Testing Probabilistic Seismic Hazard Estimates Against Accelerometric Data in two countries: France And Turkey

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Summary

Probabilistic seismic hazard models (PSHM) are used for quantifying the seismic hazard at a site or a grid of sites. In the present study, a methodology is proposed to compare the distribution of the expected number of sites with exceedance with the observed number considering an acceleration threshold at a set of recording sites. The method is applied to France and Turkey. The French accelerometric database is checked to produce a reliable accelerometric dataset. In addition, we also used a synthetic dataset inferred from an instrumental catalogue combined with a ground-motion prediction equation. The results show that the MEDD2002 and AFPS2006 PSH models over-estimate the number of sites with exceedance for low acceleration levels (below 40 $cm.s^{-2}$) or short return periods (smaller than 50 yrs for AFPS2006 and 475 yrs for MEDD2002). For larger acceleration levels, there are few observations and none of the models is rejected. In Turkey, the SHARE hazard estimates can be tested against ground-motion levels of interest in earthquake engineering. As the completeness issue is crucial, the recorded data at each station is analysed to detect potential gaps in the recording. As most accelerometric stations are located on soil, accelerations at rock are estimated using a site-amplification model. Different minimum inter-site distances and station configurations are considered. The observed numbers of sites with exceedance are well within the bounds of the predicted distribution for accelerations between 103 and 397 $cm.s^{-2}$. For higher levels, both the observed number and the predicted percentile 2.5 are zero, and no conclusion can be drawn.

1. INTRODUCTION

Probabilistic seismic hazard assessment is used for quantifying the seismic hazard on a site or on a grid of sites. Probabilistic seismic hazard maps are now the basis for establishing seismic building codes in most parts of the world. These maps provide at geographical locations the ground motions with given probabilities of being exceeded in a future time period. Typically for conventional buildings, probabilities of exceedance of 2% to 10% over a 50 years time window are taken into account, corresponding to return periods of 475 to 2475 years. Several recent Opinion papers in Seismological Research Letters and Earthquake Spectra are encouraging hazard analysts to carry out tests (Stein et al. 2011, Stirling, 2012, Iervolino, 2013). However, considering the observation time window in seismology (~100 years at maximum for instrumental networks, and several centuries for historical data), testing at the return periods of interest in engineering seismology is a real challenge. Validation of the full probabilistic hazard curve with observations at a site is strictly impossible as several thousands of years of observation would be required (Beauval et al. 2008). Nonetheless testing partially these models against observations is possible.

Since the first application of the Cornell-McGuire probabilistic method (Cornell 1968, McGuire 1976), some authors have proposed to compare hazard curves with observed intensity rates. For example in Papazachos et al. (1990), an intensity-magnitude relationship is used to generate the sequence of intensity observations at a site, as if an "observer" had been there continuously. This sequence is then converted into a recurrence curve at the site. The authors superimpose the "observed" rates with hazard curves evaluated in terms of intensities at a series of sites. More recently, Stirling and Petersen (2006) proposed a similar comparison of predictions with observations, with applications in New Zealand and in the United States, the main difference being that true macroseismic intensities were used. Intensities were converted into accelerations applying an equation. The authors discussed in detail the uncertainties that might influence the results and tried to understand the discrepancies. Another direction was explored in Mucciarelli et al. (2008), who reconstructed the intensity history at a site from observed intensities and calculated ones (based on epicentral information or neighbouring intensity observation). They chose not to include an intensity-acceleration conversion and compared probabilistic seismic hazard (PSH) and intensity-based recurrences through the ranking of hazard evaluated at many sites in Italy. Most of these studies acknowledged the difficulty of calculating observed rates from potentially short time windows. To counteract this limitation, they analysed the results considering all sites as a whole, a reasoning close to sampling in space.

At present, hazard curves are most often provided in terms of accelerations. Several authors proposed to compensate the short time periods of observations by sampling in space. Ward (1995) performed area-based probabilistic seismic hazard tests, based on a grid of sites where synthetic accelerations were predicted from an earthquake catalogue. More recently, Fujiwara et al. (2009) carried out a comparison between predictions and observations, taking advantage of the dense Japanese accelerometric network. Considering a ground-motion threshold, they summarized the hazard map in one number, the average probability of exceedance over the grid of sites covering Japan, and compared this number with the percentage of accelerometric stations with exceedance (K-NET network). Using the recorded strong motions at the New Zealand network, Stirling and Gerstenberger (2010) calculated observed numbers of exceedance for two acceleration thresholds (100 and 200 $cm.s^{-2}$) and compared these numbers with the value predicted by the PSH analysis. Number of exceedances was compared first on a site-basis, then considering all sites at once. Albarello and D'Amico (2008) used a 30-yr time recording window of the Italian strong-motion network to test a PSH model against accelerations, considering all sites at once. The present study builds on these works, and develops a method for testing PSH estimates available at the sites of an accelerometric network, and for exploring the uncertainties of the method.

The aim here is to test the final output of the probabilistic calculations, the hazard curve. Understanding the impact of the uncertainties of PSH components on the final output is not straightforward (e.g. Beauval and Scotti 2004), and we believe that the full PSH model needs to be tested. However, the comparison with observations can also be performed at the intermediary steps of the probabilistic calculations. Long-term seismicity models, predicting the frequencies, size, and locations of future earthquakes, can be tested against earthquake catalogues (e.g. Rhoades et al. 2002; Musson and Winter, 2011). Moreover, the ground-motion prediction equations (GMPEs) can be selected based on their fit to the available accelerometric data (e.g. Scherbaum et al. 2004). Such studies are underway in France; the difficulty here is to test ground-motion prediction equations developed from moderate-to-large events on low-magnitude datasets (see, e.g., Beauval et al. 2012). Testing the intermediate steps of the probabilistic calculation is complementary to testing the PSH output, but it should be underlined that conclusions from the former cannot be generalized to the later.

In the first part of this article, we present the method developed to test probabilistic hazard estimates and explore uncertainties. The method is at first applied in metropolitan France, an example of low-to-moderate seismicity region, using datasets covering different observation time windows: ground-motion data recorded at the stations of the French Accelerometric Network (RAP), and synthetic ground motions predicted from an earthquake catalogue. Then, the same methodology is applied to a more active region, Turkey, using accelerometric data recorded by the Turkish strong-motion network.

2. METHOD FOR TESTING PSH MODELS AGAINST OBSERVATIONS

2.1 Published methods

As introduced by Ward (1995), the length of observation time windows can be compensated by sampling in space. Thus, the consistency of a PSH model with observations is evaluated at several locations at once. Following Albarello and D'Amico (2008), sites need to be distant enough from each other. Acceleration occurrences must be independent from one site to the other, and the ground-motion occurrences at the different sites are assumed to belong to the same stochastic process. The acceleration thresholds with a given probability p of exceedance in a given time window are inferred from the hazard curves at all sites. Albarello and D'Amico (2008) considered only sites having the same lifetime (30 years, 68 sites). For each site, either the threshold has been exceeded during the observation time window (success with a probability p according to the PSH model), or there was no exceedance (probability 1-p). The situation is comparable to a sequence of independent yes/no experiments. Therefore the binomial distribution gives the expected number of sites with exceedances

$$P(n) = \binom{N_S}{n} p^n (1-p)^{N_S-n} = \frac{N_S!}{n!(N_S-n)!} p^n (1-p)^{N_S-n} \tag{1}$$

where $P(n)$ is the probability to observe n sites with exceedance out of the N_S sites, p is the probability of an experiment resulting in a success. If the observed number corresponds to a very low or very high probability (compared to a chosen confidence interval), the test indicates that the model over- or under-predicts the observations.

Stirling and Gerstenberger (2010) proposed another approach, adapted to the New Zealand accelerometric network where station lifetime varies a lot from one station to the other (from 6 to 44 years, 24 stations in 2009). The test aims at comparing the predicted and observed number of exceedances, while Albarello and D'Amico (2008) compare the number of sites with exceedance. At one site, for a given acceleration threshold g_0, a PSH model provides the mean annual rate of exceedance λ_i. The mean expected number of exceedances is obtained by multiplying the rate λ_i by the duration of the observation time window t_i. Again, accelerations at a site are assumed to occur according to a stationary Poisson process. The Poisson distribution, fully defined by its mean, provides the probability of observing a given number n of accelerations above the threshold g_0:

$$P(n) = \frac{(\lambda_i t_i)^n e^{-\lambda_i t_i}}{n!} \quad (2)$$

where t_i is the time window at the site i with annual rate of exceedance λ_i given by the PSH model. The authors defined the following simple statistical test: if the observed number falls within the bounds of the distribution, defined by the percentiles 2.5 and 97.5%, the observations are considered consistent with the model (model is not "rejected"). Stirling and Gerstenberger (2010) first evaluated PSH models at individual sites and then gathering all sites. They wrote p. 1408 "The summed analysis is conducted because the site-specific comparisons often involve very few events and would yield meaningless results in many cases". The sites are far enough apart so that they can be considered independent in terms of ground-motion exceedances. As the sum of independent Poisson processes constitutes a Poisson process, the total number of exceedances observed over all sites is compared to the distribution defined by the following mean:

$$N_{total} = \sum_{sites} \lambda_i t_i \quad (3)$$

Stirling and Gerstenberger (2010) obtained different results when testing each site individually and when considering all sites at once (Equation 3, threshold considered is 0.1g). When testing each site individually, the model is not rejected at 22 out of 24 sites, i.e., the observed number of exceedances is within the confidence interval of the Poisson distribution. However, when testing the whole network at once, i.e. comparing the total observed and predicted numbers of exceedances, the PSH model is rejected with 95% confidence, as it is predicting fewer exceedances than have been observed in the historical period. This suggests that testing the PSH model against the total number of exceedances is more meaningful than individual tests.

2.2 Method implemented in the present study

The French and Turkish accelerometric network has been built progressively, since 1995 in France and since 1973 in Turkey, and lifetime of stations varies from a few months to a few decades. The test must be able to handle varying lifetimes to take advantage of the full databases. A PSH calculation yields the probability that an acceleration level will be exceeded "at least once" over a time window. We prefer to focus on the number of sites with exceedance, rather than on the exact number of exceedances, although both studies are possible. In total, 62 sites in France are included in the analysis. The Monte Carlo method is used to sample the site-specific Poisson distributions (Equation 2), characterized by their means ($\lambda_i t_i$), and generate numbers of acceleration exceedances for all sites (corresponding to time windows t_i). One run yields one set of 62 numbers of exceedance. Sampling the Poisson distributions many times, many sets of numbers of exceedances are generated. All are compatible with the PSH model. For each run, we count the total number of sites with exceedance. Finally, 10.000 runs provide 10.000 total numbers of sites with at least one exceedance (out of 62), and a probability distribution can be built. This distribution describes the expected number of sites with exceedance, for a virtual network having the same number of stations as the accelerometric network, and the same lifetimes. This probability distribution has a shape very close to a binomial distribution. Note that in the case of Albarello and D'Amico (2008), where all sites have the same lifetime, this distribution is binomial and can be obtained analytically. In Fig. 1, as an example, the test is led considering 5 RAP stations and a given acceleration threshold.

3. TESTING PSHA IN FRANCE

3.1. Building the accelerometric dataset

In France, the first stations of the accelerometric network were installed in 1995 (French Accelerometric Network, RAP, Péquegnat et al. 2008). Since then, the number of stations has increased, reaching at present a total of 142 sites in Metropolitan France. Out of these 142 sites, 69 are identified as 'rock sites' (V_{S30} shear-wave velocity at 30 m depth ≥ 760 m/s; see Régnier et al. (2010) and the information given on the RAP website). Most of these stations are located in the Pyrenees (19), Alps (33) and Lower Rhine Graben (5), regions with the highest seismic hazard in metropolitan France. The RAP stations are either in triggering mode or continuous recording stations. They consist of one three-component broadband accelerometric sensor (Kinemetric episensors, except for some of the oldest stations having

Guralp CMG5). The database extends over 16 years, from June 1995 to July 2011, and contains 40431 records (horizontal two-components). To limit the size of the database, we selected only signals with Peak Ground Acceleration (PGA) higher than 1 $cm.s^{-2}$, whatever the magnitude of the earthquake, reducing the total number of records to 2207. Stations in buildings and boreholes are not used. Note that a few events recorded only on one horizontal component and on the vertical component are kept.

After a careful check of the database, we identified several issues: bad association of records with responsible earthquake, shift of signal baselines, truncation of records, and low signal-to-noise ratio. For all signals, we checked the association with an earthquake by comparing the P-wave arrival time observed on the signal with the arrival time estimated from the earthquake location and origin time given in the RAP database. If the observed and estimated arrival times differed by more than 10 seconds, we looked for an explanation. Either the clock of the station was not correct or the record had not been associated with the right earthquake. For ten records, the associated earthquake was not correct and the appropriate one was extracted from the Renass earthquake catalogue (See "Data and Resources" section). For 54 signals, the shift was likely due to a clock problem of the station. Indeed, in most cases the time shift was a multiple of 60 seconds, as often observed for clock problems. Other issues encountered are shifts in the signal baselines and truncation of signals. Forty-two records contain a sudden shift in the baseline, which we corrected. Twenty-four records were clearly truncated after the occurrence of the peak amplitude, and thus the PGA could be estimated.

The final dataset used for testing PSH models contains 701 two-component records at 47 rock sites, corresponding to 551 earthquakes (Fig. 2). At the other 15 rock stations, no ground motion higher than 1 $cm.s^{-2}$ occurred during their lifetime, these stations are nonetheless included in the analysis. To ensure independency of sites, stations located closer than 10 km to another rock station have been discarded (7 stations). In this case, we kept the station with the largest expected number of exceedances during the station lifetime. Twenty-eight stations have been recording between 5 to 10 years, and 29 of them have been recording between 10 to 16 years. Three rock stations have recorded a PGA higher than 100 $cm.s^{-2}$, SAOF in the South-East Alps and PYBB/PYAD in the Pyrenees, whereas half of the stations recorded at maximum a PGA lower than 10 $cm.s^{-2}$ (Fig. 2, Table S1 in Supplementary Files).

For our analysis, it is of primary importance to use a complete database, or at least to identify gaps in the recording. We identified potential gaps in a station recording by analysing the inter-event times (times between successive earthquakes) of the acceleration sequence, based on the raw RAP database (no threshold on the acceleration). Average inter-event times were calculated, and inter-event times larger than 10 times the mean were considered as gaps in the recording (station not functioning, Fig. 3). Station lifetimes were shortened accordingly (Table S1 in Supplementary Files). Another test can be applied to check the completeness of our database, using an earthquake catalogue and a GMPE. This test is however limited by the inherent variability of ground motions. Using the Cauzzi and Faccioli (2008) equation, which fits well the French dataset (Beauval et al. 2012), we looked for earthquakes in the Renass earthquake catalogue that should have produced a median acceleration larger than 10 $cm.s^{-2}$ at the stations considered. From 58 records, 8 were missing (2 at OGSI, 5 at PYCA, 1 at PYAT). Five of them occurred within previously identified gaps. For the three remaining earthquakes at PYAC and PYAT, we did not find an explanation for the missing record. The station seemed to be working correctly at the time of the earthquake, since it detected a few events in the preceding and following days. Even if the problem is mostly localized on two stations, this suggests that the fraction of missing records (after correcting from identified gaps in the monitoring) is around 5% (3/58).

