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# Influence of parametric nonlinear soil models on site response predictions

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ABSTRACT: In the absence of site-specific laboratory test data, a variety of dynamic soil models can be employed in ground response analysis (GRA) to represent both the shear modulus degradation and the soil damping observed during cyclic shear stress loadings. However, significant discrepancies exists among those material curves and their implementation in nonlinear codes. In this paper, we investigate the sensitivity of GRA to a range of dynamic soil models implemented using a nonlinear Masing-based model and a modified equivalent-linear method using frequency-dependent soil parameters. Case studies were carried out considering soft soil deposits and broadband earthquakes, including downhole records at the Lotung experiment site (LSST) in Taiwan. Nonlinear predictions were found to be highly sensitive to the parametrization of dynamic soil parameters along with hysteretic functions, herein using the Masing rules approach, with a tendency to attenuate the ground surface accelerations even where moderate amplitudes of ground deformation occur.

## 1 INTRODUCTION

Over the last two decades, an increasing number of dynamic soil models and numerical routines for ground response analyses have been proposed to enhance their implementation and improve their predictions. Nonlinear cyclic shear stress (CSS) models are often computed using hyperbolic relationships to define the initial stress-strain loading, termed soil skeleton or backbone curve (e.g. Kondner & Zelasko 1963), in conjunction with reversal shape functions that control the unloading-reloading path during cyclic loadings. The shape of the hysteresis loops, commonly implemented using the Masing rules (Masing 1926) or a similar approach, controls the energy dissipated during the analysis. However, the implicit formulation of energy dissipation through the use of hysteretic shape functions can introduce noticeable discrepancies in site response predictions due to the misfit in energy dissipation as compared with laboratory test measurements. Furthermore, some inconsistencies occur when hyperbolic soil models obtained from regression analyses using laboratory test data constrained by low to moderate shear strain measurements (e.g. Darendeli 2001) are extended to simulate strong earthquakes where higher strains develop within the soil profile.

This paper provides an insight into the sensitivity of ground response analyses to well-selected dynamic soil models commonly employed in earthquake engineering practice to represent the effects of soil nonlinearity. A series of one-dimensional (1-D) GRA were conducted using both a nonlinear CSS Masing-type model computed using OpenSees (Mazzoni et al. 2010), and a recently developed modified equivalent-linear method using frequency-dependent soil parameters to capture nonlinear effects. The sensitivity of model predictions was investigated considering a generic soft soil profile subject to broadband ground motions, and a case-specific study was carried out at the Lotung LSST site where vertical array records are available for comparison.

## 2 DYNAMIC SOIL MODELS

Dynamic soil models available in the literature are provided through hyperbolic relationships that can be readily implemented in nonlinear codes. In this paper, we implemented 1-D GRA with a set of hyperbolic soil models widely employed in engineering practice, these include: the Kondner & Zelasko (KZ) model (1963); the modified Kondner-Zelasko (MKZ) model developed by Matasović & Vucetic (1993); and the Darendeli model (2001) corrected to match the soil strength at large strains, herein referring to as hybrid-Darendeli model. Table 1 provides general information relative to those material curves and the model parameters.

The aforementioned hyperbolic models implemented in NL CSS constitutive soil models along with the original Masing behaviour are compared considering a medium dense sand with a relative density of 50%. Figure 1a depicts the shear modulus degradation curves across all models. One should keep in mind that the MKZ model lies between the Darendeli model, that exhibits stronger decay in shear modulus across all strain amplitudes, and the KZ model that displays a stiffer soil behaviour when subject to shearing. In this example, the hybrid-Darendeli model, modified to be strength-compatible, overlaps the MKZ model around 5% shear strain and meets the KZ curve at large strains.

The inferred Masing-based damping curves across all hyperbolic models are compared in Figure 1b against a laboratory consistent damping curve as proposed by Darendeli. As expected, the Darendeli Masing-based damping model, even after strength correction, is significantly over-predicted as compared with the laboratory consistent curve. Moreover in this example, at low to moderate strains, say below 0.1%, the MKZ model is in accordance with the laboratory damping curve by Darendeli while the KZ model tends to be underdamped. At large strains, both MKZ and KZ models depart from the laboratory damping curve and over-predict the energy dissipated.

