Deliverable 7.5

D7.5 Report on the test metrics of non-linear ground-motion models and high-resolution exposure/risk models

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Summary

This deliverable, mainly associated with the task T7.4 of Work Package 7 has been hampered strongly by the canceled deployment of low-cost sensors (due to the international chip crisis) in the test areas as were planned in the proposal. For the investigation of high-resolution ground-motion models (GMM), an experiment in the Valais, Switzerland, area was planned in order to cover the sedimentary basin and the mountain slopes on each side of the valley with instruments. Measurement in such an environment would have provide the necessary high-resolution recordings for the envisioned study. To compensate for that, we teamed up with the URBASIS project (see Acknowledgments) and conducted a study on non-linear GMMs to investigate whether or not the concept of non-linearity is warranted by the data.

Likewise, due to a lack of distributed low-cost sensors in buildings in Europe, we were not able to develop the necessary testing metrics for exposure/risk testing as no measurements were available. However, to compensate for this, we have collected damage reports of the Petrinja, Croatia, and Samos, Greece, earthquakes. The building-scale exposure model from task T2.7 will be finished for these area during summer this year so that we can provide first tests of the exposure model (in combination with the respective fragility model) against real damage assessments.

We applied the testing procedure for non-linear site amplification models as published by Loviknes et al. (2021) to two new datasets: ESM (European Engineering Strong-Motion) and NGA-West2 (Next Generation Attenuation Relationships for Western US). For the two datasets, stations from Italy and California were used, respectively. For both datasets the non-linear amplification models perform better than for the Japanese strong motion KiK-net (Kiban-Kyoshin) network tested by Loviknes et al. (2021). In particularly, several Italian stations show a down-going trend at strong ground motions. However, the non-linear models do not perform well with the 30m time-averaged shear-wave velocity (V_{S30}).

Introduction

Nonlinear site effects mainly occur for large ground motion at soft soils where there are few measured observations. Predicting and modeling such effects is therefore challenging, and most nonlinear site amplification models used in ground-motion models (GMMs) are either partly or fully based on numerical simulations. To test the prediction power of nonlinear site-amplification models, Loviknes et al. (2021) developed a testing framework using observed site-amplification from the KiK-net network in Japan. In this report we summaries the method of Loviknes et al. (2021) and show an example using the software codes given in D7.4 (see above).

The Japanese Kiban-Kyoshin network (KiK-net) is a part of the National Research Institute for Earth Science and Disaster Prevention (NIED), and one of the most comprehensive strong-motion networks in the world (Aoi et al. (2011)). The KiK-net network have been recording since 1996 and consist of 692 stations with instruments in both borehole and at the ground surface. Several of the KiK-net stations have recorded earthquakes in a wide range of ground motion intensity, including high intensity ground motions with the potential to trigger nonlinear site amplification (Régnier et al., 2013). The KiK-net network is therefore ideal for testing nonlinear site-amplification prediction models.

Method

The testing framework of Loviknes et al. (2021) consist of three parts:

1. A simple linear ground-motion model is derived on the dataset of interest.
2. The residuals between the predicted linear ground motion and each observation are split into between-event, between-site random effect and record-to-record variability.
3. Site-amplification models are tested against the residuals of individual well-recorded stations and stations grouped into site proxy bins.

Each step is described in further details in the following sections.

The aim of the two first steps in the method of Loviknes et al. (2021) is to obtain the observed site amplification. First the linear site amplification is derived using a linear GMM. The linear GMM is derived using only the linear part of the dataset, that is, small ground motions below a certain threshold or ground motions recorded on hard rock sites. Loviknes et al. (2021) sets the peak ground acceleration (PGA) threshold to PGA = 0.05g following Régnier et al. (2013) and the V_{S30} (time-averaged shear-wave velocity in the upper 30m of a 1-D soil column) threshold for rock sites to V_{S30} = 760m/s. The linear GMM of Loviknes et al. (2021) is developed following the same method and functional form as the GMM by Kotha et al. (2018):

$$\ln(\mathrm{PSA}) = f_R(M_W, R_{JB}) + f_M(M_W) + \delta B_e + \delta S2S_s + \delta WS_{e,s} \qquad (1)$$

With fixed effects $f_R(M_W,R_{JB})$ and $f_M(M_W)$ capturing the scaling of pseudo spectral acceleration (PSA) with distance and magnitude, and random effects δB_e and $\delta S2S_s$ quantifying the event and site variability, respectively. $\delta WS_{e,s}$ is the record-to-record variability. The model does not include a fixed-effect site term based on V_{S30}, and the $\delta S2S_s$ therefore captures all site-specific response and can be used as the empirical site-amplification function (Kotha et al., 2018).

