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The determination of soil attenuation by geophysical prospecting and the validity of measured Q values for numerical simulations

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Q values of shallow materials are derived from seismic experiments in different frequency ranges. Three main measurement techniques are used: the rise-time method, the spectral ratio method and the study of surface wave attenuation. Attenuation measurements are performed in different geological site conditions. The Q values obtained at high frequency with the rise-time and spectral ratio methods are found to be lower than the values inferred from surface waves at lower frequencies. These results suggest a frequency dependence of the quality factor in surficial materials.

Two sites are thoroughly investigated by geophysical prospecting. On the basis of the geometry and the dynamic characteristics of the geological formations, numerical modeling (1D and 2D) is carried out in order to compute the site response to small earthquakes or other solicitations.

Comparisons between theoretical and experimental transfer functions show a good agreement if the Q values used in the computations are those measured in the same frequency range as that of the solicitation. These results stress the importance and the need of careful investigations about the frequency dependence of Q.

INTRODUCTION

During the last few years, several attempts have been made to infer surficial ground attenuation characteristics from in-situ tests (see for example Refs 1–3). The problem is rather complex owing to the difficulty to separate intrinsic attenuation from other causes of amplitude decrease such as transmission loss or diffraction. Intrinsic Q determinations are to be limited to horizontally layered media.

On the other hand, the quality factors Q^s and Q^P constitute prominent parameters having an important effect upon the amplitude and duration of ground motions during earthquakes. Their determination by field measurements appears to be a crucial point for the quantitative interpretation of the amplification effects often produced by surficial deposits.

Many methods have been proposed to measure the ground attenuation from geophysical prospecting.[1] The results derived from different techniques usually show a large dispersion. On the other hand, several authors[4,5] have presented data indicating that the quality factor could vary with frequency. Such a frequency dependence has already been found at the scale of the lithosphere.[6]

To test if Q values actually vary with frequency in surficial deposits, seismic experiments were carried out in various sites with the aim of measuring Q values in different frequency bandwidths. Numerical simulations are carried out in different cases in order to validate the Q values by comparing theoretical and experimental results.

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METHODS OF Q DETERMINATION

The quality factor Q is usually defined[7] as:

$$Q = \frac{4\Pi E}{\Delta E} \qquad (1)$$

where E is the average energy stored during one cycle of loading at the considered frequency and ΔE is the energy dissipated by the cycle.

In the authors' study, three computational techniques were used to derive Q^p or Q^s values from surface seismic prospecting: the rise-time method, the spectral ratio technique and the study of the surface wave attenuation.

The first two techniques which are applied to body waves are classical methods used by geophysicists to infer the anelastic properties of rocks.[1] The way they are employed in this study is described in detail by Jongmans.[3]

As we are concerned with surficial soil attenuation, the surface waves generated during refraction tests are used to derive Q^s values as a function of depth. The method which was developed by Herrmann[8] is based on the inversion of the attenuation factor of surface waves. These measurements usually correspond to frequencies lower than those investigated by the two former techniques.

Table 1. Sketch velocity model for the sites in the Brabant Massif

Geological formation	Thickness (m)	V^p (m/s)	V^s (m/s)
1. Loess	5	300	180
2. Dry sand	5	430	250
3. Dry sand	30	600	400
4. Saturated sand weathered bedrock	35	2000	450
5. Bedrock	—	4500	—

The methods used for Q determination, based on the processing of different wave types, are however investigating the same soil layers.

SITE EXPERIMENTS IN THE BRABANT MASSIF (BELGIUM)

Field experiments were carried out in two different sites in Belgium, the geology of which is very similar. A velocity profile was determined from refraction tests. The structure which consists of horizontal layers of soil overlying the Cambro-Silurian basement is given in Table 1.

The quality factors of the Bruxellian sand at the first site were computed by the spectral ratio and rise-time

