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Short Note

New Relationships between V_s, Thickness of Sediments, and Resonance Frequency Calculated by the H/V Ratio of Seismic Noise for the Cologne Area (Germany)

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Abstract Noise measurements were carried out in the Cologne area (Germany), and the resonance frequency of each site was estimated from the main peak in the spectral ratio between the horizontal and vertical component. For 32 of these sites, the thickness of the sedimentary cover was known from boreholes, and a clear correlation between resonance frequency and sediment thickness was observed. A formula that correlates cover thickness with frequency of the main peak in the horizontal-to-vertical spectral ratio was derived. In addition, a best-fitting shear-wave-velocity distribution with depth, $v_s(z)$, as well as a relationship between average shear-wave velocity $\overline{Vs}$ and thickness of the sedimentary cover, was calculated. By using all of the noise measurements and applying the derived relationships, we obtained a subsoil classification for the Cologne area.

Introduction

It is widely accepted amongs the earthquake engineering community that local geology has a significant and sometimes large effect on seismic motion. Therefore, a detailed study of this effect is a matter of great importance in civil engineering. Drilling boreholes allows investigators to obtain detailed information, but it is expensive and slow. Geophysical techniques are an alternative that allow coverage of wide areas at reduced time and cost of investigation. The horizontal-to-vertical technique applied to ambient noise recordings (Nakamura, 1989) has been extensively used in recent times. The theoretical basis of the method is controversial, but the horizontal-to-vertical technique has been validated by comparison with both simulations and earthquake recordings (e.g., Field and Jacob, 1993; Lachet and Bard, 1994; Lermo and Chavez-Garcia, 1994; Bard, 1999; Bindi *et al.*, 2000; Fäh *et al.*, 2001). In general, these studies confirm that the horizontal-to-vertical (H/V) ratio, in the case of a large impedance contrast between sediments and bedrock (>2.5), provides a good estimate of the fundamental frequency of soft soils but not of the higher harmonics. On the other hand, numerical simulations carried out for sedimentary basins (Dravinski *et al.*, 1996; Coutel and Mora, 1998; Al Yuncha and Luzon, 2000) yielded less optimistic conclusions. Simulations, however, strongly depend on the model assumption about the true character of the actual noise field (Bard, 1999).

Recently, different studies (Yamanaka *et al.*, 1994; Ibs-von Seht and Wohlenberg, 1999; Delgado *et al.*, 2000a, b) showed that noise measurements can be used to map the thickness of soft sediments. Quantitative relationships between this thickness and the fundamental frequency of the sediment cover, as determined from the maximum of the H/V spectral ratio of ambient noise (Nakamura, 1989), were calculated for both the Segura River valley (Spain) (Delgado *et al.*, 2000a), and the Lower Rhine Embayment (Germany) (Ibs-von Seht and Wohlenberg, 1999). The limitations of this approach were investigated by Delgado *et al.* (2000b) and recently by Bindi *et al.* (2001).

A subproject of the Deutsches Forschungsnetz Naturkatastrophen ([DFNK]; German Research Network for Natural Disaster) aims at investigation of the site effects on earthquake shaking in the Cologne area (Germany) (Parolai *et al.*, 2001). This area lies in a region where the intensities for an exceedance probability of 10% within 50 years range between 6 and 7 of the European Macroseismic Scale (Grünthal *et al.*, 1998). During the first year of the DFNK project, seismic noise was recorded at 381 sites, some of them close to boreholes drilled down to bedrock. More details on this experiment can be found in Parolai *et al.* (2001).

The aim of this article is to derive new relationships between the main resonance frequency of the soft sedimentary cover, obtained by using the H/V spectral ratio, the thickness of sedimentary cover, and the shear-wave velocity in the Cologne area.

