Seismic Ground Motion Assessment

METADATA UNCERTAINTIES AND SENSITIVITY OF EMPIRICAL GROUND MOTION PREDICTION EQUATIONS ADAPTED TO THE FRENCH CONTEXT

(Deliverable D2-92)

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DISSEMINATION: *Authors; Steering Committee; Work Package leaders, Scientific Committee, Archiving.*

ABSTRACT

This document presents preliminary results on the development of ground motion prediction equations (GMPEs) from RESORCE-2013 database (SIGMA-2013-D2-91), which, compared to the previous version of the database, includes small-to-moderate magnitude events of relevance from the SIGMA area of interest. The impact of different data selection criteria is shown and the model performance is discussed for each dataset. Site-effect models based on Vs30 and on EC8 site classes are tested in order to include a large number of data from stations not characterized by a Vs30 value in the database. A regional stress-drop model for French events is proposed which allows to explain part of the between-event variability observed at short spectral periods for small magnitude events. The proposed preliminary model is investigated in terms of magnitude, distance, site-effects, and stress-drop scaling and it is compared to other empirical models derived from the previous version of RESORCE. In the last part of the study the uncertainties on moment magnitudes provided in RESORCE are assessed in order to evaluate their impact on the GMPEs (median ground motion and standard deviation) derived in this study. A first result suggests a minor impact of Mw uncertainties on the reduction of GMPEs standard deviation. However, median values of the GMPEs are also affected and the results indicate that such influence should be further investigated in the following of this study, in order to understand if it can have implications for derivation of GMPEs in general.

Executive Summary

The objective of the SIGMA projects is to improve knowledge on data, methods and tools to better quantify uncertainties in seismic hazard estimates. To this aim, 5 WPs are identified, the first three devoted to each main ingredient of the seismic hazard assessment (SHA): seismic source characterization, ground-motion characterization and site effects. The fourth WP is devoted to the development of the seismic hazard model and it is sensed to integrated all outcomes from the previous WPs into an improved seismic hazard model.

The study presented here is developed within WP 2 and it has downstream and upstream connections with the other WPs. Within WP 2 a database of strong-motion records for the pan-European region, RESORCE (SIGMA-2011-D2-15), has been developed with the specific aim of testing and deriving GMPEs (Douglas et al., 2013). The 2013 version of RESORCE (SIGMA-2013-D2-91), which is updated with French a Swiss data, is the starting point of the present study.

SIGMA-2013-D2-09 and

here the link with the comparaison paper of the BEE special number is not so clear

This document represents the first advancement report of the study that will be finalized in the following of the SIGMA project. The first objective is to develop a preliminary ground motion prediction equation (GMPE) based RESORCE-2013 database with particular attention to the data from small-to-moderate magnitude French and Swiss events, being relevant for the SIGMA area of interest. The second objective, tightly connected to the first one, is to investigated the effects of data selection criteria, metadata uncertainties and model parameters on the GMPEs (median value and standard deviation).

Because the ground motion characterization is one of the key element of any SHA and it is often cited as one of the largest contributors to the total uncertainty in the total hazard, the results of this study has direct implications on WP 4. Moreover, this study will largely benefit (and to some extent already did) from the results of WP 1 and WP 3 in terms of earthquake metadata accuracy (catalogue under development in WP 1) and site characterization of French stations (WP 3).

The first part of the study present different GMPEs derived using different subset of RESORCE-2013. The subsequent datasets are selected in order to include gradually, following defined selection criteria, a larger number of data and to show their impact in the GMPEs derivation. The base functional form adopted is based on the models by Boore and Atkinson (2008), Akkar and Bommer (2010) and Bindi et al. (2013).

The first data selection is performed to remove records lacking of necessary information or that are considered not relevant for the present study (dataset-0). Starting from this dataset the following selections are made: 1) only stations with a known value of Vs30 (dataset-1); 2) exclusion of events with converted Mw (dataset-2); 3) all stations with either a Vs30 measure or an assigned EC8 site class (dataset-3); 4) inclusion of French events with Mw not reported in RESORCE-2013 (dataset-4). For each dataset the functional form is investigated and the performance of the model is evaluated by residual analysis.

The main results of this analysis can be summarized as follows.

The use of a site model based on a continuous function of Vs30 or on EC8 soil categories (A, B, C and D) in the GMPEs, given the same dataset, provide the same model variance. This is in agreement with results from other studies (e.g., Luzi et al., 2011) and suggests that a site model based on soil classes can be used in the present study in order to include data from the large number of station for which a Vs30 value is not available.

The use of converted Mw for about 65 events, mostly Italian and Turkish with Mw between 4 and 5, inflate the between-event standard deviation around T=1s, whereas the median predicted ground motion is largely unaffected. This suggests a bias in the converted Mw for some of these events and prompted us to remove converted Mw from the dataset.

Including the small-to-moderate magnitudes French and Swiss events in the dataset substantially increase the between-event variability of the model at short periods. The inclusion in the functional form of a regional stress-drop model for the French events allow to explain at least part of such variability and thus to reduce the total standard deviation of the GMPE. In any case, the standard deviation remains larger for small magnitude events than for larger events, possibly indicating the true need for a heteroscedastic sigma model.

The GMPE derived with dataset-4 including the stress-drop model for France represents the preliminary model proposed in this study for PSHA. Following the indications by Bommer and Akkar (2012) two twin GMPEs are derived for a point-source distance metric (epicentral distance) and an extended-source distance metric (Joyner-Boore distance). The magnitude and distance range of validity of the preliminary GMPE are Mw=3 to 7.6 and R_{JB} (or R_{EPI}) = 0 to 200 km.

The second part of this study concern the evaluation of the metadata uncertainties in RESORCE database and the assessment of their influence on the derived GMPE. In particular it has been shown in previous studies (e.g., Rhoades, 1997; Abrahamson et Silva, 2007; Moss 2009, 2011) that metadata errors in explanatory variables, typically ignored in GMPEs derivation, affect the total standard deviation of the models and that the contribution of such epistemic uncertainties should be removed by the aleatory variability of the GMPEs. However, the amount of such reduction depends on the quality and structure of the considered dataset. We evaluated Mw uncertainties for all the events contained in dataset-4 enriched with converted Mw events from Italy and Turkey. The uncertainties in Mw are propagated into the GMPE via Monte Carlo approach by generating a large number of alternative datasets with magnitudes obtained by random sampling the error distributions.

The results show that that Mw uncertainties affect both the median ground motion and the standard deviation of the GMPEs. The median ground motion obtained without uncertainties propagation is found to be slightly different with respect to the median ground motion considering Mw uncertainties. We attribute such difference to the uneven distribution of events and Mw uncertainties in the dataset. This behavior may have implications for median motion from GMPEs derived without considering magnitude uncertainties and will be further investigated. The standard deviation of the GMPE increase when considering Mw uncertainties, however in terms of reduction of aleatory variability of the GMPE based on Mw from RESORCE, we found a negligible effect.

Contents

1. RESORCE 2013 database

The database used in this study is the updated version of RESORCE database, developed within the SIGMA project (SIGMA-2011-D2-15, Akkar et al.,2013a). The RESORCE 2013 database is object of a specific Deliverable (SIGMA-2013-D2-91) and it will not be described here in details. Anyway some of the main features of the database that are of interest for the present study will be briefly illustrated.

The database is composed by strong-motion records recorded in the broader European and Middle Eastern area with a maximum magnitude given by the 1999 Kocaeli earthquake, Mw=7.6 (if we exclude the singly recorded event of 1969 off the coast of Portugal with Mw=7.8).

The 2013 version of the database is enriched with a large number of data from small-to-moderate magnitude earthquakes, mainly from France and Switzerland. For Swiss data, the Mw is provided almost for all of them by the time-domain moment tensor inversion performed by the Swiss Seismological Survey (http://www.seismo.ethz.ch/prod/tensors). For this reason these data are also characterized by a reliable fault mechanism. The French data are characterized by a large number of events (especially for M < 4) for which the Mw is not reported in the database and only local magnitude ML is provided. Similarly the fault mechanism of these events is unknown (determination of Mw and style-of-faulting for these events will be discussed later).

Some of the events in the database are associated to converted Mw, determined from other magnitude types via empirical conversion equations. These are mostly Italian and Turkish events with Mw between 4 and 5.

The site conditions of the recording stations in RESORCE is characterized by the Vs30, where available, and alternatively by a EC8 site class estimated according to different studies and methodologies (SIGMA-2013-D2-91).

Uncertainties in the events or stations metadata, for instance in the epicentral location or in the site classification, are generally not reported in REOSRCE. For site where the Vs30 is available, information on the method used to measure the Vs30 is provided and a flag indicating whether the Vs30 is measured or estimated is reported.

1.1. Initial data selection

A preliminary selection is made on the RESORCE-2013 database in order to remove a number of data that we considered not usable, not relevant for the aim of the study or not relevant for seismic hazard studies in active crustal regions. The following exclusion criteria are employed:

- events with depth larger 30 km;
- records with epicentral distances > 200 km;
- Mw or ML smaller than 3;
- stations that are known to be not in free field (e.g., in galleries or in dams);
- records that have not been processed or for which only one horizontal component is available;
- stations for which a value of Vs30 is provided but the method used and the origin source of such value are classified as ñunknownò. These are about 150 stations with metadata from ESD or ISESD;
- stations that are not characterized by either Vs30 or EC8 site class information.

The dataset obtained after this selection will be referred to dataset-0. The records distribution in dataset-0 as a function of magnitude and epicentral distance is shown in Figure 1, where the records are color coded on a country base. The events with magnitude larger than 4 are mostly Italian and Turkish events with a smaller contribution of Greek and Iranian earthquakes. Considering smaller magnitudes (Figure 1, right) the dataset is largely composed by Swiss and French events.

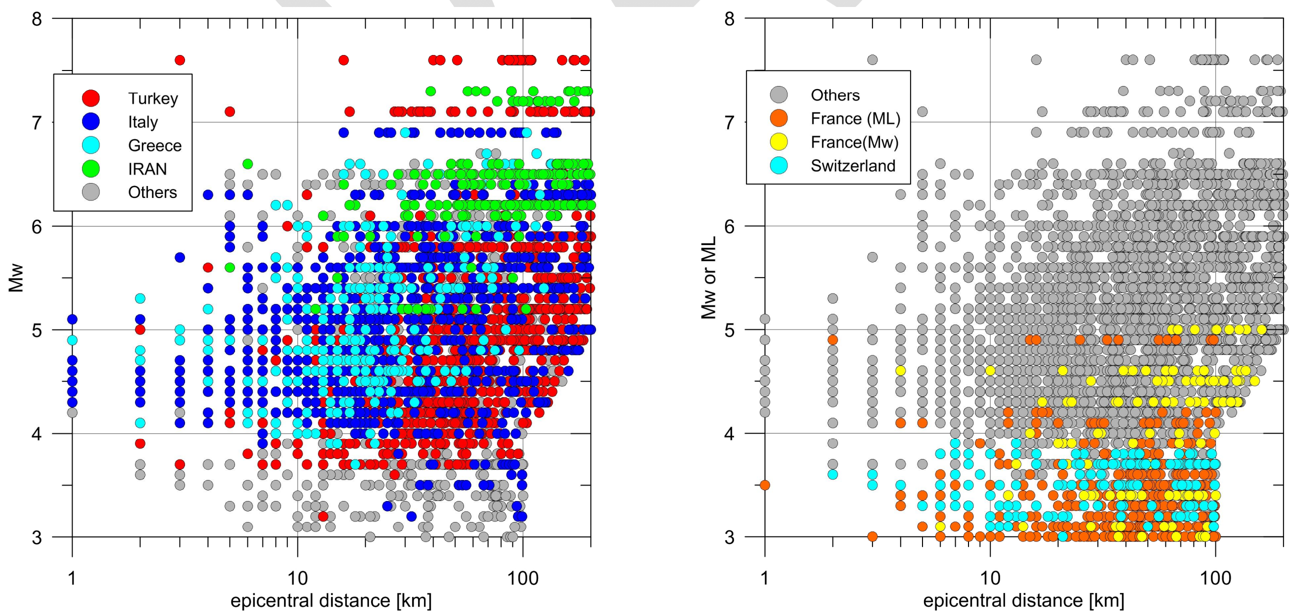


Figure 1. Magnitude versus distance distribution of data in dataset-0. The records are color coded according to the earthquake country.

Figure 2 shows the distribution of records in terms of site classification of the recording station. Roughly 40% of the records are associated to a Vs30 value, 50% to a EC8 site class and about 10% lack of information on the station site condition.

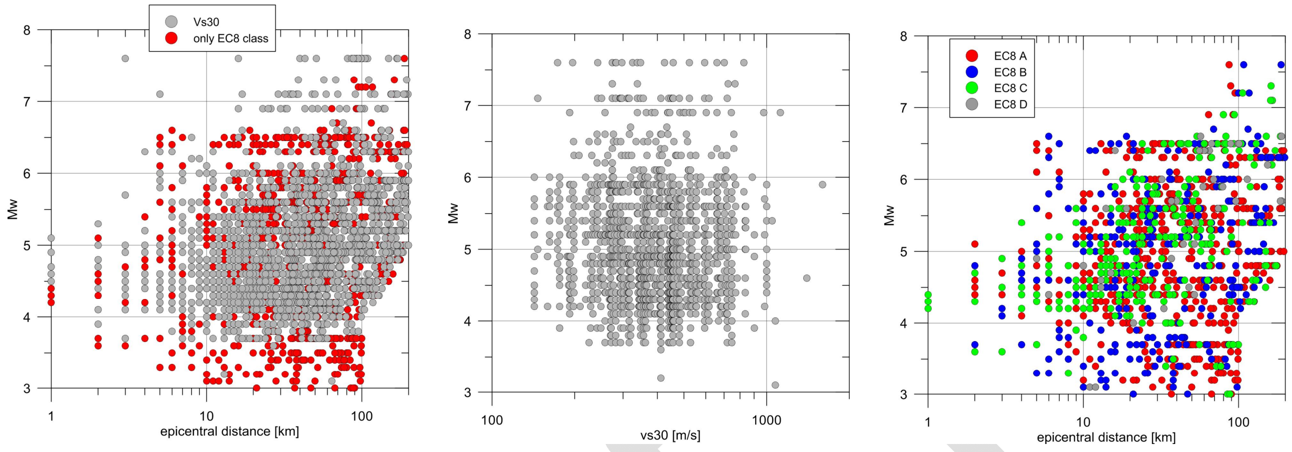


Figure 2. Distribution of records in dataset-0 in terms of site classification. Left: magnitude versus distance plot of records recorded at stations characterized by a measure of the Vs30 (gray symbol) or by a EC8 site class (red symbol). Center: magnitude versus Vs30 distribution of records. Right: magnitude versus distance distribution of records color coded according to the EC8 site class.

The dataset presented in Figure 1 and 2 contains all the processed records available in the database. However, because the records have been filtered with different filter's corners, in order to remove noise and to keep only high-quality signals, the calculated response spectra will not be usable over the entire periods range for all records. In the following of this study, only records filtered with low-pass corner frequency larger than or equal to 20Hz and, for each period T, only recordings filtered with high-pass corner frequency fhpÒ1/(1.25 T) are considered. The number of usable earthquakes and records as a function of period in shown in Figure 3 (blue curve), where the dramatic decrease of data is visible starting at about 1s. Finally it is important to mention that more than 50% of the events contained in the dataset-0 are recorded by only one station. Singly-recorded earthquakes do not allow to calculate reliable between-event residuals and will be systematically excluded from the regression presented in this study. The impact of removing singly recorded events on the earthquakes and records distribution as a function of period is shown in Figure 3. The dataset reduces to about 400 events and 2100 records at the shortest periods.

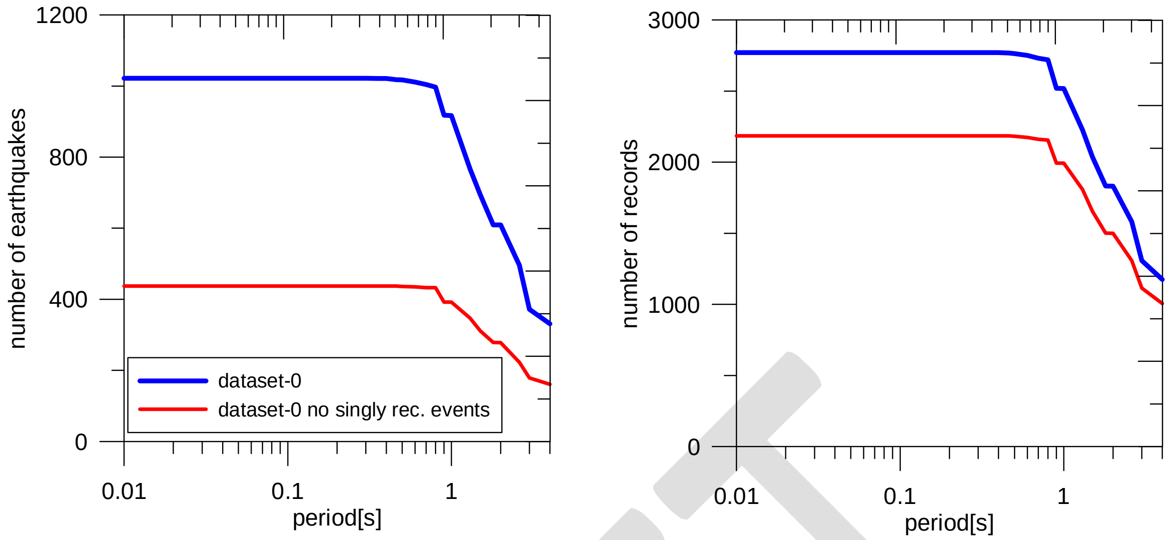


Figure 3. Number of earthquakes (left) and records (right) as a function of period considered for dataset-0 considering (blue) or not (red) singly recorded events.

2. General functional form of the GMPE

The GMPEs are derived considering a parametric model based on the following functional form (e.g. Boore and Atkinson, 2008; Akkar and Bommer, 2010; Bindi et al. 2013).

$$\log_{10} Y = a + F_D(R,M) + F_M(M) + F_S + F_{sof} \qquad (1)$$

where the distance (F_D) and the magnitude (F_M) functions are given by:

$$F_D(R,M) = \left[c_1 + c_2\left(M - M_{ref}\right)\right]\log_{10}\left(\sqrt{R^2 + h^2} / R_{ref}\right) \qquad (2)$$

$$F_M(M) = \begin{cases} b_1\left(M - M_h\right) + b_2\left(M - M_h\right)^2 & \text{for } M \le M_h \\ b_3\left(M - M_h\right) & \text{otherwise} \end{cases} \qquad (3)$$

The functional form for F_D includes a magnitude-dependent geometrical spreading term. A term describing the logarithmic decay with distance of the of ground motion, that typically accounts for anelastic attenuation, is not included in the functional form because it was found not statistically significant in the range of distances considered in this study (0-200 km). Following Bommer and

Akkar (2012), the regressions are performed considering both a point-source and an extended-source measure of the source-to-site distance R, namely the Joyner and Boore distance R_{JB} and the epicentral distance R_{EPI}. Most of the results in this document will be presented in terms of R_{EPI} and the difference with respect to R_{JB} will be discussed in Section 3.5.

The functional form for F_M includes a linear and a quadratic scaling for magnitudes lower than M_h and only a linear scaling for larger magnitudes. After trial regressions, the variables M_{ref}, M_h, R_{ref} (equations 2 and 3) have been fixed to 5.5, 6.75 and 1km, respectively. Coefficient b3 was constrained to be non-negative, is first trial regressions, and subsequently, as it was found not statistically different from zero, it was constrained to zero.

Additional explanatory variables related to the source model (e.g. hanging/foot walls effect; depth to the top of the rupture; etc.) or other measure for the source-to-station distance (e.g. distance from the rupture) are not considered because of the lack of information in RESORCE.

The functional form F_S in equation (1) represents the site amplification and it will be discussed in details in Section 3.1.

The functional form F_{sof} in equation (1) represents the style-of-faulting correction and it is given by $F_{sof}= f_j E_j$, for j=1,...3, where f_j are the coefficients to be determined during the analysis and E_j are dummy variables used to denote the different fault-mechanism classes: normal (N), reverse (R), strike-slip (S). The reference style of faulting condition (i.e. parameter constrained to zero in the regressions) is class S.

