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AMPLITUDE SPECTRA OF SURFACE WAVES GENERATED BY SHOT-HOLE EXPLOSIONS

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ABSTRACT

The object of the research was to investigate the spectral properties of Rayleigh-type surface waves, generated by shot-hole explosions during seismic refraction experiments which were carried out in the area of the Bohemian Massif and West Carpathians. The records of displacement amplitudes were spectrally analyzed and prevailing frequency f_p, relative Δf_r and absolute widths of the spectra Δf_a were chosen as essential parameters. Whilst the prevailing frequencies were recorded within the interval f ÷ 0.80 – 3.70 Hz at the site of the observations, situated on the territory of the Bohemian Massif, the respective frequency range f ÷ 0.80 – 2.6 Hz was found in the West Carpathians. Some functional dependences of the spectral amplitude parameters on epicentral distance were observed and regularities of their decrease were defined. Moreover, the influence of local seismogeological conditions at the shot point as well as at the site of observation occurred.

KEYWORDS: Rayleigh waves, shot-hole explosions, spectral analysis, amplitude spectra

1. INTRODUCTION

During the seismic refraction experiments carried out along International Profiles VI and VII, apart from body waves (Beránek, 1971; Beránek et al., 1972; Beránek and Zátopek, 1981) also short-period Rayleigh surface waves were recorded in limited areas of the Bohemian Massif and the West Carpathians. Some papers dealing with the dynamic properties of P-waves, especially displacement amplitudes, were published earlier. The initial research was aimed at determining the essential properties of body waves, such as the attenuation of P-wave amplitudes with epicentral distance, the dependence of displacement amplitudes on the amount of explosives, observed at the fixed site of observation, i.e. at a fixed epicentral distance from the explosion and/or spectral content along Profile VI and at the nearest zone of hole shots. All these problem, solved several years ago, were published, e.g., by Holub (1972; 1979; 1980), and, moreover, the results of observations were gathered in the author´s dissertation (Holub, 1989).

On the other hand some dynamic properties of short-period Rayleigh waves were also investigated. These included the decrease of vibration frequencies and displacement amplitudes with epicentral distance, the relationship between displacement amplitudes and the amount of explosives used in hole shots (see Holub, 1974; 1977; 1996). These waves were also investigated from the viewpoint of their dispersive character. The dispersive curves were later interpreted in terms of 1-D structural models, as reported in Holub and Novotný (1991; 1997) and Holub et al. (2006).

Only the materials concerning Rayleigh surface wave spectra have not been processed on the basis of the hitherto performed research work, based on refraction measurement data. Therefore this paper is intended as a study of the spectral properties of surface waves observed at sites distributed throughout the Bohemian Massif and West Carpathians, the geological structures of which differ. As a consequence of the different geological structures, the basement of the site of observations, as well as, at the shot points, affect the character of the wave trains and the measurable values of the investigated parameters.

2. SOME TECHNICAL DETAILS

The refraction seismic measurements were conducted by the Institute of Applied Geophysics, Brno (later called Geofyzika Brno, N.E.) along International Profiles VI and VII crossing the territory of the Czech Republic and Slovak Republic (former Czechoslovakia), as shown in Figure 1. During these experiments 30-channel apparatuses were used. In principle, these measurements were aimed at determining the structure of the Earth´s crust and its composition within the frame of the Upper Mantle Programme in the 1960s and 1970s. Special observations at discrete sites of observation situated either close to the refraction profiles or directly along these profiles were carried out by the Geophysical Institute of the Czechoslovak Academy of Sciences in

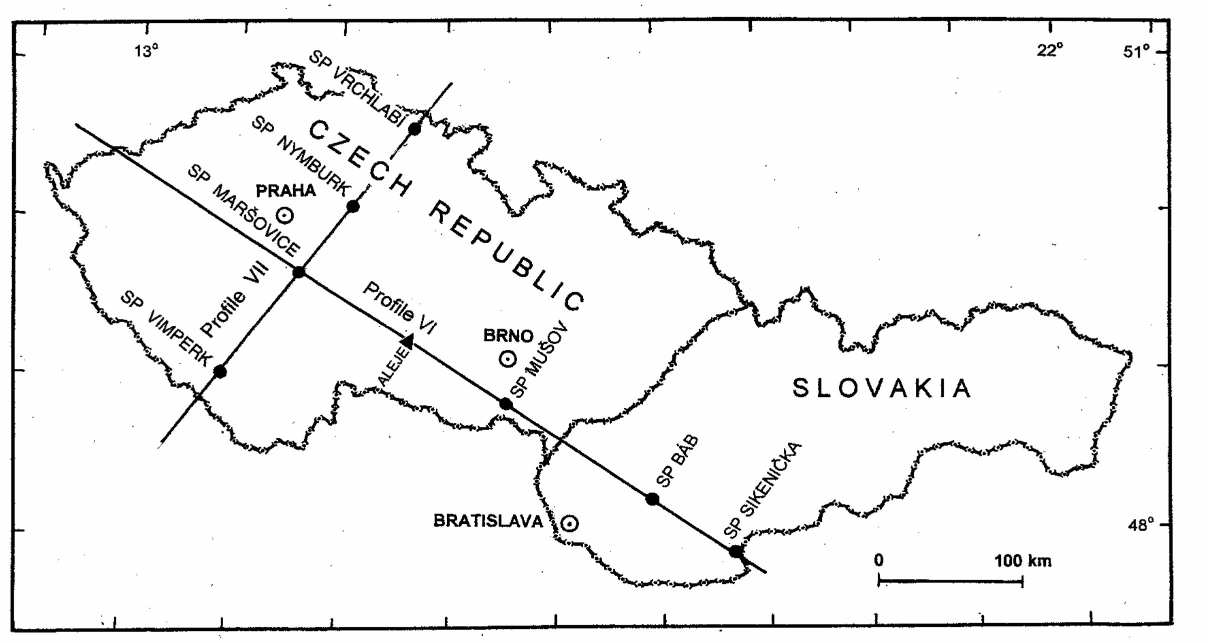

Fig. 1 Scheme of seismic Refraction Profiles VI and VII and distribution of shot points (SP) on the territory of the Czech and Slovak Republics.

Prague. These measurements were aimed at the investigating the absolute displacement amplitudes for the purpose of checking the effectiveness of the individual shot-hole explosions at a fixed site of observation and along Refraction Profiles VI and VII.