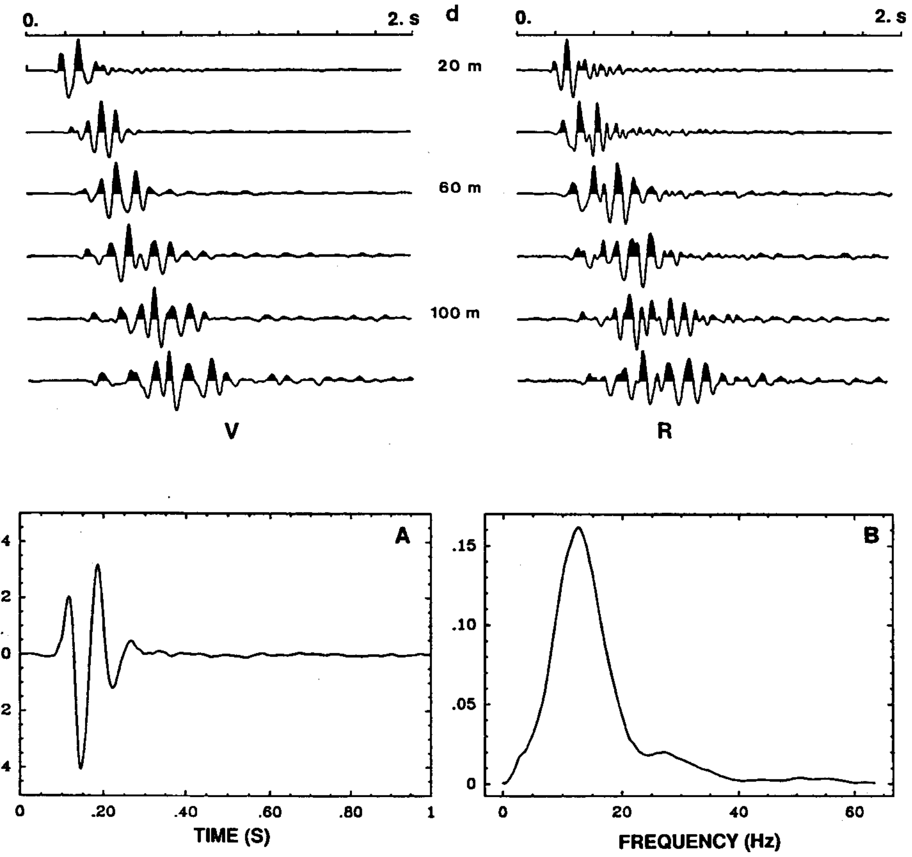

Fig. 1. Top: normalized field seismograms generated by a falling mass at distances ranging from 20 to 120 m. V, Vertical component; R, radial component. Bottom: signal source (A) and its Fourier transform (B).

methods. The results, which are already published,[3] show very low Q^P values: about 5–6 in a frequency range of 25–68 Hz. These values are similar to those found by Meissner and Theilen[4] in dry sand for the same frequencies.

On the same site a second experience with a more energetic source (a mass of 200 kg falling from 11 m) was carried out. The normalized seismograms (radial and vertical directions) are presented in Fig. 1 with the source characteristics (measured very near the mass impact).

On the basis of the elastic parameters inferred from geophysical prospecting, synthetic seismograms were computed using the discrete wavenumber method[9] which is based on the representation of the source radiation by a discrete superposition of cylindrical waves. The intrinsic attenuation was introduced by replacing the elastic velocity by a complex equivalent velocity in the propagator factor according to a formulation detailed in Aki and Richards.[10]

The theoretical seismograms were fitted to the records by varying the Q^P values. Q^S values were supposed to be the same as Q^P in each layer. Figure 2 shows vertical seismograms computed for different Q sets (A), (B) and (C).

The best fit between experimental and theoretical data (Fig. 3) is obtained for Q values of 10, 15, 15 and 10 in the first four layers. These values are clearly superior to those inferred at high frequencies from rise-time and spectral ratio techniques applied on the first arrivals.

On the second site, seismic experiments were conducted in order to determine Q^S values. S waves were generated by hitting the extremity of a loaded plank and the records from 2 to 72 m are shown in Fig. 4 with the Fourier spectrum of the nearest record to the source.

Rise-time measurements lead to Q^S values of about 6 in the different surficial layers. These values are very similar to those computed by the spectral ratio method with different couples of records. As an example, Fig. 5 shows at a logarithmic scale the spectral ratio Δ (corrected by the distance and the velocity) as a function of frequency for the seismograms recorded at 50 and 72 m from the source, respectively. In this diagram, the slope of the line gives the inverse of the quality factor. The fluctuations observed on the curve (Δ–f) can be explained by the relatively short distance between the two captors used to compute the spectral ratio.

On the other hand, Q^S values were deduced from the attenuation of Rayleigh waves generated by explosions. The authors use geophones with a natural frequency of 4·5 Hz. Figure 6 shows an example of vertical records illustrating the predominance of Rayleigh waves in the distance range 100–250 m. Figure 7 presents the attenuation factor (normally corrected for the geometrical spreading) as a function of period (0·03–0·14 seconds). The Q^S and V^S vertical profiles were computed from an inversion process assuming an initial 10-layer model. The theoretical attenuation curve is compared to the experimental dots in Fig. 7.

Q^S values as a function of depth are also presented in Fig. 7 with the error bars. In the same figure, the resolving kernals show that the resolution is good down to 16 m.

From 3 to 6 m depth, the shear wave quality factor is about 20, which is a much larger value than the results deduced at higher frequency in the same layers.