Secondly, the prediction of the linear GMM $\mu_{e,s}$ for an event e and site s is subtracted from the corresponding observed ground motion $Y_{e,s}$, to obtain the total residual $\epsilon_{e,s}$:

$$\epsilon_{e,s} = \ln Y_{e,s} - \ln \mu_{e,s} \qquad (2)$$

The total residual $\epsilon_{e,s}$ is then split to quantify the random effects of the events and sites into the event and site variability:

$$\epsilon_{e,s} = \delta B_e + \delta S2S_s + \delta WS_{e,s} \qquad (3)$$

Here δB_e and $\delta S2S_s$ are the event and site term representing the systematic deviation between the observed ground motions, from the median predictions of the GMM, and $\delta WS_{e,s}$ is the “left-over” residual capturing the record-to-record variability.

Both the GMM development and the splitting of the residuals are performed using the mixed-effects regression algorithm *lmer* by Bates et al. (2015) in the statistical program R. A mixed effects regression model includes both fixed-effect (explanatory variables) and random-effect terms (grouping factors) in the regression to deal with hierarchical data (Bates et al., 2015). The predicted response spectra and aleatory variability of the linear GMMs at 50 km R_{JB} distance for different magnitudes are shown in Figure 1.

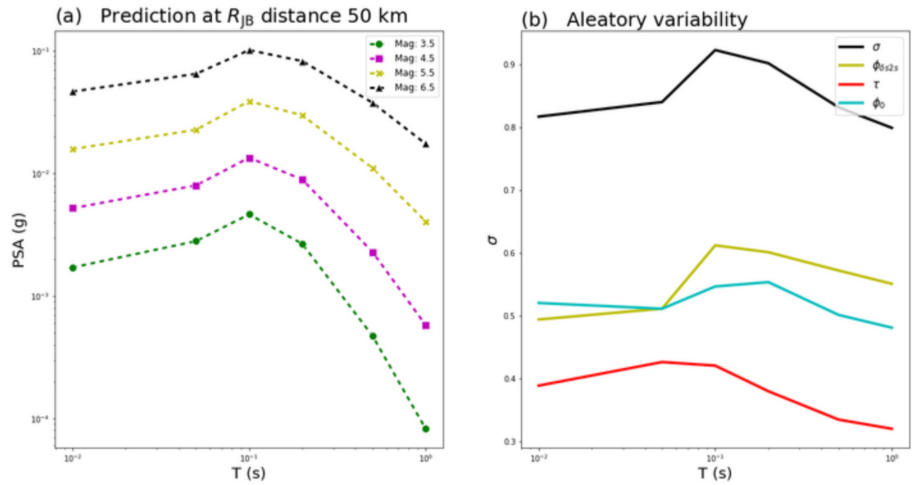

Figure 1: (a) Response spectra of pseudo spectral acceleration (PSA) for different magnitudes at R_{JB} 50 km, and (b) the total aleatory variability σ and standard deviations τ, φs2s and φ0.

To evaluate how well the derived GMM scales with magnitude and distance, a residual analysis should be performed. Figure 2 and 3 show the distributions of δB_e with respect to magnitude, $\delta S2S_s$ with respect to V_{S30}, and $\delta WS_{e,s}$ with respect to distance for the linear GMMs and the split residuals, respectively. In both figures, δB_e with magnitude and $\delta WS_{e,s}$ with distance have a mean consistently close to zero and no clear trend. This confirms that the scaling with magnitude and distance are well captured. For $\delta S2S_s$ a down-going trend with V_{S30} is observed, this is however expected because a V_{S30} site term was not included in the fixed effects (Kotha et al., 2018).

