INFLUENCE OF NON-LINEARITY MODELING STRATEGY FOR SITE RESPONSE ESTIMATION BASED ON MEASUREMENTS AND NUMERICAL SIMULATIONS AT THE KIK-NET KSRH10 SITE

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ABSTRACT

The main objective of this work is to illustrate the influence of the soil shear nonlinear behavior modeling (Equivalent Linear versus Iwan model) on 1D site response. In this aim, numerical simulations are performed on the KSRH10 site from the Japanese strong-motion network KiK-net. This site, was one of the chosen site for the validation phase of the PRENOLIN benchmark project (Régnier et al., 2018) associated with 9 input motions (borehole records) with different PGA and frequency content. Results from this numerical example emphasize the impact of soil nonlinearity on spectral response at the surface, the influence of the modeling strategy and the relative reduction of PGA amplification when increasing the input PGA. This work contributes consolidating the available methodologies for 1D GRA with code_aster software for low and moderated seismicity areas. For engineering purposes, such calculations using KiK-Net motions could be used to quantify the variability that has to be considered in order to reasonably envelop the surface response, depending on the modeling strategy adopted.

Keywords: 1D site effects; numerical simulations; PRENOLIN benchmark, nonlinear constitutive relations

1. INTRODUCTION

Seismic site effects are mainly caused by (i) the geological history and the resulting mechanical and geometrical properties of the soil deposits and (ii) the seismic source and directivity. However, lithological effects are the most prominent one, as it can result on large signal amplification around the resonance frequencies of the 1D soil column, considered as a reference study case in this work, or 2D-3D sedimentary basin. Therefore, a common engineering practice is to model only 1D site effects (perfectly vertical wave propagation), also called 1D ground response analysis (1D GRA), by considering the soil nonlinear behavior as a source of variation of the free-field seismic signal calculated from an input signal defined at a seismic bedrock in depth.

Under these hypotheses, due to the soil column dynamic response and soil nonlinearity, the free-field spectra amplitude do not linearly increase with increasing seismic loading at the bedrock-soil interface. Indeed, as the soil column first resonant frequency shifts to lower frequency values with increasing input motion, the spectra low-frequency content increases and the high-frequency content decreases, under the assumption that no significant pore-water pressure effects are observed, such as cyclic mobility.

The main objective of this work is to help identifying the capabilities of different soil modeling strategies on 1D GRA with increasing input motions, in the light of the impact of the considered nonlinear soil behavior. In order to quantify those effects, the PRENOLIN benchmark (Régnier et al., 2018), as a part of the SIGMA and SINAPS® projects, was conducted between 2013 and 2015, involving about 20 international teams with their own computational methodologies. Data used in this work comes from the PRENOLIN website: http://prenolin.org.

This paper is organized as follows: section 2 presents the main aspects of the modeling strategies and damping characteristics. Section 3 presents the KSRH10 site and used signals. Section 4 is dedicated to
main numerical results, and conclusions and perspectives from this work are given in Section 5.

2. MODELING STRATEGIES FOR 1D SOIL COLUMN RESPONSE

2.1 Equivalent linear analysis in frequency domain

The most common modeling strategy in engineering practice for 1D ground response analysis is the Equivalent Linear procedure (Idriss and Seed, 1967). The equivalent linear analysis consists in an iterative procedure of linear elastic simulations, for which the stiffness modulus and hysteretic damping values of each materials is modified to match 65% of the maximum strain value obtained on the previous iteration step, using soil shear modulus and damping degradation curves. This procedure is available on different numerical codes, such as SHAKE (Schnabel et al., 1972) and more recently on open source code_aster, which is a structural mechanics finite element software developed and maintained by EDF. Different authors have worked on defining the domain of validity of such an approach. By considering a large panel of site configurations and input motions from KiK-net downhole recordings, Kaklamanos et al. (2013) have shown that equivalent linear systematically under predicts ground motions at different spectral frequencies for maximum strain levels between $1 \times 10^{-3}$ to $4 \times 10^{-3}$. At these strain levels, nonlinear time-domain model is required to better reproduce soil behavior. Indeed, as maximum strains increase, the equivalent linear procedure considers higher damping values, therefore reducing acceleration levels and specially at medium to high frequency content.

