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Etude comparative de la capacité de différents proxies de site à réduire la variabilité aléatoire des équations de prédiction des mouvements du sol (données KiK-net).

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RÉSUMÉ. L'objectif principal de ce travail est de tester la capacité des différents proxies des conditions de site (PCS) à réduire la variabilité aléatoire du mouvement sismique (VAMS). Les PCS utilisés dans cette étude sont V_{s30} , la pente topographique (slope), la fréquence fondamentale de résonance (f_0) et la profondeur à laquelle la vitesse des ondes S dépasse 800 m/s (H_{800}). Chaque PCS est d'abord considéré individuellement, puis couplé avec un autre PCS: six couples de PCS (C-PCS) sont ainsi considérés, à savoir $[V_{s30}-f_0]$, $[V_{s30}-H_{800}]$, $[V_{s30}-slope]$, $[f_0-H_{800}]$, $[f_0-slope]$ et $[H_{800}-slope]$. Les performances de chaque PCS et C-PCS sur la VAMS sont mesurées en relatif sur la base des écarts types associés aux équations de prédictions de mouvement sismique (EPMS), et plus particulièrement de la variabilité intra-événement. Ces EPMS sont dérivées avec une approche par réseau de neurones artificiels, sur un sous ensemble de 5563 enregistrements de la base des données accélérométriques KiK-Net. Ces EPMS relient le PGA, PGV et les accélérations spectrales (pseudo-spectre PSA à 18 périodes 0.01 à 4 s) à un nombre réduit de paramètres d'entrée : M_w , profondeur focale (Depth), distance Joyner-Boore R_{JB} et CPS/C-PCS. Il ressort de cette étude comparative que, si l'on n'utilise qu'un seul proxy, V_{s30} est le plus performant des 4 PCS à courte période, tandis qu'à longue période ce sont f_0 et H_{800} qui exhibent les meilleures performances; le paramètre slope ne doit être considéré que comme un pis-aller en l'absence de toute autre information quantitative. En revanche, il est remarquable de constater que tous les C-PCS permettent une réduction significative de la VAMS, avec une attention particulière pour les deux C-PCS $[V_{s30}-f_0]$ et $[f_0-slope]$ ce dernier étant de loin le plus économique à obtenir

ABSTRACT. The aim of this paper is to investigate the ability of various site-condition proxies (SCPs) to reduce ground-motion aleatory variability. The SCPs used here are V_{s30} , the topographical slope (slope), the fundamental frequency (f_0) and the depth at $V_s=800$ m/s (H_{800}). We considered first the performance of each SCP taken alone, and then the combined performance of the 6 SCP pairs $[V_{s30}-f_0]$, $[V_{s30}-H_{800}]$, $[f_0-slope]$, $[H_{800}-slope]$, $[V_{s30}-slope]$ and $[f_0-H_{800}]$. This analysis is performed using a Neural Network approach applied on a KiK-net subset for the derivation of attenuation equations setting the relationship between various ground motion parameters (PGA, PGV and pseudo-spectral acceleration), and M_w , R_{JB} , focal depth and SCPs. V_{s30} is found to perform the best of single proxies at short periods ($T < 0.6$ s), while f_0 and H_{800} perform better at longer periods; considering SCP pairs needs to significant improvements, with particular emphasis on $[V_{s30}-f_0]$ and $[f_0-slope]$ pairs.

MOTS-CLÉS : Condition de site, variabilité aléatoire, réseau de neurones, KiK-Net, Equation de prédiction, PGA, PGV et PSA

KEYWORDS: Aleatory uncertainty, site-condition proxies, KiK-Net, Neural networks, GMPE

1. Introduction

The incorporation of the effects of near-surface geology or site classification in Ground Motion Prediction Equations (GMPEs) has gone through an evolution in the past years (Chiou and Young., 2008). At the beginning, ground-motion models typically contained a scaling parameter based on site classification (e.g.,

Boore et al. 1993), or presented different models for “hard rock” and “soil” sites (e.g., Campbell 1993; Sadigh et al. 1997). Boore et al. (1997) introduced the explicit use of the average shear-wave velocity in the upper 30 meters. V_{S30} has become

de facto a standard for Ground-Motion Prediction Equations development and seismic-hazard assessment at national and international scales. In this way, It has been observed (e.g., Borchardt, 1994) that V_{S30} is a useful parameter to predict local site amplification in active tectonic regimes. Certainly V_{S30} is a simple metric SCP but he is not a low cost SCP. For this reason Wald and Allen, 2007, Allen and Wald, 2009 have been used topographic slope from digital elevation models (DEMs) constructed through remote sensing (satellite imaging) to give a first-order estimation of site classes based on V_{S30} .