3.2 PSH models

Two PSH models are considered in the present study. The MEDD2002 model has been derived for the official French seismic building code (Martin et al. 2002, Sollogoub et al. 2007), which entered in 2010 into the French regulations. It is the first building code in France established from probabilistic seismic hazard methods following the Eurocode 8 standards. The AFPS2006 model was developed later on (Martin and Secanell 2006), involving a different group of experts who were questioning some of the decisions taken in MEDD2002 and claiming that the hazard was too high. Both models rely on the same seismicity models. The main difference in AFPS2006 with respect to MEDD2002 is the treatment of magnitude conversions and the ground-motion prediction equations used. We refer to the reports (Martin et al. 2002, Sollogoub et al. 2007, Martin and Secanell 2006) for details on the models used and their implementation in a logic tree. We do not question any of the decisions taken in these studies. We simply use these models and test them, because they are hazard references for France. The AFPS2006 study predicts hazard values that are always lower or equal to the values of MEDD2002 model (Sollogoub et al. 2007). The MEDD2002 results are only available for 4 return periods (100, 475, 975, 1975 years), whereas the AFPS2006 results are available for 10 return periods (5 to 10000 years). The stations locations usually do not fall on one of the grid nodes but in the middle of a cell (0.1°x0.1° for MEDD2002, 0.2°x0.2° for AFPS2006), the hazard rate at the location of each station is given by the average values at the four cell's nodes.

Minimum magnitudes used in the probabilistic calculations vary. In MEDD2002 study, the minimum magnitude is $M_{L,LDG}$ = 4 in local LDG magnitude (LDG, 2012), corresponding to a moment magnitude M_w around 3.5 (Drouet et al. 2010). The study uses $M_{L,LDG}$ magnitude as a surrogate for M_S. In AFPS2006 study, the minimum magnitude varies with the GMPE used, between 2.5 ($M_{L,LDG}$) and 5 (M_S). In the present study, all accelerations recorded at the stations are taken into account, regardless of the magnitude of the earthquake. Uncertainties are present at all steps of the PSH calculation and the magnitudes contributing to PSHA cannot be related easily to the magnitudes of the accelerations recorded at the sites of the RAP. The original magnitudes of earthquake catalogues have been converted using equations established over restricted magnitude range or equivalence has been assumed between magnitude scales (Martin and Secanell 2006). Most GMPEs used in the PSH studies tested here are imported from other regions, they have not been tested against local data and it is not possible to prove that they are adapted to the full magnitude range nor that their variability is truly representative at the sites considered. Besides, the level of studies on site effects varies greatly from one site to the other, and the uncertainty on the assigned class is expected to be large.

3.3 Testing results at the RAP sites

The PSH models provide median hazard curves as well as percentiles, deduced from the logic tree. Only the median hazard curve is considered here for a series of acceleration thresholds. The probability distributions for the number of sites with exceedance are obtained through Monte Carlo sampling based on 10,000 runs (Section 2.2). Tests show that 10,000 runs are large enough to get stable results. These distributions indicate the expected number of sites (out of the 62 rock sites) with at least one exceedance of the acceleration level over the lifetime of the stations (449 years in total, corrected lifetimes, see Table S1 in the Supplementary Files).

The tests can be carried out only for the acceleration levels that have been considered in the PSHA calculations. The AFPS2006 study provides accelerations for 10 return periods between 5 and 10,000 years. Obviously, the accelerations corresponding to these return periods vary from one site to the other. We chose to lead the test for a fixed acceleration threshold, common to all sites. The useful range is defined by the maximum of minimum accelerations of hazard curves (23 $cm.s^{-2}$ for the return period 5 yrs), and by the minimum of maximum accelerations of hazard curves (130 $cm.s^{-2}$ for 10,000 yrs). The AFPS2006 model can thus be tested against observations in the range 23 to 130 $cm.s^{-2}$. The example in Fig. 4 shows the results for 23 $cm.s^{-2}$. The sites with exceedance are highlighted on the map and the responsible earthquakes are indicated. The probability distribution has the shape of a binomial distribution, percentiles 2.5 and 97.5 correspond respectively to 9 and 21 sites with exceedance. The model predicts a higher number of sites with exceedance than the observed number. Note however that for acceleration thresholds higher or equal to 40 $cm.s^{-2}$, the test concludes on a consistency between predictions and observations, as will be discussed later on. The MEDD2002 study provides hazard results only for 4 return periods starting from 100 years to 1975 yrs (there was no possibility to obtain the full hazard curves, C. Martin, personal communication). Considering the 62 RAP sites, there is no common acceleration range between the 62 sites. For this reason, the MEDD2002 model is tested for a fixed return period rather than a fixed acceleration threshold.

Results of the testing are displayed in Fig. 5. The test is carried out using the modified lifetimes of stations to account for gaps in the monitoring. For each acceleration threshold, the observed number of sites with exceedance is superimposed on the expected number of sites, a probability distribution characterized by its mean and percentiles 2.5 and 97.5%. For the model AFPS2006 (Fig. 5a), observations are consistent with the model, i.e. within the percentiles 2.5 and 97.5, for all acceleration thresholds above 40 $cm.s^{-2}$. For the two lowest levels tested (23 and 30 $cm.s^{-2}$), the observed number of sites with exceedance is much lower than predicted by the model. We tested AFPS2006 also at fixed return periods (Fig. 5b). The AFPS2006 model predicts more exceedances than observed at 20 years return period. Between 50 and 200 years, the model is consistent with the observed number of exceedances (within the bounds). For 475 and 975 years, the test is not conclusive due to the lack of observed exceedances.

Results for MEDD2002 model are displayed for 100, 475 and 975 years (Fig. 5c). The observed number of sites with exceedance (1) is lower than the 2.5 percentile at 100 years (2 exceedances) and the model is rejected. For 475 and 975 years, the model is not rejected, however there is no exceedance, and the 2.5 percentile is also zero. This is not surprising, since these return periods are large with respect to the total length of the observation time window. In such a case, very different models may be consistent with the observations. In order to obtain meaningful results, we need long enough time windows and/or a large enough number of sites so that the expected total number of exceedances is larger than zero.

Sampling the sites in space and testing the hazard estimates considering all sites at once require that acceleration occurrences are independent. To reduce the correlation between records, stations closer than 10km from each other have been excluded prior to the analysis (Section 3.1). Moreover, the list of earthquakes responsible for the threshold exceedances was systematically checked. When two records at two stations were produced by the same earthquake, we simply discarded the site with the lowest acceleration recorded. They are few cases where this situation occurs. Discarding sites to ensure independence of sites brings minor changes to the plots and does not change the conclusions (see Figs 4 and 5). At each station, the earthquakes responsible for the thresholds exceedances have also been analysed to avoid including accelerations related to clustered events. We looked for events located within 10km of each other and within a time window of 30 days. Following this criterion, all events taken into account in the testing are independent.

3.4 Enlarging the observation time windows: using accelerations inferred from an earthquake catalogue

3.4.1. Methodology

Recorded accelerations are the most exact data to compare with hazard curves, but observation time windows are short, with the longest station lifetime reaching 16 yrs. An alternative to recorded ground motions is to use "synthetic" accelerations inferred from an earthquake catalogue. Earthquake catalogues provide information over longer time periods than accelerometric networks. The test can be performed following exactly the same methodology; the "only" difference is that accelerations at sites have been obtained thanks to a GMPE. This test has advantages with respect to the testing on records, such as longer time windows and a complete database over these windows. However a strong assumption has to be made regarding the choice of the GMPE.

The LDG earthquake catalogue, from the Laboratoire de Détection Géophysique (LDG, 2012) is the best candidate for this test. The first stations of the LDG network were installed in 1962. The catalogue consists of 15993 earthquakes with magnitudes from 2.5 to 5.9 (M_{L_LDG}), and spatial extension 41° to 52° in latitude and -6° to 10° in longitude. For the purpose of this study, aftershocks should be removed from the catalogue because the PSH model is not taking into account aftershocks and is predicting Poissonian rates. Therefore, the LDG catalogue is declustered using the Reasenberg declustering algorithm (Reasenberg 1985). Some 4776 events are identified as clustered events and removed from the catalogue. Then, the completeness is evaluated by plotting the cumulative number of earthquakes versus time. The catalogue is considered complete for magnitudes $M_{L,LDG} \geq 2.5$ from 1978 on. Thirty-four years are available for the test.

The synthetic accelerometric history at a site is constructed using the earthquake catalogue coupled with a ground-motion prediction equation. For all earthquakes in the catalogue, the corresponding acceleration is calculated at the site. A GMPE adapted to the region under study must be selected. The variability σ of ground motions must be taken into account (e.g. Strasser et al. 2009). For one magnitude and one source-to-site distance, the GMPE provides a Gaussian probability distribution for the expected ground motion at the site. Therefore, through Monte Carlo sampling, many accelerometric histories are generated by sampling the Gaussian probability distributions. Instead of producing one set of accelerometric histories (median values), 10,000 sequences are generated, and the distribution for the "observed" number of sites with exceedance is obtained. Note that the Gaussian distribution must be sampled within meaningful limits. PSHA studies are usually calculating probabilities of exceedance of ground-motions truncating the Gaussian distribution at $\pm 2\sigma$ or $\pm 3\sigma$. In our tests, a higher level of truncation allows higher accelerations and might have an impact on the "observed" number of sites with at least one exceedance. This number might be larger when truncating at $\pm 3\sigma$ than when truncating at $\pm 2\sigma$. The tests are performed for both truncation levels, however the results show that the truncation level has a minor impact on the results.

3.4.2. Selection of the GMPE

Two GMPE models have been identified as best fitting the French accelerometric data in Beauval et al. (2012), Cauzzi and Faccioli (2008, CF2008) developed from crustal Japanese data (80% of the dataset), and Akkar and Bommer (2010, AB2010) developed from data recorded in Europe and the Middle East. The dataset tested in Beauval et al. (2012) was made of earthquakes with M_w ranging between 3.8 and 4.5, and epicentral distances up to 300km. Here we check the fit of these equations with the actual dataset, going down to lower magnitudes and including only accelerations higher than 1 $cm.s^{-2}$. CF2008 and AB2010 model have been developed from data with $M_w \geq 5$, both models are therefore applied below their magnitude validity limits. We refer to Beauval et al. (2012) for a detailed discussion on the regional dependence of GMPEs and on the use of GMPEs outside their validity limits. Another model is tested, which could be better adapted to a lower magnitude dataset, the Atkinson and Boore (2011) equation developed from earthquakes with $M_w \geq 3.0$ recorded in western North American (update of the Boore and Atkinson (2008) equation extended towards lower magnitudes). All records available at the 54 RAP stations classified as 'rock', with PGA higher than 1 $cm.s^{-2}$, are taken into account (class A, 746 records, 578 events). For around 160 events, an M_w has been calculated by Drouet et al. (2010); for the other events, magnitudes M_{L_LDG} are converted to M_w using the equation of Drouet et al. (2010).

Histograms of the residuals are superimposed on the standard normal distribution representing each GMPE model (Fig. 6, first column). The best fitting model is Cauzzi and Faccioli (2008), since the mean of the residuals is close to 0 and the standard deviation close to 1.0. Akkar and Bommer (2010) model also provides a good fit to the data, with a mean slightly shifted towards higher values (slight under-prediction of the model) and a variability slightly larger than the dispersion predicted by the model. Atkinson and Boore (2011) predicts a much lower variability in the dataset than is observed, although providing a rather good fit for the mean. The residuals are plotted versus M_w and versus source-site distances to highlight potential trends (Fig. 6). In the case of the CF2008 model, mean of residuals are rather stable with magnitude (no specific trend, and contained within $\pm\sigma$), and rather stable also with source-to-site distance. These remarks also hold for the AB2010 model, except that the residuals are more dispersed. In the case of the AB2011 model, a strong trend is observed for residuals depending on the distance, implying that the attenuation with distance as modelled in AB2011 does not reproduce observed attenuation of ground motions in France.

Based on these results, Cauzzi and Faccioli (2008) is confirmed as the best-fitting model and selected for the present study. The model has a large σ value, which fits well the rather large dispersion in the French dataset. This large dispersion is both natural (true variability of the ground motions) and due to uncertainties in the metadata (magnitude estimates, source location, site classification, etc.). Note that the sigma predicted by the CF2008 model is much larger than the sigma predicted by the Atkinson and Boore (2011) model (CF2008: 0.344, AB2011: 0.246, $\log_{10}$ units, for the PGA). The standard deviations in Atkinson and Boore (2011) have not been adjusted to lower magnitudes and are representative of larger events (M_w>5.5), on purpose (see their paper).

3.4.3. Testing PSHM at the sites of the RAP stations with synthetic data

The test is first carried out exactly as in Section 3.3. At the 62 sites, locations of RAP stations, the synthetic time histories are now 34 years long. Assuming that the accelerations belong to the same stochastic process, and sampling the sites in space, leads to a virtual site with a total observation time window equal to 2018 years. This time window is more than four times longer than the total observation time window stacking the true-recorded periods at the same sites (449 years). The probability distribution for the observed number of exceedance is obtained by combining earthquakes in the LDG catalogue with the CF2008 GMPE, which is sampled in the range ±3σ.

The results obtained for the AFPS2006 and for the MEDD2002 models (Figs 7a and 7b) are very similar to those obtained from real data (Figs 5a and 5c). The predictions of the AFPS2006 model fit the synthetic observations above 40 $cm.s^{-2}$. For the lowest acceleration levels (23-30 $cm.s^{-2}$) the model overestimates the observations, the mean of the synthetic distribution is lower than the percentile 2.5 of the predicted distribution. The comparison with the predictions based on MEDD2002 model is once again difficult as the return periods tested are long and result in few observations at 475 and 975 yrs (Fig. 7b). At 100 yrs, the model over-estimates the observations (like in the real case, Fig. 5c). At 475 and 975 years, the mean of observations is within the bounds, however both 2.5 percentiles correspond to 0 site with exceedance. Results obtained from sampling between the CF2008 Gaussian PDF between ±2σ are slightly different, with slightly lower numbers of sites with exceedance, but the main features remain identical (Figs. 7c and 7d). Moreover, independency of sites is required in these tests. When 10000 synthetic datasets are generated, the independency of exceedances at 62 stations is controlled by checking the earthquakes causing exceedance. If two ground-motion exceedances at two different stations are produced by the same earthquake, these stations are considered as dependent and the observed number of sites with exceedance is decreased. Removing correlated accelerations has no influence on the results (Fig. 7).

The LDG catalogue consists of earthquakes with $M_{L,LDG} \geq 2.5$. While generating synthetic accelerations histories, all earthquakes are used. In order to understand the effect of this magnitude threshold on the results, the tests on the AFPS2006 model are performed again increasing the minimum bound for magnitude of earthquakes. Results based on the LDG catalogue taking into account $M_{L,LDG} \geq 3.5$ are displayed in Fig. 8. The results still highlight a consistency between predictions and observations for the upper acceleration range (above 60 $cm.s^{-2}$), and an over-prediction of the model for lower accelerations. However, the model is now strongly over-predicting the number of sites with exceedance, the mean of observations is much lower than the predicted 2.5 percentile. In the synthetic tests, the magnitudes between 2.5 and 3.5 are contributing largely in the range 23-50 $cm.s^{-2}$.

3.4.4 Stability in time

The PSH models have been tested against the RAP accelerometric data recorded between 1995 and 2011. One question posed is whether this time period is representative for the acceleration levels involved, or in other words, if the observed numbers of sites with exceedance are stable when considering different observation time windows. Using the LDG catalogue, this hypothesis can be checked, as the catalogue provides 34 years of synthetic observations at each RAP station. The LDG catalogue is divided into five sliding time periods of 16 years (from 1978 to 2011). Each period is extending over the same duration as the RAP network. However, some stations of the network covers 16 years, while others cover much shorter durations. Within each period, the accelerometric history at each station is generated using a sub-division of the period, equal to the observation time available at that station. Again, the Cauzzi and Faccioli (2008) equation is used to build the synthetic accelerometric histories. The same testing procedure is applied to the five time periods (Fig. 9). For each period, the synthetic distribution for the "observed" number of sites with at least one exceedance is superimposed on the predicted distribution (AFPS2006 model). The results are stable from one period to the other. Below 40-60 cm.s^{-2} predicted means are always lower than "observed" means, similarly to the results displayed in the real case (Fig. 5a) and when using 34 yrs of synthetic data (Fig. 7a). Above these levels, both the means and the percentiles approximately fit, for the five time periods. These results based on a sampling over France tend to show that 16 years of data is a representative period for the acceleration levels considered in the testing.