Geological Setting

In the Cologne area (Germany) (Fig. 1), sediments of Tertiary and Quaternary age cover Devonian bedrock. They consist mainly of gravel, sand, and clays. The thickness of the sedimentary layer generally increases from 0 m in the northeast-east of Cologne, where the Devonian basement rocks outcrop in the Bergisches Land, to >300 m in the west-southwest before crossing the Erft fault system. The depth of bedrock does not vary smoothly in the Bergisches Land, because paleoerosion channels and local depressions cause abrupt changes in the thickness of the sedimentary cover. West of the Erft fault system, the basement is suddenly lowered by nearly 600 m, and the sediment thickness may there exceed 1000 m (cf. Fig. 1).

The subsoil in all of the seismic areas of Germany was recently classified by Brüstle *et al.* (2000) into three classes, using data from boreholes: (1) class A: “rock”. Mainly hard rock but also with thin, soft sediments, mostly Quaternary. Hard rock *S*-wave velocity is >800 m/sec. This class of subsoil occurs in the area east of Cologne. (2) class B: “shallow sedimentary basins and transition zone”. Soft sediments, mainly Quaternary, with thickness up to 100 m, Tertiary sediments with thickness up to 500 m, and with thin or without Quaternary coverage. Shear-wave velocity increases gradually up to 1800 m/sec in the Tertiary sequence, rising to values >2000–2500 m/sec when reaching the Mesozoic sedimentary rocks or to mostly >3000 m/sec when the Tertiary is directly underlain by crystalline basement or Paleozoic rocks. This subsoil class occurs in the area east of the Erft fault system up to the boundary with area A. (3) class C: “deep sedimentary basins”. Soft Quaternary sediments thicker than 100 m, Tertiary sediments thicker than 500 m. Shear-wave velocity gradually increases in the Tertiary sediments up to 1800 m/sec with pronounced velocity increases when reaching the Mesozoic sequence or crystalline basement (as in class B). This subsoil class occurs in the area west of the Erft fault system.

Data

From 12 June to 12 July 2000, noise measurements were carried out in the Cologne area. We used 10 digital PDAS Teledyne Geotech recording stations, coupled to 10 Mark L-4C-3D sensors (flat response in velocity between 1 and 40 Hz) at 337 sites. At 36 other sites (where, on the basis of geological maps, the fundamental frequency was expected in the low-frequency range), the measurements were made using a Guralp CMG-40T sensor (flat response in velocity between 0.03 and 50 Hz). At eight sites, noise measurements were carried out with both sensors; 32 of these sites were very close to sites of drilling that had reached basement, that is, to sites with a precisely known thickness of sedimentary cover (Fig. 1).