Table 1. Details on hyperbolic soil models implemented in this study.

| Soil model | Soil types | Strain applicability | Model parameters |
|---|---|---|---|
| KZ model (Kondner & Zelasko, 1969) | All soils | Large strains, say > 1% | Frictional angle (ϕ) = variable; Cohesion (c) = 0 kPa; |
| MKZ model (Matasovic & Vucetic, 1993a) | Sand deposits | Low to moderate strains, say ≤ 1% | ϕ = variable; c = 0 kPa;<br>$\gamma_{mo} = 0.01$; β = 1.5; s = 0.86; |
| Darendeli model (2001), strength-compatible | Clay, sand and silt | Low to moderate strains, < 0.5 % | ϕ = variable; PI=0; OCR=1;<br>$\Phi_1$=0.0352; $\Phi_2$=0.0010;<br>$\Phi_3$=0.3246; $\Phi_4$=0.3483;<br>a=$\Phi_5$=0.9190; b=0.6066; |

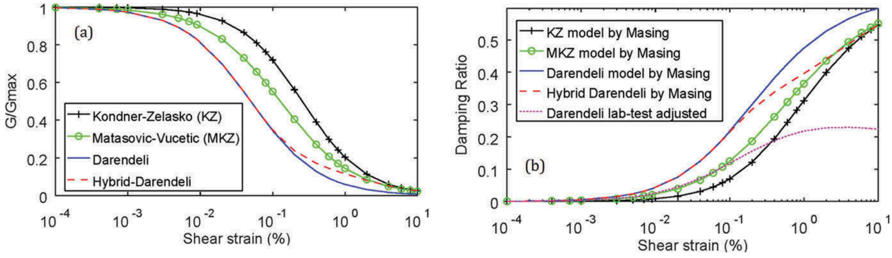

Figure 1. Comparison of hyperbolic curves for sand: (a) shear moduli reduction curves and (b) soil damping curves deriving from the original Masing rules versus a laboratory consistent damping curve obtained from Darendeli model (2001). The soil parameters considered for all models were: Gmax = 71 349 kPa – Internal friction angle = 33° - Confining pressure =274 kPa.

## 3 GROUND RESPONSE ANALYSIS

### 3.1 *Time domain nonlinear analysis*

A soil column model was implemented in OpenSees to model nonlinear 1-D site response using a finite element continuum model constrained to convey horizontal stresses when a horizontal base motion is applied. The model consists of quadrilateral elements with two degrees-of-freedom and a plane strain formulation. Total stress analyses were performed using the Pressure Independent Multi-Yield (PIMY) model in OpenSees (Mazzoni et al. 2010) to simulate the deviatoric stress-strain soil response under a monotonic or cyclic loading. The plastic stress behaviour implemented is based on the multi-yield surfaces framework (Prevost 1985) and further modified (Parra 1996, Yang 2000). OpenSees allows the implementation of user-specified shear modulus reduction ratios over a finite number of yield surfaces. In this study, the shear modulus degradation models presented in Figure 1a were generated for each soil element according to the confining pressure over depth. Importantly, the energy dissipation in the constitutive CSS soil model is constrained by the shape of hysteresis loops following the original Masing rules, as presented in Figure 1b.

### 3.2 *Frequency domain equivalent-linear analysis with frequency-dependent soil parameters*

In order to better capture soil nonlinear effects while using frequency domain analysis, the original EL method, that has been shown to attenuate the higher frequency components of ground motions, has been modified by using both frequency-dependent soil moduli and soil damping ratios. This procedure is commonly termed the Frequency-Dependent Equivalent Linear (FDEL) method. In this study, a new FDEL approach was implemented and tested to generalize the numerical scheme over a range of ground motion intensities and frequency content and to simplify its computation through the EL iterative procedure (Meite et al. 2018). Previous FDEL formulations available in the literature (Kausel & Assimaki, 2002; Yoshida & al, 2002) are based on observations of the Fourier response of the shear strain along with calibrated parameters to adjust the prediction over frequencies of interest. The proposed FDEL method relies on the Fourier Transformation (FT) of the instantaneous elastic power stress scaled on the maximal shear strain as a proxy for the frequency-dependent effective shear strain expressed as followed:

$$\gamma_{eff}(\omega) = \gamma_{max} \frac{FT[G(t)\gamma(t)\dot{\gamma}(t)]}{\max\ \{FT[G(t)\gamma(t)\dot{\gamma}(t)]\}} \tag{1}$$

where the component represents the elastic shear stress and denotes the strain rate.

