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SINGLE STATION SIGMA IN CHILE

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Abstract

Single station sigma allows for a more realistic estimation of expected seismic demand. The use of single-station sigma in a non-ergodic Probabilistic Seismic Hazard Analsyis framework avoids the double counting of uncertainties and allows for the more rigorous incorporation of site and path effects into hazard estimations. We present a ground motion prediction model (GMPE) developed from a catalogue that includes Chilean interplate and inslab events. The model is used to evaluate the quantity of uncertainty that can be attributed to source, path, site effects, and what can be treated as pure aleatory uncertainty. Our results show remarkable agreement with other studies in some components of the overall uncertainty, but differences in other components, which shed light into the areas that could be advanced in the future. Site characterization and prediction of V_{s30} through proxies represent a key challenge and where leap improvement can be achieved.

Keywords: Single-station sigma, ground motion prediction model, Chile..

1. Introduction

A Ground Motion Prediction Model (commonly known as GMPE) provides an estimation of ground motion intensity (e.g. PGA or pseudo-spectral acceleration). A GMPE is one of the most important components in seismic hazard analysis and risk mitigation, their development is vital for the design and evaluation of structures and singular sites.

A large proportion of the seismicity that affects Chile is associated with the subduction of the Nazca plate beneath the South American plate. This tectonic environment produces large earthquakes ($M_w > 7$) with high recurrence rates, which have a strong impact on civil infrastructure and continuously produce economic and social losses.

We present a ground motion prediction model and then use the model to evaluate the scatter introduced by the uncertainty on the predictive variables. We also compare source, site, and residual uncertainty (i.e. single-station standard deviation) for Chile subduction zone with other tectonics regions. The ground motion parameters predicted by the model are the peak ground acceleration (PGA) and 5% damped pseudo-acceleration response spectra up to a period of 10 seconds.

2. Strong ground motion database

The strong ground motion data used for this work is based on [1, 2], which compiled metadata from site, events, and records from the Chilean subduction zone in a public *flatfile*. This *flatfile* contains the magnitudes and locations reported by the International Seismological Centre ([3]), Harvard Centroid Moment Tensor (CMT, [4]), and *Centro Sismológico Nacional* (CSN). The moment magnitudes (Mw) were generally obtained from CMT, and for events without a reported Mw a conversion equation between the local magnitude (M_L) reported by CSN with Mw by CMT is used [2]. To segregate events by type (i.e. interface, inslab, or crustal) we combined the style of faulting of the event, based on rake angle, with the hypocentral location of the event with respect to the Perú-Chile subduction trench.

The site characterization is based on the average shear wave velocity in the upper 30 meters (V_{s30}). In sites without a measured V_{s30}, two proxies were combined to inferred a V_{s30} value, the first proxy is the predominant frequency (f_0) following the relationships between site period and V_{s30} developed by [5], and the second proxy is the topographic slope [6]. The weight of each proxy is computed using a modified approach from [7]. The sites were separated in two groups according to the type of H/V curve. Sites with *flat* H/V curves or with predominant frequencies less than 1.6 Hz show poor predictive capability using the H/V proxy, hence are treated separately.

The strong ground motion records were processed component per component, the procedure uses a bandpass Butterworth filter. The cut-off frequencies are selected to ensure that the level of noise present on each of the seismic records is the same. The source-to-site metrics available on the database are the closest distance to fault plane (Rrup), hypocentral distance (Rhyp), epicentral distance (Repi), and azimuth (Az) between station and event. The initial data used to perform the regression includes 3,220 records from 426 earthquakes, this includes 1935 records from 239 interface events and 1285 records from inslab events (Fig. 1).