4. TESTING PSHA IN TURKEY

A similar study is led in Turkey, a region of much higher seismic activity, where hazard estimates can be tested over a higher acceleration range, of greater interest in earthquake engineering. The probabilistic seismic hazard results obtained during the SHARE project are considered (Giardini et al. 2013, www.share-eu.org). Hazard estimates corresponding to the logic-tree means are tested against accelerometric data. The minimum magnitude used in the probabilistic calculation is M_w 4.5. For predicting ground motions, SHARE selected four GMPEs (Delavaud et al. 2012, respectively with weights 0.35, 0.35, 0.1, 0.2): Akkar and Bommer (2010) based on data from Europe and the Middle East; Cauzzi and Faccioli (2008) developed for Italy and based mostly on Japanese data (80% of the generating dataset); Zhao et al. (2006) based on Japanase data; Chiou and Youngs (2008) based mostly on Western North American data.

4.1 Building the accelerometric dataset

In Turkey, the first strong-motion instruments were installed in 1973 (Kinemetrics SMA-1 type), and the first significant earthquake recorded in 1976 (Denizli earthquake, 19/08/1976). Since then, a nationwide strong-motion network has been established, operated by the Earthquake Research Department (ERD) of the General Directorate of Disaster Affairs

(GDDA). At the beginning of 2009, the total number of strong motion stations in the national network was 327, all equipped with digital recorders. In 2005, a project entitled « Compilation of Turkish strong motion network according to the international standards » was launched by ERD-GDDA and Middle East Technical University. The Turkish National strong-motion Project (T-NSMP) led to the building of the new Turkish strong-motion database (http://kyh.deprem.gov.tr/; Akkar et al. 2010). Accelerometric data from the national network stations of Turkey was compiled, processed and archived using state-of-art techniques. The site characterization of 241 (out of 327) strong-motion stations were improved, either by reassessing the existing shear-wave velocity profiles and soil column lithology information, or by utilizing invasive or non-invasive site exploration techniques to compute V_{S30} and other relevant parameters (Yılmaz et al. 2008, Akkar et al. 2010, Sandikkaya et al. 2010). The majority of the events in the database are shallow crustal earthquakes (depths less than 15 km) associated with the transform North and East Anatolian faults that run in the west–east and southwest–northeast orientations across the country. The few earthquakes with depths exceeding 40 km have occurred mostly in the southwest and eastern parts of Turkey falling on the Hellenic Arc and the Bitlis-Zagros Suture Zone, respectively (Bozkurt 2001). Most events in the database are for earthquakes with strike-slip and normal faulting.

The main source of our accelerometric dataset is the Reference Database for Seismic Ground-Motion in Europe (RESORCE, Akkar et al. 2014). RESORCE is a single integrated accelerometric databank for the broader European area, consisting of earthquake and station metadata information, and accelerometric data. The Turkish component of RESORCE relies strongly on the T-NSMP database, covering the time window between 1976 and 2011, and including ground motions from magnitudes 2.8 to 7.6 (Mw). In RESORCE, the waveforms of raw accelerometric data were visually inspected one by one in terms of waveform quality and frequency content to implement a well-established data processing technique into the entire strong-motion databank (see Akkar et al. 2014 for details on the band-pass filtering and post-processing scheme). The primary parameter used for strong-motion site characterization is V_{S30}. Source-to-site distance measures are provided (e.g. Joyner and Boore distance R_{JB}).

In the present study, we focus on accelerations greater than or equal to 50 $cm.s^{-2}$, recorded at stations with known V_{S30}. Fifty-six records with a geometrical mean higher or equal to 50 cm.s^{-2} are extracted from RESORCE. As completeness is a key aspect for testing PSHA against observations, we must go back to the raw data from the Turkish Strong Motion network (TR-NSMN, http://kyh.deprem.gov.tr) to look for recordings that have been discarded, and to extend the time window to March 2013 (13/03/2013). Fifty-nine raw records, with a PGA greater than or equal to 50 cm.s^{-2} on at least 1 horizontal component are extracted from the database (no condition on the magnitude). Applying the same signal processing as performed in RESORCE (Akkar et al. 2014), 44 recordings are left with a geometrical mean greater than or equal to 50 cm.s^{-2}. Gathering the 56 records from RESORCE and these 44 records, the dataset consists of 100 records. In total, 291 Turkish stations could be used in the testing, with a V_{S30} provided either by RESORCE (235 stations) or by the TR-NSMN (56 stations).

The SHARE probabilistic seismic hazard curves are calculated for rock sites (V_{S30} 800 m/s), whereas less than 6% of the Turkish stations are actually located at rock. Using a subset of the SHARE strong-motion database (Yenier et al. 2010), Sandikkaya et al. (2013) developed a site-amplification function that considers both linear and nonlinear soil effects. This site-amplification model was developed with the data from shallow crustal earthquakes and Turkey is one of the most contributing countries in the dataset. It provides the logarithm of the amplification as a function of V_{S30} and of the acceleration at rock (750 m/s), with coefficients depending on the spectral period (Eq. 5 and Table 3 in Sandikkaya et al. 2013). For a soil site, the amplification corresponds to the PGA recorded (PGA_{SOIL}) divided by the PGA at rock (PGA_{ROCK}). PGA_{ROCK} at all accelerometric stations are therefore obtained by fixing a first starting value for PGA_{ROCK} (using a ground-motion prediction equation at rock), then estimating the amplification and the corresponding value on soil, and after several iterations the PGA_{ROCK} yielding the exact PGA_{SOIL}, given the predicted amplification, is finally obtained. After conversion to a PGA corresponding to 750 m/s, 69 records are still higher or equal to 50 cm.s^{-2}.

For testing PSHA against observations, completeness is a key aspect, operating lifetime of stations must be known, as well as the periods when the stations were out of order. Unfortunately, this information is not available for most of Turkish stations. A quick look at the data shows that some stations have been operating only a few months, sometimes with years apart. The gaps in the data can only be estimated from the recording histories. Given the uncertainty on the detection of these gaps, two methods are proposed here which provide two sets of complete time windows. These methods make use of all the (raw) data recorded at the stations, without any threshold amplitude. At 87 stations (out of 291), less than 2 records are available, and nothing can be inferred from this data about their operating lifetime. These stations are discarded. Applying the methods for detecting gaps (Section 4.2), 15 stations are left with observation time window equal to zero. Therefore, our dataset is finally made of 189 stations, with 30 stations which recorded 56 PGA higher or equal to 50 $cm.s^{-2}$ (Fig. 10, Tables S2 and S3 in the Supplementary Files).

4.2 Detecting gaps in the data

4.2.1 Technique based on average inter-event times

In the first method, the gaps in the (raw) data are detected based on the average inter-event time (as in Section 3.1 for French stations). The Turkish dataset contains a significant amount of clustered events. The average inter-event time is calculated taking into account only independent accelerations produced by mainshocks. All inter-event times longer than 10 times the average are considered as gaps. The algorithm from Reasenberg (1985) is applied on the earthquake catalogue (with the following parameters, distance factor=15, minimum look-ahead time=10 days, maximum look-ahead time=20 days). Around 70% of the earthquakes are identified as foreshocks or aftershocks. At each station, the average inter-event time is calculated from the accelerations generated by mainshocks, and the time periods identified as gaps are retrieved from the lifetime of the station. The average inter-event time including a gap is over-estimated, thus this operation is repeated until no more gap is identified. Note that at all stations, we check that the gaps identified do not contain any acceleration from foreshock or aftershock events (in a very few cases it happens, and the gap is shortened). Fig. 11 displays the results for two stations. At station 5902 a gap is identified and the lifetime of the station is reduced from 18 to 13 years. At station 1608 no gap is identified and the station lifetime is not modified. The results show that the method is quite efficient for obvious long gaps in the data, nonetheless the choice of the factor 10 is rather arbitrary, and the method is not able to identify shorter gaps.

4.2.2 Technique based on ground motion predictions

In the second method, gaps in the data are identified thanks to synthetic accelerations, obtained by coupling a ground-motion prediction equation with the earthquake catalogue used in the SHARE project for Turkey (instrumental part, the SHARE Catalogue for Central and Eastern Turkey complementing the SHARE European Earthquake Catalogue, available at http://www.emidius.eu/SHEEC/, Grünthal et al. 2013, Sesetyan et al. 2013). As this European catalogue stops in 2006, the earthquake catalogue from B.Ü. KOERI National Earthquake Monitoring Center is used for the period 2006-2013 (www.koeri.boun.edu.tr). The Akkar and Çağnan (2010) GMPE, developed from Turkish accelerometric data, is selected. At each station, for all earthquakes in the catalogue the median acceleration predicted at the site is calculated, and the synthetic history of accelerations is obtained. Details on the determination of the parameters required for predicting accelerations are given in Appendix A. The acceleration is calculated taking into account the V_{S30} value of the station. A quick analysis of the raw data shows that when a station was operating, the detection threshold was always lower than 10 cm.s^{-2}. Here gaps are identified each time one or more acceleration higher or equal to 10 cm.s^{-2} is missing in the recorded data. The gap is defined as the time elapsed between two consecutive observations including the missing records. Unlike the first method relying on inter-event times, this technique can detect gaps even when the stations recorded very few data. The list of the 189 stations that will be used in the testing is displayed in Table S2 (Supplementary Files). Figure 12 shows the gaps identified at two stations as examples. The method based on synthetic data identifies more gaps than the method based on inter-event times. The true lifetime is likely between these bounds. Corrected lifetimes of stations vary from a few month to 22 years at maximum.

4.3 Testing results

Mean hazard curves from the SHARE logic tree are considered. For a series of acceleration thresholds, the probability distributions for the number of sites with exceedance are obtained through Monte Carlo sampling, based on 10,000 runs (see the method in Section 2.2 and its application in France in Section 3.3). These distributions indicate the expected number of sites, out of the total number of sites, with at least one exceedance of the acceleration level over the total lifetime of the network.

At first, all 189 stations are considered (Fig. 10). The observed number of sites with exceedance is superimposed on the expected number of sites (Figs. 13a and 13b, red stars). Considering lifetimes corrected in Section 4.2.1 (1177 years in total), observations are consistent with the model, i.e. within the bounds of the distribution, for all acceleration thresholds greater than or equal to 103 $cm.s^{-2}$ (>0.1g). For highest levels, 556 and 778 $cm.s^{-2}$, the test is not conclusive as there is no exceedance and the 2.5 percentile is also zero. At 74 $cm.s^{-2}$, the observed number of sites with exceedance (25) is slightly lower than the 2.5 predicted percentile (26 sites). At the lowest level considered, 53 $cm.s^{-2}$, the observed number (29 sites) is much lower than the 2.5 predicted percentile (40 sites). Considering lifetimes corrected in Section 4.2.2 (892 years in total), comparable results are obtained, with observed values within the percentiles 2.5 and 97.5 for acceleration thresholds above 53 $cm.s^{-2}$. The observed numbers of sites with exceedance are identical, but the predicted numbers are decreased (as the total time window is decreased from 1177 to 892 years), resulting in a better fit between observed and predicted values. For information, the magnitudes and source-site distances of the earthquakes contributing to the threshold exceedances are reported in Fig. 14.

Imposing a minimum inter-site distances of 10 km, the number of stations is reduced from 189 to 137. The results obtained for both sets of corrected lifetimes are very similar (compare Figs. 13a with 13c, Figs. 13b with 13d). The number of sites with exceedance (predicted and observed) decreases, but the fit between prediction and observations is identical. Imposing a minimum inter-site distance of 60 km (Figs. 13e and 13f), 49 sites are now considered. The total observation time window is strongly reduced, but the results are quite stable, with observations within the bounds of the predicted distribution for all acceleration levels considered (except at 53 $cm.s^{-2}$ in Fig. 13e). Moreover, the list of earthquakes responsible for the threshold exceedances was systematically checked, to identify potential double counting. Discarding sites to ensure independence of sites brings minor changes to the plots and does not change the conclusions (Fig. 13, black stars).

5. CONCLUSIONS

We have carried out an extensive experiment to test probabilistic seismic hazard models against accelerometric datasets. A low-seismicity region, France, and a seismically active region, Turkey, are considered. Sites are sampled in space to compensate for the short observation time windows at accelerometric stations. Expected numbers of sites with exceedance, over the total observation time window, are compared to observed numbers of sites. A model is judged consistent with the observations if the observed number is within the percentiles 2.5 and 97.5 of the predicted distribution. The entire model is tested at once, the test provides an overall evaluation of the PSH model over a large geographical area.

As the maximum time window available is 16 years for the French RAP accelerometric database, the test is also carried out considering synthetic amplitudes based on an earthquake catalogue (LDG catalogue, 34 years) combined with a GMPE equation adapted to the French dataset (Cauzzi and Faccioli 2008). The tests led on true-recorded accelerations and on synthetic data provide comparable results. The AFPS2006 PSH model is consistent with the observations of the RAP network over the acceleration range 40-100 $cm.s^{-2}$ and for 50-200 years return periods (62 sites, 449 yrs in total). When using synthetic accelerations over 34 yrs at the same 62 sites (2108 yrs in total), the model predicts a number of sites with exceedance that is consistent with the “observations” over the range 40 to 130 $cm.s^{-2}$. The MEDD2002 PSH model is provided all over France only for 4 return periods, from 100 to 1975 years. For 100 years, there is only one site with exceedance, which is less than predicted. For longer return periods (475 and 975 years), the test led over the 16 years of the RAP network is not conclusive, since for these return periods both observed and predicted numbers equal zero. Using the synthetic dataset, the “observation” time window is increased. The model still over-predicts the observations at 100 years, but it is consistent with the observations for 475 and 975 years.

The results show that testing PSH models in France is at present very limited, as results are obtained only for low accelerations (≤0.1g) which are not of real interest in earthquake engineering. Considering a series of acceleration thresholds, we show that results at a given acceleration level should not be extrapolated to higher levels. Testing PSH in France can be done only at low acceleration levels, and these results cannot be extrapolated to higher levels. Moreover, although AFPS2006 and MEDD2002 are providing different hazard curves (higher values in MEDD2002 than in AFPS2006), the observations available do not permit to discriminate between these models. Both models are compatible with observations if considering the highest acceleration range or the highest return period range.

Applying the method in Turkey enable to test probabilistic seismic hazard estimates over an acceleration range useful for earthquake engineering. As the completeness issue is crucial, the recorded data at each station is analysed to detect potential gaps in the recording. Two techniques are proposed to identify gaps, and the tests are led considering both sets of corrected lifetimes. The maximum time window available is 22 years, stacking lifetimes at 189 stations provides a time window of 1177 years (or 892 years). The PSH hazard estimates produced in the SHARE project (at rock) are considered. As most accelerometric stations are located on soil, the recorded PGA are converted to PGA at rock using the site-amplification published in Sandikkaya et al. (2013). The test is carried out considering all stations (189), then 137 stations with a minimum inter-site distance of 10km, and finally 49 stations with a minimum inter-site distance of 60km. These three sets of stations are considered, combined with the two sets of corrected lifetimes. The six tests provide comparable results, with observed numbers of sites with exceedance well within the bounds of the predicted distribution for accelerations between ~0.1 and 0.4g. For higher levels, both the observed number and the predicted percentile 2.5 are zero, and no conclusion can be drawn.

