1. Introduction

- A comprehensive assessment of one-dimensional (1D) total-stress nonlinear site response predictions is performed using an unprecedented number of sites (114) and ground motions (5626).
- Vertical seismometers array in Japan’s Kiban-Kyoshin network (KIK-net) allow for site response model predictions to be directly compared to observed surface ground motions, using the downhole recording as the input.
- Nonlinear site response model predictions are calculated using the program DEEPSOIL and are compared to observed ground motions and predictions from simpler models (i.e., linear and equivalent-linear analyses in SHAKE).
- This study builds upon Kaklamanos et al. (2013), which analyzed linear and equivalent-linear site response models at a wide range of KIK-net sites, and Kaklamanos et al. (2015), which analyzed nonlinear site response model at a subset of these sites.
- Using this broad database of site response predictions and observations, we rigorously quantify the bias and uncertainty of nonlinear site response models relative to linear and equivalent-linear models.

2. Mixed effects regression

Mixed effects regression allows for the estimation of repeatable biases and variances for different groupings of the data, such as dependence between multiple observations at a site. For the P ground motion at the P site, a linear mixed effects regression model is given by:

\[ y_{ij} = \mu + \eta_i + \epsilon_{ij}, \]

where:
- \( y_{ij} \) = site response model residual = \( \text{PSA}_{\text{meas}}(T)/\text{PSA}_{\text{pred}}(T) \) = ln[\( \text{PSA}_{\text{meas}}(T) \)/\( \text{PSA}_{\text{pred}}(T) \)]
- \( \mu \) = fixed effect = repeatable bias across all sites and ground motions
- \( \eta_i \) = \( N(0, \sigma^2) \) = inter-site residual = “site term”
- \( \epsilon_{ij} \) = \( N(0, \sigma^2) \) = intra-site residual = within-site residual after accounting for the site term

The parameters estimated by the regression are the fixed effect \( \mu \), inter-site variance \( \sigma^2 \), and intra-site variance \( \sigma^2_I \). The estimated mean and variance of \( Y \) are: \( \bar{y} = \mu \) and \( \sigma^2 = \sigma^2 + \sigma^2_I \).

3. Trends in intra-site residuals

- With all repeatable effects removed, the plots of intra-site residuals are helpful for assessing the models’ deviations for large-strain behavior.
- The nonlinear residuals generally display similar behavior to the equivalent-linear residuals at large shear strains (at least 0.1–0.4%), but do not slope upward as significantly.
- The scatter in the nonlinear residuals is slightly less than that of the equivalent-linear residuals at large shear strains, suggesting that the nonlinear model is more precise than the equivalent-linear model at large shear strains.

4. Analysis of model uncertainties

- There are more significant differences among the model biases than among the model standard deviations (Figure 4).
- All 1D site response models (linear, equivalent-linear, and nonlinear) are biased toward underprediction of ground motions at short spectral periods, where nonlinear effects are strongest; however, the equivalent-linear and nonlinear model biases are smaller than the linear model bias.
- When the fixed effect for Arias Intensity (which encompasses a range of short periods) is separated by bins of maximum shear strain (Figure 5), it is shown that all models offer their most severe underpredictions for small-strain motions.

5. Physical insights

- To assess potential reasons for the bias in the 1D site response models, we investigated various aspects of the model inputs; for example, the assumed KiK-net shear-wave velocity profiles.
- At KIK-net station IWT08B (NEHRP Site Class D, \( V_\text{S30} = 305 \text{ m/s} \)), results are shown for the original versus the revised profile with a depth-dependent exponential gradient.
- Utilization of the depth-dependent gradient \( V_\text{S30} \) profile instead of the original coarser \( V_\text{S30} \) profile leads to reduced artificial localization of shear strain, and, in the aggregate, less model bias across all motions recorded at this site (Table 1).

6. Conclusions

- Differences in accuracy are largest between the linear model and the other models; there are generally small differences between the equivalent-linear and nonlinear models.
- The equivalent-linear and nonlinear site response models generally do not deviate from each other significantly until maximum shear strains of 0.05–0.1%; at larger shear strains, the nonlinear site response model residual has less scatter and offer less severe underpredictions than the equivalent-linear model.
- All models are shown to exhibit consistent positive bias (underprediction) at short periods, particularly for small-strain motions.
- Persistent model biases at short periods suggest that: (1) many of these sites may exhibit a breakdown in the site–response assumptions; and/or (2) the site investigation data provided on the KIK-net website may be over-simplified.
- Adjustments to the assumed shear-wave velocity profile have a significant impact on model predictions, in some cases more so than changing the constitutive model.

7. References


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