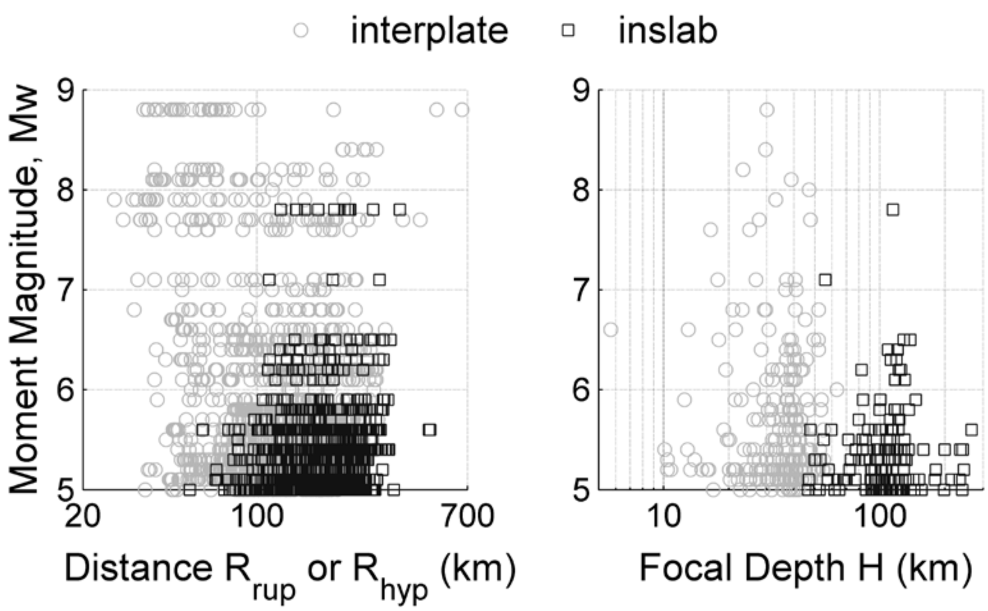

Fig. 1 – Distribution of data used in this study

The geometric mean of the horizontal components, for the 5% damped spectral acceleration, is obtained for PGA, and 22 spectral periods between 0.02 and 10 seconds, using time domain integration. The spectral response per component and metadata are available in NEEShub repository (see Data and Resource) [1].

3. Ground motion prediction model

The ground motion prediction model [8] uses the functional form proposed by [9] from the BCHydro project. Because all the stations in Chile are located on fore-arc sites, the parameters associated to fore-arc/back-arc scaling (i.e. θ_7, θ_8, θ_{15} and θ_{16}) of the original model were fixed to zero because not contribute to predict a ground motion intensity. The selection of the functional form from [9] is due to the good fit to a subset of the data from the Chilean subduction zone used in this study ([10]). This functional form has theoretical advantages over others because it includes non-linear site response. The median model is described by the following equations:

$$\ln Sa\,(T) = \theta_1 + f_{source} + f_{path} + f_{event} + f_{site} \tag{1}$$

$$f_{source} = \theta_4 \Delta C_1 + f_{mag}(M) \tag{2}$$

$$f_{mag}(M) = \begin{cases} \theta_4\left(M - (C_1 + \Delta C_1)\right) + \theta_{13}(10 - M)^2, \text{ if } M \leq C_1 + \Delta C_1 \\ \theta_5\left(M - (C_1 + \Delta C_1)\right) + \theta_{13}(10 - M)^2, \text{ if } M > C_1 + \Delta C_1 \end{cases} \quad (3)$$

$$f_{path} = \left[\theta_2 + \theta_{14}F_{event} + \theta_3(M - 7.8)\right]\ln\left(R + C_4 \exp\left(\theta_9(M-6)\right)\right) + \theta_6 R \quad (4)$$

$$f_{event} = \left[\theta_{10} + \theta_{11}(\min(Z_h, 120) - 60)\right]F_{event} \quad (5)$$

$$f_{site}(PGA_{1000}, V_{s,30}) = \begin{cases} \theta_{12}\ln\left(\frac{V_s^*}{V_{lin}}\right) - b\ln(PGA_{1000} + c) + b\ln\left(PGA_{1000} + c\left(\frac{V_s^*}{V_{lin}}\right)^n\right), \text{if } V_{s30} < V_{lin} \\ \theta_{12}\ln\left(\frac{V_s^*}{V_{lin}}\right) + bn\ln\left(\frac{V_s^*}{V_{lin}}\right), \text{if } V_{s30} \geq V_{lin} \end{cases} \quad (6)$$

$$V_s^* = \begin{cases} 1000, \text{ if } V_{s30} > 1000 \\ V_{s30}, \text{ if } V_{s30} \leq 1000 \end{cases} \quad (7)$$

Where θ are the coefficients of the regression. Sa is the 5% damped spectral acceleration or PGA in units of g, M is the moment magnitude of the earthquake, Zh is the hypocentral depth in km, R is the source-to-site distance; the model uses the closest distance to the rupture plane (Rrup) for interface and the hypocentral distance for inslab earthquakes (Rhyp), PGA1000 is the median PGA value for a site with V_{s30} equal to 1000 m/sec, and finally, F_{event} is a dummy variable which takes the value 1 when the record is from an inslab earthquake and 0 for interface earthquakes. The values of coefficients ΔC1, θ_9, C4, V_{lin}, b, c, and n are adopted directly from the BCHydro equation.