We are currently applying the same methodology to the French intensity database. Such study will enable to test ground motion levels of interest in earthquake engineering, recorded over longer time windows. However the results will also depend on some assumptions required, such as the completeness of intensity histories at sites, or the conversion of intensity into acceleration. In the future, another type of observation could be used to constrain the hazard curves, precarious rocks or other fragile geological features such as speleothems (Anderson et al. 2011). Maximum acceleration levels over given time windows could thus be constrained. Any testing method relies on some assumptions, and the discrepancies between observations and predictions can generally have more than one explanation. We believe that firm conclusions on the validity of a PSH model will only be possible if applying for the same region several techniques, using different observables, recorded over different time windows.

Data and Resources

The accelerometric database built within this article is based on data available online (French Accelerometric Network, http://www-rap.obs.ujf-grenoble.fr/, last accessed May 2013). The Renass earthquake catalogue is provided by the Réseau National de Surveillance Sismique (RéNaSS, http://renass.u-strasbg.fr/, last accessed May 2013). The LDG earthquake catalogue (2012) is provided by LDG upon request.

The SHARE seismic hazard map is available at www.efehr.org. The Turkish accelerometric data is available at http://kyh.deprem.gov.tr/ftpe.htm. The following catalogues have been used in the present paper: International Seismological Centre online bulletin, http://www.isc.ac.uk/iscbulletin/search/bulletin/ (last accessed April 2014), and GCMT earthquake catalogue, http://www.globalcmt.org/CMTsearch.html (last accessed April 2014). The SHEEC earthquake catalogue can be find at http://www.emidius.eu/SHEEC/ (last accessed May 2014), and the catalog of B.Ü. KOERI National Earthquake Monitoring Center can be find at www.koeri.boun.edu.tr (last accessed May 2014).

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Figures

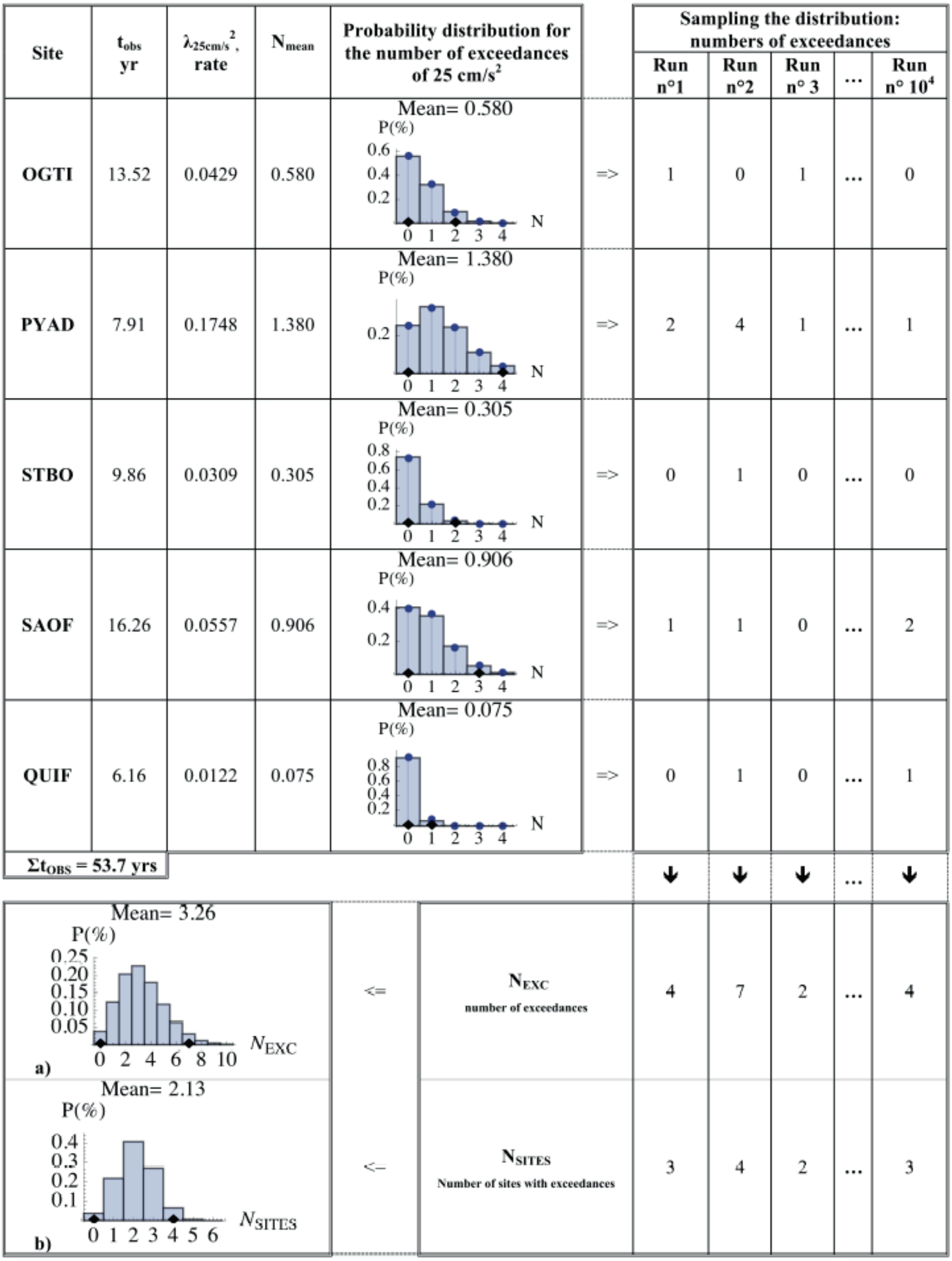

Figure 1: Scheme detailing the Monte Carlo process followed for generating a) the probability distribution for the number of exceedances (N_{EXC}) considering all sites, b) the probability distribution for the number of sites with at least one exceedance (N_{SITES}). The acceleration threshold is fixed (25 cm/s^2). Five accelerometric sites are considered in this example, with different lifetimes, resulting in a total observation time window of 55 years. The probability distributions provide numbers of occurrences over 55 years. t_{OBS}: observation time length of the stations, λ_{25cm/s^2}: predicted annual rate of

exceeding 25cm/s^2, N_{mean}: Predicted number of exceedances for a ground motion higher than or equal to 25cm/s^2 during t_{OBS}.

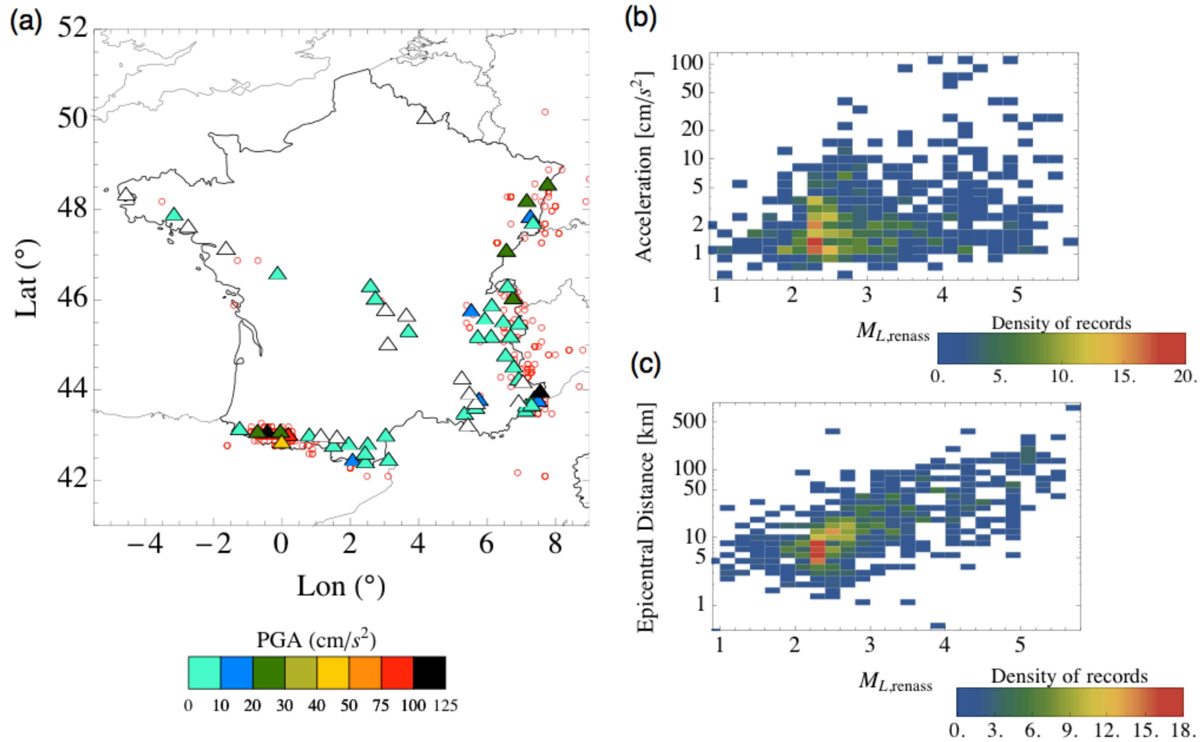

Figure 2: The accelerometric dataset built from the RAP raw database, for testing PSHA in France. (a) Coloured triangles: the 47 rock stations which have experienced at least one PGA ≥1 cm/s^2 during their lifetime, white triangles: 15 remaining rock stations. Colour scale: maximum acceleration recorded at each station. Circles: responsible earthquakes. (b) Distribution of all PGA amplitudes against the magnitude of the corresponding earthquake (M_{L_Renass}). (c) Distribution of epicentral distances of the records against the magnitude of the corresponding earthquake.

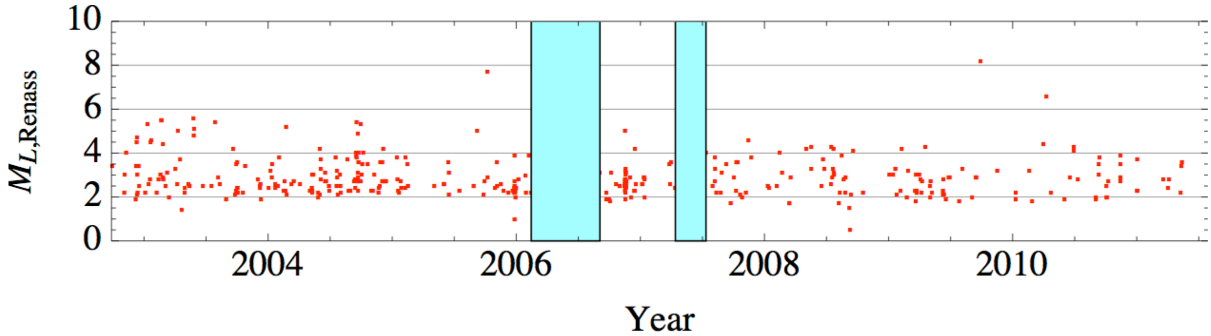

Figure 3: Detecting gaps in the observation lifetimes of RAP stations, example at station PYOR. Magnitude of the earthquake associated to the accelerometric record versus time. Original observation lifetime: 8.8 years. Shading : two gaps identified (inter-event times > 10 * average inter-event time). Corrected lifetime : 8.0 years.

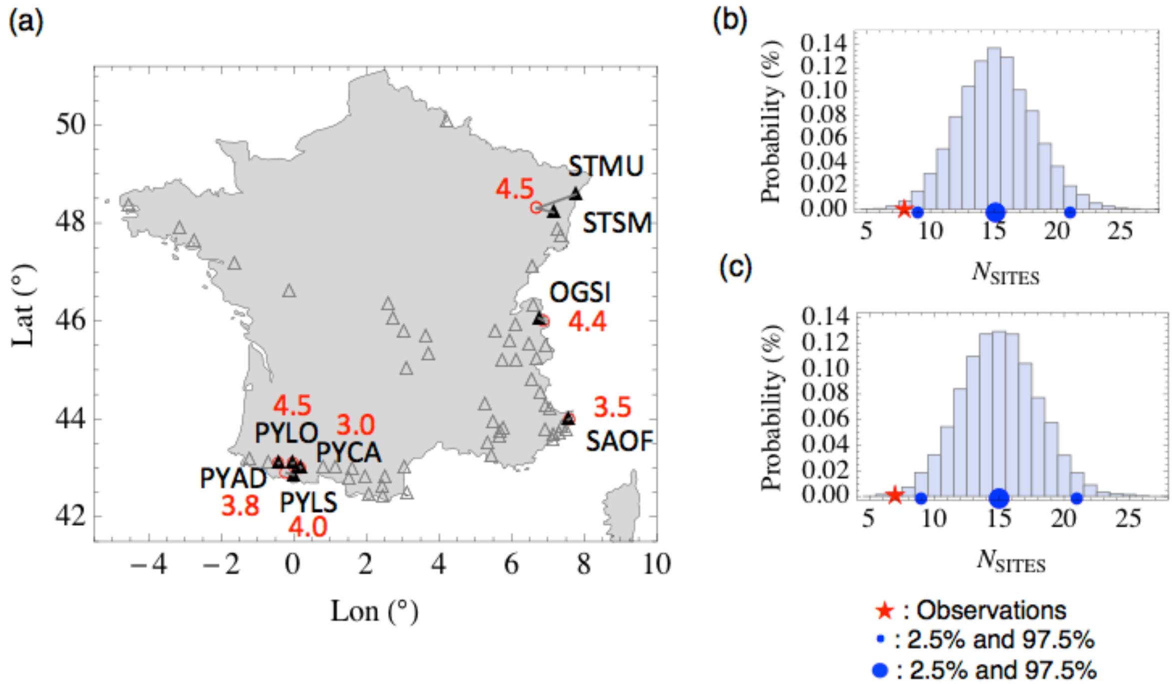

Figure 4: Testing the AFPS2006 model against the accelerometric dataset, example for the acceleration threshold A_0= 23 cm/s^2. (a) Locations of the 8 stations, out of 62, which recorded a ground motion higher than A_0 (black filled triangles, acronyms of stations indicated), and responsible events (circles, M_w indicated). Right: b) the observed number of sites where A_0 was exceeded is superimposed on the probability distribution predicted by the PSH model. In this example, the model over-predicts the observations; c) two records producing exceedance are related to the same earthquake (stations STMU and STSM), excluding one station from the analysis does not change the conclusions (predictions are for 61 stations).

