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INTERPRETATION OF THE DISPERSION CURVES OF SHORT–PERIOD RAYLEIGH WAVES OBSERVED IN THE WEST CARPATHIANS

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ABSTRACT. During seismic experiments in the region of the West Carpathians, short–period Rayleigh waves were recorded at several sites of observation. The experimental dispersion curves of Rayleigh waves have been compared with theoretical ones computed for simple models. In all the models satisfying the experimental data, a distinct velocity discontinuities at depths of 50–70 m have been found. It is assumed that such a discontinuity should be connected with the lithological and facial development of sedimentary cycle within the Carpathian foredeep and in the individual sedimentation basins in the Danubian Lowland as well.

KEYWORDS: Rayleigh waves, dispersion, short periods, West Carpathians, near–surface structure

1. INTRODUCTION

During deep seismic soundings (DSS) along the international profile VI (Fig. 1), seismic waves were recorded by standard multi–channel apparatuses and, moreover, by two broad–band seismographs (Beránek et al., 1971). At several sites in the region of the West Carpathians, the latter instruments recorded, apart from body waves, also slow short–period waves with pronounced velocity dispersion. Detailed analyses, including determination of the particle motion trajectories, proved that these slow waves are Rayleigh waves with group velocities varying in the interval 0.25 – 0.60 km/s in the period range 0.2 – 1.8 s (Holub, 1974). It was assumed that the slow Rayleigh waves may be connected with a weathered layer, the thickness of which varies between 5 and 15 m. However, no theoretical dispersion curves were calculated in the paper by Holub (1974) to support this assumption. Preliminary theoretical computations were performed later by Holub and Novotný (1991). A continuation and extension of these interpretations, based on the same experimental data, is the subject of the present paper.

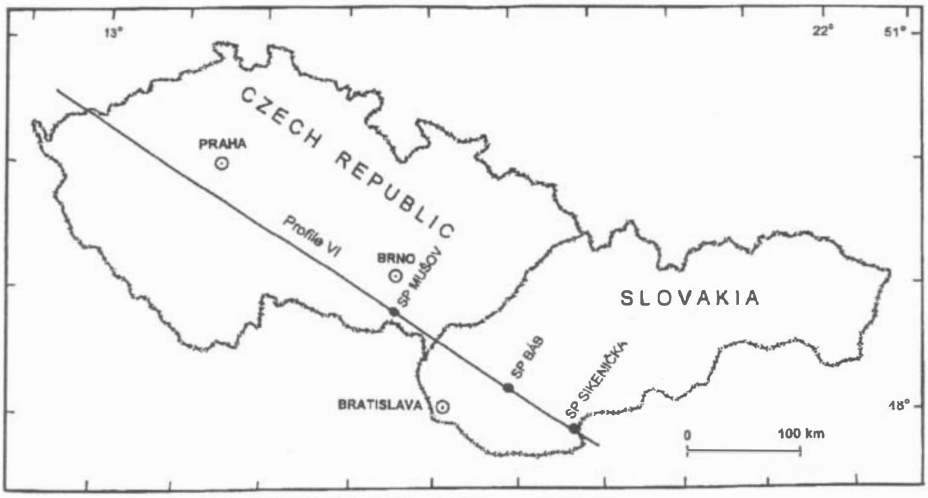

FIG. 1. Position of the DSS profile VI

In particular, we shall show that the effective thickness of the superficial low–velocity layer is substantially larger than the thickness of the weathered layer mentioned above. The structural models derived here are based on extensive computations which have been performed by means of a new computer programme.

Short–period surface waves have been used by many authors to study the uppermost crustal structure. Of recent papers we should mention the papers by Åström and Lund (1993) or by Ruud et al. (1993) where further references can be found.

2. GEOLOGICAL STRUCTURE AND OBSERVED RAYLEIGH–WAVE GROUP VELOCITIES

The uppermost part of the geological section in the region under consideration, i.e. in the Carpathian foredeep and the Danubian Lowland, is built by sedimentary filling. A schematic geological section, adopted from Beránek et al. (1971), is shown in Fig. 2. A more detailed geological characteristics of the region can be found in the paper by Holub (1972).

Figure 2 shows also the positions of the shot points and measuring stations along the DSS profile VI in the region under consideration. We shall consider here the broad-band records at the following sites: from shot point Mušov (code MU) at sites Pasohlávky (PA) and Perná (PE); from shot point Báb (BA) at Boleráz (BO), Dvorníky (DV), Malý Báb (MB) and Jarok (JA); from shot point Sikenička (SI) at Čaka (ČK) and Čata (ČT). An example of these records is shown in Fig. 3.