To fit the empirical data we use a nonlinear mixed effects regression. In [11] it is shown that this methodology has advantages over others, which split the residuals in a multistage scheme because failure to include all random effects directly in the regression may produce a bias in the median of the model. This will have an effect on the residual distribution. The *lme4* package of the statistical software R ([12]) developed by [13] provides an efficient computational method to manage models fitted using a nonlinear mixed effects regression. The total error of model was split in three components (Ec. 8), an error associated with the event term (δBe), other error associated with the site term ($\delta S2S_s$) and the remaining residual or single station residual (δW_0).

$$Ln(Sa_{obs}) = Ln(Sa_{median}) + \delta B_e + \delta S2S_s + \delta W_0 \quad (8)$$

Each component of the total residual is distributed normally; the between-event ($\delta B_e \sim norm(0,\tau^2)$), the site-to-site residual ($\delta S2S_s \sim norm(0,\phi_{S2S}^2)$) and the single-station ($\delta W0 \sim norm(0, \phi_{SS}^2)$). The total standard deviation of the model is given by the square root of the sum of their squares (i.e. $\sigma_T = \sqrt{\tau^2 + \phi_{S2S}^2 + \phi_{SS}^2}$).

The values of the coefficients for the median spectral acceleration and standard deviations are presented and discussed in [8]. An example of the response spectra predicted by the proposed model under an interplate and inslab events are shown in Fig. 2 and Fig. 3, respectively, for a site with V_{s30} = 250 m/s (NEHRP Class D).

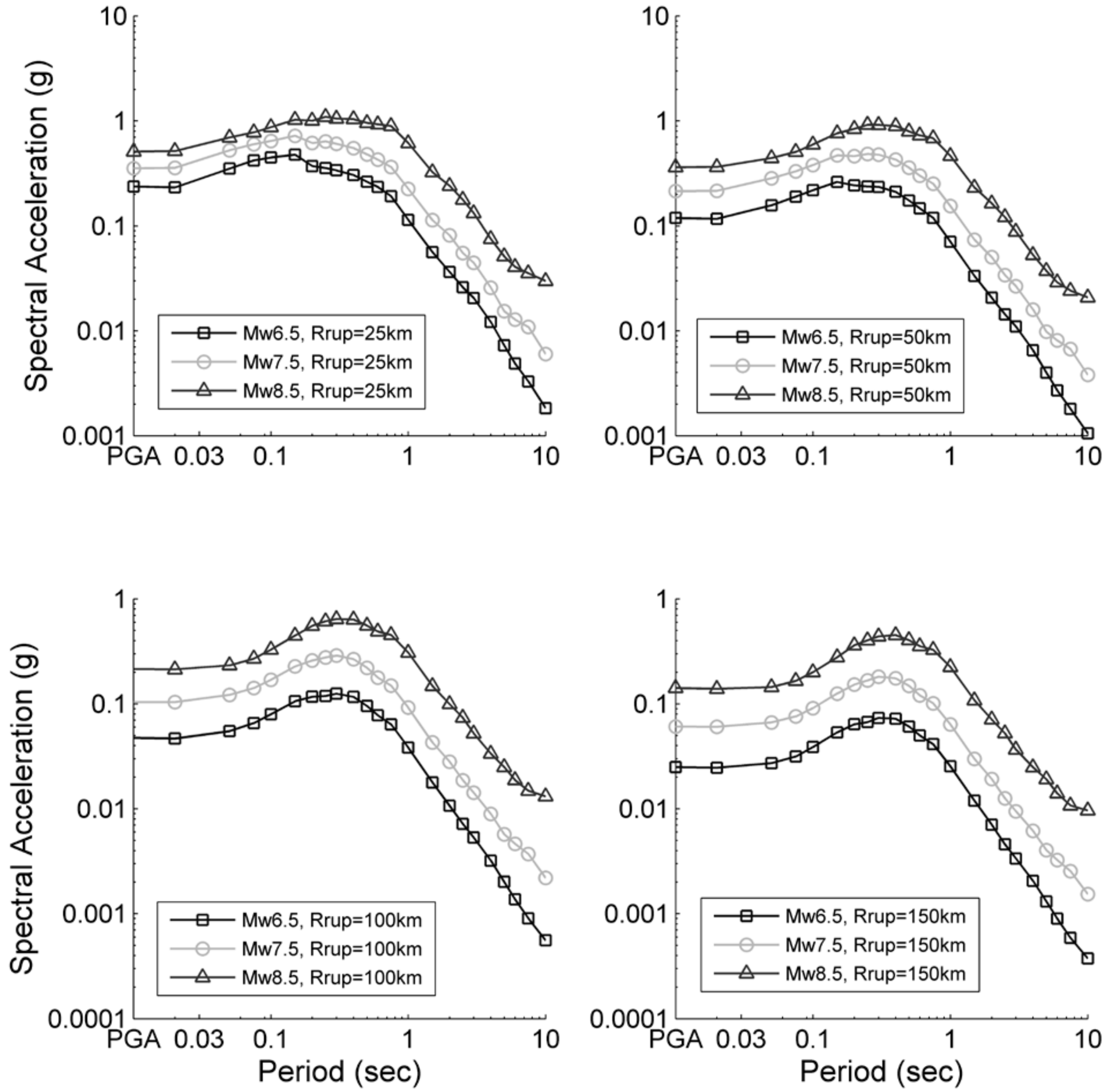

Fig. 2 – Response spectra obtained for a site with a V_{s30} = 250 m/s for an interplate earthquake.