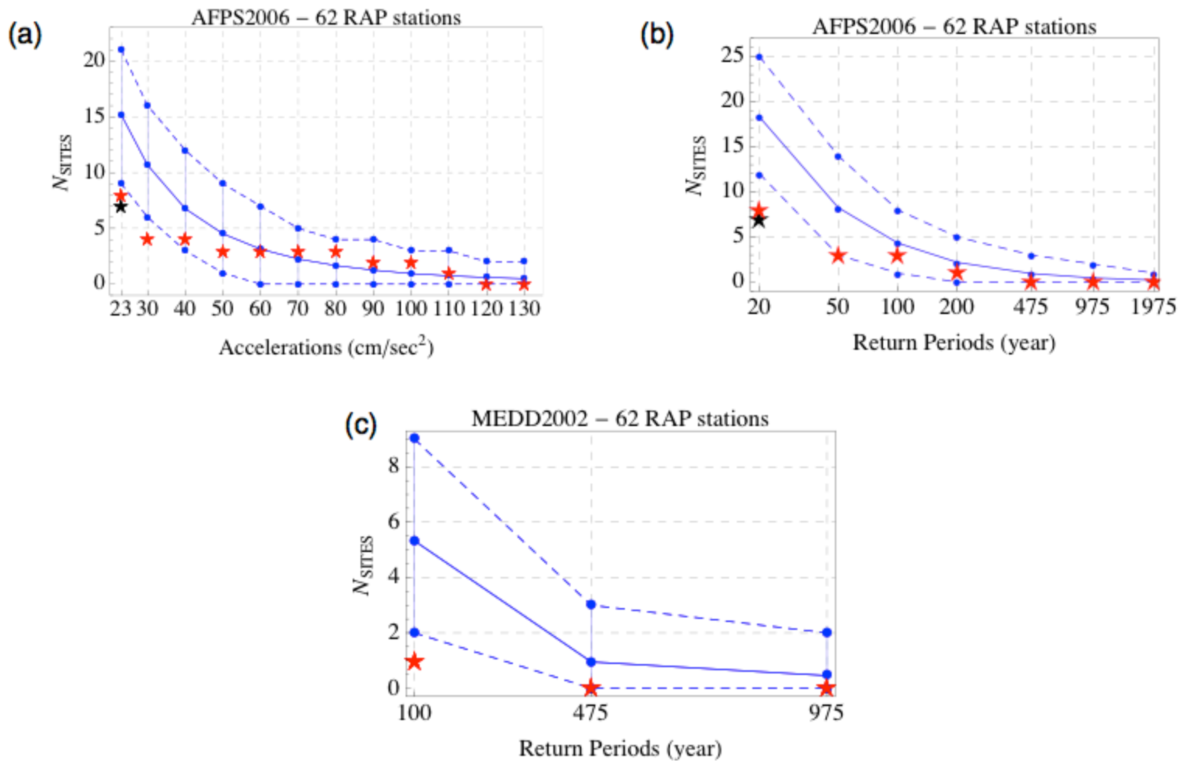

Figure 5: Testing the probabilistic seismic hazard models against accelerometric data in France: predicted and observed number of sites with exceedance (62 rock sites, total time window 449 years). Blue curves: median and percentiles 2.5 and 97.5 of the predicted distributions, red stars: observed number of sites. Black stars: reduced number of sites in the case of double counting (see Fig. 4). (a) Results for the AFPS2006 PSH model, considering a range of acceleration thresholds. (b) Results for the AFPS2006 PSH model, considering a range of return period thresholds. (c) Results for MEDD2002 model, considering 3 return periods.

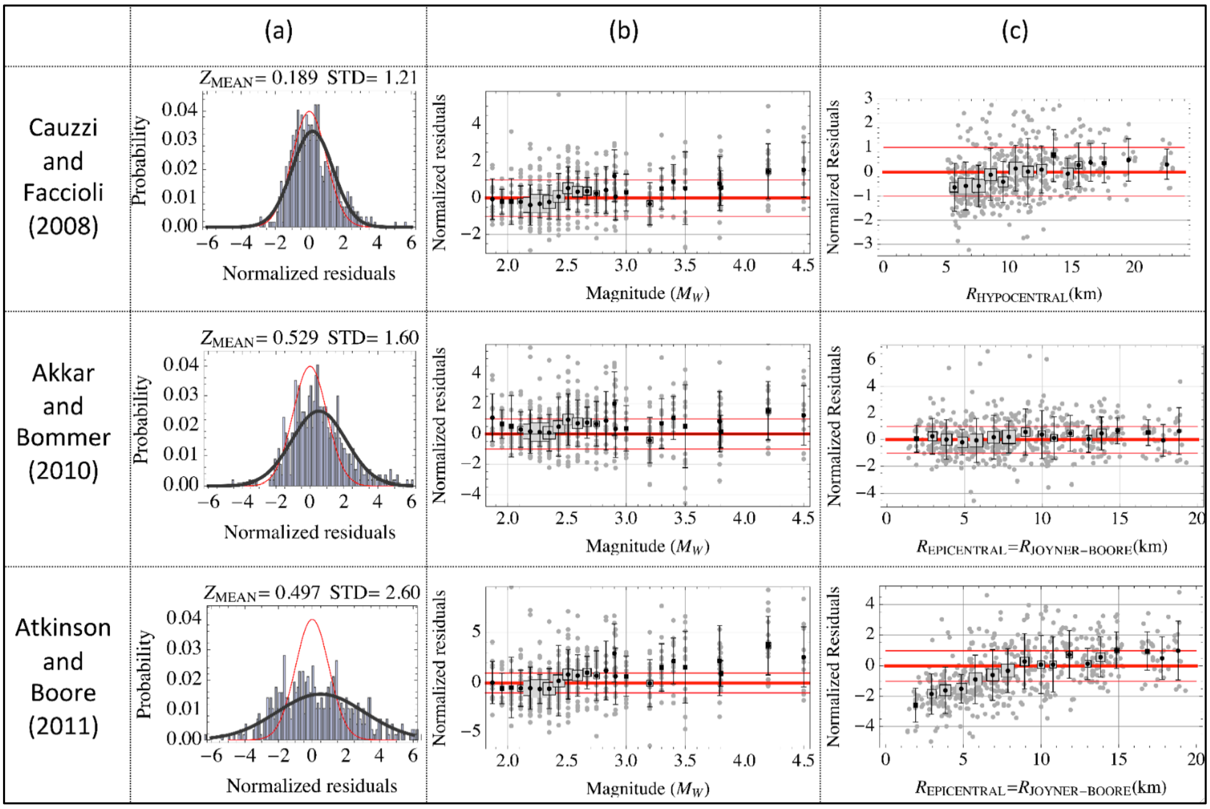

Figure 6: Testing 3 ground-motion prediction models against the newly built accelerometric French dataset. Column A: histogram of residuals superimposed on the standard normal distribution representing the model (red curve), a residual corresponds to [Log(observation)-Log(prediction)]/sigma. Column B: distribution of residuals versus magnitude (0.1 magnitude binning). Column C: distribution of the residuals with respect to source-site distance (1km distance binning). Squares: mean of residuals, size proportional to the number of residuals falling in each bin, error bars correspond to ±1 standard deviation of model (normalized residuals). (Z_{MEAN}: Mean normalized residuals, STD: Standard deviation of normalized residuals.)

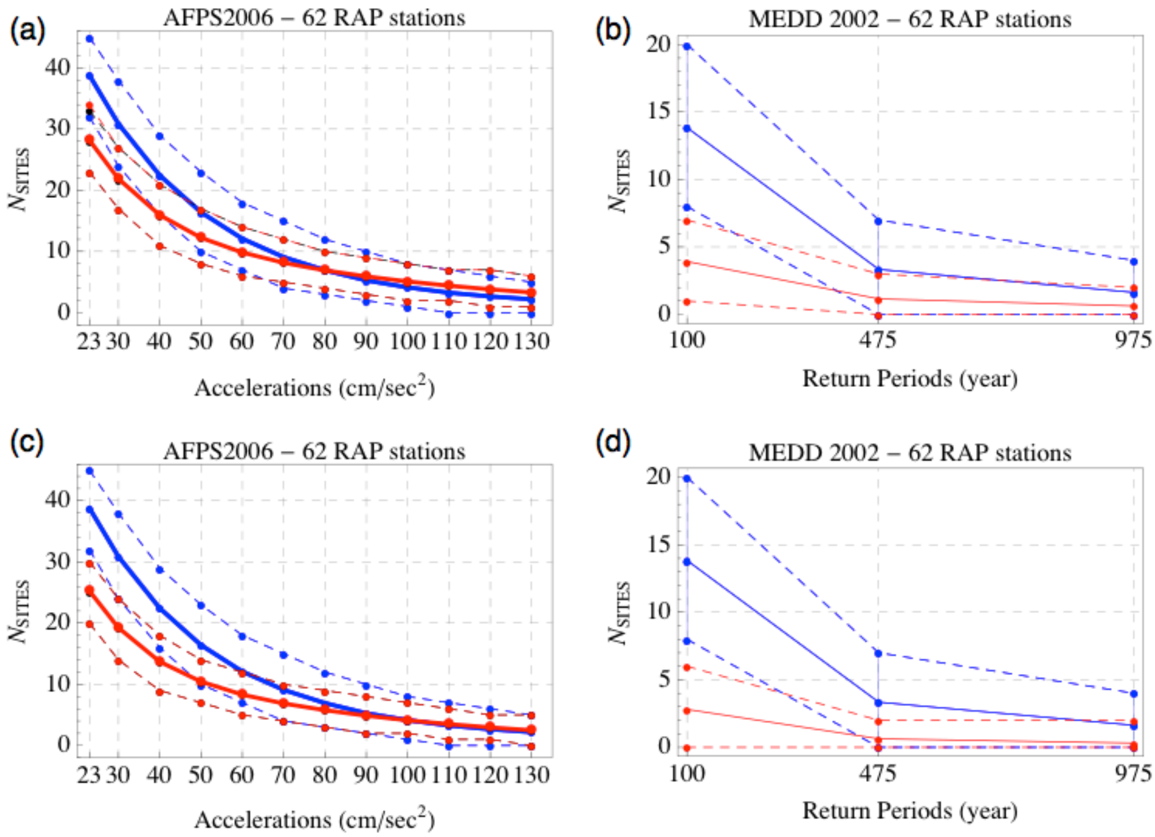

Figure 7: Application in France, testing the PSH models against synthetic accelerometric data: predicted and "observed" number of sites with at least one exceedance (62 rock sites with 34 years, total time window 2108 years). Blue curves: predicted distributions, mean and percentiles 2.5 and 97.5. Red curves: observed distributions, mean and percentiles 2.5 and 97.5. Black curves: reduced number of sites in the case of double counting. The synthetic data were generated using the LDG catalogue and sampling the Gaussian of the CF2008 GMPE between ±3σ. (a) AFPS2006 model. (b) MEDD2002 model, considering 3 return periods. (c) and (d): same as (a) and (b) but sampling the CF2008 GMPE between ±2σ (see the text).

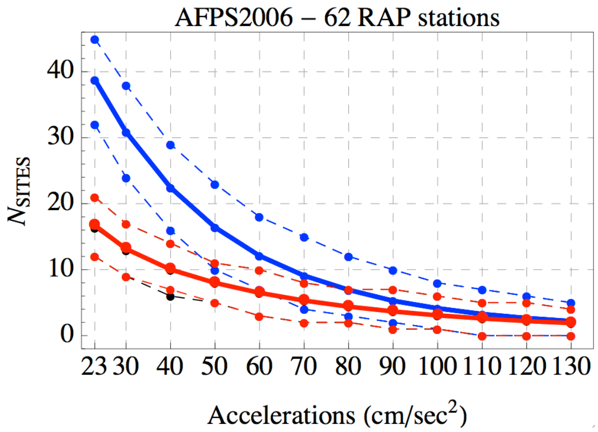

Figure 8: See legend of Fig. 7(a). AFPS2006 model, only events in the LDG earthquake catalogue with $M_{L,LDG}$≥3.5 are used for generating synthetic data, sampling the Gaussian of the CF2008 GMPE between ±3σ.

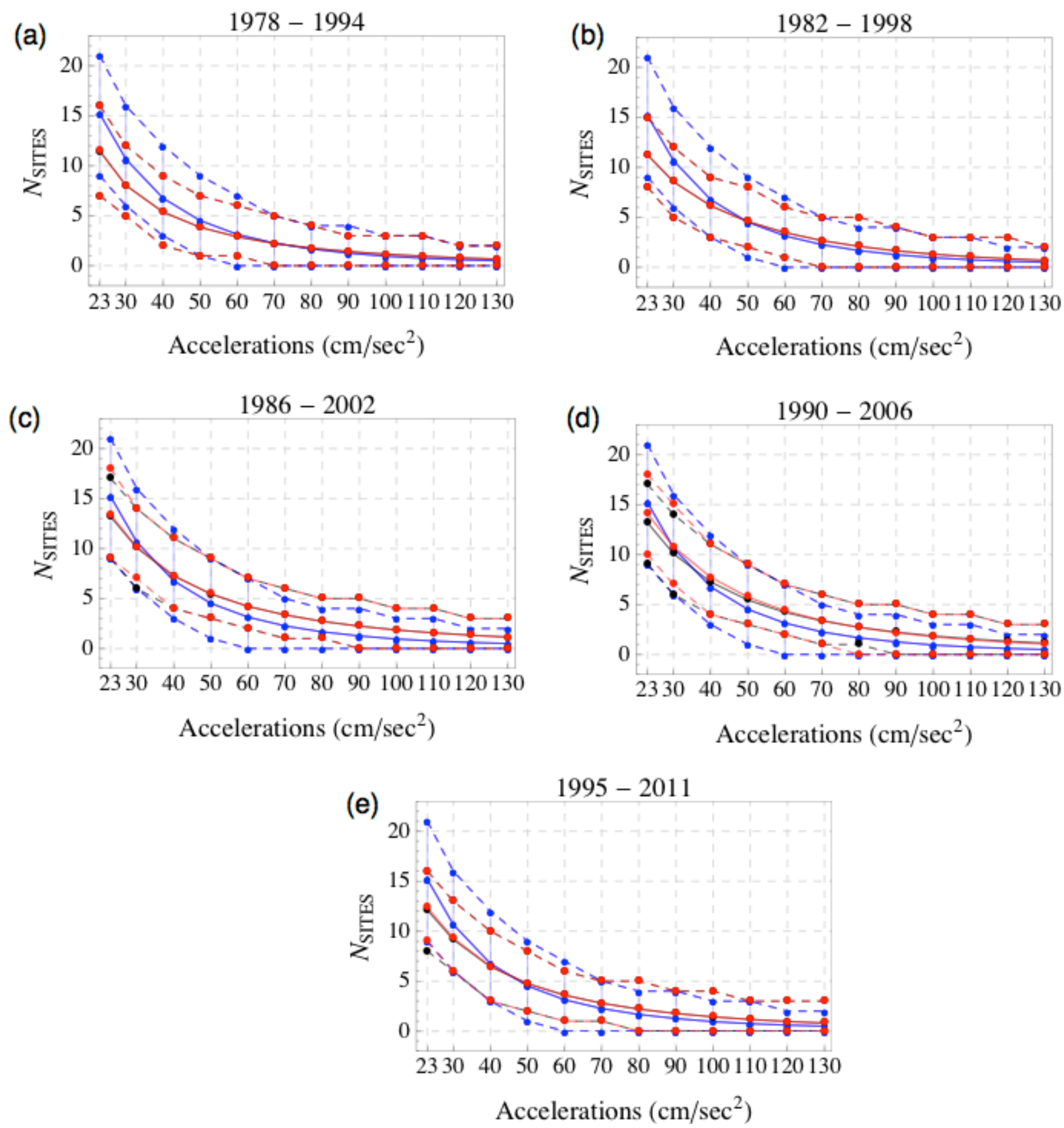

Figure 9: Testing AFPS2006 model against synthetic accelerometric data at 62 sites in France, and evaluating the stability of the results, with respect to the time window used. Five sliding windows are considered between 1978 and 2011, with length equal to the lifetime of the RAP network (16 yrs). Each station is attributed the same lifetime as in the real case. For each 16-yrs period, synthetic datasets are generated by coupling the LDG catalogue with the GMPE CF2008 (sampled between $\pm 3\sigma$). Total observation time window is 449 years, like in the real case.