The data acquisition and processing are outlined in de-

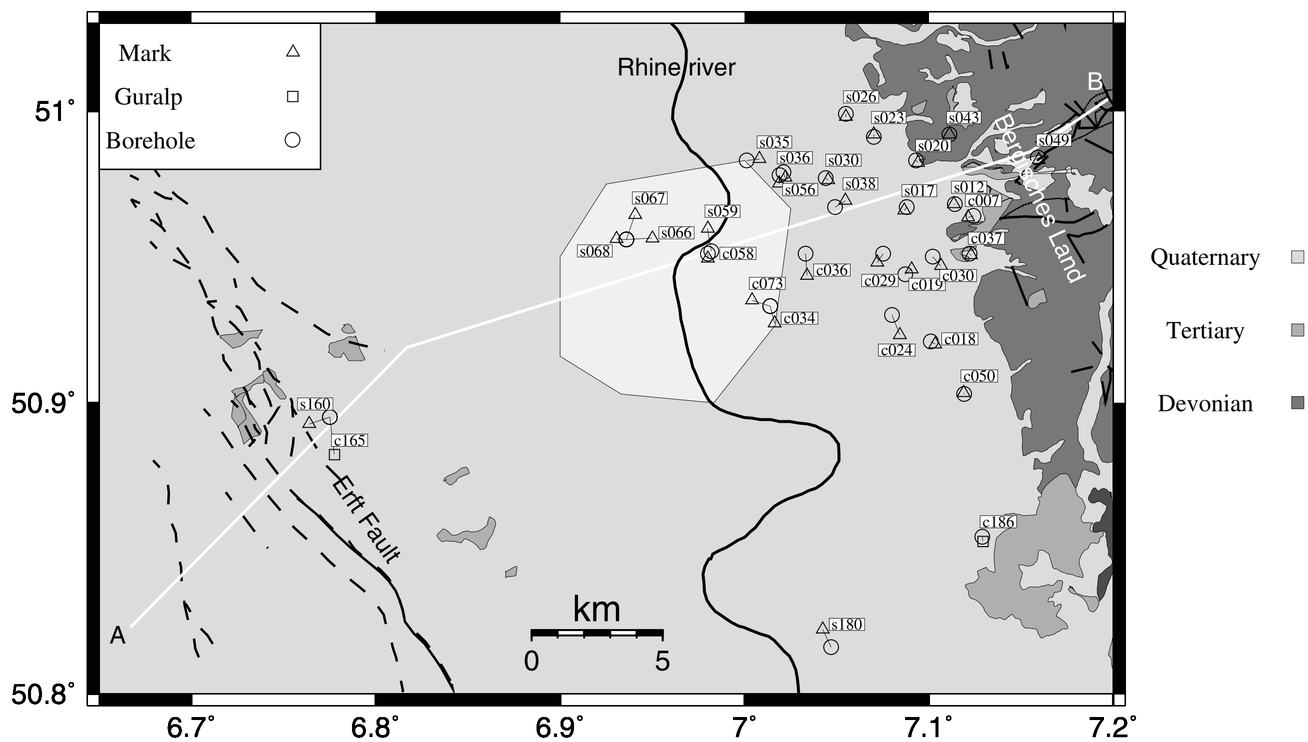

Figure 1. Map of stations and borehole locations. A rough classification of the surface geology is sketched. The gray polygon represents the urban area of Cologne. The thick white line indicates the track of the cross section shown in Figure 4.

tail in Parolai *et al.* (2001). A Hanning window of 28% bandwidth was chosen because it provides a sufficiently good smoothing without suppressing significant features in the spectrum.

Figure 2 shows the H/V spectral ratios calculated for three of the analyzed sites. These examples are representative of most of the analysed sites; that is, the choice of the peak in the H/V ratios is usually unambiguous. Only in few cases did the H/V ratios not show clear peaks. Those ratios were not used in the following analysis. At one of the analyzed sites, s020, located close to a borehole, the shape of the H/V ratio showed a clear first peak followed by a broad maximum at higher frequencies. Because the first peak was clear, it was included in our analysis.