As response variable Y, the geometric mean of the horizontal components for peak ground acceleration (PGA in cm/s^2) and with 5% damped pseudo-spectral acceleration (PSA in cm/s^2) computed over 27 periods in the range 0.01-3 s. The regressions are performed applying a random effect approach (Abrahamson and Youngs, 1992), that allows to determine the components of the standard deviation of the regression (commonly referred to as sigma, ů), namely the between-events (Ǘ and the within-event (ű) components.

3. <u>Results for different data selections</u>

In the following sections, the model described by equations 1, 2 and 3 will be applied to different datasets in order to investigate some of the model features, to show the impact of data selection on model variance and to justify the use of additional terms in the functional form. The magnitude and distance scaling coefficients from the models derived from these selections are compared in figure A1.

3.1. Site effects model: comparison between Vs30 and site coefficients (dataset - 1)

Typically in recent GMPEs, including those derived using RESORCE-2012 database, the site effects are modeled using a function of Vs30. However, in some previous European GMPEs (e.g., Akkar and Bommer 2010) the site effects are considered in terms of site classes due to the lack of Vs30 for most of the stations in the database. In the case of RESORCE-2013, and considering the aim of the study (i.e. including magnitude down to 3), we face the problem that for most of the French and Swiss stations the Vs30 information is not available and thus it appears that a site effect model based on Vs30 would not be applicable. For this reason a model based on EC8 site classes is proposed. In order to investigate the performance of the two site effects models in explaining the data, we will test the two models and compare the results on a restricted dataset. A subset of data characterized only by stations with a measured value of Vs30 is selected (dataset-1). The records are selected according to the following criteria:

- only records from station characterized by a measured value of the Vs30
- only known fault mechanism
- at least to records per event (no singly-recorded events)

The number of earthquakes and records as a function of period considered in this dataset-1 is presented in Figure 4 and compared to the initial dataset (dataset-0). As already mentioned, the selection of only stations characterized by a Vs30 values almost halve the dataset.

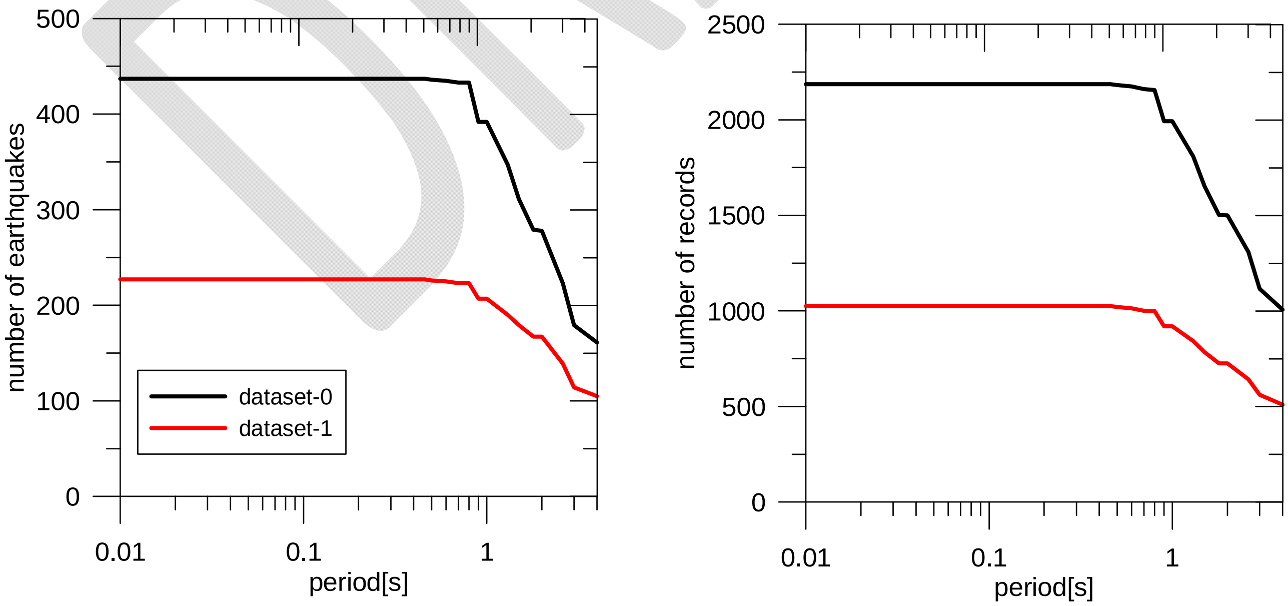


Figure 4. Number of earthquakes (left) and records (right) as a function of period considered for dataset-1 compared to dataset-0 (with singly-recorded events removed).

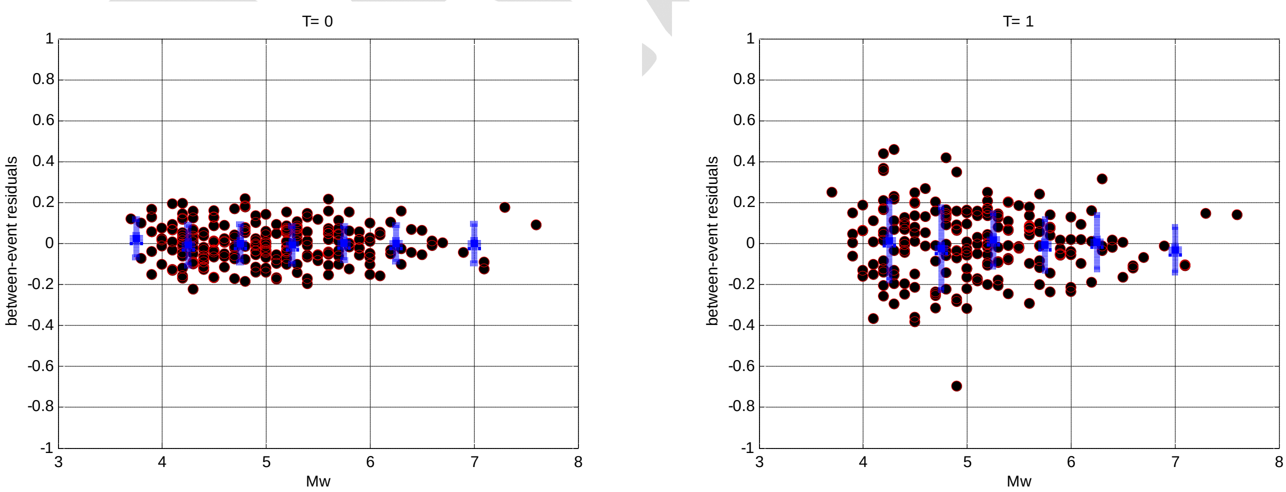
Adopting this dataset-1 and the functional form presented in equation (1) we performed two regressions changing the site effects model (*Fs* in equation 1). With this first dataset, the aim is, on the one hand, to show that the selected functional form is suitable to explain the data in terms of magnitude, distance and site effects dependencies and, on the other, to compare the performance of the models based on Vs30 and on site classes.

The first regression is performed using a linear site model based of Vs30:

$$Fs = s_1 \log_{10}\left(\frac{Vs30}{Vref}\right) \qquad (4)$$

where s_1 is a coefficient to be determined through the regression and *Vref* is a reference Vs30, that we fixed to 760 m/s.

The results are presented in terms of residuals distribution as a function of magnitude, distance and Vs30. Figure 5 shows the between-event residuals as a function of magnitude, for PGA and PSA at 1s. The between-event residuals do not show any particular trend with magnitude suggesting that the considered functional form adequately capture the magnitude scaling of the data. This holds for both PGA and T=1s, although at T=1s the dispersion of the residuals is clearly lager (this will be discussed in the next section). Figure 5 also shows that in dataset-1 only few events with magnitude smaller than 4 are retained and that there are only 3 French events and no Swiss events.



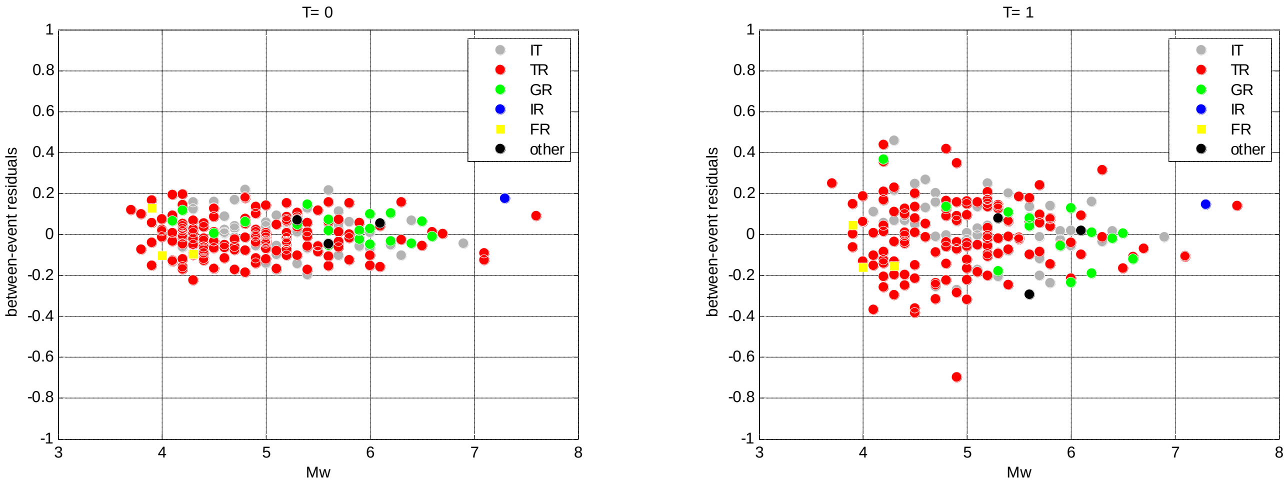
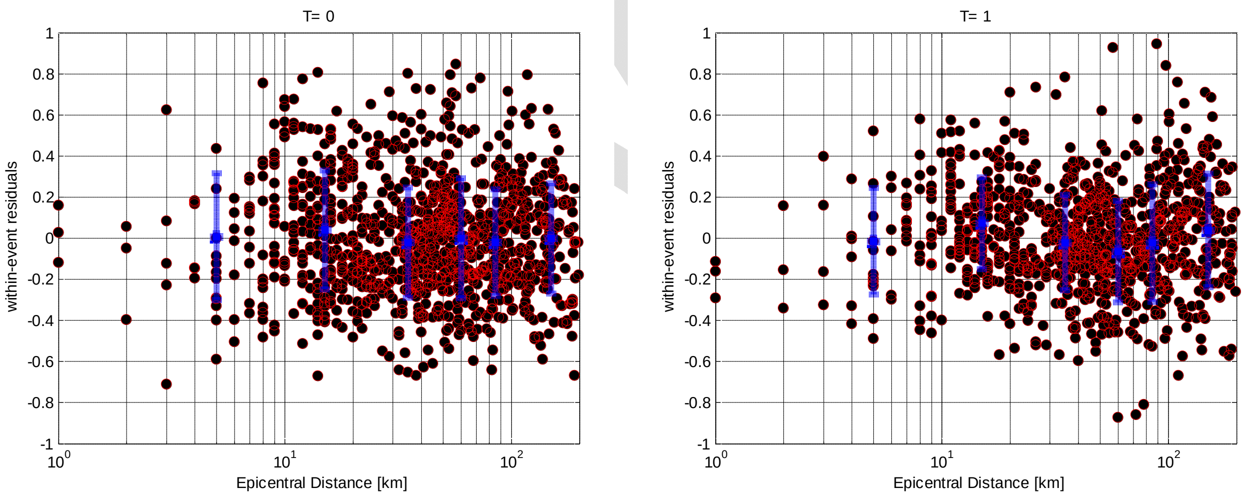


Figure 5. Between-event residuals for PGA (left column) and T=1s (right column) as a function of Mw. In the upper plots the mean and standard deviation calculated for different magnitude bins are shown by blue bars. In the lower plots the residuals are colored according to the earthquake country.

Figure 6 shows the within-event residuals as a function of epicentral distance and Vs30 for PGA and PSA at 1s. Also in this case we observe no evident trend with respect to distance and Vs30, meaning that the model in able to correctly explain the data. A slight overestimation of the model is visible for the smallest values of Vs30 and for PGA, that may be ascribed to nonlinear site effects, although the data are too scarce strengthen this hypothesis.



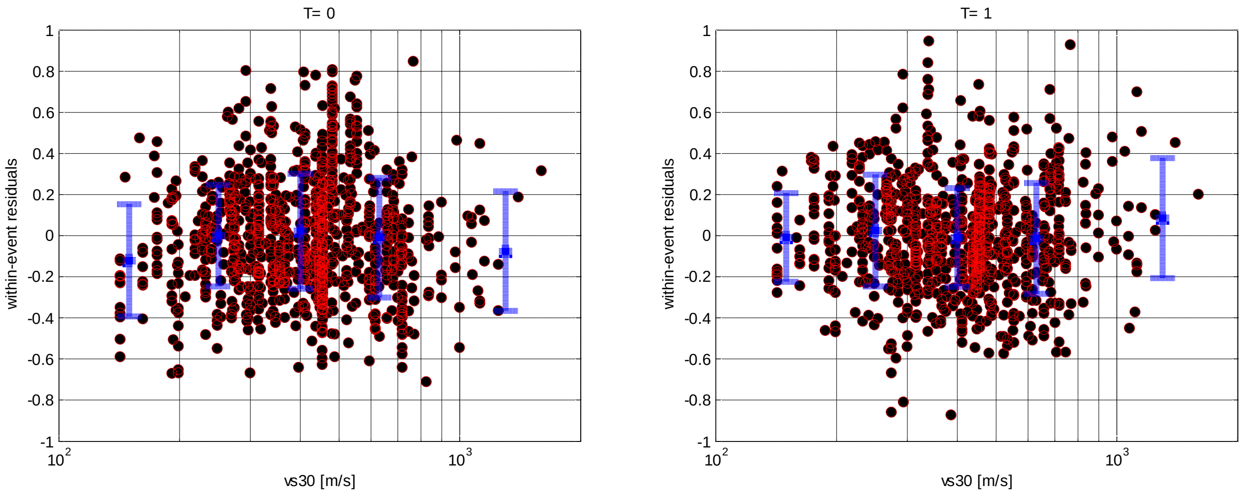


Figure 6. Within-event residuals for PGA (left column) and T=1s (right column) as a function of epicentral distance (top) and Vs30 (bottom). The mean and standard deviation of the residuals calculated for different distance and Vs30 bins are shown by blue bars.

The same dataset is used to test a site effect model based on four EC8 site classes (A, B, C, D). In this case the functional form for site amplification is given by:

$$Fs = s_1 F_A + s_2 F_B + s_3 F_C + s_{41} F_D \qquad (5)$$

where s_j (j=1,é 4) are the coefficients to be determined through the regression analysis, while F_A, F_B, F_C, F_D are dummy variables that takes the values of 0 or 1 according to the four considered EC8 site classes (A to D). The regression for the EC8 model is performed constraining to zero the coefficient for class A (reference site class).

Figure 7 presents the within-event residuals separated for EC8 site classes A, B, C and D. The results show that the mean prediction is not biased with respect to any of the site classes, although site A and D are very poorly represented in dataset-1.

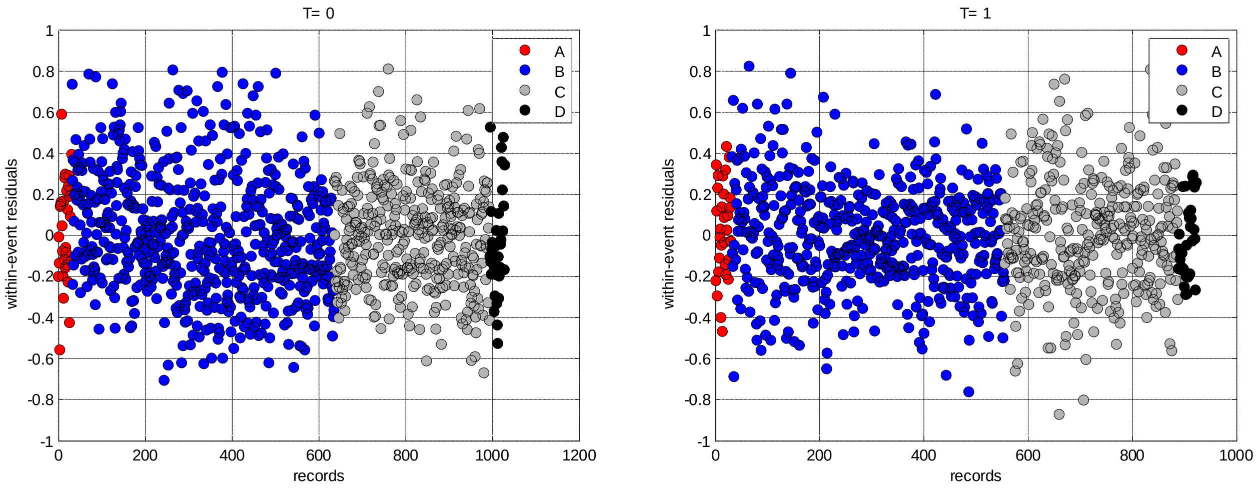


Figure 7. Within event residuals separated for the 4 EC8 site classes (A, B, C, D).

The performance of the two site effect models is presented in Figure 8, where the obtained between-event, within-event and total standard deviations are compared. The models standard deviations are very similar, meaning that the Vs30-based model and the site classes are able to explain the data equally well. In other words, when the Vs30 of the site is known, using a model based of broad site classes does not introduce any bias and does not worsen the overall fit with respect to a model based on a continuous function of Vs30, as already suggested by Luzi et al. (2011) and Bindi et al. (2013). The model derived in this preliminary study includes only a linear site amplification term although nonlinear site effects are expect to be important for strong shaking at soil sites, that is for large and close earthquakes recorded at site with low Vs30 values (e.g. classes C and D of EC8). Unfortunately these conditions are not well sampled in RESORCE (Figures 2).

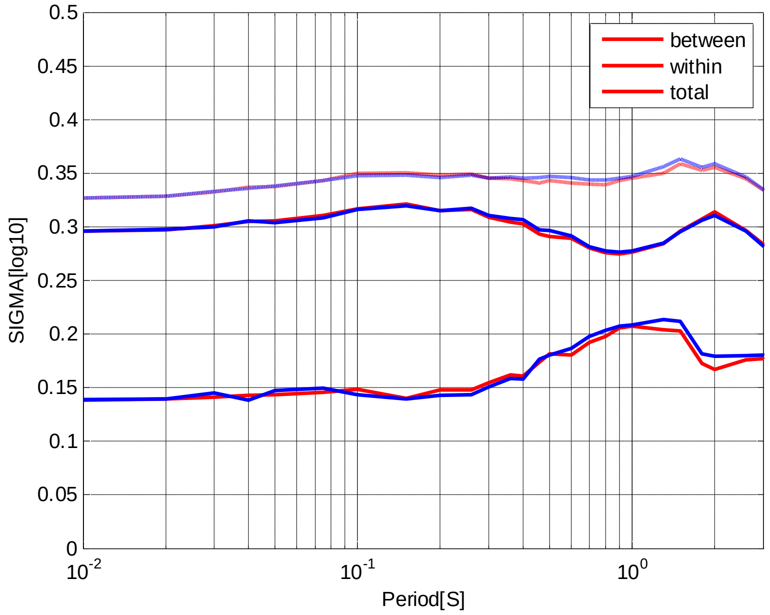


Figure 8. Between-event, within-event and total standard deviation (from bottom to top) obtained using dataset-1 and a site model based on Vs30 (red) of based on EC8 classes (blue).

3.2. Testing the effect of converted Mw (dataset-2)

RESORCE contains a number of events for which a direct determination of Mw is not available and a converted Mw is provided. These Mw are determined from other magnitude types (ML, Md, etc.) through empirical conversion equations (e.g., Akkar et al. 2010, Castello et al. 2007) that are characterized by a considerable uncertainty. Moreover the original magnitude is also affected by uncertainty due, for instance, to the number of stations used in the determination. The accuracy of such converted Mw is, therefore, much smaller than that of Mw determined via moment tensor inversions.

