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Ground-Motion Variability and Implementation of a Probabilistic–Deterministic Hazard Method

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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 Kohrs-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 M 6.4 Les Saintes earthquake, which struck the Guadeloupe archipelago (French Antilles) in 2004. 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 ratio of the stress drop of the target event to the small event. 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 an M 6.4 occurring in the rupture zone of the Les Saintes event.

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 probabilistic seismic-hazard (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, for example, the recent models developed for western North America on the Next Generation of Ground-Motion Attenuation [NGA] models database; Boore and Atkinson, 2008; Idriss, 2008). Ground-motion equations present the great advantage of being able to predict ground motions at sites covering a broad range of site classifications 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, characterized 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 (considering return periods of interest in earthquake engineering, that is, longer than 100 yr, for example, Beauval and Scotti, 2004; Ordaz, 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 standard deviations of empirical ground-motion models overestimate the actual variability

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in ground motions associated with a particular seismological scenario. Deriving an equation from data recorded at different stations distributed throughout a region might lead to an overestimation of the ground-motion variability for a specific couple source/site. However, up to now very few published studies have shown how to reduce this variability on realistic and sound grounds (Atkinson, 2006; Morikawa *et al.*, 2008).

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 Kohrs-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 ratio of the stress drop of the target event to the small event. 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. However, 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 yr, depending on the region of the world; Trifunac and Todorovska, 2001); 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 analyze the variability of ground motions predicted using the EGF simulation method in order to quantify the variability of 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 analyzed. Note that the present study focuses primarily on the aleatory variability of predicted ground motions.

This work builds on two published works. Convertito *et al.* (2005) introduced the numerical simulations of seismograms into the probabilistic seismic-hazard analysis, using the numerical simulation method of Zollo *et al.* (1997), 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 with a kinematic description of the rupture process. This study is one step further towards the establishment of a complete hybrid probabilistic methodology. The Kohrs-Sansorny *et al.* (2005) method, requiring much fewer input parameters than the Zollo *et al.* (1997) and Hutchings (1994) methods, is promising within the probabilistic seismic-hazard framework.

Data, Region of Interest, and 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, an M_{W} 6.4 earthquake occurred southeast of Les Saintes Island at 14.2 km depth (Delouis *et al.*, 2007), rupturing a 13 km 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 equation 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 10 shallow earthquakes recorded between 1999 and 2005 by the strong-motion networks operating on Guadeloupe and Martinique (Bengoubou-Valerius *et al.*, 2008; Pequegnat *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 the data satisfactorily. 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.

Because existing ground-motion prediction equations poorly estimate the observed ground motions, it is worth analyzing 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's 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 fulfill the point source approximation of the Kohrs-Sansorny *et al.* (2005) method. The variability of the simulations using the method of Kohrs-Sansorny *et al.* (2005) is tested here, for the first time, on a target event of M 6.4, the same magnitude as the 2004 mainshock. Simulating an M 6.4 enables (1) the comparison of the simulations with at least one observation in order to confirm the appropriateness of the method and (2) the ability to

