Towards a hybrid probabilistic seismic hazard assessment methodology

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ABSTRACT :

A key step in probabilistic seismic hazard assessment is the prediction of expected ground motions produced by the seismic sources. Most probabilistic studies use a ground-motion prediction model to perform this estimation. The present study aims at testing the use of simulations in the probabilistic analysis, instead of ground-motion models. The method used is the empirical Green's function method of Khors-Sansorny et al. (2005), which takes into account the characteristics of the source, propagation paths, and site effects. The recording of only one small event is needed for simulating a larger event. The small events considered here consist of aftershocks from the M6.4 les Saintes earthquake, which struck the Guadeloupe archipelago in 2004 (French Antilles). The variability of the simulated ground-motions is studied in detail at the sites of the French Permanent Accelerometric Array. Intrinsic variability is quantified: ground motions follow lognormal distributions, with standard deviations between 0.05 and 0.18 (log units) depending on the spectral frequency. One input parameter bearing large uncertainties is the stress drop ratio between the small and the target events. Therefore, overall sigma values (and medians) are recomputed, varying stress drop ratio values between 1 and 15. Sigma values increase but remain in general lower or equal to the sigma values of current ground-motion prediction models. A simple application of this hybrid deterministic-probabilistic method is carried out at several sites in Guadeloupe, for the estimation of the hazard posed by a M6.4 occurring in the rupture zone of the les Saintes event.

KEYWORDS: Seismic hazard, probabilistic seismic hazard assessment, strong motion, empirical Green's functions

1. INTRODUCTION

A key step in Probabilistic seismic hazard assessment (PSHA) is the prediction of expected ground motions at a site of interest produced by the seismic sources identified around this site. Nearly all PSH studies use a ground-motion prediction model to perform this estimation. In the last few years, the expanding strong-motion databases enabled the development of more and more complex ground-motion prediction equations (see e.g. the recent models developed for Northern America on the NGA database, the Next Generation of Ground-Motion Attenuation models; Boore and Atkinson, 2008). These models present the great advantage of being able to predict ground motions at any site, and for a wide range of magnitudes and distances. However, they also have known shortcomings. Establishing a ground-motion prediction model requires a large strong-motion database. In low seismicity regions, strong-motion recordings are too few to constitute a database, and recordings from different regions must be gathered to develop the prediction model. In high seismicity regions, a ground-motion prediction model can be derived from recordings coming specifically from the region under study, however the recordings always correspond to different strong-motion stations distributed throughout the region. Therefore, even in these high seismicity regions, the ground-motion prediction models inevitably predict average propagation paths and average site effects. Moreover, all ground-motion prediction models now provide a Gaussian probability density function for the logarithm of the ground motion, characterised by a mean and a standard deviation (sigma). This standard deviation plays a key role in PSH studies. Indeed, for a fixed mean value, the higher the standard deviation, the higher the ground motion for a given return period (e.g. Beauval and Scotti, 2004; Bommer and Abrahamson, 2006). Although strong-motion databases are expanding, the sigmas of increasingly complex ground-motion models do not decrease (Douglas, 2003). Some authors (e.g. Anderson et al., 2000) believe that the sigmas calculated from these databases do not fairly represent the uncertainty on the ground motion produced by a given seismic source at a given site during time (ergodic assumption; Anderson and Brune, 1999). They state that it leads to an overestimation of probabilistic seismic hazard.

Simulation methods present an alternative to ground-motion prediction models. Such methods can take into account the characteristics of the source, propagation paths, and site effects. The simulation method used here is the empirical Green's function (EGF) stochastic simulation method of Khors-Sansorny et al. (2005). This method presents great advantages for practical use in PSH studies: (1) the recording of only one small event is necessary to simulate the recording of a larger event at the same station; (2) only four input parameters are needed: seismic moments of the small event and of the target event, corner frequency of the small event, and the stress drop ratio between the small and the target events.

The stress drop ratio is obviously the most difficult parameter to define, as the stress drop of the target event is not known in advance. Moreover, the major shortcoming of this method for integration into a PSH study is the necessity to have at least one recording of a small event located in the vicinity of each fault to be taken into account, and also the ability to simulate ground motions only at instrumented sites. Strong-motion networks have a short lifetime (maximum 40 years, depending on the region of the world); however in the future more and more sites will be instrumented and more and more earthquakes recorded, and this requirement might become less restrictive. In any case, it is already possible to study the potential of a hybrid probabilistic method integrating deterministic simulation techniques inside a probabilistic framework. The aim in the present study is to analyse the variability of ground motions predicted using the EGF simulation method, in order to quantify the uncertainty in the predictions. Deterministic studies have shown the potential of simulation methods for providing better ground motion estimates than ground-motion prediction models. However, for PSH assessment purposes, both the median ground-motion levels and the uncertainties on these levels must be studied. Simulation methods will bring advantages over ground-motion prediction models in probabilistic hazard studies only if they provide estimates with reasonable uncertainties.