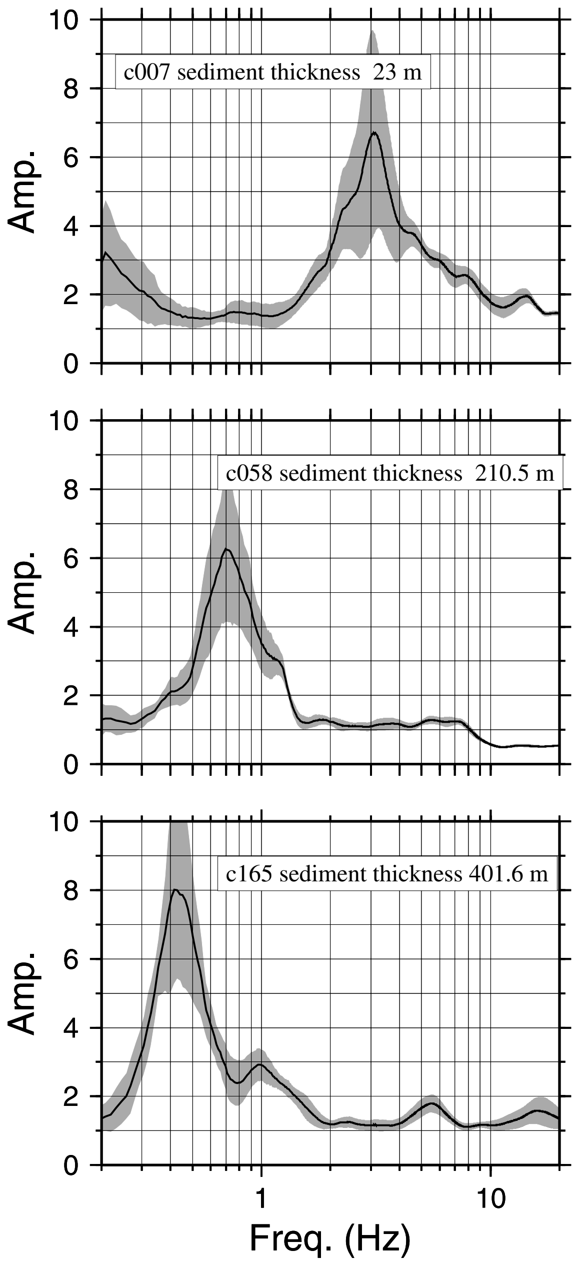

Figure 2. Examples of average H/V spectral ratios ± 1 standard deviation, calculated at sites with different sedimentary cover thickness. The resonant frequency shifts towards lower frequencies with increasing sediment thickness.

h-f_r Relationship

Ibs-von Seht and Wohlenberg (1999) showed that the frequency of resonance (f_r) of a soil layer is closely related to its thickness (h) through the relationship

$$h = af_r^b. \tag{1}$$

Using our estimates of the f_r (from the peak in the H/V ratio) and the thickness of the sedimentary cover obtained from borehole data (Fig. 3), we performed a nonlinear regression fit of equation (1) and obtained for the investigated area the following equation:

$$h = 108\ f_r^{-1.551}. \tag{2}$$

Values and standard errors of the correlation coefficients a and b are given in Table 1.

Figure 3 shows a comparison between our equation and the relation

$$h = 96\ f_r^{-1.388} \tag{3}$$

derived by Ibs-von Seht and Wohlenberg (1999) for a neighboring sedimentary basin in the area of Aachen (Lower Rhine Embayment). Note that equation (2) is based on data for $h < 402$ m only. Ibs-von Seht and Wohlenberg (1999)

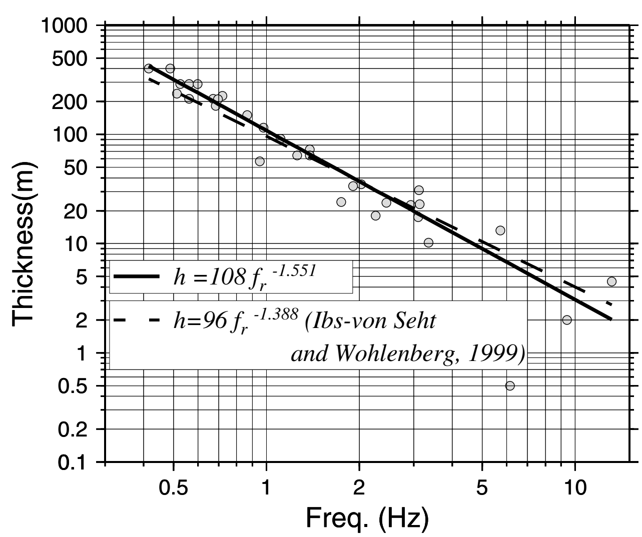

Figure 3. Fundamental resonant frequencies calculated from H/V spectral ratio vs. sediment thickness from borehole data. The solid line is the fit to the data points according to Equation (2). The dashed line is relation (3).

also used boreholes as deep as 1219 m. Both equations give similar estimates of sediment thickness estimations in the frequency range of 1.5–3 Hz. At higher frequencies, equation (2) gives shallower depths of the bedrock than those calculated by equation (3). On the contrary, at lower frequencies, the thickness of the sedimentary cover is larger when equation (2) is adopted.