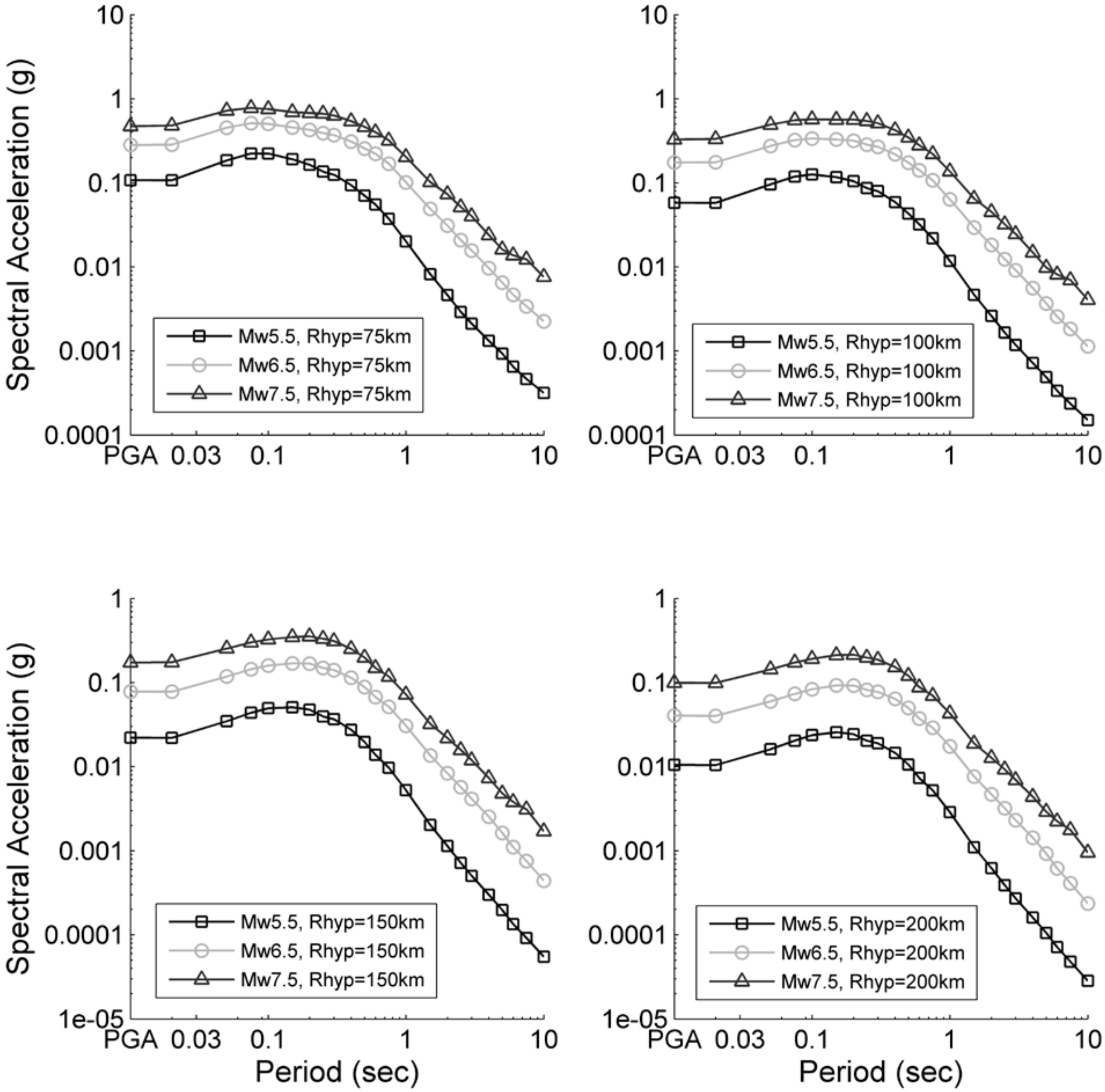

Fig. 3 – Response spectra obtained for a site with a V_{s30} = 250 m/s for an inslab earthquake.