The present study builds on two published works. Convertito et al. (2005) introduced the numerical simulations of seismograms into the probabilistic seismic hazard analysis, using Zollo et al.'s (1997) numerical simulation method; whereas Hutchings et al. (2007) showed how to establish an empirical probabilistic hazard curve by simulating seismograms using a simulation method based on empirical Green's functions. This study is one step further towards the establishment of a complete hybrid probabilistic methodology.

2. DATA, REGION OF INTEREST, SCOPE OF THE STUDY

The present study aims at testing the potential of a probabilistic hybrid methodology using data from Guadeloupe, an island of the French Antilles. In Guadeloupe, seismic hazard is posed both by close shallow crustal earthquakes (addressed here) and remote subduction earthquakes. In 2004, a M_W6.4 earthquake occurred South-East of Les Saintes island, at 14.2 km depth (Delouis et al., 2007), rupturing a 13km long fault zone (Bertil et al., 2005), and producing a long aftershock sequence. Aftershocks with magnitudes up to 5.1 were recorded in the area, yielding a unique strong-motion data set of shallow events with epicentral distances between 20 and 80 km. These earthquakes occurred within an active normal fault zone where previous tectonic studies had identified faults that could generate earthquakes with magnitudes higher or equal to 6 (Feuillet et al., 2002).

There is no published peer-reviewed ground-motion prediction model for the prediction of strong motions based on data recorded in the Antilles (Douglas, 2006). Therefore, seismic hazard studies have to use ground-motion models based on data from other regions of the world. Douglas et al. (2006) examined the available data, composed of ten shallow earthquakes recorded between 1999 and 2005 by the strong-motion networks operating on Guadeloupe and Martinique (Pequegnat et al., 2008; Bengoubou-Valerius et al., 2008). Six of these events belong to the les Saintes sequence. In order to determine which existing ground-motion model is adapted to the region, they applied the Scherbaum et al. (2004) method. They concluded that among the commonly-used ground-motion models for shallow crustal earthquakes, none is predicting satisfactorily the data. However, the Ambraseys et al. (2005) model was found to be the most appropriate (capability class C; Scherbaum et al., 2004). In the next two decades, it is possible that there will be sufficient data of engineering significance to develop a region-specific ground-motion model.

Since existing ground-motion prediction models are poorly predicting presently available data, it is worth analysing the integration of simulations for predicting ground motions in probabilistic hazard studies. Six aftershocks of the les Saintes earthquake with magnitudes between 4.2 and 5.1 are used here as empirical Green functions (Fig. 1 and Table 1). Stations belong to the French Permanent Accelerometric Array (Bengoubou-Valerius et al., 2008) and are far enough from the fault zone to fulfil the point source approximation of the Khors-Sansorny et al. (2005) method. The variability of the simulations is tested here on a target event of M6.4, same magnitude as the 2004 mainshock. It is the first study on the variability of the Khors-Sansorny et al. simulation method. Simulating a M6.4 enables 1) the comparison of the simulations with at least one observation in order to confirm the efficiency of the method and 2) to dispose of an estimation for the stress drop (determined from the les Saintes mainshock). Note that the 2004 event is only one of many possible M6.4 events that might occur in the considered normal fault zone.

3. SIMULATION METHOD USED, AN EMPIRICAL GREEN'S FUNCTION APPROACH

In the Khors-Sansorny et al. 2005 method, the ground motions produced by an earthquake are simulated by summing the recordings of a single small event taken as an empirical Green's function (Hartzell, 1978). For each realization, the target event records are obtained by the convolution between an equivalent source time function, representing the time history of the rupture over the fault, and the small event record. A large number of equivalent source time functions are generated using a precise summation scheme (see details of the probability density functions used for the time delays in

Khors-Sansorny et al. (2005) and Ordaz et al. (1995)). The synthetic time histories agree on average with the ω^{-2} Brune (1970) model in the whole frequency band. This approach, based on a point source representation of the fault, is easy to apply and relies only on two unknown parameters: the seismic moment of the target event and the stress drop ratio between the target event and the small event used as EGF. This stress drop ratio (C) is the crucial parameter. The method is able to generate a set of accelerograms that could realistically be generated by a given earthquake.

