Systematic assessment of nonlinear soil behaviour at KiK-net sites (Japan) and correlation with geotechnical and geological indicators

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Systematic assessment of nonlinear soil behaviour at KiK-net sites (Japan) and correlation with geotechnical and geological indicators

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Abstract: In this study we propose the SoilGrid database with predicted soil properties down to 2 meters depth and geological maps of Japan as geotechnical indicators with the potential to explain nonlinear site-effects. To test these indicators, we measure the nonlinear site-response in the Japanese Kiban–Kyoshin Network (KiK-net) as the change in amplitude and shift in frequency between strong-motion events and the linear site-response. These measurements are then fitted to a hyperbolic tangent function. We plan to use the coefficients and parameters from the fitted hyperbolic tangent function to explore the correlation between the geotechnical indicators and sites with strong nonlinear soil-behaviour.

Keywords: site-effects, nonlinearity, soil properties, site proxies

1. Introduction

Earthquake ground-motions are heavily influenced by the local soil conditions at a site. For small ground motions and stiff sites, the local soil-response behaves linearly. However, for larger ground motions and softer sites nonlinear site-effects have been observed. Nonlinear site-amplification is characterised by a simultaneous decrement of shear modulus and an increment of shear-wave damping ratio as a function of increasing levels of strains; this results in a decrease in amplitude of the site-amplification transfer function (due to increased damping) and a shift of resonance frequency to lower frequencies (because of the decrease in shear-wave velocity; Régnier et al., 2013; Bonilla et al., 2005).

Site-effects are generally captured using the average shear-wave velocity in the upper 30 meters of the soil column (V_{S30}), but Darendeli (2001), among others, have shown that nonlinear soil behaviour mainly occurs in the upper few meters of a site, and that soil materials with similar V_{S30} may exhibit different susceptibility to nonlinear response. Indeed, several studies have shown that V_{S30} is not a suitable proxy for characterizing nonlinearity (e.g. Loviknes et al. 2021). In this study we therefore aim to test new geotechnical indicators characterising the upper part of the soil columns for predicting nonlinear site-effects.

A first challenge in this work is to identify and quantify the nonlinear site-effects from the ground-motion records. Here we follow the work of Régnier et al. (2013) to compute the amplitude change and frequency shift in the surface-to-borehole spectral ratios of strong ground-motion recorded by stations in the Kiban–Kyoshin Network (KiK-net, Aoi et al., 2004; National Research Institute for Earth Science and Disaster Resilience (NIED), 2019) in Japan.

Studies characterizing the nonlinear soil response at the scale of geotechnical laboratory testing have identified i) the grain size of the loose sediments and ii) the effective pressure acting upon them, as two key parameters controlling nonlinear soil behaviour (Darendeli, 2001). To identify site condition indicators which could characterize and map the susceptibility to nonlinearity, we resorted to two databases:

- the pedologic database SoilGrid (Poggio et al., 2021), which is a global gridded map of predicted soil properties
- the Seamless Digital Geological Map of Japan (SDGM, 2014)

Our aim is testing whether nonlinear site-effects can be better explained by geotechnical parameters describing the uppermost layers of the soil.

This extended abstract describes i) the strategy we followed to systematically characterize the nonlinear soil amplification over a large set of instrumented sites in the KiK-net network, and ii) the geotechnical site condition indicators we retrieved at these sites with the intention of testing their potential use as proxies for nonlinear site-effects.

2. Dataset

We use earthquake ground-motions recorded by the Japanese Kiban–Kyoshi Network (KiK-net). Because of the unique configuration of the KiK-net network as a nationwide network with more than 600 sites with instruments at both the surface and in borehole, the network is well suited for studies of site-effects. In this study we only use the 539 stations which has recorded at least one event with PGA >= 0.05 g. From these stations we use all ground-motions recorded between 1997 and 2017 with magnitude above 3.