Both studies performed on the two sites seem to indicate that the quality factor (Q^P or Q^S) is dependent on the frequency. For a dry sandy soil the relation found is that the attenuation is stronger at high frequency (above 30 Hz). This phenomenon could explain the discrepancy between the Q values determined from seismic experiments and the higher values needed to be considered in modeling to simulate in a realistic way the response of geological structures.

SITE RESPONSES TO EARTHQUAKES (UBAYE VALLEY AND SART–TILMAN)

In order to test the validity of Q values determined from seismic prospecting and the possibility of dependence of Q on frequency, theoretical and experimental site responses are compared in two cases. The first site is a 1D structure (Sart–Tilman) where a permanent station of the Belgian network is set up. The second case consists in a small 2D valley (Ubaye) in the Alps, the response of which has been studied by a temporary array of five stations.

The Sart–Tilman site

The first example concerns the response of a horizontally layered medium to a vertical incident P wave.

The geology of the site, which has been thoroughly investigated, and the dynamic characteristics are presented in Table 2. Q^P values in the surficial layers were determined by the spectral ratio method for frequencies between 30 and 150 Hz.

The permanent seismological station consists of a 1 Hz vertical seismometer located in a borehole at a depth of 16·5 m. For a few months (from July 1988 to November 1988), a second seismometer was installed at the surface and both recorded a local earthquake ($M^L = 3{\cdot}5$, epicenter distance: 44 km). The seismograms and the Fourier spectra of P waves are given in Fig. 8.

The experimental transfert function which corresponds to the spectral ratio of the two signals is shown in Fig. 9 where it is compared to the theoretical site response computed by the Thomson–Haskell method on the basis of the dynamic parameters given in Table 2.