4. QUANTIFYING THE INTRINSIC VARIABILITY OF GROUND-MOTION PREDICTIONS

To begin with, the variability of simulated ground motions is analysed at station IPTA, a rock station located near the main city Pointe à Pitre (Figs. 1 and 2). The event used as EGF is the aftershock n°2 (M4.2, Table 1), the stress drop of the target event is for the moment supposed to be equal to the 2004 les Saintes stress drop. A large number of acceleration time histories are generated; they correspond to different rupture processes that could happen if the earthquake occurs. For each time history the response spectrum is calculated. Response spectra corresponding to a magnitude 6.4, occurring at the same location as the M4.2 event, are superimposed in Fig. 2 (left, light grey curves). For each frequency, a distribution of spectral acceleration values is obtained. Logarithms of accelerations are considered. Figure 2b displays the distribution corresponding to 2 Hz; the logarithms of accelerations are revealed to be normally distributed, exactly in the same way as residuals in real strong-motion databases. This Gaussian behaviour is confirmed at each frequency by applying the Kolmogorov-Smirnov statistical test. The distributions are therefore fully described by their means and standard deviations. For all frequencies, mean and standard deviations are calculated and superimposed to the response spectra in Fig. 2a (black curves). Mean and standard deviations are calculated from 500 simulations, this number is large enough to ensure stable statistical features.

In a previous study, Courboulex et al. 2007 showed that the EGF simulation method predicted quite well the observed M6.4 Les Saintes mainshock, by applying on 25 response spectra Anderson's (2004) method of quantifying the goodness-of-fit. This observation is confirmed here by superimposing the observed response spectrum on the mean and mean±σ values. Figure 3 displays the results obtained at two example stations, the rock station MOLA and the station GGSA located on soil and prone to site effects. The mean and mean±σ predicted by Ambraseys (2005) model are also superimposed. The main observation is that for the rock station, the simulations are coherent both with the ground-motion model predictions and the observed spectrum. Whereas for the soil station, the simulations are coherent with the observed spectrum, but differ from the ground-motion model predictions (for this soil class). As already observed in Courboulex et al. 2007, site amplifications are poorly predicted by the ground-motion model.

Moreover, the uncertainty on the mean values predicted by the ground-motion model (sigma) is much larger than the sigma based on the EGF simulations. The sigma has a key role in probabilistic hazard assessment and deserves careful analysis. Sigma represents the uncertainty in the ground motion produced by one magnitude at a given distance from the site. For fixed median levels, reducing the sigma leads to a reduction of hazard estimations. This key role of the sigma in PSH studies has made attempts to reduce or truncate the sigma a current hot topic in the engineering seismology field (e.g. Bommer et al., 2004; Strasser et al., 2008).

The Gaussian distributions are calculated at all available stations and for the six EGF (Table 1). Sigma values correspond to intrinsic uncertainties and are directly linked to the convolution of the EGF to a large number of different equivalent source time functions stochastically generated. Results show that the sigma values are roughly similar from one station to the other, and from one EGF to the other (Fig. 4). Calculations were performed for all stations but results are displayed for six stations, representative of rock stations. Three stations are located in the Eastern part of the island (BERA, MESA, MOLA), two stations are situated in the Western part (PIGA, PRFA) and the last one on another small island West of Guadeloupe (GBGA). The sigma values globally increase from 0.4Hz to 1.0Hz and then decrease from 1.0Hz towards high frequencies, taking values between 0.05 and 0.18. These sigma values are much lower than the sigmas of recent regional ground-motion prediction models, in the range of 0.22 to 0.35 log units (Douglas, 2003; Atkinson, 2006). Note that Causse et al. 2008 calculated spectral accelerations distributions corresponding to a M5.5 event at one rock station located at an epicentral distance of 15 km, using a different EGF simulation method. They found a similar trend and values for the intrinsic standard deviations, over the frequency range 1-20 Hz. Furthermore, these sigmas can be compared to the single station – single source sigma evaluated by Atkinson (2006). Interestingly, Atkinson (2006) found a 0.18 value for the minimum sigma in the case of a single station and a single source of earthquake at a fixed azimuth, considering a range of magnitudes. Whereas Anderson et al. (2000) suggested that the maximum sigma corresponding to a single station, single source, and a characteristic earthquake on this source, is between 0.05 and 0.13, depending on the methods used (simulations or precarious rocks). Our results are coherent with these estimations. Here only one magnitude is considered, 0.18 is the upper limit for our intrinsic sigmas and 0.05 the lower limit, depending on the spectral frequency.

