SITE INSTRUMENTATION USEFULNESS: EXAMPLE OF APPLICATION OF EMPIRICAL OF SITE EFFECT ESTIMATION IN LOW SEISMICITY CONTEXT AND IMPLEMENTATION RECOMMANDATIONS

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Executive Summary

Implementing an instrumentation that allows to record real seismic events is an essential complement to numerical simulation approaches of site effect assessment. Such "empirical" approaches allow for example to implement "site / reference" amplification measurements (SSR) or other quantification of the site-specific transfer function (coda, duration...) and to evaluate the attenuation of high frequency of seismic signals (characterized by the "kappa" parameter) that is mandatory for host-to-target adjustments.

While these approaches seem readily available in areas of high seismicity (Japan, Greece ...), where the data are both numerous and correspond to earthquakes of moderate to high magnitude, they are more difficult to implement in areas of low seismicity, as in metropolitan France. Indeed, earthquakes we can record in these area are few and correspond to remote earthquakes (earthquakes with medium or high magnitude but far from the site of interest), or regional and local earthquakes, but with low to moderate magnitude.

The fact that the French metropolitan area is in low to moderate seismic context is sometime a feature that is adduced to avoid implementing seismic instrumentation. The first objective of this study, conducted within the SIGMA/WP3 and Cashima programs, is to provide some elements to evaluate the usefulness of such site instrumentation, especially in the aim of site effect evaluation. A second objective is to give some recommendations for the implementation of instrumentation.

In this study, we basically worked with a database, recorded from February 2012 to January 2014 on several stations, located on "Site A", located in the South-East of France, in an area of low to moderate seismicity. The number of useable events (that is to say that provide a good signal to noise ratio) obtained from this quite short duration database is very high in comparison with what we expected before implementing the instrumentation. On "Site A", this allowed to evaluate very robust amplification function, based on SSR analysis, with more than one hundred of usable events in the intermediate frequency range. It seems also possible to evaluate the κ_0 parameter, which is more difficult to assess because it needs a high frequency analysis, where S/N is usually lower.

We also tried to extrapolate the very encouraging results (in terms of amount of usable recorded events) from "Site A" to other sites that have a higher ambient noise level and/or a lower seismicity. Even if the strictness of the approach we used to comment this attempt of extrapolation could be widely discussed, it seems to us at least possible to conclude that on these other sites, an instrumentation implantation may produce in very few years of recording a quite appreciable number of events that could be used to assess the site effect amplification, even if the estimation of κ_0 parameter, with the current classical methods, appear more difficult due to the high level of noise at high frequency and / or a too low local seismicity.

We also provide some recommendations for instrumentation implementation, emphasizing the fact that the use of velocimeters will lead to far better results than the use of accelerometers. We also strongly recommend the use of continuous recordings.

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1 INTRODUCTION AND OBJECTIVES

In case of unfavorable geological and geomorphological local features, site effects can significantly amplify ground motions. It is possible to quantify these site effects by numerical simulation with a given seismic scenarios (source location, magnitude ...) and a description of geological, geophysical and geotechnical environment. However, these simulations cannot alone address the whole issue of site effect evaluation. Indeed, the geological features will probably never be described with the required resolution to characterize the seismic motion up to high frequency. It is therefore essential to complete the simulations with seismic records of real earthquakes. Such "empirical" approaches allow:

- to access "site / reference" measurement or other quantification of the site-specific transfer function (coda, duration, ...),
- to consider the use of methods by empirical Green's functions,
- to evaluate the attenuation of high frequency of seismic signals (characterized by the "kappa" parameter).

While these approaches seem readily available in areas of high seismicity (Japan, Greece ...), where the data are both numerous and correspond to earthquakes of moderate to high magnitude, they are more difficult to implement in areas of low seismicity, as in metropolitan France. Indeed, earthquakes we can record in these area are few and correspond to remote earthquakes (earthquakes with medium or high magnitude but far from the site of interest), or regional and local earthquakes, but with low to moderate magnitude.

The fact that the French metropolitan area is in low to moderate seismic context is sometime a feature that is adduced to avoid implementing seismic instrumentation.

The first objective of this study, conducted within the SIGMA/WP3 and Cashima programs, is to provide some elements to evaluate the usefulness of such site instrumentation, especially in the aim of site effect evaluation. A second objective is to give some recommendations for the implementation of instrumentation.

As it is very difficult –or even impossible– to talk about instrumentation usefulness without real data, recorded on a real site, we will present results from data recorded over a 2 years period on a real site, named “site A”. But it seems then also worth to warn what are *not* the objectives of this present report. This report does not aim to present and highlight the site effect on the “site A”. The amount of usable recorded earthquakes over a given period in a given frequency band is here more important that the value or the amplification of true kappa value on “site A”. This report neither aims to present new or “cutting edge” signal processing approaches: we will present here just a few applications with standard methods. Development on optimized methods is an ongoing work within the SIGMA and Cashima programs and will be provided later in another deliverable.

As it is difficult to draw general conclusion just with the data recorded on one site (especially due to the local noise context), we will attempt to extrapolate our results on other context on the basis of noise records, performed on several week or month, on other sites (sites B, C and D) but we will not comment the earthquake records on these complementary sites.

Before presenting the database of “Site A”, we wish to comment what seem to us the three major factors that will have an impact on the chance to get a sufficient amount of usable recorded earthquakes:

- 1. The local seismicity: obviously, higher will be the number of earthquakes that may occur at a regional scale, higher will be the chances to record valuable times histories. Nevertheless, we will see that distant earthquake can also be used.
- 2. The local level of noise (we use here the word “noise” to describe what is useless in the record and that may reduce the usable amplitude of recorded earthquakes: therefore, in the present deliverable, “ambient vibration” that are useful for other applications are included in the noise!). Indeed, the local level of noise could be very different from one location to another one. The industrial context of industrial facilities is definitely not favorable to earthquake recordings.
- 3. The frequency range of the site effect that we aim to study. This is also important because if we consider a low frequency site effect context, small EQ, even close from the site, will be unusable because they will not produce a sufficient amount of low frequency. Conversely, even distant earthquakes (but with quite high magnitude) could produces valuable records.

2 PRESENTATION OF THE “SITE A” DATABASE

“Site A” is located in the South-East of France, within the “Provence Alpes Côte d’Azur” region. On this site, we deployed an instrumentation at the beginning of the 2012 year. This instrumentation consist in a set of several broaband velocimeters and two accelerometers. In this report, we will comment results obtained on 4 sites: 2 reference sites (S01, S02) located on hard rock substratum (limestone with Vs>2000 m/s) and 2 sedimentary sites (S03 and S04), affected by site effects. The site effect present a quite high fondamental frequency (above 3 Hz).

The velocimeters are Güralp CMG6-TD instruments (30 s seismometers with integrated digitalizer: http://www.guralp.com/documents/DAS-T60-0002.pdf). The accelerometers are CMG-5TDE (also seismometers with integrated digitalizer: http://www.guralp.com/documents/DAS-050-0006.pdf). These instruments are relatively inexpensive but reliable according to our own experience. The intergrated acquisition features with 16 Gb of built-in Flash memory alow several months of 100 Hz sampling frequency acquisition in continous mode with the need of external action out of 12V DC power supply. Instruments are placed on contrete in dedicate seismic installation or burried in the soil (see Figure 1).

The material was progressively installed, starting from February 2012. This instrumentation, used within the Cashima, Sigma and now also Sinaps@ programs, is used most of time on “Site A”, but not only. On brief periods of several weeks, this material could be used for other application (for example, the whole set of velocimeters was used for the acquisition of ambient vibration arrays for the Sigma InterPacific subproject during the end of the 2013 summer). So, the acquisition period presents some gaps over the 2 year commented period.

Our choice was to perform continuous measurements with a 100 Hz sampling frequency, with both velocimeters and accelerometers. In order to constitute the EQ database, we use seismicity catalogs (CSEM, RéNass and Géoazur), with a first extraction using an automatic algorithm, then with a “manualy” check that also consists in picking P wave arrival, S wave arrival and also the end of the coda. One consequence this approach is that very local weak EQ that are not indetify by regional or national obervatory are not yet included within the database, and the completion magnitude is thus linked to the one of the three used catalogs.

Figure 1: Typical installation of a CMG6-TD broadband sensor on "site A". Top-left: the seismometers before installation; bottom-left: the seismometer buried and connected to power supply; right: the battery and seismometer are protected by a stainless steel coverage with thermal insulation, the system is powered by a solar panel.

We keep in the database EQ that are identifiable out of the noise in at least a given frequency band (roughly, a minimum signal to noise ratio of 3 at one frequency at least). Even if the frequency of the site effect of "Site A" is quite high, we kept in database EQ that present a good S/N only in very low frequency (very low for earthquake engineering purpose, here 0.25 Hz).

The first noticeable recorded event presents in the database showed in this report is the M=4.5 (MLv Renass) occurred near Jausiers (Alpes-de-Haute-Provence) on the 26th February 2012. The last one is the M=6.1 occurred in Kefalonia Island (Greece) on the 26th January 2014 (this EQ and the subsequent aftershock sequence motivated a post-seismic survey on the Kefalonia Island within the Framework on the Sinaps@ program and the instrumentation was then use for this post-seismic intervention). The instrumentation was again deployed on "Site A" for the last M 5.2 (MLv Renass) EQ occurred near Jausiers on the 7th April 2014 but this last event, likely the highest in terms on PGV on "Site A" since the beginning of 2012, is still not included in the database presented here.

This lead to a 360 events, that have been recorded from 14 to 10 000 km epicentral distances and in a range of magnitude from 1.2 to 8.4. The Figure 2 presents the map of epicenter distribution of the database. The Figure 3 gives the chronology of recordings.