In dataset-1 converted Mw were included for Turkish and Italian events since no filter on the type of Mw was imposed.

It is to note that, in the first version of RESORCE (SIGMA-2011-D2-15), the converted magnitudes were not identified and information on the used conversion equations were not provided. After interaction between partners during the development of RESORCE 2013 it was decided to clearly identify converted Mw.

The increase in between-event variability around 1s resulted by the previous test (Figure 8) may be indeed caused by the epistemic uncertainty in the converted Mw values. To test this hypothesis we show, in Figure 9, the between-event residuals obtained from regression of dataset-1 and we highlight the events with converted Mw values. At T=1s, the residuals related to converted Mw show a larger dispersion compared to the other events.

The converted Mw are then excluded from the dataset-1 and a new dataset-2 is used in the regression. The number of earthquakes and records in dataset-2 are shown in Figure 10 and compared to the previous datasets.

The model derived using dataset-2 will not be discussed here in details as it has the only purpose of showing the effect of the exclusion of converted Mw on the standard deviation of the model. This is shown in Figure 11 where the between-event, within-event and total variability obtained by regressing the same functional form on dataset-1 and dataset-2 are shown.

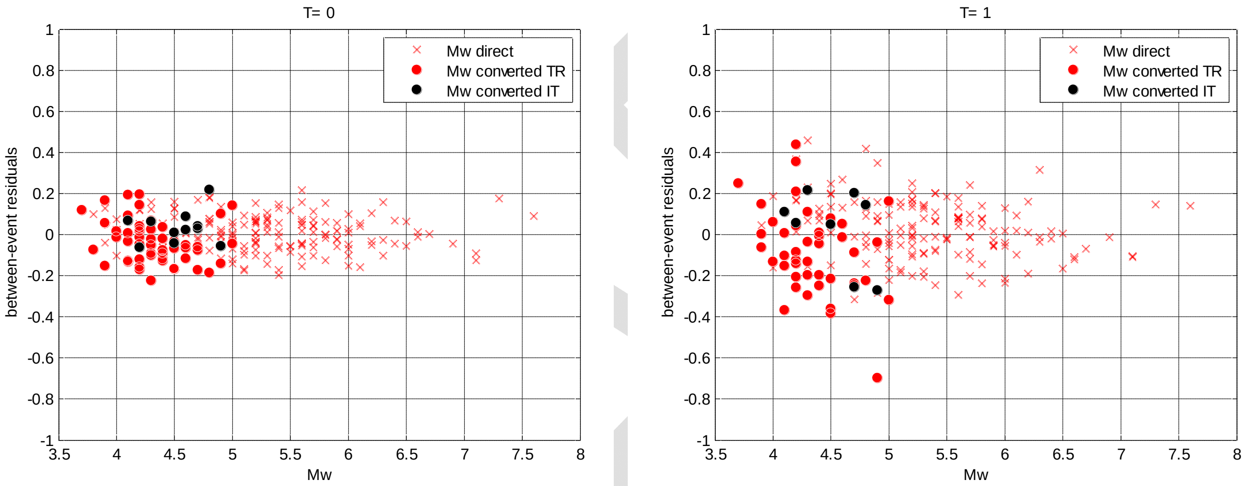


Figure 9. between-event residuals for PGA (left) and T=1s (right) obtained using dataset-1. Events with direct Mw (crosses), Turkish events with converted Mw (red dots), and Italian events with converted Mw (black dots) are shown.

The results show that the increase in between-event standard deviation around 1s observed with dataset-1 disappear when using dataset-2. The within-event standard deviation shows a small decrease in the short period range with respect to that obtained with dataset-1, likely due to the smaller number of records used in dataset-2 (Figure 10). Figure 11 shows that once removed the converted Mw the between-event and within-event standard deviation are characterized by a very weak dependence on period. The mean prediction of the GMPEs derived from the two datasets does not show significant differences, suggesting the events with converted Mw inflate the ground motion variability without affecting the overall mean values.

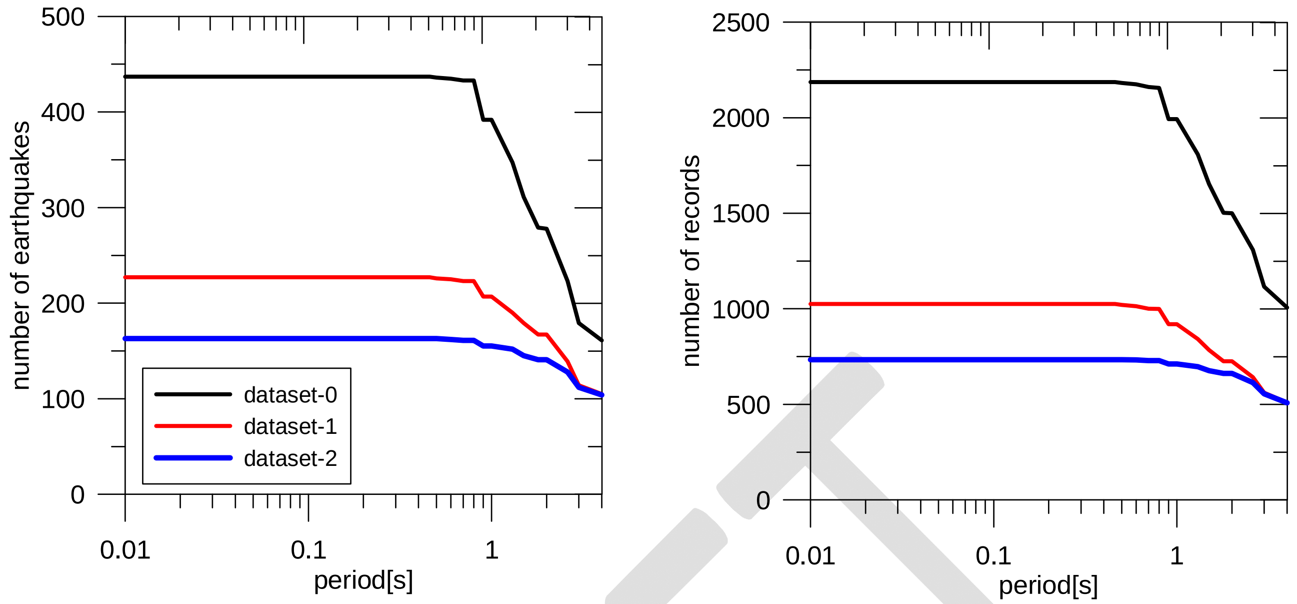


Figure 10. Number of earthquakes (left) and records (right) as a function of period considered for dataset-2 compared to dataset-0 and dataset-1.

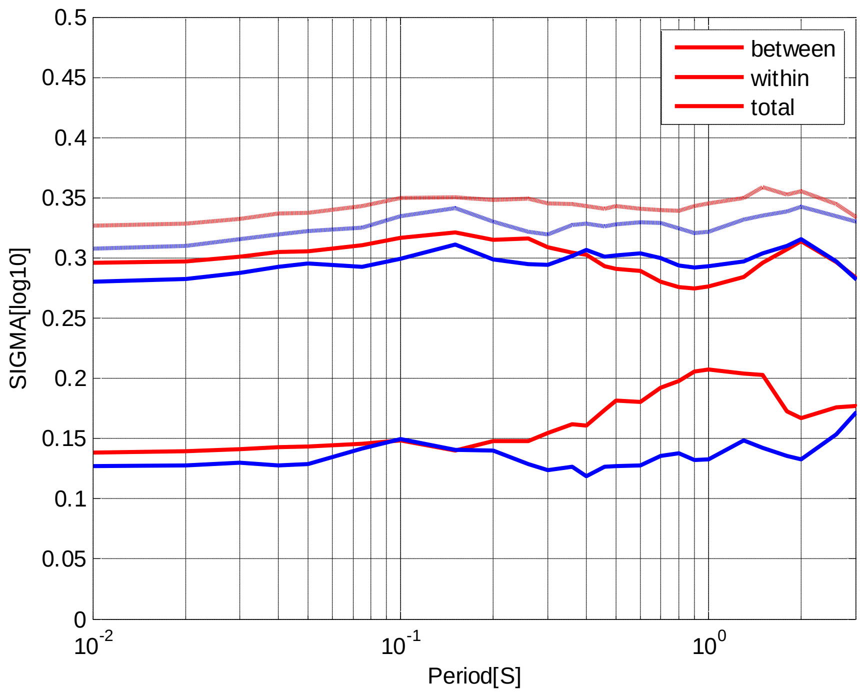


Figure 11. Between-event, within-event and total standard deviations (from bottom to top) for dataset-1 (red) and dataset-2 (blue).

3.3. Including all stations with EC8 site class information (dataset-3)

After the tests discussed above we decided to proceed with a site effects model based on EC8 soil classes in order to include a much large number of data, especially for small magnitude events. It is also decided to exclude converted Mw leading to an increase in the between event variability at long period that is likely due to some bias in Mw estimate.

The third data set that we use in this study includes all stations characterized either by a Vs30 value or by an EC8 site class. In this step we still exclude the French data for which only a ML value is provided in RESORCE, whose Mw will be discussed in the next section. In this way the dataset for small events is largely populated by Swiss data, for which a Mw determination by SED exists, and by few French data with available Mw (Figure1). The records are selected according to the following criteria:

- records from stations characterized by a measured value of the Vs30 or by an EC8 site class;
- only known fault mechanism;
- at least to records per event (no singly-recorded events).

The number of events and records used in dataset-3 is shown in Figure 12 and it is compared to that of previous datasets. The number of records significantly increase being almost double compared to dataset-2.

Dataset-3 is used to derive a GMPE based on equation (1) and (5) adopting the same regression scheme as for the previous datasets.

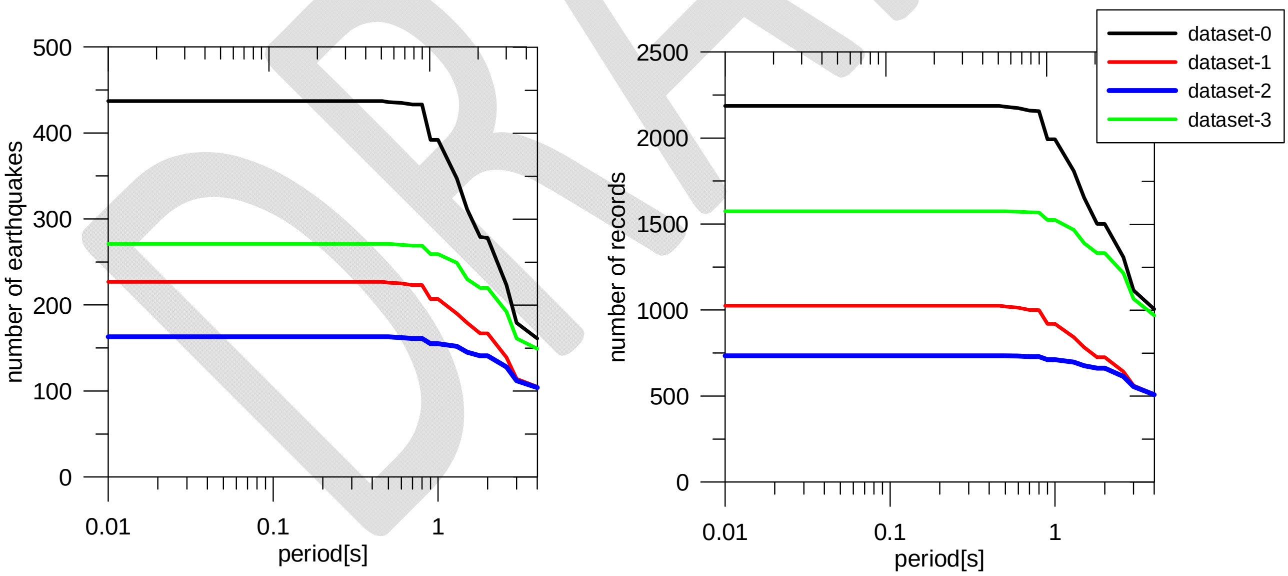


Figure 12. Number of earthquakes (left) and records (right) as a function of period considered for dataset-3 compared to dataset-0 and dataset-1.

The results are presented in terms of between-event and within-event residuals in Figure 13 and Figure 14, respectively. The between-event residuals do not show any significant trend with magnitude. However, for the smallest magnitude bin a slight overestimation by the model is observed (average negative residuals). Overall the residuals do not strongly suggest to include another brake in the magnitude scaling of equation (3) for magnitude smaller than 4. Interestingly, the between-event residuals show a larger dispersion for PGA than for PSA at 1s, and this seems to be largely related to events with magnitude smaller than 4. The lower panel of Figure 13 shows that the larger variability of between-event residuals for short periods is mostly related to Swiss and French small magnitude events, and to three French events with Mw > 4 characterized by large absolute residuals.

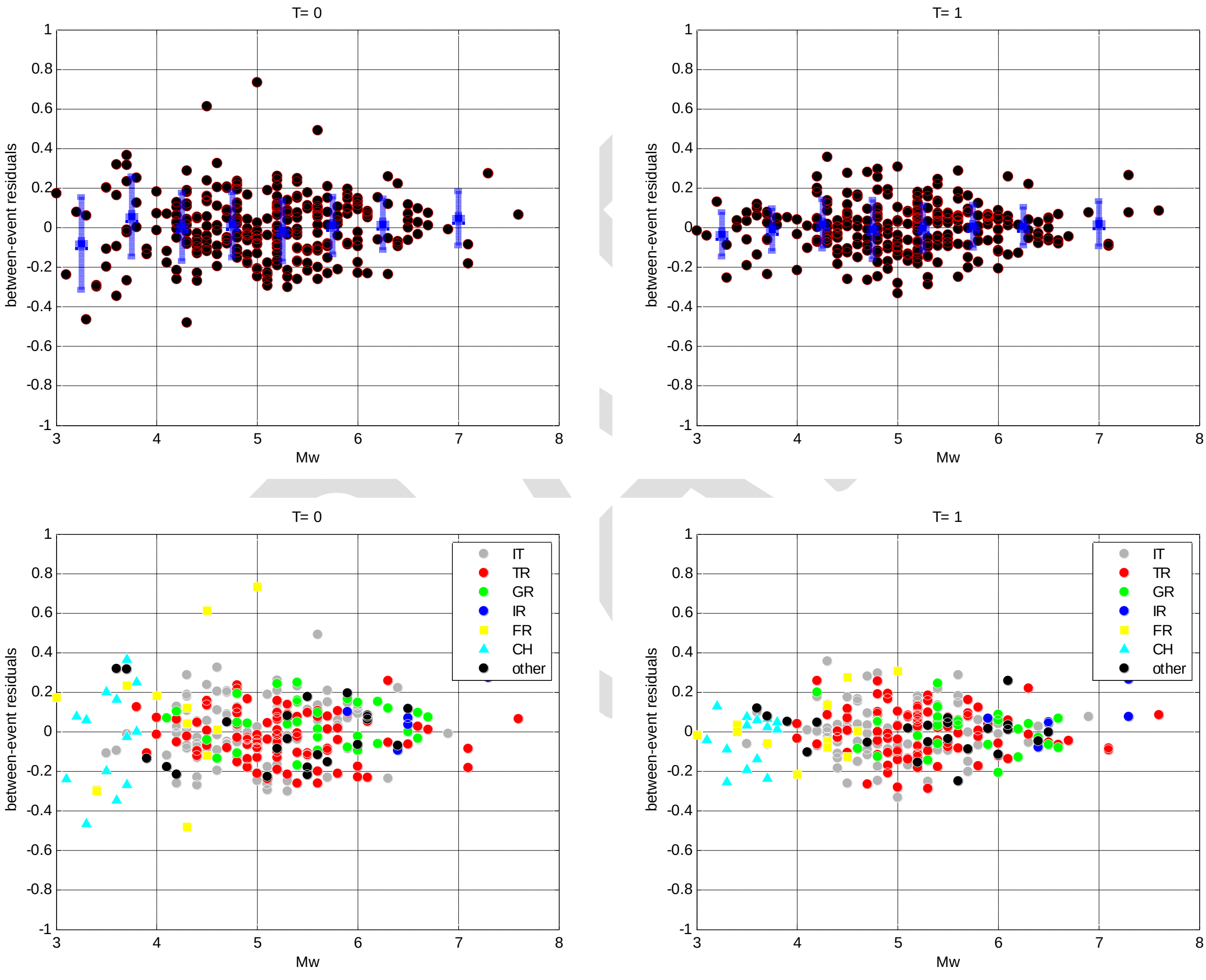


Figure 13ï Between-event residuals for PGA (left column) and T=1s (right column) as a function of Mw for dataset-3. In the upper plots the mean and standard deviation calculated for different magnitude bins are shown by blue bars. In the lower plots the residuals are coloured according to the earthquake country.

The within-event residuals (Figure 14) do not show dependencies with respect to epicentral distance and site class, confirming, as already observed in the previous tests, that the distance dependence of the considered dataset in correctly described by equation 2. Classes A, B and C are almost equally represented in the dataset, whereas only few records belong to stations classified as D.

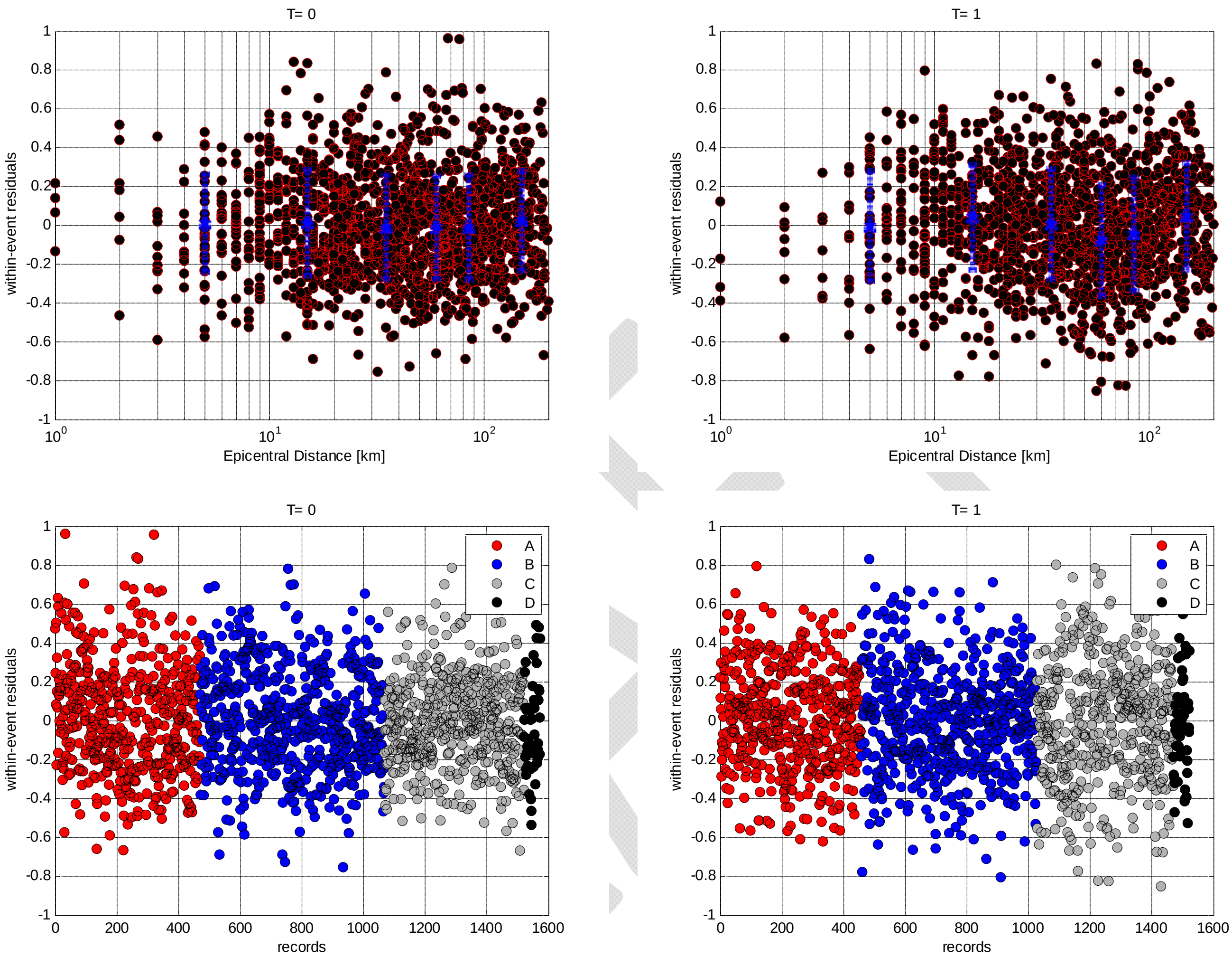


Figure 14. Within-event residuals for PGA (left column) and T=1s (right column) as a function of epicentral distance (top) and EC8 site classes (bottom) for dataset-3. The mean and standard deviation of the residuals calculated for different distance bins are shown by blue bars.