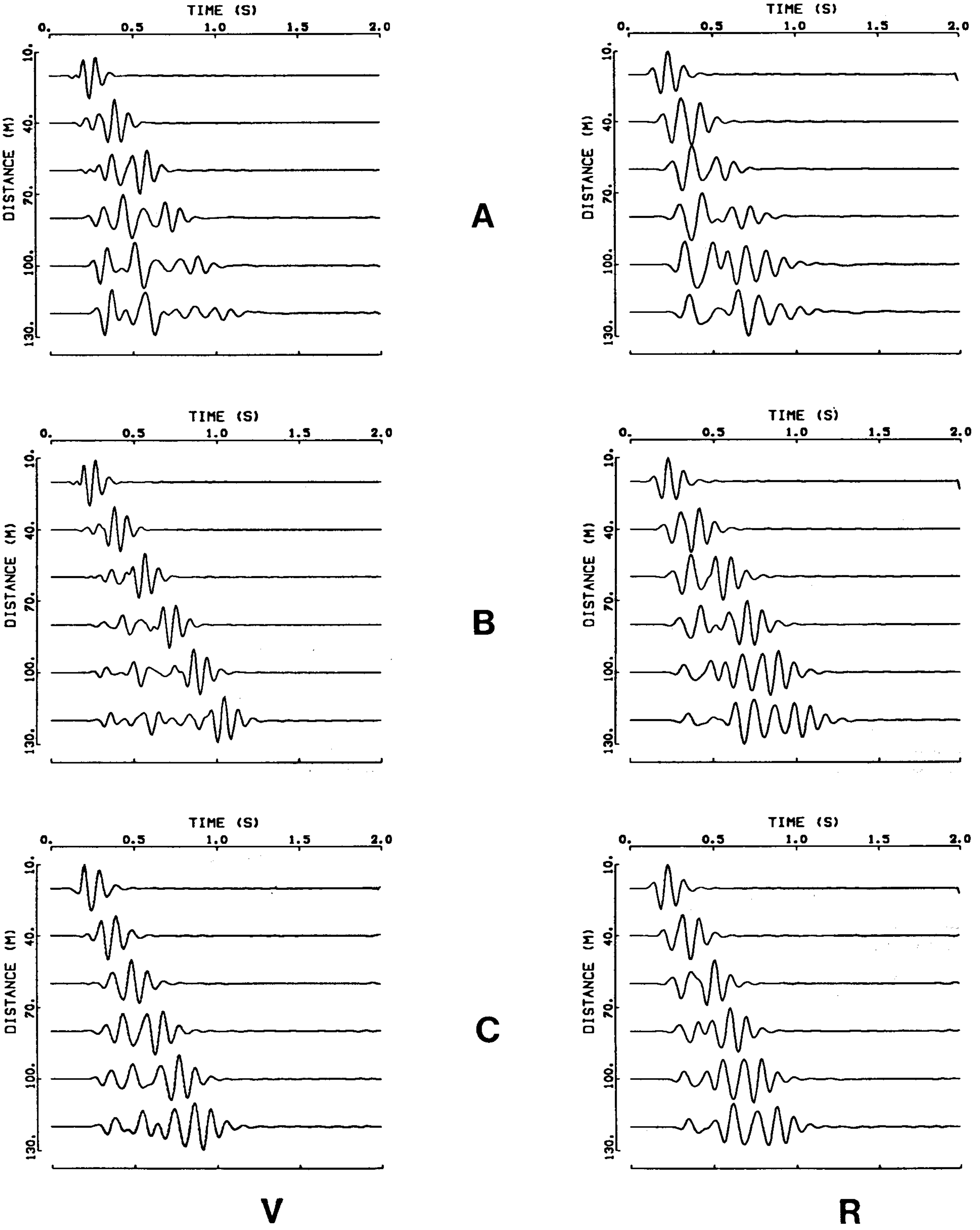

Fig. 2. Vertical seismograms computed for different Q sets in the four layers. (A) $Q = 6, 6, 6$ and 10; (B) $Q = 15, 15, 15$ and 15; (C) $Q = 10, 15, 15$ and 10. V, Vertical component; R, radial component.

The main feature of the site effect, which is an amplification of 7 at a frequency of about 38 Hz, is predicted well by the numerical simulation. To show that the good fitting of the two curves results from the correct determination of the quality factor, the transfert functions were also calculated for Q^P values of 3 and 10 (Fig. 9). The comparison between the different amplification curves illustrates the sensitivity of the maximum amplification to Q^P values. From this figure, Q determinations appear to be reliable but one has to

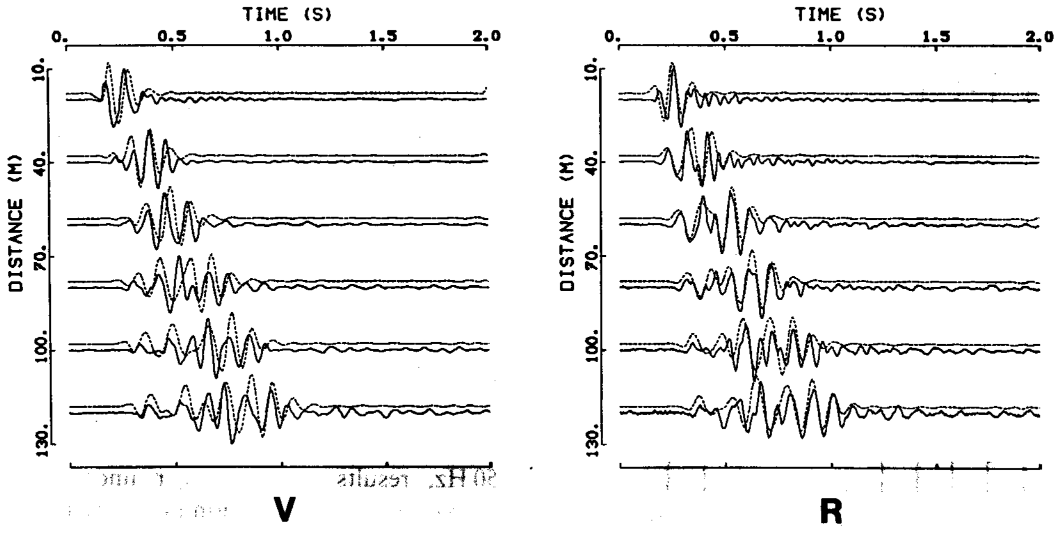

Fig. 3. Comparison between synthetic seismograms (case (C) of Fig. 2) and experimental data (solid lines).

notice that Q^P has been measured for a frequency range (30–150 Hz) including the bandwidth where the amplification occurs.