In a previous study, Parolai *et al.* (2001) compared the thickness of the sediments in the Cologne area, obtained by means of equation (3), with that derived from the geological cross section of a 1:100,000 geological map (Von Kamp, 1986). The cross section was derived by geological reconstruction, with good control from a few boreholes in the area east of the Erft fault, but only with control from regional boreholes west of the fault system. Parolai *et al.* (2001) found some discrepancies, especially where the thickness of the sediments is large. There the depth of the bedrock was generally underestimated by up to 30%. This systematic error is certainly larger than the random errors due to uncertainties in the fitting procedure, errors in picking the value of the fundamental frequencies, errors in deriving the geological cross section, and errors in the borehole data. It suggests that equation (3) is inadequate for the Cologne area.

Figure 4 shows the same geological cross section that was shown in Parolai *et al.* (2001) (for its position, see the profile in Fig. 1). Using the fundamental f_r calculated by means of the H/V spectral ratio of noise for some sites close to the profile, we estimated the thickness of the sedimentary cover by both equations (2) and (3). Figure 4 clearly shows that equation (2) provides a better estimate of the sediment thickness down to >1000 m, although it was calibrated only up to bedrock depth of 400 m. Therefore, we think that the new equation (2) is more suitable than equation (3) for the Cologne area.

Velocity–Depth Function

A velocity–depth function in a sedimentary layer may be written as

$$v_s(z) = v_{so} (1 + Z)^x, \tag{4}$$

where v_{so} is the surface shear-wave velocity, $Z = z/z_0$ (with $z_0 = 1$ m), and x gives the depth dependence of velocity. Taking this into account and considering the well-known relation among f_r, average shear-wave velocity of soft sedimentary cover $\overline{Vs}$, and its thickness h,

$$f_r = \overline{V}s/4h, \tag{5}$$

the dependency between thickness and f_r becomes

Table 1
Values of *a, b, c, d* of Equations (2), (3), and (8) and Correspondent Standard Errors

Equation	*a*	Δ*a*	*b*	Δ*b*	*c*	Δ*c*	*d*	Δ*d*
2	108	7	1.511	0.108				
3	96	4	1.388	0.025				
8					73	10	0.380	0.027

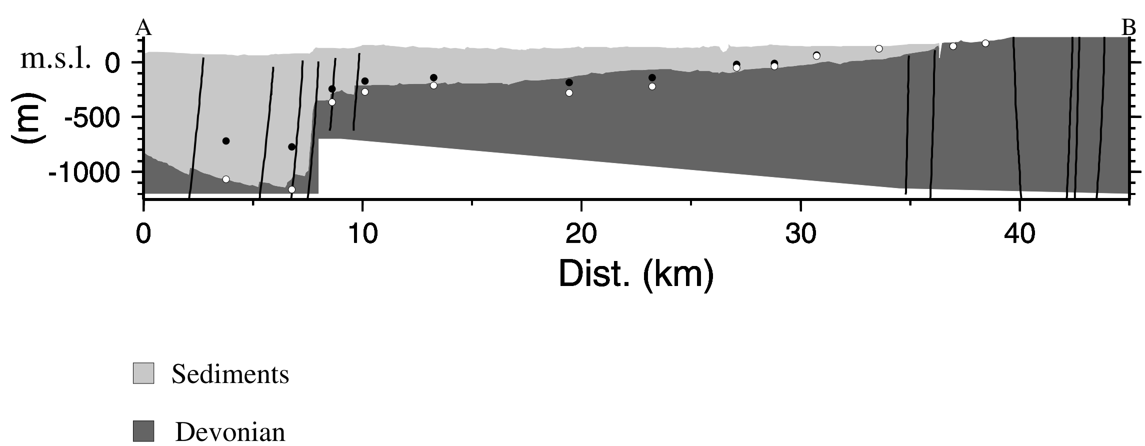

Figure 4. Cross section showing thickness of the sedimentary cover obtained on sites located close to the profile in Figure 1. The black dots indicate the thickness of the sediments derived by using relation (3). The white dots indicate the thickness of the sediments derived by using relation (2) in this study. The subvertical black lines indicate faults.

$$h = \left[v_{so} \frac{(1 - x)}{4f_r} + 1 \right]^{1/(1-x)} - 1, \qquad (6)$$

where f_r is to be given in Hz, v_{so} in m/sec, and h (soft sedimentary layer thickness) in m (Ibs-von Seht and Wohlenberg, 1999).