The components of standard deviation obtained for dataset-3 are shown in figure 15 and are compared with those derived from dataset-2. The between-event standard deviation largely increase with respect to that obtained from dataset-2, especially in the short-period range. On the other hand, the within-event variability is similar to the one previously derived, despite the fact that the number of records used in dataset-3 is significantly larger than that used in dataset-2.

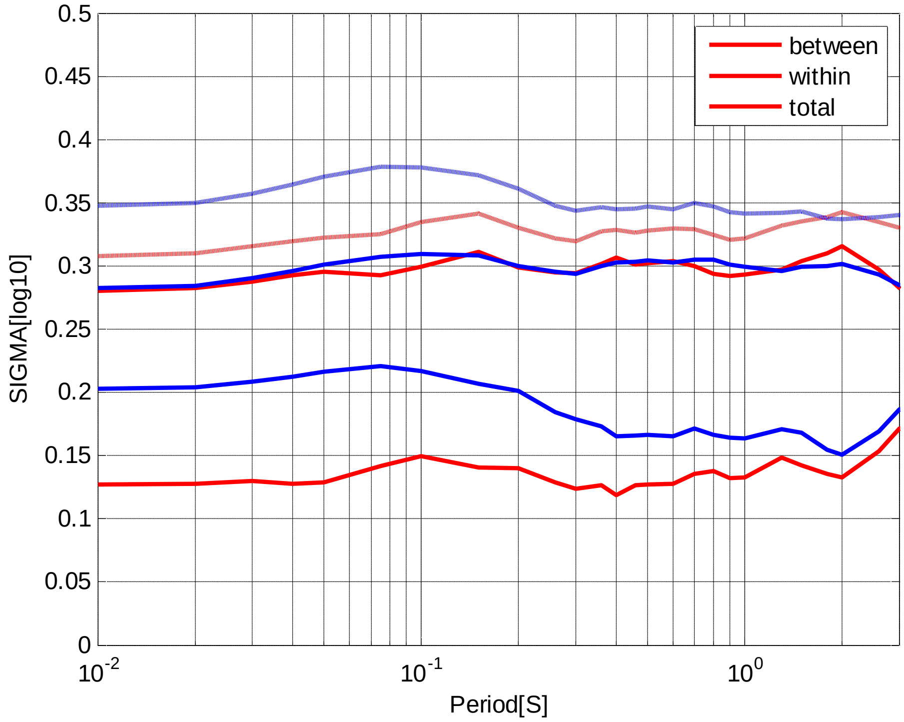


Figure 15. Between-event, within-event and total standard deviations (from bottom to top) for dataset-2 (red) and dataset-3 (blue).

One of the possible causes of the large variability of between-event residuals at short periods for small earthquakes is a magnitude-dependent variability of the stress drop (e.g., Youngs et al., 1995). The stress drop scales the high-frequency ground-motion amplitudes which is consistent with results in Figure 13. In the case of the present dataset, Drouet et al. (2010), performed a parametric inversion in order to separate source, path and site effects from the Fourier spectra of the recordings from a large number of earthquakes in France and estimated source parameters (seismic moment and corner frequency). Drouet et al. (2010) found different average stress values for events in the French Alps, in the Pyrenees and in the Rhine Graben. In particular events in the French Alps are on average characterized by smaller stress drop with respect to events in the other two regions, where the stress drop is found to be similar (though slightly larger in the Pyrenees). In Figure 16 the between-event residuals for French earthquakes are plotted as a function of the Bruneôs stress drop calculated as:

$$\Delta\sigma = \frac{7}{16} Mo \left(\frac{fc}{0.37\beta} \right) \qquad (6)$$

where the corner frequency (fc) for each event is provided in Drouet et al. (2010), the seismic moment is available in the database and the shear-wave velocity β=3.5 km/s. For the events used here and not included in the analysis by Drouet et al. (2010), the empirical relation between Mw and *fc* provided by the authors is used. Figure 16 suggests a positive trend of between-event residuals as function of qů for PGA. The events in the French Alps, characterized by a smaller stress drop provide mostly negative residuals, while events in the Pyrenees and in the Rhine Graben provide positive residuals. No trend is visible for PSA at 1s. This dependence of the residuals on qů for French events will be further investigated in the next Section.

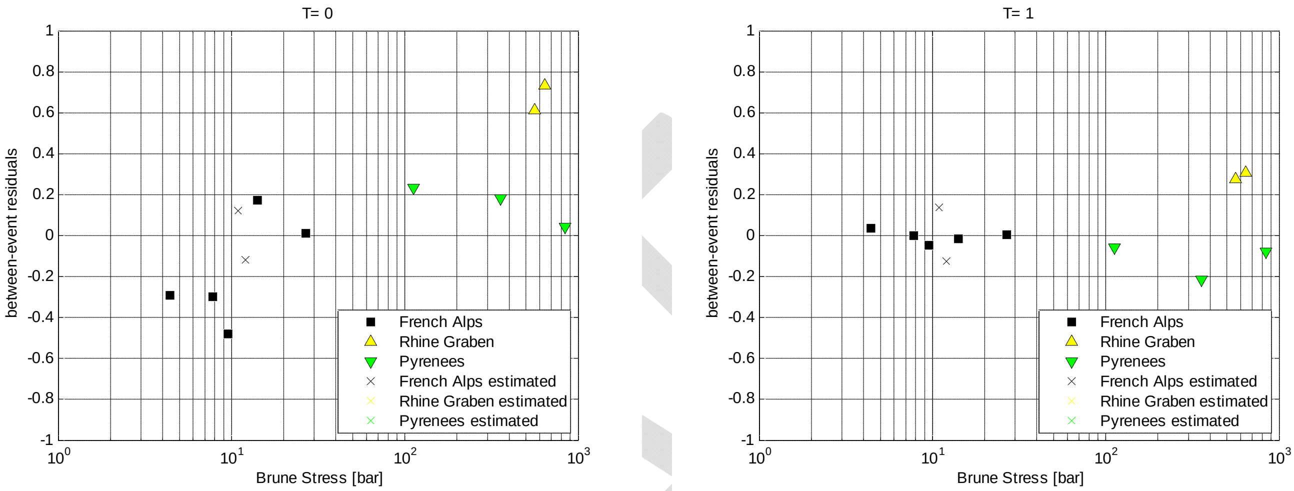


Figure 16. between-event residuals for PGA (left) and T=1s (right) as a function of Bruneøs stress drop for earthquakes in three different French regions.

3.4. Including all French events and a Bruneøs stress model (dataset-4)

In order to further investigate the dependence of French between-event residuals on Brune's stress drop we considered all the French events contained in RESORCE-2013 (i.e., contained in dataset-0). However, for a relevant number of French earthquakes (about 80%) the Mw is not provided. The magnitude of these events is given in terms of local magnitude (ML) as provided by RéNaSS (http://renass.unistra.fr/). Moreover, for many of these events, the style-of-faulting is not known, which further limits the use of these data for deriving GMPEs. In order to assign a Mw value and a fault mechanism to these events we follow the approach detailed below.

The Mw is obtained based on the results of the spectral inversion performed by Drouet et al. (2010). The source functions, in terms of Bruneøs source model, are derived for each event and thus the seismic moment (and Mw) is estimated. Drouet et al. (2010) also derived Mw-ML conversion equations for three different regions in France (Alps, Pyrenees and Rhine Graben) that exhibit different source scaling behavior. Thus:

- For the events that has been used in the study by Drouet et al. (2010) the Mw derived in the inversion has been used;
- For the other events the Mw-ML conversion equation is used.

The style-of-faulting was missing for 94 events, excluding singly-recorded event. A bibliographic research was conducted in order to identify studies devoted to the analysis of seismic sequence and where information on fault mechanism of small events could be retrieved. Table 1 summarize the papers providing the style-of-faulting information for 15 French events.

Table 1. Events for which the dominant style of faulting is defined in this study based on bibliographic research.

Event Date yyyymmdd hhmm	**Style-of-faulting**	**Reference paper(s)**
19990111 0336	Strike-slip	Thouvenot et al. 2003
19991101 1722	Strike-slip	Courboulexet al. 2007
20001219 1420	Strike-slip	Courboulexet al. 2007
20001220 0545	Strike-slip	Courboulexet al. 2007
20020905 2042	Normal	Rigo et al. 2005
20021211 2009	Normal	Rigo et al. 2005
20040718 0216	Normal	Cara et al. 2007
20061024 0004	Normal	Sylvander et al. 2008
20061117 1819	Normal	Sylvander et al. 2008
20061118 2034	Normal	Sylvander et al. 2008
20061118 2217	Normal	Sylvander et al. 2008
20061119 1316	Normal	Sylvander et al. 2008
20061120 0401	Normal	Sylvander et al. 2008
20061216 0817	Normal	Sylvander et al. 2008
20071115 1347	Normal	Sylvander et al. 2008

For the remaining events, the fault mechanism was estimated based on the dominant stress regime and the seismotectonic zonation developed at France national level by Baize et al. (2013). We are aware that this is a quite rough approach but we believe that it gives a first order approximation on the dominant fault mechanism of the event.

By including these events in dataset-3 we obtained a dataset-4 which contains about 300 events and 1700 records (Figure 17).

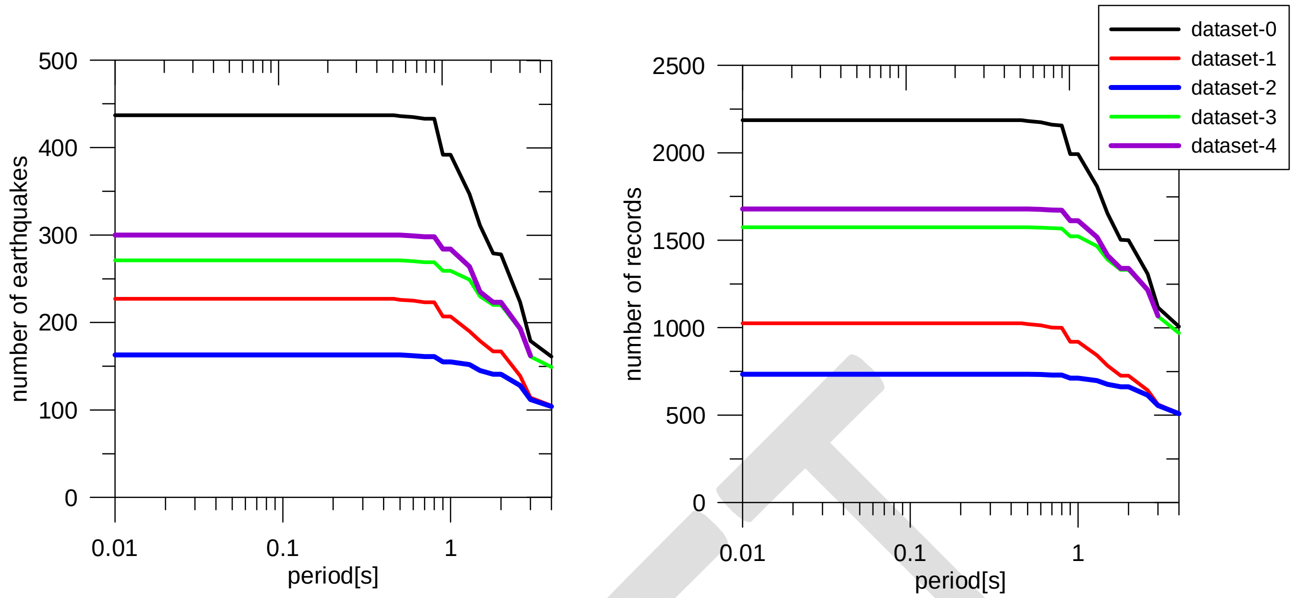


Figure 17. Number of earthquakes (left) and records (right) as a function of period considered for dataset-4 compared to the previously discussed datasets.

The regression is performed using the same model as in the previous test. The between-event residuals as a function of Mw, presented in Figure 18, confirm the large dispersion at small magnitudes and short spectral periods, already observed for dataset-3. This is now evident also for French events, that are much more represented than in the previous case.

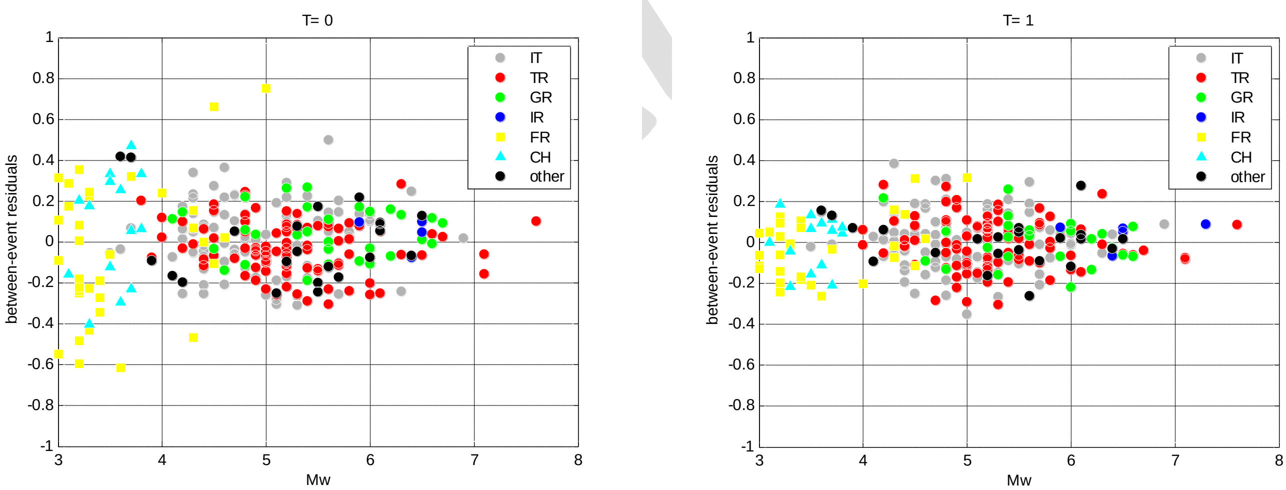


Figure 18. Between-event residuals for PGA (left column) and T=1s (right column) as a function of Mw for dataset-4. Residuals are colored according to the earthquake country.

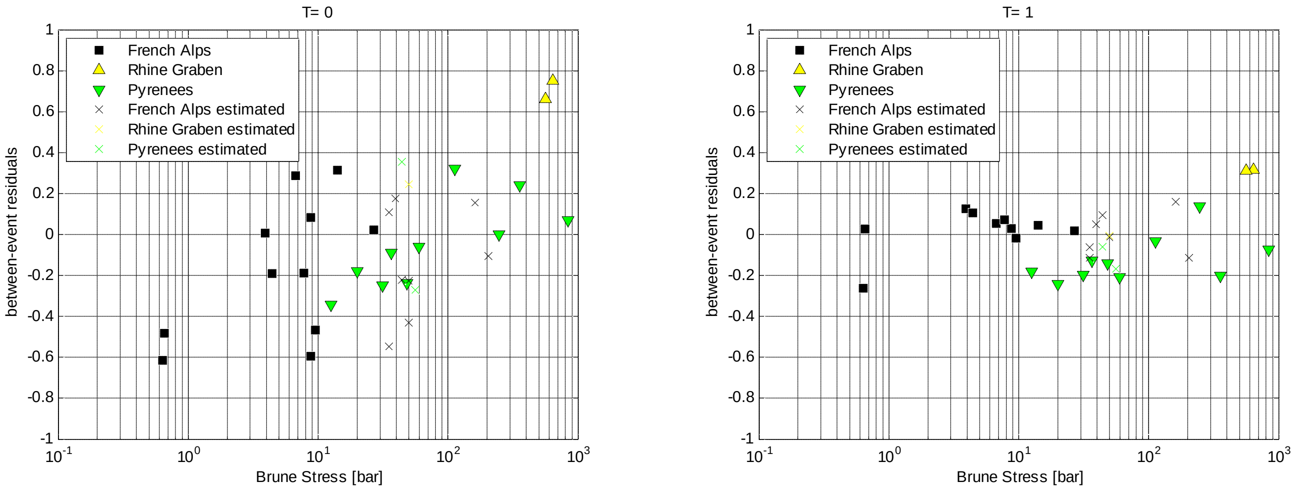


Figure 19. Between-event residuals for PGA (left) and T=1s (right) as a function of Bruneôs stress drop for earthquakes in three different French regions.

The dependence of the between-event residuals for French events on the Bruneôs stress drop is presented in Figure 19. The trend with stress drop is now much clearer than that observed on figure 16 suggesting that accounting for such dependency would reduce the scatter in the residuals for French data.

Based on this result a regional term is added to equation (1) in order to account for stress drop scaling for French events. The regional stress drop model is:

$$regionFR(\Delta\sigma, Mw) = \begin{cases} F_{FR} s_2 \log_{10}\left(\dfrac{\Delta\sigma}{\Delta\sigma_{REF}}\right) & \text{for Mw} < 5.0 \\ F_{FR} s_2 \log_{10}\left(\dfrac{\Delta\sigma}{\Delta\sigma_{REF}}\right)(6.0 - Mw) & \text{for } 5.0 \le \text{Mw} \le 6.0 \\ 0 & \text{for Mw} > 6.0 \end{cases} \qquad (7)$$

where F_{FR} is a dummy variable that takes the value of 0 or 1 according to the region (1=France, 0=elsewhere), s_2 is a coefficient to be determined through the regression and $\Delta\sigma_{REF}$ is a reference Bruneôs stress drop assumed equal to 50 bars (the mean stress drop found by Drouet et al. 2010). The stress drop model is developed for small magnitudes, Mw < 5, which is the magnitude limit of the French data. For Mw larger than 5 we tapered the stress drop scaling so that it goes to 0 for M larger than 6.0 where the model it is not constrained by the data.

The between-event residuals obtained by including the regional stress-drop model for France are presented in Figure 20. The scatter in the residuals for French earthquakes at short periods is significantly reduced accounting for stress-drop dependency. Despite this reduction, the variability of small magnitude between-event residuals at short period is still larger compared to magnitudes larger than 4. The variability of between-event residuals suggest that a heteroscedastic sigma model, dependant on magnitude, should be investigated. This will be one of the object of the following of this study.