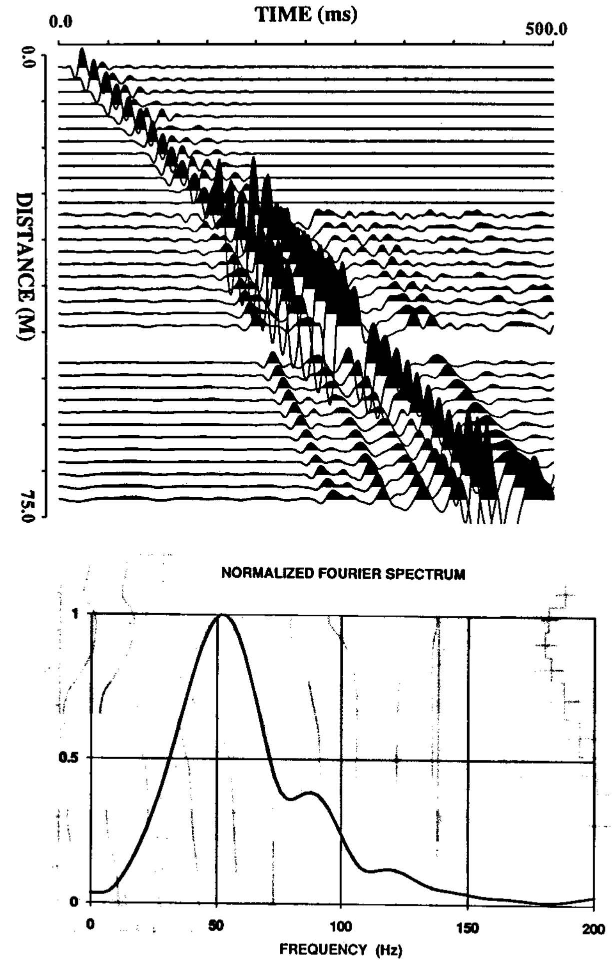

Fig. 4. SH seismograms (2–72 m) with the Fourier spectrum of the first signal.

The Ubaye valley

The Ubaye valley, located in the French Alps, is characterized by a relatively high seismicity. A temporary network of five three-component stations was set up during one month to study the site response.

The geological structure, which was previously unknown, was investigated by geophysical prospecting including refraction tests, reflection profiles and surface wave inversion methods.[11] A North–South cross-section through the valley which can be considered as two-dimensional is presented in Fig. 10. The limestone bedrock ($V^s = 2400\,\text{m/s}$) is overlaid with a consolidated moraine lens ($V^s = 1100\,\text{m/s}$) and a mixing of alluvial deposits and colluvium ($V^s = 250$ and $600\,\text{m/s}$).

Q^s measurements were carried out by the rise-time method and the surface wave attenuation study. The two techniques give rather different results. Q^s values of 5–6 were determined by the rise-time method at relatively high frequency (30–59 Hz) whereas surface

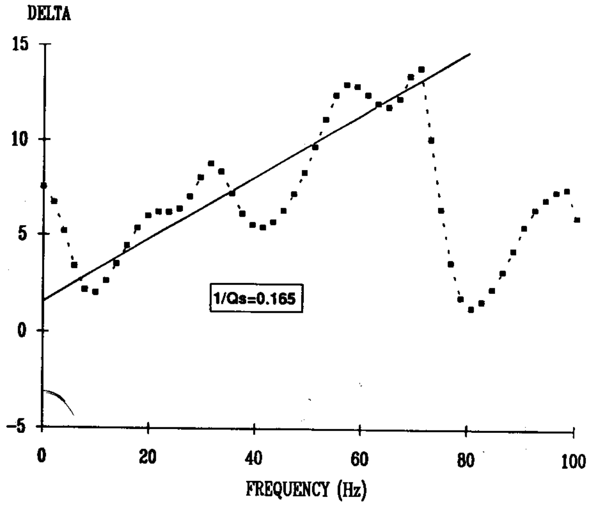

Fig. 5. Spectral ratio method. The slope of the line gives the attenuation ($1/Q$).

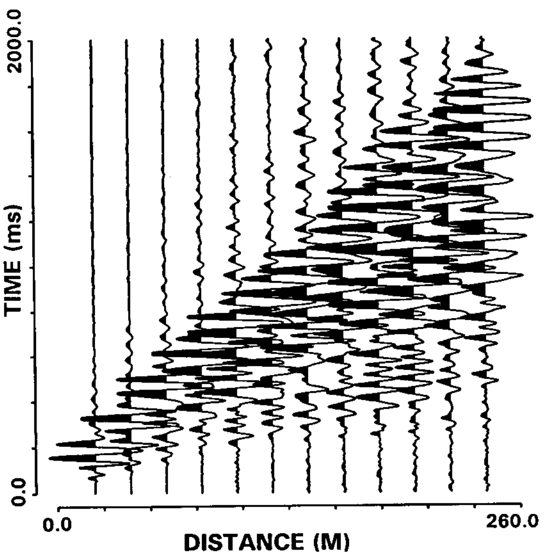

Fig. 6. Seismograms (vertical component) generated by an explosion.

wave study leads to Q^s values of 10–20 in a lower frequency range (9–16 Hz).

Local earthquakes with epicenter locations in the plane of the section were recorded by the five stations the position of which is indicated in Fig. 10. Station 1 was located on a limestone outcrop, whereas the others were installed across the valley. Average spectral ratios were computed in order to obtain the spectral amplification at the stations in the valley with respect to the rock motion. The amplification at station 2, computed for the EW horizontal component (SH case), is presented in Fig. 11.

