Identifying and Modeling Complex Site Response Behavior: Objectives, Preliminary Results, and Future Directions

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Abstract: Blind prediction experiments have consistently shown that dynamic soil models rarely reproduce observed behavior. We hypothesize that the primary reason for the poor performance of existing site response models is that the standard assumptions do not adequately represent the complexity of site response behavior in many cases. In this research, we seek to evaluate site response at multiple sites where both weak and strong motions have been measured and three-dimensional (3D) soil information exists. Ultimately, we will test whether or not a more complex site response model can explain the site response behavior that is observed at some of these sites, and we will develop a method to identify and model complex site response behavior when needed.

1. Introduction: The near-surface properties of the earth (e.g., seismic velocities, density, and attenuation) modify seismic waves as they propagate from depth to the surface where they are felt and impact society. This process is often called site response, and it is an important factor that contributes to the seismic hazard at a specific location. As observed in the 1989 Loma Prieta earthquake as well as other more recent earthquakes, the softer materials near the free surface influence damage patterns over short distances [1–4]. Impedance contrasts within the geologic materials at a site modify incoming waves and create seismic resonances. In addition, soil is known to behave nonlinearly under earthquake loading. For site response studies, soil behavior is generally characterized with in situ measurements of mechanical properties (e.g., S-wave velocity, Vs) for the low-strain behavior paired with an appropriate constitutive law; site response is a function of both the physical properties of near surface materials, the spatial distribution of those properties, and the constitutive law that governs their behavior.

Unfortunately, blind prediction experiments within the linear range of accelerations have shown that predicted amplifications rarely match the observed amplifications [5]. Nonlinear studies also fail to accurately predict observed amplifications with the standard assumption of vertically propagating S-waves through laterally constant media [6]. Though there are many potential sources of uncertainty in site response modeling, we expect that the assumption one-dimensional (1D) wave propagation is a major factor due to the limited ability of soil models to reproduce linear soil behavior.

In this project, we seek to evaluate site response at a wide range of sites where both weak and strong motions have been measured, spanning a range of geologic settings. The selected sites provide a sequence from simple to complex site response behavior. This project builds from our recent analysis of linear site response at several sites in the Kiban-Kyoshin network (KiK-net) of vertical receiver arrays [7]. We showed that modeling the full wavefield through a 3D spatially...
heterogeneous medium is necessary to accurately model near-surface amplifications from moderate earthquakes at complex sites. Thompson et al. (2009) [7] showed that the largest differences between the observed and predicted amplification result because the interference of the upgoing and downgoing waves at the downhole receiver is substantially less than predicted by the assumption of 1D plane SH-wave viscoelastic (SH1D) wave propagation. Thompson et al. (2009) [7] hypothesized that the diminished interference between the upgoing and downgoing waves (termed the “downgoing-wave effect”) results from scattering of the wavefield. This scattering can be explained by incorporating 3D spatial variability of seismic properties of the medium, characteristic of naturally-formed geologic materials. While the previous results were focused on linear site response, this project extends the study to more KiK-net sites so that model validation can be performed across a larger range of geologic materials and with more intense ground motion records.

This project has three major goals:

1. Empirically test the previously-described hypothesis suggested by Thompson et al. (2009) [7] with recently collected in situ measurements of the spatial distribution of soil stiffness.
2. Introduce a procedure that uses weak ground motions to identify sites where 3D effects must be included in the site response model.
3. Develop and validate a complex site response model that will include nonlinear constitutive material behavior as well as 3D spatially variable mechanical properties.

We focus on two KiK-net sites that fulfill the following criteria: (1) the sites recorded large accelerations from the 2003 M 8.3 Tokachi-Oki earthquake, and (2) the pair of sites includes those that are characteristic of the best and worst fit to the SH1D response for weak ground motions (i.e., simple to complex site response behavior). The Thompson et al. (2009) [7] hypothesis will be confirmed if the spatial variability of S-wave velocity ($V_S$) is correlated with the misfit of the SH1D response.