Moreover, two stations located at soil sites show slightly higher sigma values (up to 0.2 for GGSA). We do not discuss this issue here, since only two stations are located over soil sites and they recorded only two out of the six EGF, and further studies are required to understand the physical/numerical reasons and whether or not this observation can be generalised.

5. VARIABILITY OF PREDICTIONS INCLUDING THE SOURCE UNCERTAINTY

One of the input parameters for the simulation method bears large uncertainties: the C value, which is the stress drop ratio between the target event and the small earthquake (EGF). Previous calculations were performed using the C values determined from the ratios between the recordings of the small events and the les Saintes mainshock event (varying between 2 and 11, Table 1). However, this event is only one of the possible M6.4 events that could occur on the normal fault zone. Future events can be characterised by different stress drops and this uncertainty must be included in the strong-motion prediction. Khors-Sansorny (2005) showed that C values can be as high as 15. Causse (2008) explored a range of C values roughly in the interval 0-5. Here, the stress drop of the large target event is supposed to be higher than the stress drop of the small event (Kanamori and Riviera, 2004), as observed by Courboulex et al. (2007). In the following, C values between 1 and 15 are tested for each EGF (Table 2).

Figure 5 illustrates the calculation of the acceleration distributions including possible stress drop ratios between 1 and 15, on the example station BERA and using the EGF n°2 (Table 1). Seven C values are tested and the corresponding seven sets of spectral acceleration distributions are superimposed (Fig. 5a). The median acceleration levels increase with increasing C values. As the overall distribution is still Gaussian (see at 2Hz, Fig. 5b), overall means and standard deviations are calculated for each frequency. The overall sigmas are superimposed in Fig. 5c, together with the individual sigmas. Overall sigmas vary between 0.15 and 0.24, over the frequency range 0.4-20 Hz. The sigmas predicted by the Ambraseys (2005) ground-motion prediction model are also superimposed. They depend only on the magnitude of the earthquake; they decrease from 0.32 at 0.4 Hz to 0.28 at 20 Hz. These sigmas are representative values of other recent ground-motion models (e.g. Berge-Thierry et al., 2003; Bommer and Akkar, 2007). The overall variability of the ground motion predicted by the EGF simulation method is still lower than the variability predicted by the ground-motion prediction model, for the whole frequency range.

Now the variability including the C uncertainty is calculated for all EGF at all available stations in order to determine if this result can be generalised (Fig. 6, six example stations). The results show that for the same EGF, the sigmas calculated from the overall acceleration distribution including the uncertainty on the C parameter are very similar from one station to the other. However, differences appear from one EGF to the other. Sigma values vary between 0.15 and 0.3. Therefore, except for one EGF (n°3) slightly higher over 1-20 Hz, the sigmas remain lower or equal than the ground-motion model sigmas over the whole frequency range. This result is of importance, since keeping uncertainties lower or equal to the ground-motion model uncertainties is a necessary condition for encouraging the use of numerical simulations in probabilistic seismic hazard studies. Below, a probabilistic seismic hazard experiment is proposed, for the estimation of the hazard posed by a M6.4 event occurring in the rupture zone of the 2004 event.

6. EXPERIMENTAL PROBABILISTIC SEISMIC HAZARD ESTIMATION

The probabilistic hazard study is carried out at the same strong-motion stations. This part of the study is purely an exercise to show how the hybrid method can be implemented. In a true hazard assessment study, all potential seismic sources posing a threat to the site under study should be taken into account. Here, the hazard is estimated for a magnitude 6.4 occurring in the rupture zone of the M6.4 les Saintes event. Moreover, very few events are reported in this normal fault region in the seismic catalogue (Bertil et al., 2005), and it is extremely difficult to evaluate recurrence times of earthquakes in this zone, even more for one magnitude only. Therefore, a fictive recurrence interval of 100 years for this characteristic M6.4 earthquake is assumed, yielding an annual rate of 0.01 under the Poisson hypothesis.

To build the hazard curve at a site, annual rates of exceedance of different acceleration levels must be calculated (Cornell, 1968). For each acceleration level, this annual rate is obtained by summing the contributions of earthquakes. The contribution of one earthquake is obtained by multiplying the probability of this earthquake engendering an acceleration higher than the target acceleration, times the annual rate of occurrence of this earthquake. In classical PSHA studies, the probability of exceedance is calculated from the Gaussian probability density function provided by the ground-motion prediction model. Here this probability is calculated from the Gaussian probability density functions based on the EGF simulation method.

If only one empirical Green function was available in the fault zone, the probability of exceedance of an acceleration level at a site would be obtained simply by multiplying the annual rate of the earthquake M6.4 times the probability of exceedance obtained from the Gaussian predicted by this EGF. However, one can take advantage of the different EGF available, and distribute the annual rate of the earthquake over the different EGF, in order to sample the fault zone and to allow the future M6.4 fault plane to be at slightly different locations. The probabilities of exceedance are calculated from the probability density function including the uncertainty on the C parameter.