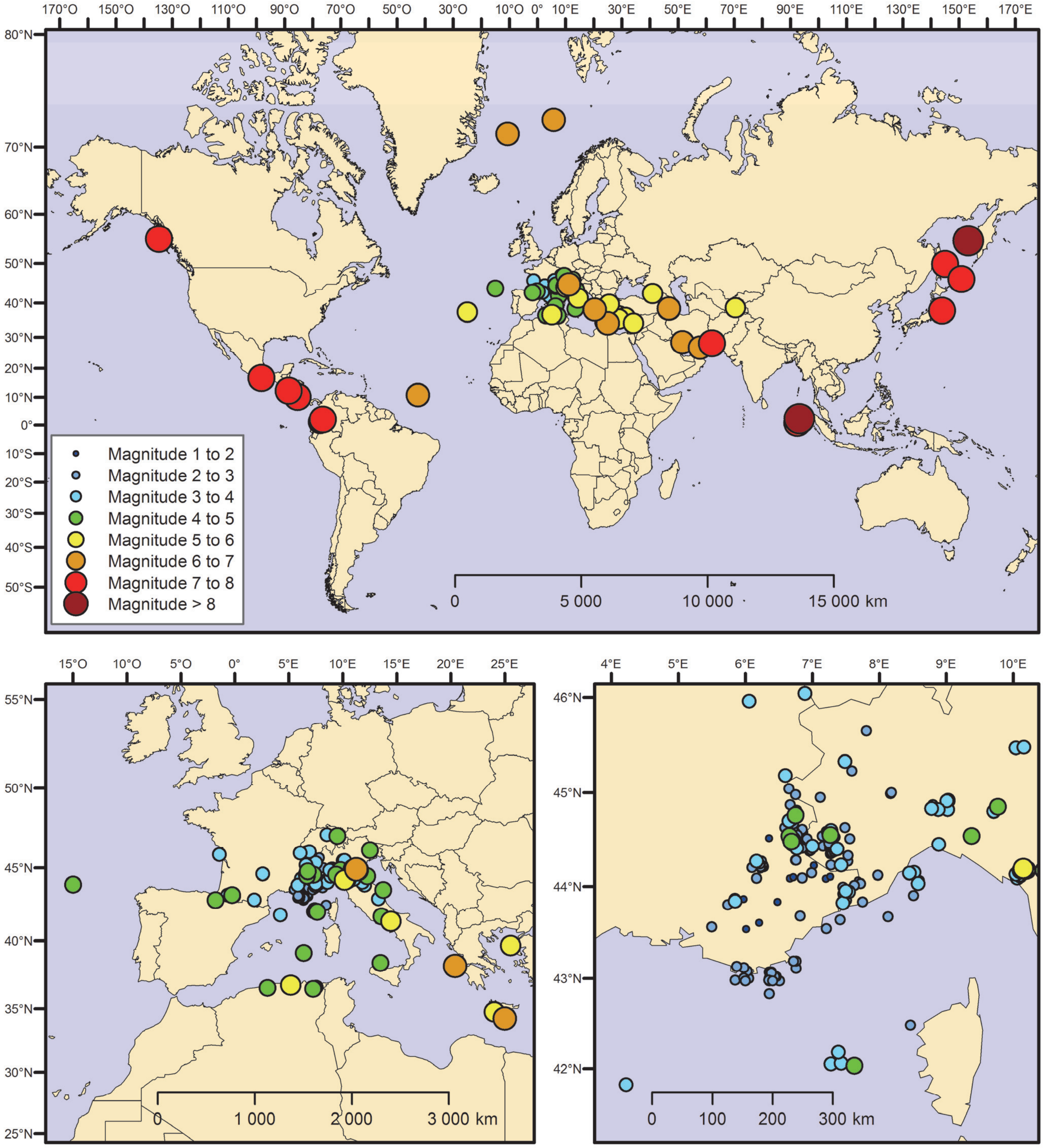

Figure 2: Maps of the epicenters of the earthquake constituting the "Site A" database from February 2012 to January 2014 at three different scales.

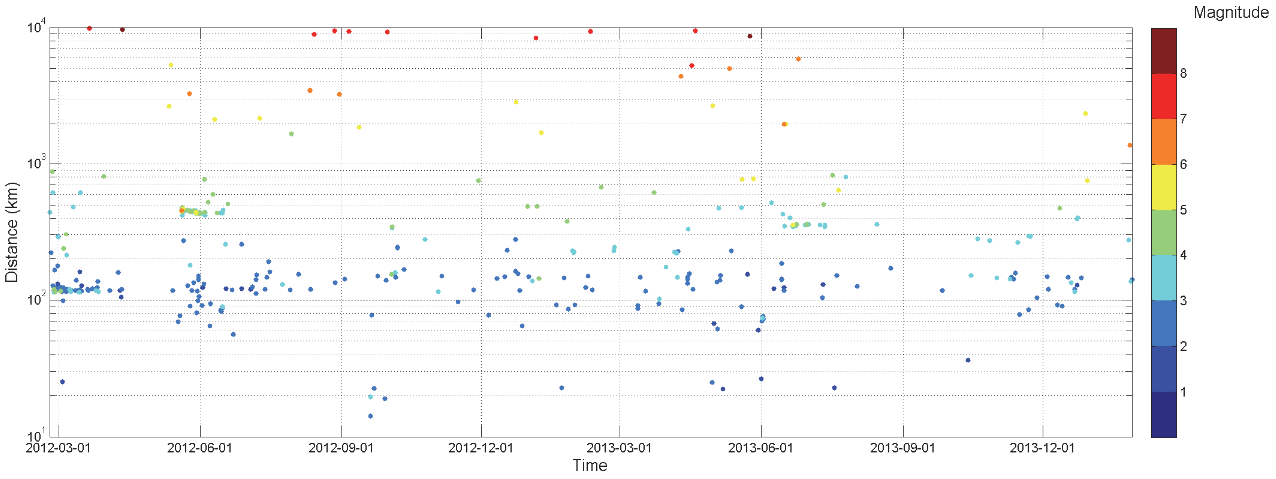

Figure 3: Chronology of seismic recording form the "Site A" database from February 2012 to January 2014.

In order to evaluate the quality of this database, it is mandatory to analyse more in details its quality in terms of signal-to-noise ratio. As the records may be usefull in different frequency band depending on the type of analysis we want to apply on it, we propose to investigate these S/N ratio from 0,25 Hz to 32 Hz by increment of a two factor.

This S/N ratio are analysed on the S wave part of time histories. If t_P is the picked arrival time of the P wave and t_S the arrival time of the S wave, then the signal time window used for a given analysis starts from t_S and goes to $t_S + 2 \times (t_S\text{-}t_P)$. The noise time window is selected few seconds before the arrival of P wave. We do not provide S/N values when the signal window is shorter that ten times the corresponding period. This explains why the EQ that have quite short epicentral distances are not included in analysis for very low frequencies. Before computing the Fourier Transform, we applied a "cosine" taper (width of 5% of the total windows) to time histories.

The results computed on the reference rock station S01 of "site A" are shown Figure 4 (where 330 events were recorded on a cumulated duration of 550 days of continuous recording). For the soil station S03 of "site A" (231 events recorded on a cumulated duration of 513 days), results are shown Figure 5. The results are presented of the height frequencies in epicentral distance / magnitude plots, where the color of points informs about the S/N ratio for four classes ($S/N < 3$, $3 \leq S/N < 10$, $10 \leq S/N < 50$, $S/N \geq 50$).

We see that the numbers of good and very good records are numerous, especially with in intermediate frequencies. For example, we get 200 events with a S/N greater that 10 at 4 Hz for S01, for EQ up to 1000 km of epicentral distance. If we look at lower frequency, the number of events with S/N > 10 are less numerous, but still appreciable. It is here surprising to see that very distant EQ (up to 10 000 km) can give noticeable S/N value below 1 Hz. At 0.5 Hz, 21 events give a S/N > 10. We also see on this figure that small magnitude EQ (eg. less that ~3.5 at 0.5 Hz) do not produce enough low frequency due to the small size of their rupture surface. At high frequency, only quite short distance events produce good S/N values. At 16 Hz for example, we get 26 events with a S/N > 10 for epicentral distance roughly lower that 200 km, which was expected due to high frequency attenuation. For the S03 stations, the overall number of events with S/N > 10 is slightly lower due to a higher level of noise than in station S01.

Obviously, we stress that this number of good quality records, performed on about one year and an half in terms of cumulated days of records is high. Even though we were already convinced by the usefulness of implementation of site instrumentation, this result appears as very demonstrative and encouraging.

