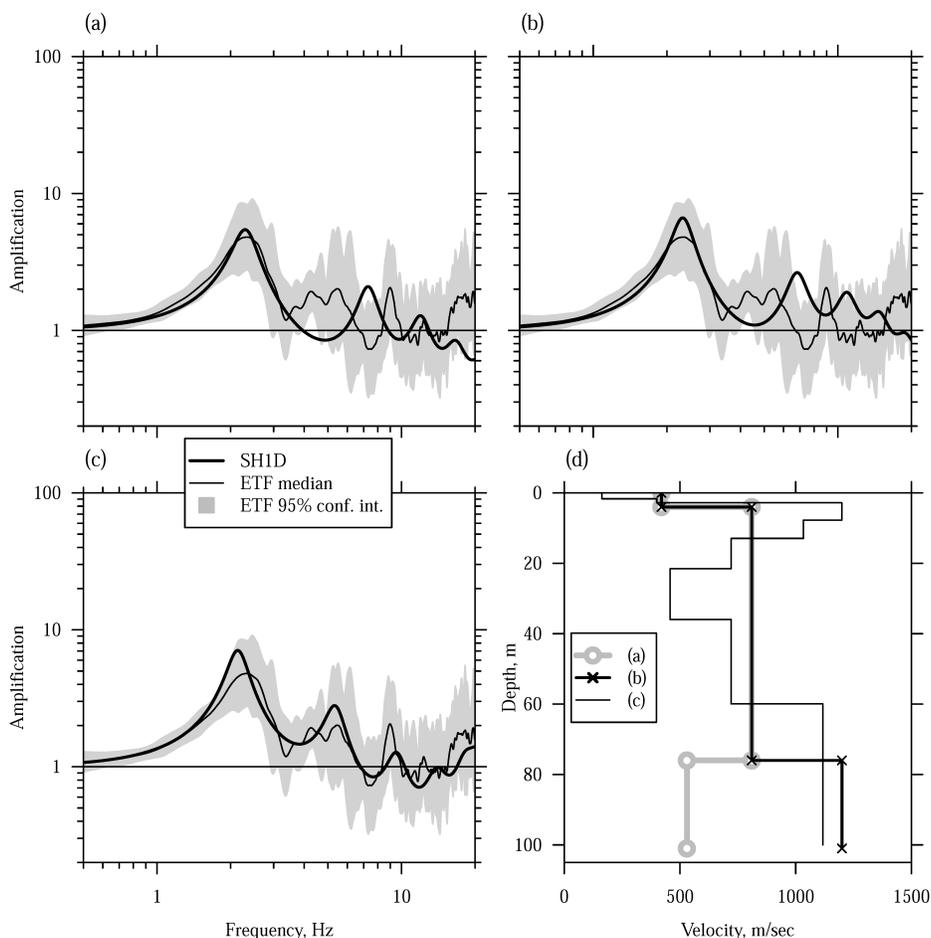
Fig. 10. Optimization of the soil profile to match the ETF at ISKH02: (a) original velocities and varying incidence angle from vertical to 31 degrees from vertical, (b) changing velocity in base layer, (c) allowing velocities to vary in entire profile and optimizing with a genetic algorithm, and (d) adjusted profiles for the three cases.