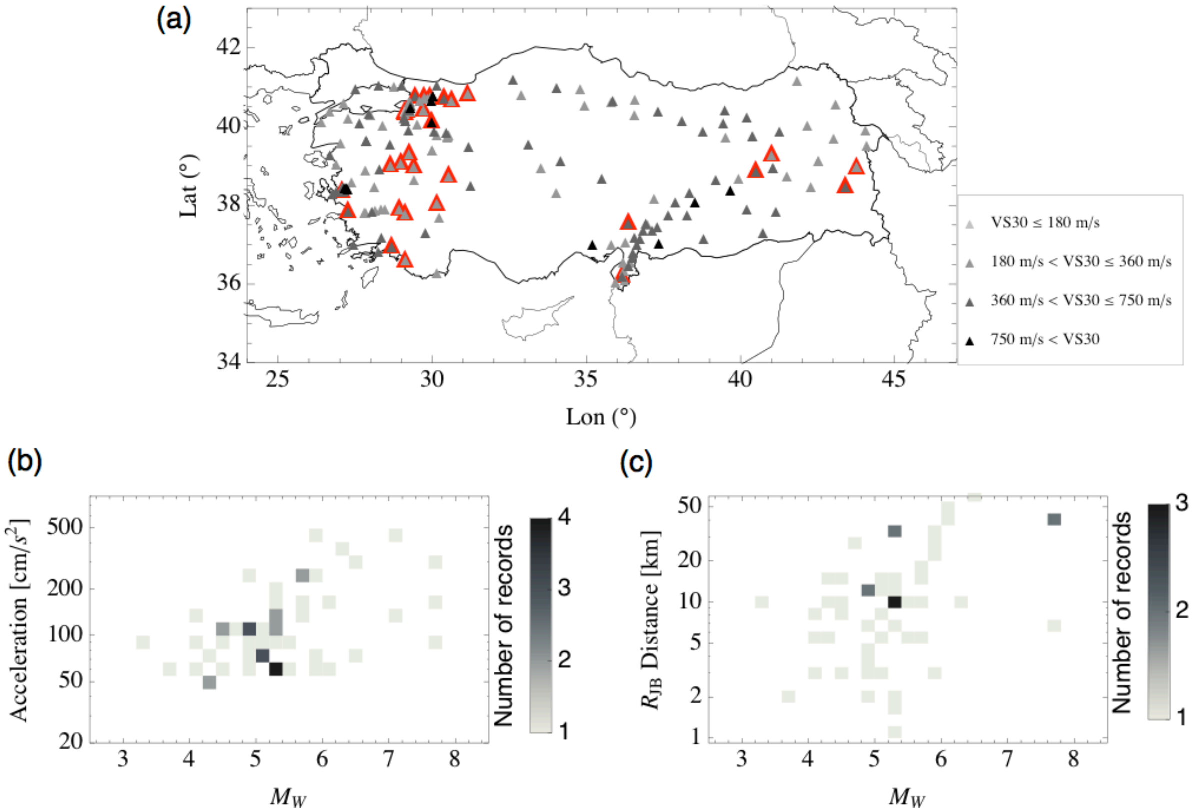

Figure 10: Location of Turkish stations and content of the final database used for testing. (a) 189 accelerometric stations, with known V_{S30} values. Triangles: stations used in the testing (V_{S30} indicated). Red Triangles: 30 stations (out of 189) that observed a median $PGA_{ROCK} \geq 50$ cm.s^{-2}. (b) Distribution of the 56 records with $PGA_{ROCK} \geq 50$ cm.s^{-2} recorded at 30 stations, in terms of PGA versus M_w of the earthquake ; (c) in terms of epicentral distance versus M_w.

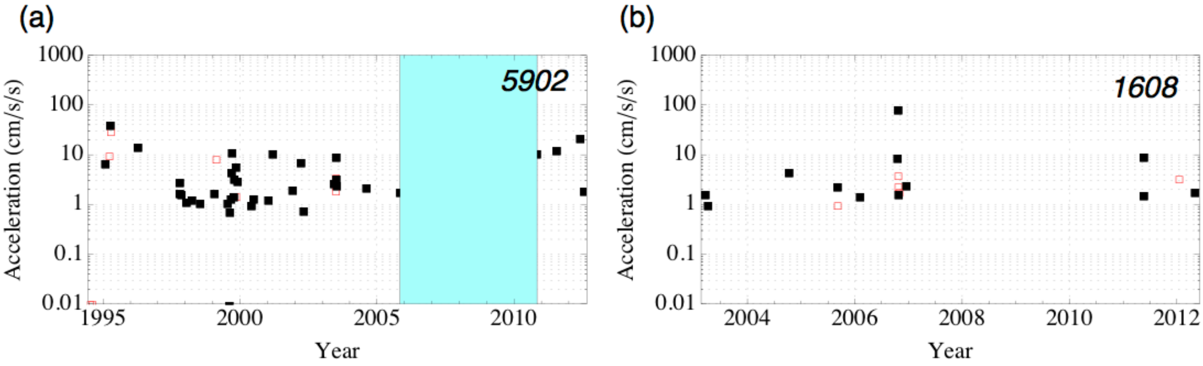

Figure 11: Identification of gaps at Turkish stations using average inter-event times (raw data, Section 4.2.1), example at two stations. (a) Time history at station 5902 (lifetime 18.03 years); shaded area : gap identified (5 years). (b) Time history at station 1608, no gap identified. Solid squares : observed PGA from mainshocks, red square : observed PGA from foreshocks/aftershocks.

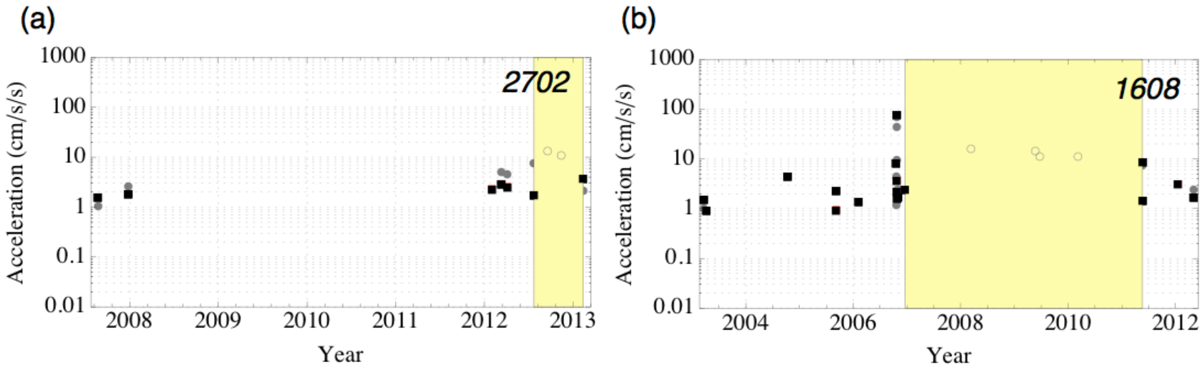

Figure 12: Identifying gaps in operating lifetime of stations (second method, Section 4.2.2), example at 2 Turkish stations (n° 2702 and n° 1608.). Black squares: observed PGA, grey circles: predicted PGA for events in the database, plain circles: predicted PGA ≥10 cm.s^{-2} missing in the database. Shaded time window: identified gap. Synthetic PGA are generated at each site by combining the Turkish earthquake catalogue and a GMPE (Akkar and Cagnan 2010).

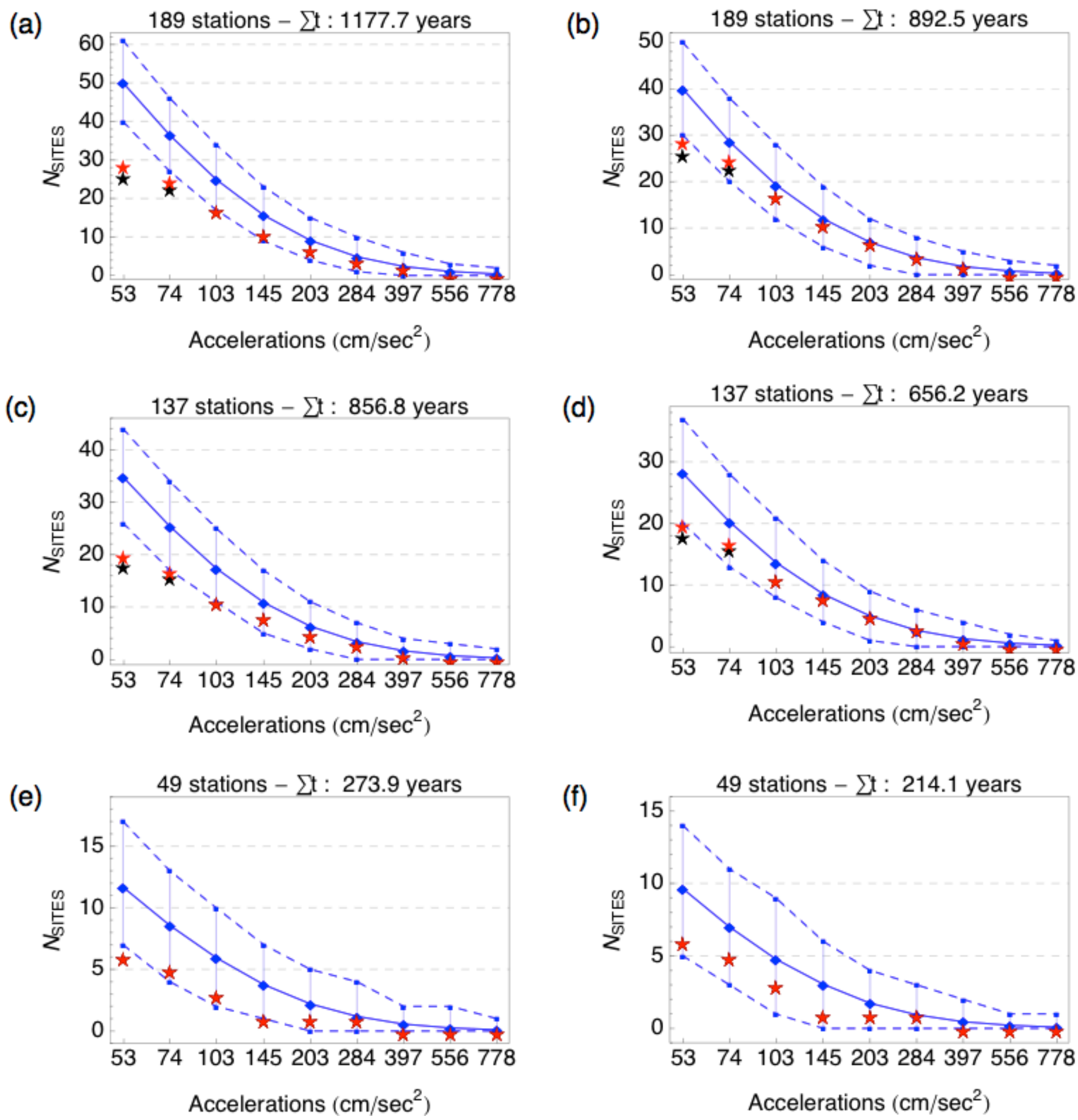

Figure 13: Testing PSHA in Turkey, comparison of the observed and predicted number of sites with exceedance at different acceleration levels, over the observation lifetime of the network. Predicted numbers are based on the SHARE hazard curves. (a) 189 stations, 1st set of corrected lifetimes (1177 years in total); (b) 189 stations, 2nd set of corrected lifetimes (889 years in total). (c) and (d): same as (a) and (b) with 137 stations with minimum inter-site distance of 10 km (856 and 656 years in total). (e) and (f): same as (a) and (b) with 49 stations with minimum inter-site distance of 60 km (274 and 214 years in total). Blue curves: median and percentiles 2.5 and 97.5 of the predicted distributions; Red stars: observations. Black stars: reduced number of sites in case of double counting (see the text).

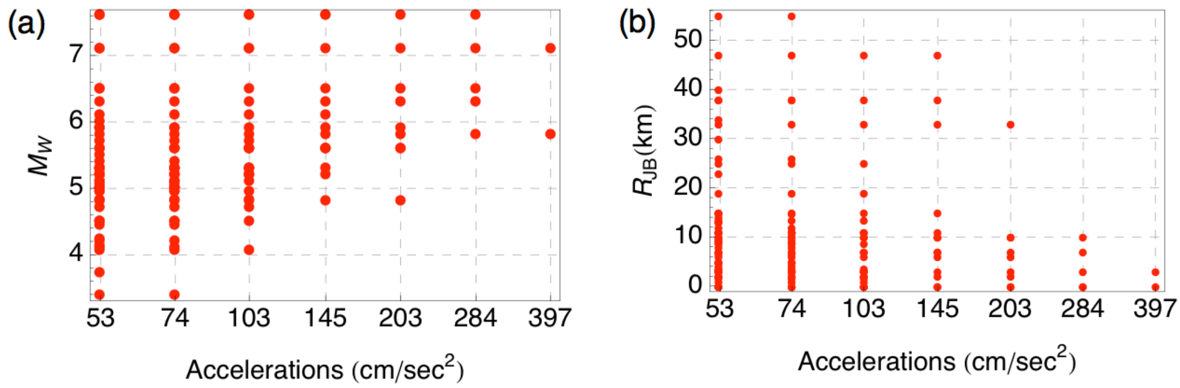

Figure 14: (a) Magnitudes of earthquakes producing ground-motion exceedances at the Turkish sites (results in Figs. 13a and 13b, considering 189 stations); (b) Joyner and Boore source-site distances of the events producing ground-motion exceedances. All events producing the threshold exceedance are reported, thus the same event can be reported for different thresholds.

Appendix A: Input parameters for applying Akkar and Çağnan (2010) GMPE

The ground-motion prediction equation developed by Akkar and Çağnan (2010) is used to predict accelerations at the sites. The earthquake catalogue used is a combination of the catalogue used in SHARE and of the KOERI catalogue for the most recent period ($M_w \geq 4.0$). The GMPE has been developed from Turkish data, using earthquakes with magnitudes M_w 3.5 to 7.6. Predictions are performed considering the V_{S30} values of the sites. To apply the equation, the magnitude of the earthquake, the style of faulting, and the Joyner and Boore source-to-site distance (R_{JB}) are required. R_{JB} is assumed equal to epicentral distance for earthquakes with M_w lower than 5.5. For earthquakes with M_w higher than 5.5, most R_{JB} distances are taken from the RESORCE database (Akkar et al. 2014). If not in RESORCE, R_{JB} is estimated from the nodal plane and an estimate of the fault width and length (scaling relations, Leonard 2010). For some earthquakes, two nodal planes are possible, then the nodal plane is deduced from the location of the earthquake on the faulting map of Turkey (Bozkurt 2001). If M_w is not available in RESORCE, following Akkar et al. (2014) a magnitude is looked for in international earthquake catalogues (GCMT, ISC, SED-ETH). If the faulting style of M_w higher than 5.5 is not available in RESORCE, the faulting style is determined following the same approach as Akkar et al. 2010 (approaches of Frohlich & Apperson 1992, Campbell 1997). For all earthquakes with M_w lower than 5.5, the focal mechanism is assumed to be strike-slip (2/3 of the generating dataset of Akkar and Çağnan 2010 corresponds to strike slip mechanism).

Supplementary Files

Table S1: List of the 62 rock RAP French stations used in this study.