The proposed formulation appears to be more reliable than the existing FDEL methods that were found to display unrealistic departures in ground response spectral accelerations when motions that exhibit high frequency content are simulated (Hartzell 2004).

## 4 SENSITIVITY OF NONLINEAR SITE RESPONSE ANALYSES

### 4.1 *Methodology*

1-D site response analyses were carried out considering a generic local site condition that would be classified as site class D according to NZ1170.5 (2004), which characterizes a deep and soft soil deposit. The shear wave velocity profiles were defined for a multi-layered soil system consisting of loose to dense sand in a drained condition suitable for performing a total stress analysis. Details of the soil profiles are summarized in Table 2.

A suite of 10 records consistent with a rock site class B condition as defined in the NZ1170.5 (2004) loadings standard were selected and used as control motions. Selection was made across range of source mechanisms for crustal earthquake scenarios along with a set of motion intensities suitable for performing site response analyses. One half of the records were

Table 2. Characterization of site profile used for 1-D site response analysis.

| Site Class* | Site Period (s) | $V_{s,30}$** (m/s) | Description | Top of layer (m) | Layer Thickness (m) | Density (kg/m$^3$) | $V_s$ (m/s) | Friction Angle (°) |
|---|---|---|---|---|---|---|---|---|
| D | 0.88 | 188 | Loose Sand | 0 | 7.5 | 1.7E+03 | 165 | 28 |
| | | | Medium Sand | 7.5 | 7.5 | 1.8E+03 | 181 | 33 |
| | | | Medium Sand | 15 | 7.5 | 1.8E+03 | 197 | 33 |
| | | | Medium Sand | 22.5 | 7.5 | 2.0E+03 | 219 | 39 |
| | | | Medium Sand | 30 | 7.5 | 2.0E+03 | 241 | 41 |
| | | | Dense Sand | 37.5 | 7.5 | 2.1E+03 | 263 | 44 |

Note: * Site Class according to NZS1170.5 standard * * $V_{s,30}$ denotes the time-averaged shear wave velocity to 30 m depth

sourced from the Pacific Earthquake Engineering Research Center ground motion database (PEER, NGA-West2) and the other half are from the New Zealand database GeoNet developed by GNS Science (www.geonet.org.nz). These records comprise recent seismic events in New Zealand from the 2010-2011 Canterbury earthquake sequence and the Kaikoura earthquake (2016), all recorded from stations that exhibit rock site class B conditions. A scaling factor was applied to the time-history records to match the PGA of the Uniform Hazard Spectrum (UHS) defined in the NZS1170.5 standard (Z=0.25, R=1, N=1). Figure 2 shows the pseudo-response spectra of the 10 records and the geometric mean response spectrum compared to the UHS spectrum.

## 4.2 *Site response predictions*

Nonlinear 1-D GRA were performed in OpenSees using the aforementioned set of hyperbolic shear modulus reduction curves, herein comparing the KZ model, the MKZ model and the hybrid-Darendeli model (Table 1). While nonlinear models were implemented along with the Masing-based damping model, frequency domain analyses computed using the FDEL procedure, with both targeted shear modulus reduction and damping curves as proposed in the Darendeli lab-test adjusted model (Figure 1).