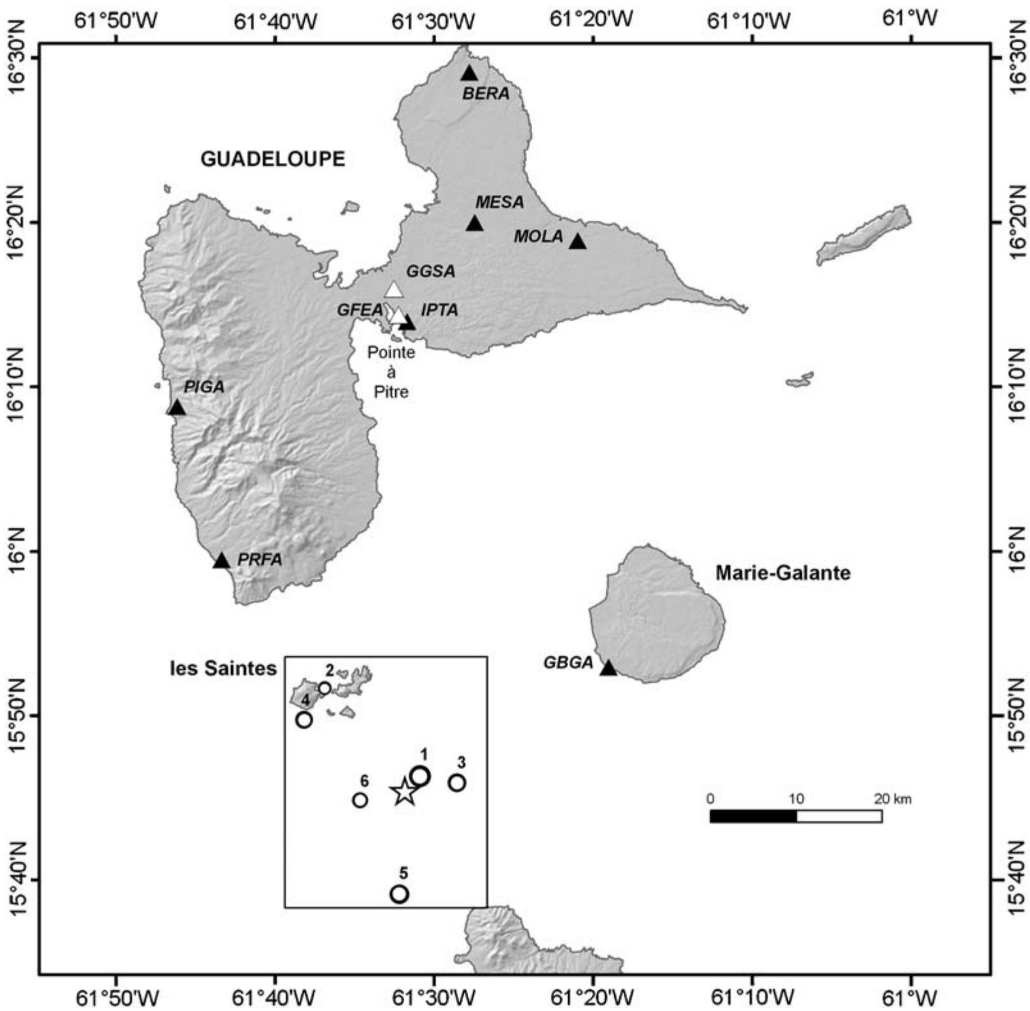

Figure 1. Guadeloupe archipelago. Triangles mark the strong-motion stations used in this study (RAP network). Black triangles, rock stations; white triangles, soil stations. Circles show the events used as empirical Green's functions (see Table 1). Star shows the mainshock *M* 6.4 of the 2004 Les Saintes sequence.

obtain one estimated value of the stress drop (determined from the Les Saintes mainshock). Note that the 2004 event is only one of many possible *M* 6.4 events that might occur in the considered normal fault zone.

Simulation Method Used, an Empirical Green's Function Approach

In the Kohrs-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 Kohrs-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 ratio of the stress drop of the target event to the small event used as EGF. This stress drop ratio (C) is the crucial parameter. As shown by Kohrs-Sansorny *et al.* (2005), the method is able to generate a set of accelerograms that could realistically be generated by a given earthquake.

Quantifying the Intrinsic Variability of Ground-Motion Predictions

To begin with, the variability of simulated ground motions is analyzed at station IPTA, a rock station located near the main city Pointe à Pitre (Figs. 1 and 2). The east–west horizontal component is considered. The event used as EGF is the aftershock event 2 (*M* 4.2, Table 1), and the stress drop

Table 1
Characteristics of the Mainshock and Six Aftershocks of the Les Saintes Sequence

Event	Time (mm/dd/yy, hr:min)	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

Input parameters for the aftershocks used in the simulations as empirical Green's functions; f_C is the corner frequency, C is the stress drop ratio of the mainshock event to the small event, N^4 is the number of small events summed, C and N have been determined from the spectral ratios (Hough and Kanamori, 2002; Kohrs-Sansorny *et al.*, 2005).

of the target event is, within this section, assumed to be equal to the 2004 Les Saintes stress drop. The best value of C has been determined using the spectral ratio of the Les Saintes mainshock event to the small event used as EGF.

A large number of acceleration time histories are generated; they can be considered as different rupture processes that could happen if the earthquake occurred (Ordaz *et al.*, 1995). For each time history the response spectrum is calculated. Response spectra corresponding to a magnitude 6.4, occurring at the same location as the M 4.2 event, are superimposed in Figure 2 (left, light gray curves). For each frequency, a distribution of log spectral acceleration values is obtained. Figure 2b displays the distribution corresponding to 2 Hz; the logarithms of accelerations are revealed to be normally distributed, in the same way as residuals in real strong-motion databases. This hypothesis of a Gaussian behavior is not rejected when applying the Kolmogorov–Smirnov statistical test at each frequency (Massey, 1951). 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 Figure 2a (black curves). Mean and standard deviations are calculated from 500 simulations, a number large enough to ensure a good statistical estimation.