The selected seismograms were processed using the standard graphical–numerical method (Savarenskij, 1959). In this approach, the group velocities U are calculated using the simple formula

$$U(T) = x/t\,, \qquad (1)$$

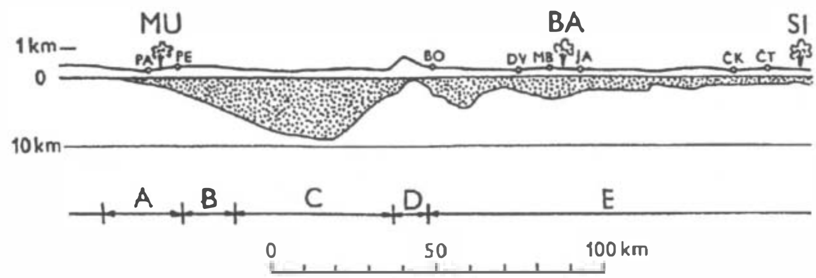

FIG. 2. Positions of shot-points and measuring stations along a section of the DSS profile VI; the bottom part of the figure shows the boundary between the Neogene basins and their basement. The geological formations of the region are denoted as follows: A – the Carpathian foredeep, B – West Flysh Carpathians, C – Vienna basin, D – Little Carpathians, E – Danubian Lowland

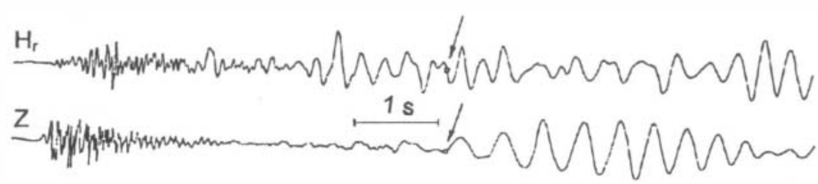

FIG. 3. Vertical (Z) and radial (H_r) seismograms recorded at an epicentral distance of 3.6 km from the shot point Mušov

where x is the epicentral distance, t is the arrival time of the corresponding peak or trough of the seismic wave, and T is the instantaneous period. In order to take the phase shift of the seismograph into account, we have used the generalized formula

$$U(T) = x / [t + \triangle t] , \tag{2}$$

where $\triangle t(T)$ is the instrumental time shift. The values of $\triangle t$ were described by Holub (1974). The group velocities, determined in this way, are shown in Fig. 4 by the isolated points. These experimental dispersion curves characterize mean structures between the corresponding shot points and the points of observation.

3. METHOD OF INTERPRETATION

In interpreting the experimental dispersion curves we restricted ourselves only to horizontally layered models of the medium, since effective matrix algorithms can be used in this case for computing theoretical dispersion curves. All the layers and the half-space are assumed to be homogeneous and isotropic. Rayleigh wave dispersion in such a layered medium is a function of the following parameters:

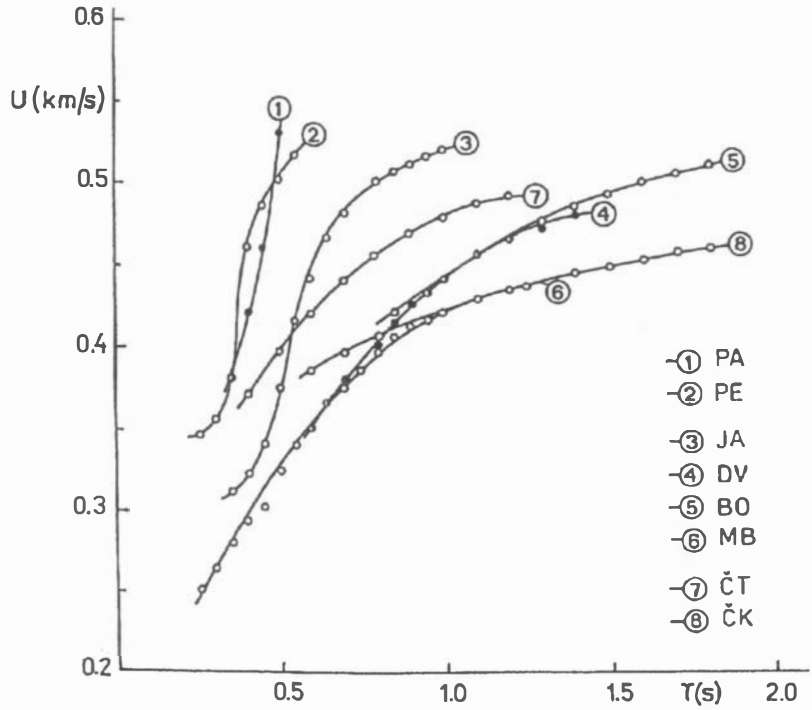

FIG. 4. Dispersion curves of short–period Rayleigh waves for the region of the Carpathian foredeep and West Carpathians: U is the group velocity, T is period, the points denote the experimental values, and the lines are the theoretical curves for the models in Tab. 2

compressional wave velocities v_P (P–wave velocities), shear wave velocities v_S (S–wave velocities), densities ρ and thicknesses d of the individual layers, and of the corresponding velocities and the density in the half–space.