2.1. Geotechnical indicators

The SoilGrid database is a globally gridded map of soil properties predicted using machine learning with observed soil profiles and environmental covariate data as input (Poggio et al., 2021). The database consists of predicted pedological properties at 250 m resolution for six depth levels down to 2 meters. In this study we focus on the volumetric fraction of coarse fragment ($cm^3/dm^{3)}$ and weight fractions of silt, clay and sand (g/kg) predicted for a depth range 1-2 m (deepest available layer). The distributions of these layers are shown in Figure 1, and the nonparametric correlation (Cleveland, 1979) between V_{S30} and the layers are shown in Figure 2 with the coarse fraction showing a clear increase with V_{S30} (Figure2a). The data was downloaded from the SoilGrid webpage (https://soilgrids.org/, last accessed March 2022). Previous studies have shown the correlation between inferred pedological parameters from the SoilGrid database and site condition parameters (Vs30, H800), as well as the local earthquake response (Bergamo et al., 2019, 2021). In this study, we therefore plan to explore the relation between the SoilGrid soil-properties and nonlinear site-effects.

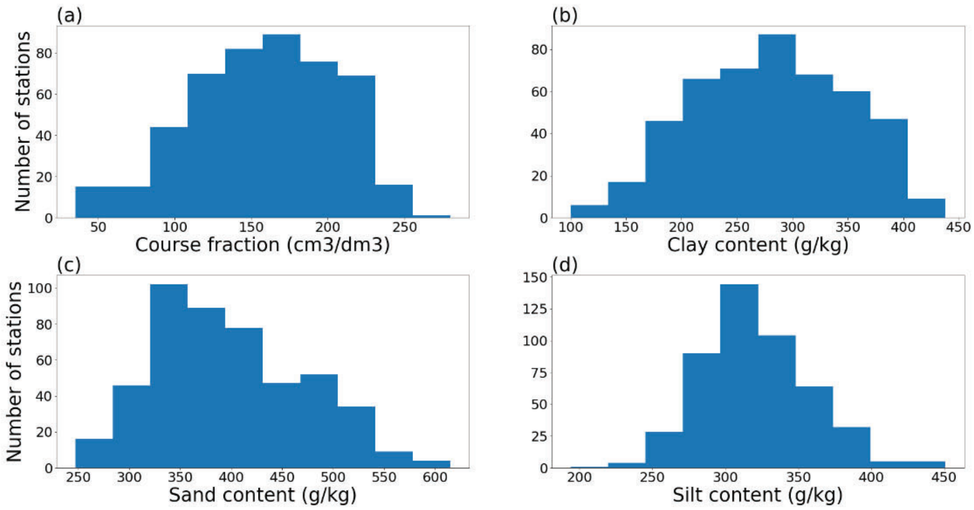

Fig. 1 – The station distribution of the SoilGrid layers (a) course fraction, (b) clay content, (c) sand content and (d) silt content.