2.2 Iwan-type nonlinear model in time domain

Iwan model is a total stress model based on elastoplasticity multi-mechanisms theory, with a series of linear kinematical hardening mechanisms (Iwan, 1967, Mroz, 1967). This formulation allows to directly fit the degradation curve ($G/G_{\text{max}}$) by a fit procedure of the kinematical hardening coefficients, the elastic domain being defined by the size of the first kinematical surface ($\gamma_{\text{elas}}=1 \times 10^{-5}$ in the implemented model). However, the damping curves cannot be directly fitted by the considered model implementation, and plastic volumetric strains induced by deviatoric stress are also not considered. Therefore, material damping curve is simulated by cyclic shear tests and the matching of required and obtained behavior is done on a trial and error basis. Higher damping is usually obtained for cyclic strains higher than $10^{-3}$, although differently than by Equivalent Linear analysis, material damping is variable during the simulation as obtained directly from the hysteresis loop. Besides the two elastic parameters, the calibration of the numerical implementation of the model relies on a hyperbolic model parameterized by two additional constants: the value of cyclic strain for which $G$ is half of its initial value ($\gamma_{\text{ref}}$) and the exponent of the hyperbolic law ($n$), see Equation (1). The impact of modifying $\gamma_{\text{ref}}$ and $n$ values is summarized on Figure 1. Increasing $\gamma_{\text{ref}}$ decreases stiffness degradation and damping, whereas increasing parameter $n$ slightly affects the stiffness reduction curves but increases the damping for $\gamma>10^{-1}$. The $n$ value is directly related to the maximum shear stress of the soil.

$$\frac{G}{G_{\text{max}}} = \frac{1}{1+\left(\frac{\gamma}{\gamma_{\text{ref}}}ight)^n}$$ (1)
Correctly estimating the damping characteristics of the soil column is a main issue for predictive simulation. Indeed, overestimating the different sources of damping leads to an underestimation of the model’s response, especially when maximum values such as PGA are of interest. Therefore, the different sources of damping are briefly discussed in this section.

For Linear Equivalent calculation, soil damping is usually considered as hysteretic, frequency-independent. Therefore, linear equivalent analysis relies on hysteretic damping by considering real and imaginary parts of the shear modulus. By using a frequency domain numerical scheme, the considered damping in the model is fully controlled.

For non-linear calculations, time domain simulations are required. In this case, damping sources are not only the material characteristics, but additional damping from the numerical scheme is introduced. Rayleigh damping can also be considered (under different formulations), in order to account for the damping at very small strains ($\gamma<10^{-5}$) observed on experimental transfer functions, cf. Figure 3 and in inverse soil column calculation (Kokusho, 2004).

Therefore, carrying out nonlinear time domain simulations requires an additional calibration procedure for correctly assessing the damping characteristics of the soil column. In this work, numerical damping at small frequencies is minimized by considering the Hilber-Hughes-Taylor numerical scheme (Hilber et al., 1977) with parameter $\alpha=-0.05$ ($\xi < 0.5\%$ for frequencies lower than 25Hz) and no Rayleigh damping is considered. Therefore, the main source of damping in the time domain nonlinear model is the material damping induced by Iwan model.
3. DESCRIPTION OF THE SITE AND SIGNALS

3.1 1D soil profile definition

KSRH10 is a KiK-Net station located in the Kushiro district, Hokkaido, Japan. The soil profile is composed of thin gravel fill and sandy soil material (both considered with nonlinear characteristics) (Régnier et al., 2018) down to GL-39 m, over an elastic clayed rock soil. Rigid bedrock condition is considered at GL-255m, where borehole motion is recorded. The elastic properties as well as nonlinear characteristics are given on Table 1. Nonlinear curves are denoted 1 to 6 in the SC2 soil column according to the available cyclic triaxial tests. These curves as well as the Iwan calibration and parameters are given on Figure 2.