Station Name	Latitude (°)	Longitude (°)	Original Lifetime (years)	Corrected Lifetime (years)	# of records with PGA ≥ 1 cm/s^2	Maximum recorded PGA (cm/s^2)
ANTF	43.564	7.123	8.6	3.0	2	2.6
ARBF	43.492	5.332	11.7	4.3	1	1.6
CAGN	43.667	7.146	8.1	3.8	6	2.8
ESCA	43.831	7.374	7.8	6.1	3	2.9
IRJO	43.630	5.660	15.6	15.6	1	5.8
IRPV	43.803	5.759	14.1	0.8	2	11.8
IRSE	44.530	6.780	6.7	6.7	1	2.0
MENA	43.784	7.489	12.5	7.9	18	16.1
NBOR	43.690	7.301	10.6	10.6	3	3.8
OCCD	45.319	3.699	8.0	5.4	1	1.0
OCMN	46.328	2.589	5.7	5.7	1	2.4
OCSJ	46.051	2.733	7.9	5.2	2	3.1
OGAG	44.788	6.540	16.1	6.9	2	2.3
OGCH	45.589	5.933	14.1	5.1	3	1.8
OGGM	45.204	6.117	16.6	7.3	1	1.7
OGLE	45.533	6.473	13.6	13.0	1	4.5
OGMA	45.774	5.535	12.3	10.4	7	15.7
OGAN	45.892	6.136	14.4	9.6	1	1.2
OGMO	45.208	6.685	14.8	10.6	8	9.0
OGMU	45.195	5.727	14.5	9.0	4	1.4
OGSI	46.057	6.756	15.4	12.1	18	27.7
OGTB	46.319	6.596	12.5	12.5	5	2.9
OGTI	45.494	6.925	13.5	13.5	17	6.2
PYAD	43.097	-0.428	7.9	6.6	220	100.9
PYAS	43.012	0.797	9.1	9.1	4	2.9
PYAT	43.094	-0.713	7.7	6.7	63	22.6
PYBA	42.474	3.117	9.3	6.0	3	2.4
PYBE	42.819	1.951	7.3	5.9	3	1.6
PYCA	43.024	0.183	7.9	5.6	127	84.6
PYFE	42.814	2.507	10.1	9.3	5	3.3
PYLL	42.453	2.065	7.6	5.3	2	10.1
PYLO	43.097	-0.049	7.4	6.3	20	26.5
PYLS	42.860	-0.008	10.0	8.7	34	40.8
PYOR	42.783	1.507	8.8	8.0	7	2.7
PYPM	42.416	2.439	10.6	7.9	1	6.8
PYP1	43.156	-1.241	6.8	6.8	1	0.93
PYPR	42.614	2.429	7.6	5.4	3	1.9
PYPT	43.009	3.033	9.9	9.9	1	2.1
QUIF	47.910	-3.160	6.2	2.2	1	2.0
SAOF	43.986	7.553	16.3	13.5	12	117.9
SMFF	46.600	-0.130	6.3	6.3	4	2.4
STBO	47.861	7.262	11.1	5.4	10	10.9
STET	44.260	6.929	12.1	9.5	25	6.6
STFL	47.112	6.563	11.3	3.6	5	22.6

STMU	48.584	7.766	9.9	3.6	28	28.1
STRB	47.723	7.341	5.7	3.0	7	8.1
STSM	48.215	7.159	11.6	8.7	4	25.4
BAIF	50.059	4.208	2.8	2.8	0	†
BRGM	43.237	5.438	9.7	9.7	0	†
UBBR	48.358	-4.562	3.5	3.5	0	†
UBNA	47.156	-1.637	2.8	2.8	0	†
UBVA	47.645	-2.746	2.9	2.9	0	†
CALF	43.753	6.922	15.8	12.0	0	†
IRIS	44.190	7.050	6.6	6.6	0	†
OCOL	45.676	3.636	6.0	6.0	0	†
OCOR	45.798	3.028	7.4	6.5	0	†
OCSF	45.034	3.097	4.0	4.0	0	†
OGBB	44.281	5.259	12.2	12.2	0	†
OGCA	43.732	5.672	15.1	6.5	0	†
PYFO	42.968	1.607	10.6	10.6	0	†
PYLI	43.002	1.136	9.3	9.3	0	†
RUSF	43.941	5.484	10.5	5.2	0	†

† maximum recorded PGA is lower than our database minimum threshold (1 cm/s²)

Table S2: List of 189 Turkish accelerometric stations considered in this study

Station ID	Latitude (°)	Longitude (°)	V_{S30} (m/s)	Observation time window	Original duration T (yrs)	T_{COR1} (yrs)	T_{COR2} (yrs)	Maximum recorded PGA (cm/s²)	# of records with PGA≥ 50 cm/s²	Maximum PGA_{ROCK} (cm/s²)	# of records with PGA_{ROCK}≥ 50 cm/s²
301	30.53	38.78	226	1998.3 2013.1	14.87	14.87	9.19	103.4	1	82.5	1
905	27.27	37.86	369	1986.4 2013.1	26.72	6.97	10.25	113.9	7	91.5	4
1201	40.50	38.90	529	1997.5 2011.7	14.15	14.15	12.64	388.3	2	358.6	2
1206	41.01	39.29	356	2007.7 2012.6	4.99	4.99	4.99	143.9	1	119.4	1
1606	29.12	40.36	301	2003.2 2013.1	9.89	9.89	6.52	169.1	1	139.6	1
1608	29.18	40.41	366	2003.2 2012.3	9.12	9.12	4.70	83.0	1	66.4	1
1609	29.17	40.43	229	2003.3 2013.0	9.75	9.75	6.68	78.9	1	59.9	1
1612	29.72	40.44	197	1999.6 2000.6	1.02	1.02	0.78	106.4	1	88.3	1
2002	29.11	37.81	356	1994.3 2012.4	18.17	18.17	13.94	165.4	2	136.5	1
2007	28.92	37.93	233	2003.3 2012.5	9.25	6.18	5.18	114.5	3	90.9	2
3102	36.16	36.21	470	1981.5 2006.1	24.64	11.68	11.27	143.1	2	122.9	2
3506	27.08	38.39	771	1977.9 2013.1	35.20	5.69	5.69	221.1	2	223.7	2
1101	29.98	40.14	901	2006.8 2011.5	4.74	4.74	4.74	87.4	1	96.2	1
4106	29.45	40.79	701	1999.6 2013.0	13.39	13.39	5.13	183.4	1	182.6	1
4107	29.93	40.76	305	1999.7 2013.0	13.32	2.65	2.65	448.7	1	444.1	1
4113	29.73	40.78	300	2010.4 2013.0	2.58	2.58	2.58	97.9	1	76.8	1
4304	29.40	38.99	343	2006.8 2012.8	6.02	6.02	3.71	98.1	3	76.9	1
4305	28.98	39.09	259	2006.8 2012.8	6.01	6.01	2.78	196.2	5	170.5	4

4306	29.25	39.34	304	2010.6	2012.8	2.22	2.22	2.20	73.7	1	56.4	1
4504	28.65	39.04	336	2006.8	2013.0	6.22	6.22	6.22	288.2	3	261.2	2
4604	36.36	37.57	611	1997.1	2012.6	15.50	15.50	15.15	265.2	2	253.9	2
4803	29.12	36.63	248	2007.5	2012.5	4.97	4.97	3.97	177.0	1	154.9	1
302	30.15	38.06	198	1995.7	2013.1	17.40	17.40	5.33	295.4	12	318.5	9
4804	28.69	36.97	372	1985.9	2008.5	22.60	22.60	11.71	108.3	2	86.0	2
5401	30.38	40.74	412	1994.5	2012.5	18.06	18.06	18.04	261.8	6	228.5	5
5402	30.62	40.67	272	2000.6	2009.3	8.73	8.73	5.51	87.4	1	67.2	1
6501	43.40	38.50	363	1995.1	2013.2	18.06	18.06	4.64	187.0	1	159.6	1
6503	43.77	38.99	293	1997.8	2012.3	14.51	14.51	1.52	174.0	2	144.6	1
1607	29.10	40.39	176	2003.2	2012.9	9.68	9.68	7.88	190.1	2	190.9	1
8101	31.15	40.84	282	1999.6	2007.1	7.47	7.47	6.12	455.6	2	466.1	2
1801	32.88	40.81	348	1977.8	2006.5	28.76	6.37	6.36	62.8	1	48.9	0
3401	29.01	41.06	595	1995.1	2010.8	15.65	15.65	15.54	50.8	1	47.3	0
502	35.85	40.67	443	1995.9	2006.9	10.99	10.99	10.99	57.8	1	46.7	0
2301	39.19	38.67	407	1995.0	2011.5	16.52	16.52	14.82	55.0	1	44.7	0
4902	42.53	39.14	311	1997.8	2012.2	14.40	14.40	1.18	55.9	1	42.1	0
907	28.47	37.91	301	2003.6	2012.5	8.92	8.92	4.15	54.8	1	40.9	0
4302	30.00	39.42	243	1998.2	2007.7	9.54	9.54	8.92	54.7	1	39.4	0
3502	27.23	38.46	270	1995.8	2007.9	12.10	12.10	12.03	54.0	1	39.4	0
1601	29.08	40.23	249	2003.3	2013.0	9.75	9.75	9.75	53.5	1	38.6	0
1006	28.00	40.33	321	2000.6	2013.0	12.38	12.38	4.90	50.4	1	37.3	0
3409	28.76	41.03	283	2010.8	2012.8	2.04	2.04	2.04	50.3	1	36.1	0
6512	43.76	38.99	293	2012.3	2013.1	0.74	0.74	0.32	†	0	†	0
4906	42.53	39.14	311	2012.5	2012.7	0.25	0.25	0.25	†	0	†	0
1007	27.94	40.34	417	2003.3	2003.5	0.24	0.24	0.24	†	0	†	0
2902	39.44	40.12	612	2011.7	2012.1	0.35	0.35	0.35	†	0	†	0
402	44.09	39.55	271	2006.0	2007.0	0.97	0.97	0.34	†	0	†	0
3801	35.50	38.69	407	2008.9	2009.0	0.17	0.17	0.17	†	0	†	0
902	27.80	37.85	271	2003.7	2004.0	0.28	0.28	0.28	†	0	†	0
5801	38.11	40.17	413	2011.7	2012.0	0.31	0.31	0.31	†	0	†	0
6004	37.33	40.39	376	2012.5	2013.0	0.50	0.50	0.50	†	0	†	0
1001	27.86	39.65	662	1997.7	2008.5	10.76	10.76	9.72	†	0	†	0
4802	27.44	37.03	747	1999.2	2008.5	9.37	9.37	9.31	†	0	†	0
1701	26.40	40.14	192	1997.4	2013.0	15.61	15.61	15.61	†	0	†	0
2501	41.26	39.90	375	1994.9	2009.1	14.19	14.19	12.73	†	0	†	0
1613	29.23	39.92	401	2006.8	2013.1	6.34	6.34	6.34	†	0	†	0
2401	39.51	39.74	314	1993.1	2011.9	18.88	18.88	13.32	†	0	†	0
1502	30.22	37.70	294	1998.2	2012.4	14.29	14.29	13.80	†	0	†	0
4401	38.34	38.35	481	1994.5	2013.0	18.52	18.52	18.50	†	0	†	0
5902	27.52	40.98	409	1994.5	2012.6	18.03	13.03	18.03	†	0	†	0
3510	27.04	38.41	313	2010.6	2013.1	2.56	2.56	2.54	†	0	†	0
3701	34.04	41.01	362	1999.4	2011.6	12.21	12.21	11.78	†	0	†	0
901	27.84	37.84	311	1998.2	2002.1	3.87	3.87	3.87	†	0	†	0
1009	28.63	39.58	561	2006.8	2013.0	6.22	6.22	6.22	†	0	†	0
4810	28.24	36.84	393	2011.3	2013.0	1.78	1.78	1.73	†	0	†	0

3503	26.89	39.07	193	2006.8	2013.0	6.22	6.22	6.15	†	0	†	0
1604	29.13	40.18	457	1997.8	2001.5	3.68	3.68	3.67	†	0	†	0
3516	26.89	38.37	460	2010.8	2013.1	2.30	2.30	2.28	†	0	†	0
3524	27.11	38.50	459	2010.9	2013.1	2.28	2.28	2.26	†	0	†	0
3511	27.26	38.42	827	2010.8	2013.1	2.30	2.30	2.30	†	0	†	0
2603	30.45	39.88	629	2006.9	2012.5	5.58	5.58	5.58	†	0	†	0
6401	29.40	38.67	285	1998.2	2012.5	14.32	14.32	13.80	†	0	†	0
3530	27.22	38.45	270	2010.3	2013.1	2.81	2.81	2.79	†	0	†	0
3523	26.77	38.33	414	2010.8	2013.1	2.30	2.30	2.28	†	0	†	0
4811	28.69	36.97	372	2012.3	2013.1	0.87	0.87	0.87	†	0	†	0
4901	41.50	38.76	315	1994.7	2012.2	17.53	17.53	6.42	†	0	†	0
3521	27.08	38.47	145	2010.9	2013.1	2.28	2.28	2.26	†	0	†	0
3520	27.21	38.48	875	2010.8	2013.0	2.20	2.20	2.20	†	0	†	0
3519	27.11	38.45	131	2010.8	2013.1	2.29	2.29	2.27	†	0	†	0
3514	27.16	38.48	836	2010.8	2013.1	2.29	2.29	2.29	†	0	†	0
3525	27.11	38.37	745	2010.8	2013.1	2.30	2.30	2.30	†	0	†	0
4501	27.38	38.61	340	1998.2	2011.4	13.21	13.21	12.03	†	0	†	0
104	35.81	37.02	223	1998.5	2011.5	13.00	13.00	3.68	†	0	†	0
1003	27.86	39.65	456	2006.8	2013.0	6.19	6.19	3.35	†	0	†	0
603	33.12	39.56	450	2008.2	2011.7	3.48	3.48	3.19	†	0	†	0
1014	27.64	40.11	397	1983.5	2013.0	29.51	6.22	3.46	†	0	†	0
3515	27.09	38.46	171	2010.8	2013.1	2.29	2.29	2.22	†	0	†	0
1208	41.05	38.97	485	1997.7	2007.2	9.45	9.45	5.90	†	0	†	0
2602	30.50	39.79	326	2006.8	2012.9	6.07	6.07	3.66	†	0	†	0
201	38.27	37.76	391	2008.0	2013.0	5.03	5.03	5.03	†	0	†	0
4606	37.14	37.39	484	2004.5	2012.9	8.35	8.35	8.16	†	0	†	0
3512	27.15	38.40	468	2011.0	2013.1	2.16	2.16	2.16	†	0	†	0
3522	27.20	38.44	249	2010.8	2013.1	2.29	2.29	2.22	†	0	†	0
3513	27.17	38.46	196	2010.8	2013.0	2.20	2.20	2.13	†	0	†	0
2606	30.50	39.75	346	2010.6	2012.9	2.26	2.26	2.26	†	0	†	0
3518	27.14	38.43	298	2010.8	2013.0	2.21	2.21	2.10	†	0	†	0
4505	28.28	38.94	629	2012.3	2012.8	0.52	0.52	0.52	†	0	†	0
2406	40.38	39.78	417	2003.3	2006.9	3.56	3.56	3.53	†	0	†	0
6001	36.56	40.33	324	1999.4	2013.2	13.80	13.80	13.80	†	0	†	0
4506	28.12	38.48	273	2007.9	2012.6	4.75	4.75	4.75	†	0	†	0
904	28.05	37.86	367	2003.3	2007.3	4.04	4.04	3.79	†	0	†	0
908	28.34	37.91	267	2003.3	2008.0	4.75	4.75	4.75	†	0	†	0
4301	29.99	39.43	267	2006.8	2012.3	5.53	5.53	5.53	†	0	†	0
909	28.15	37.88	355	2003.3	2012.6	9.32	9.32	9.06	†	0	†	0
1615	29.29	40.42	349	2003.2	2011.4	8.17	8.17	8.17	†	0	†	0
8002	36.56	37.19	430	2010.9	2012.9	2.07	2.07	2.07	†	0	†	0
4111	29.59	40.68	300	2010.4	2013.0	2.65	2.65	2.65	†	0	†	0
4105	29.97	40.67	289	2008.2	2012.5	4.32	4.32	4.32	†	0	†	0
2601	30.53	39.81	231	2006.8	2011.5	4.73	4.73	3.51	†	0	†	0
2404	38.77	39.91	413	2011.7	2012.9	1.22	1.22	1.22	†	0	†	0
4801	28.36	37.21	468	2007.8	2012.7	4.84	4.84	2.76	†	0	†	0