On another hand, V_{S30} alone cannot satisfactorily predict the amplification for sites underlain by deep sediments, which require knowledge of the geology to depths greater than 30 m (e.g., Choi et al., 2005). Campbell (1989) found that adding a parameter for depth to basement rock improved the predictive ability of empirical ground motion models. On their side, Cadet et al., 2011 and Derras et al., 2012 used another SCP: the fundamental resonance frequency, f_0 , as determined by the horizontal-to-vertical (H/V) spectral ratio technique (Bard et al., 2010). As the f_0 (H/V) SCP is able to identify low frequency amplification on thick sites, its relevance is compared with another SCP often proposed to properly account for sediment thickness, H_{800} (depth at which the shear wave velocity exceeds 800 m/s). This analysis is performed by interpreting results obtained from ground-motion prediction equations (GMPEs).

The aim of this work is to evaluate and analyze the relative decrease of the ground-motion aleatory variability achieved by the consideration of V_{S30} and/or local slope as a site condition proxy, a priori more relevant for short period ground-motions, and f_0 (H/V) and/or H_{800} SCP that may be more suitable for long periods. The analysis is performed using firstly four continuous proxy values [$\log_{10}(V_{S30})$ or $\log_{10}(\text{slope})$ or $\log_{10}(f_0)$ or $\log_{10}(H_{800})$] named one-SCP and 6 configurations [$\log_{10}(V_{S30})$ and/or $\log_{10}(\text{slope})$ and/or $\log_{10}(f_0)$ and/or $\log_{10}(H_{800})$] for testing the effect of the two site condition proxies (two-SCPs).

The KiK-net database used here consists of shallow crustal events recorded on sites with V_{S30} , H_{800} values directly derived from downhole measurements of V_s profile (Dawood et al., 2014) and available slopes (Ancheta et al., 2014), while f_0 values are taken from Régnier et al. (2013). The dataset used in this manuscript has been collected between 1997 and 2011. The Artificial Neural Network (ANN) approach and a random-effects like procedure (Derras et al., 2014a) have been used for the derivation of GMPEs setting the relationship between various ground motion parameters (PGA, PGV and 5% damped pseudo-spectral acceleration PSA from 0.01 s to 4 s), and event/station meta-parameters (moment magnitude M_w , Joyner &Boore distance R_{JB} , focal depth, and site condition proxies V_{S30} , slope, H_{800} and f_0).

After a short presentation of the dataset and the selection criteria used for the present study, a section is dedicated to the presentation of the ANN models and its specific implementation in the present application. The following section concentrates on the results of the application to the KiK-net data. The ANN has the advantage that no prior functional form is needed (Derras et al., 2012): the actual dependence is established directly from the data, and can therefore be used as a guide for a better understanding of the factors which control ground-motions. The ANN approach is used to discuss the respective influences of each considered site proxy and the combined effect of the two SCPs.

2. Data set

The Kiban-Kyoshin network (KiK-net) is one of two strong motion seismograph networks constructed in Japan following the 1995 Kobe earthquake. The KiK-net has now more than 650 stations that are each equipped with a pair of surface and downhole sensitive 3-component digital accelerometers, allowing for an empirical evaluation of the site response at each station.