This experimental amplification is compared in the same figure with theoretical transfert functions computed in a 2D model deduced from the results of seismic prospecting. Two Q^s data sets are considered in the modeling to take into account the variation with frequency. To compute the response of the 2D structure, the authors used a boundary integral equation method[12] in the case of vertically incident SH waves. The comparison of observed amplification with theoretical transfert function shows that the 2D prediction slightly underestimates the amplification for the higher values of Q^s. On the other hand, the second data set, determined for frequencies between 30 and 50 Hz, results in a stronger underestimation of the amplification phenomenon in the frequency range of 2–20 Hz. These results, which were also obtained at the other stations, again seem to show a frequency dependence of Q. Comparisons between theoretical and experimental amplifications show a better agreement if the Q values used in the computations are those measured in the same frequency range as that of the solicitation.

Table 2. Dynamic characteristics of the layers (Sart–Tilman site)

Geological formation	Depth (m)	V^P (m/s)	Q^P
Loess	0–2	600–750	5
Weathered bedrock	2–9	1000–1200	5
Bedrock	> 9	1900–2200	50

DISCUSSION AND CONCLUSIONS

In this paper, the quality factor in soils was derived from seismic experiments for frequencies ranging mainly from 10 to 150 Hz. The measured quality factors are usually low (5–20) and some very low values are not theoretically compatible with eqn (1) and a standard viscoelastic behavior. The good fit between computed and measured ground motions seems, however, to show that the introduction of low Q values in the propagation equation gives surprisingly good results, at least for weak motions.

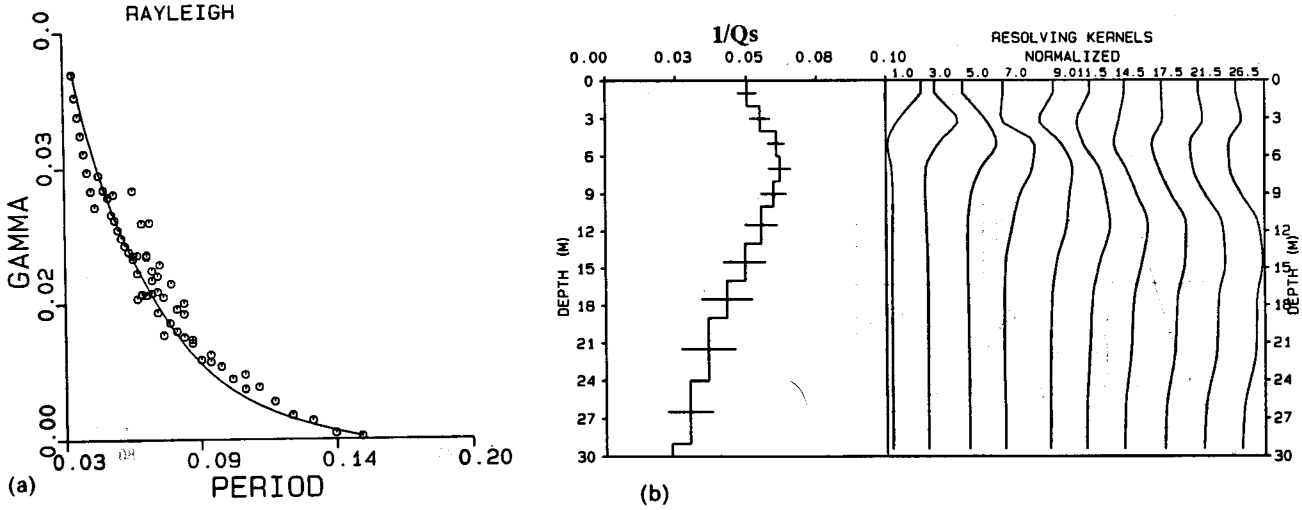

Fig. 7. (a) Attenuation factor γ versus period, computed from the seismograms of Fig. 6; (b) vertical Q^s profile and resolving kernels.

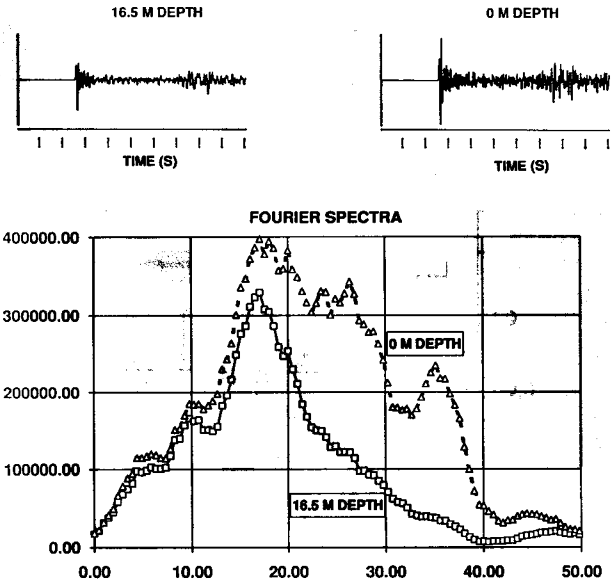

Fig. 8. Sart–Tilman site. Top: earthquake records (vertical component) at the surface and in a borehole. Bottom: fourier spectrum of P waves.