Non-vertical incidence and attenuation. In Fig 10a, we demonstrated how non-vertical incidence and attenuation can improve a site from a LP to a LG site. However, in some cases, the misfit cannot be reduced significantly with these techniques. In Thompson et al. (2009), we identified OKYH07 (a LP site) in the KiK-net array that demonstrated a misfit to SH1D that could not be improved by altering the soil properties or allowing for non-vertical incidence. Figure 11 shows the results at OKYH07 when we varied attenuation and incidence angle. Even with these variations, the ETF did not contain the peaks in the TTF that result from the downgoing wave effect.
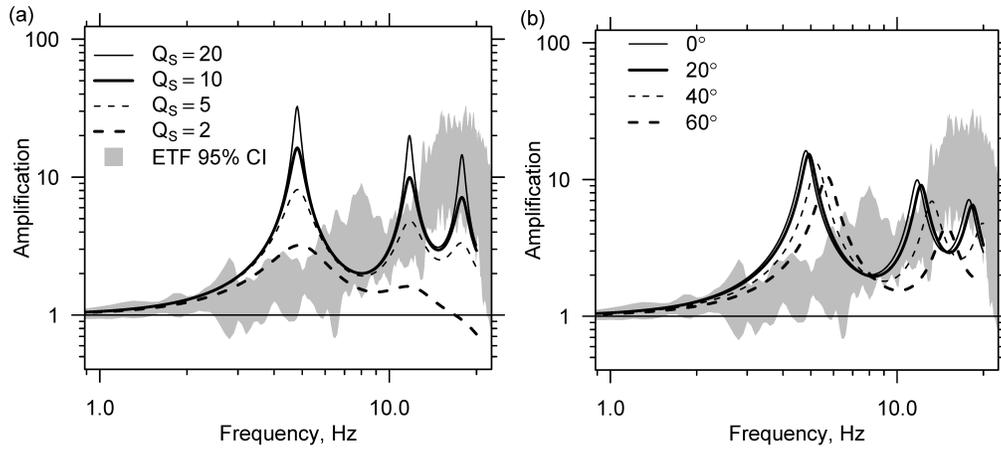
Fig. 11. Transfer functions at LP site OKYH07: varying (a) attenuation, and b) incidence angle, to try to achieve a better fit of the TTF to the ETF.

Soil heterogeneity. In Thompson et al. (2009), our hypothesis was that the downgoing wave was scattered by a heterogeneous soil body. In that work, we demonstrated that by allowing the soil properties to vary spatially, we could simulate scattering and produce a TTF that resembled the observed ETF at the site. Figure 12 shows the SH1D TTF versus the ETF at OKYH07 versus the 95% confidence interval for 25 calculated TTFs through a heterogeneous media (using finite difference calculations; see Thompson et al. [2009] for details).
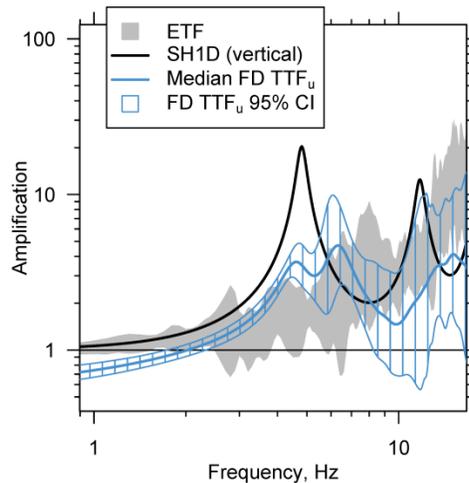
Fig. 12. Original TTF (SH1D), ETF, and the 95% confidence interval for 25 TTFs calculated using a finite difference (FD) scheme through a heterogeneous media at OKYH07

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CONCLUSION

In this paper, we used both weak and strong motions recorded at vertical seismic arrays to study site response. Our focus here was to identify sites where SH1D behavior could be confirmed with weak motions and use those sites to evaluate the accuracy of nonlinear soil response models. Our results show that the linear SH1D model is often unable to capture nonlinear soil behavior for a wide range of geologic site conditions. The use of more advanced models (such as the equivalent-linear representation of nonlinear site response in SHAKE) often results in an increase in the goodness-of-fit. Next, when SH1D behavior could not be confirmed with weak motions, we set out to identify what site behavior was causing the misfit. Using examples from the KiK-net array, we identified sites where the misfit could be reduced with changes in incidence angle or alteration to the velocity and attenuation profile. We also identified sites where soil profile changes could not improve the misfit within a SH1D formulation. At one of these sites, we demonstrated that scattering of waves through spatial heterogeneity of soil profiles could improve the fit of the TTF to the ETF. Site response is a complex phenomena caused by a variety of factors. It is important to identify when complexities exist and should be included in the site response formulation and when site complexities can be ignored in favor of the SH1D formulation.