In a previous study, Courboulex *et al.* (2007) showed that the EGF simulation method predicted quite well the observed M 6.4 Les Saintes mainshock by applying Anderson's (2004) method of quantifying the goodness-of-fit on 25 response spectra. This observation is confirmed here by superimposing the observed response spectrum on the mean and mean $\pm\,\sigma$ 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 $\pm\,\sigma$ predicted by Ambraseys *et al.* (2005) model are also superimposed. Note that the predictions based on simulations are not as blind as the predictions of the ground-motion model; the stress drop of the target event used in the simulation is assumed equal to the stress drop of the observed Les Saintes event (in the following section this condition is removed). 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

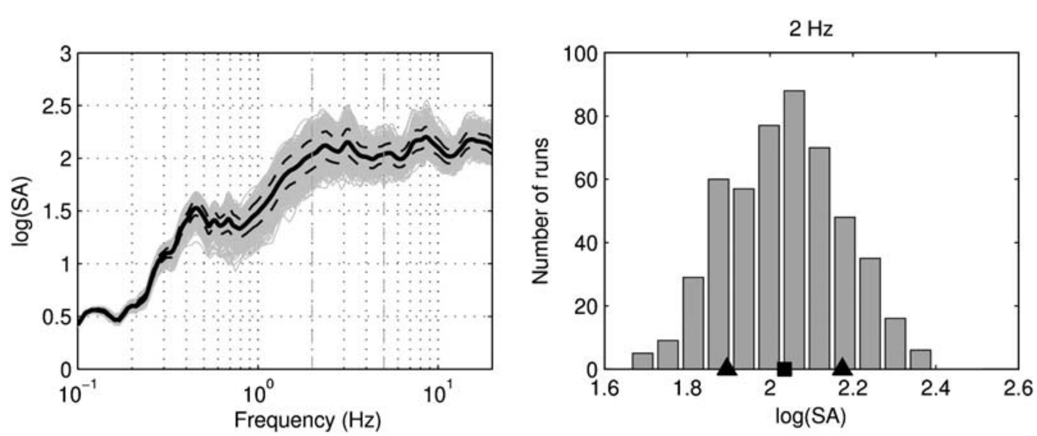

Figure 2. Quantification of the variability of the predictions, at station IPTA. Left, gray curves: response spectra of 500 simulations; black solid line: means of distributions for each frequency; dashed lines: means ±standard deviations(σ); spectral acceleration (SA) in cm.s^{-2}; east–west horizontal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

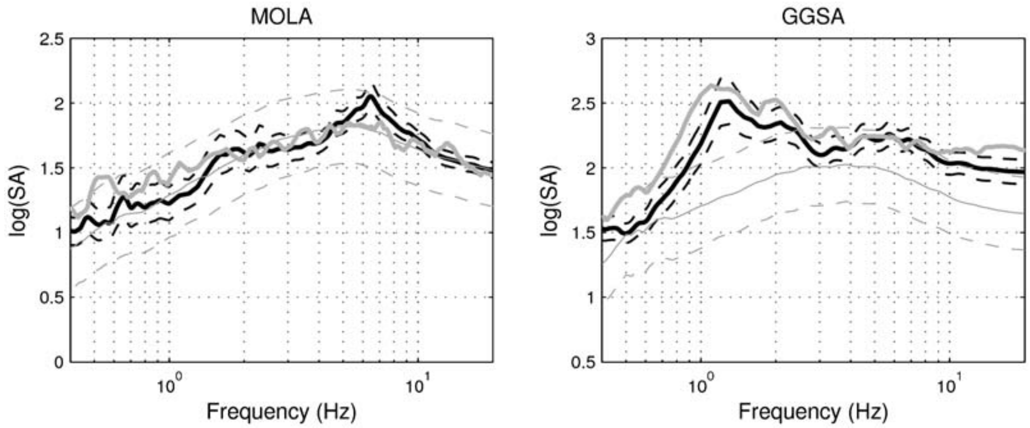

Figure 3. Comparisons of acceleration levels predicted by the EGF simulation technique for an M 6.4 event (black lines) with the observed spectrum corresponding to the 2004 Les Saintes mainshock (thick gray line) and with the acceleration levels predicted by the Ambraseys *et al.* (2005) ground-motion model (thin gray lines). Spectral accelerations in cm × sec^{-2}. Dashed lines correspond to mean $\pm\sigma$. MOLA is on rock and GGSA on soil. EGF used is aftershock event 6 (Table 1).