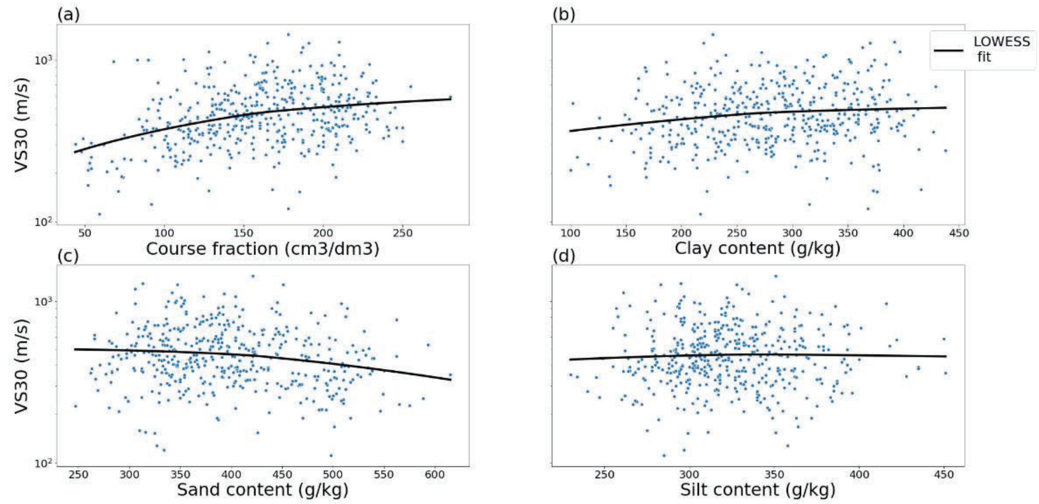

Fig. 2 – The SoilGrid layers (a) course fraction, (b) clay content, (c) sand content and (d) silt content with V_{S30}. A nonparametric locally weighted linear regression (LOWESS) is fitted to the soil layers to better illustrate the trend with V_{S30}.

The geological formations of surface layers were also retrieved from the Seamless Digital Geological Map of Japan (SDGM, 2014, downloaded from https://gbank.gsj.jp/seamless/index_en.html). The map has a 1:200,000 resolution and was derived by merging geologic quadrangle maps covering all of Japan. The different formations were re-classified to fewer groups by Bergamo et al., (2019, 2021). The Station distribution of these geological subclasses is shown in Figure 3.

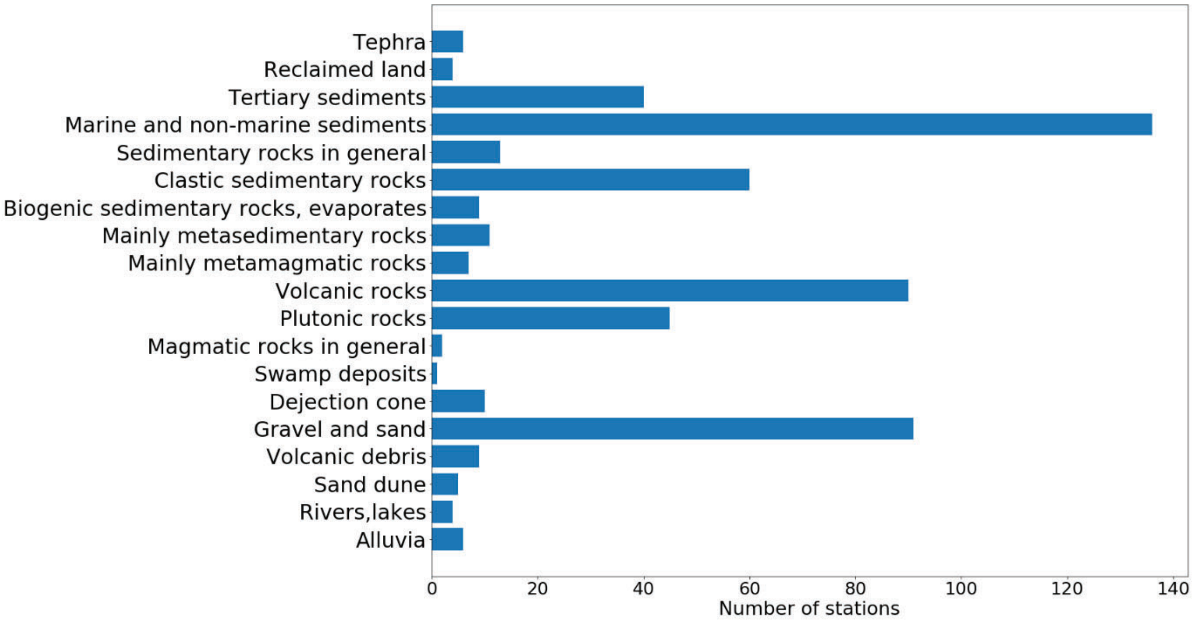

Fig. 3 – The station distribution of the geological subclasses grouped by Bergamo et al., (2019, 2021) from the Seamless Digital Geological Map of Japan.