Table 1. Linear and nonlinear properties of Kushiro10 soil column.

<table>
<thead>
<tr>
<th>Layer GL [m]</th>
<th>Vs [m/s]</th>
<th>Vp [m/s]</th>
<th>ρ [kg/m³]</th>
<th>Qs</th>
<th>SC2</th>
<th>τmax [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>140</td>
<td>1520</td>
<td>1800</td>
<td>25</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>11</td>
<td>180</td>
<td>1650</td>
<td>1800</td>
<td>25</td>
<td>2</td>
<td>30</td>
</tr>
<tr>
<td>15</td>
<td>230</td>
<td>1650</td>
<td>1500</td>
<td>25</td>
<td>3</td>
<td>40</td>
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<td>24</td>
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<td>1650</td>
<td>1600</td>
<td>25</td>
<td>4</td>
<td>60</td>
</tr>
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<td>140</td>
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<td>-</td>
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<td>2400</td>
<td>3400</td>
<td>2500</td>
<td>240</td>
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</tr>
</tbody>
</table>

Figure 2. Calibration of Iwan parameters for SC2 material parameters. Blue lines indicate calibrated Iwan behavior and gray lines the considered laboratory test results (directly used for Equivalent Linear analysis).

3.3 Input motions

The 9 seismic events considered in the PRENOLIN benchmark targeted three acceleration levels at the downhole sensor (lower than 0.1m/s², between 0.2m/s² and 0.3m/s², higher than 0.6m/s²), each group being composed of 3 input motions with different frequency content (especially for peak accelerations at the borehole lower than <0.1m/s²). As prescribed by benchmark, these input motions are implemented on a rigid base approach, in order to directly impose the borehole acceleration at the base of the soil column. The calculation performed in this study considered EW and NS components separately.
Table 2. Main considered input motion characteristics (Régnier et al., 2018)

<table>
<thead>
<tr>
<th>EQ #</th>
<th>Magnitude Mw</th>
<th>Epicentral distance [km]</th>
<th>Depth [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.1</td>
<td>31.90</td>
<td>48.0</td>
</tr>
<tr>
<td>2</td>
<td>6.9</td>
<td>44.14</td>
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<td>37.47</td>
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</tr>
<tr>
<td>4</td>
<td>5.8</td>
<td>43.21</td>
<td>47.0</td>
</tr>
<tr>
<td>5</td>
<td>5.4</td>
<td>69.03</td>
<td>38.0</td>
</tr>
<tr>
<td>6</td>
<td>6.4</td>
<td>37.94</td>
<td>50.0</td>
</tr>
<tr>
<td>7</td>
<td>5.0</td>
<td>38.62</td>
<td>85.0</td>
</tr>
<tr>
<td>8</td>
<td>5.1</td>
<td>63.04</td>
<td>88.0</td>
</tr>
<tr>
<td>9</td>
<td>6.5</td>
<td>105.03</td>
<td>43.0</td>
</tr>
</tbody>
</table>

Figure 3. Transfer function between Surface and borehole sensors: green = small linear events, dashed black: KiK-Net Vs profile, red: soil column initial Vs profile, other colours (see legend on the left): events 1, 2, 4 and 9, NS and EW components (right) and Vs profile associated (same colours), adapted from PRENOLIN benchmark (left).

4. IMPACT OF MODELING STRATEGIES FOR 1D SITE RESPONSE AT KSRH10

The different modeling strategies for 1D GRA discussed on Section 2 are evaluated regarding their aptitude to reproduce soil nonlinearity observed on the measured signals. These nonlinearities are expressed in terms of spectral ratio analysis and PGA amplification function.

4.1 1D Spectral ratio analysis

The 1D Ratio of spectral response nonlinear to linear (1D RSR$_{NL\rightarrow L}$) measures the relative influence of soil nonlinearity on the spectral response of the soil column. The 1D RSR$_{NL\rightarrow L}$ considered in this work is adapted from Régnier et al. (2016) and is obtained by simply dividing the surface/borehole frequency response modulus function of the considered signal by the soil column transfer function modulus under small strains conditions. Signal 8 is used for small strain conditions for the measured signals, whereas the elastic transfer function (red curve on Figure 3) is considered for the numerical models.