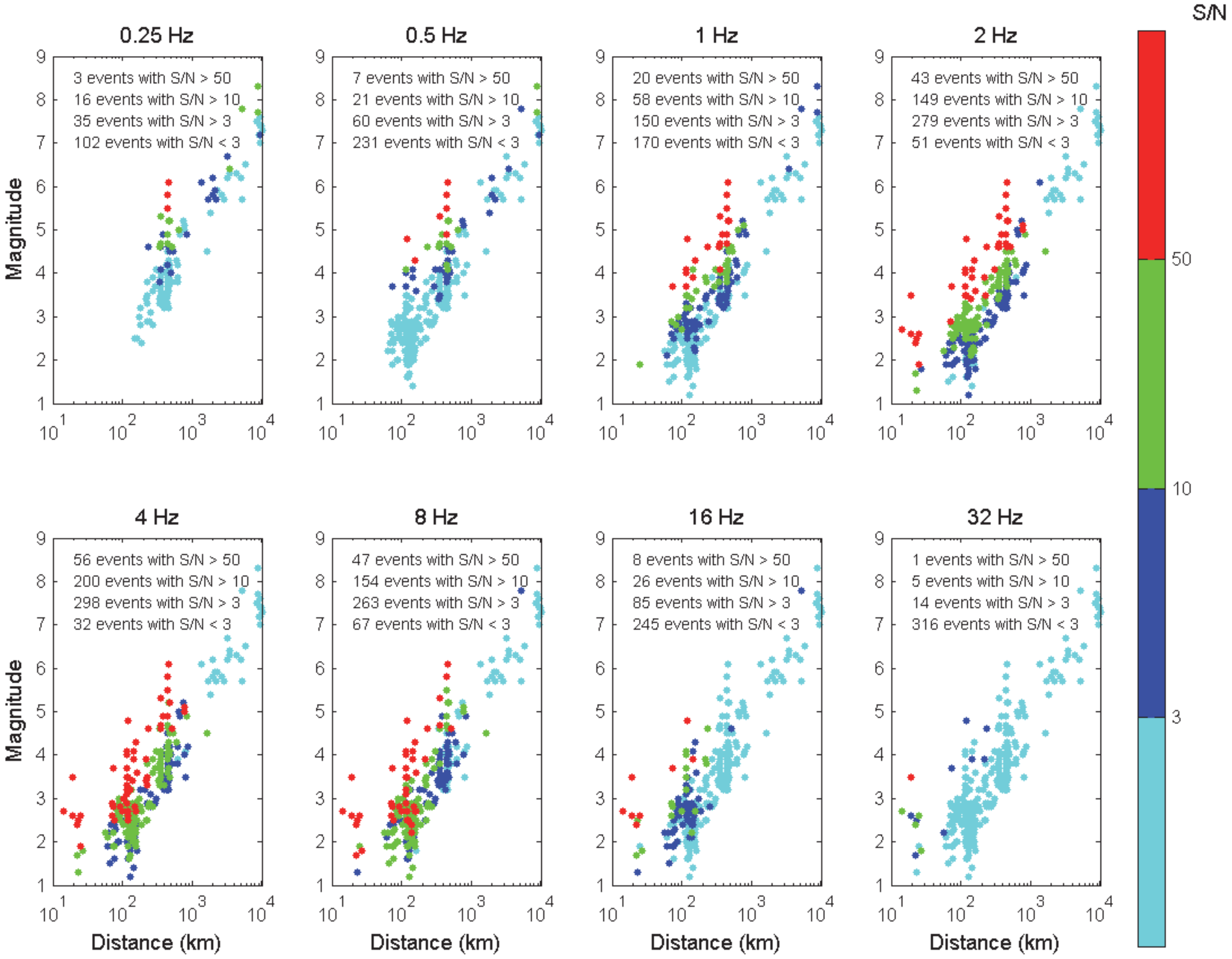

Figure 4: Evaluation of the signal to noise ratio of the 330 events recorded on a cumulated duration of 550 days of continuous recording at the rock site station S01.This analysis is performed on high frequencies from 0.25 to 32 Hz.

3 EXAMPLE OF EMPIRICAL SITE EFFECT ANALYSIS OF “SITE A”

In this section, we present a few examples of application about what could be obtained with the available database on “Site A”.

3.1 STANDARD SPECTRAL RATIO

The “Standard Spectral Ratio” (SSR) method is one of the most common approach to empirically evaluates the site effect amplification. This method consists in implementing one “reference” station, basically on rock site where we assume that there is no site effect; and another station, basically a soft site where we aim to evaluate site effect amplification. When earthquakes are recorded, we compute a spectral ratio between the “site” station and the “reference” station signals.

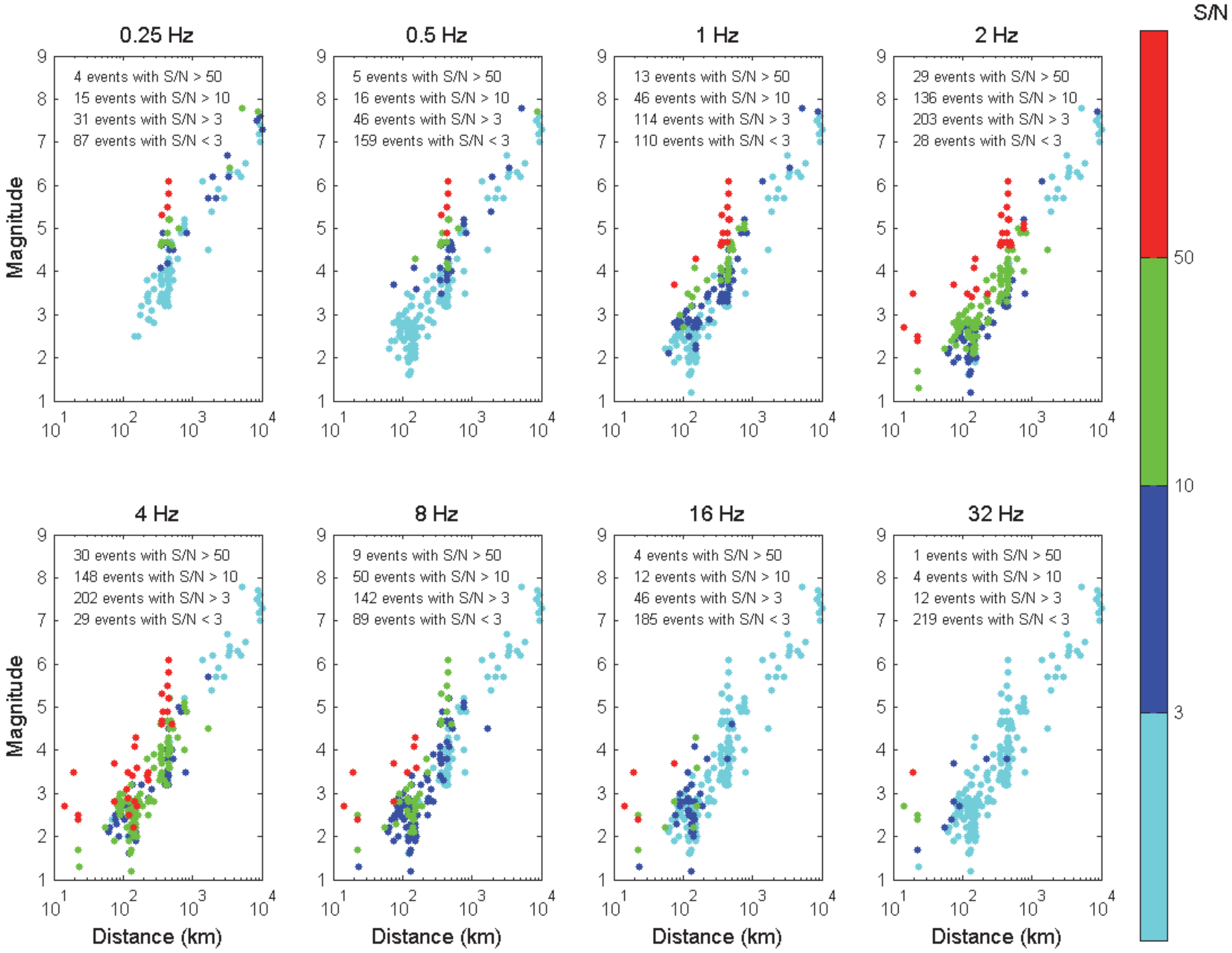

Figure 5: Evaluation of the signal to noise ratio of the 231 events recorded on a cumulated duration of 513 days of continuous recording at the soil site station S03.This analysis is performed on high frequencies from 0.25 to 32 Hz.

We applied the SSR approach on all events jointly recorded on stations S01 (rock) and S03 (soil). For each EQ, we select a S wave time window (between t_S and t_S + 2 x (t_S-t_P)) and a corresponding noise time windows few seconds before the EQ signal. We then taper the time windows (cosine taper with a width of 5% of the total windows) and proceed to the spectral density computation. The spectra are slightly smoothed (with Konno and Ohmachi (1998) approach with b parameter equals to 40) and we finally comput the “site” / “reference” ratio. We in parallel compute the S/N ratios on both “site” and “reference” stations in order to indetify in which frequency band the “site” / “reference” ratio is relevant. This overall process on a “single event” is illustrated on Figure 6.

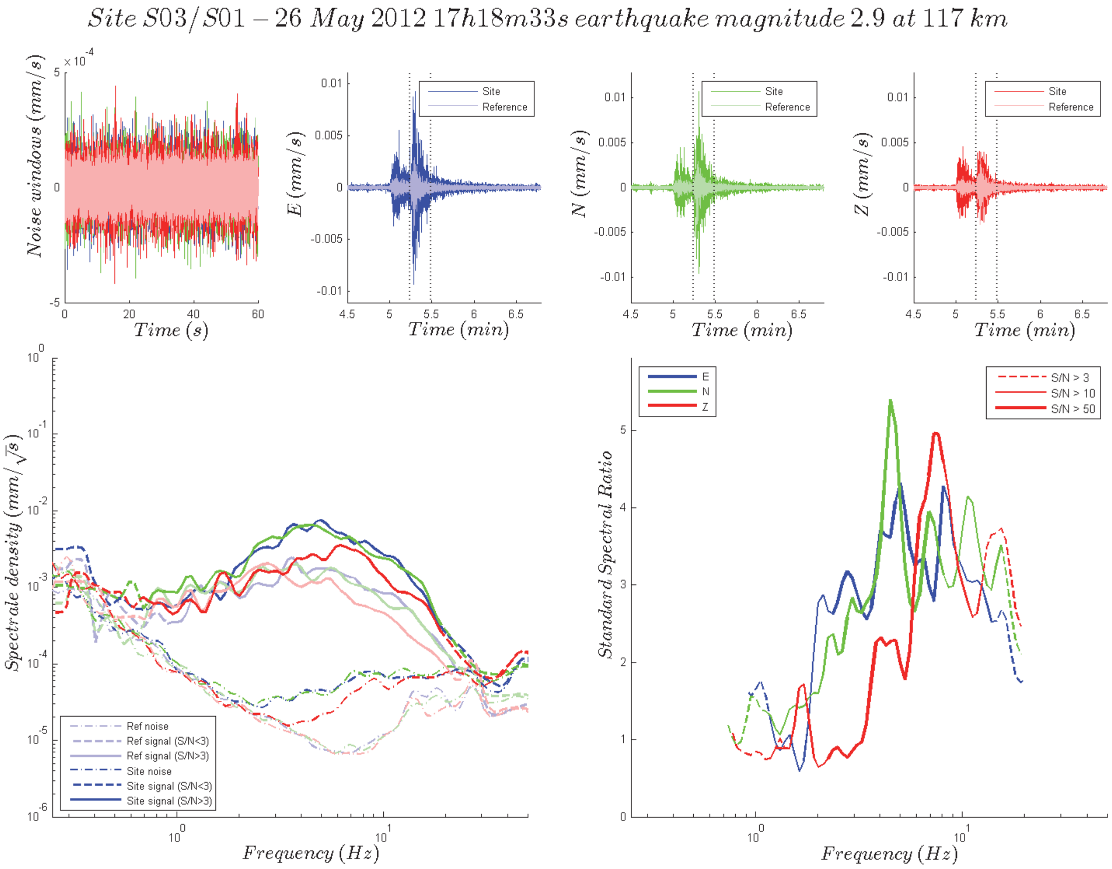

Figure 6: Example of SSR assessment for a single event. Top: time windows used to compute noise and S waves spectrum are displayed for the "site" station (dark line) and the "reference" station (light line). Bottom-left: signals spectrum (solid line) and noises spectrum (dotted line) show that significant signals is between 0.7 and 20 Hz. Bottom-right: results on the three components of the SSR computation when S/N ratio is up to 3 (dotted line), 10 (solid line) and 50 (thick line).