Hazard curves obtained at different example sites are superimposed in Fig. 7, for the spectral frequencies 1, 2 and 5 Hz. For a given annual exceedance rate, the sites closer to the fault rupture zone (PRFA and GBGA) yield the highest acceleration levels. Note that the truncation of ground-motion variability (e.g. Strasser et al., 2008) is not addressed here, as the aim is not to obtain absolute acceleration estimates but only to show a simple first implementation of the methodology. Moreover, hazard curves are calculated using a ground-motion prediction model (Ambraseys, 2005), as in any classical PSH study. Figure 8 displays the hazard curves obtained for two stations, PRFA and MOLA, superimposed on the hazard curve based on the hybrid probabilistic method. For a given annual rate of exceedance, the hybrid method yields lower levels than the classical probabilistic methodology, for both stations and for the three frequencies. This comparison is made here for illustration purposes only, since the Ambraseys et al. (2005) model has not proved to be well adapted to the region under study (Douglas, 2006).

7. CONCLUSIONS

A hybrid methodology for the computation of probabilistic seismic hazard using an empirical Green's function simulation technique is developed. The Khors-Sansorny et al. (2005) EGF simulation technique appears well adapted for a practical use in a probabilistic hazard study, as the recording of only one small earthquake is required for the simulation of a larger earthquake. The study focuses on the hazard posed by a M6.4 event in the rupture zone of the les Saintes mainshock event (M6.4, 11/21/2004). For each EGF, the stochastic simulation method provides at each instrumented site of interest a distribution for the ground motion produced by a future M6.4 event. Gaussian distribution characterised by means and sigmas are determined. These probability density functions are used in the probabilistic seismic calculation exactly in the same way as the Gaussian probability density functions predicted by a classical ground-motion prediction model. Therefore, the implementation of this hybrid deterministic-probabilistic methodology is straightforward.

The intrinsic variability of the predicted ground motions is quantified. The sigma values reveal themselves to be comparable to the findings of previous studies (Atkinson, 2006; Anderson et al., 2000; Causse et al., 2008), at least for rock stations. More work is required in order to understand the influence of site effects on the sigma values. Furthermore, the simulation method relies on the parameter C bearing large uncertainties: the stress drop ratio between the small event used as EGF and the large target event. New sigma values (and new medians) are estimated on the ground-motion distributions obtained from varying C between 1 and 15. As expected, the dispersion is larger and all sigma values increase. However, these overall sigmas remain in general lower or equal than the sigmas of current ground-motion prediction models, for the whole frequency range. Note that this uncertainty interval for the C parameter would need to be more precisely defined, and this will be possible only when more studies are led on the estimation of the stress drop ratio between small and large earthquakes.

Hybrid methodologies taking advantage of ground-motion simulations (empirical, numerical methods) are promising. In a complete probabilistic seismic hazard analysis, all seismic sources posing a threat to the site must be taken into account. At the moment, no simulation method is able to provide realistic and complex seismograms for the whole set of seismic sources and in the whole frequency range of engineering interest. However, the future might lie in the combination of different techniques for the prediction of ground motions within a PSH study, using ground-motion prediction models, empirical Green's functions, or synthetic Green's functions, etc … depending on the availability of strong-motion recordings at the site, but also depending on information about the source, the propagation path, and the site effect.

8. TABLES

Table 1: Characteristics of the mainshock and six aftershocks of the les Saintes sequence, input parameters for the aftershocks used in the simulations as empirical Green functions; f_C is the corner frequency, C is the stress drop ratio between the small event and the mainshock event, N^4 is the number of small events summed, C and N have been determined from the spectral ratios (Hough and Kanamori, 2002; Khors-Sansorny et al., 2005).

Event	Time	Magnitude	Longitude	Latitude	Depth	f_c	C	N
mainshock	11/21/04 11:41	6.4 (M_W)	15.7573	-61.5305	14.2	-	-	-
1	11/21/04 13:36	5.1 (M_D)	15.7720	-61.5148	12.4	0.62	2	5
2	11/21/04 22:32	4.2 (m_b)	15.8613	-61.6142	14.6	0.87	5.81	7
3	11/21/04 22:56	4.8 (m_b)	15.7653	-61.4758	9.9	0.62	2.77	5
4	11/22/04 02:01	4.7 (M_D)	15.8293	-61.6358	12.4	0.5	5.54	4
5	12/02/04 14:47	4.9 (M_D)	15.6522	-61.5363	13.7	0.37	6.58	3
6	12/26/04 15:19	4.5 (m_b)	15.7477	-61.5773	10.5	0.5	11	4

Table 2: Stress drop ratios (C) tested for the computation of the overall acceleration distributions including the uncertainty on the C value. All values contained in the interval [1 15] and in accordance with an N integer and the equation $M_0=C.N^3.m_0$ are tested (M_0 and m_0 seismic moments of the EGF and of the target event, see Khors-Sansorny et al. 2005, eq. 3).