The principle of parsimony demands that numerical models be only as complex as the data they require. Thus, we will quantify the accuracy that can be obtained at various levels of complexity so that practitioners can make informed decisions about the extent of spatial data and complexity of the constitutive law needed for a particular project. Site response models have two major components: the spatial model (spatial variability of the material properties) and the constitutive law (mathematical model of material behavior). We will evaluate and compare SH1D versus 3D wave propagation models; models with homogeneous layers versus heterogeneous layers; and a sequence of constitutive laws. We will quantify the accuracy that can be obtained for various levels of complexity for each of these components of the site response model. In this paper, we describe our progress on each of the three project goals, as we work towards developing a method to identify and model complex site response.

2. Background of Theoretical and Empirical Site Response Transfer Functions: 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 either above a downhole input motion, or seated on soil near the outcrop motion. A conceptual overview of site response is shown in Figure 1. 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), which can be compared to theoretical predictions of the transfer function (TTF) based on in situ estimates of the seismic properties of the soil. The transfer function (empirical or theoretical) shows how the soil amplifies and attenuates seismic waves as a function of frequency, $\omega$. Thus, it is convenient to visualize the transfer function in the frequency domain.

A transfer function $F(\omega)$ may be written in simple
The mathematical form is given by

\[ F(\omega) = \frac{u_{\text{surface}}}{u_{\text{downhole}}}, \]  

where \( u_{\text{surface}} \) is the Fourier series representation of the ground motion at the surface, and \( u_{\text{downhole}} \) is the Fourier series representation of the downhole ground motion. The transfer function 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 from the same earthquake source: one recording at the surface and another recording downhole. As the number of surface/downhole pairs increases, we can obtain stable estimates of the median transfer function and its confidence intervals.

We evaluate the accuracy of site response models by comparing the theoretical amplifications to the 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 with the Thomson-Haskell matrix method [8–9].

The SH1D input parameters are the S-wave velocity (\( V_S \)), density (\( \rho \)), and the intrinsic attenuation of S waves (\( Q^{-1} \)). Since we do not have in situ estimates of \( \rho \), we use the procedure recommended by Boore (2007) [10] for estimating \( \rho \) from the P-wave velocity \( V_P \), where \( V_P \) is reported by the surface-source downhole-receiver survey. We assign \( V_S \) and \( \rho \) 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.

3. Empirical analysis using in situ measurements of soil properties: Thompson et al. (2010) [11] addresses the question: Do sites with poor fit to SH1D also exhibit larger three-dimensional (3D) variability than sites with good fit to SH1D?

Ground motions at two KiK-net strong motion downhole array sites in Hokkaido, Japan (TKCH08 in Taiki and TKCH05 in Honbetsu) demonstrate the link between 3D subsurface variability and fit to SH1D. These sites recorded the M 8.0 2003 Tokachi-Oki earthquake, as well as numerous ground motions from smaller events.

Figure 2 shows that weak ground motions at TKCH08 are well-modeled by the SH1D assumptions, while TKCH05 is characteristic of a poor fit to the SH1D. The misfit between the ETF and TTF at TKCH05 indicates that one or more SH1D assumptions are substantially violated at this site. Since the ETF only includes ground motions with small maximum accelerations, the assumption of viscoelasticity cannot explain the misfit. Thus, we hypothesized that the misfit at TKCH05 largely results from the assumption of a laterally constant medium where the subsurface exhibits large lateral variations, and we collected in situ measurements of shear wave velocity to test this hypothesis.

**Figure 2.** SH1D theoretical amplifications at KiK-net sites TKCH08 and TKCH05 compared to the 95% confidence interval of the linear ETF from 10 earthquakes, and the ETF from the 2003 Tokachi-Oki earthquake [11].
We measured four $S$-wave velocity profiles in the vicinity ($<300$ m) of each site with the spectral analysis of surface waves (SASW) method, a noninvasive method of measuring the $V_S$ profile [12]. Figure 3 displays vicinity maps of the two KiK-net stations (showing the locations of the four SASW surveys with respect to the downhole arrays), as well as boring logs illustrating the subsurface profiles. The descriptions of the lithology provided by the KiK-net website (Figure 3c and d) provide evidence that TKCH05 may be more heterogeneous than TKCH08. TKCH08 consists of 78 m of Quaternary sandy gravel over Cretaceous sandstone. In contrast, the top 80 m of TKCH05 is mostly sediment and consists of eight layers of Neogene deposits including fill, sandy gravel, sandstone, silt, and gravelstone. The stratigraphy below 80 m is mostly gravelstone and sandstone with thin interbeds of silt.