The synthesis of all "single event" computations is given on Figure 7. This figure gathers all SSR computations applied of 189 events recorded at both S01 and S03 during a common record period of 513 days. Only results with S/N>10 are plotted (gray points) and this allow to compute the mean amplification with associated standard deviation. We also plotted the number of events that produce one SSR value as a function of the frequency. At very low frequencies, we have about 15 events. The maximum event number is reached between 2 and 6 Hz with about 130 events. Here, the fact that the maximum site effect is in the same frequency band that the maximum "event amount" to compute mean SSR is just a coincidence. This "number of events" peak is to link to frequency band where the site noise is minimum, as we will see below.

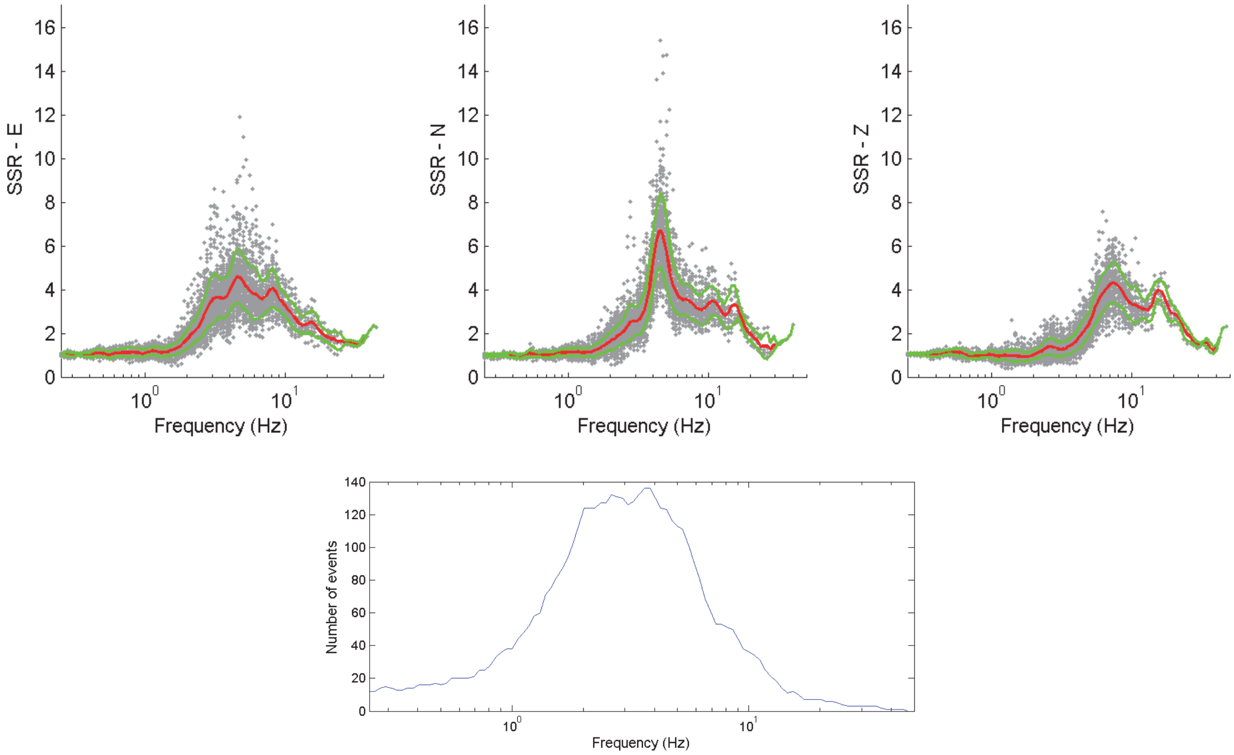

Figure 7: Top: SSR assessment between the soil "site" station S03 and rock "reference" stations S01 for the three components (total of 189 events with S/N>10 recorded in 513 days). Bottom: number of events that were used, per frequency, to compute mean SSR and associated standard deviation.

3.2 κ_0

κ_0 is now a well-known parameter, and its influence on seismic hazard evaluation may be high, especially for host-to-target adjustments. We will not describe this parameter in details here since it is widely discussed in SIGMA/WP2. In comparison with other parameters or analyses we may apply on EQ records, κ_0 evaluation has the specificity to need a "high frequency" analysis. As we saw on Figure 4, the amount of good quality events drastically deacreases at high frequency. Nevertheless, a few tens of its could may be used for this test.

As we will try to "add it the right subscript"… we will try to follow the taxonomy proposed by Ktenidou et al. (2014). κ_0 is the extrapolation to zero epicentral distance of a set of individual observations, denoted κ_r. Our attempt to evaluate κ_0 is based on the "original" method proposed by Anderson & Hough (1984), so denoted κ_{0_AS}.

In order to determine κ_{r_AS} "single event" values, we first derive our velocity times histories into accelerograms. Then, we chose a time window of the S wave (between t_S and t_S+2x(t_S-t_P)) and a corresponding noise time windows few seconds before the EQ signal. We plot the acceleration spectrum in linear scale in frequency and log scale for the spectrum. Then, we manually pick the frequency range where the spectrum decay seems "linear" in this representation scale. The Figure 8 illustrates this procedure.

Figure 9 and Figure 10 show a first attempt of κ_{r_AS} estimation for the two rock stations S01 and S02 of "Site A". These are very preliminary results that have to be refined and controled, but for the purpose of the present study, one may be able to conclude that κ_0 estimation is feasible on "Site A".

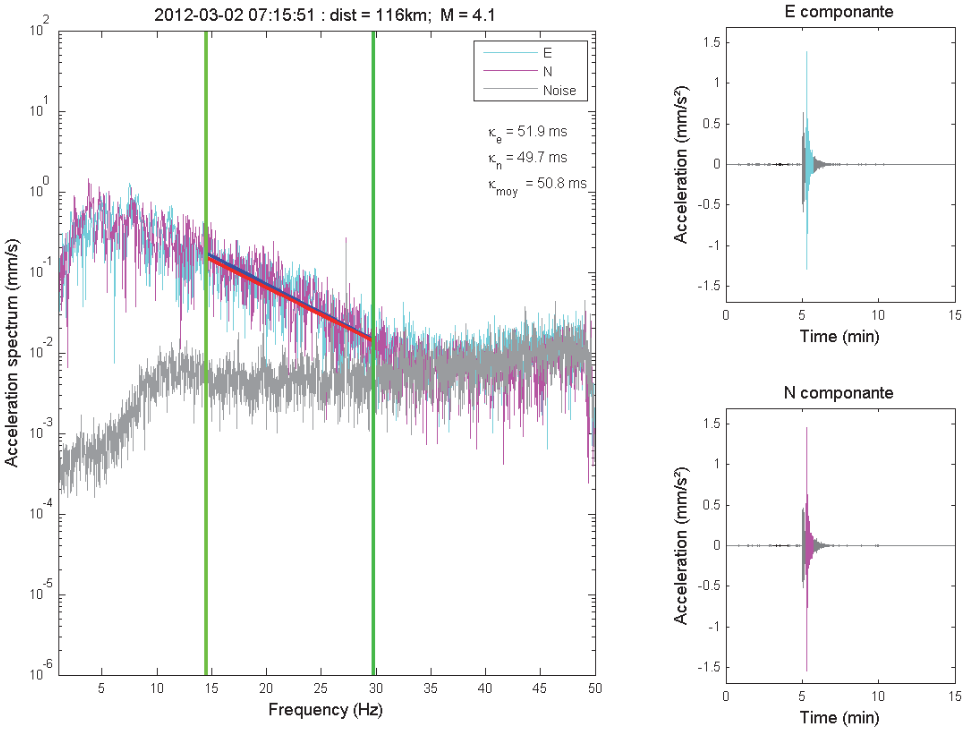

Figure 8: Example of κ_{r_AS} assessment on a single event at the rock site S01.

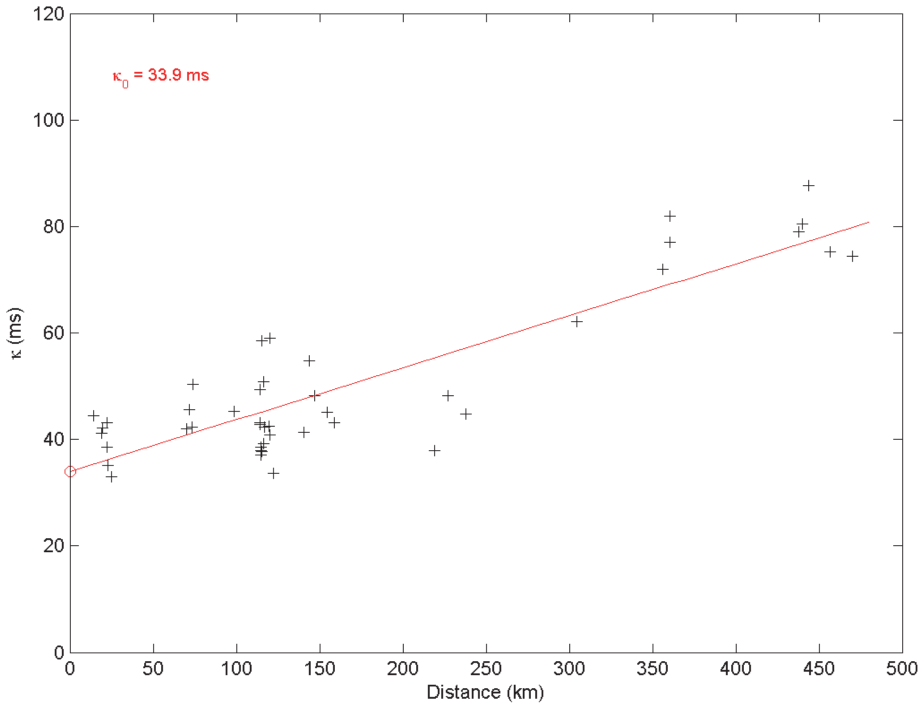

Figure 9: κ_{0_AS} extrapolated from 40 events κ_r assessment on the rock station S01 in 550 cumulated days of recording.