A sensitivity analysis of regression coefficients is performed. Use the *bootstrap* technique to define 95% confidence interval for all model coefficients. 1000 *bootstrap* replications, using datasets with the same number of records that original database, but accepting duplicate data, allow the same number of regressions. The confidence interval is obtained through the bias corrected percentile method ([14]). Also, a resampling analysis is performed to evaluate the sensitivity of the model's coefficients to the number of records in the dataset. The coefficient values associated to magnitude and path terms (i.e. θ_2 y θ_4) have a stable behavior at subsets with at least 1000 records, while the values associated to site term (i.e. θ_{12}) is stabilized at subsets with at least 1500 records. The mean for smaller samples is always within the confidence intervals limits (Fig. 4).

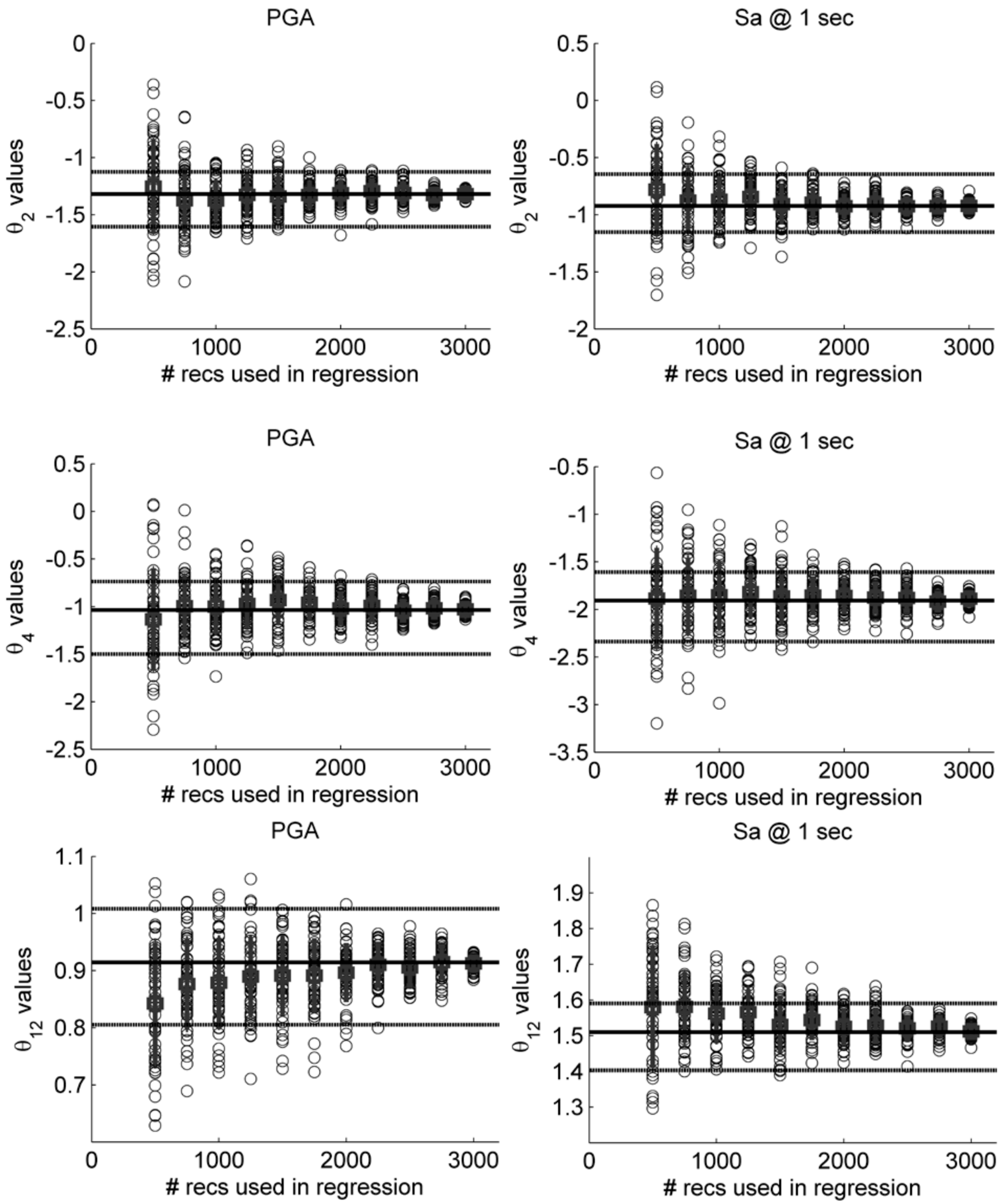

Fig. 4 – Resampling analysis for θ_2, θ_4 y θ_{12} for PGA and spectral acceleration at 1 second

4. Uncertainty analysis

For engineering applications in seismic hazard analyses, the standard deviations are as important as the median predictions. Under the probabilistic seismic hazard approach (PSHA) the probability of exceeding any specific intensity value decreases with a decrease in total deviation, so is a relevant issue recognize the extra uncertainty added to ground motion model due to poor quality data. To study the uncertainty introduced by inferred explanatory variables a new subset of high-quality information (i.e. a measured V_{s30} and moment magnitude reported by CMT) called HQ model was created. The scope of this analysis is trying to remove some of the scatter introduced by the uncertainty associated with the conversion of local magnitudes to moment magnitudes, and from the inferred V_{s30} values.