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 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 for returns periods of interest in earthquake engineering. This key role of the sigma in PSH studies has made attempts to reduce the sigma or truncate the ground-motion probability distribution 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 events (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 is on another small island west of Guadeloupe (GBGA). The sigma values globally increase from 0.4 to 1.0 Hz and then decrease from 1.0 Hz towards high frequencies, taking values between 0.05 and 0.18. These sigmas are source and site dependent. Therefore, as expected, these 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 an M 5.5 event at one rock station located at an epicentral distance of 15 km, using a kinematic 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, Morikawa *et al.* (2008) applied source-area factors at individual observation stations, in order to reduce the uncertainty of source, path and site effect; the resulting standard deviations vary between 0.15 and 0.2. Douglas (2001) tested seven different methods for combining the two horizontal components and showed that the impact on the associated standard deviations is low, with the largest difference between two measures reaching 7%. In this study, different measures are not tested; however, applying this factor to the sigmas quantified here leads to adjusted values between 0.05 and 0.19.

Hence, as the prediction equations average different seismic sources, ground-motion propagation paths and sites, it is not surprising that the variability of these equations result higher than the intrinsic variability of the EGF method applied for one EGF at one site. The question posed is whether the EGF method used here catches the full range of uncertainties for a given couple site/source. The small event contains the information in the path and site effect, and only the variability in the source is explored by generating many different equivalent source time functions. The true