The empirical and theoretical dispersion curves for each SASW survey at sites TKCH08 and TKCH05 are summarized in Figure 4. The theoretical dispersion curves in Figure 4 correspond to the $V_S$ profiles in Figure 5. Figure 5 also shows the KiK-net downhole profiles and the K-net profile at HKD090 because it is installed adjacent to TKCH05. The increased lateral variability of the in situ $V_S$ profiles in the vicinity of...
TKCH05 relative to TKCH08 supports our hypothesis that the TTF misfit observed at TKCH05 in Figure 2 is caused by 3D spatial variability of the soil properties.

This KiK-net site pair is ideal for assessing the relative importance of 3D site effects and nonlinear site effects. The linear ground motions at TKCH05 isolate the 3D site effects, as we hypothesized from the linear ground motions and confirmed with our subsequent SASW surveys. The Tokachi-Oki time history at TKCH08 isolates the effects of nonlinearity from spatial heterogeneity because the 3D effects are negligible. The Tokachi-Oki time history at TKCH05, on the other hand, includes both nonlinear and 3D site effects. Comparisons of the accuracy of the SH1D model predictions of these surface time histories from the downhole time histories indicate that the 3D site effects are at least as important as nonlinear effects in this case. The errors associated with the assumption of a 1D medium and 1D wave propagation will be carried into a nonlinear analysis that relies on these same assumptions. Thus, the presence of 3D effects should be ruled out prior to performing a 1D nonlinear analysis. The SH1D residuals show that 3D effects can be mistaken for nonlinear effects.

4. Identifying complex site response using weak ground motion records: For Goal 2 of this project, we develop an objective methodology to identify complex site response behavior using weak ground motion data. A few extensively-studied downhole arrays are commonly used for the calibration and validation of nonlinear models, such as the Large-Scale Seismic Test

![Figure 4](image4.png)

**Figure 4.** Empirical (points) and theoretical (lines) dispersion curves near sites (a) TKCH08 and (b) TKCH05 [11].

![Figure 5](image5.png)

**Figure 5.** SASW and invasive $V_s$ profiles near KiK-net sites (a) TKCH08 and (b) TKCH05 [11].
(LSST) in Lotung, Taiwan [13–18]. However, reliable calibration and validation require a range of material properties and loading sequences. An objective classification system will help expand the number of case studies that can be used for calibration and validation of soil models.

To develop our preliminary classification system, we use 78 KiK-net stations having at least one ground-motion record where the peak ground acceleration (PGA) exceeds 0.3g. Using these 78 stations, we have 2,551 total ground-motion records from 1,038 total earthquakes, illustrated in Figure 6. From these 78 stations, we select 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). As explained in the next section, we define “linear events” as events having an input PGA less than 0.1g. 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.

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 effects, and could result from source or path effects. Our measure is the standard deviation (\( \sigma_i \)) of the ETF in natural logarithmic space (\( \sigma_{ln} \)). We only consider the ETF in the \( f = 0.5 \) to 5 Hz passband; we do not include higher frequencies because the TTF is sensitive to details of the geophysical survey that are not reliably resolved [19]. To classify strong motion stations, we also need a threshold value. We currently have selected a threshold of \( \sigma_i = 0.15 \) for differentiating between sites with high and low inter-event variability. Figure 7 compares the empirical transfer functions for two sites, one with high inter-event variability (a), and one with low inter-event variability (b).

Second, the goodness-of-fit between the ETF and the TTF (using the SH1D formulation) is quantified using Pearson’s correlation coefficient, \( r \):

\[
r = \frac{\sum_{i=1}^{n} (y_i - \bar{y})(\hat{y}_i - \bar{\hat{y}})}{\sqrt{\sum_{i=1}^{n} (y_i - \bar{y})^2 \sum_{i=1}^{n} (\hat{y}_i - \bar{\hat{y}})^2}},
\]

where \( y \) denotes an observed value (from the ETF) and \( \hat{y} \) denotes a predicted value (from the TTF). 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 8 compares the transfer functions for two sites, one with good fit between the ETF and TTF (a), and one with poor fit between the ETF and TTF (b).