REFERENCES

Abercrombie, R. E. [1998], "A summary of attenuation measurements from borehole recordings of earthquakes: the 10 Hz transition problem," Pure Appl. Geophys., 153, 475-487.

Aki, K., and P. G. Richards [2002], "*Quantitative Seismology: Theory and Methods* (2nd ed.)," University Science Books, Sausalito, California, 700 p.

Aoi, S., K. Obara, S. Hori, K. Kasahara, and Y. Okada [2000], "New Japanese uphole-downhole strong-motion observation network: KiK-Net." Seism. Res. Letters, 72, 239.

Archuleta, R.J., S.H. Seale, P.V. Sangas, L.M. Baker, and S.T. Swain [1992], "Garner Valley downhole array of accelerometers: instrumentation and preliminary data analysis, Bull. Seism. Soc. Am. 82 (4), 1592-1621.

Assimaki, D., J. Steidl, and P.C. Liu [2006], "Attenuation and velocity structure for site response analyses via downhole seismogram inversion." Pure Appl. Geophys. 163(1), 81-118.

Baise, L.G., S.D. Glaser, and D.S. Dreger [2003a], "Site Response at Treasure and Yerba Buena Islands, San Francisco Bay, California." Journ. Geot. Geoenv. Eng.,, 129 (5), 415-426.

Baise, L.G., D. S. Dreger, and S.D. Glaser [2003b], "Modeling of the Northern San Francisco Bay Velocity Structure for the 18 August 1999 Bolinas Earthquake." Bull. Seism. Soc. Am., 93 (1), 465-479.

Boatwright, J., L. C. Seekins, T. E. Fumal, H. P. Liu, and C. S. Mueller [1991], "Ground Motion Amplification in the Marina District," Bull. Seism. Soc. Am., vol. 81, pp. 1980–1997.

Boore, D. M. [2007], "Some Thoughts on Relating Density to Velocity," available at <http://daveboore.com/daves_notes.php> (last accessed Nov. 2010), 12 pp.

Boore, D. M., and W. B. Joyner [1997], "Site Amplifications for Generic Rock Sites," Bull Seism. Soc. Am., vol. 87, 327−341.

Borcherdt, R. D. [1970], "Effects of Local Geology on Ground Motion Near San Francisco Bay," Bull. Seism. Soc. Am., 60, 29–61.

Borcherdt, R.D. and J.F. Gibbs [1976], "Effects of local geological conditions in the San Francisco Bay region on ground motions and the intensities of the 1906 earthquake." Bull. Seism. Soc. Am., 60(2), 467-500.

Darendeli, M. B. [2001], "Development of a new family of normalized modulus reduction and material damping curves," *Ph.D. Thesis*, University of Texas at Austin, Austin, Texas, 396 p.

Electric Power Research Institute (EPRI) [1993], "Guidelines for determining design basis ground motions," *Final Report No. TR-102293,* Electric Power Research Institute, Palo Alto, California.

Hanks, T. C. and A. G. Brady [1991], "The Loma Prieta Earthquake, Ground Motion, and Damage in Oakland, Treasure Island, and

San Francisco," Bull. Seism. Soc. Am., vol. 81, pp. 2019–2047.

Hashash, Y. M. A., and D. Park [2001]. "Nonlinear One-Dimensional Seismic Ground Motion Propagation in the Mississippi Embayment," Engineering Geology, vol. 62, 185-206.

Hashash, Y. M. A., and D. Park [2002]. "Viscous Damping Formulation and High Frequency Motion Propagation in Nonlinear Site Response Analysis," Soil Dyn. Earthquake Eng., vol. 22, 611-624.