Budny (1984), using downhole measurements in the Lower Rhine Embayment, obtained a value for the surface shear-wave velocity of $v_{so} = 162$ m/sec and the depth dependence $x = 0.278$. When these parameters are used in equation (6), a fair fit (not shown in Fig. 3) of the data points is obtained without any systematic over- or underestimation of thickness. This evidence is consistent with the hypothesis that the peak in the H/V ratio is a reasonable estimate of the fundamental f_r. However, Budny's parameters might not be the most appropriate ones for the area under investigation.

Therefore, to derive an improved velocity–depth function for the Cologne area, an iterative fitting procedure was carried out. h was calculated for every site near a borehole, varying the velocity v_{so} and the depth dependence of the velocity x in a wide range of values (for v_{so} between 80 and 2500 m/sec and for x between 0 and 0.99, respectively) in steps of 5 m/sec and 0.01, respectively. This grid search allows us to find the optimal combination of v_{so} and x that led to minimum misfit between the observed and the computed h. The misfit is calculated as the root mean square of the differences between the observed and the calculated h. The absolute minimum was obtained when $v_{so} = 115$ m/sec and $x = 0.37$.

Figure 5 shows the comparison between the Budny (1984) relationship and the one derived in this study. The latter shows higher velocities for depths >60 m inside the sedimentary cover. This result is consistent with relationship (2). A profile with higher shear-wave velocities $v_s(z)$ leads to a higher average shear-wave velocity $\overline{Vs}$, and thus, using equation (5), a certain value of f_r corresponds to a larger thickness of the soil layer.

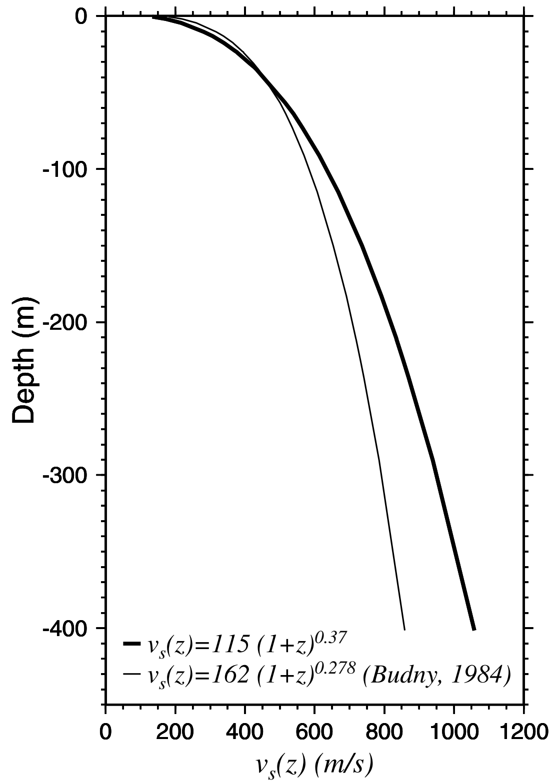

Figure 5. *S*-wave velocity vs. depth as derived in this study (thick line) compared with that of Budny (1984) (thin line).

Average Shear-Wave Velocity ($\overline{Vs}$)–Thickness Relationship

Delgado *et al.* (2000b) showed that the average shear-wave velocity of the soft sedimentary column, $\overline{Vs}$, can be related to its thickness h through a relationship of the form

$$\overline{Vs} = ch^d. \qquad (7)$$

Using the h values and the fundamental f_rs calculated for sites where boreholes were drilled, the average shear-wave velocity $\overline{Vs}$ was calculated by expression (5). Then, $\overline{Vs}$ and h data were fitted to equation (7), yielding the relation:

$$\overline{Vs} = 73\ h^{0.380}. \qquad (8)$$

Values and standard errors of the correlation coefficients c and d are given in Table 1.