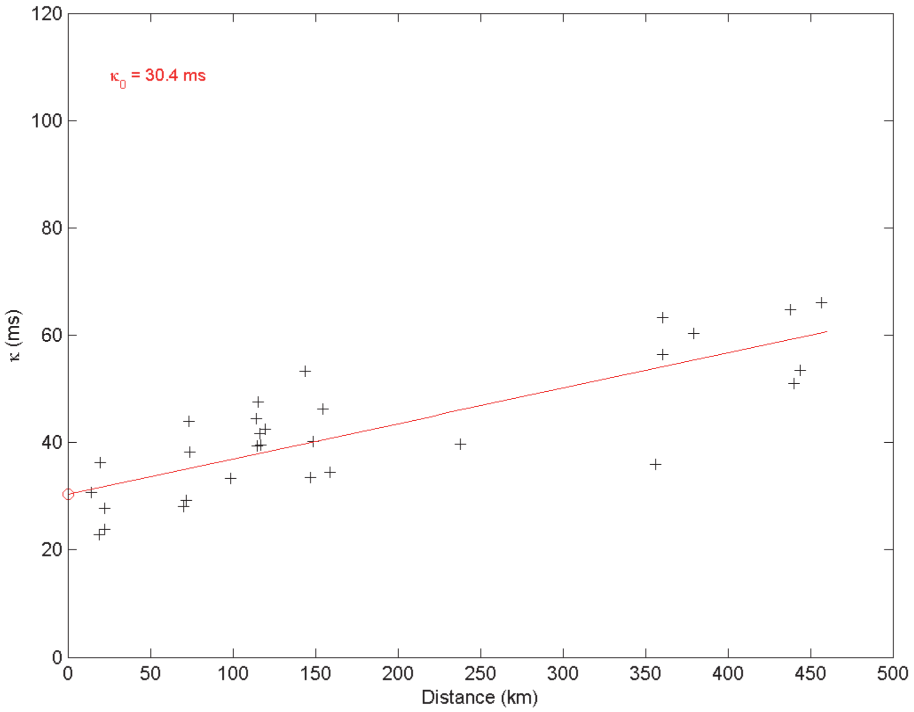

Figure 10: κ_{0_AS} *extracted from 30 events* κ_r *assessment on the rock station S02 in 469 cumulated days of recording.*

4 ATTEMPT OF “EXTRAPOLATION” TO OTHER SITES

On “Site A”, we showed that the seismic events that can be recorded on a quite short period of time are numerous and allow to get information on site effects features, even at high frequency. In order to try to extrapolate this conclusion to other, where seismicity may be lower (even if the seismicity of “Site A” is already rather low) and where the noise level may be different, we performed recordings with the same equipment on short periods (few weeks) on two other sites (“Site B” and “Site C”).

“Site B” has an overall seismicity similar to “Site A”, nay higher. We performed the noise measurements in a single point, on soil condition. The a priori environmental context is highly noisy.

“Site C” has a lower seismicity has a seismicity lower that “Site B”. We performed the noise measurements on two points, one on a rock condition, a second one on soil. Here, the a priori environmental context is surely higher that site one, but lower that “Site B”.

We will now use these recordings in terms of noise analysis. The Figure 11 compares the mean noise level computed on 5 stations (rock & soil station of “Site A”, soil station of “Site B”, rock & soil station of “Site C”). This figure confirm that “Site B” has a very high level of noise in comparison with “Site A”, from a factor 5 at low frequency (< 1 Hz) to almost a factor 100 between 4 and 8 Hz (with respect to the “Site A” rock station. “Site C” are in-between “Site A” and “Site B” in terms of noise level.

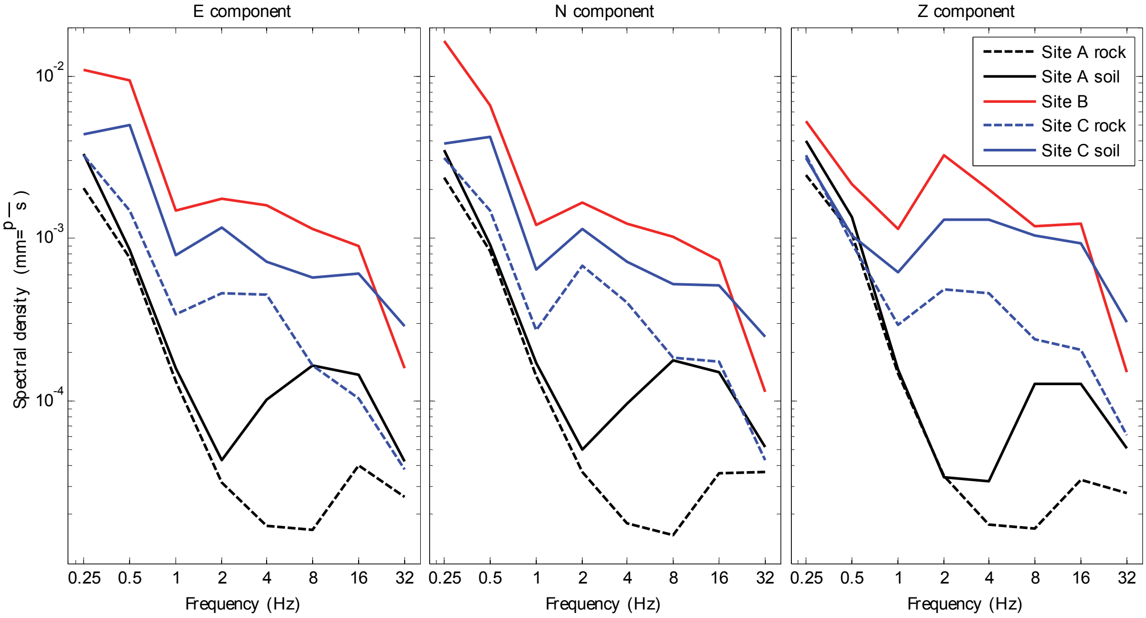

Figure 11: Comparison of noise level for Site A, B and C.

In order to have an idea of the number of records that may be expected to be record on sites B and C, we will use the noise level values recorded at site B and C and then apply them to the site A event database. This is illustrated on Figure 12 and Figure 13, using the same formalism that the one used to generate Figure 4. On these figures, in order to compute the signal to noise values, we hence use the "signal" measured for each event on site A and the "noise" measured on other sites.

Of course, the strictness of this approach suffers of many weaknesses: events are not recorded on sites B and C; we are using here mean noise values and we do not take care about the possible noise evolution (night / days, working days / WE, etc.); and above all, the seismicity of site B and C is not the same, in other word, the epicentral distance of events of the database are not the same and events that may be recorded in site B and C, close from them, are not included in the site A database.

Nevertheless, within the framework of the objective of this study, we think that this approach may at least provide some orders of magnitude of what can be expected in terms of recordable EQ on site B and C (during a given record period and taking into account local environmental conditions).

On site B (Figure 12), which has an overall seismicity (or event higher seismicity) than site A, the number of events given a good S/N ratio are logically less numerous than on site A. In low and intermediate frequency ranges, if we optimize the S/N threshold (using a value between 3 and 10), we nevertheless could use a ten of events that is yet appreciable to compute a reliable SSR ratio. However, at high frequency, the amount of records with a good S/N ratio is here too low to think about the definition of an empirical value of κ_0 in a period of few years. Here, the problem is clearly due to a noise values, not seismicity level. The station used here for site B is in soil conditions, in a very noisy environment. The κ_0 estimation is basically important on rock conditions (as close as possible of the site to be studied) for host-to-target adjustments. A rock condition station would have produce a lower level of noise that would have allowed better "statistics" of high frequency records for κ_0 estimation.

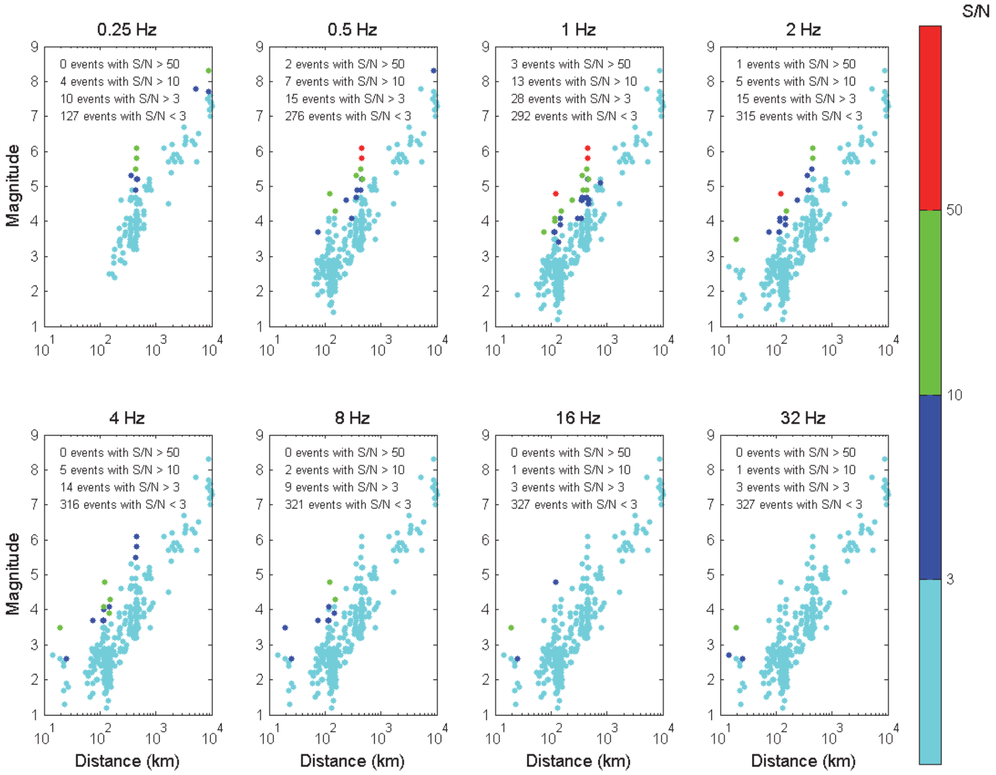

Figure 12: Evaluation attempt of potential amount of event records on "Site B" using the "Site A" database (cf. Figure 4) for event signal level and "Site B" noise level (cf. Figure 11).