Three types of analogue instruments were used during seismic measurements:

a) A special recording device was used for measuring at the fixed site of observation close to the explosion at SP VIMPERK with only a vertical short-period seismometer (VEGIK), whose eigenperiod $T_0 = 2$ s and damping constant $D_S \approx 0.7$, the magnification of this device varying between $V = 12 - 1\,200$ and recording speed ~ 45 mm/s.

b) The seismic station on the Profile VI for measuring at the fixed site of observation ALEJE (ALJ) was equipped with two broad-band seismographs (VEGIK) whose eigenperiod $T_0 = 2$ s and damping constant $D_S \approx 0.7$, the orientation of the components being vertical (Z) and horizontal-radial (H_r) and the magnification for displacement amplitudes $V \approx 1.6 \times 10^5$. The recording speed was ~ 25 mm/s and the exact time was checked by the time normal of transmitter DCF 77.5 kHz.

c) The measurements along the refraction profiles were carried out with a 3-channel apparatus with seismometers (VEGIK) oriented one vertically (Z) and two horizontally (NS and EW) whose eigenperiod $T_0 = 2$ s and $D_S \approx 0.7$, but the magnification reached almost $V \approx 2.10^5$, its recording speed being about 25 mm/s. Both devices recorded displacement amplitudes and their magnifications were changed according to the size of the explosive charge and epicentral distance from the shot point.

Boreholes were drilled for blasting operations whose diameters were about 10-12 cm, their depth 60 m at the most, and their number depended on the overall mass of the explosives (TNT or mixture of TNT and gun powder) applied. The mass of the charge $Q \approx 200$ kg was set as the maximum for one borehole, and more boreholes had to be drilled for larger charges. The individual charges were put into boreholes and the remainder was packed with sandy material in order to guarantee the safety of the blasting operations taking into account the required length of the stemming. If the charge was distributed among several boreholes, all charges were fired simultaneously. The exact time of explosions was synchronized by the time normal of transmitters OMA 50 kHz and/or DCF 77.5 kHz.

3. CALCULATION OF THE AMPLITUDE SPECTRA

The spectral analysis of seismic waves was a part of the investigation of their dynamic parameters. The significance of this analysis is in that some time patterns of the wave trains can be considered as periodical plots and/or as a superposition of periodical plots. Nevertheless, the resulting amplitude spectra characterize the properties of dynamics of the seismic waves in every case.

Considering that the applied mathematical approach (Filon, 1928-29), which was modified by Schenk (1975), required the input of data in digital form, the original analogue data had to be digitized first. A special device, including an analogue-to-digital converter, made it possible to obtain these digital data from the analogue ones (Kolesnikov et al., 1963). The sampling step changed according to the character of the time pattern and varied within the range of $\Delta t \approx 0.0035 - 0.061$ s. The data obtained in the process of digitizing can be described by a series of values $f(t_0)$, $f(t_1)$, $f(t_2)\dots f(t_n)$, i.e. a series of values of recorded displacement amplitudes corresponding to the respective times $t_0, t_1, t_2,\dots t_n$. It was then necessary to find and adopt a numerical method in order to reach the solution of the integral in Eq. (1). The calculation of spectra is based here on the assumption that each seismic record f(t) can be considered a non-zero function within a time interval (0; T). Its spectrum S(ω) is then defined as

$$S(\omega) = \int_0^T f(t)\exp(-\mathrm{i}\omega t)\mathrm{d}t. \qquad (1)$$

Spectrum S(ω) is a complex function, whose real and imaginary parts read:

$$R(\omega) = \int_0^T f(t)\cos\omega t\mathrm{d}t;$$
$$I(\omega) = -\int_0^T f(t)\sin\omega t\mathrm{d}t. \qquad (2)$$

It is then possible to express spectrum *S(ω)* as

$$S(\omega) = A(\omega)\exp[\mathrm{i}\varphi(\omega)], \qquad (3)$$

where A(ω) and φ(ω) are the amplitude and phase spectra of function f(t), respectively:

$$A(\omega) = \left[R^2(\omega) + I^2(\omega)\right]^{1/2},$$
$$\varphi(\omega) = \arctan[I(\omega) : R(\omega)]. \qquad (4)$$

To describe the amplitude spectra qualitatively, several parameters were introduced (Berzon et al., 1962):

- Predominant frequency f_p - this value corresponds to the maximum value of the spectral amplitude A_f;
- The absolute spectrum width Δf_a - this parameter is determined at the level of $0.7A_f$ between the values f_1 and f_2 and is defined as $\Delta f_a = |f_1 - f_2|$;
- The relative spectrum width Δf_r - is defined as the quotient of Δf_a and f_p , i.e. $\Delta f_r = \Delta f_a/f_p$.

The individual spectra can be compared either by comparing the calculated spectral amplitudes in dependence on the corresponding frequencies, or by comparing the normalized spectra, related to the value f_p/f_i, which implies that the peak of such a spectrum at the value of f_p represents a spectral amplitude unit, i.e. $A_f = 1$.

4. FIELD EXPERIMENTS AND DATA INTERPRETATION

4.1. *SEISMIC CHECKING STATIONS*

Considering that the seismic effect of the individual explosions usually changes, which subsequently also influences the displacement amplitudes investigated along the profiles, reasonable measures were recommended, which were represented by the continuous observations of seismic waves in the near zone of the explosions. As an example of application of the recommended measures, a seismic station was erected near the SP VIMPERK at a distance r ≈ 800 m. Apart from the displacement amplitudes of body waves which we were previously studied, also a distinct wave group of Rayleigh waves was recorded, which later underwent the procedure of spectral analysis.

Using the approach described in Section 3, the overall set of seismograms of Rayleigh waves was digitized and later spectrally analyzed within the frequency range 1 - 10 Hz. The results of computing the amplitude spectra are displayed in Figure 2, where simultaneously an example of determining the spectrum parameters, i.e. f_1, f_2, f_p and Δf_a, are marked. On the l.h.s. of the resulting spectra, analyzed cuts-off are shown, while on the r.h.s. the appropriate charges Q = 400-810 kg applied during the blasting operations are shown. Most of the calculated spectra have their maxima within the interval f = 5-6 Hz, while the only spectrum corresponding to the charge of Q = 600 kg differs from the further spectra. The basic parameters of this explosion are: Q = 600 kg and boreholes 3 x 35 m; the corresponding spectrum parameters being: $f_p = 4.30$ Hz, $\Delta f_r = 0.480$ and $\Delta f_a = 2.10$ Hz. The rest of the spectra have individual parameters within the ranges: $f_p = 4.95$-5.70 Hz, $\Delta f_r = 0.41$-0.53 and $\Delta f_a = 2.30$-2.90 Hz. After inspecting the area of the shot point, this exceptional case was explained by the partial radiation of the explosion energy through the disintegrated material from the forgoing explosion, and therefore, the seismic effect was spread over a larger surface which decreased its efficiency and shifted the spectral content to lower frequencies. Another checking seismic station denoted as ALEJE (ALJ) was set up near Profile VI, roughly in the middle between SP MUŠOV (MU) and MARŠOVICE (MA), the epicentral distances were r ≈ 80.8 km and r ≈ 90.3 km, respectively (see Fig. 1). The fixed distances from both shot points enabled us to search for the changes of displacement amplitudes versus size of explosive charge, which varied within the range Q ÷ 40-400 kg (MU) and Q ÷ 300–1 200 kg (MA). The records of the broad-band seismographs