3. Method

Régnier et al, (2013) proposed several parameters for describing nonlinear soil-behaviour at KiK-net stations. In this study we use the frequency shift (Sh_{ev}) and percentage of nonlinearity (PNL_{ev}), which are measured as the shift in frequency and change in amplitude, respectively, of the site-response curve of each record compared to the linear site-response. As in Régnier et al, (2013) we use the Surface-to-Borehole ratio (SBr) as the empirical site-response calculated for each record, and the linear site response as the mean SBr ± standard deviation (std) of all records with PGA < 0.01 g at a site.

PNL_{ev} for event *ev* is measured as the area between the event SBr_{ev} and the upper limit of the linear SBr (SBr_{lin}^{+}), divided by the area under the mean linear Sbr_{lin} (equation 5 and 6 in Régnier et al., 2013):

$$A = \sum_i^N \begin{cases} SBr(i) - SBr_{lin}^{+}(i) \log_{10}\frac{f_{i+1}}{f_i} & for\ SBr(i) \geq SBr_{lin}^{+}(i) \\ SBr_{lin}^{+}(i) - SBr(i) \log_{10}\frac{f_{i+1}}{f_i} & for\ SBr(i) \leq SBr_{lin}^{+}(i) \\ 0 & otherwise \end{cases} \quad (1)$$

$$PNL_{ev} = \frac{A}{\sum_i^N |SBr_{lin}| \log_{10}\frac{f_{i+1}}{f_i}} \quad (2)$$

where N is number of frequencies f between 0.6 and 20 Hz.

The shift in frequency (Sh_{ev}) is measured by cross-correlating the SBr of a record with the mean linear SBr. The PNL and Sh for each record and site is shown with increasing PGA in Figure 4.

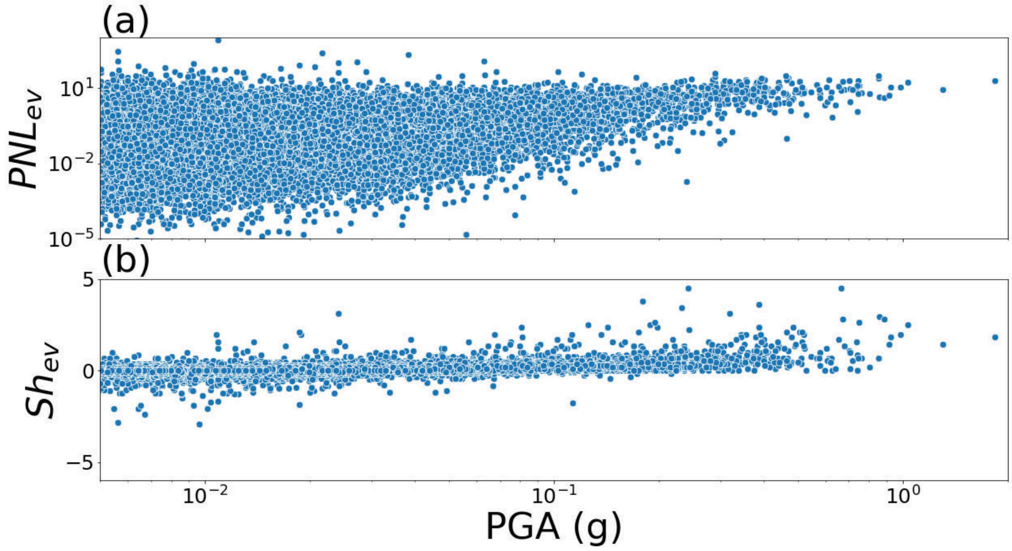

Fig. 4 – The Percentage of Nonlinearity PNL_{ev} (a) and the shift in frequency Sh_{ev} (b) with Peak Ground Acceleration (PGA).