Figure 4 shows similar τ values for both HQ- and Full-model, but strong differences in ϕ_{S2S}. The slight differences between deviations associated with the event term imply that a low scatter is added to the model when Mw is estimated from other magnitudes. On the contrary, the site-to-site standard deviation (ϕ_{S2S}) for the Full model is clearly higher than HQ model, this means that the two proxies (topographic slope and predominate frequency) used to infer a V_{s30} must be improved or used with caution.

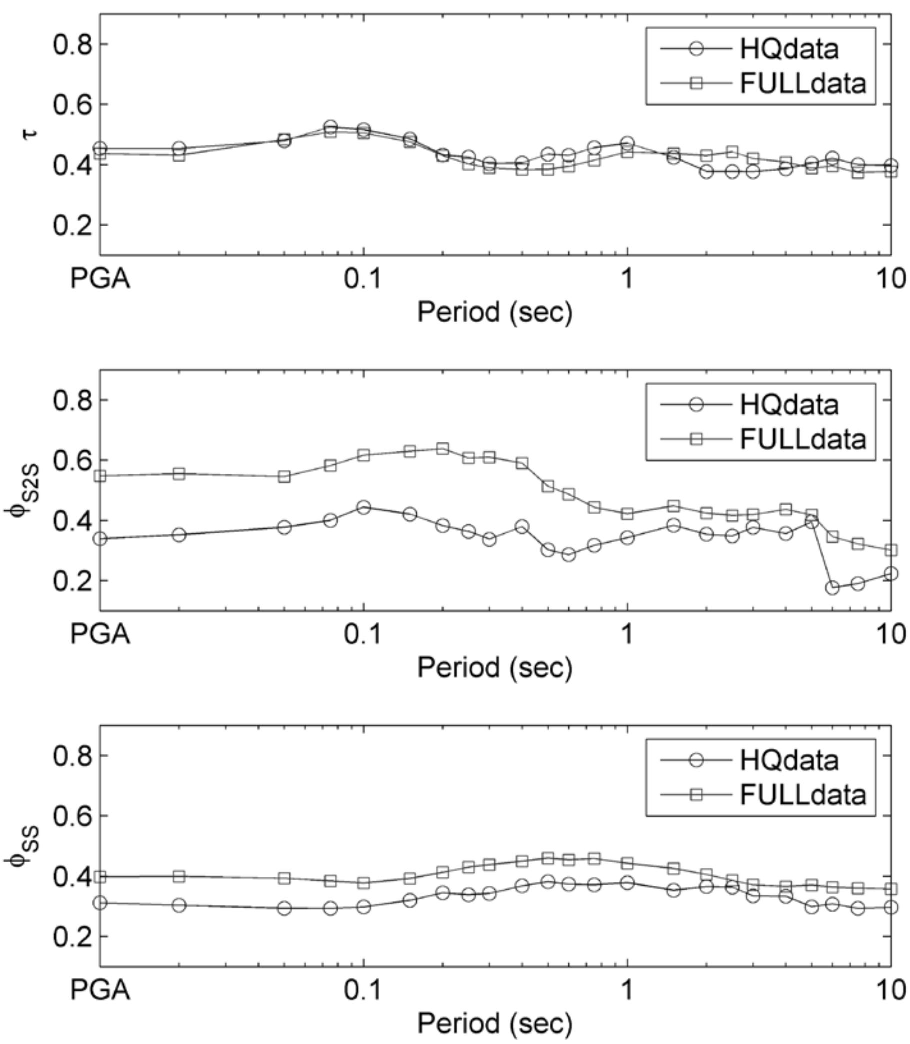

Fig. 5 – Comparison of deviations between HQ model and full model

A residual analysis, shown in Figure 6, shows no trends among the between-event residual and moment magnitude, the single-station residual against source-to-site distance, nor the site-to-site residual versus V_{s30}.