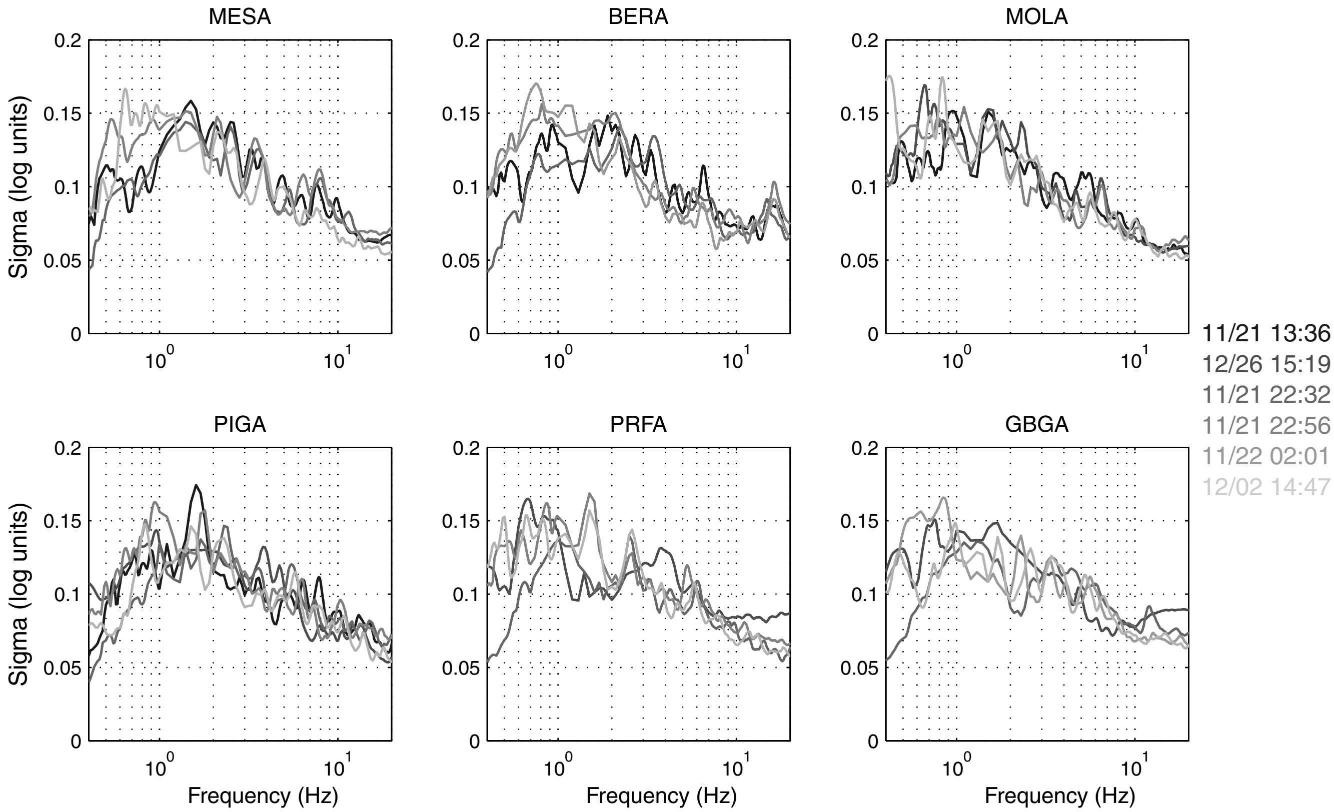

Figure 4. Standard deviations calculated from the spectral acceleration distributions (in log units) at 6 different strong-motion stations, and for the available EGF at each station (see Table 1).

ground-motion variability for a given couple site/source must be in between both estimations.

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 ratio of the stress drop of the target event to the small event (EGF). In the previous section, calculations were performed using the C values determined from the ratios between the recordings of the Les Saintes mainshock event and the small events (varying between 2 and 11, Table 1). However, this event is only one of the possible M 6.4 events that could occur on the normal fault zone. Future events can be characterized by different stress drops, and this uncertainty must be included in the strong-motion prediction. Kohrs-Sansorny (2005) showed that C values can be as high as 15. Causse *et al.* (2008) explored a range of C values roughly in the interval 0–5. Here, the stress drop of the large target event is assumed 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). Note that recent studies (e.g., Allmann and Shearer, 2009) show that no clear correlation between static stress drop and size of earthquakes can be demonstrated.

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 event 2 (Table 1). Seven C values are tested and the corresponding seven sets of spectral acceleration distributions are superimposed (Fig. 5a). Note that all C values are assumed equally likely. The median acceleration levels increase with increasing C values. As the overall distribution is still close to a Gaussian distribution (see at 2 Hz, Fig. 5b), overall means and standard deviations are calculated for each frequency. The overall sigmas are superimposed in Figure 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 *et al.* (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; Akkar and Bommer, 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.

The variability including the C uncertainty is calculated for all EGF at all available stations in order to determine if this result can be generalized (Fig. 6, six example stations). The results show that for the same EGF, the sigmas calculated

Table 2
Stress Drop Ratios (C) Tested for the Computation of the Overall Acceleration Distributions Including the Uncertainty on the C Value

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

All values contained in the interval [1 15] and in accordance with an N integer and the equation $M_0 = C \times N^3 \times m_0$ are tested (m_0 and M_0 seismic moments of the EGF and of the target event; see Kohrs-Sansorny *et al.*, 2005, equation 3).

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 (event 3) slightly higher over 1–20 Hz, the sigmas remain lower or equal than the ground-motion model sigmas over the whole frequency range. These estimated sigmas take into account the uncertainty in the source, but they must still be considered as source- and site-dependent (they are valid only for an M 6.4 earthquake at a given location and for the recording site studied). As stressed before, the true sigma must be in between the sigma based on the EGF method (integrating the uncertainty in the source parameter) and the sigma of ground-motion prediction equations. The overall sigma calculated here does not take into account the uncertainty in the propagation path between the source and the site nor the uncertainty in the local site effect characterising the station. These results yield an estimate of the variability on the ground motions predicted by the Ordaz *et al.* (1995) and Kohrs-Sansorny (2005) simulation method. Once again, the source and site dependence of these results must not be forgotten, and the comparison with global ground-motion models' sigmas must be interpreted with great caution.

Experimental Probabilistic–Deterministic 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 M 6.4 Les Saintes event. Moreover, very few events are reported in this normal fault region in the seismic catalog (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 fictitious recurrence interval of 100 yr for this characteristic M 6.4 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 producing 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's 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 M 6.4 times the probability