To obtain site-specific parameters capturing nonlinearity in a synthetic fashion, the PNL_{ev} and Sh_{ev} for each station are plotted against PGA (recorded at surface) and fitted to a hyperbolic tangent function (as in Régnier et al, 2013):

$$PNL_{fitted} = a\,\{\tanh[\log(PGA) + b] + 1\} \tag{3}$$

Note that a hyperbolic tangent function can also be used to model the increase in damping and reduction of the shear-modulus with increasing deformation, and it is therefore well suited for describing nonlinear soil behaviour (Régnier et al., 2013). The linear SBr and SBr of three strong-motion events for the station FKSH12 is shown in Figure 5a. The de-amplification and frequency shift is clearly observed. The PNL_{ev} and Sh_{ev} of the station is shown in Figure 5b and 5c, respectively, along with the fitted hyperbolic function.

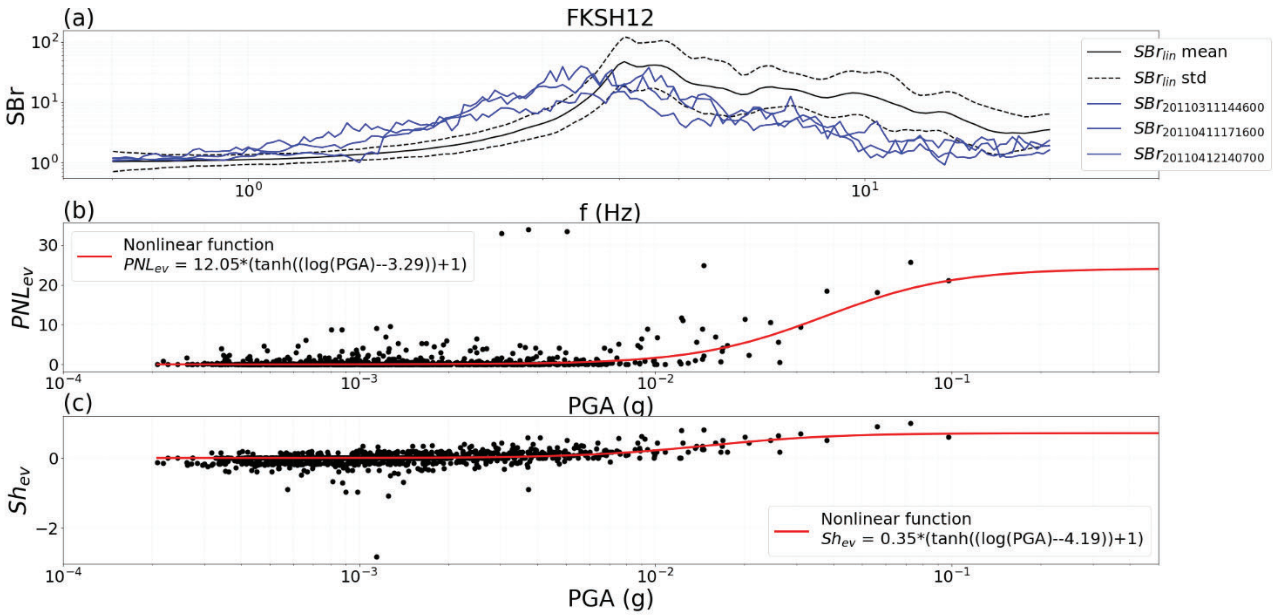

Fig. 5 – (a) The mean linear SBr (black solid line) with standard deviations (black dotted line) and SBr of three strong-motion events (blue lines) for the station FKSH12. The frequency shift and change in amplitude is clear. (b) The PNL_{ev} with increasing PGA (black dots) and the fitted hyperbolic function (red line). (c) The Sh_{ev} with increasing PGA (black dots) and the fitted hyperbolic function (red line).

The derived coefficients of the hyperbolic functions of PNL and Sh a_{st} and b_{st} for each station *st* are used as site-specific parameters for nonlinearity. For PNL a_{PNL} represent the degree of amplitude shift, while for Sh, a_{Sh} represent the degree of frequency shift. The distribution of *a* for PNL and Sh are shown in Figure 6. For both PNL and Sh the exponential of *b* corresponds to the PGA value at which the relative change (derivative) of PNL and Sh is maximum. This value is not necessarily the same for PNL and Sh, as demonstrated in Figure 7.