To diminish the number of the variable parameters of the medium, we assumed the shear wave velocities and densities to be related to the compressional wave velocities as follows:

$$v_S = v_P/\sqrt{3}\,, \qquad \rho = 1.7 + 0.2 v_P\,, \tag{3}$$

where the density ρ is given in g/cm^3 if the compressional wave velocity is in km/s. Relations (3) have been used in many investigations of the crustal structure in Central Europe; see (Novotný et al., 1981; 1995). Another relation will be considered below.

The interpretation of the experimental data usually proceeded in the following three steps:

(1) As a first approximation, a simple model composed of a layer on a half–space was proposed for each experimental dispersion curve.

(2) The parameters of such a model were modified in order to minimize the root mean square of deviations of the observed and theoretical group velocities.
(3) More complicated models were searched in case that the simple model was not satisfactory.

Let us add several comments to this procedure. In the first step we estimated the velocities in the half–space directly from the observed dispersion curves in Fig. 4. We assumed that the shear wave velocity in the half–space is slightly higher than the Rayleigh wave velocities at long periods. Using (3) we then arrived at the compressional wave velocity in the half–space. These values for the individual profiles are given in Tab. 1. The compressional wave velocities in the layer were taken close to 0.8 km/s. This value was derived from the travel times of P waves observed at short epicentral distances. We chose a value of 10 m as a starting thickness of the layer for all profiles.

TABLE 1. Parameters of the initial models composed of a layer on a half–space: v_{P_1} and v_{P_2} are the compressional wave velocities in the layer and in the half–space (in km/s), respectively

Profile	v_{P_1}	v_{P_2}
MU–PA	0.80	1.10
MU–PE	0.80	1.10
BA–JA	0.70	1.10
BA–DV	0.80	1.05
BA–BO	0.95	1.15
BA–MB	0.80	1.00
SI–ČT	0.80	1.05
SI–ČK	0.85	1.00

A computer programme, called INDIS, was developed to interpret the experimental data. Starting from an initial model, it changes the model parameters by given steps in order to draw the theoretical dispersion curve nearer to the experimental curve. The calculation of the theoretical dispersion curves is based on the matrix method described by Proskuryakova et al. (1981).

Keeping the velocities from Tab. 1 fixed, we first increased the layer thickness step by step by 10 m. It was found that thicknesses between 50 and 70 m satisfied the experimental data best. Further improvement of the models was then achieved by changing the velocities and by splitting the layers. The final models are given in Tab. 2, and the corresponding theoretical dispersion curves are shown in Fig. 4 by the full lines. The P–wave velocity cross–sections for these models are shown in Figs 5 to 7 by the full lines.

In addition to the velocity ratio $v_P/v_S = \sqrt{3}$ we have repeated all the interpretations also for the ratio $v_P/v_S = 2$. The results are also given in Tab. 2, and

Table 2. Final models of the medium for two ratios of the compressional and shear wave velocities v_P/v_S. Each row contains the compressional wave velocity v_P, shear wave velocity v_S (both in km/s), density ρ (g/cm^3) and thickness d (in meters) of the corresponding layer