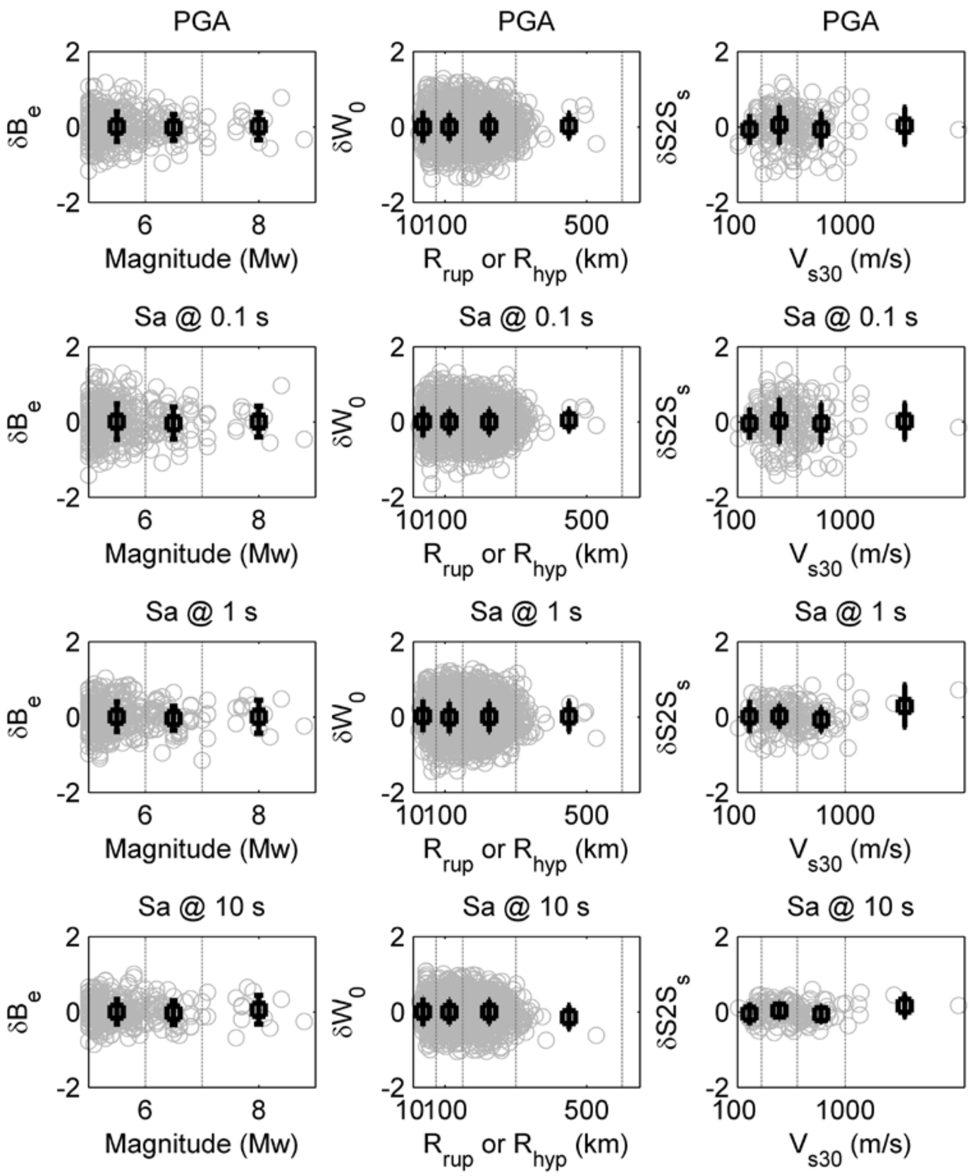

Fig. 6 – Residual analysis

5. Single-station analysis

Rodriguez-Marek and co-workers [15] compared ergodic within event standard deviations (ϕ with $\phi = \sqrt{\phi_{SS}^2 + \phi_{S2S}^2}$) and event corrected single-station standard deviations (ϕ_{SS}) for multiple regions, concluding that in particular (ϕ_{SS}) is a very stable parameter across different tectonic environments. The same data is used to compare the standard deviations of the proposed model for Chile including between event standard deviations (τ). Figure 6 (top) shows the remarkable agreement of the proposed model with the parameters obtained from other regions and tectonic environments. The HQ model has lower ϕ_{SS} values which might be due to the high magnitude events in this smaller dataset. The values for τ show greater dispersion.