The final step of the testing procedure is to evaluate the prediction power of non-linear site-amplification models compared to the prediction power of a linear site amplification model. Because "left-over" residual $\delta WS_{e,s}$ is expected to contain the non-linear site response, the linear site-amplification model is defined as $\delta WS_{e,s} = 0$ for every value of $PGA_{rock} \exp(\delta B_e)$. The models are tested

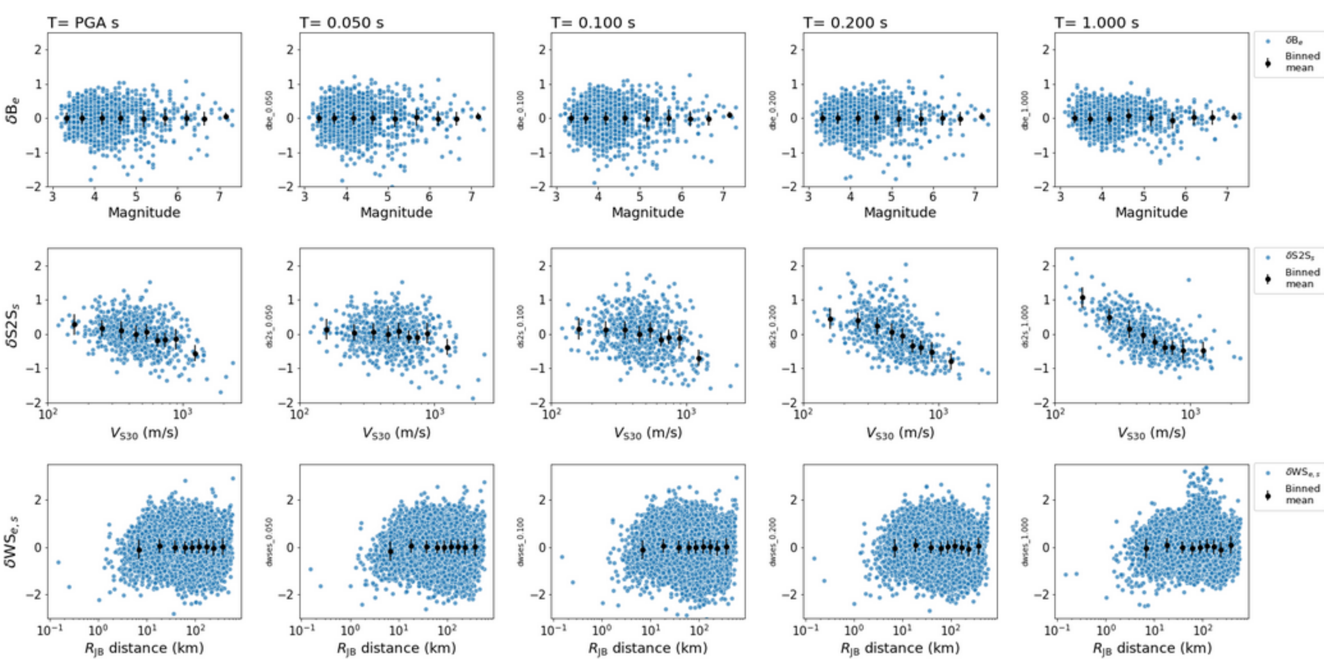

Figure 2: Random effect residual plot from the mixed-effect regression used to develop the linear ground-motion model. (Top row, a–d) Distribution and binned mean of δBe with magnitude for each period T. (Center row, e–h) Distribution and binned mean of δS2Ss with VS30 in log-scale for each period T. (Bottom row, i–l) Distribution and binned mean of δWSe,s with R_{JB} distance. The binned means are with 95% confidence interval. The means of δBe and δWSe,s has a mean centered around zero and do not show any trend with magnitude and distance, this show that the GMM regression has captured the scaling of magnitude and distance, while δS2Ss shows a negative trend with V_{S30} because a V_{S30} site-term was not included in the fixed effects (Equation 1).