Figure 4 presents the 1D RSR$_{NL\rightarrow L}$ for the three highest input motions (1.2 and 3, input motion peak acceleration higher than 0.6m/s$^2$) for both NS (left) and EW (right) components for measured signals, Equivalent Linear and Iwan model. The curves are obtained by applying Konno-Ohmachi filtering (Konno and Ohmachi, 1998) to the spectral ratios with smoothing parameter b=40. Full line curves are
the mean values of the three considered signals and dotted lines stand for one standard deviation. First of all, the soil profile being the same for both Equivalent Linear and Iwan models, it can be seen that the soil column resonant frequencies are the same for both methodologies. However, Equivalent Linear analysis tends to overestimate the reduction of spectral response of the soil column at the medium/high frequency range, according to the considered frequency. Iwan model, as a nonlinear model, tends to spread input energy over a larger frequency content linked to the dispersive nature of waves in nonlinear regime, which leads to a smoother ratio along the frequencies of interest. This effect is more pronounced on NS direction, although it is also expected in the EW direction for higher input motions.

For low frequencies, the equivalent linear analysis better performed than Iwan model for the considered simulations, particularly regarding the amplification of the first resonant frequency. This can be viewed as a direct consequence of the higher damping obtained for the calibrated parameters of Iwan (Figure 2), especially for the soil material near the surface. However, for higher frequencies (10-15 Hz) the equivalent linear model underestimate the soil column response, as a consequence of considering a constant damping value approximated to match the 65% of maximum shear strains. For this frequency range, the obtained results of Iwan model is in better accordance with the measured signals, especially to the fact that at high frequencies the 1D RSR_{NL\rightarrow L} is expected to value 1.

![Figure 4. 1D Ratio of Fourier Spectra Response nonlinear to linear for measured signals (Signal), Equivalent linear (EQL) and Iwan model. NS component (left) and EW component (right). Full line is the mean value and dotted line is +/- one standard deviation for signals 1, 2 and 3.](image)

For these simulations, maximum shear strains do not exceed 4.10^{-3} and were mostly lower than 1.10^{-3}, which as previously discussed seems to be the maximum strain transition range for practical use between equivalent linear and nonlinear models (Kaklamanos et al., 2013). Although the obtained numerical 1D RSR_{NL\rightarrow L} are in good agreement with the one obtained from measurements for some frequencies, neither of the considered numerical simulations is capable of correctly predicting the measured 1D RSR_{NL\rightarrow L} for the whole frequency range of interest, using only the best estimate soil characteristics without any variability. These discrepancies may come from differences between theoretical and real shear wave velocity profile, the considered degradation curves and mechanical modeling strategies. In this sense, some variability on the soil characteristics (mainly in the Vs soil profile and in the degradation curves) has to be taken into account. Considering a nonlinear model with additional dissipative mechanisms as well as the simultaneity of both horizontal input motions could help tackling the aptitude of modeling strategies on 1D GRA simulations.

### 4.2 Site-specific PGA amplification function

In order to illustrate the soil nonlinearity impact on PGA values, the site-specific amplification function given by the following mathematical expression (Stewart et al., 2014) is considered:
\[ \ln Y = f_1 + f_2 \ln \left[ \frac{x_{IM\text{ref}} + f_3}{f_3} \right] \]  

(2)

\( Y \) is the PGA amplification (peak acceleration on free-field divided by the peak acceleration of input signal), \( x_{IM\text{ref}} \) is the peak acceleration of the input signal and \( f_1, f_2 \) and \( f_3 \) are parameters to be determined according to the available data. Parameter \( f_1 \) is the linear amplification, which can be determined directly from small strain measurements. \( f_2 \) and \( f_3 \) account for the reduction on PGA amplification due to soil nonlinearity. Figure 5 shows the results obtained for the PGA amplification function by considering both NS and EW components for measured signals, Equivalent Linear and Iwan model. Full line curves are the median values obtained by least squares method and dotted lines stand for three standard deviations.