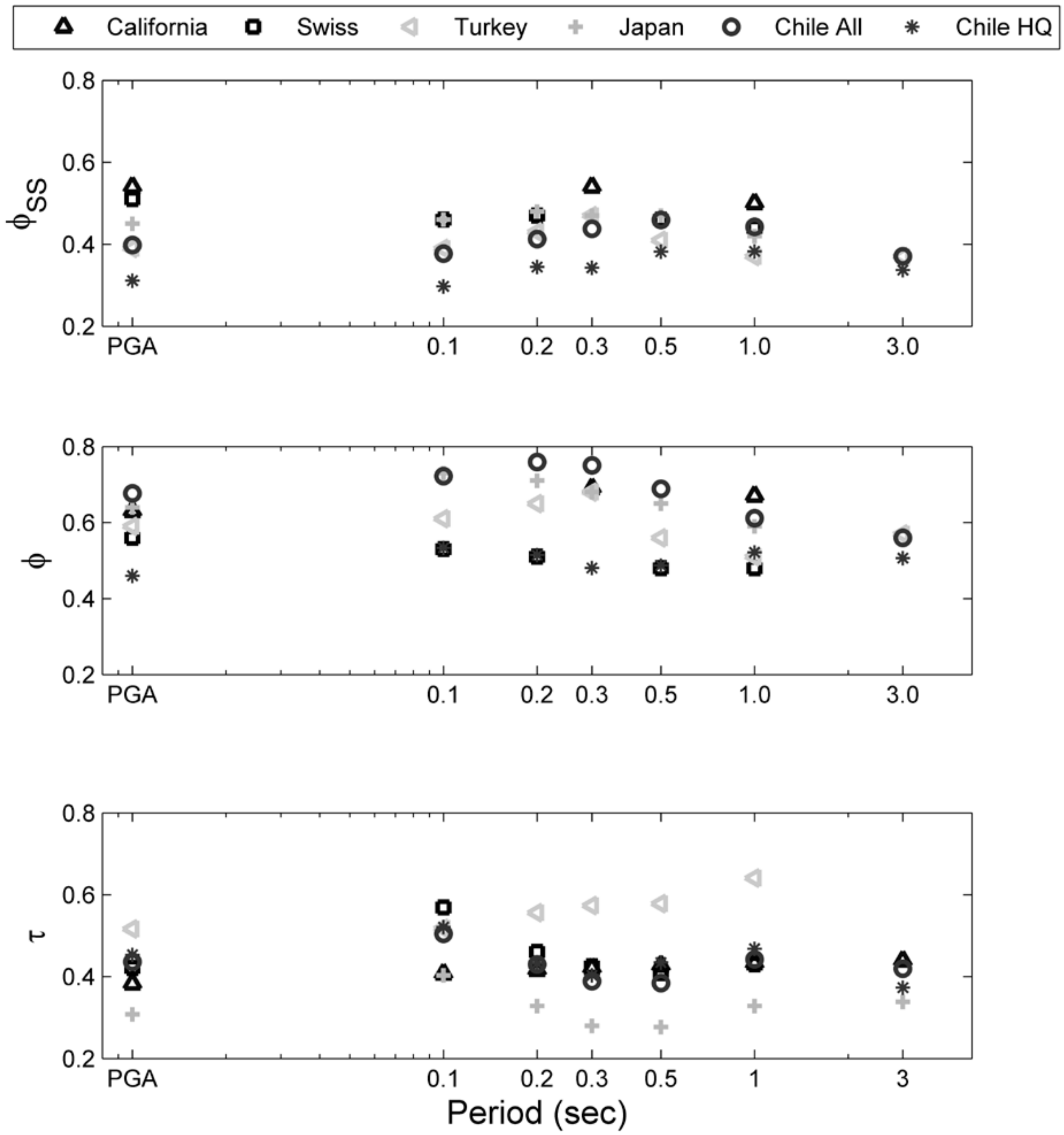

Fig. 7 – Single-station analysis for Chile and other tectonic region

6. Conclusion

A modern ground motion prediction model is developed for the Chilean subduction zone [8]. The data used to fit this model is based on analog and digital records from 1985 to 2015 for inslab and interface events, compiled and processed by [2].

We fitted for a GMPE using only a high-quality subset of the database (i.e., HQ model). The aim of this model is to assess parts of the extra uncertainty added to the model by estimating some of the explanatory variables. The comparison shows similar deviation associated with event term (δB_e), this means than conversion equations between M_L and M_w develop by [2] do not introduce a significant bias to model. On the other hand, the deviation associated to site term ($\delta S2S$) shows clear disparity and presents an opportunity to further improve the prediction of the site response through simple proxies.

The difference between the total intra-event variability (ϕ) and the single-station event-corrected variability (ϕss) is a clear indication that a better constraint on site parameters should reduce the value of ϕ_{S2S} and hence the value of the total intra-event variability (ϕ), which would take it closer to the values observed in other regions of the world.

7. Data and resources

All the data used in this work is freely available at https://nees.org/resources/13694, which has been processed according to Bastías and Montalva (2016).

8. Acknowledgements

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8. References

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