The geometric mean responses across all soil models are compared in Figure 3a in terms of pseudo-spectral acceleration at the ground surface, and the peak shear strains calculated within the soil profile are depicted in Figure 3b. One can be drawn is that nonlinear site response predictions vary significantly over the range of hyperbolic material curves tested. The main outcomes when comparing those soil models are summarized below:

- NL analyses using the hybrid-Darendeli model exhibits higher peaks of shear strain over depth as compared with other hyperbolic curves whose dynamic soil properties decay less

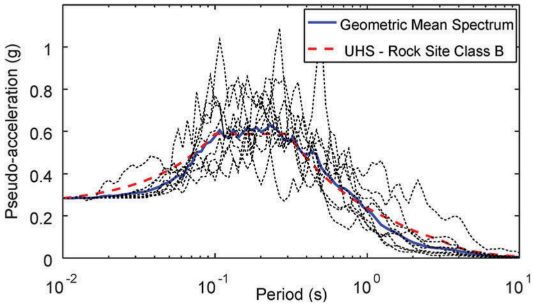

Figure 2. Record response spectra with PGA scaled on normalized UHS rock spectrum, site class B, according to NZ1170.5 (2004) standard – Spectral shape factors: Z=0.25, R=1, N=1.

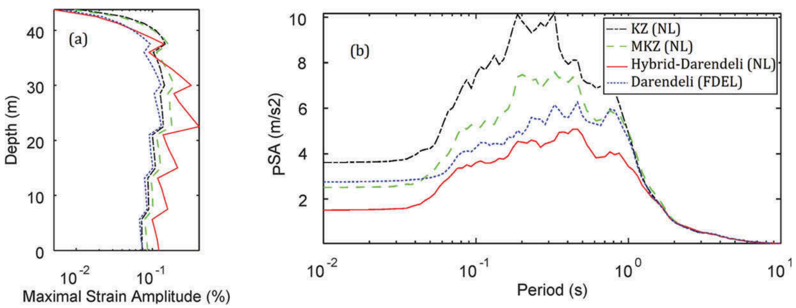

Figure 3. Comparison between the geometric mean predictions obtained across all methods: (a) Peak shear strains within soil profile and (b) site response spectra in acceleration.

rapidly when sheared, suggesting a potential for over-prediction of nonlinear effects and numerical instabilities when strong earthquakes are simulated.

- NL analyses using strength-based backbone curves as proposed in the KZ model produce higher spectral accelerations, suggesting a tendency to under-damp the ground response motions, especially when the range of shear strains that develop within the soil profile is low.
- In contrast, NL Masing-based models may predict ground motion intensities that are substantially over-damped even at low to moderate shear strain, as compared with the frequency-domain FDEL method using laboratory consistent damping curves by Darendeli.

## 5 COMPARISON AGAINST DOWNHOLE RECORDS AT LOTUNG LSST SITE

### 5.1 *Data*

Further investigations on 1-D site response analysis were carried out at the Lotung Large Scale Seismic Test (LSST) site in Taiwan, where multiple historical vertical array records are available. In this study, two events were considered, namely Event 7 that represents a strong earthquake of magnitude 6.2 (ML) triggered at 15.8 km depth with an epicentral distance of 66 km, and Event 11 corresponding to a weak earthquake of magnitude 4.3 (ML) that set off at 2 km depth with an epicentral distance of 6 km. The motions recorded at the bedrock, herein found at 47 m depth with PGA comprised between 0.46 m/s$^2$ and 0.97 m/s$^2$, were used as control motions in within rock condition, i.e. assuming a rigid boundary. The Lotung LSST site has been subject to extensive research studies in ground response simulations incorporating nonlinear constitutive soil models. The variety of site-specific geotechnical soil conditions that have been published account for the difficulties to properly represent the effects of soil nonlinearity, especially when various type of materials are encountered at shallow depth. In this study, for the sake of simplicity, we considered a full sand profile to represent the nonlinear site effects which was found to be compatible at shallow depths with the nonlinear curves proposed by Seed et al. (1984) for sand material. The geotechnical site characterization as provided by the company HCK in its survey for Taiwan Power Company (1986) was used. Basically, the soil model herein implemented consists of 15 layers ranged from loose to dense sand over 47 m depth and exhibits a site period around 0.88 s again, i.e. an average shear wave velocity equal to 214 m/s, with a water table located at a depth of 1 m. Figure 4 depicts the site-specific material curves published by Zeghal et al. (1995) at three different depths (6 m, 11 m and 17 m), compared against the standardized hyperbolic relationships provided in Table 1 implemented at the same depths. In this case, the shear modulus reduction curves across hyperbolic models compared well with the site-specific predictions at all depths, aside from the KZ model that exhibits a stiffer soil behaviour as expected. Interestingly, as compared to site-specific damping curves, the Masing-based damping ratios derived from hyperbolic relationships are under-predicted at low strains and over-predicted at larger strains, with a threshold strain amplitude of approximately 0.05%.