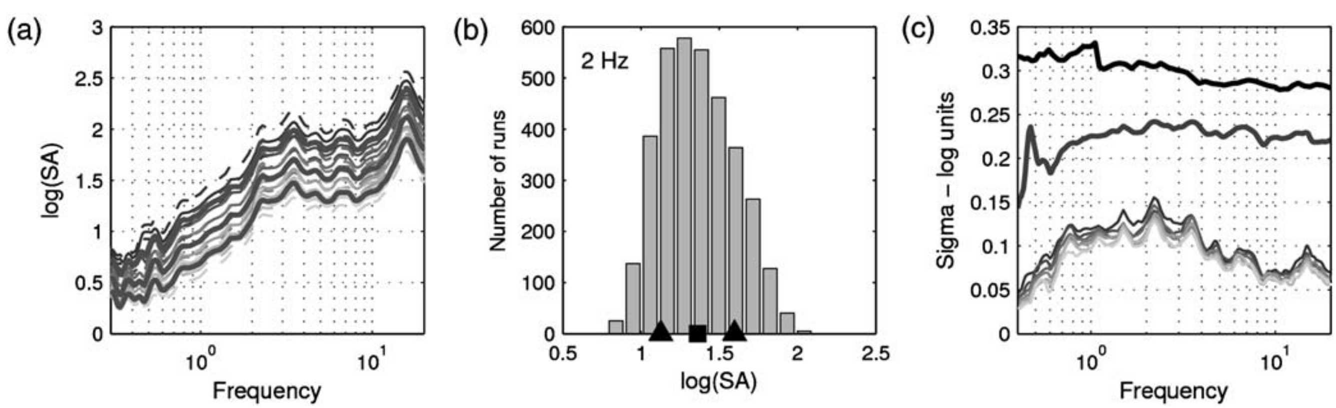

Figure 5. Variability in the prediction of accelerations including the uncertainty on the C parameter, at the example station BERA (EGF event 2): spectral accelerations in cm × sec^{-2}. (a) The overall mean and mean $\pm\sigma$ (thick solid lines) are superimposed on the values obtained from each C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