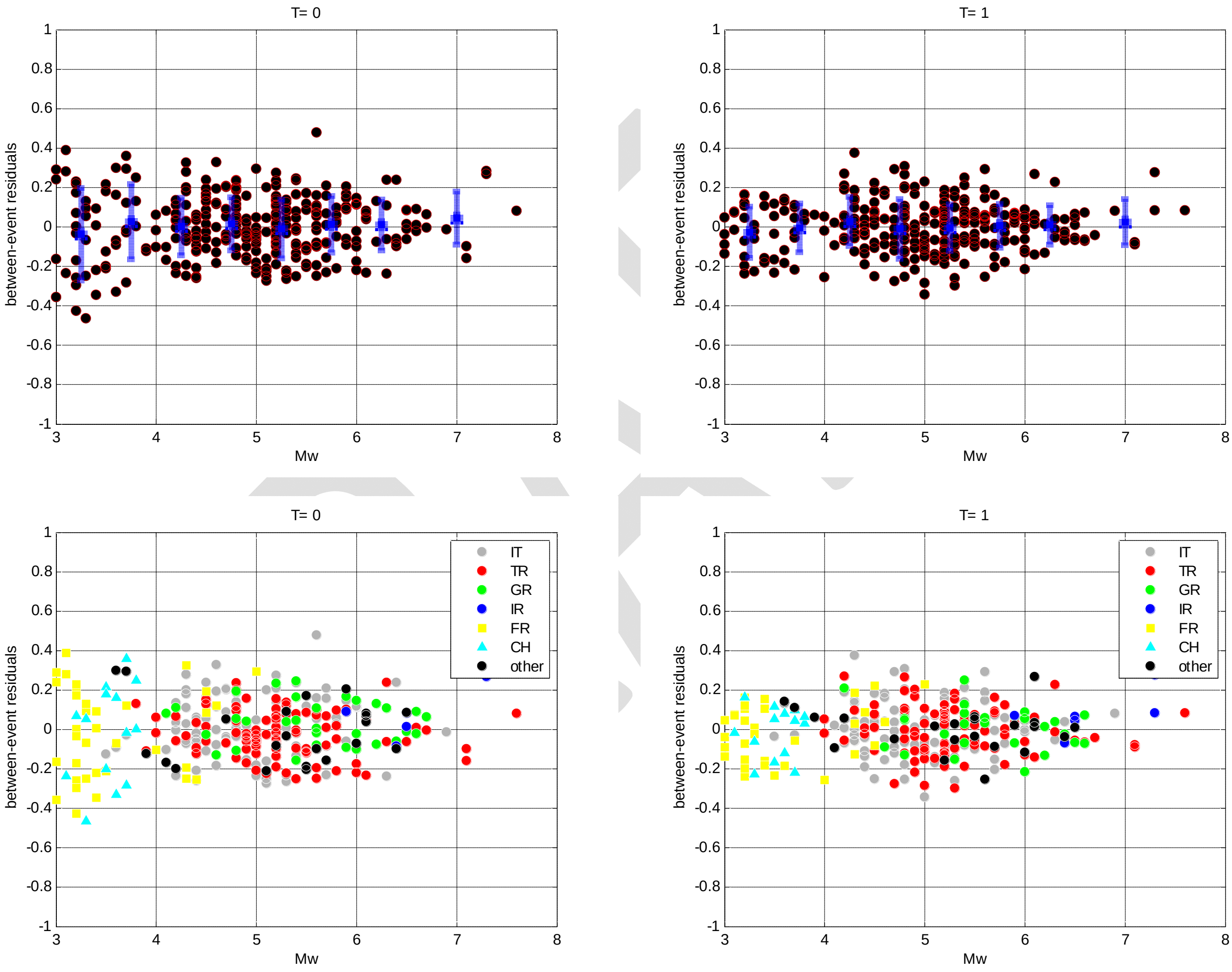


Figure 20. Between-event residuals for PGA (left column) and T=1s (right column) as a function of Mw for dataset-4 including the regional stress drop model for France. In the upper plots the mean and standard deviation calculated for different magnitude bins are shown by blue bars. In the lower plots the residuals are coloured according to the earthquake country.

In order to investigate potential regional dependencies of the attenuation of ground motion with distance for French data, we show in Figure 21 the within-event residuals as a function of epicentral distance separating the French data as a whole (Figure 21, left) or dividing the data in three regions:

French Alps, Pyrenees and Rhine Graben. Due to the relatively small amount of data it is hard to comment on possible trends in the residuals. However, at a first analysis we do not observe any strong distance dependencies of the French residuals, or of the residuals from one of the sub-region.

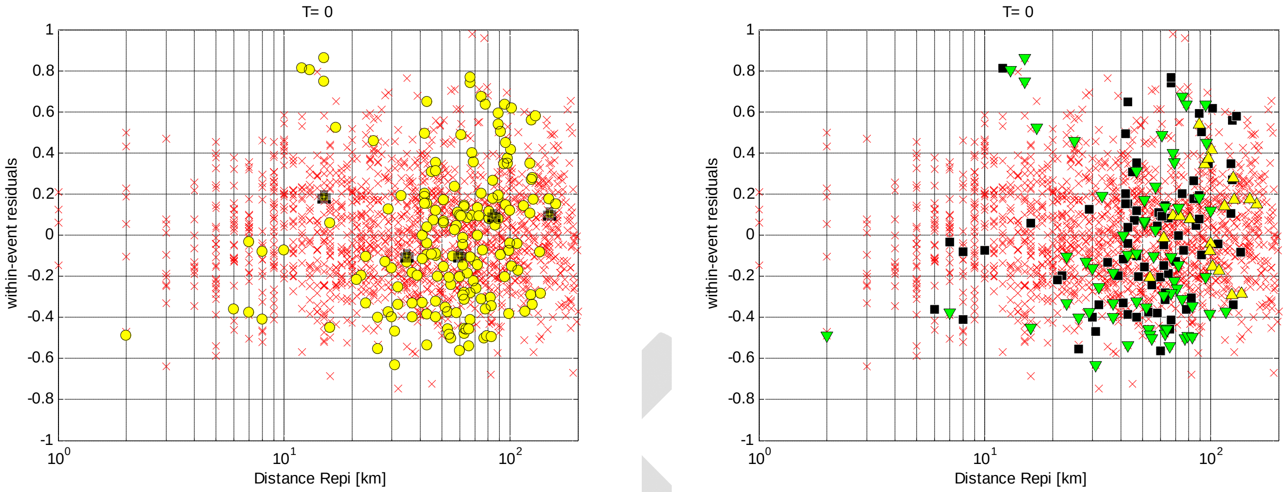


Figure 21. Within-event residuals for PGA as a function of epicentral distance for dataset-4. Left: French data are marked by yellow symbols and the mean residuals are calculated for different distance bins. Right: French data are marked by different symbols according to the region (Alps: black squares; Pyrenees: green triangles; Rhine Graben: yellow triangles.

Figure 22 shows the between-event, within-event and total standard deviation of the models derived using dataset-4 and including or not the regional stress-drop model for small-to-moderate magnitude French events. By considering the stress-drop model, the between-event sigma is substantially reduced at short periods, whereas the within-event sigma is unaffected. The price to pay for having reduced the aleatory standard deviation of the model is that we have increased the epistemic uncertainties in the median estimation. Indeed the stress-drop value for future events cannot be known exactly and it can only be estimated, typically through correlations with other earthquake parameters (e.g., Mw). In PSHA such epistemic uncertainty shall be treated in a logic tree framework assuming different stress drop values (or a magnitude-dependent stress drop) as different branches.

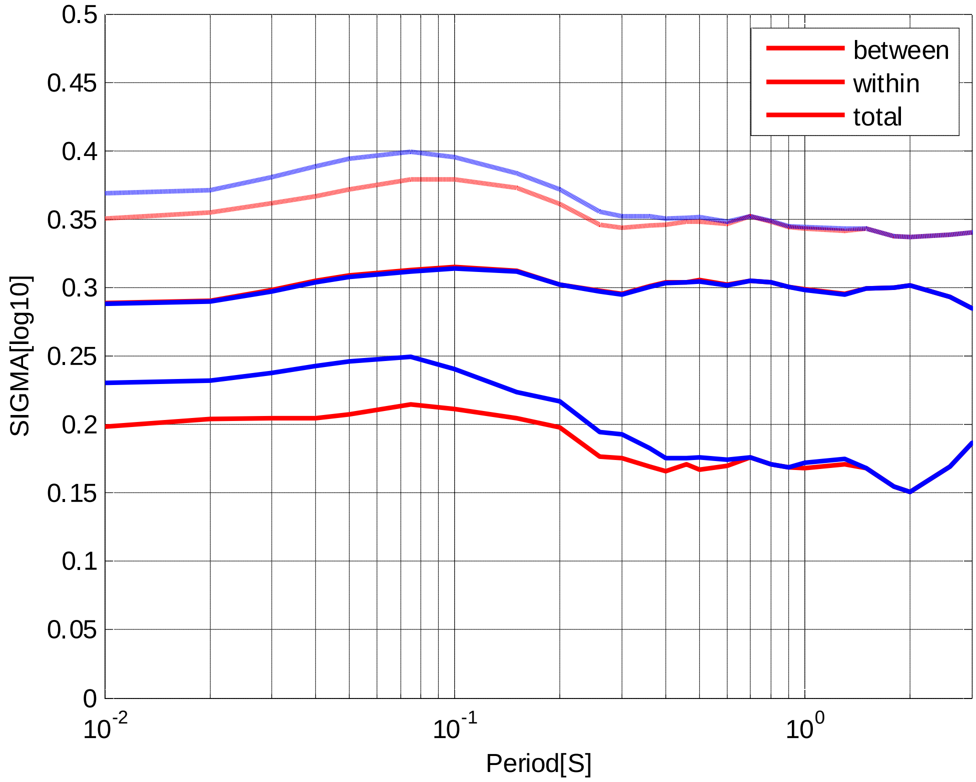


Figure 22. Between-event, within-event and total standard deviations (from bottom to top) for dataset-4 including (red) or not (blue) the regional stress drop model in the functional form.

3.5. Comparison between point-source and extended-source distance metrics.

Recent GMPEs are usually derived as a function of an extended source distance metric such as the Joyner-Boore distance (R_{JB}) or the rupture distance (R_{RUP}). This is the case for NGA-west1 and NGA-west2 models. However, models based on data from the broader European region (e.g., Akkar and Bommer, 2010) are typically derived as a function of R_{JB} due to the lack of R_{RUP} information for a significant number of records in the relative database. This is also the case for RESORCE-2013 database (SIGMA-2013-D2-91). Indeed GMPEs derived with the 2011 version of RESORCE are all based on R_{JB} (Douglas et al., 2013).

Recently Bommer and Akkar (2012) pointed out that in PSHA where zone of diffuse seismicity are considered, the use of GMPEs based on extended-source distance can result in an hazard underestimation if the considered hazard calculation code is not able to model extended ruptures. They showed this effect deriving twin GMPEs based on the same dataset but using a point-source and extended-source distance metric and they proposed to use both of them in PSHA according to the specific seismic source characterization. Based on these reasoning recently derived GMPEs

(Akkar et al., 2013b and Bindi et al., 2013) propose models for epicentral, hypocentral and Joyner-Boore distances.

The models presented so far in this study were discussed in terms of epicentral distance (R_{EPI}), here we briefly present and discuss the results in terms of R_{JB}. We considered dataset-4 in which we replaced R_{EPI} with R_{JB} for all the records for which the information was available in RESORCE, otherwise R_{EPI} was kept but only for MwÒ5. The records with M>5 and no R_{JB} information were excluded. The functional form is composed by equations 2, 3, 5 and 7.

The within-event residuals as a function of R_{JB} are presented in Figure 23 for PGA and PSA at 1s. As for the case of epicentral distance, the residuals do not show any significant trend.

In Figure 24 the influence of the use of epicentral or Joyner-Boore distances is shown for Mw 4, 5.5 and 7, and considering EC8 class A and a strike-slip mechanism. The two models predict similar values for low magnitudes (Mw=4) at all distances. Since the point source approximation can be applied, for small magnitudes, R_{JB} is similar to the epicentral distance. For short distances and large magnitudes the model based on R_{EPI} predicts larger values than the one based on R_{JB}, as the difference in the definition of the two metrics, cause R_{JB} to be equal or less than R_{EPI} thus reducing the ground-motion amplitudes for a given distance.

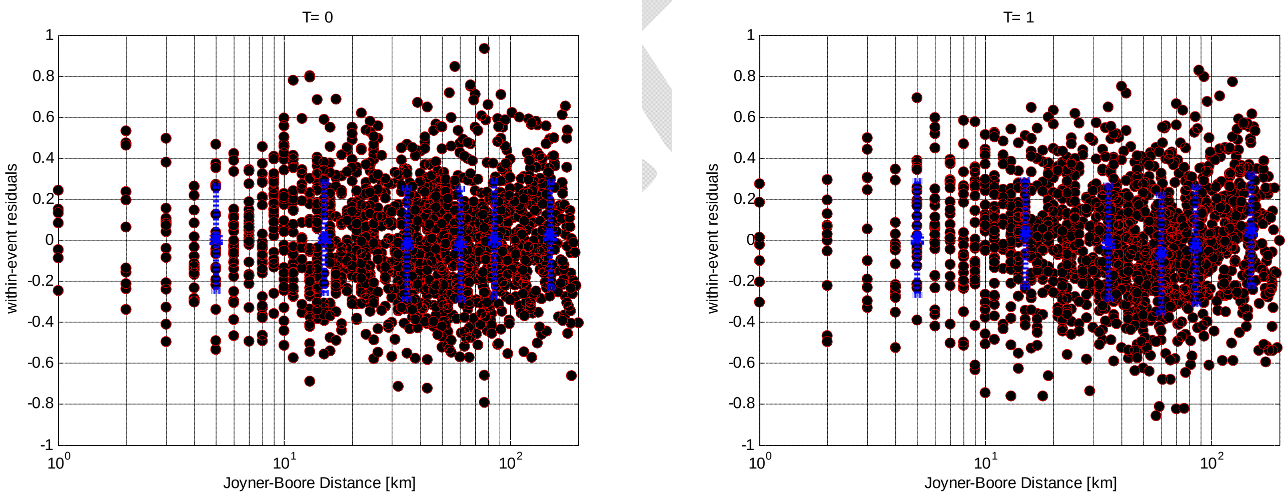


Figure 23. Within-event residuals for PGA (left column) and T=1s (right column) as a function of Joyner-Boore distance for dataset-4 (updated with RJB). The mean and standard deviation of the residuals calculated for different distance bins are shown by blue bars.

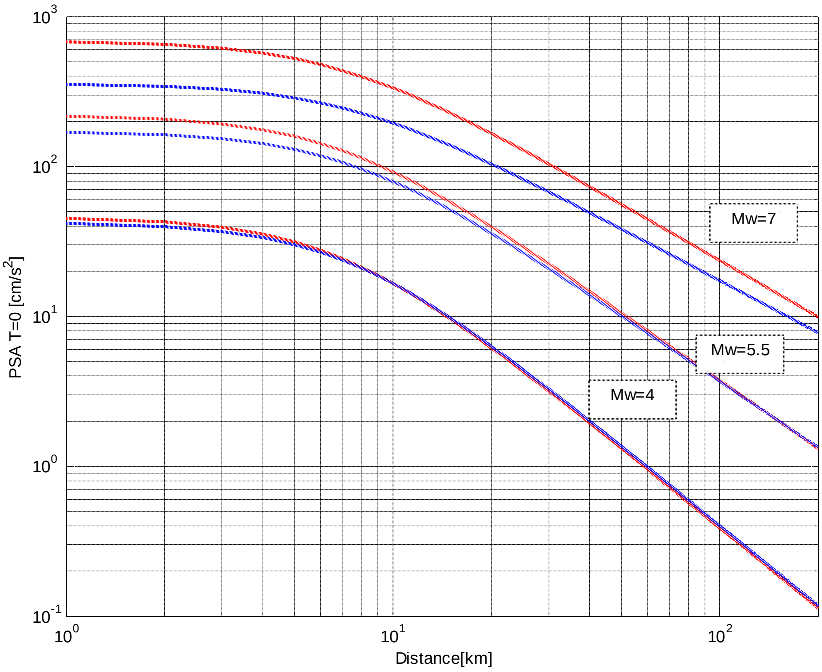


Figure 24. Comparison between models based on Joyner-Boore (blue) or epicentral distances (red) for PGA considering EC8 class A, strike slip faulting and no regional model for stress drop.

The standard deviations of the models derived for R_{JB} and R_{EPI} are compared in Figure 25. The standard deviation of the two models are very similar, with a slightly smaller within-event variability obtained with the R_{JB} model. Akkar et al. (2013b) suggested that the similar performance of the two model, in terms of models standard deviation, may be due to the lack of date for large magnitudes (Mw>6) and short distances.

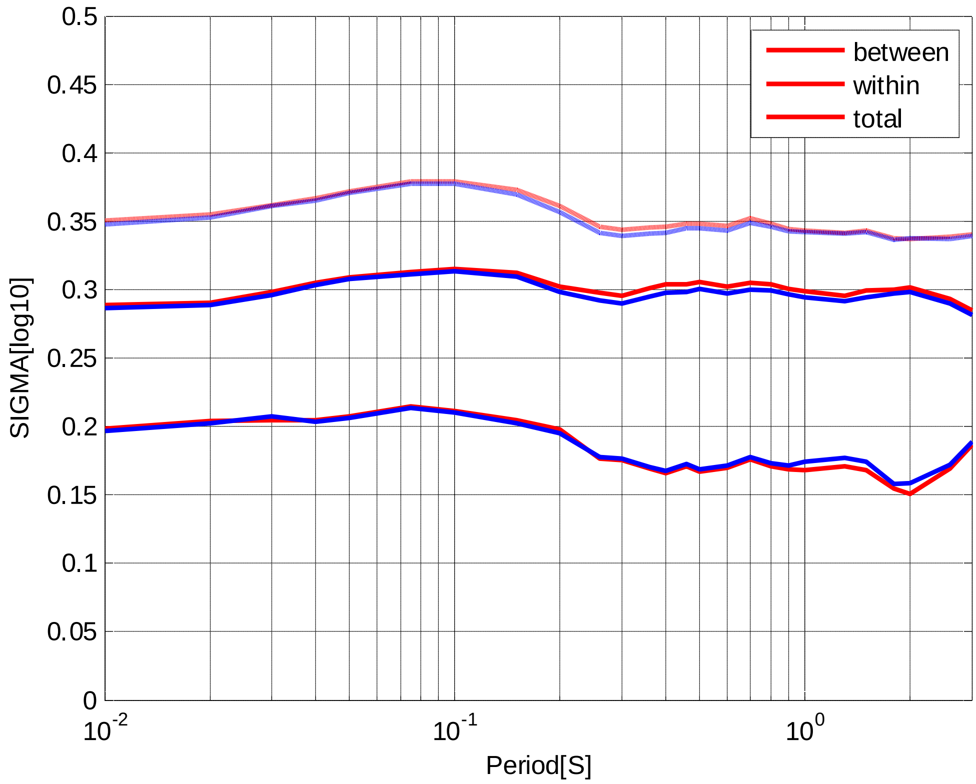


Figure 25. Between-event, within-event and total standard deviations (from bottom to top) for dataset-4 for epicentral distance (red) and Joyner-Boore distance (blue) in the functional form.

4. Median ground motion predictions for representative scenarios and comparison with other GMPEs

The model derived using dataset-4 and including stress-drop scaling fro French events represents the preliminary GMPE proposed in this study for PSHA. The magnitude, distance, site class and stress-drop scaling of median ground motions will be presented in this section for several representative scenarios in order to highlight the main features of the model.

The magnitude scaling is presented in Figure 26 for three epicentral distances (10, 50 and 150 km) and for PGA and PSA at 1s. The magnitude range considered in the dataset is 3-7.6. As expected, the magnitude scaling is stronger at longer spectral periods. Note also the change is the magnitude scaling after the hinge magnitude (Mw=6.75).

The distance scaling is presented in Figure 27 for four magnitudes (Mw=3.5, 4.5, 5.5 and 7.0) and for PGA and PSA at 1s. The epicentral distance range in the considered dataset is 1-200 km. The different decay with distance of large and small magnitude, modeled by the distance dependence geometrical spreading in equation 2, is clearly visible, especially for PGA.