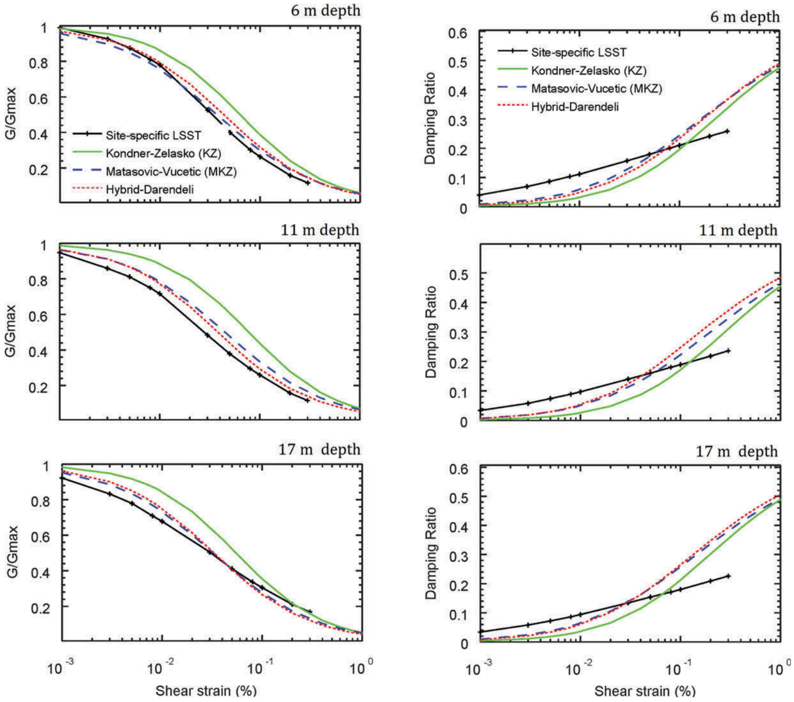

Figure 4. Soil model comparison between standardized hyperbolic relationships and site-specific material curves recommended at Lotung LSST site. The soil parameters considered for hyperbolic models were: Internal frictional angle = 33°; Plasticity Index (PI) = 0; Horizontal earth pressure coefficient ($K_o$) = 0.5.

## 5.2 *Results and discussion*

The capability of nonlinear soil models to capture the local site amplification at the Lotung LSST site was investigated by comparing the spectral acceleration predictions to recorded ground motions at the ground surface Spectral residual accelerations were defined by the ratios between model predictions and recorded motions in the logarithmic scale. NL models were computed in OpenSees using hyperbolic models with Masing behaviour, whereas the FDEL model was implemented with the set of site-specific material curves recommended by Zeghal.

Figure 5 shows the site amplification predictions considering the Event 11 for both horizontal directions of motion. As expected when weak motions are investigated, all methods provide similar predictions that are in line with the recorded motions, apart from the KZ model which tends to under-damp the site response with a positive residual bias. Likewise, Figure 6 depicts the site response predictions considering the Event 7 that exhibits higher intensity motions. In this case, the NL models implemented using both the MKZ and Darendeli modulus reduction curves tend to overdamp the site response with a negative residual amplification across all frequencies. This bias can be explained by the misfit in energy dissipation observed at large strains when Masing rules are employed to derive the hysteretic behaviour (Figure 4). As for the FDEL method using site-consistent material curves, the spectral accelerations predicted are in line with the downhole records, with improved agreement of the higher frequency content of motions as compared to nonlinear models when higher ground motion intensities are considered.