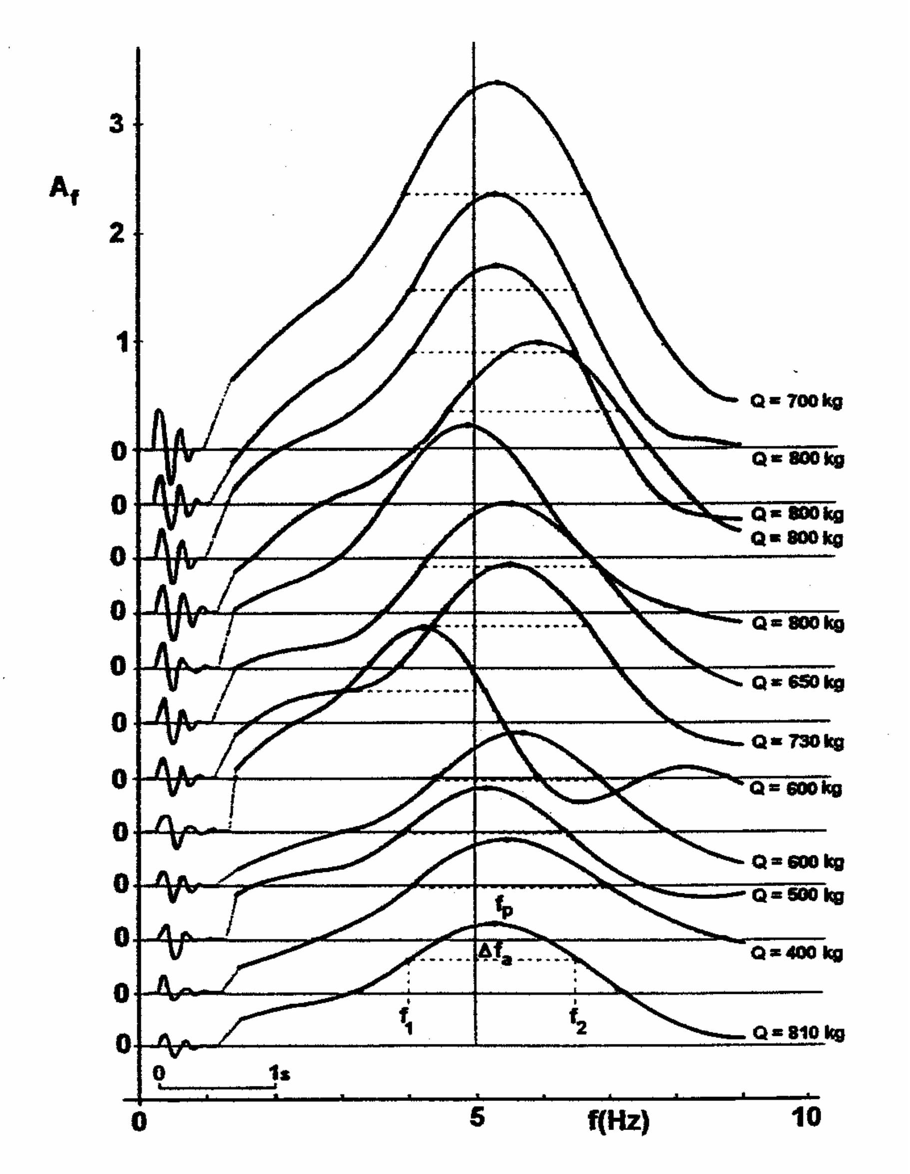

Fig. 2 Normalized amplitude spectra of Rayleigh waves recorded in the neighbourhood of shot point VIMPERK, r ≈ 800 m. The weights of charges are given on the r.h.s., while the analyzed wave train is displayed on the l.h.s. of the spectra.

also guaranteed the reliable determination of typical frequencies within the range of interest without seismic signal distorsions. Apart from deriving the empirical dependences A = f (Q) (Holub et al., 1965), also the spectra of body and surface waves were calculated. To be able to compare the different spectral contents of these waves, their spectra are shown in Figures 3 and 4. Figure 3 documents the differences in spectra of refracted waves Pg (a) $f_p = 6$ Hz and the P_MP wave reflected from the Moho (b) $f_p = 15$ Hz, which were generated at the SP MU. On the other hand Fig. 4 shows the spectra of the surface waves from SP MU having $f_p = 1.1$ Hz (a) and SP MA $f_p = 1.45$ Hz (b). It is obvious that the slight differences between the two epicentral distances can be neglected, and therefore, it can be concluded that the differences of the spectral maxima f_p from both shot points are influenced mostly by the different seismogeological situation at these shot points. Whereas SP MU was situated in the Carpathian foredeep with fluvial sediments of the River Dyje (Thaya) in the underlying bed, where seismic waves with lower frequences were generated, the SP MA located in the Central Bohemian Pluton, represented mostly by granite, syenite and diorite, radiated waves with higher frequencies and rather smaller amplitudes.

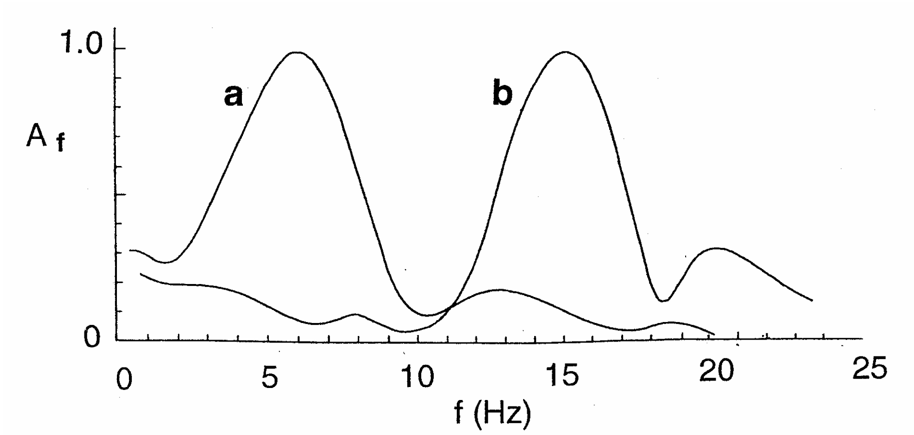

Fig. 3 Normalized amplitude spectra of P-waves recorded at the checking seismic station ALEJE from SP MUŠOV, r = 80.8 km. a - refracted Pg wave, b - P_MP wave reflected from the Moho.