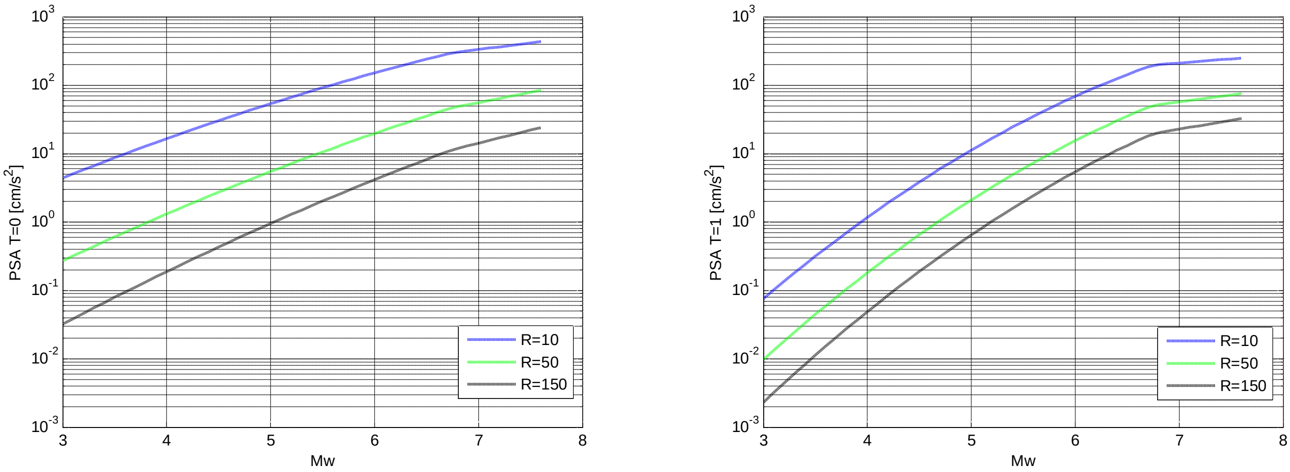


Figure 26. Magnitude scaling of the median ground motion for strike-slip earthquakes and site class A (EC8) for different epicentral distances for PGA (left), PSA(1s) (right).

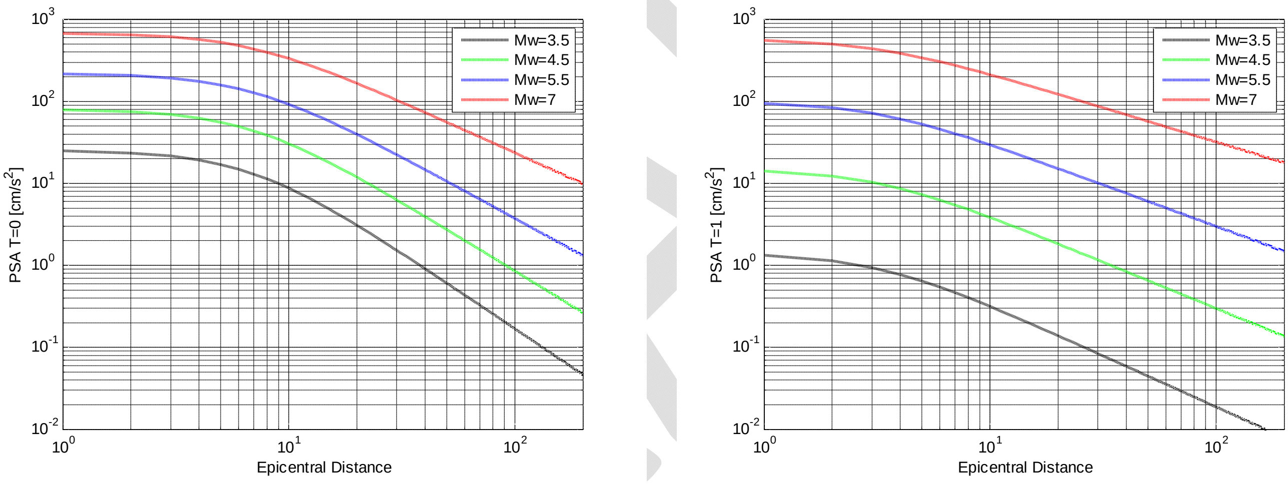


Figure 27. Distance scaling for strike-slip earthquakes and site class A (EC8) for different Mw for PGA (left), PSA 1s (right).

The scaling of predicted response spectra for different EC8 site classes is presented in Figure 28 for a Mw=4.5 at 25 km and for Mw=6.5 at 25km (see also the site coefficients of the model in Figure A2). The ground motion generally increase from class A to C, however for class D sites the amplitudes are generally comparable to class B and C at short periods, whereas at long periods (around 1s) they are larger. The period of largest amplification with respect of class A is shifted to longer periods from class B to D, according to the fact the softer sites generally respond at longer periods. It is worth mentioning that site class D are poorly represented in the dataset and the model has to be considered not well constrained for this site class.

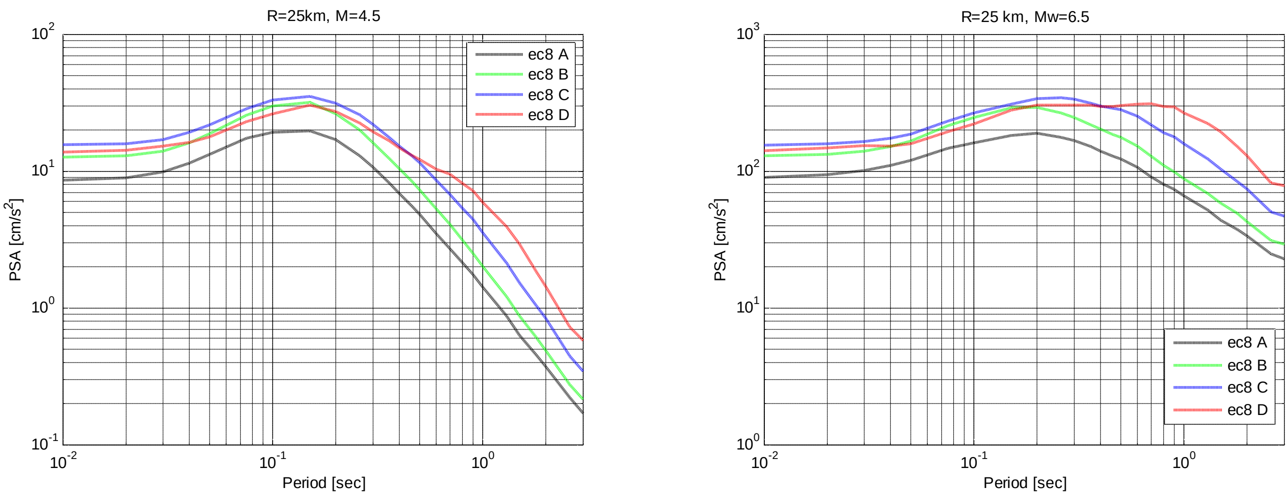


Figure 28. Scaling of response spectra for the considered EC8 site classes for two representative scenarios for strike-slip earthquakes. Left: Mw=4.5 and R=25km; Right: M=6.5 and R=25km.

The scaling of response spectra with stress drop for the regional model for France is presented in Figure 29 for four different magnitudes at 25 km distance. The stress-drop model significantly modify the spectral amplitude at short periods (below 0.2- 0.3 s) increasing the ground motion level with increasing stress drop. At long periods the spectra are almost unaffected. The scaling with stress drop is tapered to decrease linearly for Mw>5 (equation 7) and after Mw=6.0 no scaling with stress drop is modeled.

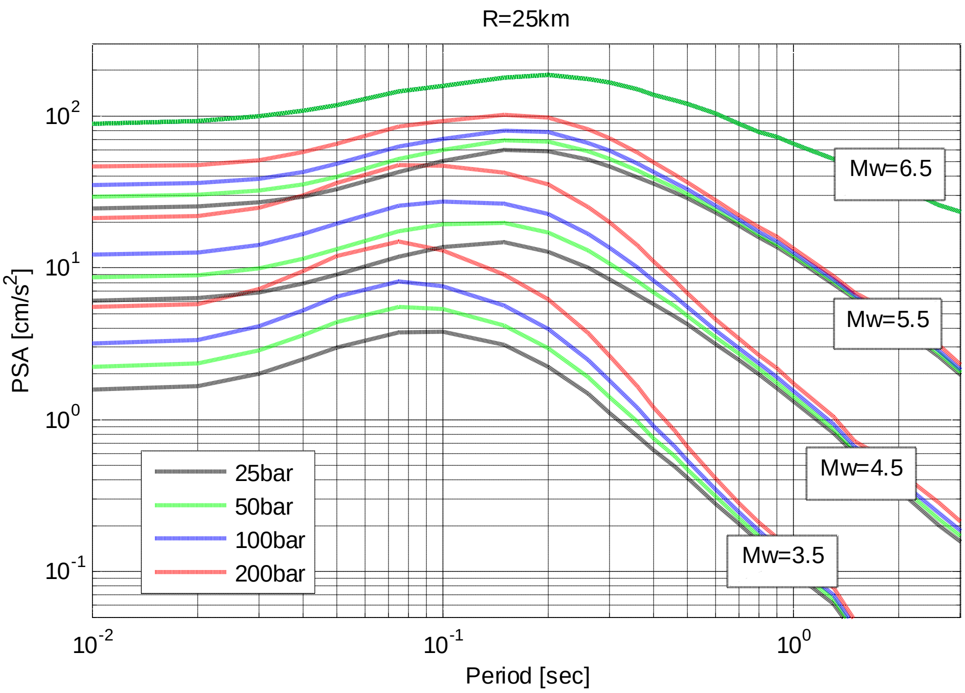


Figure 29. Response spectra stress drop scaling for different magnitude values at an epicentral distance of 25km for strike-slip earthquakes and EC8 class A.

In Figure 30, the predicted response spectra for a Mw=4.5 at a distance of 25 km are presented for two French regions characterized by significantly different stress drop (Drouet et al. 2010). The stress-drop values for French Alps and Pyrenees are calculated based on the results by Drouet et al. (2010) and are equal to 12 bars and 200 bars, respectively. The response spectrum estimated without considering the regional stress-drop model for France is also shown for comparison. At short periods the spectral acceleration for Pyrenees are about a factor of 2 larger than the that estimated without stress-drop model and about a factor of 4 larger than that for French Alps.

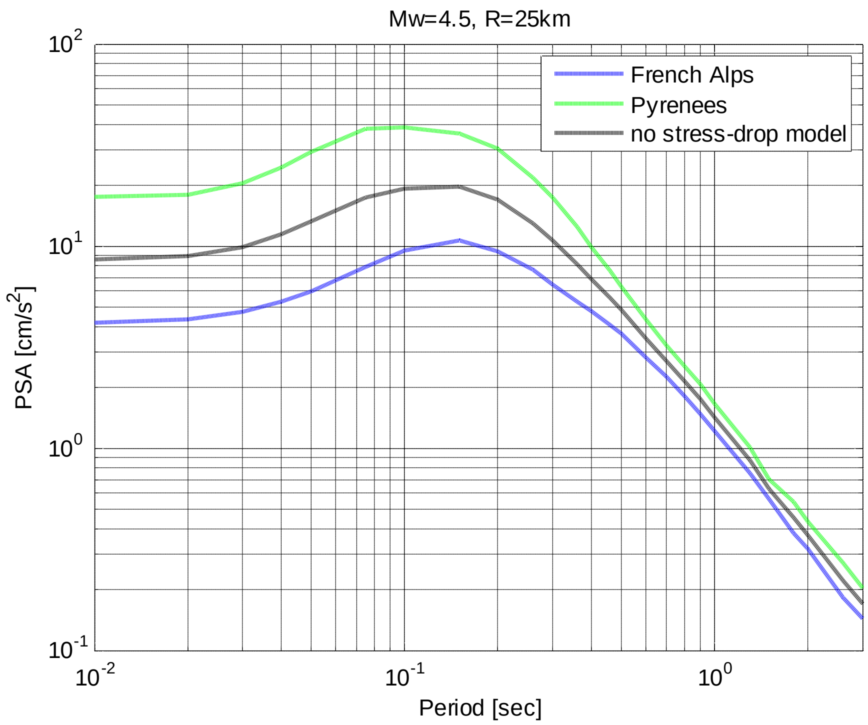


Figure 30. Predicted response spectra for French Alps and Pyrenees for a Mw 4.5 at an epicentral distance of 25 km. The stress drop is estimated based on Drouet et al. (2010). The response spectra obtained without the stress drop model are also shown. Predictions are for strike-slip earthquakes and EC8 class A.

Finally, the magnitude and distance scaling and the standard deviation obtained from this preliminary study are compared with two GMPEs derived form RESORCE-2011 (Akkar et al., 2013b and Bindi et al., 213). The comparison is performed without considering the stress-drop scaling for French events. The magnitude scaling of the three models is substantially similar (Figure 31). The model by Akkar et al (2013b) provide larger values for Mw< 5, especially for PGA. Note that the lower magnitude limit of applicability of the two mentioned model is Mw=4. We extrapolated the models down to magnitude 3 on purpose in order to show the differences with respect to the model derived in this study. The distance scaling (Figure 32), presented for a Mw=6, is very similar for the three models at PGA, whereas differences appear at PSA 1s for short distances. The Akkar et al. (2013b) model provide smaller values, particularly for R_{JB} < 10 km.

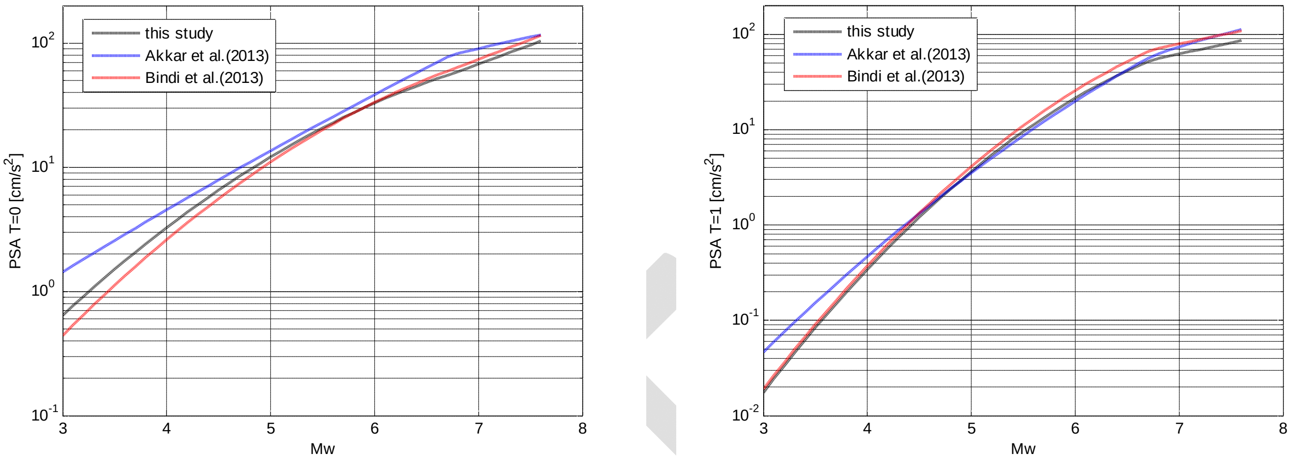


Figure 31. Comparison of magnitude scaling of the median ground motion for the model derived in this study (black), the model by Akkar et al. 2013 (blue) and the model by Bindi et al. 2013 (red). Comparison is performed for Joyner-Boore distance of 25 km, strike-slip earthquakes and site class A (EC8) or a Vs30=800 m/s (for Akkar et al. 2013b) for PGA (left), PSA(1s) (right).

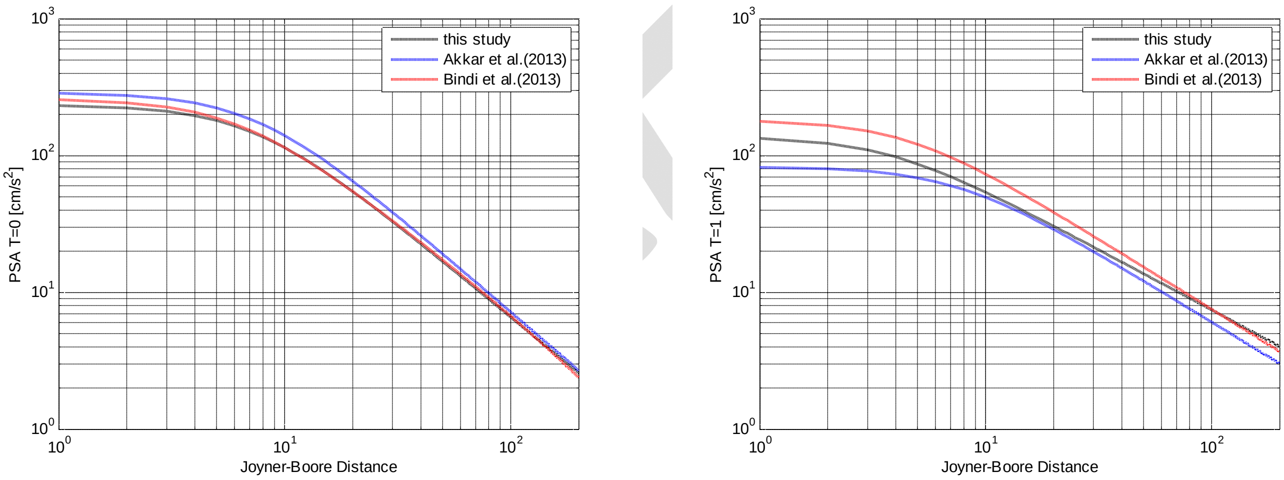


Figure 32. Comparison of distance (R_{JB}) scaling of the median ground motion for the model derived in this study (black), the model by Akkar et al. 2013 (blue) and the model by Bindi et al. 2013 (red). Comparison is performed for Mw=6, strike-slip earthquakes and site class A (EC8) or a Vs30=800 m/s (for Akkar et al. 2013b) for PGA (left), PSA(1s) (right).

Figure 33 compares the components of standard deviation for the three GMPEs. The between-standard deviation of the model derived in this study is similar to the model by Akkar et al. (2013) for periods larger than 0.3 s, while at shorter periods our model show a larger standard deviation. As discusses this is ascribed to the between-event variability of small magnitude events that we included in the dataset, whereas they were not included by Akkar et al. (2013b) and Bindi et al. (2013). The within-event standard deviation are similar over the three GMPEs.

We stress that in dataset-4 we included a significantly larger number of events and records with respect to those considered by Akkar et al. (2013b).

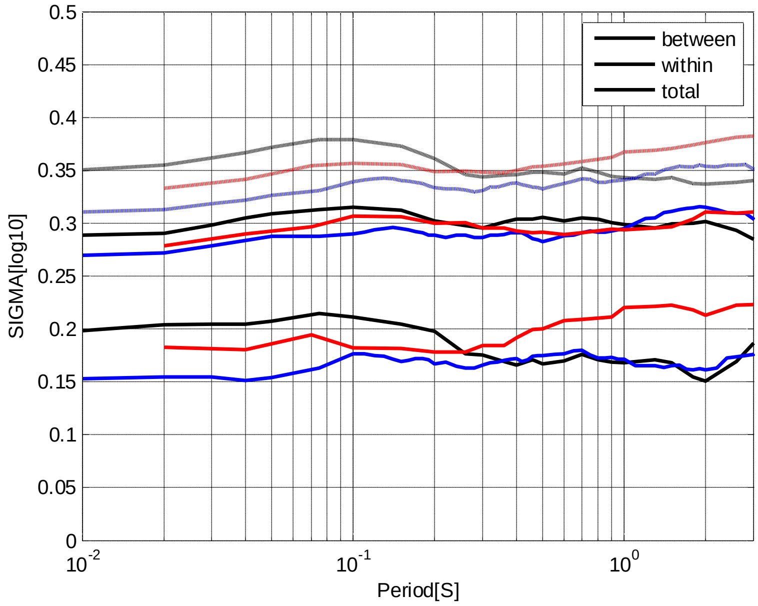


Figure 33. Comparison of between-event (dashed-dotted lines), within-event (dashed lines) and total (continuous line) standard deviation of the GMPE derived in this study (black) and those by Akkar et al. 2013b (blue) and by Bindi et al. 2013 (red).

5. Assessment of metadata uncertainties in RESORCE

5.1. Motivation and strategy

One of the aim of the study is to evaluate the metadata errors in RESORCE database and to assess their influence on the GMPEs. In particular it has been shown in previous studies that metadata uncertainties, typically ignored in GMPEs derivation, affect the total standard deviation of the models and that the contribution of such epistemic uncertainties should be removed by the aleatory variability of the GMPEs. However, the amount of such reduction depends on the quality and structure of the considered dataset. For example Rhoades (1997) was one of the first to study the contribution of magnitude uncertainties on the standard deviation of the GMPEs. Starting from the dataset collected by Joyner and Boore (1981), Rhoades (1997) assigned an uncertainty of 0.1 to Mw directly determined from moment tensor inversion and an uncertainty of 0.3 to Mw converted from other magnitude types. He showed that the magnitude uncertainty contributed to about 50% of the between-event variability, whereas the within-event variability was not affected.