Finally, when using the Masing-based CSS model in NL analysis for the purpose of investigating site amplification effects, the Darendeli model, extended to be strength-compatible, does not address the issues related to energy dissipation. In an attempt to utilize hyperbolic shear modulus reduction models in conjunction with the Masing behaviour, the MKZ model provide a better trade-off when all solutions are compared.

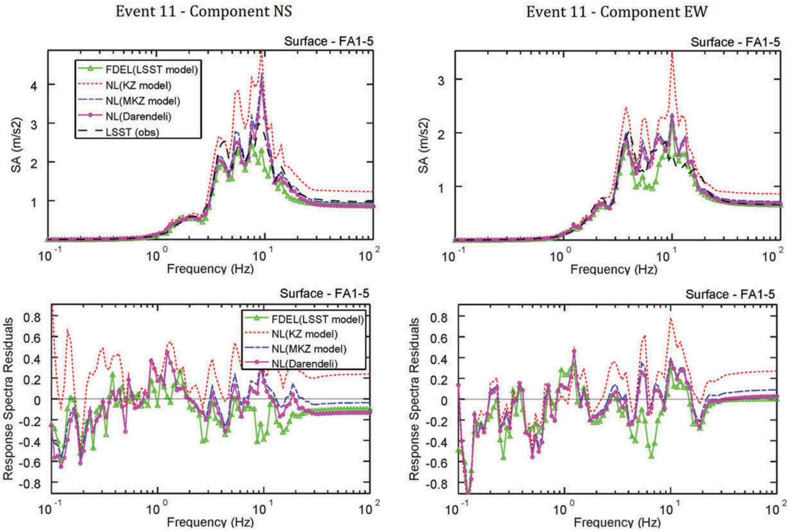

Figure 5. 1-D ground response predictions at Lotung LSST vertical array – Event 11.

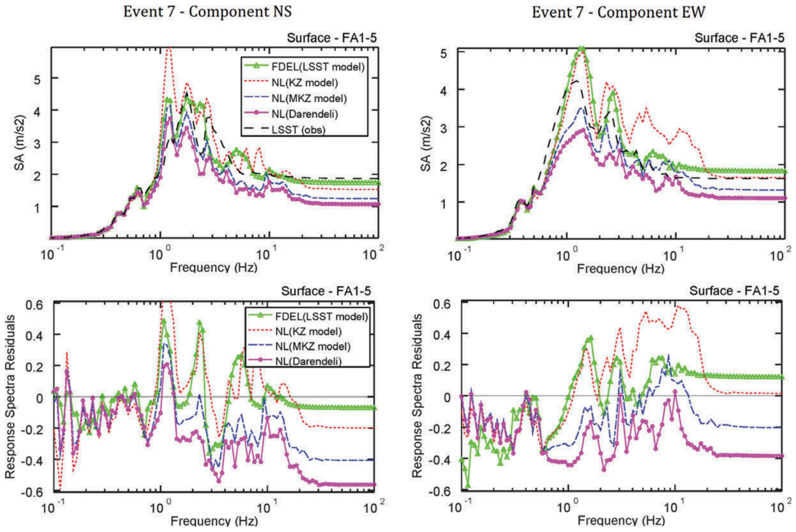

Figure 6. 1-D ground response predictions at Lotung LSST vertical array – Event 7.

## 6 CONCLUSIONS

A comparative study was carried to gain insights into the sensitivity of 1-D site response predictions to range of dynamic soil models commonly employed to simulate soil nonlinearity effects. One should keep in mind that when performing site response analysis, nonlinear methods are much more sensitive to the set of input dynamic soil parameters as compared with frequency domain methods. The variability inherent to the parametrization of nonlinear soil models becomes greater in soft soil deposits where higher strains develop within the soil profile. Therefore, dynamic soil models should be selected with due consideration to the degree of soil nonlinearity expected during the analysis in conjunction with the seismic intensities. Hyperbolic models using laboratory test data constrained by low to moderate shear strains should not be used to investigate strong earthquakes, even after correction to match the soil strength at large strains.

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