EGF n°1	1.16	2.0	3.9	9.27	-	-	-
EGF n°2	1.16	1.5	2.0	2.74	3.9	5.83	9.25
EGF n°3	1.0	1.6	2.77	5.41	12.81	-	-
EGF n°4	1.03	1.64	2.84	5.55	13.16	-	-
EGF n°5	1.42	2.78	6.58	-	-	-	-
EGF n°6	1.38	2.06	3.27	5.66	11.06	-	-

3. FIGURES

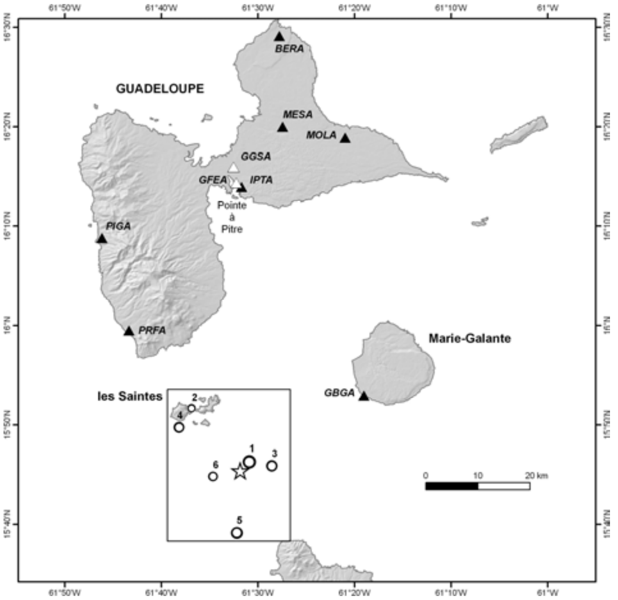

Figure 1: *Guadeloupe achipelago. Triangles: strong motion stations used in this study (RAP network), black: rock stations, white: soil stations. Circles: events used as empirical Green functions (see Table 1). Star: mainshock M6.4 of the 2004 les Saintes sequence.*

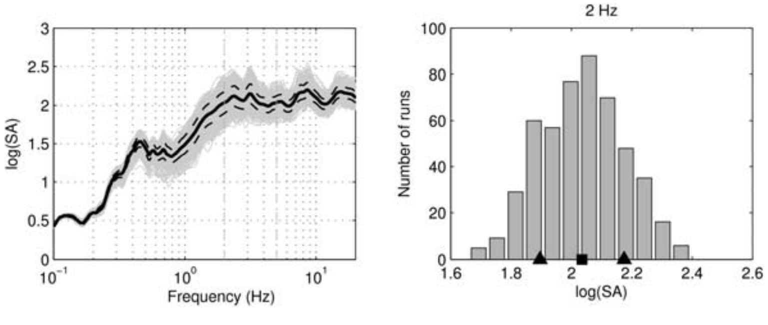

Figure 2: *Quantification of the variability of the predictions (IPTA). Left, grey curves: response spectra of 500 simulations, black solid line: means of distributions for each frequency, dashed lines: means ± standard deviations (σ), spectral acceleration (SA) in $cm.s^{-2}$, East-West horizontal component. Right, example at 2 Hz, distribution of the 500 accelerations simulated, square and triangles: mean and mean ± σ.*

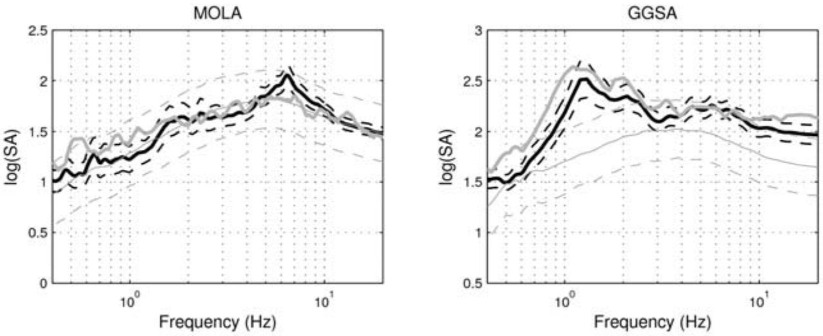

Figure 3*: Comparisons of acceleration levels predicted by the EGF simulation technique for a M6.4 event (black lines) with the observed spectrum corresponding to the 2004 les Saintes mainshock (thick grey line), and with the acceleration levels predicted by the Ambraseys (2005) ground motion model (thin grey lines). Spectral accelerations in cm.s*$^{-2}$*. Dashed lines correspond to mean ±* σ*. MOLA is on rock and GGSA on soil. EGF used is aftershock n°6 (Table 1).*