More recently, Abrahamson et Silva (2007, 2008) evaluated the impact of magnitude, distance and Vs30 uncertainties on their NGA-1 GMPE by applying a simple first-order approximation of error propagation. They used fixed uncertainties for the whole dataset, being 0.12 for Mw and 3 km for rupture distance. Their results showed a small impact of metadata uncertainties on the reduction of the standard deviation of the model at short spectral periods but, especially for magnitude and Vs30, larger effect at longer periods.

Finally, Moss (2009, 2011) evaluated the impact of Vs30 uncertainties on the GMPEs derived by Chiou and Youngs (2008) using different methodologies. He found that the reduction of the standard deviation due to the epistemic uncertainties in Vs30 can reach 10% at long spectral periods. The results are obtained by assigning an uncertainty of 27% on the initial vs30 value.

The approach followed to assign uncertainties to earthquake magnitudes in RESORCE is necessarily pragmatic. RESORCE database is combination of data coming from other databases or scientific publications, and the magnitude and earthquake location estimation methods can be very different. In this context, it would extremely time-expensive to attempt a magnitude calculation or earthquake relocation based on the original data for each event in order to establish uncertainties based on a common methodology.

In the context of assigning an uncertainty to the earthquake metadata (e.g., magnitude or location) it is useful to indentify to approaches. The first one aim to identify the uncertainty of the single estimate, for instance, which is the uncertainty in the epicentral location provided by one particular agency. The second identify the uncertainty based on comparison between different best estimates, for instance different epicentral locations provided by different agencies. In the present study the first approach will be the preferred one, assuming that the metadata retained in RESORCE already comes from the preferred source after screening of several sources of information. The second one will be adopted in case the first one cannot be followed due to lack of information.

5.2. Magnitude uncertainties

In the first version of RESORCE (SIGMA-2011-D2-15) the information on the Mw type (direct or converted) was not provided. Thus, it was not possible to assess the reliability of the Mw values in the database and to know which conversion equation was used. During the development of RESORCE-2013 the review meeting of the preliminary release was held in Paris on 5 July 2013, where it was proposed to clearly identify the converted Mw with a flag in the database also indicating which conversion equation was used for each event.

Table 2 summarize the magnitude conversion equations and their uncertainties used in RESORCE.

Table 2. Magnitude conversion equations adopted in RESORCE-2013 to estimate Mw. The star (*) indicates values that not provided in the reference papers but approximated in the present study based on information such as R^2 and number of data used in the regression and available in the relative publications. For the Akkar et al. (2010) equations, when it was not possible to identify which conversion has been used a general standard deviation of 0.25 was assigned.

Reference paper	Country of validity	Standard deviation
Gasperini and Ferrari (2000)	IT	0.3 (ML)
Castello et al. (2007)	IT	0.25*(ML)
Akkar et al. (2010)	TR	0.25*(mb) 0.35*(Md) 0.3* (ML) 0.2* (Ms)
Papazachos et al. (2002)	GR	0.23
Drouet et al. (2011)	FR	0.3* (ML RéNaSS)

The uncertainty values to the RESORCE Mw are assigned based on the following cases:

1. the magnitude is a converted Mw based on one of the equations provided in Table2. In this case the uncertainties provided in Table 2 are assigned;

2. the uncertainty is directly available in the original database, catalogue or publication (then merged into RESORCE). This is the case, for instance, of magnitudes provided by the ISC-GEM (2012) catalogue. It is also the case for few publications (e.g., Lyon-Caen et al.,1988, Walker et al., 2003) where the uncertainty of the estimated seismic moment is provided;
3. mainstream Harvard, Global CMT or RCMT type Mw, obtained using digitally recorded seismograms. The corresponding Mw uncertainty is set to 0.1 (as suggested in ISC-GEM, 2012);
4. Mw from Swiss moment tensor solutions determined by SED, generally used in RESORCE for small magnitude Swiss and French events, an uncertainty of 0.15 is assigned (Braunmiller et al. 2005);
5. French events, for which the Mw estimated by spectral inversion in Drouet et al. (2010) is used, corresponding uncertainty is set to 0.2;
6. Mw for which the source of origin is the European Strong-Motion Database, either referred to ESD or ISESD, we distinguished two cases, because the original source of Mw was not available. For Mw>5, we compared the values with GCMT and if the difference was Ò0.1 an uncertainty of 0.1 was assigned, otherwise 0.15. For M<5 an uncertainty of 0.15 was assigned.

Figure 34 shows the Mw uncertainties as a function of the Mw values provided in RESORCE for a dataset (that will be dataset-5) selected by adding to dataset-4 the Turkish and Italian events with converted Mw that were excluded in Section 3.2. As expected the uncertainties are generally larger for smaller Mw, and the converted Mw for Turkish and Italian events between magnitude 3 and 4, are clearly visible.

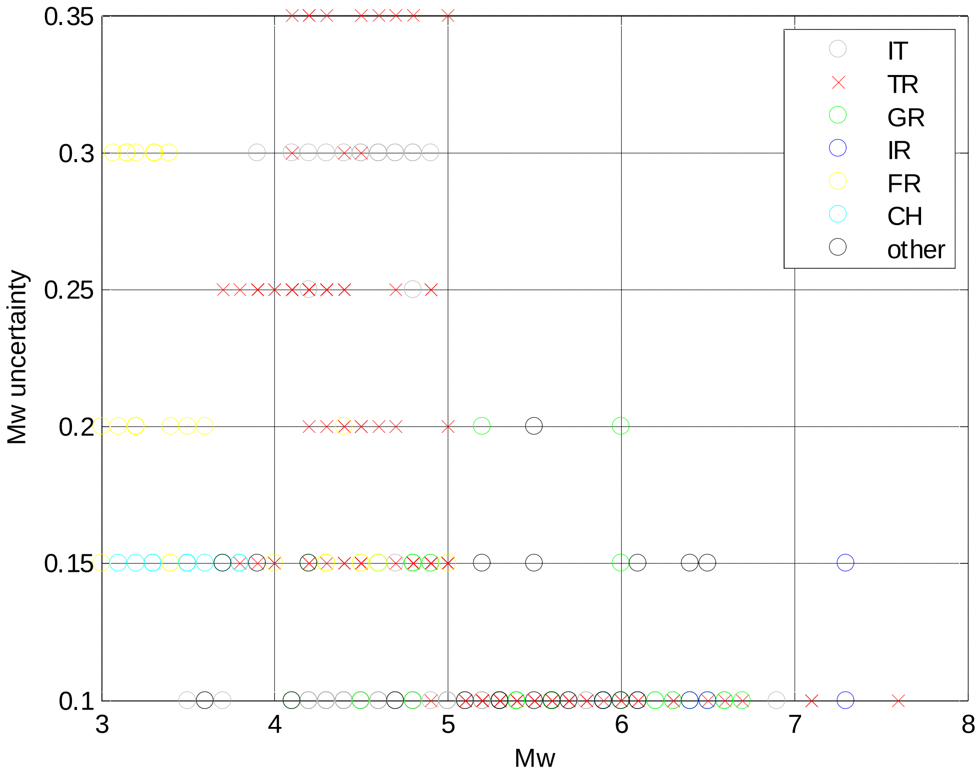


Figure 34. Magnitude uncertainties for events in dataset-5 as a function or best-estimate Mw in RESORCE (selection for a period T=0s).

6. Effect of Mw uncertainties on the GMPE: median ground-motion and standard deviation

The uncertainties in the moment magnitudes contained in the dataset are propagated into the GMPE via Monte Carlo (MC) approach by generating a large number of alternative datasets with magnitudes obtained by random sampling the error distributions. We considered a normal distribution with mean value given by the Mw provided in RESORCE and standard deviation given by the Mw uncertainties estimated for each event. The normal distributions are truncated at two standard deviations.

In this section, we discuss the effect of Mw uncertainties on the derived model and the implications for the model derived with Mw provided in RESORCE (that we will call best-estimate Mw).

First, we inspected the coefficients of the GMPEs and their variation with respect to the MC realizations. Figure 35 shows the distribution of coefficients *a*, *b1*, *b2*,*c1*, *c2* and *h* (see equation 1,2 and 3) at T=1s. Note that coefficient *b3* is constrained to zero.

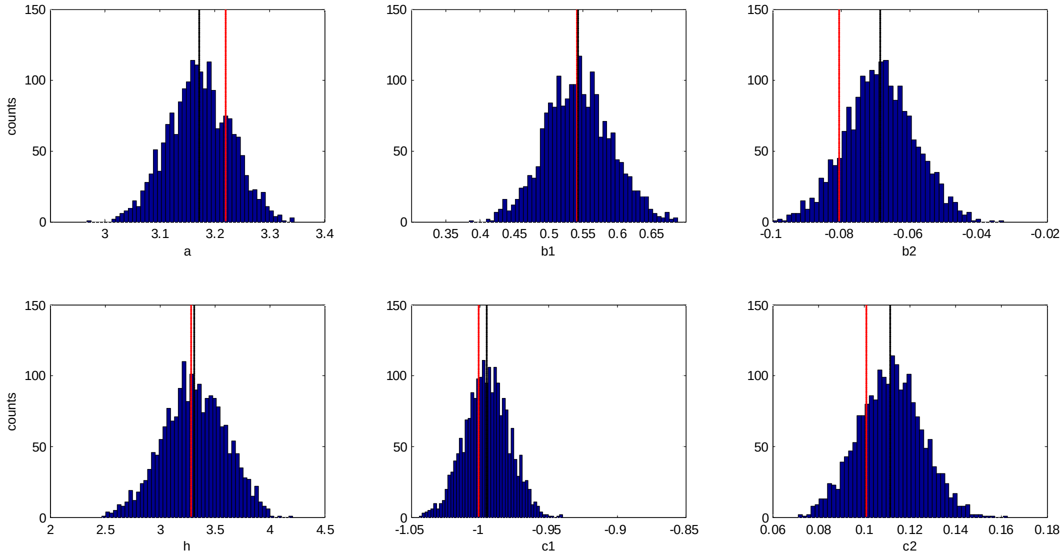


Figure 35. Distributions of magnitude and distance coefficients of the model (equations 1, 2 and 3) for the 2000 MC realizations of the magnitude errors in the dataset. The black vertical line indicates the mean of the distributions. The red vertical line indicates the coefficient value obtained from a single regression using the best-estimate magnitudes from RESORCE.

The vertical black and red lines show the mean of the distributions and the coefficients values for the model derived with the best-estimate Mw, respectively. The first observation is that the coefficients are normally distributed. The second is that, for coefficients *a*, *b2* and *c2*, the mean of the distribution is significantly different from the coefficient derived with the best-estimates Mw (red lines). In particular, the mean of *a* coefficients is smaller, the mean of *b2* coefficients is smaller (in absolute value) and the mean of *c2* is larger. This implies on average smaller ground motion amplitudes, a smaller quadratic magnitude scaling and a larger magnitude-dependant attenuation.

The magnitude scaling for PSA at T=1s of the GMPEs derived from the MC realizations (using coefficients for each single regression and the mean coefficients from all regressions) are shown in Figure 36 and compared to the GMPE derived from best-estimate Mw. In order to facilitate the comparison the right panel of Figure 36 shows the ratio between the ground-motion values obtained from the best-estimate Mw GMPE and the those obtained from MC models. The black curve shows the ratio with respect to the model based on the mean coefficients from the MC regressions. It is interesting to note that the model from best-estimate Mw predicts larger motion than the mean model from MC realizations for Mw larger than about 4.5 whereas the opposite is observed for smaller Mw. The dispersion of the models from MC realizations is larger at the upper and lower limits of the magnitude range, due to the considered functional form (where the F_D function, eq.2, takes the larger values) and to the fact that at large Mw the model is less constrained by the data. As expected it is also larger for long spectral periods, where the magnitude scaling of ground motion is stronger.

The difference between the mean model from MC realizations and the model from best-estimate Mw is not that large, being at most about a 10% at large Mw and 20% at small Mw and it is likely not much significant for PSHA applications but it is interesting from the point of view of GMPEs derivation. Although not presented here similar considerations hold for other spectral periods. A first interpretation of this results lies in the uneven distribution of events with Mw in the dataset (larger number of events for small-to-moderate Mw) and in the uneven distribution of Mw uncertainties (larger for Mw below 5, see Figure 34).

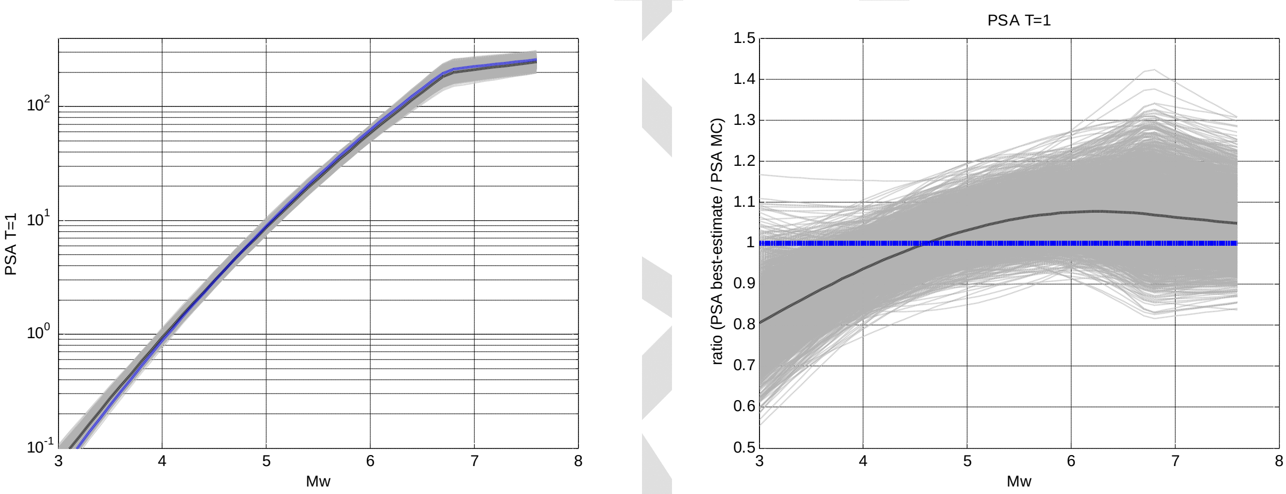


Figure 36. Left: magnitude scaling of the models derived from MC realization of Mw errors in the dataset (gray), the model with mean coefficients from the MC realizations (black) and the model from a original best-estimate magnitudes (blue). Right: ratio between the ground motion values obtained from the best-estimate Mw GMPE and the MC models (gray), and the model with mean coefficients from MC (black). Predictions are for a distance of 10km, for strike-slip earthquakes and site class A (EC8).

Consider the distribution of random Mw generated by MC approach (according to the defined distributions) as a function of the initial Mw in RESORCE (Figure 37). The distributions clearly reflect the fact that for Mw<5 larger uncertainties are associated to the Mw (for instance the large uncertainties associated to converted Mw between 4 and 5), whereas the Mw>5 mostly come from GCMT and an uncertainty of 0.1 is assigned. We focus on three different magnitudes and on a range of plus/minus 0.3 from these magnitudes, highlighted by the red dots and red horizontal bars, respectively (Figure 37). As a first case we consider what happen around Mw=5. We can observe that the chance that an earthquake that was assigned a Mw=4.7 to 5 in RESORCE is actually a Mw larger 5 is larger than the chance that an earthquake that was assigned a Mw 5 to 5.3 is actually a Mw smaller than 5. As a second case, we consider a 0.3 magnitude interval around Mw 6.7. For these magnitudes the uncertainties are much smaller and similar to each other, however because the dataset is getting sparse with increasing magnitudes the same consideration done for magnitudes around 5 holds. In other words, the chance that a ground motion assigned to an event Mw=6.4 to 6.7 is actually from an event with Mw larger than 6.7 is larger than the chance that a ground motion assigned to an event Mw=6.7 to 7 is actually from an event smaller than 6.7.

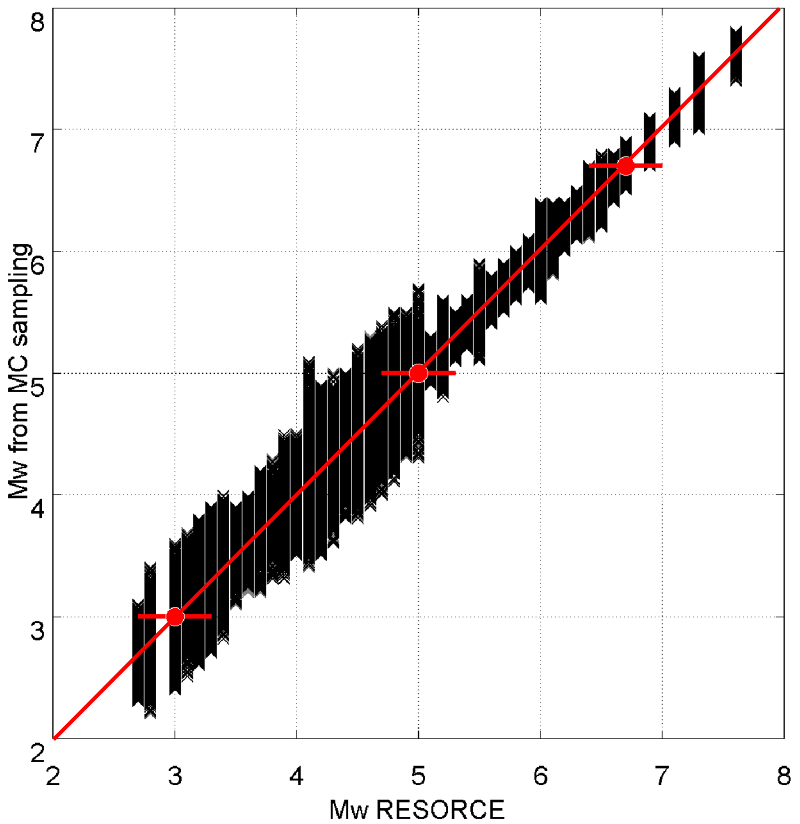


Figure 37. Moment magnitudes (Mw) provided in RESORCE versus Mw obtained by random sampling the normal distributions with mean value equal to Mw RESORCE and standard deviation defined as explained in the text. The red dots indicate Mw=3, 5 and 6.7 and a plus/minus 0.3 interval is indicated by the horizontal bars.

These first two cases illustrate the reason why the prediction from the GMPE derived with best-estimate Mw is larger than the prediction from mean GMPE with Mw uncertainties, for Mw larger than about 4.5.

The reason of the larger values of the mean GMPE with uncertainties at small Mw is less clear as the randomly generated Mw smaller than 3 will be discarded in the data selection (due to the minimum magnitude Mw=3 used in this study).

Because this behaviour is based on general considerations that hold for most of the datasets used for many GMPEs derivation (i.e., larger uncertainties for small-magnitude events and decrease of the number of events with increasing magnitudes), we believe that it may have implications for median motion from GMPEs derived without considering magnitude uncertainties. For this reason we plan to further investigate this issue using ground motion simulations to generate a synthetic dataset of controlled magnitudes and data distribution.

We now consider the standard deviations of the GMPEs derived from the MC sampling of the Mw uncertainties (Figure 38). As expected, when considering the Mw uncertainties, the mean between-event standard deviation increase with respect to the between-event standard deviation from the model with best-estimate Mw from RESORCE. On the other hand, the within-event standard deviation does not show any significant variation. This is also expected because the Mw uncertainties will mostly effect the between-event residuals.