The resulting dataset considered here consists of 5563 recordings from 393 sites to 249 earthquakes. This subset is downloaded from <http://nees.org/dataviewer/view/1050:ds/1094/>. The range of the Joyner &Boore distances (R_{JB}) for the selected records is from 3.0 km to 1416 km, the range of M_w is from 3.7 to 7.3. The focal depth is from 0 to 30 km. The range of the recorded PGA is from 10^{-4} g to 0.4 g. Regarding V_{S30} , we have

$V_{s30min}= 106.83$ m/s and $V_{s30max}=1433$ m/s. H_{800} ranges from 1 to 1000 m. The topographical slope values are obtained from the NGA-West2 flatfile (Ancheta et al. 2014), slope=[0.0011 to 0.375] m/m. Finally, the fundamental resonance frequency, f_0 , is determined from the horizontal-to-vertical (H/V) and surface/downhole spectral ratios. The values of f_0 were calculated as detailed in Régnier et al., 2013. They range between 0.22 Hz and 22.71 Hz.

Fig. 1 represents the cumulative distribution function (CDF) of the used dataset versus R_{JB} , M_w , V_{s30} , topographical slope, H_{800} , f_0 , focal depth and PGA. The four SCP distributions are found to follow a lognormal law, while M_w and focal depth follow a normal law. In our ANN models, we thus used the logarithm values of all SCPs and spectral ordinates PSAs.

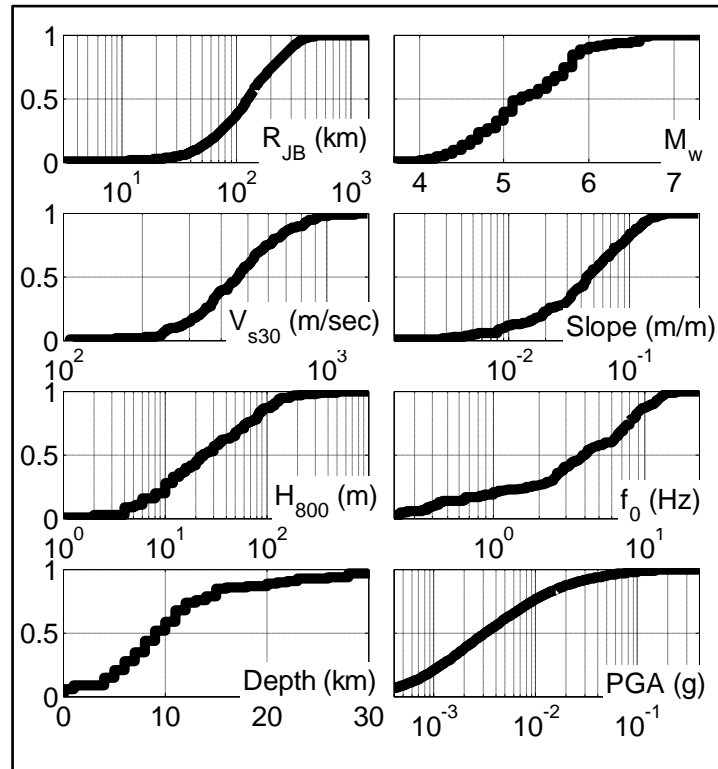


Figure 1. Cumulative distribution function (CDF) versus R_{JB} , M_w , V_{s30} , slope, H_{800} , f_0 , focal depth and PGA

The misfit and the correlation coefficient (R) of the 6 SCP configurations are plotted in Fig. 2. Although some pairs do exhibit some correlation ($R_{max}= 0.57$ between $\log(V_{s30})$ and $\log(f_0)$), the scatter is large enough for the SCPs to be considered as almost independent site parameters for the derived ANN models.

3. ANN prediction models

The Artificial Neural Network Model of Multilayer Perceptron with a total connection is used here, with one hidden layer with three neurons (Fig. 3). The ANN type used in this work is the feed-forward ANN. The Quasi-Newton Back Propagation technique also called “BFGS” has been applied for the training phase (Shanno and Kettler, 1970). To avoid “over-fitting” problems we chose the adequate regularization method (Derras et al., 2012). Moreover, the selected activation functions are a “tangent sigmoid” for the hidden layer and “linear” for the output

layer. In Fig. 3, the symbols W and b represent the synaptic weights and bias with subscripts representing the corresponding neurons between two layers, respectively. The output layer groups all the considered ground motion parameters, i.e. PGA, PGV, and 5%-damped PSA at 18 periods from 0.01 to 4 s. A procedure similar to the random-effects approach was used to provide between- and within-event standard deviations, as described in Derras et al., (2014a). 11 different ANN models were built, differing by the site proxy or the pair of site proxies used in the input layer. The first ANN model is built on the basis of the moment magnitude M_w , $\log_{10}(R_{JB})$ and focal depth as inputs: it accounts only for source and path effects, and can set the reference to quantify the gains achieved by the consideration of the various site proxies in the other ANN models. The second pack of 4 ANN models considers only one-SCP in the input layer, namely, V_{s30} , slope, H_{800} , f_0 (proxy_{1site} in fig. 3). The next 6 ANN models investigate the combined influence of pairs of SCPs (proxy_{1site} and proxy_{2site} in fig. 3).