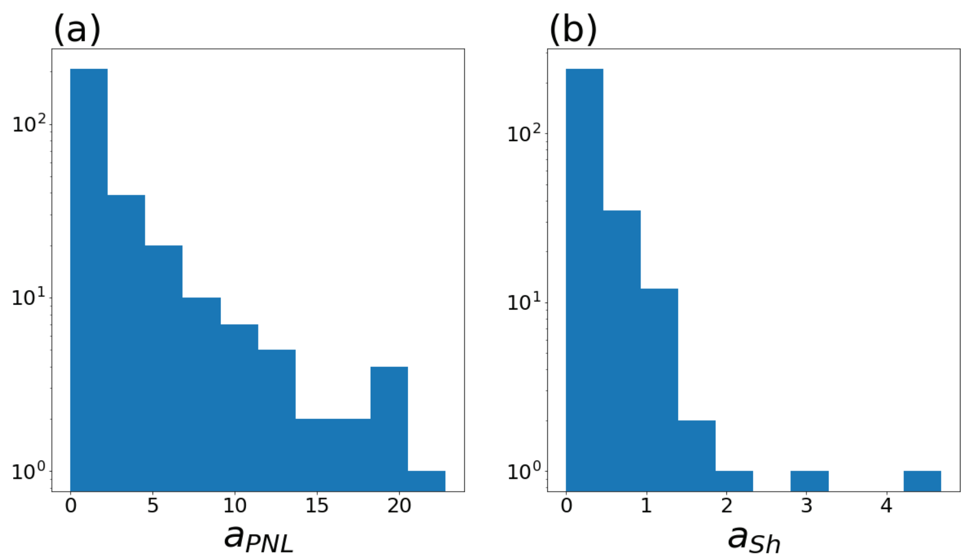

Fig. 6 – The Station distribution of the *a* coefficients from the hyperbolic tangent function fitted for the (a) PNL_{ew} and (b) Sh_{ev}.

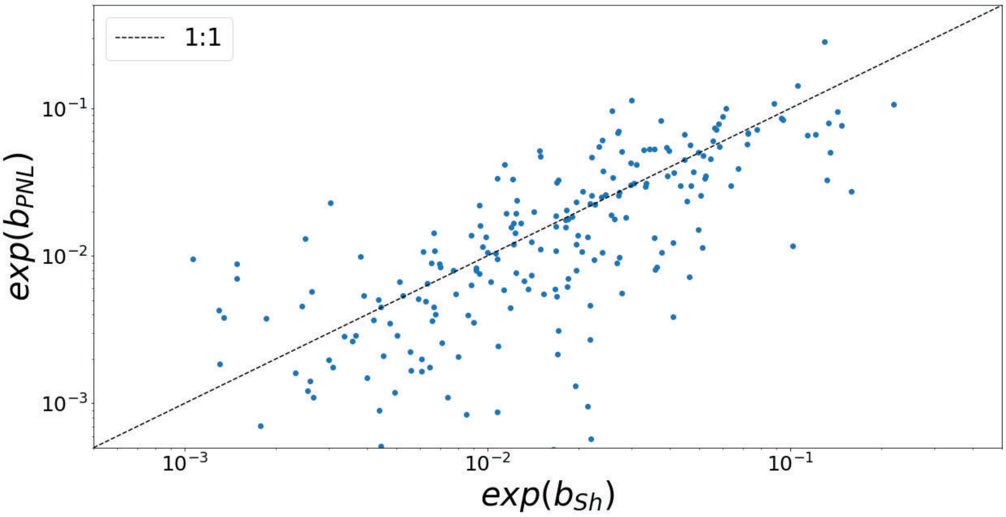

Fig. 7 – The exponential of the *b* coefficient for PNL_{ev} (y-axis) and Sh_{ev} (x-axis)

In addition to *a* and *b*, the PGA at 10% of the maximum PNL and Sh PGA_{thPNL} and PGA_{thSh}, the percentage of nonlinearity at PGA=0.05 g, PNL_{site}, and the frequency shift Sh_{site} at PGA=0.05 g, Sh_{site} is derived for each station.