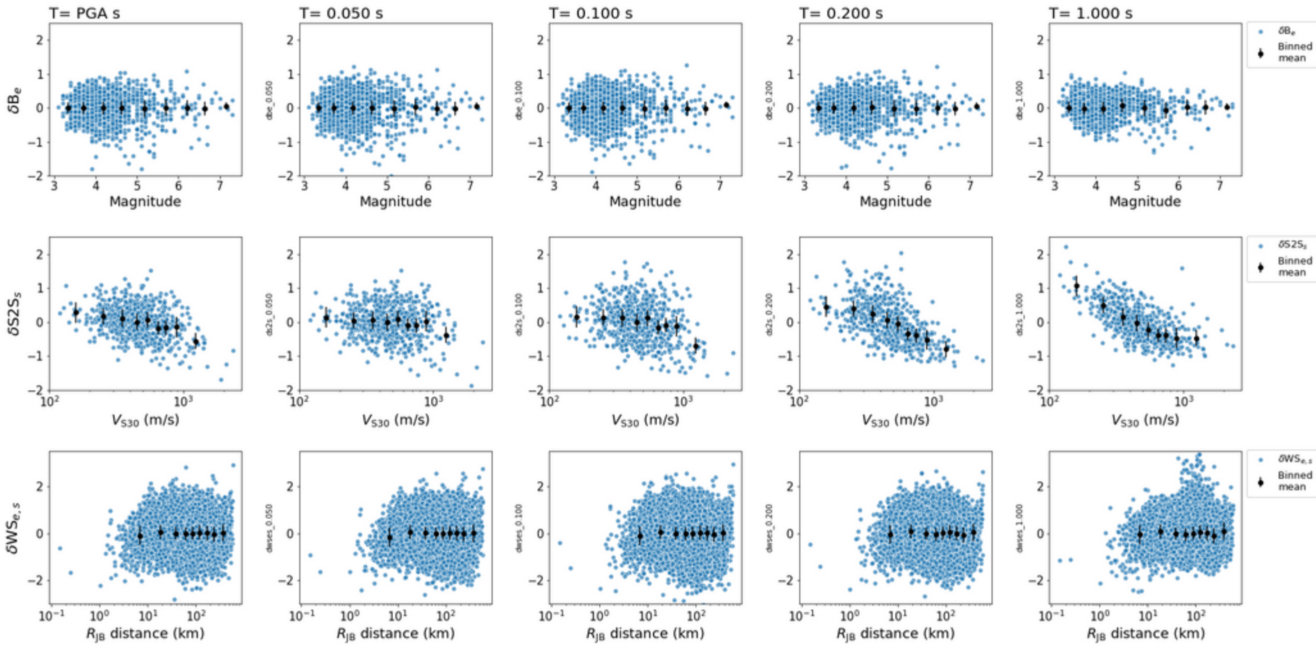

Figure 3: Random effect residual plot as in Figure 2. Here the residuals are from the splitting of the total residual (Equation 2) using mixed-effect regression.

on the site response of individual soft-soil stations (V_{S30} < 760 m/s) that have recorded at least 4 records with PGA > 0.05g.

The prediction power of the amplification models is measured in mean absolute error (MAE):

$$MAE_S = \frac{\sum_{e}^{N} \delta WS_{e,s} - F_{e,s}}{N} \tag{6}$$

here $F_{e,s}$ is the modeled site-amplification and MAE$_s$ is the mean absolute error for each site s for N number of events e. For each site and period the model with the lowest score is considered the best model. However, it is important to note that the MAE score only measures the deviation between the residuals and the predictions of the amplification models and does not have direct physical meaning. The model is therefore only best in a relative sense (Mak et al., 2015).

Models and Dataset

Loviknes et al. (2021) tested the non-linear site-amplification models of Seyhan and Stewart (2014), Sandikkaya et al. (2013), Hashash et al. (2020) and the site-amplification model in the GMM of Abrahamson et al. (2014). In this report, for simplicity, we only test the site amplification models of Seyhan and Stewart (2014) (SS14) and Abrahamson et al. (2014) (ASK14). Both these models were developed as a part of the NGA-West2 project and based on the simulations of Kamai et al. (2014).

We test the models against site amplification derived from ground motion records recorded by KiK-net stations and processed and compiled into a dataset by Bahrampouri et al. (2020). We only use onshore events with depth ≤ 35km, recorded at R_{JB} < 600km, with the recommended usable frequency bandwidth of at least 60% of the range from zero to the Nyquist frequency (Bahrampouri et al., 2020).