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 \( \sigma_i \) and good fit to SH1D. These sites are ideal for calibration and validation of one-dimensional constitutive models.
- LP sites have low \( \sigma_i \) and poor fit to SH1D. These sites are appropriate for nonlinear modeling but care must be taken to identify the source of the misfit.
- HG and HP sites have high \( \sigma_i \). These sites are not likely to be informative for nonlinear constitutive models unless path and source effects can be accounted for.

Figure 6. Map of Japan, showing the KiK-net stations we considered (orange circles) as well as the earthquake epicenters (yellow circles).
**Figure 7.** The mean empirical transfer functions derived from all linear events at KiK-net stations (a) IWTH25 and (b) IWTH05. The +/- 95% prediction intervals for the ETFs are also shown. The width of the prediction interval is indicative of the inter-event variability at each of the sites. The station in (a) has high $\sigma_i$ (0.374) and thus has high inter-event variability, whereas the station in (b) has low $\sigma_i$ (0.055) and thus has low inter-event variability.

**Figure 8.** The TTF (thick line), mean ETF (thin line), and +/- 95% prediction intervals for the ETF are shown for KiK-net stations (a) IWTH04, and (b) HRSH03. The station in (a) has high $r$ (0.73) and thus has a good fit to the TTF, whereas the station in (b) has low $r$ (~0.71) and thus has poor fit to the TTF.
Figure 9 displays the preliminary classifications of the 74 KiK-net stations we analyzed in this study, as a function of $V_{S30}$, the average S-wave velocity over the top 30 m of the subsurface. As an example, for the two sites described earlier in this paper (TKCH08 and TKCH05), TKCH08 is classified as LG and TKCH05 is classified as LP. As we describe in the next section, site TKCH08 is an excellent candidate for the calibration and validation of one-dimensional constitutive models.

5. Modeling of complex site response: In modeling site response (Goal 3 of this project), we will consider two baseline models: the SH1D formulation (as described previously), and the 1D vertically-propagating SH-waves equivalent-linear formulation of SHAKE [20–21]. SHAKE is the most frequently-employed code for nonlinear site response analysis. In addition to the soil properties required by the SH1D model ($\rho$ and $V_s$), SHAKE requires the user to specify modulus reduction and damping curves. Modulus reduction curves quantify the reduction in shear modulus ($G$) that occurs as the level of shear strain ($\gamma$) in the soil increases, and damping curves quantify how hysteretic damping ($\zeta$) increases with shear strain, due to a greater level of energy dissipation at higher strains. In the equivalent-linear formulation, linear analyses are performed using values of $G$ and $\zeta$ that are iteratively adjusted to match the effective level of shear strain induced in the soil; these values are assumed to remain constant throughout the duration of loading. Along with the SH1D results, SHAKE will be used as our nonlinear baseline model from which we will judge the improvement in accuracy of alternative constitutive laws. The performance of complex models (e.g., 3D heterogeneous medium and/or fully nonlinear) will be quantitatively presented in terms of improved accuracy over the SH1D and SHAKE results.

Our first step is to model the linear (weak) ground motions at each site. We classify linear events as those having an input $PGA < 0.1g$, which has been used by others as a reference intensity, defined as having no nonlinear effects [22]. To justify the classification of linear versus nonlinear events, we carefully analyzed ground-motion records near the borderline of $PGA_{\text{input}} = 0.1g$, by comparing the results assuming pure linear behavior (no reduction in shear modulus) and equivalent-linear behavior (using the Seed and Idriss (1970) [23] curves for shear modulus reduction). We verified that the assumption of linearity did not result in a significant overprediction of surface $PGA$, and that the calculated strains were reasonably small (~0.01%).

Thus far, we have focused our analyses on site TKCH08, which is well-fit by the SH1D and SHAKE formulations. In analyzing this site, we first analyzed the sensitivity of the ground-motion predictions to the soil profile. We analyzed sites using (a) an original, “pre-optimized” soil profile, and (b) a “post-optimized” soil profile obtained by selecting the soil parameters that optimize the matches between the resonant peaks of the TTF and the ETF. Because higher frequencies carry little seismic energy, these frequencies are less...
important for amplification functions, and thus we focus on matching the first two resonant peaks of the transfer functions. For site TKCH08, comparisons of the site response transfer functions for the pre- and post-optimized soil profiles are illustrated in Figure 10.