The main result is that Q appears to be frequency dependent. The attenuation values versus frequency are plotted in Fig. 12. For the site conditions investigated in this study the attenuation at low frequency — roughly below 30 Hz — is smaller than the one measured for higher frequencies.

The dependence of the quality factor on frequency in the lithosphere is confirmed by many authors and a power-law relationship of the type

$$Q = Q_0\left(\frac{f}{f_0}\right)^{n} \qquad (2)$$

with a positive exponent n between 0·1 and 0·5 is currently used to describe this behavior.

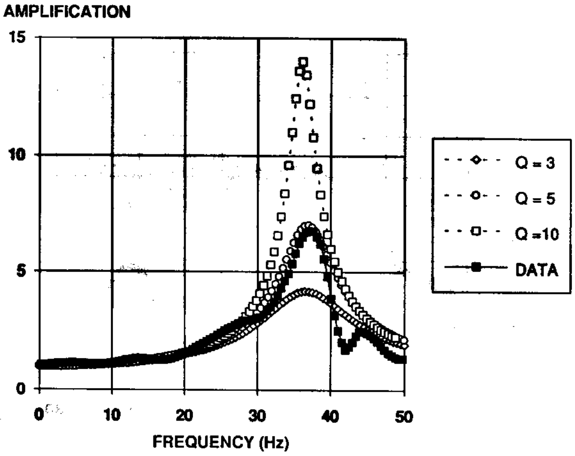

Fig. 9. Comparison between the experimental amplification and 1D modeling for different Q values.

On the other hand, Sato[13] has recently studied the frequency dependent amplitude attenuation on the basis of the scattering process in the randomly inhomogeneous lithosphere. He theoretically predicted the frequency dependence of Q^{-1} at this scale and found a curve having a peak at a frequency of about 1 Hz. The scattering process is likely to develop at smaller scales and at higher frequencies, depending on the heterogeneity size.

Such a result in a higher frequency range has already been obtained by Meissner and Theilen during seismic experiments at sea. In a frequency range of 300–6000 Hz, they observed a frequency dependence of Q^{P} with a possible attenuation peak at about 900 Hz.

Finally, a bimodal behavior in Q with relatively high level at Q at low frequencies and a marked decrease above a particular frequency value has recently been described by Blakeslee and Malin[5] for two sites at Parkfield. In their study, they used microearthquake

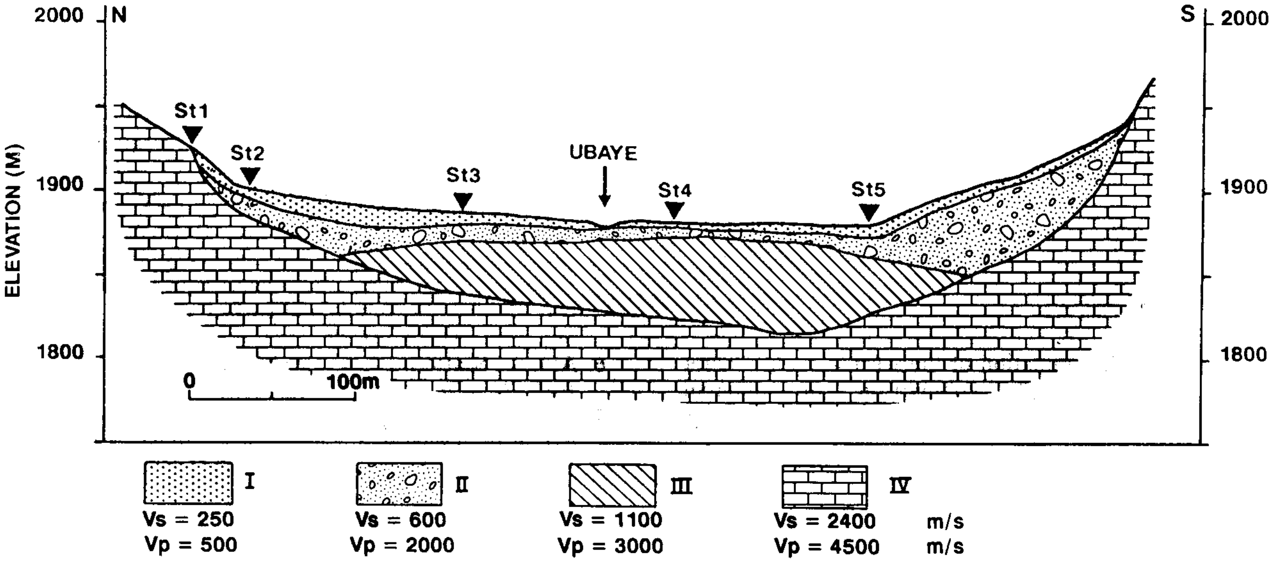

Fig. 10. Geological cross-section through the Ubaye valley.