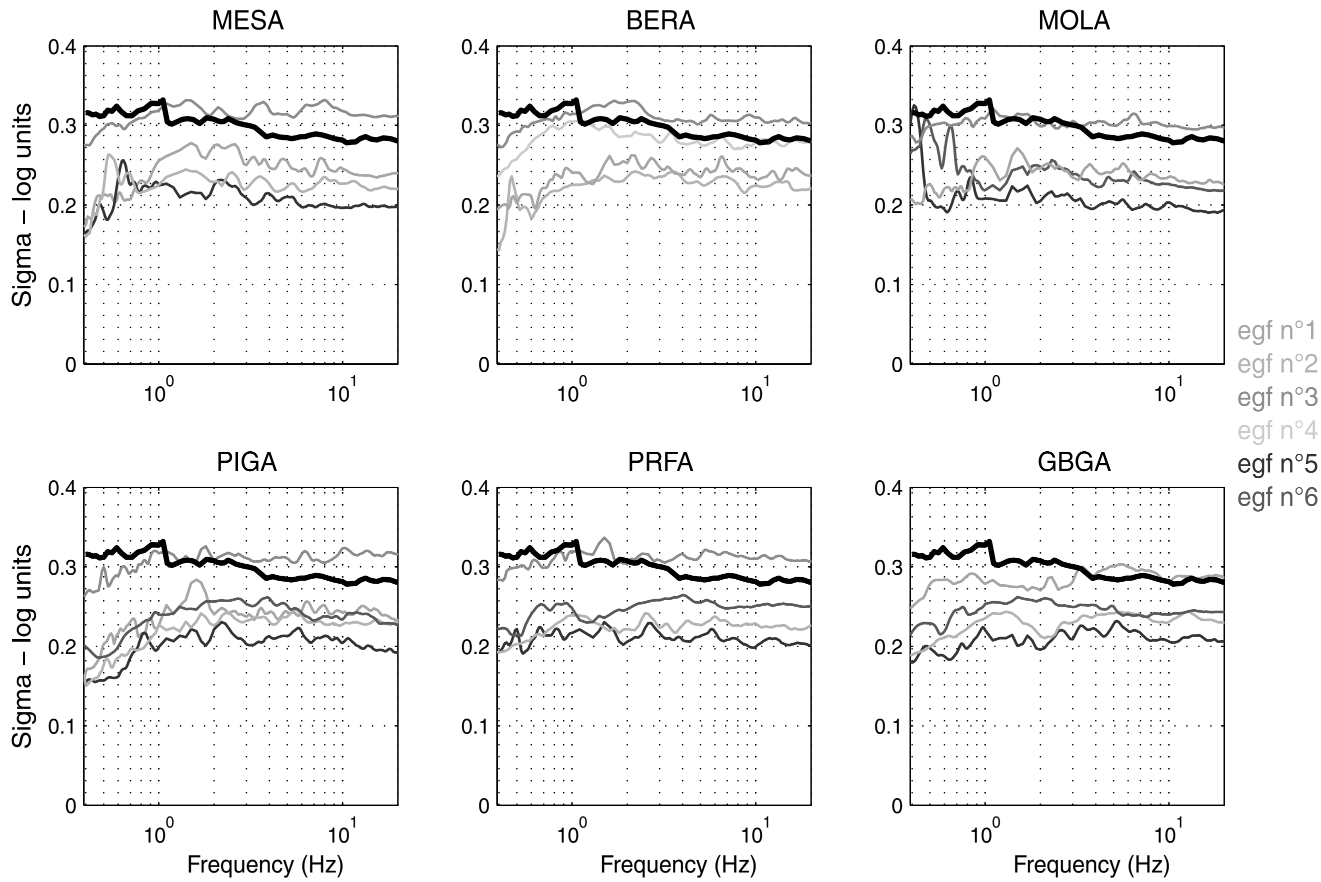

Figure 6. Standard deviations of acceleration distributions based on the EGF simulation technique including the uncertainty on the stress drop ratio (gray curves), compared to the sigmas predicted by the Ambraseys *et al.* (2005) ground-motion model (dark curves). For each station, the sigmas obtained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

of exceedance obtained from the Gaussian predicted by this EGF. However, one can take advantage of the different EGF available, distributing the annual rate of the earthquake over the different EGF, in order to sample the fault zone and to allow the future *M* 6.4 fault plane to be at slightly different locations. The annual rate is distributed equally over the available small events used as EGF. The probabilities of exceedance are calculated from the probability density function including the uncertainty on the *C* parameter. Sampling different small events can be considered equivalent to taking into account the uncertainty in the propagation path and in the site effect; the influence of the number of available small events on the results should be tested in future studies.

Hazard curves obtained at different example sites are superimposed in Figure 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 *et al.*, 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 result is specific to the present exercise and cannot be generalized. Note that both the sigma and the median levels have an impact on the calculated probabilities of exceedance of ground motions. This comparison is made here for illustration purposes only because the Ambraseys *et al.* (2005) model has not proven to be well adapted to the region under study (Douglas *et al.*, 2006). The next step will be to take into account different magnitudes in order to implement an experiment closer to real probabilistic seismic-hazard studies.

Conclusions

A hybrid methodology for the computation of probabilistic seismic hazard using an empirical Green's function simulation technique is developed. The Kohrs-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

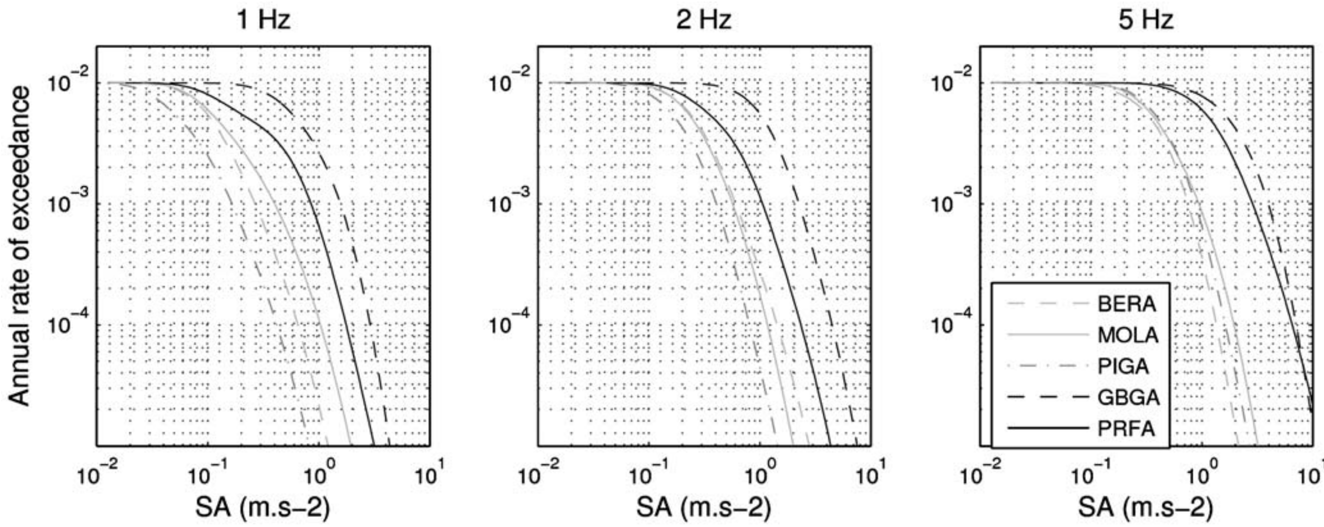

Figure 7. Hazard curves obtained at different strong-motion stations and for three spectral frequencies, using the hybrid methodology (see text for details). Note that this PSH study is purely an exercise as the annual rate of an earthquake of magnitude 6.4 in the fault zone cannot presently be determined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