Hollnack (2001, personal communication), using borehole data in the Cologne area, derived the relationship for the shear-wave velocity in the bedrock v_{sb} versus depth z as

$$v_{sb}(z) = 210(1 + z)^{0.448}, \qquad (9)$$

which is applicable in the depth range from 20 to 377 m. For smaller depths, v_{sb} is fixed to 800 m/sec, and for depths below 377 m, to a velocity of 3000 m/sec.

Considering equations (2), (8), and (9), it appears that the minimum impedance contrast between the sedimentary layer and the bedrock, estimated from the velocity contrast alone, is >2.5 in the whole frequency range that we analyzed. Taking into account the density difference between sedimentary cover and basement rock, the actual impedance contrast is surely >3, that is, big enough to yield conspicuous H/V peaks (Bard, 1999).

Because the practice in earthquake engineering requires consideration of the average *S*-wave velocity in the uppermost 30 m we discuss our results considering their usefulness for soil classification in the Cologne area. However, two general points have to be made. First, the subsoil classification based on the average *S*-wave velocity of the uppermost 30 m of the site can highlight 1D site effects, but it is of no help when 2D or 3D site effects occur. Second, sites with sedimentary cover thinner than 30 m and with low shear-wave velocity might still amplify the ground motion at higher frequencies (with wavelengths <30 m), which may be close to the fundamental frequency of vibration of low-rise buildings.

Figure 6 depicts the increase with depth of the average velocity $\overline{V}s$. The subsoil classification proposed by Ambraseys *et al.* (1996), similar to that used by Boore *et al.* (1993), is also shown. The classification of Ambraseys *et al.* (1996) is based on shear-wave velocity averaged over the upper 30 m of the site. The classes of site geology are defined as follows: rock, > 750 m/sec; stiff soil, 360–750 m/sec; soft soil, 180–360 m/sec; and very soft soil, <180 m/sec.

From Figure 6, it follows that at sites where the soft sedimentary cover in the Cologne area is thicker than 30 m, the average *S*-wave velocity in the uppermost 30 m can be calculated using equation (8). The obtained velocity indicates that these sites should always fall into the soft soil category of the Ambraseys *et al.* (1996) classification. In contrast, sites with soil columns thinner than 30 m may, depending on the depth of and the velocity in bedrock, fall into any of the aforementioned classes, that is, even into the rock class. Therefore, a proper risk-relevant classification of such sites requires more detailed investigations with precise measurements of both sediment and bedrock velocity.

Using the f_rs calculated in this area by Parolai *et al.* (2001), the soil thickness was calculated for the whole area by equation (2). Figure 7 shows the respective map. Small inconsistencies between the sedimentary cover thickness measured at the borehole sites and the calculated ones shown in Figure 7 are due to the interpolation procedure used for producing a continuous map. Figure 7 also shows the location of all measurement points used to produce the map and the subdivision of the investigated area in zones where the thickness of sediments is >30 m and <30 m, respectively. Note that the sedimentary thickness is well constrained only in areas with dense, neighboring points. The borderline between the two depicted zones nearly follows the 2-Hz contour line in figure 12 of Parolai *et al.* (2001).