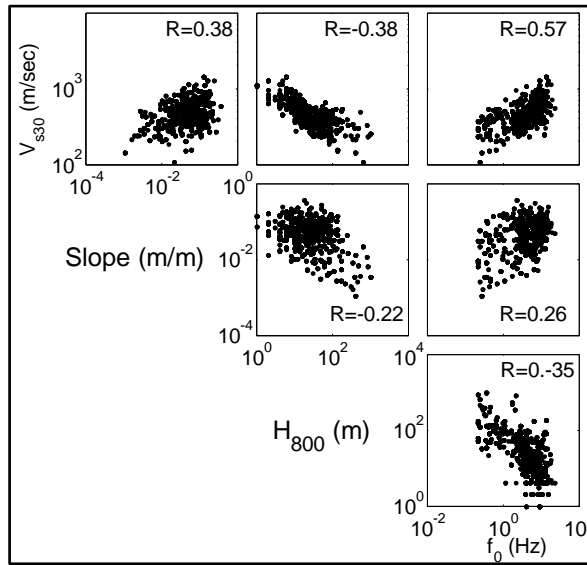


Figure 2. Correlation between different SCPs, with the correlation coefficient values.

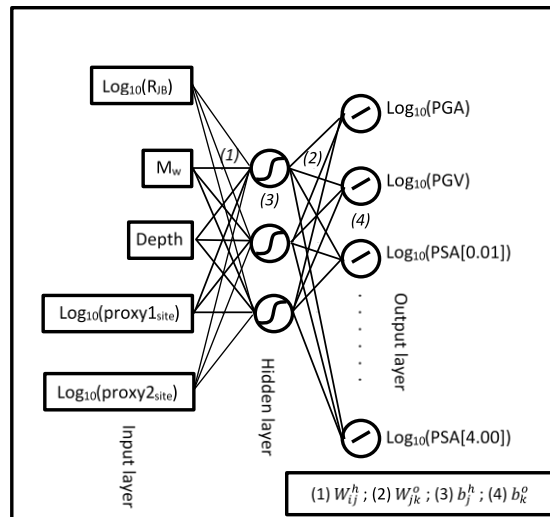


Figure 3. Structure of the Neural Networks models considered in this study.

4. Results

1. Performance of SCPs in reducing the aleatory variability

The use of a random-effect like procedure (Abrahamson and Youngs, 1992) allows to analyze the structure of the aleatory variability σ , and to quantify the performance of each model and SCPs through the reductions in σ . Each residual between an observation and the corresponding prediction (with a total standard deviation σ) can be decomposed into a between-event and a within-event component: both are zero-mean, independent, normally distributed, random variables with standard deviations τ and ϕ , respectively (Al Atiket al., 2010). The between-events and within-event residuals are uncorrelated, so the total standard deviation σ at a period T of the ground-motion model, σ , can be written as:

$$\sigma(T) = \sqrt{\tau(T)^2 + \phi(T)^2} \quad [1]$$

The variations of τ , ϕ and σ versus period are displayed on Fig. 4 for all ANN models: without SCPs, one-SCP and two-SCPS.