4. Conclusions

This extended abstract describes geotechnical indicators with the potential to describe nonlinear soil-behaviour and a method to capture the degree of nonlinear site-amplification in earthquake ground-motions recorded at KiK-net stations in Japan.

Because nonlinear site-effects are mainly expected to occur in the upper few meters of the soil, we propose the use of SoilGrid database parameters such as the predicted fractions of course fragments clay, silt and sand content, as potential site proxy for nonlinearity. An additional potential site indicator for nonlinear site-effects is the information on the geological formations from the Seamless Digital Geological Map of Japan.

The nonlinear site-response is measured as the change in amplitude (percentage of nonlinearity, PNL_{ev}) and the shift in frequency (Sh_{ev}) of the surface-to-borehole ratio for each event recorded at a site. At each station, a hyperbolic tangent function is then fitted to these two parameters with increasing PGA. The coefficients to the hyperbolic function, along with the PNL and Sh value at PGA=0.05 g and the PGA at 10% of the maximum PNL and Sh, are finally considered as the site-specific parameters describing the nonlinear behaviour of the site. We have applied this method systematically to all KiK-net stations and plan to use the parameters to investigate the correlation between the sites that show a strong nonlinear behaviour and the proposed geotechnical properties.

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References

- Aoi, S., T. Kunugi, and H. Fujiwara (2004). Strong-motion seismograph network operated by NIED: K-net and KiK-net, J. Jpn.Assoc. Earthq. Eng. 4, 65–74.
- Bergamo, P., C. Hammer, and D. Fäh (2019). SERA WP7/NA5-Task 7.4: towards improvement of site characterization indicators. Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe (SERA) Project, Deliverable D7.4, available at http://www.sera-eu.org/en/Dissemination/deliverables/ (last retrieved on March 2022).
- Bergamo, P., C. Hammer, and D. Fäh (2021). Correspondence between Site Amplification and Topographical, Geological Parameters: Collation of Data from Swiss and Japanese Stations, and Neural Networks-Based Prediction of Local Response, Bull. Seismol. Soc. Am. XX, 1–23, doi: 10.1785/0120210225
- Bonilla, L. F., Archuleta, R. J., and Lavallée, D. (2005). "Hysteretic and dilatant behavior of cohesionless soils and their effects on nonlinear site response: Field data observations and modeling." *Bulletin of the Seismological Society of America*, **95**(6):2373–2395.
- Cleveland, W. S. (1979). Robust locally weighted regression and smoothing scatterplots, J. Am. Stat. Assoc. 74, 829–836.
- Darendeli, M. B. (2001). *Development of a new family of normalized modulus reduction and material damping curves*. The university of Texas at Austin.
- Poggio, L., de Sousa, L. M., Batjes, N. H., Heuvelink, G. B. M., Kempen, B., Ribeiro, E., and Rossiter, D.: SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty, SOIL, 7, 217–240, https://doi.org/10.5194/soil-7-217-2021, 2021.
- Loviknes, K., S. R. Kotha, F. Cotton, and D. Schorlemmer (2021). Testing Nonlinear Amplification Factors of Ground-Motion Models, Bull. Seismol. Soc. Am. 111, 2121–2137, doi: 10.1785/0120200386
- National Research Institute for Earth Science and Disaster Resilience (2019), NIED K-NET, KiK-net, National Research Institute for Earth Science and Disaster Resilience, doi:10.17598/NIED.0004
- Régnier, J., Cadet, H., Fabian Bonilla, L., Bertrand, E., and Semblat, J. F. (2013). "Assessing nonlinear behavior of soils in seismic site response: Statistical analysis on KiK-net strong-motion data." *Bulletin of the Seismological Society of America*, **103**(3):1750–1770.
- SDGM (2014). 1:200,00 Seamless Digital Geological Map of Japan (SDGM), Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, https://gbank.gsj.jp/seamless/index_en.html?