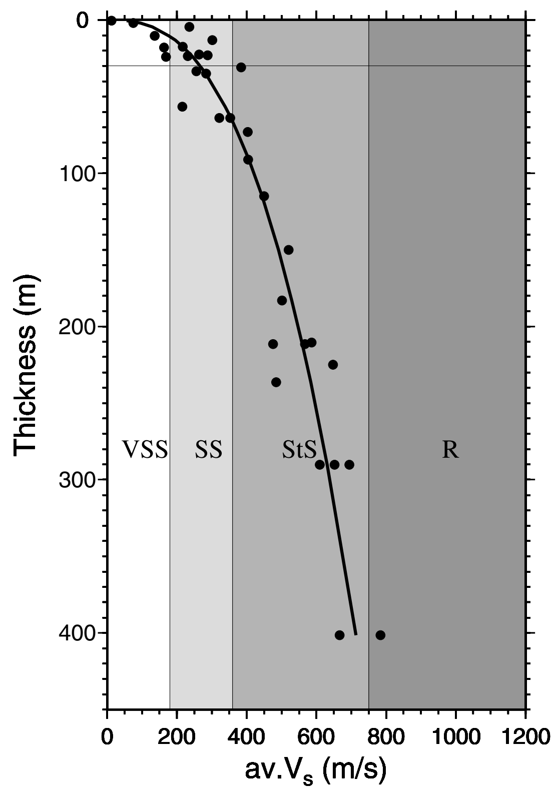

Figure 6. Average shear-wave velocity $\overline{V}s$ vs. sediment thickness *h* (or depth of bedrock below the surface). Dots indicate $\overline{V}s$ values calculated by means of equation (5). The black line represents the fit to the data points. VSS, very soft soil; SS, soft soil; StS, stiff soil; R, rock. The thin horizontal line indicates the sediment thickness of 30 m.

Conclusions

The H/V spectral ratio of seismic noise was calculated for sites close to boreholes where the thickness of the sedimentary cover was known. Consistent with previous studies, a relationship between sediment thickness and the frequency of the main peak in the H/V spectral ratios was calculated. The new relationship, validated for the area of Cologne, yields better estimates of the thickness of the sedimentary cover, along the profile shown in Figure 1, than equation (3). Using all of the noise measurements carried out in the framework of the DFNK project, the new equation allows us to calculate the sedimentary layer thickness in a wider area.

Our results confirm the suitability of the H/V ratios of seismic noise as a geophysical exploration tool, at least in geological structures with a significant impedance contrast between the sedimentary layers and bedrock.

In addition, we estimated the shear-wave-velocity distribution with depth within the sedimentary column, $v_s(z)$, and the average shear-wave velocity, $\overline{V}s$, depending on the thickness of the column. This allowed a classification of the sedimentary cover, which can be used for seismic-hazard assessment. It can also guide the choice of the optimal response spectrum, at least where the sediment thickness is >30 m.

Acknowledgments

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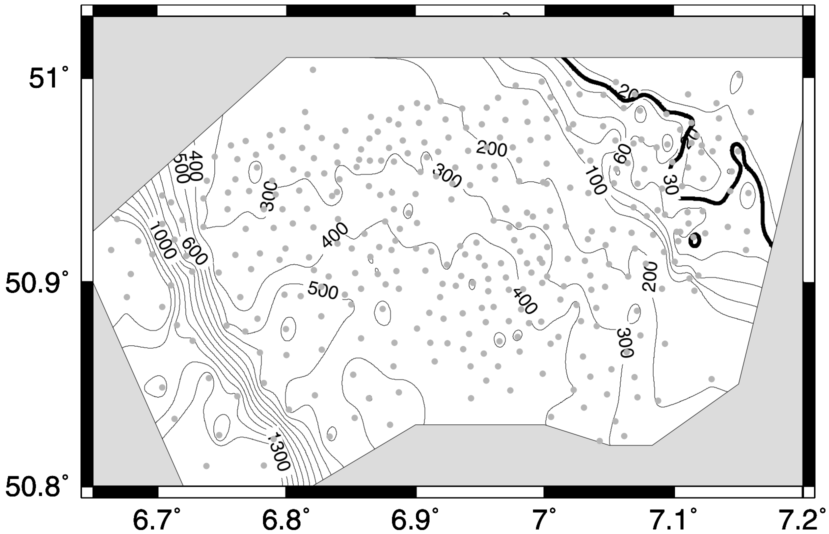

Figure 7. Sediment thickness obtained from equation (2) and the fundamental resonant frequencies f_r by Parolai *et al.* (2001). The thick line is the 30-m contour line. Contouring is performed every 20 m for thicknesses <100 m. For thickness >100 m, contouring is shown every 100 m. Gray dots indicate the position of the sites where the resonant frequency was determined by Parolai *et al.* (2001).

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