In addition, to better quantify the gains achieved by each SCP model, the values of the variance reduction coefficient RC defined in Eqn. 4.2 are listed in Table 4.1 for a few output parameters, i.e. PGA, PGV and PSA at $T=[0.2, 0.5, 1.0, 2.0]$ s.

$$RC(T) = \left(\frac{\sigma(T)_{proxy}}{\sigma(T)_{none}} - 1 \right) \cdot 100 ; (\%) \quad [2]$$

As usual for most GMPEs, the values of the between-event variability τ are much lower than the within-event variability ϕ values. τ , ϕ and σ are found identical at very short period ($T < 0.05$ s) whatever the ANN model: none of the SCP is efficient at high frequency. The various variability components then increase from 0.05 to about 0.15 s, and then decrease significantly as period is increasing. At short to intermediate periods, i.e. for T between 0.1 and 0.7 s, the ϕ of the one-SCP models are found smaller compared to the reference model. The smallest ϕ are obtained for the V_{s30} SCP, followed by f_0 and H_{800} proxies which have comparable performance, while the slope proxy exhibits the poorest performance. At longer periods, as expected, f_0 and H_{800} give the lowest values of ϕ and perform better than V_{s30} . V_{s30} is confirmed to be relevant mainly for short to intermediate periods, as expected from the fact it samples only the shallow subsurface, while f_0 and H_{800} are more sensitive to the deep sediments and more relevant for long periods.

As expected, the two-SCP models lead to largest variance reductions, but it is interesting to notice that all pairs of proxies exhibit very similar performance. At short to intermediate periods, i.e. from 0.1 to 0.7 s, the $[V_{s30}, \text{slope}]$ pair is found to provide the smallest values of ϕ , while for $T > 0.7$ s the "best" pair turns out to be $[f_0, H_{800}]$ as logically expected since both parameters are much sensitive to the bedrock depth. Interestingly enough, the $[f_0, \text{slope}]$ pair has a good performance over the whole period range $[0.1 - 4]$ s, while it is the associated with the lowest measurement cost.

The obtained results confirm that the reduction becomes significant beyond $T = 0.2$ s and for PGV as well. Overall, the largest reduction is observed for the SCP pair $[f_0, H_{800}]$ at $T = 2.0$ s, where it reaches 17 %. As in Derras et al., 2014b, the best performance of one-SCP models is found for V_{s30} at short periods (around 5% reduction), and for H_{800} or f_0 at long periods, with variance reduction around 13-15% (14.65 % at 2 s for H_{800}). Two-SCPs models exhibit significantly larger reductions, especially at long periods. The gains achieved with the slope proxy are systematically smaller than those achieved with other proxies

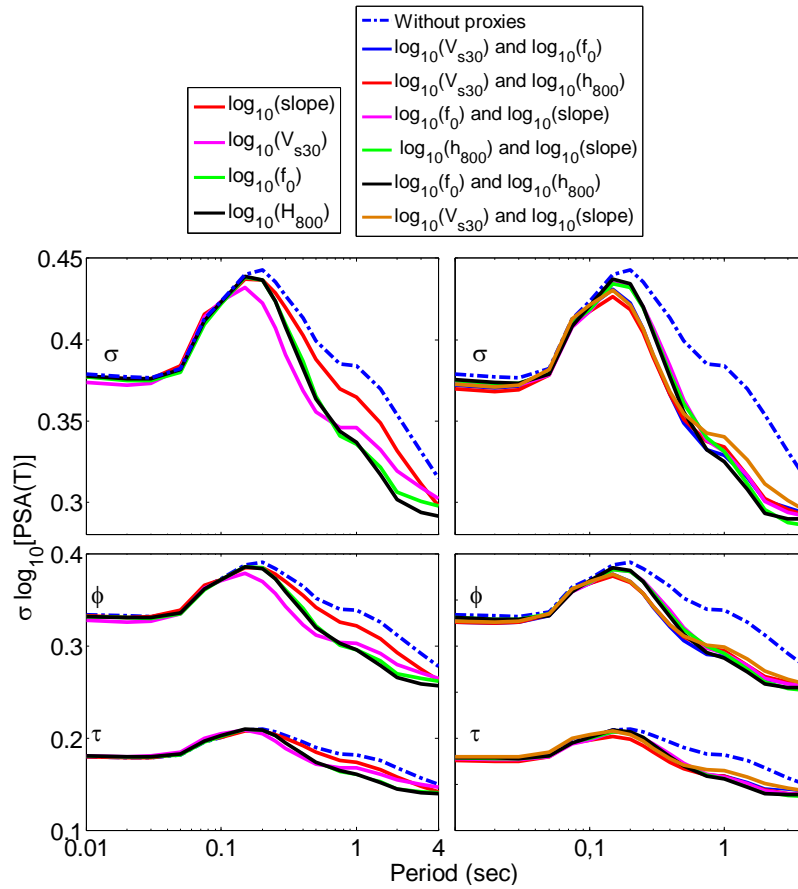


Figure 4. Sensitivity of the aleatory variability to the site proxies used as input for the neural network.