Haskell, N. A. [1953], "The Dispersion of Surface Waves on Multilayered Media," Bull. Seism. Soc. Am., no. 72, pp. 17–34.

Idriss, I. M. and J. I. Sun [1992], "User's Manual for SHAKE 91, A Computer Program for Conducting Equivalent Linear Seismic Response Analyses of Horizontally Layered Soil Deposits," University of California, Davis, California, 37 p.

Ishibashi, I., and X. Zhang [1993], "Unified dynamic shear moduli and damping ratios of sand and clay," Soils and Foundations, vol. 33, 182–191.

Johnson, L.R. and W. Silva [1981], "The effects of unconsolidated sediments upon the ground motion during local earthquakes." Bull. Seism. Soc. Am., 71(1), 127-142.

Kaklamanos, J., E.M. Thompson, L.G. Baise, and L. Dorfmann [2011], "Identifying and Modeling Complex Site Response Behavior: Objectives, Preliminary Results, and Future Directions." Proceedings of the 2011 NSF Engineering Research and Innovation Conference, Atlanta, Georgia, Grant #1000210.

Kaklamanos, J., E.M. Thompson, L.G. Baise, and L. Dorfmann [2012], "Modeling Nonlinear 1-D Site Response Behavior at Six Well Behaved Sites in the KiK-Net Array," in preparation.

Matasovic, N. [2006]. "D-MOD_2—A Computer Program for Seismic Response Analysis of Horizontally Layered Soil Deposits, Earthfill Dams, and Solid Waste Landfills, User's Manual," GeoMotions, LLC, Lacey, Wash.

Okada, Y., K. Kasahara, S. Hori, K. Obara, S. Sekiguchi, H. Fujiwara, and A. Yamamoto [2004], "Recent progress of seismic observations networks in Japan – Hi-net, F-net, K-net and KiK-net, Earth Planets Space, 56 XV-XXVIII.

Park, D., and Y. M. A. Hashash [2004]. "Soil Damping Formulation in Nonlinear Time Domain Site Response Analysis," J. Earthquake Engineering, vol. 8, 249-274.

Schnabel, P. B., J. Lysmer, and H. B. Seed [1972], "SHAKE: A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites," Report UCB/EERC-72/12, Earthquake Engineering Research Center, University of California, Berkeley, 102 pp.

Seale, S. H., and R.J. Archuleta [1989], "Site amplification and attenuation of strong ground motion," Bull. Seis. Soc. Am., 79, 1673-1696.

Seed, H. B. and I. M. Idriss [1970]. "Soil Moduli and Damping Factors for Dynamic Response Analyses," Report EERC 70-10, Earthquake Engineering Research Center, University of California, Berkeley, 40 p.

Steidl, J., A.G. Tumarkin, and R. Archuleta [1996], "What is a reference site?" Bull. Seism. Soc. Am, 86, 1733-1748.

Thompson, E. M., L. G. Baise, R. E. Kayen, and B. B. Guzina [2009], "Impediments to Predicting Site Response: Seismic Property Estimation and Modeling Simplifications," Bull. Seism. Soc. Am., vol. 99, pp. 2927–2949.

Thompson, E. M., L. G. Baise, Y. Tanaka, and R. E. Kayen [2011], "A Taxonomy of Site Response Complexity," Soil Dynamics and Earthquake Engineering, in review.

Thomson, W. T. [1950], "Transmission of Elastic Waves Through a Stratified Solid," Journal of Applied Physics, vol. 21, pp. 89–93.

Vucetic, M., and R. Dobry [1991], "Effect of soil plasticity on cyclic response," Journal of Geotechnical Engineering, vol. 117, 89–107.

Zhang, J., R. D. Andrus, and C. H. Juang [2005]. "Normalized shear modulus and material damping ratio relationships," Journal of Geotechnical and Geoenvironmental Engineering, vol. 131, 453–464.