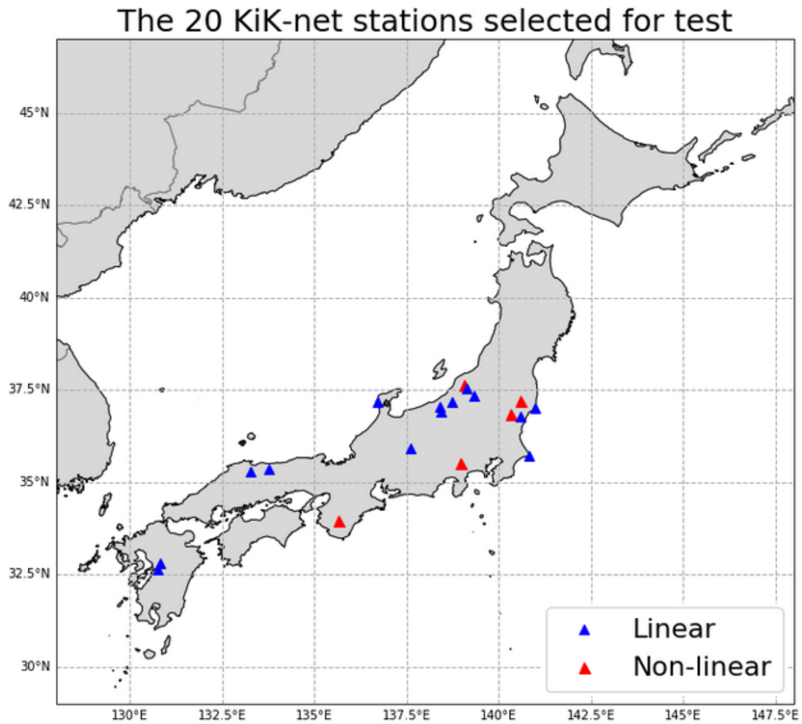

Figure 4: Map of Japan showing the location of the stations selected for the test. The blue triangles show the stations where the linear amplification model had the best score, and the red triangles show the stations where one of the non-linear amplification models had the best score.

Results

Out of all the soft-soil stations in the KiK-net network, 19 stations have recorded sufficient strong-motion records to be included in the test, the locations of these stations are shown in Figure 4. For most of the selected stations, the linear site amplification model had the best score (blue triangles in Figure 4). Only 5 stations had a nonlinear site amplification model score better than the linear amplification model (red triangles in Figure 4). Figure 5 shows the site response of one of the stations selected for the test. For this station, IBRH12, the two non-linear amplification models has the best score for most of

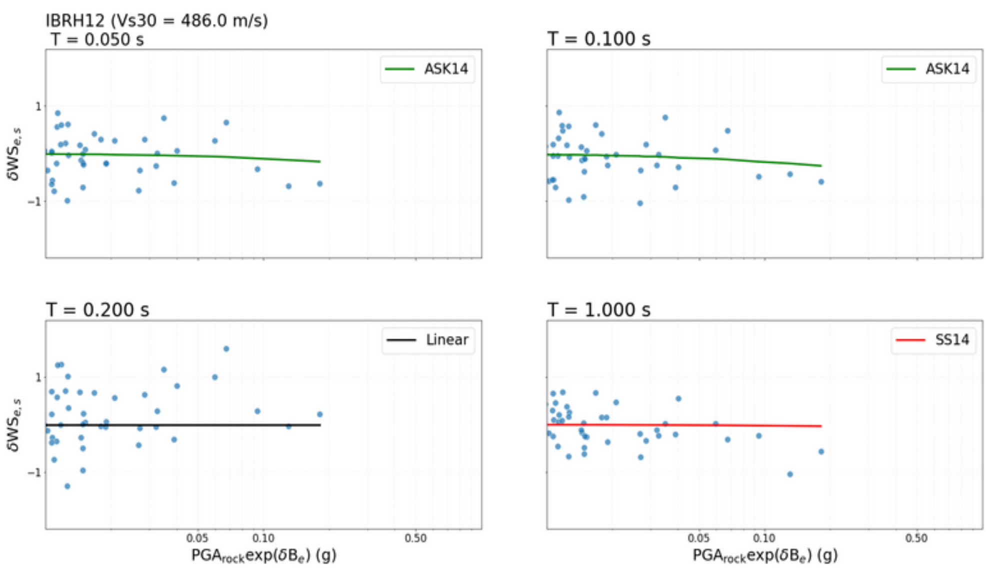

Figure 5: Station IBRH12 with the best linear and non-linear site amplification models of each period, compared to δWSe,s with respect to rock peak acceleration with event variability (PGA_{rock} exp(δBe)). The non-linear models are from Seyhan and Stewart (2014) (SS14) and Abrahamson et al. (2014) (ASK14).