Because the KiK-net station TKCH08 records ground motions both downhole (at 103 m depth) and at the ground surface, we are able to compare the observed surface ground motion to the predicted surface ground motion calculated using SHAKE. We compare the predicted and observed surface ground motions using acceleration time histories. Three goodness-of-fit statistics are used to quantify the fit between the observed and predicted accelerations: (1) the coefficient of efficiency ($E$), (2) the correlation coefficient ($r$), and (3) the root mean square error (RMSE).

The first statistic we use as our basis of comparison is the Nash-Sutcliffe model efficiency coefficient ($E$), a commonly used statistic in hydrology [24]. The coefficient of efficiency is calculated by the equation

$$E = 1 - \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2},$$

where $n$ is the total number of points in the acceleration time history, $y_i$ is an observed value, and $\hat{y}_i$ denotes a predicted value. The value of $E$ may vary between $-\infty$ and 1; when $E$ is less than zero, the arithmetic mean of the observed values has greater prediction accuracy than the model itself [24]. The numerical values of $E$ may be used to compare alternative models, with higher values indicating better agreement between observations and predictions. As explained in detail in Legates and McCabe (1999) [25] and Kaklamanos and Baise (2011) [26], the coefficient of efficiency has some important advantages over other commonly-used goodness of fit statistics, such as the Pearson correlation coefficient ($r$). Most importantly, $E$ is more sensitive to additive and multiplicative differences between the model predictions and observations, and thus is a better indicator of goodness of fit.

The second goodness-of-fit statistic we use is the correlation coefficient ($r$) between the predicted and observed accelerations (Equation 2). Although $r$ has some disadvantages compared to $E$, we report the values of $r$ because it is so commonly used as a goodness-of-fit statistic.

The third goodness-of-fit statistic we use is the root mean square error (RMSE), which retains the original units of acceleration (g):

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i - \bar{y})^2}. $$

Boxplots of $E$, $r$, and RMSE, comparing the acceleration time histories for 33 linear events for the pre- and post-optimized soil profiles for site TKCH08, are shown in Figure 11. The coefficients of efficiency and correlation display a significant difference between the pre- and post-optimized soil profiles, but RMSE does not display as large of a difference. These results show that even for a “well-fit” site such as TKCH08, the adjustment of the soil profile can further improve the fit. This type of sensitivity analysis will be more challenging for poorly-fit sites (such as TKCH05, where 3D events have been found to be significant), because the distinctive interference patterns of the downgoing-wave effect are absent.

In addition to comparing the linear events, we have compared the performance of SHAKE for the pre- and post-optimized TKCH08 soil profiles using the one nonlinear event recorded at this site: the 2003 $M=8.3$ Tokachi-Oki mainshock. Using a purely linear formulation (no modulus reduction, as in the SH1D formulation), the comparisons between the pre-optimized and post-optimized soil profiles are shown in Table 1. Both the east-west and north-south

<table>
<thead>
<tr>
<th>Comp.</th>
<th>Goodness-of-fit measure</th>
<th>Pre-optimized Soil profile</th>
<th>Post-optimized Soil profile</th>
</tr>
</thead>
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<tr>
<td>E-W</td>
<td>$E$</td>
<td>$-0.302$</td>
<td>$-0.300$</td>
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<td></td>
<td>$r$</td>
<td>$0.154$</td>
<td>$0.216$</td>
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<td></td>
<td>RMSE</td>
<td>$0.0660g$</td>
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<td>N-S</td>
<td>$E$</td>
<td>$-0.757$</td>
<td>$-0.528$</td>
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<tr>
<td></td>
<td>$r$</td>
<td>$-0.0056$</td>
<td>$0.177$</td>
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<td></td>
<td>RMSE</td>
<td>$0.0665g$</td>
<td>$0.0621g$</td>
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</table>