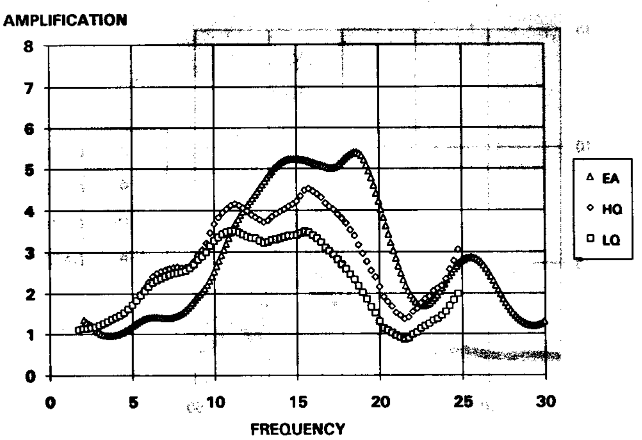

Fig. 11. Transfer functions at station 2 (Ubaye valley). EA, Experimental amplification; HQ, computed amplifications with $Q1 = 10$, $Q2 = 10$, $Q3 = 20$ and $Q4 = 200$; LQ, computed amplifications with $Q1 = 6$, $Q2 = 6$, $Q3 = 6$ and $Q4 = 50$.

data recorded at the surface and at 200 m depth. The separation frequency values range from 8 to 30 Hz according to the site and the wave type. The present authors' results, obtained in a different way, support this type of behavior. They are likely to explain the discrepancy between Q field determinations and the values to be used in computations to simulate site effects in the low frequency range.

Clearly, a frequency variation of the attenuation appears in unconsolidated sediments. From the authors' results and those of Blakeslee and Malin[5] the quality factor is likely to decrease with frequency. These results stress the importance and the need for careful investigations into the frequency dependence of Q.

From a practical point of view, analysis of surface waves which are characterized by relatively low frequencies appears to be a promising method to derive Q^s values for earthquake engineering purposes.

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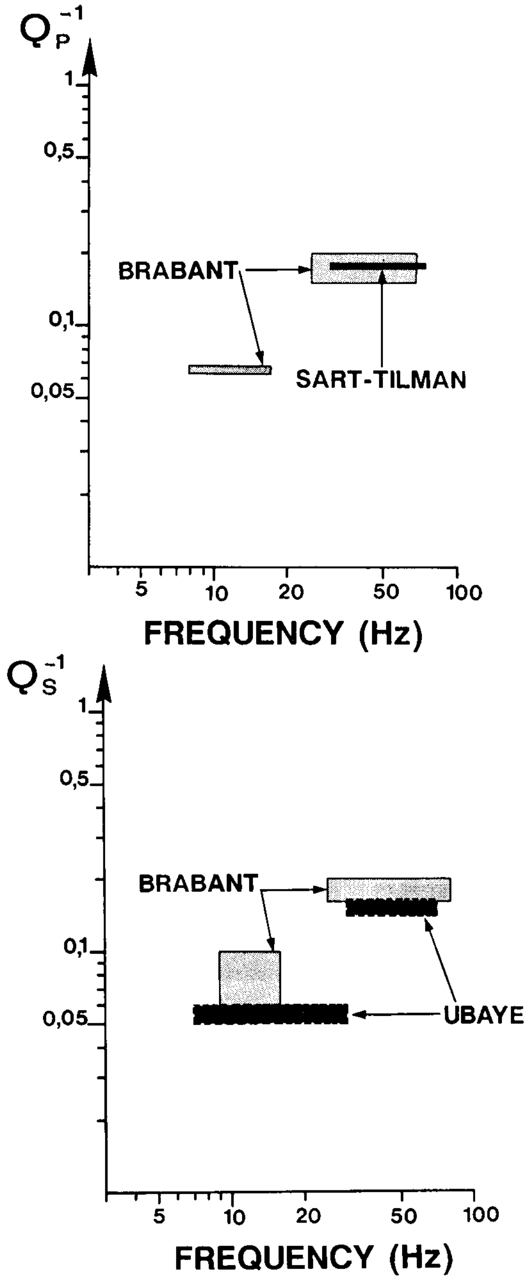

Fig. 12. Attenuation values versus frequency.

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