a larger earthquake. The study focuses on the hazard posed by an M 6.4 event in the rupture zone of the Les Saintes mainshock event (M 6.4, 21 November 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 M 6.4 event. Gaussian distribution characterized 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, once the probability density functions are calculated, the implementation of this hybrid deterministic–probabilistic methodology is straightforward. In the future, other summation techniques able to take into account extended sources should be tested. Moreover, the nonlinear issue will have to be addressed because an important shortcoming of this EGF simulation method is that potential nonlinear site effects cannot be taken into account.

The intrinsic variability of the predicted ground motions is quantified. The sigma values reveal themselves to be comparable to the findings of previous studies (Anderson *et al.*, 2000; Atkinson, 2006; 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 ratio of the stress drop of the target event to the small event used as EGF. New sigma values (and new medians) are estimated on the ground-motion distributions

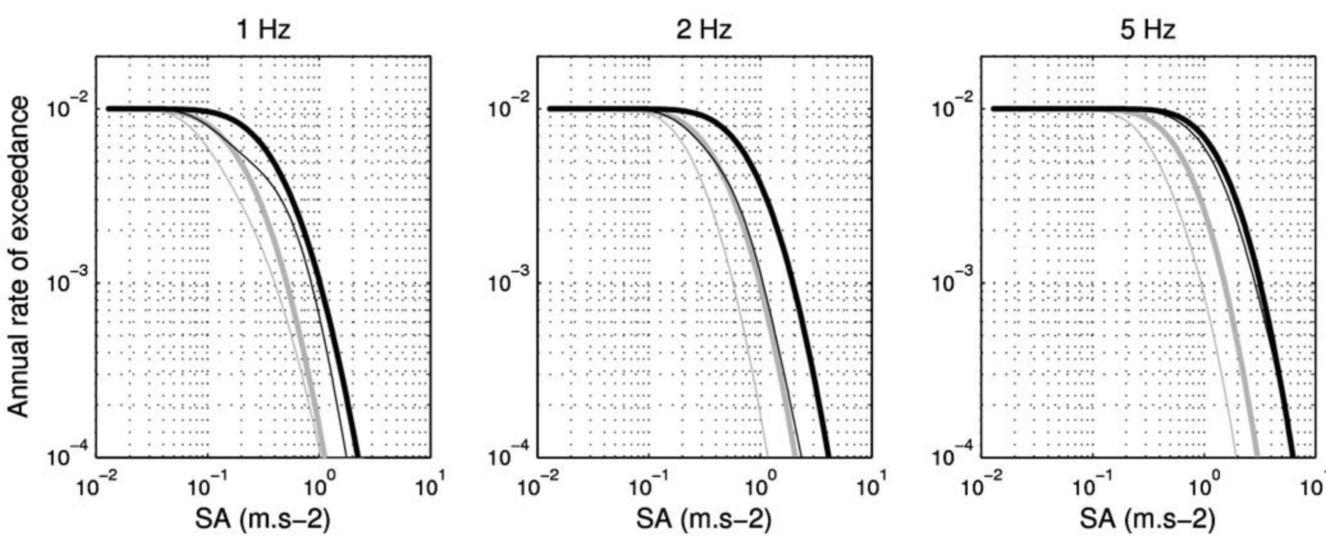

Figure 8. Comparison of hazard curves obtained at two different stations using the hybrid methodology and using the classical method based on the Ambraseys *et al.* (2005) ground-motion model. Gray curve, MOLA; dark curve, PRFA. Thin lines, hybrid method; thick line, classical method.

obtained from varying *C* between 1 and 15 and assuming that *C* values are equally likely. 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 equations for the whole frequency range. This result is expected as these equations average many different sources, paths, and site effects. The true sigma must be in between the sigma based on the EGF method and the sigma of ground-motion prediction equations. Note that the 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 large and small earthquakes. Note also that a real PSHA study led in the Guadeloupe archipelago would require the use of a ground-motion model as classically done as all seismic sources posing a threat to the site must be taken into account in the probabilistic hazard estimation.

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 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.

Data and Resources

Seismograms used in this study were collected by the French Accelerometric Network (RAP). Data can be obtained from the RAP Data Center at www-rap.obs.ujf-grenoble.fr (last accessed March 2009).

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