309	31.24	38.53	387	2007.3	2012.5	5.22	5.22	5.22	†	0	†	0
910	27.80	37.85	271	2010.8	2012.5	1.76	1.76	1.76	†	0	†	0
4603	36.93	37.58	466	1995.3	2004.2	8.92	8.92	8.92	†	0	†	0
1005	26.69	39.31	387	2006.8	2013.0	6.22	6.22	6.22	†	0	†	0
4112	29.84	40.72	352	2010.4	2013.0	2.65	2.65	2.65	†	0	†	0
208	37.65	37.79	469	2011.2	2013.0	1.78	1.78	1.78	†	0	†	0
2701	36.64	37.03	421	1994.0	2012.7	18.71	18.71	7.27	†	0	†	0
4502	27.82	38.91	292	2007.6	2012.9	5.30	5.30	1.23	†	0	†	0
2405	40.39	39.78	320	1992.2	2003.1	10.87	10.87	5.87	†	0	†	0
4608	36.84	37.38	390	2006.3	2012.9	6.56	6.56	6.56	†	0	†	0
2607	30.15	39.82	274	2006.8	2011.4	4.58	4.58	4.58	†	0	†	0
1616	29.26	40.45	572	2004.4	2011.4	7.01	7.01	5.10	†	0	†	0
1603	29.13	40.18	457	2006.8	2013.0	6.22	6.22	6.22	†	0	†	0
4605	37.20	38.20	315	1996.9	2001.5	4.63	4.63	4.63	†	0	†	0
2307	39.93	38.70	329	2011.4	2013.1	1.72	1.72	1.72	†	0	†	0
2604	30.51	39.77	296	2006.8	2012.3	5.54	5.54	1.04	†	0	†	0
5904	27.12	40.61	225	2012.2	2013.0	0.83	0.83	0.83	†	0	†	0
4607	37.30	37.49	671	2006.3	2012.9	6.60	6.60	6.60	†	0	†	0
4403	37.89	38.10	654	1996.8	2007.0	10.15	10.15	10.15	†	0	†	0
3105	36.51	36.80	618	2004.6	2012.9	8.28	8.28	8.28	†	0	†	0
1301	42.28	38.50	273	1997.4	2011.8	14.39	14.39	2.02	†	0	†	0
3109	36.41	36.58	272	2004.6	2012.9	8.28	8.28	3.09	†	0	†	0
1904	34.94	40.55	193	2008.8	2012.9	4.11	4.11	2.63	†	0	†	0
4104	29.97	40.68	757	2010.7	2012.5	1.77	1.77	1.77	†	0	†	0
4110	30.15	41.07	380	2010.4	2012.5	2.14	2.14	2.14	†	0	†	0
1614	28.39	40.03	265	2006.8	2012.3	5.54	5.54	5.54	†	0	†	0
1610	29.51	40.07	252	2012.3	2013.0	0.73	0.73	0.73	†	0	†	0
1013	27.02	39.59	223	1983.5	2013.0	29.51	29.51	5.17	†	0	†	0
6301	38.80	37.17	652	2008.5	2010.7	2.20	2.20	2.20	†	0	†	0
4601	36.98	37.54	346	2004.5	2012.9	8.41	8.41	5.00	†	0	†	0
703	30.15	36.30	299	2000.8	2012.4	11.63	11.63	11.63	†	0	†	0
604	33.52	38.96	291	2008.2	2011.4	3.20	3.20	3.20	†	0	†	0
2703	37.35	37.06	758	2008.7	2012.8	4.12	4.12	4.12	†	0	†	0
3104	36.49	36.69	688	2004.6	2012.9	8.28	8.28	8.28	†	0	†	0
3101	36.16	36.21	470	2006.1	2013.1	6.97	6.97	2.35	†	0	†	0
4102	30.03	40.78	1013	2010.7	2013.0	2.27	2.27	2.27	†	0	†	0
2702	36.73	37.18	599	2007.6	2013.1	5.47	5.47	4.91	†	0	†	0
1102	30.05	39.90	407	2006.8	2011.5	4.73	4.73	4.73	†	0	†	0
7701	29.31	40.56	375	2004.4	2013.0	8.65	8.65	8.65	†	0	†	0
4701	40.72	37.33	709	2008.7	2012.6	3.93	3.93	3.93	†	0	†	0
1605	29.10	40.27	495	2003.2	2012.5	9.25	9.25	5.72	†	0	†	0
3111	36.22	36.37	338	2005.6	2012.7	7.15	7.15	2.77	†	0	†	0
3107	36.18	36.58	310	2004.5	2012.7	8.18	8.18	1.53	†	0	†	0
7801	32.62	41.20	703	2000.1	2001.7	1.53	1.53	1.53	†	0	†	0
1211	41.05	38.97	463	2011.8	2012.7	0.93	0.93	0.93	†	0	†	0
7702	29.27	40.59	359	2004.8	2011.4	6.61	6.61	4.90	†	0	†	0

8001	36.27	37.08	350	2005.1	2012.9	7.86	7.86	1.31	†	0	†	0
1703	27.26	40.23	304	2012.3	2013.0	0.74	0.74	0.74	†	0	†	0
1710	26.67	40.42	286	2012.4	2013.0	0.64	0.64	0.64	†	0	†	0
2302	39.68	38.39	907	2011.5	2012.7	1.19	1.19	1.19	†	0	†	0
1017	27.86	39.65	662	2012.2	2013.0	0.83	0.83	0.83	†	0	†	0
7201	41.15	37.87	450	2010.2	2012.5	2.27	2.27	2.27	†	0	†	0
1505	29.78	37.32	367	2012.4	2013.0	0.57	0.57	0.57	†	0	†	0
1611	29.72	40.43	251	2004.4	2013.0	8.65	8.65	0.68	†	0	†	0
1617	29.30	40.49	1598	2004.4	2013.0	8.65	8.65	1.99	†	0	†	0
4404	38.52	38.12	1380	2011.5	2012.4	0.92	0.92	0.92	†	0	†	0
2901	39.50	40.45	469	2010.2	2011.6	1.40	1.40	1.40	†	0	†	0
3501	27.17	38.46	196	1992.8	1995.1	2.24	2.24	0.69	†	0	†	0
4103	30.03	40.79	1013	2008.2	2012.5	4.32	4.32	4.32	†	0	†	0
3408	28.26	41.07	639	2010.8	2013.0	2.26	2.26	1.03	†	0	†	0
2608	31.18	39.52	476	2008.0	2011.4	3.42	3.42	3.42	†	0	†	0
2507	42.17	40.04	316	2012.0	2013.1	1.10	1.10	1.10	†	0	†	0
506	35.80	40.64	284	2010.8	2013.2	2.41	2.41	2.41	†	0	†	0
118	35.19	37.02	946	2008.0	2011.5	3.46	3.46	3.46	†	0	†	0
3108	36.37	36.50	539	2008.3	2012.9	4.53	4.53	4.53	†	0	†	0
3103	36.25	36.12	344	2006.1	2008.3	2.20	2.20	2.20	†	0	†	0
401	43.02	39.72	295	2007.1	2011.8	4.76	4.76	4.76	†	0	†	0
1903	34.80	40.98	255	2011.7	2012.2	0.52	0.52	0.52	†	0	†	0
7704	29.25	40.66	195	2008.2	2013.0	4.82	4.82	1.97	†	0	†	0
4001	34.16	39.16	460	2008.7	2012.8	4.03	4.03	4.03	†	0	†	0
3110	35.95	36.08	210	2004.3	2008.3	3.99	3.99	3.99	†	0	†	0
6005	36.57	40.70	327	2010.9	2013.2	2.32	2.32	2.32	†	0	†	0
7703	29.28	40.65	278	2010.4	2012.3	1.90	1.90	1.90	†	0	†	0
2101	40.20	37.93	519	2010.2	2010.7	0.53	0.53	0.53	†	0	†	0
6901	40.21	40.26	519	2011.0	2011.8	0.82	0.82	0.82	†	0	†	0
801	41.84	41.18	350	2011.1	2013.0	1.94	1.94	1.94	†	0	†	0
3601	43.08	40.60	270	1995.8	1997.8	2.10	2.10	2.10	†	0	†	0
7601	44.05	39.93	216	1998.1	1998.7	0.67	0.67	0.67	†	0	†	0
6801	34.03	38.35	208	2008.9	2011.5	2.59	2.59	2.59	†	0	†	0

T: time elapsed between the 1st and the last record available at the station
T_{COR1}: corrected observation time window, gaps identified using method 1 (inter-event times)
T_{COR2}: corrected observation time window, gaps identified using method 2 (synthetic accelerations)
PGA: recorded PGA at the site (176 soil sites, 13 rock sites)
PGA_{ROCK}: estimated PGA at V_{S30}=750m/s, inferred from the recorded PGA and the site-amplification model of Sandikkaya et al. (2013)
† maximum recorded PGA is lower than our database minimum threshold (50 cm/s^2)

Table S3: 56 observations with PGA_{750}≥50 cm/s/s recorded at the stations of the Turkish network and used in the testing

Record ID (yyyymmddhhmmss)	M_W	Lat (°)	Long (°)	Depth (km)	Style of Faulting	Station ID	R_{JB} (km)	PGA_{ROCK} (cm/s/s)	PGA (cm/s/s)
19771209155338	5.1	38.35	27.23	26.9	Strike-Slip	3506	13.4	115.5	114.2
19771216073729	5.6	38.39	27.19	4.0	Normal	3506	6.0	223.7	221.1
19810630075909	4.7	36.17	35.89	63.0	Normal	3102	25.0	111.4	130.4
19851206223530	5.1	36.97	28.85	8.9	Strike-Slip	4804	14.7	86.8	108.3
19860601064310	4.2	37.96	27.39	10.0	Strike-Slip	0905	15.5	50.4	64.7
19921106190809	6.0	38.09	27.05	15.0	Strike-Slip	0905	40.0	59.3	75.7
19941113065601	5.3	36.91	29.05	10.0	Normal	4804	30.0	64.0	81.2
19950314000651	4.1	37.88	29.07	5.0	Normal	2002	8.7	136.5	165.4
19950926145809	4.9	38.03	30.17	18.8	Strike-Slip	0302	3.3	119.8	138.0
19950927141554	5.0	38.07	30.20	11.3	Strike-Slip	0302	4.1	102.5	122.0
19951001155713	6.5	38.12	30.11	10.0	Normal	0302	0.0	318.5	295.4
19951001180256	5.3	38.05	30.16	28.4	Strike-Slip	0302	1.7	137.2	153.6
19951001211442	4.4	38.00	30.08	16.8	Strike-Slip	0302	8.9	102.7	122.2
19951003073811	4.9	37.97	30.08	11.0	Strike-Slip	0302	11.9	79.8	99.7
19951005161521	5.0	38.00	30.14	11.8	Strike-Slip	0302	6.7	93.8	113.7
19951006161558	4.8	38.03	30.14	34.5	Strike-Slip	0302	3.6	106.6	125.8
19970122175720	5.7	36.21	35.97	20.0	Normal	3102	19.0	122.9	143.1
19980404161747	5.2	38.1	30.1	19.3	Normal	0302	2.0	112.9	131.7
19990817000139	7.6	40.76	29.96	17.0	Strike-Slip	1612	38.0	88.3	106.4
19990817000139	7.6	40.76	29.96	17.0	Strike-Slip	4106	38.0	182.6	183.4
19990817000139	7.6	40.76	29.96	17.0	Strike-Slip	8101	7.0	322.2	337.4
19990913115529	5.8	40.76	30.05	15.0	Strike-Slip	4107	3.0	444.1	448.7
19991111144127	5.6	40.79	30.22	14.3	Strike-Slip	5401	10.0	228.5	261.8
19991112165721	7.1	40.82	31.20	11.2	Strike-Slip	8101	0.0	466.1	455.6
20000402185742	4.5	40.86	30.29	8.8	Strike-Slip	5401	15.0	62.1	76.8
20000823134129	5.5	40.68	30.72	15.0	Strike-Slip	5402	5.0	67.2	87.4
20020203071129	6.5	38.58	31.16	10.0	Normal	0301	55.0	80.9	103.4
20021214010248	4.8	37.52	36.20	10.0	Normal	4604	13.0	57.3	62.0
20030501002708	6.3	38.95	40.40	15.0	Strike-Slip	1201	10.0	358.6	388.3
20030501093555	4.1	38.87	40.54	9.1	Strike-Slip	1201	5.0	83.0	94.3
20030723045609	5.3	38.05	28.89	28.3	Normal	2007	11.0	82.7	105.7
20030726083654	5.4	38.06	28.91	21.3	Normal	2007	11.0	90.9	114.5
20060208040743	4.5	40.71	30.41	6.8	Normal	5401	3.0	109.6	132.2
20060208052427	4.1	40.71	30.38	4.1	Strike-Slip	5401	3.3	63.1	78.0
20061024140025	5.2	40.42	28.99	7.9	Normal	1609	13.0	59.9	78.9
20061024140026	5.2	40.42	28.99	7.9	Normal	1608	14.0	66.4	83.0
20061024140038	5.2	40.42	28.99	7.9	Normal	1606	11.0	139.6	169.1
20061024140041	5.2	40.42	28.99	7.9	Normal	1607	7.0	190.9	190.1
20070825220536	5.3	39.29	41.03	15.8	Strike-Slip	1206	1.0	119.4	143.9
20090217052819	5.2	39.13	29.05	15.5	Normal	4504	34.0	63.9	82.9
20101111200800	5.0	37.86	27.37	14.0	Normal	0905	8.0	79.3	99.6

20101208215052	3.4	37.83	27.36	13.5	Strike-Slip	0905	9.2	91.5	113.9
20110120020936	4.2	40.73	29.77	12.5	Strike-Slip	4113	5.0	76.8	97.9
20110519201522	5.9	39.14	29.08	12.0	Normal	4304	26.0	76.9	98.1
20110519201522	5.9	39.14	29.08	12.0	Normal	4306	23.0	56.4	73.7
20110519201522	5.9	39.14	29.08	12.0	Normal	4504	33.0	261.2	288.2
20110524025528	3.7	39.10	28.96	5.0	Strike-Slip	4305	2.0	63.5	84.7
20110528054717	5.1	39.12	29.05	9.2	Normal	4305	5.0	75.0	98.0
20110627211358	5.0	39.11	29.03	10.4	Normal	4305	3.0	80.1	103.7
20110711160912	4.5	40.25	29.95	5.0	Normal	1101	11.0	96.2	87.4
20111023104120	7.1	38.75	43.46	16.0	Reverse	6503	0.0	144.6	174.0
20111109192333	5.6	38.43	43.23	8.0	Strike-Slip	6501	15.0	159.6	187.0
20120503152025	5.3	39.18	29.09	3.1	Normal	4305	11.0	170.5	196.2
20120610124415	6.1	36.34	28.67	40.0	Strike-Slip	4803	47.0	154.9	177.0
20120707070745	4.2	40.82	30.41	6.6	Strike-Slip	5401	9.6	53.3	66.3
20120722092602	4.8	37.55	36.38	7.6	Normal	4604	2.0	253.9	265.2

Lat and Lon : Latitude and longitude of the earthquake

Depth: Depth of the earthquake in kilometres.

R_{JB} distances are mainly from RESORCE database

PGA: recorded PGA at the site (176 soil sites, 13 rock sites)

PGA_{ROCK}: estimated PGA at V_{S30}=750m/s, inferred from the recorded PGA and the site-amplification model of Sandikkaya et al. (2013)