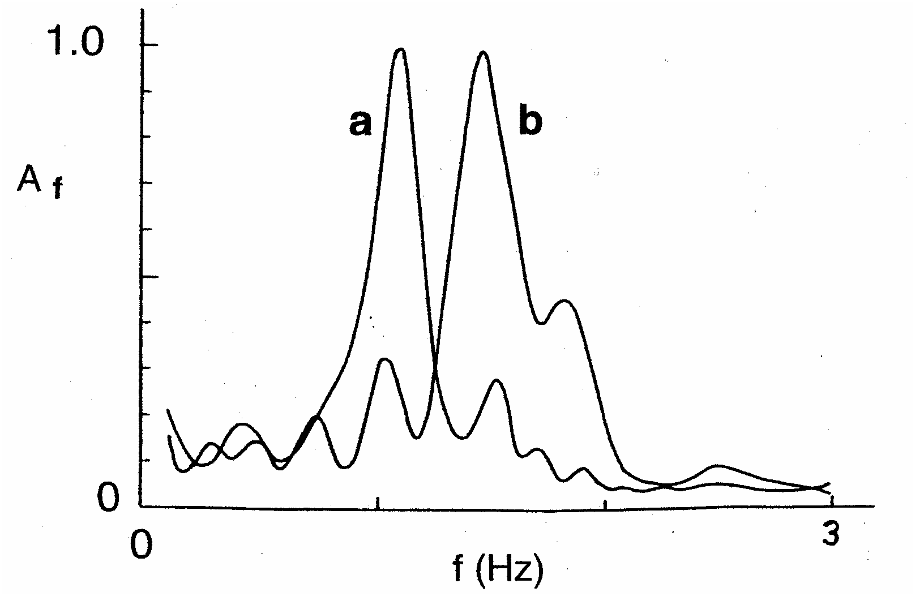

Fig. 4 Normalized amplitude spectra of Rayleigh waves recorded at the checking seismic station ALEJE from SP MUŠOV, r = 80.8 km (a) and from SP MARŠOVICE, r = 90.3 km (b).

4.2. MEASUREMENTS ALONG PROFILE VII IN THE BOHEMIAN MASSIF

The properties of the spectra of Rayleigh waves were investigated in detail during the refraction measurements along Profile No. VII crossing Bohemia in the north from Mt. Sněžka in the Giant Mts. to south Bohemia and ending at the top of the Bohemian Forest at Mt. Boubín. As seen in Figure 1 four shot points were distributed along this profile whose beginning is at the Czech Republic-Poland border; the representative records of Rayleigh waves generated at the individual shot points along Profile VII are given in Figure 5.

According to the results of the spectral analysis of seismograms from SP VRCHLABÍ (VR) which are shown in Figure 6, it is evident that beside the value $f_p \approx 2.0$-2.5 Hz in Figure 6a at the site ŽDÍREC, also secondary peaks occur in the spectra. These peaks mentioned latter are probably caused in the near zone of the explosion or due to the geological structure in its wide neighbourhood. This conclusion is based on the observations at all three sites at epicentral distances r = 10.8 ± 0.2 km, where the character of the spectra was almost the same. By analogy, at the next site ŠTĚKOV prevailing frequencies were observed at $f_p \approx 0.99$ Hz and the shape of the spectrum was disturbed also by secondary peaks. Moreover, at this site, further a wave group of rather slower Rayleigh waves ($v_R \approx 1.13$ km/s) was recorded, which had its spectral amplitude maximum at $f_p \approx 1.32$ Hz (see

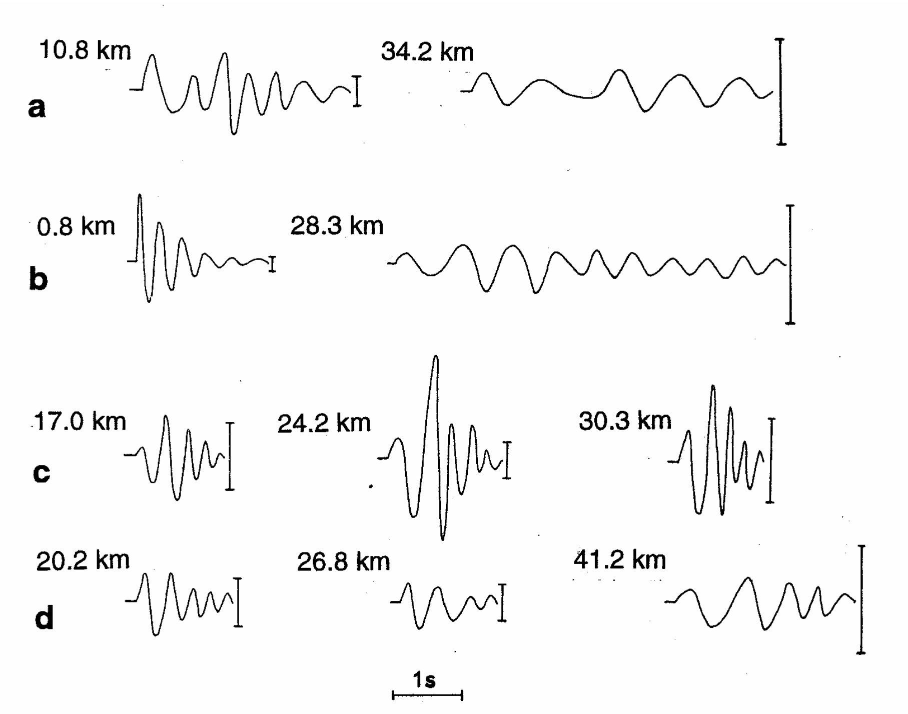

Fig. 5 Examples of seismograms of Rayleigh waves during refraction measurements along Profile VII. a – SP Vrchlabí, b – SP Nymburk, c – SP Maršovice and d – SP Vimperk. The straight lines in the individual seismograms correspond to the displacement amplitudes of A = 0.1 μm.

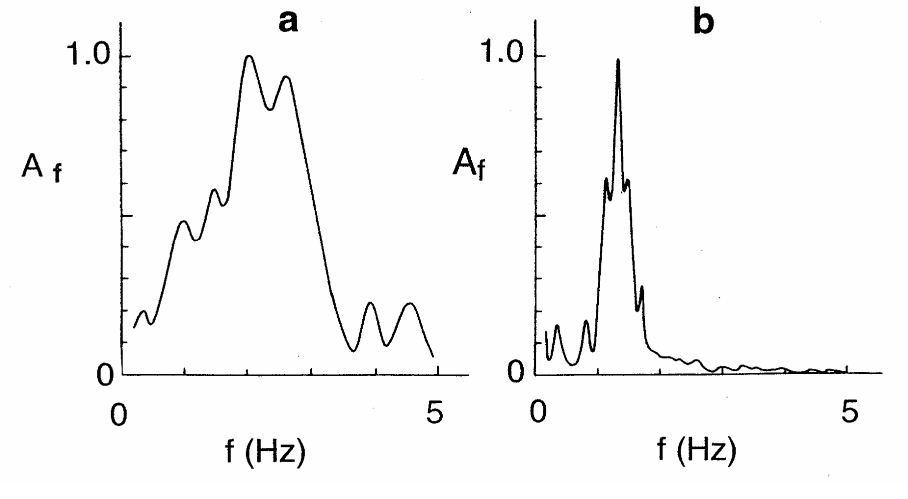

Fig. 6 Normalized amplitude spectra of Rayleigh waves from SP Vrchlabí recorded along Profile VII at sites Ždírec, r = 10.6 km, Q = 880 kg (a) and Štěkov (2^{nd} group of R-waves), r = 34.2 km, Q =1 400 kg (b).

Fig. 6b). Simultaneously, some substantial changes in the values of Δf_a and Δf_r were observed and corresponding values of the spectrum parameters are given in Table 1. The decrease of peaks of the approximated spectral amplitudes can be described by the following common power function:

$$P = k \times r^{-n}, \qquad (5)$$

where P can be substituted by one of the parameters, f_p, Δf_r or Δf_a ,
k is a proportional coefficient,
r is the epicentral distance [km],
n...exponent characterizing the decrease of spectral parameters.

For the SP VR were coefficients k, r and n derived which conform to power function defined by Eq. (6).

Table 1 Averaged values of parameters of the normalized amplitude spectra of Rayleigh waves generated at SP VRCHLABÍ and SP NYMBURK situated along Profile VII.

Shot point	**site**	**r (km)**	**f_1 (Hz)**	**f_p (Hz)**	**f_2 (Hz)**	**Δf_a (Hz)**	**Δf_r**
VRCHLABÍ	Ždírec	10.6	1.80	2.00	2.20	0.40	0.20
		10.8	1.90	2.10	2.60	0.70	0.35
		11.0	1.80	2.10	2.40	0.60	0.29
	Štěkov	34.22	0.82	0.99	1.06	0.24	0.24
			1.24*	1.32*	1.39*	0.15*	0.11*
NYMBURK	Křečkov	0.8	2.75	3.08	3.67	0.92	0.30
	Vrbčany	18.50	1.39	1.76	1.95	0.56	0.32
	Dobré pole	24.95	1.14	1.33	1.53	0.39	0.29
	Svatbín	28.32	1.14	1.36	1.60	0.46	0.34
	Kostelní Střimelice	38.30	0.86	1.23	1.33	0.47	0.38
	Přestavlky	45.55	1.05	1.23	1.41	0.36	0.29
	Pomněnice	52.30	0.98	1.13	1.29	0.31	0.27
	Tvoršovice	59.30	0.96	1.16	1.28	0.32	0.27
	Vojkov	72.35	0.97	1.04	1.12	0.15	0.14
	Jesenice	79.10	1.00	1.12	1.24	0.24	0.20
	Dražka	85.55	1.08	1.16	1.24	0.16	0.14
	Branišov	91.85	0.86	1.00	1.06	0.20	0.20
	Zbelítov	98.62	1.00	1.08	1.20	0.20	0.18
	Květov	105.30	0.90	1.01	1.10	0.20	0.20
	Záhoří	114.55	0.86	0.95	1.02	0.16	0.17
	Písek	122.35	0.82	0.88	0.93	0.11	0.12
	Jiřetice	142.15	0.75	0.80	0.89	0.14	0.17
	Dolní Nakvasovce	148.66	0.78	0.83	0.90	0.12	0.14

* values are valid for the 2nd group of Rayleigh waves with the lower propagation velocity ($v_R \cong 1.13$ km/s).

$$f_p = 5.188 \times r^{-0.387} \quad R^2 = 0.922 \quad r \div 11 - 34 \text{ km}, \tag{6}$$

where R^2 is a coefficient of correlation.

A very important part of our investigations are the measurements along Profile VII from SP NYMBURK (NY) to the southwest towards SP VIMPERK (VIM) (see Fig. 1). The amplitude spectra of the predominant frequencies recorded at SP NY were calculated mostly for the interval $f \approx$ 0-3 Hz, only for the nearest site of observation KŘEČKOV ($r \approx 0.8$ km) were computations performed for the frequency interval 0-10 Hz. In comparison with the foregoing spectra, these discussed spectra differ in all the parameters investigated, i.e. f_p, Δf_a and Δf_r. The shapes of the normalized spectra are characterized by narrow spectra and, in most cases, these spectra are smoothed and occasionally some secondary spectral peaks occurred; two examples of amplitude spectra are given in Fig. 7. The averaged values of the calculated spectrum parameters for the section of Profile VII, almost 150 km in length were observed within the following intervals: f_p = 0.8 - 3.1 Hz, Δf_a = 0.11 – 0.92 Hz and Δf_r = 0.12 – 0.30, which are given in Table 1. Figure 8 represents the empirical dependeces of the individual spectrum by a power function using the least-squares regression method; the results of the computations of the empirical dependences are as follows:

$$f_p = 3.140 \times r^{-0.253} \qquad R^2 = 0.963 \tag{7}$$

$$\Delta f_r = 0.532 \times r^{-0.216} \qquad R^2 = 0.618 \tag{8}$$

$$\Delta f_a = 1.346 \times r^{-0.421} \qquad R^2 = 0.861. \tag{9}$$

It is obvious that the data approximation using Eq. (1) fits the power function well, as substantiated by the coefficient of correlation R^2, which displays minimum scatter of the observed f_p data.

The amplitude spectra of seismic waves, generated at SP MA, underwent the same procedure of computation within the frequency range $f \div$ 0-5 Hz. These spectra had a smoothed shape without secondary peaks. It was shown that, up to the epicentral distance of about $r \approx 30$ km, the value Δf_a varies within the interval of 1.15-2.10 Hz, while at the site at an epicentral distance of approximately $r \sim 40$ km, a pronounced change of up to Δf_a = 0.35 Hz was observed (see Table 2). If the wave train images are compared, there is no doubt

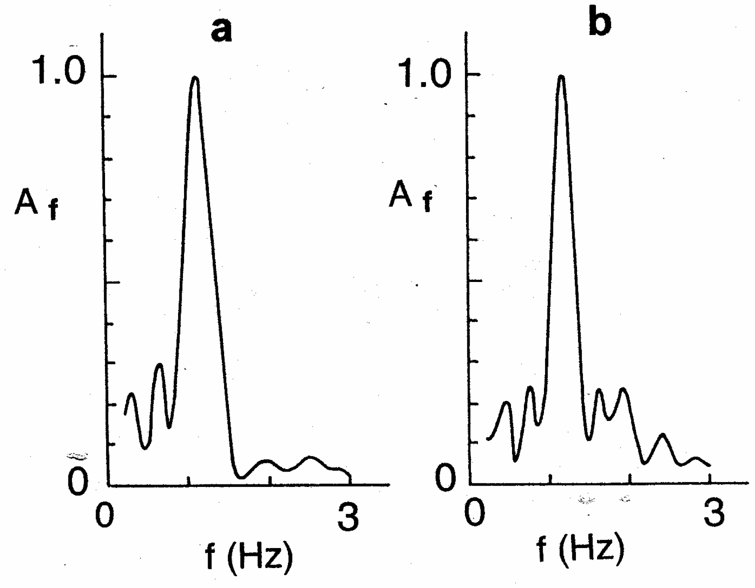

Fig. 7 Normalized amplitude spectra of Rayleigh waves from SP NYMBURK recorded along Profile VII at sites Pomněnice, r = 52.3 km, Q = 880 kg (a) and Zbelítov, r = 98.6 km, Q = 1 000 kg (b).

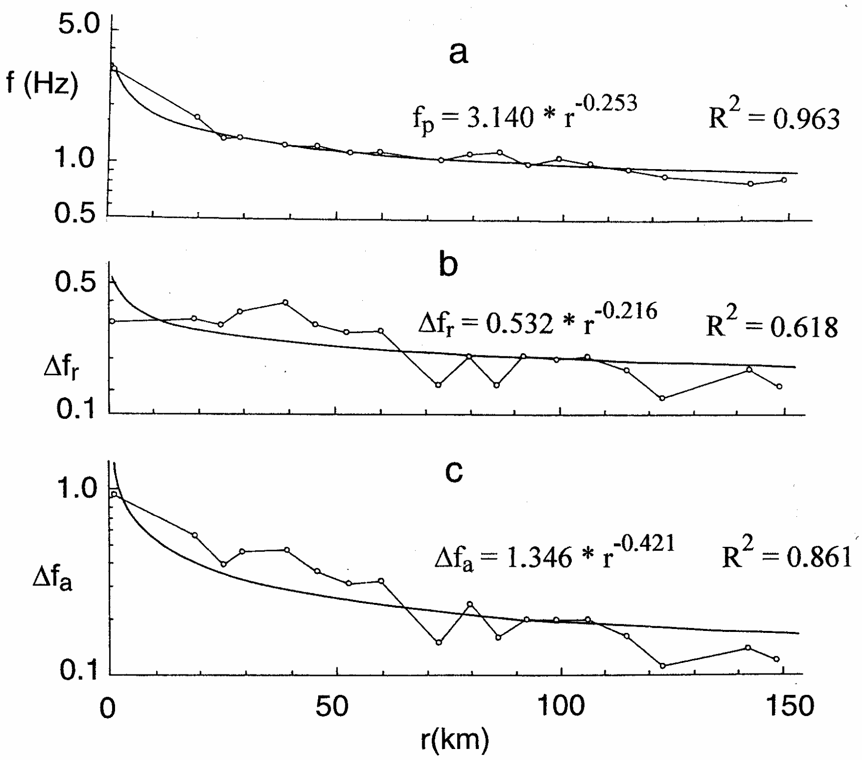

Fig. 8 Changes of spectrum parameters f_P (Hz) (a), Δs_r (b) and Δf_a (Hz) (c) with increasing epicentral distance r (km) from shot point NYMBURK; the observed values were approximated by a power function.

Table 2 Averaged values of parameters of the normalized amplitude spectra of Rayleigh waves generated at SP MARŠOVICE and SP VIMPERK situated along Profile VII.

Shot point	**site**	**r (km)**	**f_1 (Hz)**	**f_p (Hz)**	**f_2 (Hz)**	**Δf_a (Hz)**	**Δf_r**
MARŠOVICE	Přestavlky	17.0	2.20	3.00	3.50	1.30	0.40
	Ondřejov	24.28	1.30	1.70	3.40	2.10	1.20
	Průhonice	30.31	1.90	2.30	3.05	1.15	0.50
	Dobré Pole	39.70	1.44	1.60	1.79	0.35	0.22
VIMPERK	Dolní Nakvasovice	6.3	2.70	3.50	4.30	1.60	0.46
	Jiřetice	12.85	2.40	3.20	3.90	1.50	0.47
	Jiřetice	14.25	2.85	3.70	4.55	1.70	0.46
	Radějovice	20.25	2.05	3.35	3.85	1.80	0.53
	Ražice	26.80	1.75	2.25	2.65	0.90	0.40
	Záhoří	41.85	1.10	1.40	1.60	0.50	0.36

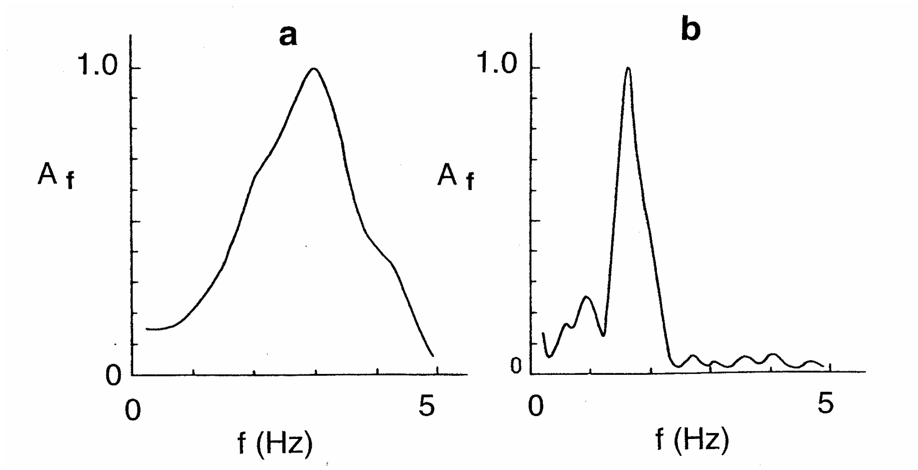

Fig. 9 Normalized amplitude spectra of Rayleigh waves from SP MARŠOVICE recorded along Profile VII at sites Přestavlky, r = 17.0 km, Q = 300 kg (a) and Dobré Pole, r = 39.7 km, Q = 1200 kg (b).

that the broadening of the spectra at the sites mentioned first can be explained by the dispersive properties of Rayleigh waves, while at the site at epicentral distance r > 40 km the width of their spectra are narrower, as seen in Figure 9. The decrease of the peaks of the approximated spectral amplitudes with increasing frequency can be described by the following power function:

$$f_p = 11.015 \times r^{-0.479} \quad R^2 = 0.512 \quad r \div 17 - 40 \text{ km}. \tag{10}$$

The amplitude spectra of Rayleigh waves, which resulted from the explosions at SP VIM and which were recorded in the near zone of explosions, have already been discussed in Section 4a). The refraction measurements along the last section of Profile VII were conducted in reverse direction from the shot point to the northeast, up to an epicentral distance of roughly r ~ 42 km. The shapes of the spectra calculated within the range of frequencies f ÷ 0-10 Hz for sites situated between r ÷ 6 – 20 km had a character similar to that as shown in Figure 10a. At greater epicentral distances, i.e. r ≥ 27 km, the spectra of surface waves resembled spectra of interference waves, an example of which is in Figure 10b, where simultaneously a shift of the maxima of spectral amplitudes to lower values f_p is evident, moreover, a visible narrowing of the absolute width Δf_a occurs. An overview of the appropriate investigated parameters is given in Table 2. Using the calculated values of f_p, the gradual decrease of the spectral peaks approximated by a power function, can be described as follows:

$$f_p = 13.304 \times r^{-0.587} \quad R^2 = 0.775 \quad r \div 11 - 34 \text{ km} \tag{11}$$

4.3. MEASUREMENTS ALONG PROFILE VI IN THE CARPATHIAN FOREDEEP AND DANUBIAN LOWLAND

As opposed to the Bohemian Massif, Rayleigh waves, the character of which was rather different,

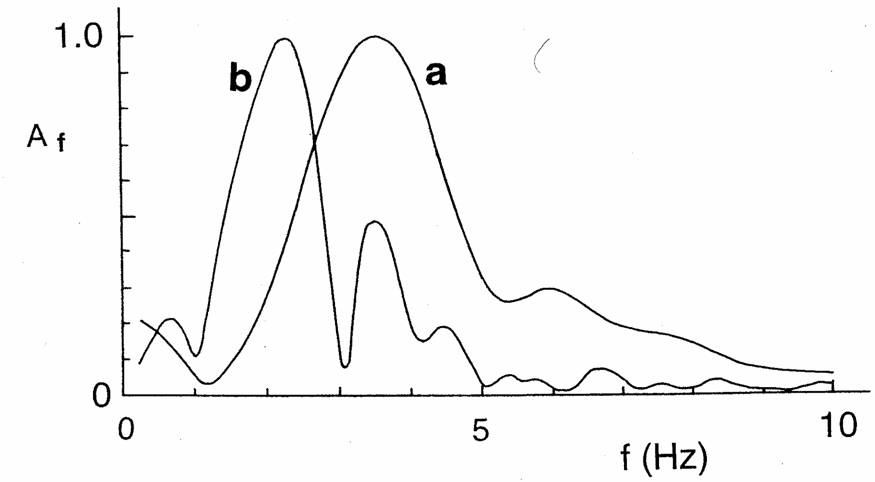

Fig. 10 Normalized amplitude spectra of Rayleigh waves from SP VIMPERK recorded along profile VII at sites Dolní Nakvasovice, r = 6.3 km, Q = 10 kg (a) and Ražice, r = 26.8 km, Q = 200 kg (b).

were recorded at the sites in the region under investigation. If we ignore their low group propagation velocities, long-lasting groups of Rayleigh waves, i.e. $\tau \approx 3.2 - 20.1$ s, were observed in this area. Most of the waveforms displayed group velocity dispersion. Typical waveforms during the hole-shot explosions at the individual shot points are shown in Figure 11. The process of calculating amplitude spectra was identical with the approach applied previously. The refraction measurements were carried out on the section of the profile, where three shot points were chosen, i.e. SP MUŠOV (MU), SP BÁB (BA) and SP SIKENIČKA (SI) (see Fig. 1).

At SP MU, which was situated in the Carpathian foredeep, two observation sites were established symetrically to the SP at epicentral distances $r \approx 4$ km. Considering that the locality was close to the River Dyje, the underlying beds (several tens of metres) were built of fluvial sediments, mostly water-saturated sands, and with some series of limestone at larger depths. Two examples of normalized amplitude spectra are shown in Figure 12 and the shape of the spectra is almost the same at both localities. The resulting values of the individual parameters, i.e. f_p, Δf_r and Δf_a, were included in Table 3.

Typical amplitude spectra which were calculated on the basis of records from the hole shots at SP BA are presented in Figure 13. It was also observed at other localities ($r > 6$ km), that due to the increasing epicentral distances, a breaking shift towards lower frequencies does exist. The very pronounced change in the value of the absolute width of spectrum Δf_a was found at locality Boleráz ($r = 38.6$ km), the value of which was $\Delta f_a = 0.07$ Hz. As implied by theoretical computations, the increasing number of oscillations usually causes a narrowing of the spectrum width. The representative values of the investigated parameteres are included in Table 3.

The last shot point in the Danubian Lowland was SP SI, situated near the River Hron; the underlying beds there are similar to those at SP MU, i.e. water-saturated sands up to tens of metres thick.

The normalized amplitude spectra for a section of Profile VI are shown in Figure 14, and the corresponding values of the spectrum parameters are summarized in Table 3. If the data from SP BA and SP SI, shown in Table 3, are applied to the search for the decrease of values f_p with epicentral distance, after approximation by power function this dependence is expressed as:

$$f_p = 2.79 \times r^{-0.311} \qquad R^2 = 0.722 \qquad r \div 3.1 - 38.6 \text{ km.} \qquad (12)$$

5. CONCLUSIONS

The following conclusions result from the investigation of the spectral properties of recorded and analyzed surface Rayleigh waves:

- Distinct short-period Rayleigh waves, which very often displayed dispersion, were recorded along refractrion Profiles VI and VII;
- The computation of amplitude spectra proved that surface waves display the lowest predominant frequencies in wave trains ($f_p \approx 0.80$-3.70 Hz); higher frequencies were observed with refracted Pg waves ($f_p \approx 4$-10 Hz), and the highest frequencies belong to waves reflected from the Moho (P_MP) ($f_p \approx 12$-17 Hz);
- It was found that, in the area of the Bohemian Massif, the wave trains of Rayleigh waves are relatively short compared with the wave trains at the sites in the Carpathian foredeep and Danubian Lowland;
- Seismic measurements have proved that the geological basement below the observation site,

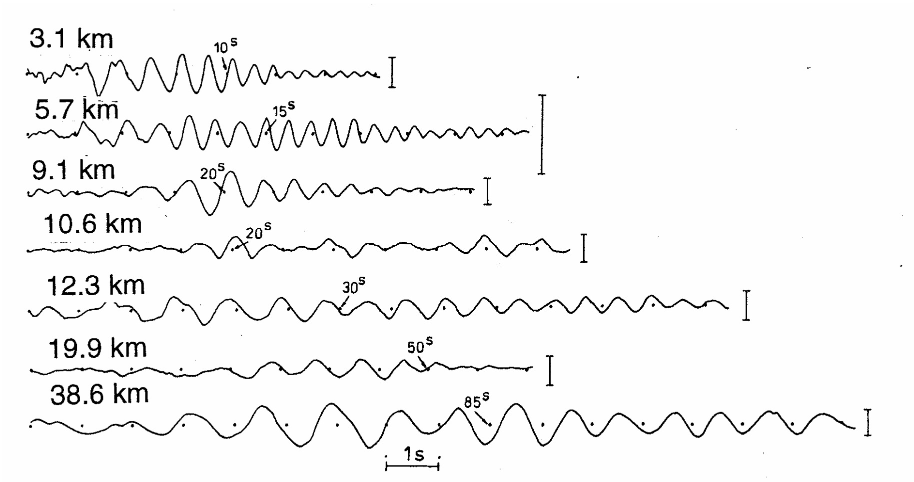

Fig. 11 Examples of seismograms of Rayleigh waves during refraction measurements along Profile VI from SP BÁB to SP MUŠOV (sites at 3.1, 5.7,12.3 and 38.6 km) and between SP SIKENIČKA towards SP BÁB (sites at 9.1 and 19.9 km). The straight lines in the individual seismograms correspond to the displacement amplitudes of A = 0.5 μm.

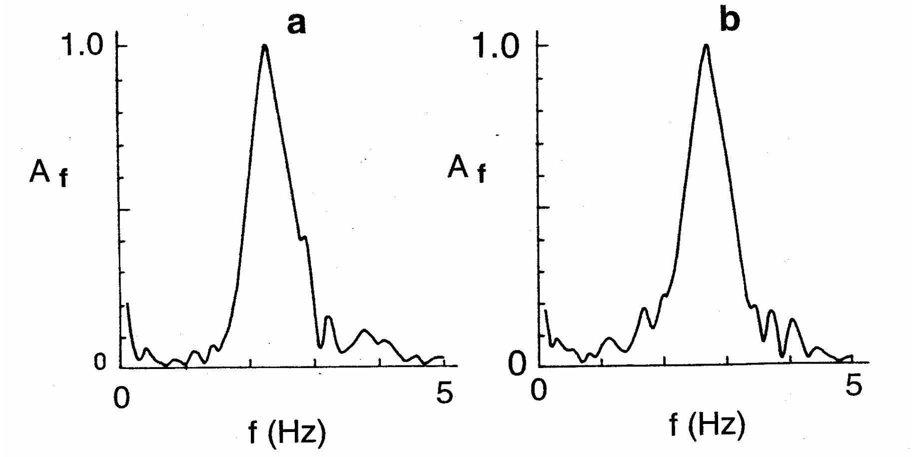

Fig. 12 Normalized amplitude spectra of Rayleigh waves from SP MUŠOV recorded along Profile VI at sites Pasohlávky, r = 3.6 km, Q = 10 kg (a) and Perná, r = 4.4 km, Q = 10 kg (b).

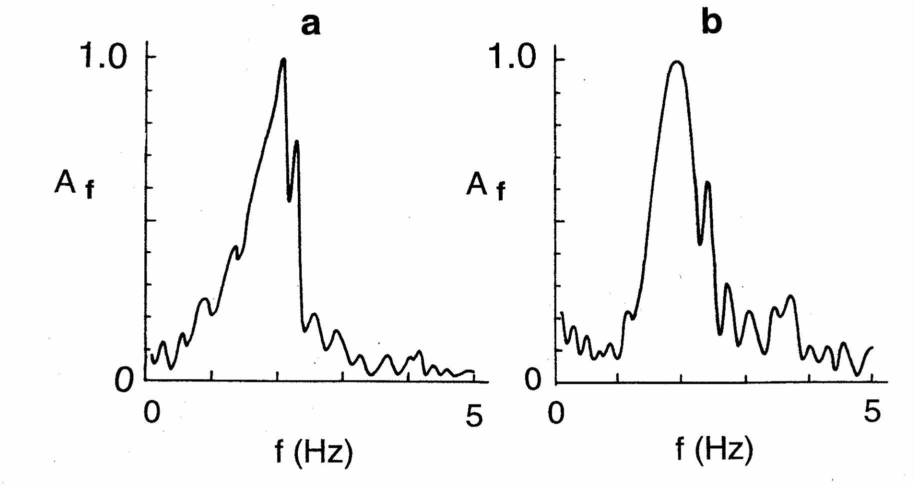

Fig. 13 Normalized amplitude spectra of Rayleigh waves from SP BÁB, recorded along Profile VI at sites Malý Báb, r = 3.1 km, Q = 8 kg (a) and Jarok, r = 5.75 km, Q = 8 kg (b).

Table 3 Averaged values of parameters of the normalized amplitude spectra of Rayleigh waves generated at SP MUŠOV, SP BÁB and SP SIKENIČKA situated along Profile VI.

Shot point	site	r (km)	f_1 (Hz)	f_p (Hz)	f_2 (Hz)	Δf_a (Hz)	Δf_r
MUŠOV	Pasohlávky	3.60	2.07	2.29	2.53	0.46	0.20
	Perná	4.42	2.43	2.63	2.82	0.39	0.14
BÁB	Malý báb	3.10	1.47	1.74	2.04	0.57	0.33
	Jarok	5.75	1.70	2.01	2.17	0.47	0.22
	Dvorníky	12.35	0.86	0.94	1.08	0.22	0.23
	Boleráz	38.65	0.76	0.80	0.83	0.07	0.09
SIKENIČKA	Čata	9.10	1.04	1.37	1.68	0.64	1.68
	Čaka	19.90	0.96	1.12	1.22	0.24	1.22

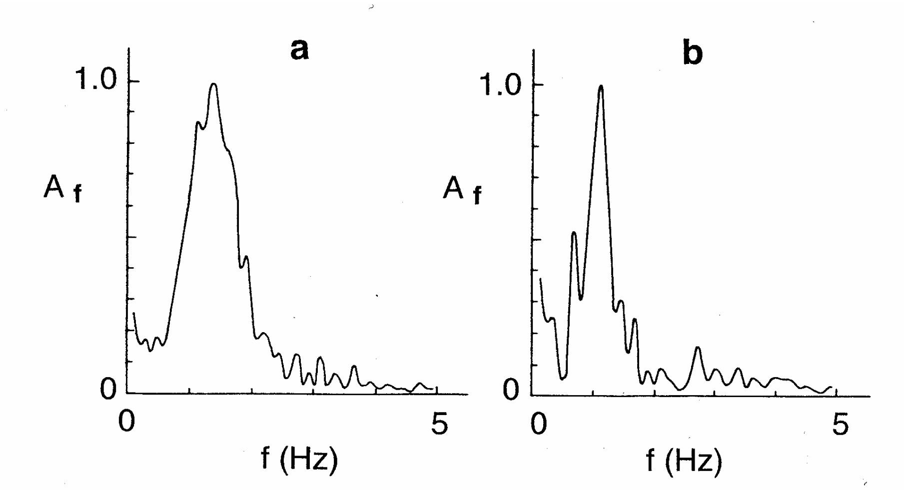

Fig. 14 Normalized amplitude spectra of Rayleigh waves from SP SIKENIČKA, recorded along Profile VI at sites Čata, r = 9.1 km, Q = 50 kg (a) and Čaka, r = 19.9 km, Q = 200 kg (b).

as well as the neighbourhood of the location of the explosion, have a principal influence on the character of the waveform;

- The decrease of predominant frequencies in the individual geological structures differs which is expressed by the exponents n in Eqs. 5, 6, 9, 10 and 11. The highest values of n were determined, e.g., in the Moldanubicum (n = 0.587) and Central Bohemian Massif (n = 0.479), where hard rocks occur; the smaller values in the Krkonoše (Giant Mts.) foothill basin (n = 0.387) correspond to Permian sediments. According to the analysis of measurements betwen SP NY and SP VIM the lowest value observed was n = 0.253, though the profile crossed the Bohemian Createceous Platform, Central Bohemian Massif and Moldanubicum. This discrepancy can be explained by the assumption that the nearest neighbourhood of the shot point, where seismic waves are generated has the essential influence on the predominant frequencies of amplitude spectra. Finally, the value n = 0.311 was determined at the locations in the Danubian Lowland, where the attenuation of seismic wave amplitudes in sedimentary layers is low
- Tables 1, 2 and 3 present only the averaged values of f_p though more measurements were performed and more values were available for computations at many of the localities.

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