4.2 – Impact of the various SCPs on median predictions

The choice of SCP significantly impacts the ground-motion aleatory variability. We investigate here their impact on the median estimates, first through a comparison of the 4 one-SCP ANN models. Fig. 5 displays of distance dependence of the spectral acceleration at for $T=0.0, 0.2$ and 1.0 s, for the median magnitude ($M_w=5.5$) and focal depth (10 km), and the median values of the various SCPs (i.e., $V_{s30}=500$ m/s, $f_0=4$ Hz, $H_{800}=30$ m and slope=0.04 m/m, as derived from Fig. 1). The site proxy type ($V_{s30}/f_0/H_{800}/\text{slope}$) is observed not to have any impact on median predictions for $R_{JB}>10$ km, and only limited one at shorter distances, where the scatter is coming mainly from the small number of data.

A complementary information is provided by the amount of difference in predictions for "extreme" values of the SCP. Fig. 6 displays the "site/rock" spectral ratio for various periods ($T=0.0$ s, 0.2 s and 1.0 s: a consistent definition of "site" and "rock" was taken for all SCPs, simply by considering the SCP values corresponding to 10 % and 90 % of the CDF distributions shown in Fig. 1.

Besides an intriguing trend of site amplification to increase with distance, the site amplification is found to generally increase with period (except for slope SCP), as classically found in most GMPEs. V_{s30} and slope SCPs are found to provide the largest amplification at short periods (which remains however smaller than 60%). The situation is opposite at long period ($T = 1.0$ s) where the SCP providing the largest amplification is f_0 (H/V) with amplification ranging from 3 to 3.5. None of the four tested SCP is thus "optimal" over the whole period range.

Similar results for two-SCPs models are displayed on Fig. 6 bottom: all SCP pairs are confirmed to provide very similar results, with a slightly larger amplification however for the $[V_{s30}, f_0]$ and $[slope, f_0]$ pairs at long periods at $T=1.0$ s, with amplifications in the range $[3.5 - 4.5]$.

| | one-SCP in \log_{10} | | | | two-SCPs in \log_{10} | | | | | |
|-------|------------------------|-------|-----------|-------|-------------------------|--------------------|--------------|------------------|----------------|------------------|
| | V_{s30} | f_0 | H_{800} | slope | V_{s30}, f_0 | V_{s30}, H_{800} | $f_0, slope$ | $H_{800}, slope$ | f_0, H_{800} | $V_{s30}, slope$ |
| PGA | 1.36 | 0.51 | 0.29 | 0.36 | 1.75 | 2.41 | 1.23 | 1.07 | 0.90 | 1.61 |
| PGV | 8.12 | 5.60 | 5.94 | 3.39 | 8.92 | 8.79 | 6.89 | 7.31 | 7.19 | 8.99 |
| 0.2 s | 4.56 | 1.38 | 1.35 | 1.35 | 4.60 | 5.50 | 2.32 | 2.43 | 1.92 | 4.87 |
| 0.5 s | 11.02 | 8.56 | 9.00 | 2.89 | 12.70 | 12.11 | 9.09 | 9.65 | 10.9 | 11.30 |
| 1 s | 9.85 | 12.56 | 12.24 | 4.96 | 14.25 | 13.00 | 13.72 | 13.67 | 15.2 | 11.33 |
| 2 s | 9.72 | 13.34 | 14.65 | 6.16 | 14.80 | 14.56 | 15.02 | 16.43 | 17.0 | 11.94 |

Table 1. Variation reduction (RC) in % for the 10 ANNs types for PGA, PGV and at $T=[0.2, 0.5, 1.0, 2.0]$ s