On site C (Figure 13), in low and intermediate frequency (up to at least 4 Hz), the number of useable events is fair good (a ten to few tens) on both site conditions. The seismicity of site C is lower than on site A, but if we consider the epicentral distance of events that produce fair good S/N values in this frequency range and the distance between site C and A (around 100 km) we see that even if we consider the seismicity decrease, the number of usable events remains appreciable to compute a reliable SSR ratio.

However, at high frequency, the number of events possibility recorded is already low, even at rock station. Here, according to the location of site C stations, yet quite optimized in terms of noise levels, it seems difficult to reduce the overall noise level. Since these "high frequency" events correspond usually to short epicentral distances, taken here into account the lower seismicity of site C, the possible recordable EQ on a period of time of few years appears possibly too few to allow direct estimation of κ_0.

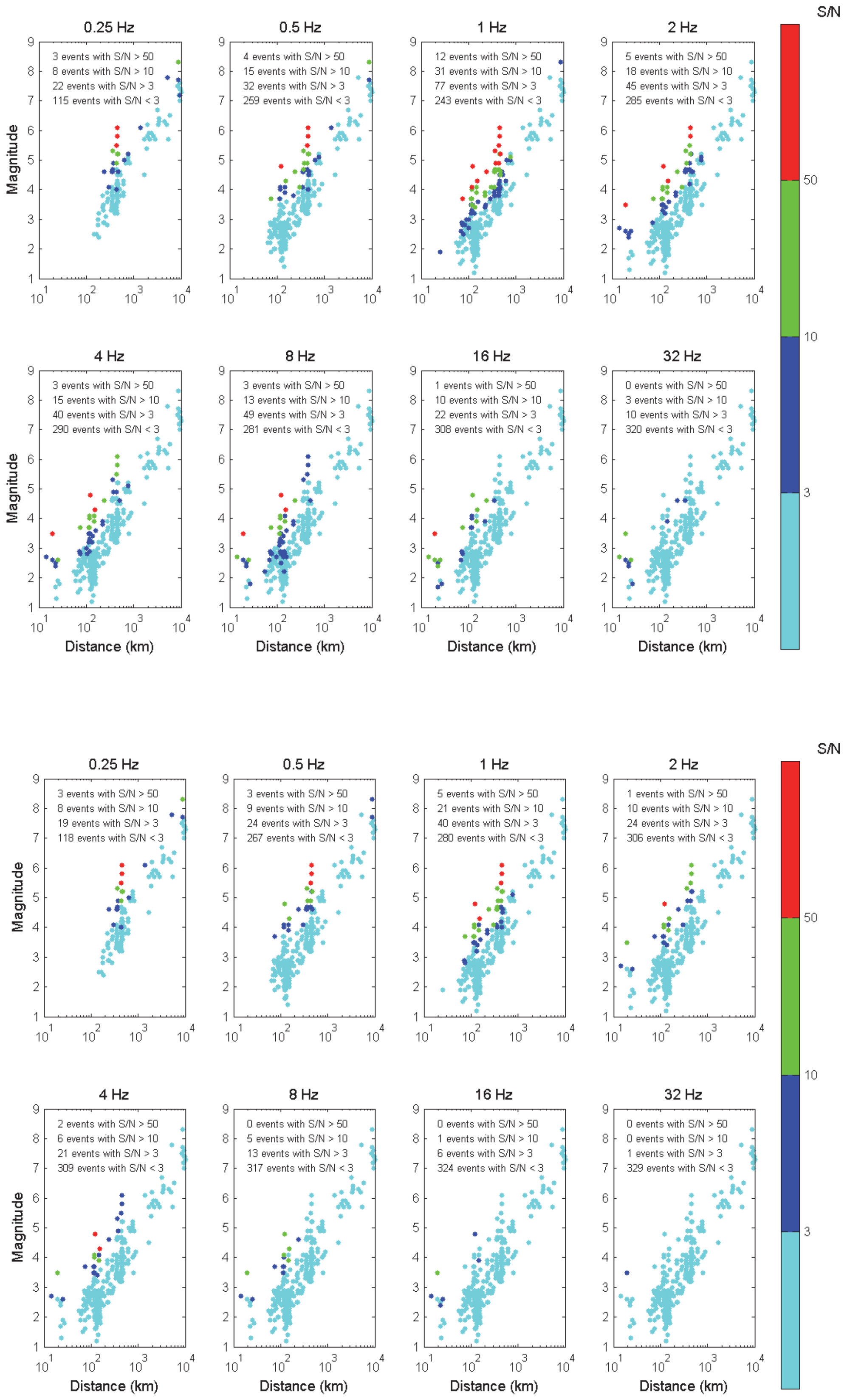

Figure 13: Evaluation attempt of potential amount of event records on "Site C": rock station (top) and soil station (bottom), using the "Site A" database (cf. Figure 4) for event signal level and "Site C" noise level (cf. Figure 11).

5 VELOCIMETERS OR ACCELEROMETERS?

The choise of the type of instrument is also an important issue. The first choice to do is: shall we prefer accelerometers or velocimeters? Accelerometers have the advantage of being able to record strong motions without saturation, but are also characterized by a quite high instrumental noise. Conversely, velocimeters have a comparatively low level of instrumental noise that allows to record very weak motions, but they will saturate (and then will be useless) for strong motions.

When we consider the instrumental equipment, linked to regulation application, that has to record times histories for “significant” earthquakes (with PGA > 0.01 g), or that has to trigger automatic safety actions in case of strong motions, the choise of accelerometers is obvious. But this “default” choice may be reconsidered in the framework of instrumental implementation that target the study of site effects.

We will now go back to “Site A” where a comparative experiment has be done on rock station S02 where both accelerometer and velocimeter reccorded simultaneously during a cumulated duration of 231 days. 101 events where recorded over this period. Figure 14 and Figure 15 give the results in terms of S/N values at different frequencies for accelerometer and velocimeter repectively. The differences between both instrument is high: up to 4 Hz, the velocimeter produced more than 10 times more events (on the same location and the same peridod) than the accelerometer. At higher frequency, the difference decreases, but the velocimeter always produces better S/N values. On the whole period of 2 years recording on “Site A”, no event was strong enough to saturate velocimeters. It is evident that the number of events we may “loose” by using accelerometers (only) due to high instrumental noise level is much more important that the number of events we may “loose” by using velocimeter (only) due to saturation. Of course, the best choice is to use both instruments, but this is an issue of overall budget and less a scientific issue.

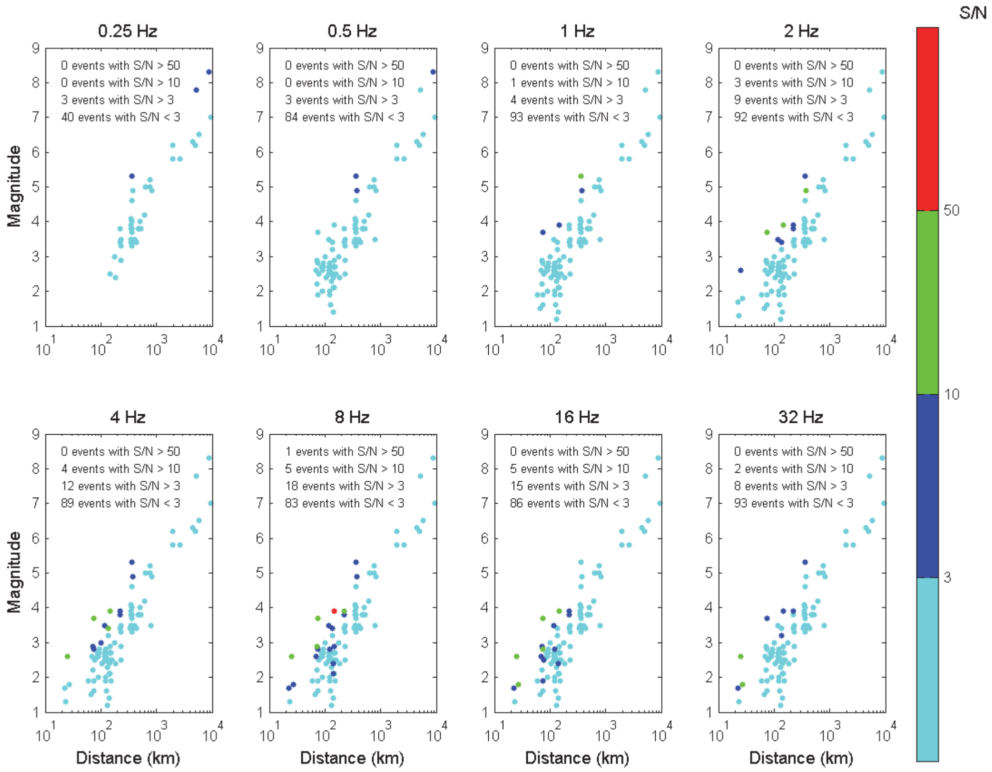

Figure 14: Evaluation of the signal to noise ratio of the 101 events recorded on a cumulated duration of 231 days of continuous recording at the rock station S02 of “Site A”. Results are from an accelerometer.

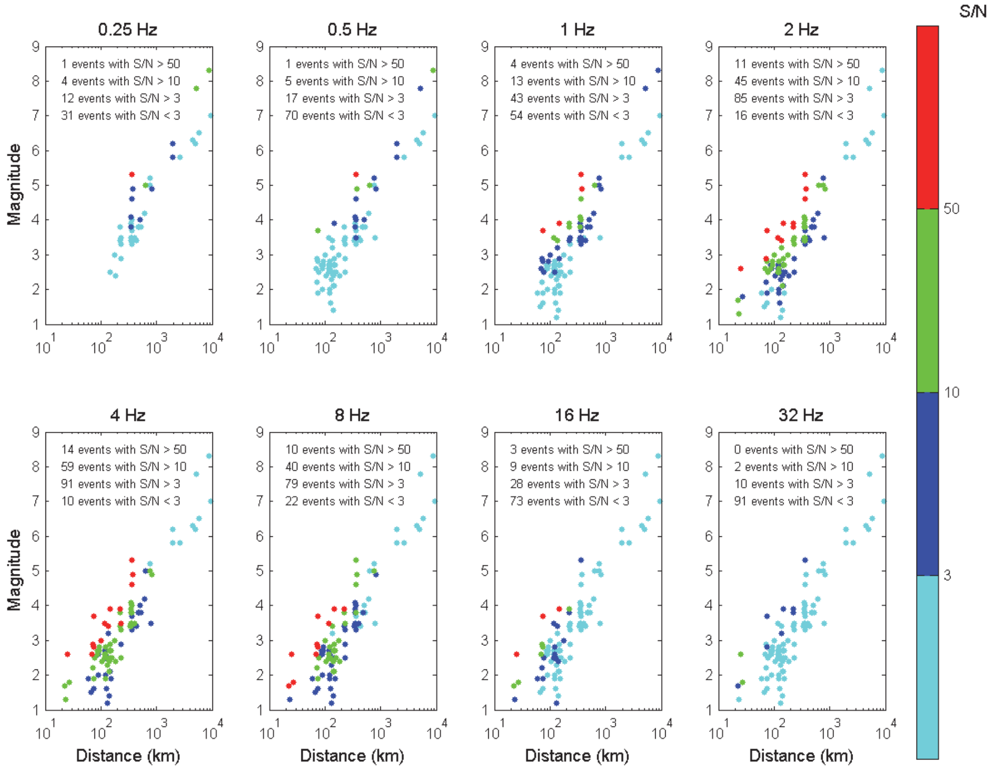

Figure 15: Evaluation of the signal to noise ratio of the 101 events recorded on a cumulated duration of 231 days of continuous recording at the rock station S02 of "Site A". Results are from a <u>velocimeter</u>.

6 CONCLUSIONS AND IMPLEMENTATION RECOMMENDATIONS

6.1 MAIN CONCLUSIONS

The implementation of a seismic instrumentation that aims to record seismic events may lead to provide some useful information about site effects (or other associated parameters like κ_0). In this study, we basically worked with a database, recorded from February 2012 to January 2014 on several stations, located on "Site A", located in the South-East of France, in an area of low to moderate seismicity.

The number of useable events (that is to say that provide a good signal to noise ratio) obtained from this quite short duration database is very high in comparison with what we expected before implementing the instrumentation. On site A, this allowed to evaluate very robust amplification function, based on SSR analysis, with more than one hundred of usable events in the intermediate frequency range. It seems also possible to evaluate the κ_0 parameter, which is more difficult to assess because it needs a high frequency analysis, where S/N is usually lower, and also needs numerous events for the extrapolation of single events κ_r values to κ_0.

We also tried to extrapolate the very encouraging results (in terms of amount of usable recorded events) from "Site A" to other sites that have a higher ambient noise level and/or a lower seismicity. Even if the strictness of the approach we used to comment this attempt of extrapolation could be widely discussed, it seems to us at least possible to conclude that on these other sites, an instrumentation implantation may produce in a very few years of recording a quite appreciable number of events that could be used to assess the site effect amplification, even if the estimation of κ_0 parameter, with the current classical methods, appear more difficult due to the high level of noise at high frequency and / or a too low local seismicity.

Even if instrumentation can provide important information about site effects, that seems to us essential to acquire, it is also worth to stress that such instrumentation cannot alone solve the whole site effect issues. Indeed, the events that we can expect to record within a reasonable duration have usually quite high epicentral distances that imply that the incidence angle of the wave field is almost ever vertical. The events that may occur closer from the site are very weak events and are then “point source” events. Numerical simulations remain indispensable to assess the effect of incidence angle and extended source events on site effect. And above all, the recordable events produce (very) weak motions; they cannot address the non-linearity issues. Nevertheless, the instrumentation appears to us as essential to produce empirical amplification function that are mandatory to validate numerical simulations for a given range of incidence angles, source sizes and motion levels. Once the simulations are validated thanks to empirical measurements, they can explore other scenarios involving extended sources, non-linearity, etc.

Finally, we mention that we did not test until now “coda” analysis, or “Empirical Green’s Function” approaches. From the site effect point of view, the coda analysis can be considered as an optimization of SSR approaches that could potentially allow using “reference” stations that are rather far from “site” stations. Further tests will be done on “Site A” database and other ones. “Empirical Green Function” analysis addresses other applicability issues if we want to use it within an applied site effect study, as the availability of event records on the geological structures that are relevant for strong motion scenarios. These events should have rather “high” magnitude for a good extrapolation (typically, not less than 2 magnitude degrees less than the target magnitude). Empirical Green’s Function approaches cannot address non-linearity issues.

6.2 IMPLEMENTATION RECOMMENDATIONS

In order to implement an instrumental setup that aims to provide information about site effects, we strongly recommend to use (at least) velocimeters as we demonstrated in section 5. Of course, few accelerometers can be used in complement for example one at the reference station and another one as close as possible form the location to study.

The position of velocimeters in soil conditions should be a compromise between noise level (as low as possible) and distance from the site to study (as close as possible). In French context, facilities are usually already built on sites that are under investigation. This is of course a drawback for instrumentation. We then recommend to making first a quick analysis on noise on several locations around the site before implementing longer recordings. In order to choose a “rather low noise” location, we may consider the overall geometry of the basin that causes site effects, in order to prefer station location that are in similar context (eg. depth of the basin beneath the station, distance from the border of the basin…) with respect to the exact location of the target site. In addition to one or a few “rather low noise” stations equipped with velocimeters, we recommend to implement a station that is located closer from the target site. This “closest station” will implement both velocimeter and accelerometer.

The “rather low noise stations” will be here to record as much events as possible. This “closest” station will be here to 1/ compare response with other stations on “strongest” events (the one that will exceed noise level), 2/ to record events that may induce a velocimeter saturation thanks to the accelerometer (in this situation, local environmental noise or instrumental noise are no more an issue).

The choice of the reference stations is also an important issue. If the noise issue may appear here as less problematical, a good reference station are characterized by these features: 1/ a station that is not too far from “site” stations 2/ a station that is not affected by topographic site effects (indeed, rock situation in the border of basin can have significant topographic site effects), 3/ a station that is representative of the rock condition that is present beneath the basin, 4/ a station that is not affected by any “lithological” site effect, even at high frequency (the presence of a thin colluvium deposit layer or a weathered layer may induce a high frequency site effect) 5/ etc. This implies the need of a real characterization of the reference station local condition (and at least the establishment of a robust local Vs profile and a Vs30 evaluation). For topographic site effect estimation, the computation of a quite simple proxy (Maufroy 2010, Maufroy et al. 2014) could easily be evaluated.

In very wide basins, finding the “optimal” location of a reference station is not an easy issue. The use of coda processing to evaluate site amplification may allow using “reference” stations that are farther from “site” stations in comparison with standard SSR evaluation. This solution will be investigated soon within the SIGMA/WP3 project. Another alternative is the use of downhole reference stations that reach the rock beneath the basin. These solutions are quite expensive and the use of such reference station has their own issues: How to deconvolve the free surface effect at each frequency? How to deal with upward and downward wave field interferences? This solution will be also investigated soon within the SIGMA/WP3 project.

Another question concerning instrumental implementation is the recording mode: continuous or triggered? Some tests made on “Site A” (with a former instrumentation) allow us to formulate these observations: 1/ configuring an acceptable trigger setup takes times during which we may miss a lot of events, 2/ using too high threshold leads to miss a lot of events, whereas using too low threshold leads to get a very high amount of false events that are finally more difficult to manage than a continuous database. Today, both instruments (that have now local storage devices that allow several months of continuous recordings) and transmission capabilities allow to implement instrumentation in continuous mode, without any problem, the choice of continuous recordings appears to us as an evidence.

7 REFERENCES

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Review on the deliverable SIGMA-2014-D3-116 - D. Baumont on June 3rd 2014.

“SITE INSTRUMENTATION USEFULNESS: EXAMPLE OF APPLICATION OF EMPIRICAL OF SITE EFFECT ESTIMATION IN LOW SEISMICITY CONTEXT AND IMPLEMENTATION RECOMMANDATIONS” by V. Perron, F. Hollender and C. Guyonnet-Benaize

The document SIGMA-2014-D3-116 has been sent for review before the scientific committee of the SIGMA program research which will be held on June 4-6th 2014. This study aims to provide some insights on the contribution of instrumentation to site effect evaluation as well as to propose recommendations related to the instrumentation implementation.

General comments

I share the general philosophy expressed by the authors in this document related to the need of collecting EQ recordings at the site of interest to support and/or supplement the seismic response modeling of the site effects. The document presents some preliminary results obtained for 3 sites. The sites are defined anonymously which makes the reading and the evaluation more difficult. I would recommend that the authors try to describe in a more specific manner the sites where the experiments were conducted. Ultimately, the authors drew recommendations on the instrumental implementation, which are based on the experience they acquired.

I must indicate that, naturally, in this review, there is a great temptation to discuss of the results obtained with the data already collected, which is not the purpose of this document as presented by the authors.

Specific comments on site A

Concerning the site A, I think that the recordings database collected over almost two years is very valuable. It clearly demonstrated that, even in a weak to moderate seismicity environment, it is still possible to collect numerous on-site measurements. The preliminary analyses performed by the authors on these data are promising, both in terms of kappa evaluation (in the perspective of applying a host-to-target adjustment on the hard-rock GM prediction) and of SSR determination (in the perspective of the evaluation of the site amplification). On this latter point, the authors should clarify the way they envisage to use these measurements in the general framework of the hazard calculation and in the PSHA framework in particular. Moreover, to illustrate the importance of this type of measurements (in link with the title of this document and with the objectives defined by the authors), the authors could present comparisons between modeling and SSR observations for instance.

Since the site location is not shown on Fig 2, the authors should also provide the distribution of the back-azimuth of the recordings.

In the text, the authors mentioned (page 6) that “Even if the frequency of the site effect of “Site A” is quite high, we kept in database EQ that present a good S/N only in very low frequency (very low for earthquake engineering purpose, here 0.25 Hz).” This sentence is confusing for me. It seems to indicate that a criteria was applied to select the data based on the S/N calculated at 0,25 Hz. I may have misunderstood the sentence. If not, I would expect that every single record that brings information on any frequency range of interest should be kept in the database. It seems also contradictory with what was done in Figure 4 where it seems that there are in the database more usable recordings at intermediate frequencies than at low frequencies. The authors should clarify this point.

The time window selected by the authors for their analysis is based on Ts and Ts + 2 x (Ts-Tp). An example is shown on Fig. 6. Could the authors illustrate this selection on various examples for very short and very long epicentral distances? Depending on the results, the authors may also consider a time window selection based on the group velocity range.

Specific comments on sites B and C

The authors mentioned in page 4 a site D, but it is not reported later on in the document.

The authors explained that they performed short time period experiments at sites B and C. On this basis, they evaluated the seismic noise level of the sites B and C and tried to infer some forecasting concerning the ability of collecting usable EQ records on sites B and C. Based on this analysis, the authors concluded that SSR analysis may still be possible on site B but kappa evaluation seems to be difficult to achieve in a period of few years. In my understanding, the kappa evaluation is envisaged for host-to-target adjustment of the reference GM prediction. However, the authors do not have recordings on site B on rock conditions. It should be question whether their analysis obtained on sediments applies on rock site.

Are there any significant S/N ratio differences between day and night recordings which may modify their conclusions?

Specific comments on the use of velocimeters and accelerometers

The results shown in this section are rather clear and demonstrative and support well the conclusion raised by the authors. In such moderate context, velocimeters seem to be more appropriate for this type of study than accelerometers (which may be needed for other type of analysis or purposes).

Conclusions

Concerning the empirical Green function approach, the authors mentioned that “These events should have rather “high” magnitude for a good extrapolation (typically, not less than 2 magnitude degrees less than the target magnitude). Empirical Green’s Function approaches cannot address non-linearity issues”. It has to be noticed that this statement strongly depends on the strategy retained for the GM modeling. Some techniques would benefit from low magnitude recording with good S/N ratio. On this point, the authors should be more specific on their future application.

Recommendations

The authors proposed to consider the possibility of instrumenting areas having characteristics similar to the one of the site in a “low noise” environment. Beside the questionable aspect of the transposability of the results, it is also, in my point of view, fundamental to instrument the site of interest using several sensors to characterize the spatial variability of the basin response at the scale of the site.

Finally, I share, in particular, the comments related to the continuous mode which should be favored as it offers many possibilities for the exploitation of the data later on.

Review of the report SIGMA-2014-D3-116
SITE INSTRUMENTATION USEFULNESS:
EXAMPLE OF APPLICATION OF EMPIRICAL OF SITE EFFECT ESTIMATION IN LOW SEISMICITY CONTEXT AND IMPLEMENTATION RECOMMANDATIONS BY V. PERRON, F. HOLLENDER, C. GUYONNET-BENAIZE

Review performed by Marco Mucciarelli, CRS-OGS and Basilicata University

According to the authors, the report "neither aims to present new or cutting edge signal processing approaches... Development on optimized methods is an ongoing work ... will be provided later in another deliverable."

The main scope here is limited to investigate the reliability of empirical estimates of seismic site amplification in a low-seismicity area in relation with the level of seismic noise. The report is clear and concise in describing the outcomes of the experiments carried out in three sites in the South of France.

There are some misspellings that may be corrected by the word processor, while my main comments are detailed in the following.

It would have been useful to provide an H/V analysis for the rock sites considered, in order to check the presence of resonance peaks (even at high frequency) that might affect both the SSR and $\mathbf{k_0}$ estimates performed in the experiment.

In fig. 8 the spectra seems un-smoothed as it was done for SSR estimates previously described in the report. Il could be possible that a limited amount of smoothing could reduce the subjectivity in selecting the linear tract? (see the added blue dashed line for example)

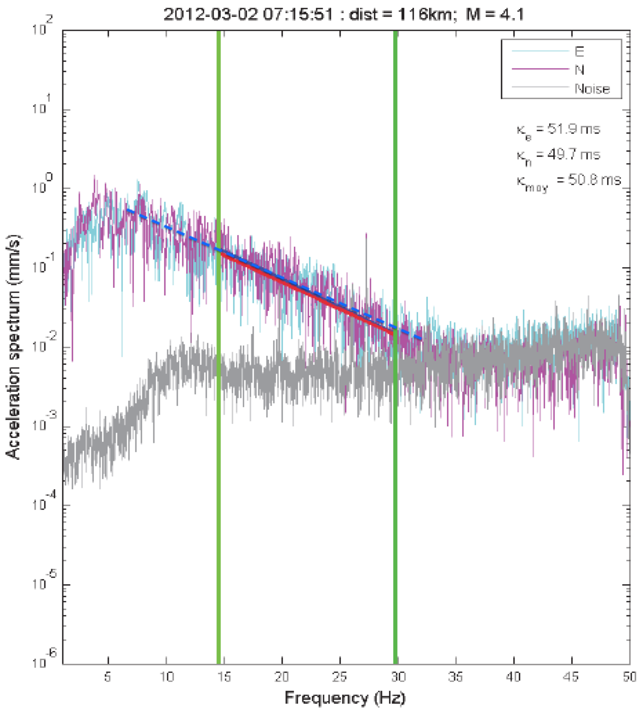
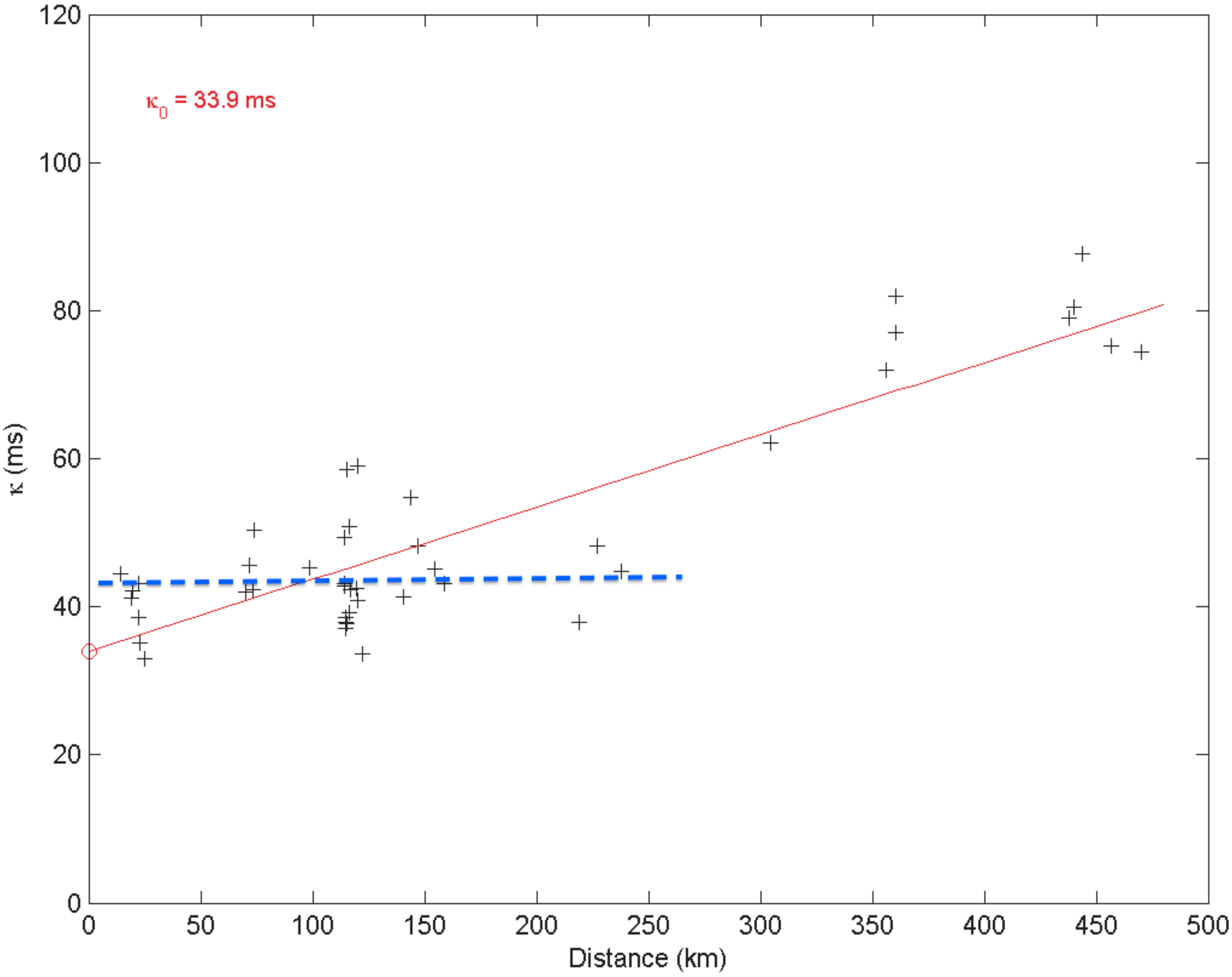


Fig. 9 points out a problem in data selection. It would give very different results for **k0** if D>250 km were excluded, as shown in the modified picture below. No explanation is given on the reason why the distance interval shown was originally selected.



A further remark on **k0** concerns the estimate of this parameter for soft-soil sites to check the sensitivity of the **k0** estimates in low-seismicity areas. It would be expected to have a much larger variation than that observed in the two rock sites.

The final remarks concerns the noise level observed at B and C sites. Observing the photos of installation given in fig. 1, it looks like the seismometer is not actually buried as said in the text, but simply put on a small hole, then covered with a protection that stands above the surface. The burying of sensor, even of a small amount, reduces the level of noise. This could be an experiment for the future, to see if frequency-domain techniques could benefit of this strategy as described for time-domain in Withers M.M., Aster R.C., Young C.J., Chael E.P. (1996). *High frequency analysis of seismic background noise as a function of wind speed and shallow depth, Bull seism. Soc. Am., 86(5), 1507–1515.*