First of all, it can be seen that the PGA amplification from measured signals reduces with increasing peak acceleration from the input signal, which is in accordance with the expected effect of soil nonlinearity. Interestingly, although the PGA amplifications obtained from numerical simulations do not match the measured ones for different signals, the amplification function from measured signals is consistently approximated for both numerical models, both for small strain and larger strain amplification.

Regarding the uncertainty on site-specific PGA amplification, the obtained standard deviation from numerical simulations and measured signals (\( \phi_{lnY} \approx 0.45 \) for measured signals and \( \phi_{lnY} \approx 0.35 \) for numerical simulations) is higher than the one generally observed in site amplification (\( \phi_{lnY} \approx 0.3 \)). Indeed, the actual practice for site-specific PSHA studies is to rely on \( \phi_{lnY} \) already established from the literature and to consider to median PGA amplification function obtained from numerical simulations. Small strain amplification have to be identified directly from onsite measurements, in order to validate the shear wave velocity profile.

Moreover, when considering site-specific PSHA with 1D GRA, epistemic uncertainty on the numerical simulation and soil data should also be considered. This can be done by considering the values proposed by the validation phase of the PRENOLIN benchmark (Régnier et al., 2018), which are based on the epistemic uncertainty propagation method proposed for the analysis of code-to-code variability. The obtained standard deviation for PGA residuals on log scale are comprise between 0.2 (strong motions) and 0.1 (weak motions).

5. CONCLUSIONS AND PERSPECTIVES

Some aspects of soil nonlinearity on 1D ground response analysis are highlighted in this work, both from recorded motions and numerical simulations, which were performed on code_aster open source
software. The instrumented KiK-net KSRH10 site is chosen to illustrate these aspects, as this site and the recorded motions have benefited from previous validation of 1D site conditions performed during the PRENOLIN benchmark.

By looking at the 1D Ratio of spectral response nonlinear to linear (1D RSR\textsubscript{NL\rightarrow L}), it is shown that soil nonlinearity leads to an increase (ratio higher than 1) on the spectral response for frequencies lower than the fundamental frequency, and generally a reduction (ratio lower than 1) for higher frequencies (Régnier et al., 2016). Nonetheless, amplification can also be observed for higher frequencies, as a consequence of resonances attributed to the soil shear wave velocity profile.

From the modeling point of view, both Equivalent Linear analysis and Iwan model were unable to correctly predict the spectral ratio over the whole frequency range, given only the best estimate shear wave velocity profile and degradation curves. Nevertheless, Equivalent Linear model seems to better capture the soil column amplification previously to the fundamental frequency while Iwan model seems to better capture the energy spread along frequencies characteristic of nonlinear behavior, especially at mid and high frequency contents.

Regarding PGA amplification from borehole to free-field, the considered measured signals clearly illustrate the relative reduction of PGA amplification with increasing input motion PGA. This aspect is numerically approximated in the literature by a nonlinear PGA amplification function (Stewart and al., 2014). In this work, both modeling strategies were able to correctly capture the median PGA amplification function, although the obtained standard deviation is higher in the considered case than the one usually obtained in the literature, as only the input motions selected for the PRENOLIN benchmark were considered and not the whole database from KSRH10 site.

These two aspects help to illustrate that the increase of both spectral response at the free-field and PGA are constrained by the shear wave velocity profile and degradation curves for 1D GRA, when no pore water effects are considered.

This work contributes consolidating the available methodologies for 1D GRA with code\_aster software for low and moderated seismicity areas. For engineering purposes, such calculations using KiK-Net motions could be used to quantify the amount of variability (in the Vs soil profile and in the degradation curves) that has to be taken into account in order to reasonably envelop the surface response, on the whole frequency range, depending on the modeling strategy adopted.

Further work should also consider a nonlinear model with additional dissipative mechanisms, in order to help tackling the aptitude of different levels of modeling strategies on 1D GRA simulations and specially the role of effective stress and water presence for a higher seismicity context.

6. REFERENCES