Figure 10. Comparison of site response transfer functions for pre- and post-optimized soil profiles at site TKCH08.
The optimization of the profile does not improve the results as greatly as it did for the linear events. The profile optimization offers little to no improvement for the east-west component of ground motion, and slight improvement for the north-south component of ground motion (which initially had a poorer fit than the east-west component). For the levels of ground motion experienced during this earthquake, it is unreasonable to assume that no shear modulus reduction occurs. The analysis is repeated using the Seed and Idriss (1970) [23] modulus reduction and damping curves, and the results are shown in Table 2. By increasing the complexity of the constitutive relationship (incorporating shear modulus reduction), the goodness-of-fit is significantly improved. Additionally, the optimization of the soil profile does not help at all; in fact, it actually makes the results worse. Because the shear moduli (and thus the shear wave velocities) are altered from those of the initial profile during the equivalent-linear ground motion calculation, it is not surprising that the optimization of the initial profile does not play as large a role in improving the results. (There is no alteration of the profile during the purely linear calculation.) Another reason for the poor performance of the post-optimized profile is that the soil profile was selected to optimize the theoretical transfer function—a function that is valid for linear systems because it is based upon the principle of superposition in the frequency domain. For nonlinear events, we would not expect superior performance for a soil profile optimized for a linear system.

Seeing that the numbers in the “pre-optimized” column in Table 2 are comparable to the median values in Figure 11, we see that the incorporation of the simplest nonlinear constitutive model can capture a large amount of the nonlinearity at site TKCH08. Future work will show if more advanced constitutive models can reduce even more of the scatter, or whether the simple equivalent-linear formulation of SHAKE is sufficient for modeling nonlinearity at this site.

6. Future directions: Our work thus far has focused upon the SH1D and SHAKE site response models, which will be used as the baseline of comparison for more complex site response models. While SH1D and SHAKE may be sufficient to model the site response at TKCH08, we will quantify the improvement in accuracy that can be achieved when a 3D spatial model is used instead of the 1D model. We will document the level of strain at which the predictions by SHAKE break down, and we will quantify the gains using a fully-nonlinear finite element code. We will expand

![Boxplots of goodness-of-fit measures for TKCH08 mainshock](image)

Figure 11. Boxplots of (a) efficiency coefficient, (b) correlation coefficient, and (c) RMSE, comparing the acceleration time histories for 33 linear events for the pre- and post-optimized soil profiles for site TKCH08. The median values are printed on the boxplots.

<table>
<thead>
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<th>Post-optimized soil profile</th>
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</thead>
<tbody>
<tr>
<td>E-W</td>
<td>( E )</td>
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our analysis to additional LG sites besides TKCH08, and for LP sites (like TKCH05), which tend to have more heterogeneous soil profiles that are not easily modeled by simple site response models. For strong ground motions at simple sites (like TKCH08), we will pair the 1D spatial model with nonlinear material behavior to isolate the predictive power of each constitutive law. For strong ground motions at complex sites (like TKCH05), the 3D spatial model will be paired with each constitutive law. The results will be critically evaluated to justify the increase in complexity of the spatial model and/or constitutive law at each of the sites (representing simple to complex site behavior). We will recommend the simplest constitutive formulation to capture all necessary physical phenomena — only increasing the complexity of the material laws when required to fit empirical observations. Therefore, this work involves a continuous verification and validation process.

To test a hierarchy of site response models, from 1D to 3D and linear to various nonlinear representations, we will employ the finite element software ABAQUS/Explicit. This involves explicit time integration and is ideally suited to simulate wave propagation in solid continua. ABAQUS/Explicit allows for propagation of the full wavefield through a medium where the material properties vary spatially, so both 3D and nonlinear effects can be accounted for.

7. Conclusion: Using in situ measurements of soil stiffness at several KiK-net sites in Hokkaido, Japan, we empirically validated the hypothesis of Thompson et al. (2009) [7] that the misfit in the site response formulation at some of these sites is caused by the 3D spatial variability of the soil properties. In addition, we have used ground-motion data from 74 KiK-net stations to introduce a preliminary procedure that uses weak ground motions to identify sites where 3D effects must be included in the site response model. We have begun modeling site response using the simplest formulations (SH1D and SHAKE), which will serve as the baseline of comparison for more complex site response models. Ultimately, we will test whether or not a more complex site response model can explain the site response behavior that is observed at some of these sites. By specifying the degree to which nonlinear constitutive material behavior and the 3D spatially-variable mechanical properties improve the fit, we will ultimately develop a method to identify and model complex site response behavior.

8. Acknowledgements: This work was supported under National Science Foundation Grant No. 1000210.

9. References:


