UCRL-JRNL-211990

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

UNBIASED MOMENT-RATE SPECTRA AND ABSOLUTE SITE EFFECTS IN THE KACHCHH BASIN, INDIA, FROM THE ANALYSIS OF THE AFTERSHOCKS OF THE 2001 Mw 7.6 BHUJ EARTHQUAKE

L. Malagnini, P. Bodin, K. Mayeda, A. Akinci

May 5, 2005

Bulletin of the Seismological Society of America

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

UNBIASED MOMENT-RATE SPECTRA AND ABSOLUTE SITE EFFECTS IN THE KACHCHH BASIN, INDIA, FROM THE ANALYSIS OF THE AFTERSHOCKS OF THE 2001 Mw 7.6 BHUJ EARTHQUAKE

Luca Malagnini[1], Paul Bodin[2], Kevin Mayeda[3], and Aybige Akinci[1]

Bulletin of the Seismological Society of America,

Submitted: April 26, 2005

Revised:

Accepted:

[1] Istituto Nazionale di Geofisica e Vulcanologia, Rome, Via di Vigna Murata 605, 00143 Rome, Italy malagnini@ingv.it, akinci@ingv.it
[2] Center for Earthquake Research and Information, University of Memphis, Memphis TN 38152 bodin@ceri.memphis.edu
[3] Lawrence-Livermore National Laboratory, mayeda2@llnl.gov

ABSTRACT

What can be learned about absolute site effects on ground motions and about earthquake source spectra from recordings at temporary seismic stations, none of which could be considered a "reference" (hard rock) site, for which no geotechnical information is available, in a very poorly instrumented region? This challenge motivated our current study of aftershocks of the 2001 Mw 7.6 Bhuj earthquake, in Western India. Crustal attenuation and spreading relationships based on the same data used here were determined in an earlier study. In this paper we decouple the ambiguity between absolute source radiation and site effects by first computing robust estimates of moment-rate spectra of about 200 aftershocks in each of two depth ranges. Using these new estimates of sourcespectra, and our understanding of regional wave propagation, we extract the absolute site terms of the sites of the temporary deployment. Absolute site terms (one for each component of the ground motion, for each station) are computed in an average sense, via an L_1-norm minimization, and results for each site are averaged over wide ranges of azimuths and takeoff angles. The Bhuj deployment is characterized by a variable shallow geology, mostly of soft sedimentary units. Vertical site terms in the region were observed to be almost featureless and slightly < 1.0 within wide frequency ranges. As a result, H/V spectral ratios mimic the absolute behaviors of absolute horizontal site terms, and they generally overpredict them. On the contrary, with respect to the results for sedimentary rock sites (limestone, dolomite) obtained by Malagnini et al. (2004), H/V spectral ratios in their study did not have much in common with absolute horizontal site terms. Spectral ratios between the vector sum of the computed horizontal site terms for the temporary deployment with respect to the same quantity computed at the hardest rock station available, BAC1, are seriously biased by its non-flat, non-unitary site response. This indicates that often the actual behavior of a rock outcrop is far from that of an ideal, reference site.

INTRODUCTION

Two challenges for seismologists involved in monitoring activities are estimating earthquake moment magnitudes accurately and understanding and accounting for the complicated and varying effects of wave propagation at each of the recording sites ("site

effects"). While it may not appear obvious in theory, these two problems are linked in practice. This is particularly true when dealing with earthquakes smaller than, say, M_w~3 that are difficult to waveform model because their radiated seismic energy is dominantly at high frequencies, and high frequencies suffer (relative to the lower frequencies generally modeled) stronger attenuation, scattering, and distortion, much of this from site effects. So while "crustal" wave propagation from the earthquake source to the site is generally regarded as being well-behaved enough to be accounted for, there remains the problem of deciding which stable feature(s) of recorded high frequency seismograms represents the imprint of the source and which were caused by variable site effects underneath the recording stations.

Both "ends" of the earthquake process, its source and the effect of local geology at the recording site, are important, but often for different seismological specialties. Seismologists interested in reliable detection and determination of earthquake source parameters and understanding rupture processes will focus on the source problem, while those studying seismic hazards are generally concerned about site effects.

This paper takes the approach of trying to separate out these effects in an averaged sense—that is, trying to find parameters that best reproduce the ensemble features of a particular regional dataset. [One could, alternatively, try to model individual waveforms]. We use a dataset for which we earlier studied the average regional crustal propagation: aftershocks of the 2001 Bhuj, India earthquake, in western India. Data were recorded on a seismic network deployed temporarily in a hitherto poorly studied region. In this sense, our study also addresses another challenge: what can be usefully learned (from both the source and site perspective) from an opportunistic study of earthquakes in an otherwise poorly characterized region, at a collection of not-well-documented sites? In earlier studies of these data we located the earthquakes accurately (Bodin and Horton, 2004) and studied the average crustal attenuation and spreading functions (Bodin et al., 2004). However, Bodin et al., (2004) did not attempt to determine site terms (the spectral transfer function of seismic signals arriving at a seismic station after radiation from the source and propagation through the crust to a depth under the site where the distortions induced by local geological structure become important) in an absolute sense. Nor did

Bodin et al. (2004) compute source spectra without making some assumptions about the site effects.

In this paper we build on these earlier studies by employing an efficient and accurate method of determining moment-rate source spectra based on stable coda-derived spectral measurements (Mayeda and Walter, 1996; Mayeda et al., 2003). This method yields moment-rate spectra unbiased by the distorting effects of the surface geology; it has been tested extensively in a variety of regions, and may be used for monitoring chemical/nuclear underground explosions. We then invert the observations to determine the site terms, after computing the coda-derived source spectra for the Bhuj aftershock data, and accounting for crustal wave propagation using the parameters determined by Bodin et al. (2004). We interpret our results to explore several timely issues in earthquake source mechanics and near-site wave propagation, which we introduce in the remainder of this introduction.

If the moment-rate spectra can be calibrated accurately in a wide frequency range (but particularly at frequencies above the source "corner frequency") it becomes possible to assess the radiated seismic energy (or, equivalently, the dynamic stress drop) of each event (Mayeda and Walter, 1996). Numerous recent studies have addressed the quantification of the seismic energy and/or dynamic stress drop (Ide and Beroza, 2001; Mayeda et al., 2003; Morasca et al., 2005; Malagnini et al., 2004; Brodsky and Kanamori, 2001; Kanamori and Heaton, 2000, etc.). These studies basically focused on the variations of the normalized radiated energy as a function of the earthquake size (moment magnitude) to yield information on fundamental dynamic properties of the breaking faults. Some studies (e.g., Kanamori and Heaton, 2000; Brodsky and Kanamori, 2001) proposed specific physical mechanisms as governing the energy budget during the rupture of a fault patch. Their main motivation was to answer the fundamental question: is there more energy available for radiation, per unit fault surface, per unit slip, when the earthquake gets larger?

The hypothesis that stress drop of earthquakes is independent of size is venerable, and has been recently reiterated by Ide and Beroza (2001), and by Prieto et al. (2004). However, many researchers believe that the dynamic stress drop gets larger for larger events (Mayeda and Walter, 1996; Kanamori and Heaton, 2000; Brodsky and Kanamori,

2001; Mayeda et al., 2003; Morasca et al., 2004; Malagnini et al., 2004). Since the same measurements (seismograms) are used to derive the static and the dynamic relationships regarding the radiated seismic waves, they are not independent. Kanamori and Rivera (2004) recently suggested that small earthquakes have smaller static stress drops than large earthquakes, as a consequence of the dynamic relationship between the seismic moment and the radiated energy.

Turning our attention to site effects, whatever the specific form and scaling of the source spectra, if accurate absolute source moment-rate spectra exist and if we possess accurate measures of regional crustal propagation, then we have the information necessary to estimate the absolute site effects for the stations that were used in both the source and the attenuation studies. For example, starting from unbiased source spectra of earthquakes recorded in the Eastern Alps by the Friuli-Venezia Giulia Seismic Network (FVGSN), and using the empirically-determined regional wave propagation parameters in the Eastern Alps (Malagnini et al, 2002), Malagnini et al. (2004) estimated the absolute site effects of the FVGSN seismic stations. In the present study we followed procedures similar to Malagnini et al. (2004) in order to obtain the absolute source and site effects in the Kachchh Basin, India, using the aftershocks of the 2001 Mw 7.6 Bhuj earthquake.

In the scientific literature of the last decades, site transfer functions have been obtained by computing, from recordings of earthquake-induced ground motions, either the Standard Spectral Ratio (SSR) (Field and Jacobs, 1993, 1995; Borcherdt, 1970; King and Tucker, 1984; Tucker and King, 1984), to a reference station, or the Horizontal/Vertical spectral ratio (HVSR) (Nakamura, 1999, 2000; Theodulidis et al., 1996; Lachet and Bard, 1994; Mucciarelli, 1998; Mucciarelli and Gallipoli, 2001; Mucciarelli and Monachesi, 1998). Given an ideal reference site (one with a flat absolute site response of unit amplitude) the SSRs yield accurate estimates of the absolute site terms.

HVSRs may identify frequencies at which site effects may be important while not reliably quantifying absolute levels of spectral amplification or loss at a site. For example, Romanelli and Vaccari (1999) simulated the site response of the SH and P-SV motion in the town of Catania (see also: Panza et al., 2001). While the horizontal ground motions were strongly affected by the surface geology, the vertical motions were not.

Their synthetic HVSRs, in agreement with observational results of other scientists (e.g., Theodulidis et al., 1996; and Lachet and Bard, 1994) clearly identified the resonance frequencies of sites, but were not predictive of their absolute amplitudes.

Although azimuthal variations are thought to be important in defining different site behaviors (see, for example, Papageorgiou and Aki, 1990), only 1-D attenuation functions are used in this study, and no attempts are made in order to investigate azimuthally varying properties of sites. Because a number of tradeoffs exist between the different variables that are specific for each site, estimating the absolute site terms of real seismic stations is challenging, and any estimate may depend on the specific choices of the different ingredients used. For example, in this study we use a function for crustal attenuation and spreading that is an average over azimuth and ray takeoff angle, and thus we can only obtain azimuth- and incidence angle-averaged 'absolute' site terms. Nevertheless, we recognize that site effects may be strongly azimuth-dependent, which probably contributes to the dispersion in our regression results.

THE BHUJ SEQUENCE DATA SETS

The data used in this study were recorded by a network of 8 portable seismographs deployed for 3 weeks, between 12 and 28 February 2001, starting 17 days after the 26 January 2001 Bhuj earthquake, M_w 7.6 (Bodin and Horton, 2004). The network recorded aftershocks as shallow as 5 km and extending to 35 km, or nearly through the presumed 40 km thick crust. The strongest concentration of earthquakes is observed in the lower crust, at depths around 26 km (Bodin and Horton, 2004).

Bodin et al. (2004) selected two partially-overlapping subsets of these events (860 shallow events, $H \leq 25$ km, and 535 deeper events, $H \geq 20$ km), and obtained a function describing the frequency-dependent crustal attenuation for seismic waves in the region. They observed slightly different apparent geometrical spreading and frequency dependence for the crustal parameter $Q(f)=Q_0(f/1.0)^{\eta}$ in the two cases. For both datasets $Q_{0Shallow}=Q_{0Deep}=790$ at f=1.0 Hz while $\eta_{Shallow}=0.22$, and $\eta_{Deep}=0.35$. Moreover, the distribution of the stress parameter of the source spectra for the two data sets showed substantial differences in its dependence on the earthquake magnitude (Bodin et al., 2004, their Figure 8).

For this study, we selected two smaller subsets of seismic data from the deep and shallow ones defined by Bodin et al. (2004). We based our choice on their estimates of moment magnitude, obtained using the parameters of their crustal attenuation. We selected 981 observed waveforms from 174 events of $M_w > 2.7$ from the shallower data set, and 1808 observed waveforms from 215 deeper earthquakes of $M_w > 2.5$. This choice was not *a priori*, but rather selected after an initial analysis yielded noisy results when smaller earthquakes were included. Figures 1 and 2 shows maps, and depth distributions of the two resulting subsets, and their relationship to the seismic stations. The largest earthquake in the dataset was M_w 5.2, for an event common to both sets.

DATA ANAYSIS

We obtained unbiased moment-rate spectra for the two subsets of seismic data by analyzing the coda waves in different frequency bands, and tying these to scalar seismic moments derived from waveform modeling of the larger events in the dataset. Moment-rate spectra were computed at a set of central frequencies that was slightly different from that by Bodin et al. (2004), and subsequently re-sampled to match the central frequencies in their study. Before re-sampling, moment-rate spectra are transformed in ground velocity Fourier amplitudes.

Results from Bodin et al. (2004) are used in order to "propagate" the re-sampled moment-rate spectra to the arbitrary hypocentral distance of 40 km (the same used in their study for obtaining their excitation terms). After the propagation is achieved, the technique used in Raoof et al. (1999), Malagnini et al. (2000, 2002), Akinci et al. (2001), and Bodin et al. (2004) is applied to the Fourier amplitudes of the recorded earthquakes. An individual regression is run on the Fourier amplitudes observed for each sampling frequency, and the absolute site terms of each component of the ground motion of each one of the seismic stations are obtained. Regression results are quite different from those obtained by Malagnini et al. (2004) for alpine sites located on limestone and dolomite outcrops, in the sense that soil sites behave in a fundamentally different way with respect to rock sites.

a) Obtaining Absolute Moment-Rate Source Spectra

Typically, obtaining the average source spectrum from the direct waves requires either some *a priori* information on the source mechanism, or the availability of multiple stations to average out the source heterogeneities (e.g., source mechanism and directivity). In addition, path and site corrections can be significant, contributing to increased error in the final source spectrum. To minimize these effects we have used the coda methodology outlined in Mayeda et al. (2003) to derive stable source spectra. This methodology has been shown to provide the lowest variance estimate of the source spectrum in a number of tectonically diverse regions. We show in Figure 4 that the distance-corrected coda amplitudes have roughly a factor of 5 times less scatter than direct wave estimates. This 1-D methodology has been applied to local and regional distances and appears to be well suited for small-scale studies. Because the coda envelope amplitudes are relative measures, we tie the long-period values to independently derived estimates from long-period waveform modeling (see Figure 5 for an example). This approach accounts for the S-to-coda transfer function and site effect corrections for frequencies below ~1.0-Hz. For the higher frequencies, we use a number of very small events as empirical Green's functions. Figure 6 shows representative coda-derived moment-rate spectra in units of dyne-cm. Notice that independent of distance or azimuth, the individual station spectra are very similar, confirming that our calibration procedure is correct and demonstrating that the coda is not as sensitive to radiation pattern effects. All corrections were applied to the rest of the data set to form source spectra. For additional stability, we formed the average spectra.

b) Absolute Site Terms

Let $a_k(r_{ij}, f)$ be the rms-average of the Fourier spectral amplitudes, in the

frequency window: $\left[f/\sqrt{2}, \sqrt{2}f \right]$, observed on the k-th waveform, at the j-th site and during the i-th event, at the hypocentral distance r_{ij}. We can write:

$$A_k(r_{ij}, f) = EXC_j(r = r_{ref}, f) + SITE_i(f) + D(r_{ij}, r_{ref}, f) \quad (1)$$

where:

$$A_k(r_{ij}, f) = \log(a_k(r_{ij}, f)) \quad (2)$$

Using eq. (1), we can cast all our observation in a matrix form, and invert for the site terms: $SITE_i(f)$, fixing the attenuation term, $D(r_{ij}, r_{ref}, f)$, and all the excitation terms, $EXC_j(r = r_{ref}, f)$. The empirical attenuation terms are taken from the study by Bodin et al. (2004), for both the deep and the shallow data sets. The attenuation terms for the Fourier amplitudes at all the individual central frequencies are shown in Figure 3, whereas the excitation terms are obtained from the absolute moment-rate spectra described in the previous section. The spectra are transformed in ground velocity Fourier amplitudes, and "propagated" to the reference distance $r_{ref} = 40$ km by using equations (3) and (9-12) from Bodin et al. (2004).

Table 1 from Bodin and Horton (2004) gives the available information about all eight seismic stations used in this study. As mentioned in their paper: *"Most stations were sited on rock (sandstone or basalt) or on a thin layer of soil overlying rock. LIQ is a notable exception…"*. However, we point out that no geotechnical studies have been done at any of these sites and the geological mapping available is at a reconnaissance scale. For example, station BAC (Figure 1) is on a small outcrop of Cretaceous-aged Deccan Trap basalt flow, overlooked in the geological map that forms the basis for the regional geology sketched in the figure.

RESULTS

Site effects in an absolute sense

In the following we describe the characteristics of each of the seismic stations' absolute site terms, and of their known or inferred geological features. It is believed that

strong-motion recordings are mainly controlled by the local geology, in the upper 30 m (Anderson et al., 1996). Figures 7 and 8 show the absolute vertical and horizontal site effects, and the H/V ratios for all stations, and form the basis for this discussion.

Station *ANJ1* is characterized by amplification of the horizontal ground motions, over the entire frequency range studied (1 – 12 Hz). Both the horizontal and vertical site terms are almost featureless (i.e., no discernible hills, valleys, or trends). The corresponding H/V ratio shows a positive trend, up to 8 Hz, where this quantity assumes a value around 5. This station was set upon a sandstone formation.

Station *BAC1*, which we initially considered a good candidate for a "reference" rock site because it was directly on a basalt flow, shows a slight amplification of the horizontal ground motions around 2 Hz and a strong de-amplification at high frequencies (above 5 Hz). These features would result in a substantial bias of the inter-station spectral ratios, since they will be amplified at high frequency because of the strong attenuation at shallow depths beneath site BAC1. A similar trend characterizes the vertical site term of this station, and results in an almost flat H/V ratio, up to about 8 Hz. This quantity also shows a fast decrease at high frequency. Results relative to site BAC1 (Figure 9) are consistent with the conclusions by Steidl et al. (1996), who showed that the site response of surface rock are not spectrally flat due to attenuation and scattering from near-surface weathering and cracking of the rock.

The estimate of the absolute response of station *BHA1*, although deployed over deeply weathered sandstone, is very similar to that of station BAC1. The H/V ratio at this station is almost flat in the entire frequency band available, and has the lowest absolute value.

Station *DUD1* was the "best-behaved" station in the data set. Response is about flat and close to unity for the horizontal ground motion. The same behavior is observed on the vertical transfer function, and the H/V ratio for this station is almost featureless and low in amplitude. The station was deployed on the ground of a small (1-story) structure upon a soil layer of unknown thickness (Bodin and Horton, 2004).

Station *KHA1* was deployed over a thin layer of soil of unknown thickness, overlying deeply weathered sandstone (Bodin and Horton, 2004). Some of the unusual characteristics of this site, compared to others in the network, may reflect that it was

located on the floor of a cellar about 2 m below the surrounding ground surface. This station is characterized by a slight, broadband amplification of the horizontal ground motions, between 1 and 8 Hz. Amplification of the horizontal site term is sharply terminated at the higher frequencies. The vertical site effect at this station is relatively high between 1 and 2 Hz, and then decays to quite a low level. The H/V ratio at this station mimics the horizontal site term.

Station *LBR1* reveals, together with KHA1 and LIQ1, the largest variations in the H/V ratios. The horizontal site term is characterized by a large amplification between 5 and 12 Hz. The vertical site term is flat and very low in amplitude. The H/V ratio reproduces the horizontal site term. The surface geology at LBR1 is characterized by the presence of slightly indurated sediments, cropping out on a bluff several meters high above the surrounding Great Rann of Kachchh.

Station *LIQ1* shows a broadband amplification of horizontal ground motions at frequencies between 1 and 5 Hz. The trend at high frequency, observed on both the vertical and the horizontal ground motions, indicates a strong deamplification. The H/V ratio at this station is consistent with the observed horizontal site term. In the immediate vicinities of this station, extensive liquefaction phenomena were induced by the Bhuj main shock. LIQ1 was intentionally located at the site of a large sand-blow, where the thickness of unconsolidated sediments is thought to be around 500 m (Bodin and Horton, 2004).

Station *LOT1* experiences amplification between 2 and 8 Hz in the horizontal absolute site term. At higher frequencies, the amplitudes of the horizontal site term decrease strongly. The vertical term at LOT1 is quite smooth, with a sharp peak at 8 Hz. The H/V ratio for this station shows a slight amplification with a relatively broad maximum between 5 and 8 Hz. At station LOT1, a thin soil layer overlies sandstone bedrock.

Differences between deep and shallow data sets

Differences between site terms of the same stations, obtained by regressing the two different data sets are within the error bars of each term (Figure 10). For this reason, we have discussed only the site terms derived from the deeper set of earthquakes.

However, we note that the regional attenuation obtained by Bodin et al (2004) for the two sets of data differed, undoubtedly because seismic waves in the two cases would sample the regional structure slightly differently. It is a comforting "reality check" that the site terms we compute from two different datasets are so similar, because one would expect site terms to be (to first order) independent of the path taken to the site. This confirms our argument that, for the frequency band investigated in this study, the terms shown in Figures 7 and 8 reveal the absolute responses (in an average sense) of the very shallow geologic formations. Variations among the incidence angles of observed seismic waves, while they must contribute to the dispersion of the observations, do not seem to cause clear first order systematic effects in the analyses.

H/V spectral ratios: differences with the results by Malagnini et al. (2004)

Comparing the absolute horizontal site terms with their corresponding HVSR (Figure 8) reveals similar values for both measures at low frequency ($f < 5$ Hz). At higher frequencies, the HVSRs generally ***overestimate*** the absolute site terms. We also conclude that, for the sites shown in the picture, the spectral shapes of the two measures are generally similar. It is difficult to quantify these general remarks, given both the variability between stations and the uncertainties in the results. However, at the lower end of the available frequency window ($f \approx 1$-2 Hz), for the sites studied in this paper, the hypothesis underlying the use of HVSRs, that vertical motions are undisturbed by the shallow geology, seems to be largely borne out.

The vertical absolute site terms (Figure 7), slightly less than unity over wide frequency ranges, do not show large variations. A notable exception is that of station KHA1, whose vertical absolute site term is characterized by quite a strong falloff (almost a factor of five) between 1 and 5 Hz. The overall variability in the absolute levels of the vertical site terms is quite large (about a factor of five).

Station ANJ1 (sandstone formation) shows the largest amplification, station LBR1 (slightly indurated sediments) is characterized by the lowest amplitudes at low-frequency, and stations KHA1 (cellar-deployed on thin soil layer of unknown thickness) and LIQ1 (deployed over a large sand-blow, unconsolidated deep soil) show the lowest amplitudes at high-frequency ($f > 3$ Hz).

DISCUSSIONS AND CONCLUSIONS

In our study of Bhuj aftershocks the general pattern of absolute horizontal site terms at most stations is somewhat similar to their HVSRs. In the eastern Alps, Malagnini et al. (2004) demonstrated that rock sites revealed no clear relationships between the HVSRs and the corresponding absolute horizontal ground motion transfer functions. They concluded that, although the HVSRs were strongly correlated with the site characteristics (geometry) and to the shallow geology, the hypothesis that the vertical motion is almost undisturbed, and that only the horizontal motion is strongly affected by the shallow geology, was not correct in general.

While the spectral shapes of the HVSRs, and the absolute site terms for Bhuj earthquakes are similar, the HVSRs do not successfully reproduce the absolute amplitudes of the amplification/resonance effects induced by the shallow geology, even at soil sites. In Bhuj, as in the Eastern Alps, our presumed "reference" rock site (station BAC1) is characterized by a strong de-amplification of both the horizontal and the vertical ground motions. This result seems to be consistent with those by Malagnini et al. (2004). Unlike the results by Malagnini et al. (2004), the absolute horizontal site terms at station BAC1 are well reproduced by its HVSR.

Figure 9 shows the SSRs of all the horizontal absolute site terms of all stations with respect to BAC1. Each SSR is strongly biased by the de-amplification effects at BAC1. The comparison between the SSRs (Figure 9), the HVSRs, and the absolute horizontal site terms (Figure 8), clearly shows that the SSRs to station BAC1 are the farthest from the actual absolute site terms.

At all sites in the present study, variations of the spectral shapes and amplitudes of the vertical site terms were only marginal. Different sites, though, may have very different levels of vertical site response. This is not true universally, however, for example in the Eastern Alps, Malagnini et al. (2004) determine for one site a strong de-amplification at high frequency on both the horizontal and the vertical site transfer functions. Although the H/V ratio is strongly related to the shallow site geology, and to the geometry of the buried units, it may not always describe the horizontal site transfer function. In this study, HVRSs show similar general trends in spectral shape and low-

frequency amplitude as the horizontal motion transfer functions, although they ***overpredict*** them at most sites, at higher frequencies.

For both data sets, HVSRs describe the horizontal site transfer function (at least in terms of spectral shape, if not amplitude) better than inter-station spectral ratios. The latter may be biased by the non-flat high-frequency response of rock sites.

Havenith et al. (2002) pointed out that SSRs and HVSRs were similar for the set of stations used in their paper. Moreover, HVSRs were always lower or comparable to SSRs, and were most consistent at frequencies lower than the fundamental resonance frequency. Beyond the resonance frequency, the HVSR may be considered as a lower bound of the corresponding SSR. In turn, the SSRs described in their paper were up to a factor of 3 higher than the corresponding HVSRs. They also concluded that the investigated SSRs and HVSRs consistently indicated the same fundamental frequency at a specific site, with the HVSRs computed over different waves (direct S-waves, S-coda, noise) showing very stable spectral shapes.

We feel that the major drawback in our study is the limited resolution in frequency on the "propagated" source spectra. This issue arises because two independent studies are needed in order to apply our regression: one on the ground motion scaling, the second on the absolute source scaling. There are specific physical reasons not to use the same set of sampling frequencies, and bandwidth. On the one hand, beyond the event corner frequency, bandwidths must be very small because coda envelopes tend to be strongly dominated by signals in the lower side of the filtered band; on the other hand, the ground motion studies need to rely on relatively large bandwidths in order to have meaningful and clear peak values.

Limited resolution in the 1-5 Hz frequency band does not allow us to see details in the absolute site spectra. The relatively large variability of the site terms at about 1.0 Hz suggests that the differences in the shallow geology (first 30-50 m?) can be large, and can be responsible for the different site responses. At frequencies lower than 1.0 Hz, the results from the ground motion study by Bodin et al. (2004) were unstable, and are not used here.

The lack of resolution in the important (for structural engineers) frequency band between 1.0 and 5.0 Hz is mitigated by the strong averaging actions implicitly taken in

the regressions (results would have been smooth anyhow). In fact, results are averaged over takeoff and azimuth angles, and Herrmann and Malagnini (2004) demonstrated that variations in the two parameters may be responsible for the overall variability seen in their synthetic study.

ACKNOWLEDGEMENTS

The study was partially supported by project FIRB, Prot. RBAU013NRZ. K. Mayeda was supported by BAAThe authors are particularly grateful to Lupei Zhu and Robert B. Herrmann, for their help in the determination of the moment tensor solution of some of the small events used. This work performed for DOE by UC, LLNL Contract W-7405-Eng-48.

REFERENCES

Akinci, A., L. Malagnini, R.B. Herrmann, N.A. Pino, L. Scognamiglio and H. Eyidogan (2001). Predictive relationships for the ground motion in the Erzincan region (Turkey), Bull. Seism. Soc. Am., 91, 1446-1455.

Anderson, J.G., Y. Lee, Y. Zeng, and S. Day (1996). Control of strong motion by the upper 30 m, Bull. Seism. Soc. Am., 86, 1749-1759.

Biswas S. K., (1980) Structure of Kutch-Kathiawar Region, W. India.- Proc. 3rd Ind. Geol. Congr. Pune, 255-272.

Bodin, P., L. Malagnini, and A. Akinci (2004). Ground-Motion Scaling in the Kachchh Basin, India, Deduced from Aftershocks of the 2001 Mw 7.6 Bhuj Earthquake, Bull. Seism. Soc. Am., 94, 5, 1658-1669.

Bodin, P., and S. Horton (2004). Source parameters and tectonic implications of aftershocks of the Mw 7.6 Bhuj earthquake of January 26, 2001, Bull. Seism. Soc. Am. 94, 818-827.

Borcherdt, R.D, (1970). Effects of local geology on ground motion near San Bull. Seismol. Soc. Am., 60, 29-61.

Borcherdt, R.D. (1994). Estimates of site-dependent response spectra for design (methodology and justification), Earthquake Spectra, 10, 617-653.

Borcherdt, R.D. (1992). Simplified site classes and empirical amplification factors for site-dependent code provisions, in Proc. NCEER, SEAOC,BSSC Workshop on Site Response during Earthquakes and Seismic Code Provisions}, November 18-20, University of Southern California, Los Angeles, California.

Brodsky, E.E. and H. Kanamori (2001). Elastodynamic lubrication of faults, J. Geophys. Res., 106, 16357-16374. Ide, S. and G.C. Beroza (2001). Does apparent stress vary with earthquake size?, Geophys. Res. Lett., 28, 3349-3352.

Field, E. H., and K. Jacob (1993). The theoretical response of sedimentary layers to ambient seismic noise, Geophys. Res. Lett. 20,2925 –2928.

Field, E. H., and K. A. Jacob (1995). Comparison and test of various site-response estimation techniques including three that are not reference-site dependent, Bull. Seism. Soc. Am. 85,1127

Herrmann, R.B., and L. Malagnini (2005). Interpretation of High Frequency Ground Motion from Regional Seismic Network Observations, Bull. Seism. Soc. Am. (in press).

Kanamori, H., and L. Rivera (2004). Static and dynamic scaling relations for earthquakes and their implications for rupture speed and stress drop, Bull. Seism. Soc. Am., 94, 314-319.

Kanamori, H. and T.H. Heaton (2000). Microscopic and macroscopic physics of earthquakes, GeoComplexity and the Physics of Earthquakes, Geophysical Monograph 120, AGU, 284 pp.

King, J.L., and .E. Tucker (1984). Observed variations of earthquake motion across a sediment-filled valley, Bull. Seism. Soc. Am., 74, 137-151.

Lachet, C., and P.-Y. Bard (1994). Numerical and theoretical investigations on the possibilities and limitations of the Nakamura's technique, J. Phys. Earth 42(4),377 – 397.

Malagnini, L., R.B. Herrmann, M. Di Bona (2000). Ground-Motion Scaling in the Apennines (Italy), Bull. Seism. Soc. Am., 90, 1062-1081.

Malagnini, L., A. Akinci, R.B. Herrmann, N.A. Pino and L. Scognamiglio (2002). Characteristics of the ground motion in Friuli (Northeastern Italy), Bull. Seism. Soc. Am., 2186-2204.

Mayeda, K., A. Hofstetter, J.L. O'Boyle, and W.R. Walter (2003). Stable and transportable regional magnitudes based on coda-derived moment-rate spectra, Bull. Seism. Soc. Am., 93, 224-239.

Mayeda, K. and W.R. Walter (1996). Moment, energy, stress drop, and source spectra of western United States earthquakes from regional coda envelopes, J. Geophys. Res., 101, 11195-11208.

Morasca, P. K. Mayeda, L. Malagnini, and W.R. Walter (2005). Coda-derived source spectra, moment magnitudes and energy-moment scaling in the Western Alps, Geophys. J. Int., 160, 263-275.

Mucciarelli, M. (1998). Reliability and applicability of Nakamura's technique using microtremors: an experimental approach, J. Earthquake Eng. 2,625 –638.

Mucciarelli, M., and M. R. Gallipoli (2001). A critical review of 10 years of microtremor HVSR technique, Boll. Geof. Teor. Appl. 42.

Mucciarelli, M., and G. Monachesi (1998). A quick survey of local amplifications and their correlation with damage observed during the Umbro–Marchesan earthquake of September 26, 1997, J. Earthquake Eng. 2,325 –337.

Nakamura, Y. (1989). A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface, Q. Rept. Rail. Tech. Res. Inst. 30(1),25 – 33.

Nakamura, Y. (2000). Clear identification of fundamental idea of Nakamura's technique and its applications, Proc. 12th World Conference on Earthquake Engineering, New Zeland, CD-Rom.

Panza, G.F., Romanelli, F. and Vaccari, F., (2001). Seismic wave propagation in laterally heterogeneous anelastic media: theory and applications to seismic zonation. Advances in Geophysics, 43, 1-95.

Papageorgiou, A.S. and K. Aki (1983). A specific barrier model for the quantitative description of inhomogeneous faulting and the prediction of strong ground motion. Part II. Applications of the model, Bull. Seism. Soc. Am., 73, 953-978.

Raoof, M., R.B. Herrmann and L. Malagnini (1999). Attenuation and excitation of three-component ground motion in Southern California, Bull. Seism. Soc. Am., 89, 888-902.

Romanelli F., Vaccari F. "Site response estimation and ground motion spectral scenario in the Catania Area" Journal of Seismology 1999; 3 (3): 311-326.

Steidl, J.H., A.G. Tumarkin, and R.J. Archuleta (1996). What is a reference site?, Bull. Seism. Soc. Am., 86, 1733-1748.

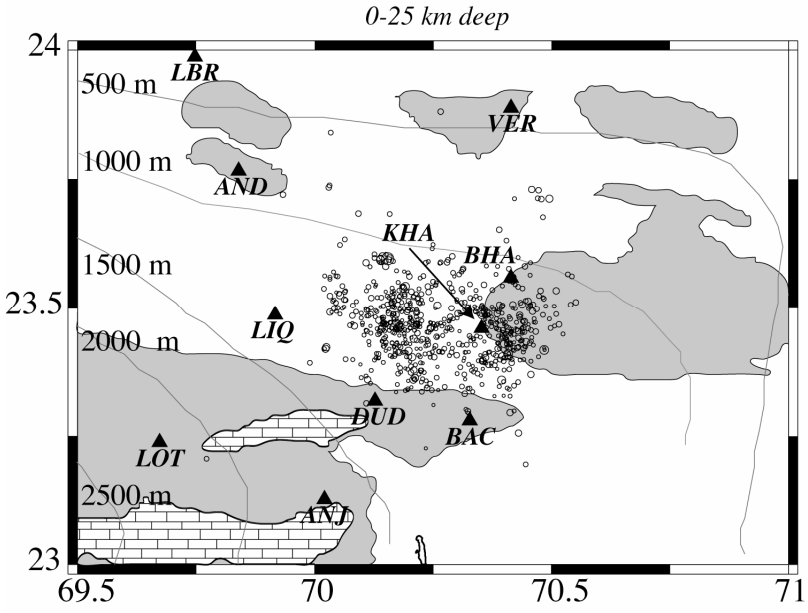
Theodulidis, N., P.-Y. Bard, R. Archuleta, and M. Bouchon (1996) Horizontal to vertical ratio and geological conditions: the case of Garner Valley Downhole Array in Southern California, Bull. Seism. Soc. Am. 86,306 –319.

Tucker, B.E. and J.L. King (1984). Dependence of sediment-filled valley response on input amplitude and valley properties, Bull. Seism. Soc. Am., 74, 153 – 165.

Zhao, L.-S. and D. V. Helmberger, Source estimation from broadband regional seismograms, Bull. Seism. Soc. Am., 84 (1), 91-104, 1994.

Zhu, L. and D. V. Helmberger, Advancement in source estimation techniques using broadband regional seismograms, Bull. Seism. Soc. Am., 86 (5), 1634-1641, 1996.

FIGURES AND CAPTIONS



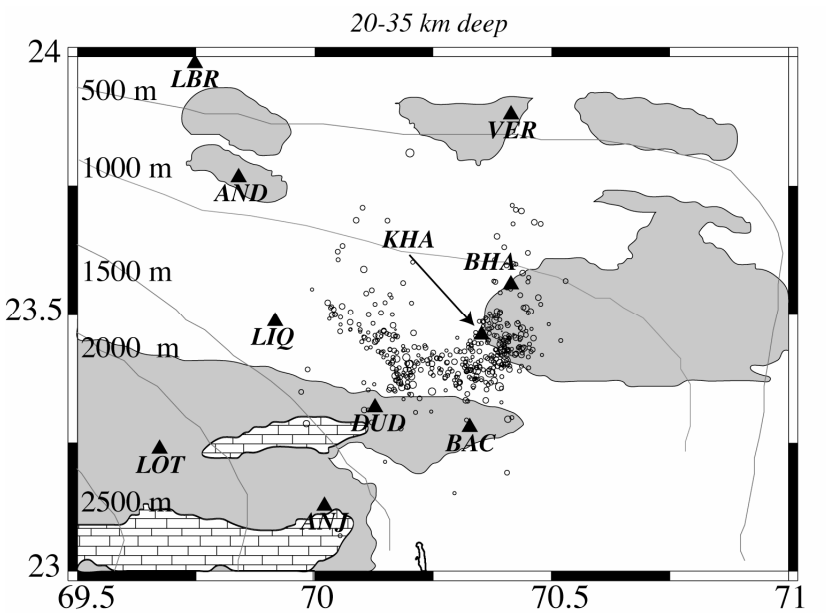


Figure 1 Maps of the region, showing earthquake epicenters of the events studied, locations and station codes of the 3-component stations used, and generalized regional geology (according to Biswas, 1980). White backgrounds indicate areas of Quaternary outcrop, blocked fill patterns represent Cretaceous-aged outcrops, and grey is Jurassic sediments. Depth contours are labeled (in m) with depth to Archean granite basement. a) events of the "Shallow" data set (981 observed waveforms from 174, events occurred within 25 km from the free surface, with magnitude Mw > 2.7); b) events of the "Deep" data set (1808 observed waveforms from 215 earthquakes deeper than 20 km, with magnitude Mw > 2.5).

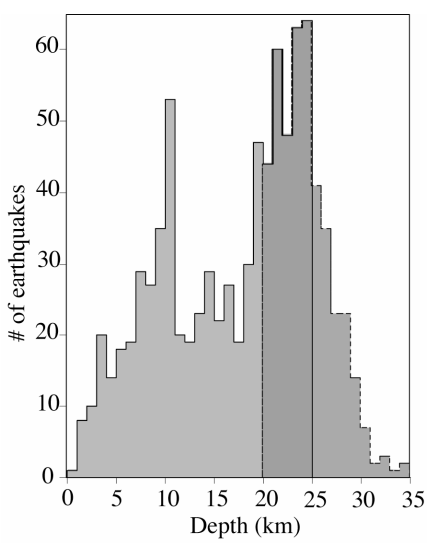


Figure 2 Histogram of the depth distributions of the aftershocks shown in Figure 1. The depth ranges of the two different data sets (Deep and Shallow) overlap between 20-25 km.

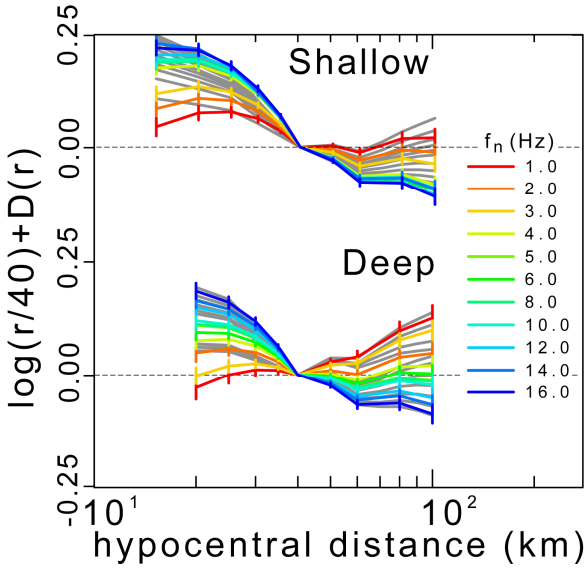


Figure 3 Empirical functions describing the regional attenuation for the shallow and deep bandpass-filtered peak ground motion (from Bodin et al., 2004). Attenuation curves are normalized to 1/r (horizontal lines represent a 1/r decay of the filtered peak ground motion). Curves in color represent the empirical attenuation, whereas the gray curves in the background are theoretical predictions based on RVT, given a geometrical spreading function, a crustal parameter Q=Q(f), and an empirical function describing the frequency-dependent duration of the ground motion as a function of hypocentral distance. Deep and Shallow data sets are characterized by a different attenuation features because the radiated energy in the two cases samples the crust in a different way.

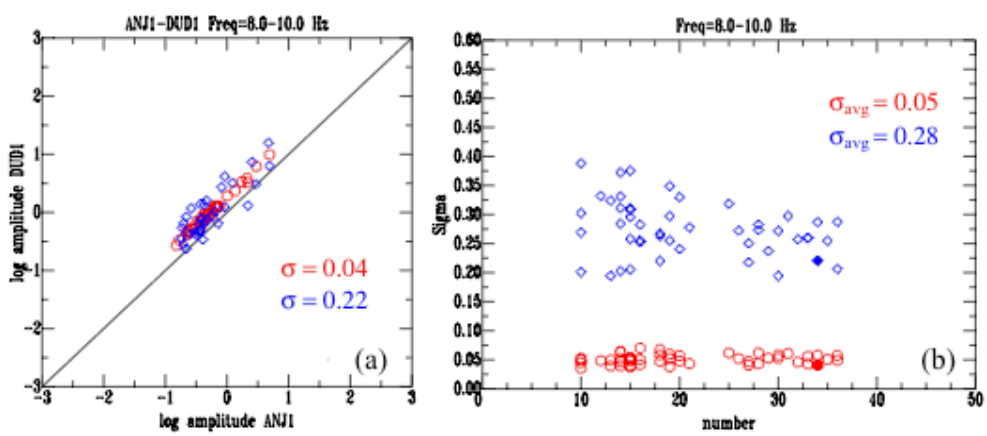


Figure 4 Left: inter-station scatter plot between stations DUD1 and ANJ1, in the frequency range between 8.0 and 10.0 Hz, obtained by plotting the distance-corrected coda spectral measurements (red symbols), and the distance-corrected direct-wave amplitudes (blue symbols). Note the large variance reduction when coda measurements

are used. Direct-wave measurements are corrected for distance using the functional form provided by Bodin et al. (2004). DC-offsets represent the inter-station site effect.

Right: summary plot for over 55 pairs of stations in the 8.0 – 10.0 Hz band, where the x-axis represents the number of common events for each station pair, and the y-axis is the data standard deviation. We also show the data point of the Figure in the left frame as solid symbol. As shown also in the left frame Figure, the average amplitude scatter is over 5 times smaller for the coda.

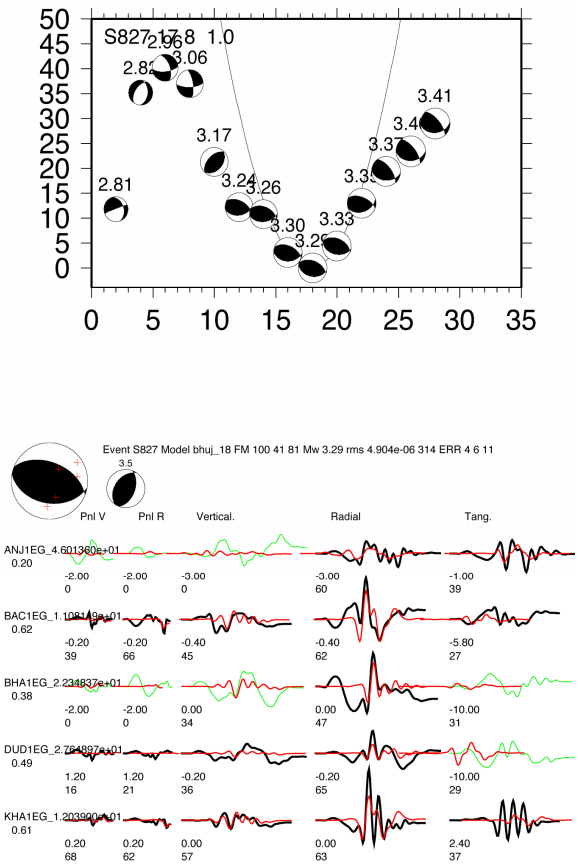


Figure 5 Waveform modeling of one of the calibration events. Top: misfit (normalized) as a function of centroid depth. In the figure are shown the best mechanisms of every point of the grid search on source depth. The method of Zhao and Helmberger [1994], further improved by Zhu and Helmberger [1996], was used to obtain this solution.

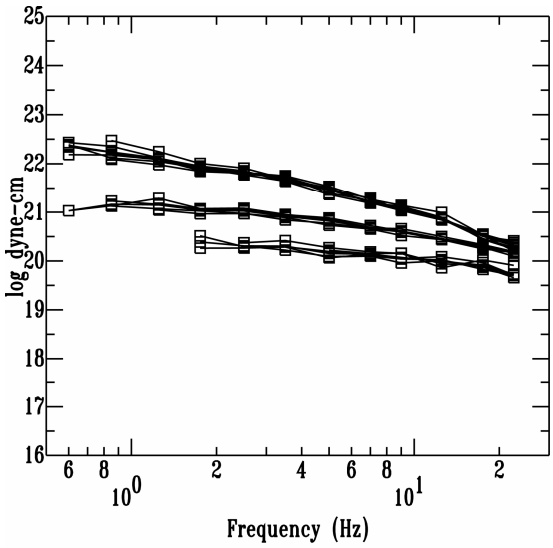


Figure 6: Individual moment-rate spectra computed for three events, each one at a specific set of recording stations: note, for each event, how small is the scatter of the spectral amplitudes.

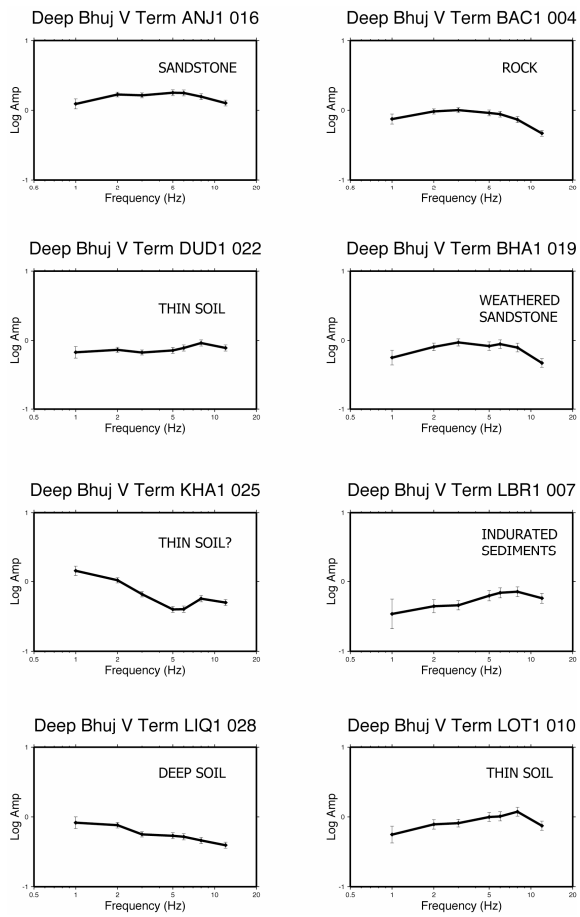


Figure 7 Vertical absolute site terms for the stations of the Bhuj temporary deployment. Error bars represent ± σ. The terms shown in these frames were computed from the Deep earthquakes data set.

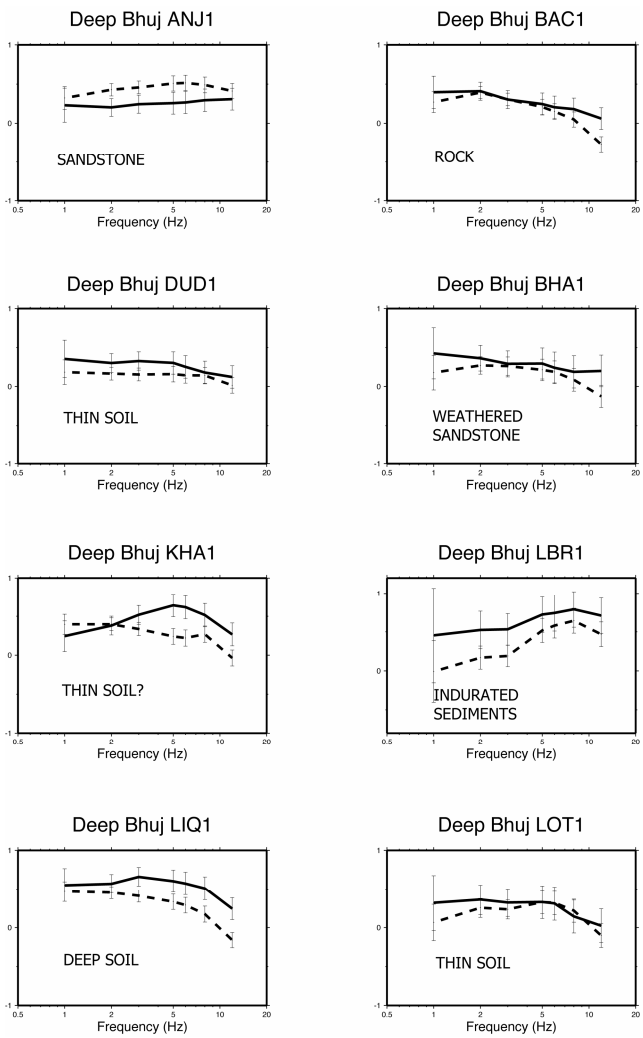


Figure 8 Horizontal absolute site terms and H/V spectral ratios for the Deep Bhuj aftershocks. Dashed lines: horizontal absolute site terms (vector sum of the radial and the transverse individual site terms) for the stations of the Bhuj temporary deployment; solid lines: H/V ratios. Error bars represent ±σ.

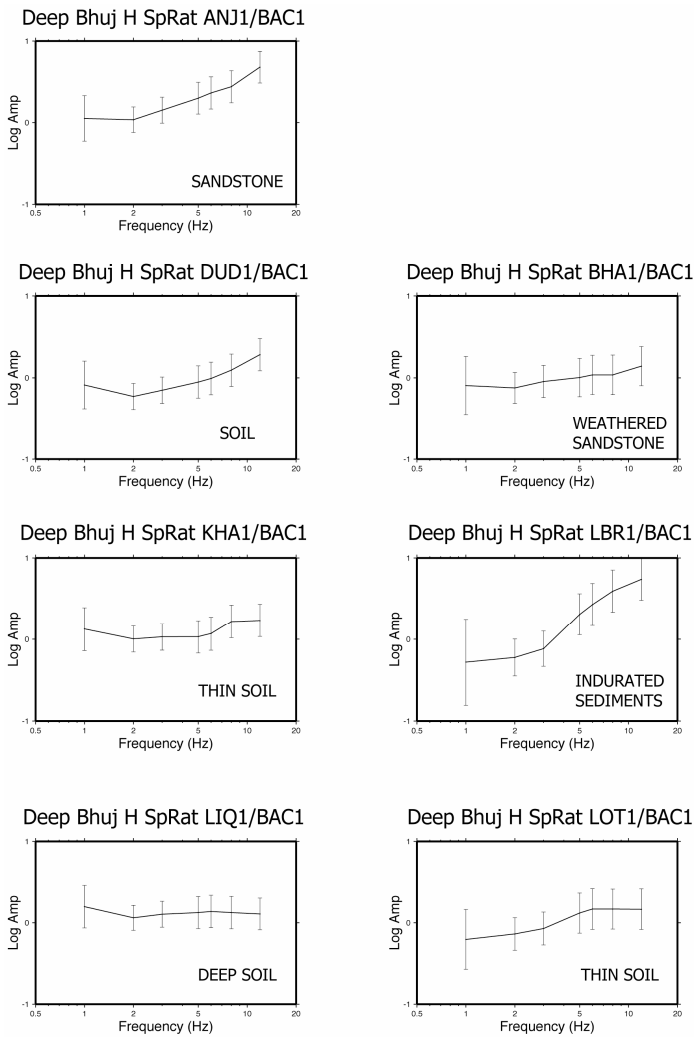


Figure 9 Spectral ratios between the absolute horizontal site terms (vector sum of the radial and the transverse site terms) of all stations to the horizontal absolute site term of station BAC1. Error bars represent ±σ.

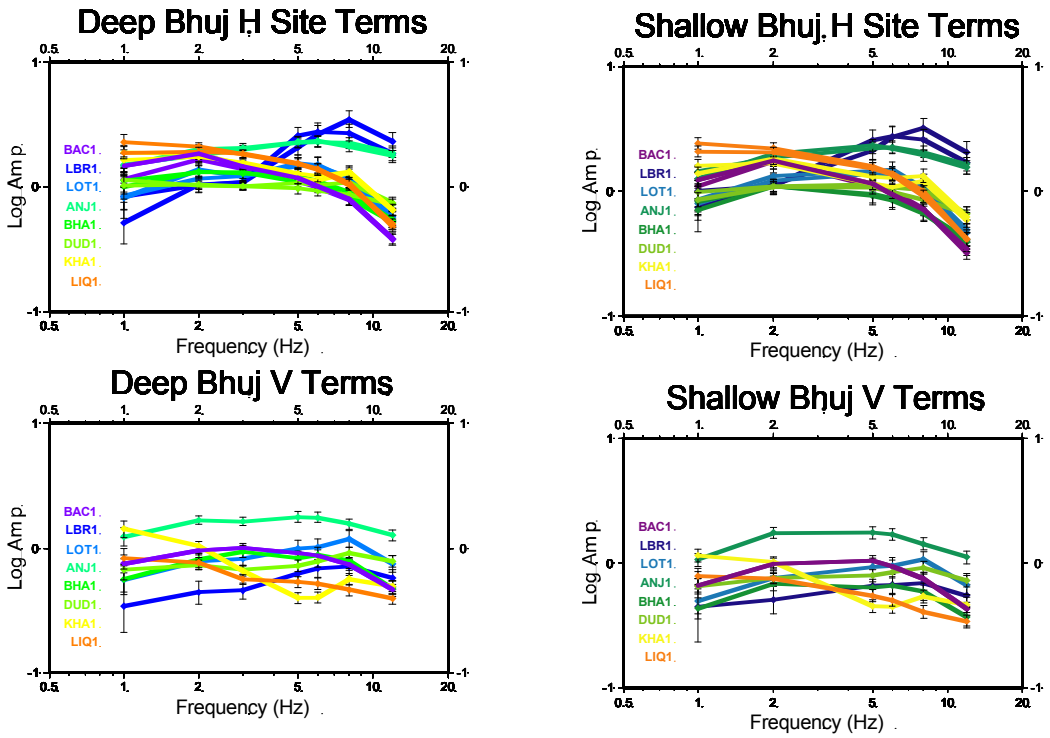


Figure 10 Absolute site terms obtained from the deep data set (left frames), and from the shallow one (right frames). Upper frames show the individual horizontal terms (radial, transverse); lower frames show the vertical absolute site terms. The two sets of results are practically equivalent. Error bars represent ±σ.