5. Summary and conclusions

The application of neural network approach to a KiK-net data set offered the possibility to test the performance of various site condition proxies to reduce the aleatory variability in ground motion prediction equations. The four available SCPs are V_{s30} and H_{800} (both derived from downhole measurements), f_0 (the fundamental frequency derived from H/V ratios and surface/downhole spectral ratios), and the slope derived from DEM data, which has been proposed as a proxy to V_{s30} values. A total of 11 neural network models were derived to describe the dependence of response spectra ordinates on moment magnitude M_w , Joyner &Boore distance R_{JB} , focal depth D and various combinations of SCPs : one without any SCP which provides the "reference case", 4 with each single SCP, and 6 with the 6 possible pairs of SCPs $[V_{s30}-f_0]$, $[V_{s30}-H_{800}]$, $[f_0-slope]$, $[H_{800}-slope]$, $[V_{s30}-slope]$ and $[f_0-H_{800}]$.

When only one-SCP is used, the largest reduction of aleatory variability with respect to the "reference case" is found to be provided by V_{s30} at short to intermediate periods ($T \leq 0.6$ s), and by f_0 or H_{800} at longer periods. Amongst the four SCPs, the parameter "slope" is thus found to provide the worst performance when considered alone. However, when SCP pairs are considered, comparable performance is found whatever the pair of proxies. In particular, the "best pairs" are found to be $[V_{s30}-H_{800}]$ at short periods and $[f_0-H_{800}]$ at long periods, while the "low cost" pair $[f_0-slope]$ provides a good compromise over the whole period range $[0.1 - 4]$ s. These results should of course be tested for other data sets, but the four SCPs are only rarely available simultaneously.

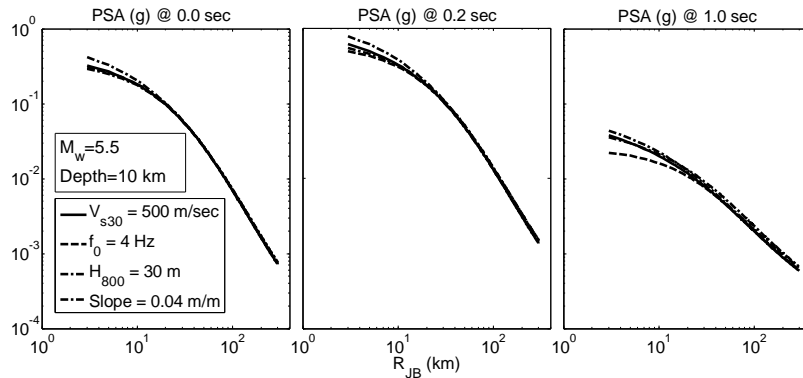


Figure 5.Effect of the site-condition proxies on the median ground motion.

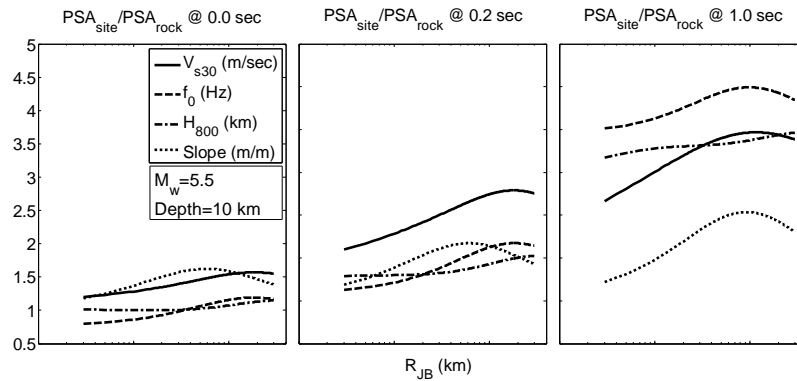


Figure 6.Comparison of ratios between PSA versus R_{JB} for site to PSA for rock for $M_w = 5.5$ focal depth=10 km. We consider One-SCP (top) and Two-SCPs bottom.

Data and resources

PSA, V_{s30} and H_{800} used in this study were collected from the KiK-net web site <http://nees.org/resources/7849>. slope have been collected and disseminated by the The Pacific Earthquake Engineering Research Center at <http://peer.berkeley.edu/ngawest2/databases/>. f_0 from (Régner et al., 2013)

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