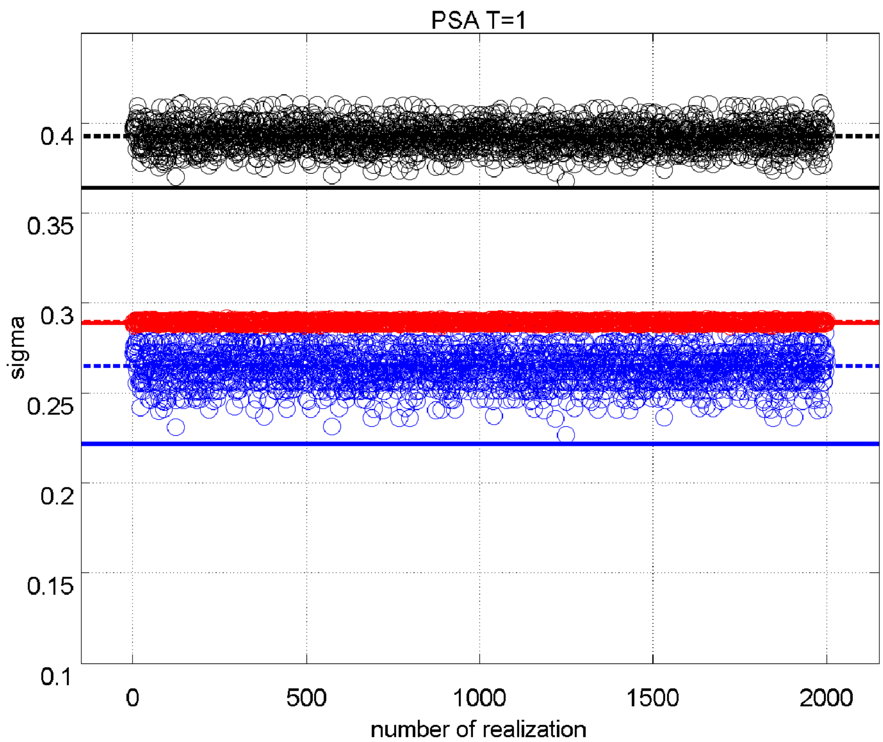


Figure 38. Between-event (blue), within-event(red) and total (black) standard deviations from the models derived by the 2000 MC realizations of the Mw uncertainties. The dashed lines represent the mean of the standard deviations of all the models. The continuous lines represent the standard deviations of the model derived from best-estimate Mw in RESORCE.

The standard deviation of the distribution of standard deviations represents the contribution of the Mw uncertainties to the model standard deviation and, because it is an epistemic uncertainty, it should be removed from the standard deviation of the GMPE derived with best-estimate Mw. The standard deviation of the distribution of between-event standard deviation is 0.01. Thus, the consequent reduction in the total standard deviation is negligible.

7. Future developments

The following points will be investigated in the following of this study:

- stress-drop model for Swiss data. A study on source parameters of Swiss events, including stress-drop, has been performed by Edwards and Fäh (2013). Once the values of stress-drop for Swiss events contained in RESORCE will be available we plan to investigate the dependence of Swiss between-event residuals on stress-drop;
- heteroscedastic sigma model. The preliminary results presented in this report suggest a magnitude-dependent sigma model. We will further investigate this aspect.
- Assessment of uncertainties in RESORCE metadata. Distance uncertainties (related to the uncertainties in epicentral location and/or in the determination of rupture geometry) will be investigated. We also plan to investigate uncertainties in the site classification (either based on Vs30 or site classes). The effect of such uncertainties on the derivation of GMPEs will be evaluated.
- The effect of Mw uncertainties (and of distance uncertainties) will be further studied using synthetic datasets.

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9. Annex

The magnitude and distance coefficients (as in equations 1, 2 and 3) of the models derived with different data selections are compared as a function of period in Figure A1. The models include different functional forms for site effect model and a model for stress-drop scaling of French events.

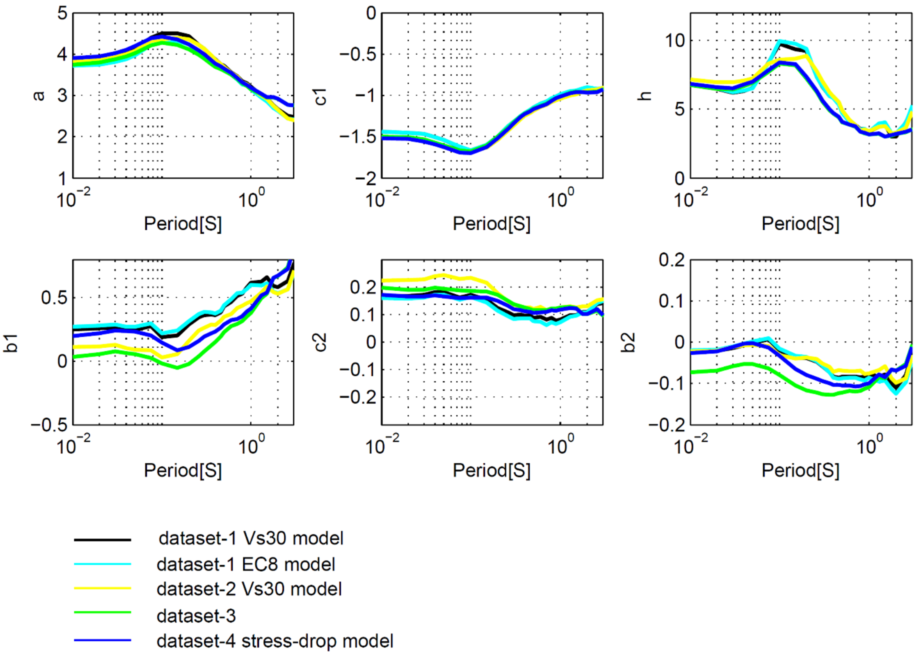

Figure A1. Magnitude and distance coefficients (equations 1, 2 and 3) as a function of periods for different data selection and functional forms used in this study.

Figure A2, shows the EC8 site model coefficients for the considered classes (A, B, C and D) as a function of spectral period for dataset-1 and dataset-4 (see Figure 17). The reference site class is A.

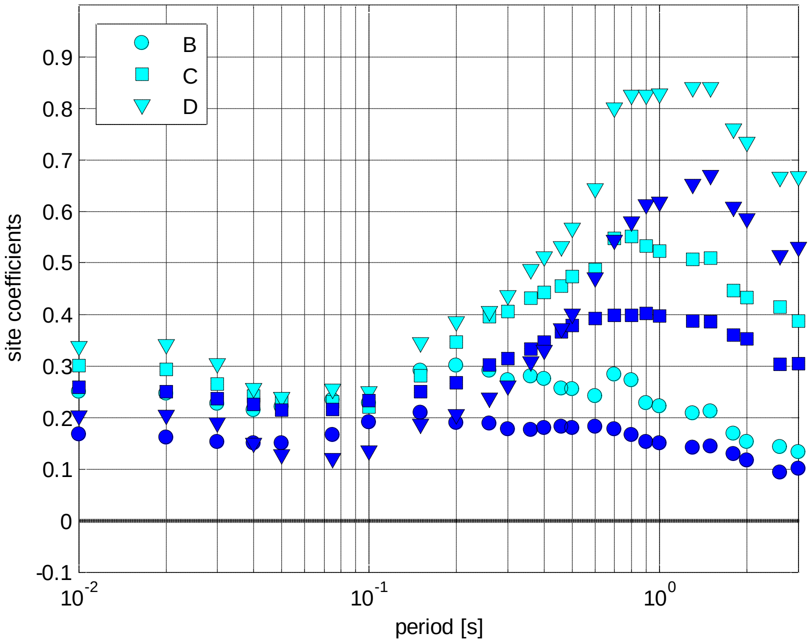

Figure A1. Site coefficients for the considered EC8 classes (A, B, C and D) obtained from regressions of dataset-1 (cyan) and dataset-4(blue), as a function of period. The reference site class, constrained to zero, is class A (black line).

Comments on deliverable D2-92

Preliminary GMPEs based on RESORCE-2013: effect of data selection and metadata uncertainties

Ref SIGMA-2012-D2-92 Version 01

Frank Scherbaum
University of Potsdam
Potsdam, Oct. 31, 2013

General remarks

The report documents first results of the development of a preliminary ground motion prediction equation (GMPE) based on the RESORCE-2013 database in which particular attention is given to the contributions from small-to-moderate magnitude French and Swiss events. It reports on the influence of data selection criteria, metadata uncertainties and the choice of model parameters on the resulting median values and the corresponding standard deviations of the GMPE residuals.

Overall, the procedure for the generation of the preliminary GMPE is well documented and I have little to criticize regarding this aspect.

What I find lacking, however, is information which allows me to judge the stress drop model (Drouet, 2010) and how it contributes to the presented results.

Specific remarks

Page 7:
One of the exclusion criteria listed on page 7 is: *stations for which a value of Vs30 is provided but the method used and the origin source of such value are classified as „unknown".*

I don´t see why records from such stations be treated differently from records with EC8 site class information with unknown origin.

Page 16:
The conversion relations referred to on page 16 should be given in explicit form.

Page 23:
It is not clear what was the basis for selecting the records shown in Fig. 16, nor how well the stress drop model of Stephane Drouet is actually able to model the corresponding spectra. From the figure caption I don´t understand, what is actually displayed.

Page 31 Fig. 24:
Despite the fact that there are nearly no records for epicentral distances of 1 km, the author recommends to use the GMPE down to 0 km which I find very brave.

Page 34 Fig. 29:
The influence of the stress drop on the response spectra is very interesting, but also partially counterintuitive to me. For the Mw 3.5 case, the 200 bar stress drop model not only shows a higher spectral level (as expected) but also a shift in the peak of the response spectrum. The latter is in contrast to my experience from stochastic simulations in which the peak of the response spectra are closely correlated to changes in the kappa value. This raises the question of a potential sampling problem. Could it be that the stations which record high stress drop events are different from those which record low stress drop events?

Page 35 Fig. 30:
A similar question arises regarding this figure. The peak of the response spectrum at more than 20 Hz would suggest a very low kappa (similar to ENA). Is this consistent with other evidence?

Conclusions

The study shows some interesting first results but also raises some technical questions, e.g. regarding the proper separation of stress drop and kappa effects which in order to be addressed need more information than provided in the report.

In addition to looking into this issue, I would recommend to compare the results with the results by Sanjay Bora at the University of Potsdam (Sanjay.Singh@geo.uni-potsdam.de) who has developed a GMPE based on combining a Fourier spectrum model with a duration model (the approach was presented during the last SIGMA meeting in Paris) for the same data set and in which stress drop, kappa, and site conditions are also dealt with explicitely.

Overall, I believe that the presented approach is definitely worth pursuing. However, in order to judge the model and its potential consequences in more detail, I would need more information on the Fourier spectrum model for the individual records contributing to the present analysis.

Project SIGMA

Preliminary GMPEs based on RESORCE-2013: effect of data selection and metadata uncertainties

(Ref : SIGMA-2013-D2-92)

Review by : Jean B. Savy
October 25, 2013

1. Scope of the work reviewed

This is a review of the research work documented in EDF Ref: SIGMA-2012- D2-92 by Gabriele Ameri. This work is to be presented at the CS6 of November 13 th to 15th, 2013, in Paris.

The purpose of the study was to make use of the most recent updated information in RESORCE data base (SIGMA-2013-D2-91), to develop new GMPEs, to characterize the various sources of uncertainties in the data and metadata of the database, and to study their respective influence on the uncertainties in the ground motion predictions.

The scope of the study is limited to applications to the French territory of investigation in SIGMA. It is limited to distances of 200 km, and it extends the magnitude range downward to magnitude 3.

As a preliminary study, it identifies the parameters, the influence of which should be further studied in a continuation study. From the results of this study, it is expected that a full and better characterization of the uncertainties on these parameters will potentially reduce epistemic uncertainty in the ground-motion predictions.

2. Review approach

One important aspect and goal of several of the studies in SIGMA is to provide the necessary information, data and models to help WP4 in its evaluation of the effects of the uncertainties in RESORCE-2013 for the prediction of the hazard. Therefore, my review concentrated on evaluating whether the documented study achieved this goal. Hence, my comments are directed at the following elements:

- The overall strategy/approach
- The tools used and their implementation
- The data

- The implementation of the methods and tools
- The information generated (results), its analysis and insights drawn
- Contextualization, relative to other WPs
- The general conclusions of the study
- Future work
- General form

3. General review conclusions

The study achieved the goal of informing on the nature and effect of uncertainties in RESORCE-2013. It did not however clearly and/or sufficiently elaborate on how this new information will be factored in other WPs.

The document reviewed describes a considerable amount of work. The development and analysis part of the study are well constructed with a systematic exploration of the sensitivity to the "independent" parameters of the GMPEs. The methods used are appropriate and state-of-the-art and well implemented. Consequently, I have only minor comments.

The explanations are, in general, clear and complete and well referenced. So are the interpretations of the results, with a few exceptions where I found that the authors were somewhat optimistic and drew conclusions based on insufficient statistics based on too few data points or questionable visual inspections of figures.
On the whole, this study provides a wealth of very useful insights, which will be important for the sensitivity study in WP4 or possibly for WP3.

The reviewed document is well written, but with many typos and it needs to be edited. Furthermore, I recommend adding a section that gives, possibly in table form, a summary of all the important findings.

- *Overall strategy/approach:*
  The general approach consists of selecting subsets of the RESORCE dataset to use only le data relevant to the study, and assigning the best known characterizations of uncertainty for each of the parameters. To investigate uncertainty in Mw, it uses a Monte-Carlo simulation of earthquake catalogs. This is a well established approach for this type of studies. The authors explain clearly their choice of parameters for the distribution functions of all meta parameters. The choice of the general functional form of the GMPEs is also well demonstrated as it is the results several well accepted previous studies for the regions of interest in SIGMA (Boore and Atkinson, 2008; Akkar and Bommer, 2010; Bindi et al. 2013).

- *The tools used and their implementation*
  Aside from all the post processing standard statistical tools, appropriately the random effects model of Abrahamson and Youngs (Abrahamson and Youngs, 1992) is used for the regressions. No specific details are given on the implementation (codes used, whether they are validated, etc.).

- *The data*
  The RESORCE data set has been updated, including in other tasks of SIGMA, to satisfy the needs of this study, and the criteria selected to down-select the relevant subsets of Dataset-0 are fine.
  In section 3.1, it is demonstrated that using a EC8 class characterization of the sites is equivalent to using V_{S30} characterization, with respect to uncertainty. The document should, at this point, give a description of the EC8 class system, and explain briefly how sites only characterized by V_{S30} are

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assigned to an EC8 class.

- *The information generated (results), its analysis and insights drawn*
  The reliability of this study relies essentially on the data selection criteria, the regression method, and the choice and how the results are presented, especially the display and comparison of residuals, which is used to support the conclusions.
  I find the figures of the type of figure 4 that show the number of earthquakes and records as a function of the period considered to be very useful.

  Figures of the type of Figure 5 show the residuals, and often in the document some general conclusions are made based on a subjective, and not always obvious, visual inspection.
  Providing a single, mean value of the residuals for example, would in some cases help the reader appreciate the overall differences between the different cases considered. In my instance of the document, labels in the figure 5 types are not all visible, because the (automatic) color selection chose a very faint color. This is particularly true for the .pdf publication where the label for FR disappears completely, but it is faintly visible in the .docx version. In both cases it is difficult to follow the explanations in the text based on an examination of the figures. Please verify that the labels are well visible on the figures after publishing.

  Figures of the type of Figure 8 that show the between-event, within-event, and total standard deviation are using dashed lines “styles” that do not show in the .pdf publication formats, but it is fine in the .docx format.
  Same comment as above. Please check after publishing.

  Figure type Figure 16. Rhine Graben data labels very faint in .docx, not visible in .pdf.

- *Contextualization, relation to other WPs*
  I find that the authors contextualized very well their work when it comes to the input to their study, but I did not find much in the way of how useful, where, and how the results will be used by other WPs downstream, in particular by WP3 and WP4 for which some of the results are very important. I suggest that the authors add an explanation of the downstream use of the results, including what is already planned and if any, what this study suggests that should be added to work planned.

- *The general conclusions of the study*
  The document does not have a section that gives general conclusions. I suggest that it should be added as section 7. This section should give the important findings of the study and clearly point to the use that will be made of them in other WPs.

- *Future work*
  All mentioned future studies mentioned in this section are worth doing in my opinion. I suggest adding one task related to the study of correlation of the regression parameters in Section 6, and to discuss how to use that information (see in details below). Another possible additional study, mentioned below in the detailed comments, is to consider a thorough investigation of the conversion of magnitudes to Mw to better determine the uncertainties in the estimation of Mw.

- *General form*
  In terms of format of the document, I found it well organized and well written. It is consistent with the

type of format discussed at the last CS. I only mention (see above comments) the need for adding a general summary/conclusion section.

A few problems need correction:

- Many misspellings, and
- A few minor problems with the labeling of the figures (see above comments)
- A few missing references for equations used

4. Detailed comments

Abstract

- No comments.

Executive Summary

- No comments.

1. RESORCE 2013 database

- It would be useful to show the standard table that shows both types of classification, V_{S30} and EC8.

2. General functional form of the GMPE

- No comments

3. Results for different data selections

- Equation 4: Needs a reference
- What is the rationale for selecting V*ref* as 760m/s?
- In section 3.2 (page 16) the following statement is made:
  "The accuracy of such converted Mw is, therefore, much smaller than that of Mw determined via moment tensor inversions. "
  This brings a number of questions:
  First, if the conversion really leads to a better determination of Mw than using the direct determination of Mw, then we should use the converted value. But we know that this is not right as we will not prefer to choose a derived magnitude from a conversion over a "direct" determination.
  Followed by a second set of questions:
  Since the conversion does not reflect all the uncertainties, what can be done to improve the conversion? We observe a possible bias. Can we determine this bias? We observe that the uncertainty is unrealistically small. What can be done to better determine this uncertainty?
  This suggests another needed investigation that would be worthwhile in this project, possibly as an additional future work.
  As a general comment, I find that statements based on visual inspections are difficult to convince. Case in point is Figure 9 from which the following statement is based: (page 17)
  "*At T=1s, the residuals related to converted Mw show a larger dispersion compared to the other events*."
  Given the small number of data points considered (8 points, I believe), I wonder if the changes are statistically significant, and just inspecting the plot does not give me much confidence that the statement is supported. Maybe some summary numerical parameter would help.
- In section 3.3 (page 22): need reference for Brune's stress-drop, equation 6.

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- In section 3.4 (page 25):
  "*The between-event residuals as a function of Mw, presented in Figure 18, confirm the large dispersion at small magnitudes and short spectral periods, already observed for dataset-3. This is now evident also for French events, that are much more represented than in the previous case.*"
  Yes, but since they are small and they are also close to the site, the definition of distance and fault mechanism is more important, so we cannot with high degree of confidence say that the causal effect is Mw variability.
- Figure 20: Same comment as for Figure 9 regarding difficulty to conclude. But Figure 22 makes the point more clearly.
- Section 5, (page 30):
  "*For short distances and large magnitudes the model based on R_{EPI} predicts larger values than the one based on R_{JB}, as the difference in the definition of the two metrics, cause R_{JB} to be equal or less than R_{EPI} thus reducing the ground-motion amplitudes for a given distance.*"
  This sentence is confusing and needs to be changed. Does not seem to correlate with what is seen in Figure 24.

4.Median ground-motion predictions for representative scenarios and comparison with other GMPEs

- No comments.

5. Assessment of metadata uncertainties in RESORCE

- No comments.

6. Effect of Mw uncertainties on the GMPE: median ground-motion and standard deviation

- In this section where a large sample of parameters are generated (*a*, *b1*, *b2*,*c1*, *c2* and *h*), there is an opportunity to perform additional statistical studies without much effort. It would be interesting to investigate the correlation between parameters, in particular to get insights into the role of "*h*" which is not clearly related with the actual rupture process (R), and/or with the build-up of the seismic waves but could be more correlated with magnitude (some correlation with *c1, c2*, *b1* and *b2*), or with distance (correlation only with *c1* and *c2*).

7. Future developments

- Consider adding to the list of future developments:
  - Investigation of correlation of regression parameters of the GMPEs, and how to use it
  - Investigation of conversion of magnitudes to Mw, including uncertainty estimate.

8. References

- Missing reference for equation 4
- Missing reference for equation 6

Respectfully submitted, October 25, 2013.

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