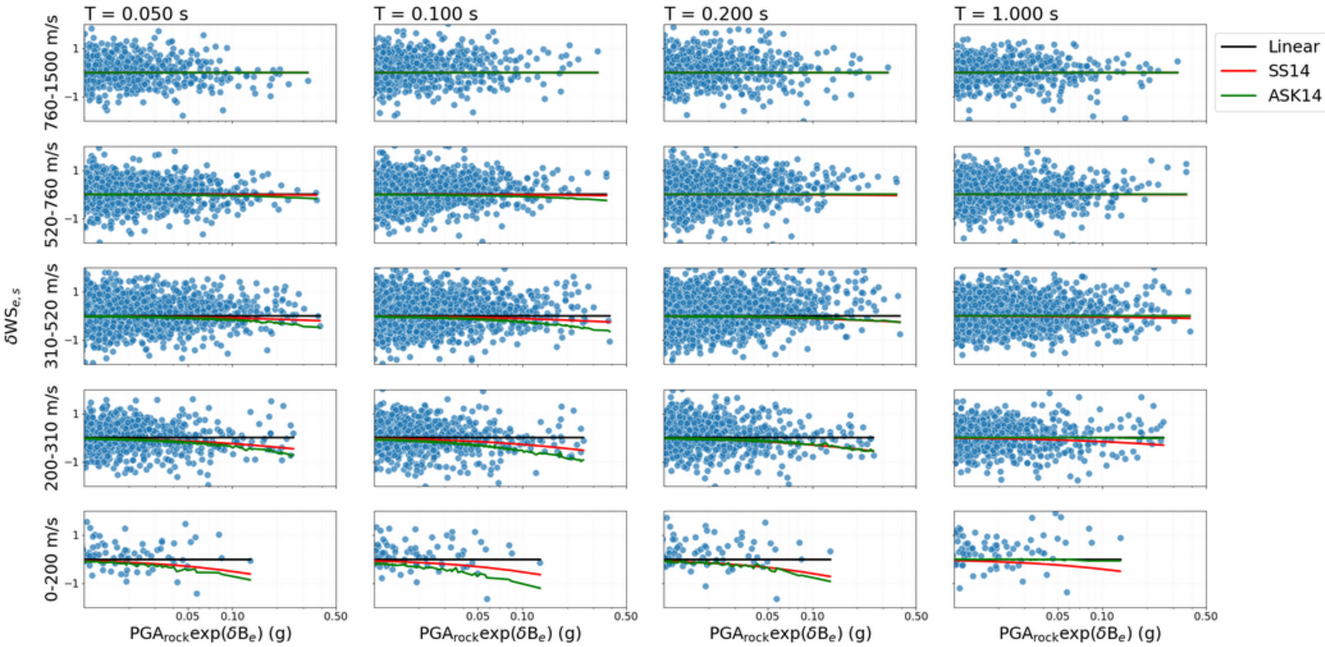

Figure 6: The KiK-net stations grouped by V_{S30} with the linear and non-linear site amplification models compared to δWSe,s with respect to rock peak acceleration with event variability (PGA_{rock} exp(δBe)). The non-linear models are from Seyhan and Stewart (2014) (SS14) and Abrahamson et al. (2014) (ASK14). The trend predicted by the models are not observed.

the periods and a down-going trend is observed. However, for most of the KiK-net stations, the observed site response shows a large variability and little clear trend, even within stations with similar V_{S30} values. This is especially clear when the stations are grouped by V_{S30} as in Figure 6.

Discussion and conclusion

This report summaries the method of the testing framework of Loviknes et al. (2021) for testing nonlinear site amplification model used in ground motion models. The method uses mixed-effects regression to derive a linear GMM and split the residuals between the observation and linear predictions into event, site and record-to-record variability. The residuals are then used to test nonlinear site-amplification models against a linear site-amplification model. Loviknes et al. (2021) found that, for most stations, the simple linear site amplification model has the best performance. Loviknes et al. (2021) considered ground motions up to 0.2 g, and therefore argues that using nonlinear site-amplification models in this ground-motion range is not necessary. The study only considers nonlinear amplification models based on V_{S30} and PGA, other models using other parameters to capture non-linearity should therefore be tested in the future.

The main limitations of the test is the limited number of strong ground-motions. For Japan adding records from the Knet network to the test, is in planning. For Italy and California, Loviknes et al. (2022) applied the same test using the ESM (Luzi et al. 2016, Lanzano et al., 2021) and NGA-West2 (Ancheta et al., 2014) datatsets, respectively. Loviknes et al. (2022) found that for both Italy and California, the within-station site-response variability was smaller than for Japan and the nonlinear site-amplification models had an overall better performance. However, the number of strong ground-motions are still limited and the nonlinear amplification models are not able to capture the non-linearity at high V_{S30} > 500 m/s. Alternative site proxies used to characteristic non-linear site amplification should therefore be investigated in future studies.

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