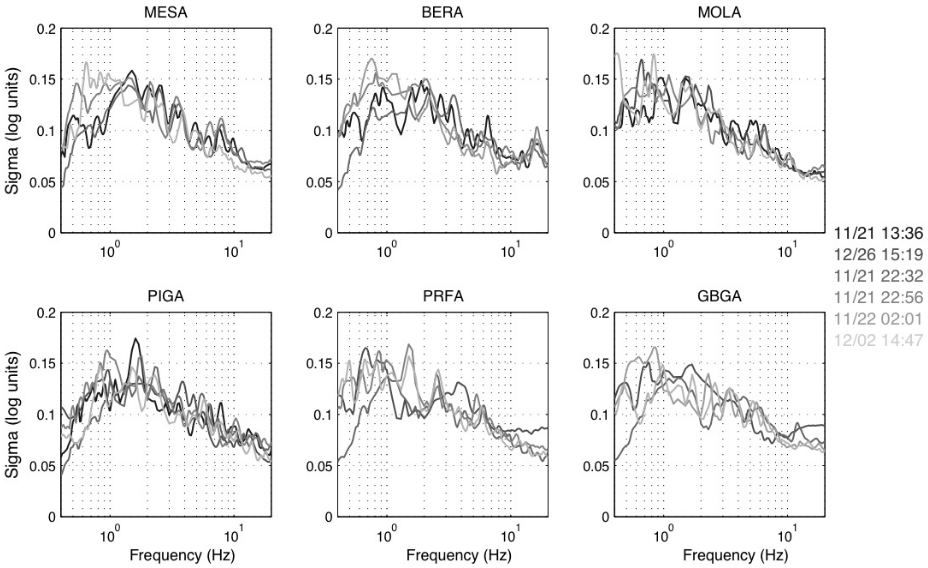

Figure 4: *Standard deviations calculated from the spectral acceleration distributions (in log units) at 6 different strong motion stations, and for the available EGF at each station (see Table 1).*

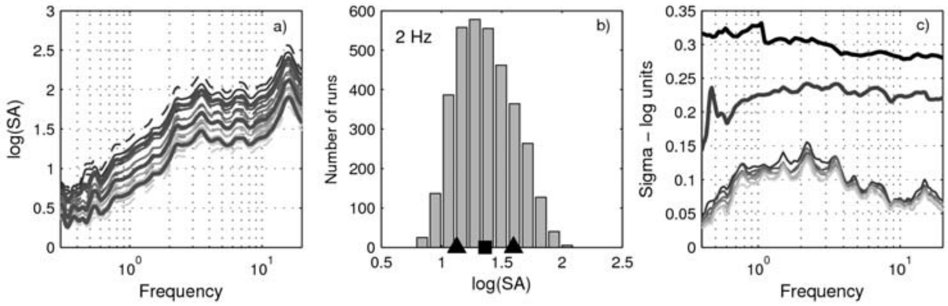

Figure 5*: Variability in the prediction of accelerations including the uncertainty on the C parameter, at the example station BERA (EGF n°2) - spectral accelerations in cm.s*$^{-2}$*. (a) The overall mean and mean ±* σ *(thick solid lines) are superimposed on the values obtained from each C value (thin lines, means ±* σ*), C values are increasing from light grey to dark. (b) Example at 2 Hz: the distribution of the logarithms of accelerations is still Gaussian. (c) The overall sigma (dark grey solid line) is larger than the intrinsic sigmas and lower than the sigma predicted by Ambraseys et al. 2005 (dark solid line).*

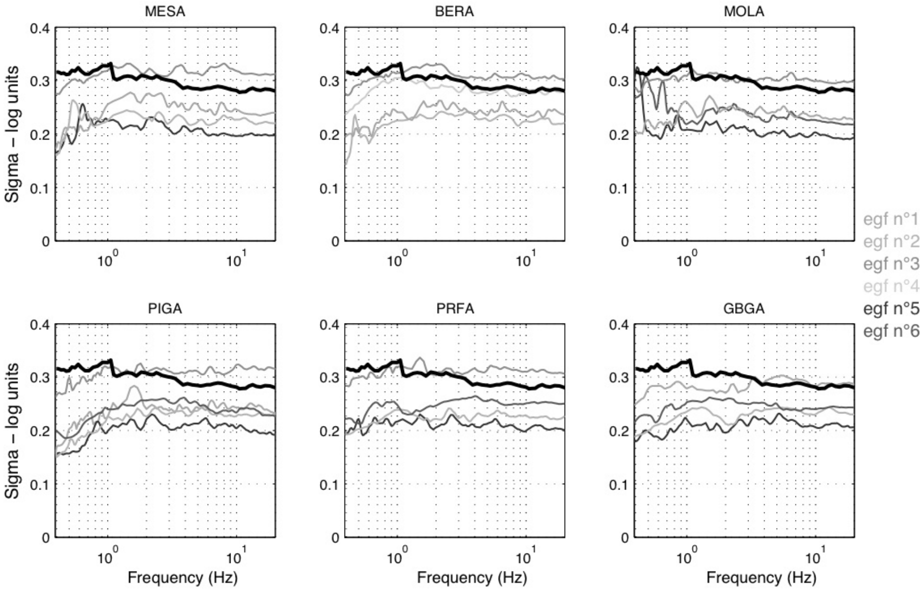

Figure 6: *Standard deviations of acceleration distributions based on the EGF simulation technique including the uncertainty on the stress drop ratio (grey curves), compared to the sigmas predicted by the Ambraseys et al. (2005) ground motion model (dark curves). For each station, the sigmas obtained from the different EGF event recorded are superimposed.*

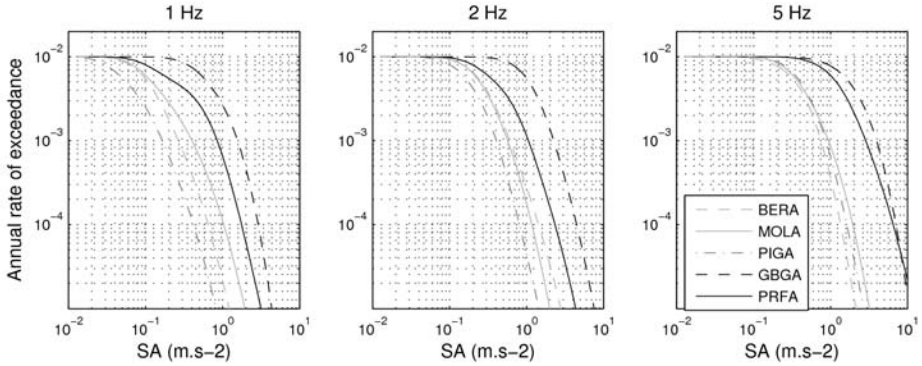

Figure 7*: Hazard curves obtained at different strong motion stations and for three spectral frequencies, using the hybrid methodology (see text for details). Note that this PSH study is purely an exercise as the annual rate of an earthquake of magnitude 6.4 in the fault zone cannot presently be determined and is assumed equal to 0.01.*

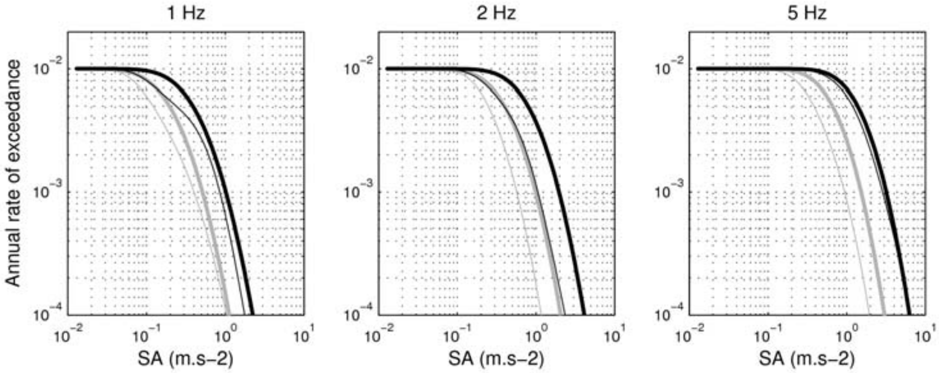

Figure 8: *Comparison of hazard curves obtained at 2 different stations using the hybrid methodology (thin lines) and using the classical method (thick line, based on Ambraseys et al. 2005 ground motion mode)l. Grey curve: MOLA, dark curve: PRFA.*

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