Profile	$v_P/v_S = \sqrt{3}$				$v_P/v_S = 2$			
	v_P	v_S	ρ	d	v_P	v_S	ρ	d
MU–PA	0.800	0.462	1.86	60	0.900	0.450	1.88	60
	1.300	0.751	1.96	∞	1.300	0.650	1.96	∞
MU–PE	0.800	0.462	1.86	25	0.850	0.425	1.87	50
	0.750	0.433	1.85	25	1.300	0.650	1.96	∞
	1.200	0.693	1.94	∞				
BA–JA	0.700	0.404	1.84	35	0.800	0.400	1.86	70
	0.750	0.433	1.85	35	1.250	0.625	1.95	∞
	1.150	0.664	1.93	∞				
BA–DV	0.659	0.375	1.83	70	0.750	0.375	1.85	35
	1.000	0.577	1.90	∞	0.700	0.350	1.84	17.5
					0.750	0.375	1.85	17.5
					1.050	0.525	1.91	∞
BA–MB	0.600	0.346	1.82	30	0.650	0.325	1.83	30
	0.650	0.375	1.83	30	0.750	0.375	1.85	30
	0.900	0.520	1.88	∞	1.000	0.500	1.90	∞
BA–BO	0.700	0.404	1.84	35	0.650	0.325	1.83	35
	0.550	0.318	1.81	35	0.700	0.350	1.84	35
	1.050	0.606	1.91	∞	1.150	0.575	1.93	∞
SI–ČT	0.750	0.433	1.85	70	0.850	0.425	1.87	70
	1.000	0.577	1.90	∞	1.100	0.550	1.92	∞
SI–ČK	0.650	0.375	1.83	60	0.750	0.375	1.85	60
	0.900	0.520	1.88	∞	1.000	0.500	1.90	∞

the P–wave velocity cross–sections are shown in Figs 5 to 7 by the dashed lines. Nevertheless, some results of the field seismic measurements indicate that even a higher ratio of v_P/v_S, from 2 up to 5, can be expected at corresponding depth levels (Filková, 1989). We have not considered these high ratios in the present paper but future investigations should take this problem into account.

It is well known that Rayleigh wave velocities are affected more by shear wave velocities than by compressional wave velocities (Brune and Dorman, 1963). Consequently, we expect that the interpretations of the Rayleigh–wave dispersion curves with different ratios of v_P/v_S will yield different models of the v_P distribution, but similar models of the v_S distribution.

4. Discussion of the Results

The highest velocities of Rayleigh waves in Fig. 4 have been obtained for profiles

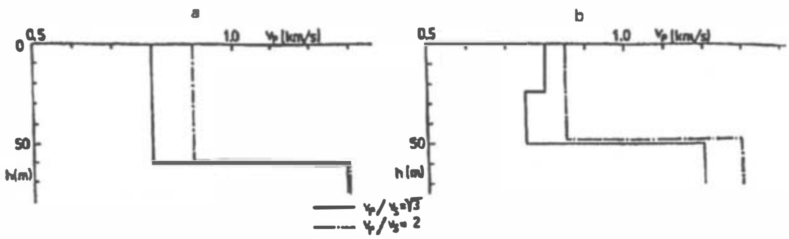

FIG. 5. Models of the velocity-depth distribution of P waves for the profile between the shot point Mušov and observation sites Pasohlávky (a) and Perná (b)

Mušov-Pasohlávky and Mušov-Perná. The models for these profiles (Fig. 5 and Tab. 2) are characterized by a relatively sharp velocity interface at depths of 50–60 m for both variants of the body waves velocity ratios. A slight difference in the sedimentary overburden thickness along these profiles can be explained by the general geological situation. The site Pasohlávky was located in the fluvial plane of the Dyje river, while the site Perná was situated in an area reaching from the shot point towards the foot of the Pálava Hills, i.e. in the area where the thickness of alluvial sediments is reduced. In this connection we should repeat that all the models considered here are homogeneous in the horizontal direction. Consequently, any lateral inhomogeneities in the real structure will be averaged in our models.

For all models from the shot point Báb, a sharp interface at depths of 60–70 m is characteristic. Simple models have been found for profile Báb-Jarok, i.e. in the southeastern direction from the shot point. For the northwestern direction from the shot point, the models are more complicated, containing two or three layers on a half-space (Fig. 6 and Tab. 2). It seems that relatively low velocities to the northwest from the shot point could be connected with the synsedimentary process of the partial basin filling (it even seems that a low-velocity layer increases its thickness toward the site Boleráz). The geological structure here is represented by "submerged" Tribeč mountain range, which is detached from surrounding sedimentary rocks by a system of tectonic faults. These deeper structures are probable causes of the different character of the experimental dispersion curves at opposite sides of the shot point Báb.

Simple models were found to be sufficient to explain the observed dispersion for profiles Sikenička-Čata and Sikenička-Čaka (Fig. 7 and Tab. 2). The models contain a sharp velocity interface at depths of 70 and 60 m, respectively, for both variants of the body wave velocity ratio, v_P/v_S.

As mentioned above, all quantitative interpretations described here yielded only simplified models. There were no data from seismic exploration or well-logging which could be used for verifying or constraining our interpretations. In particular, the pronounced velocity discontinuity in a narrow depth interval, $h = 50$–70 m, is a surprising common feature of all the models, which was not expected at the beginning of the investigations. It was usually assumed that the low-velocity superficial

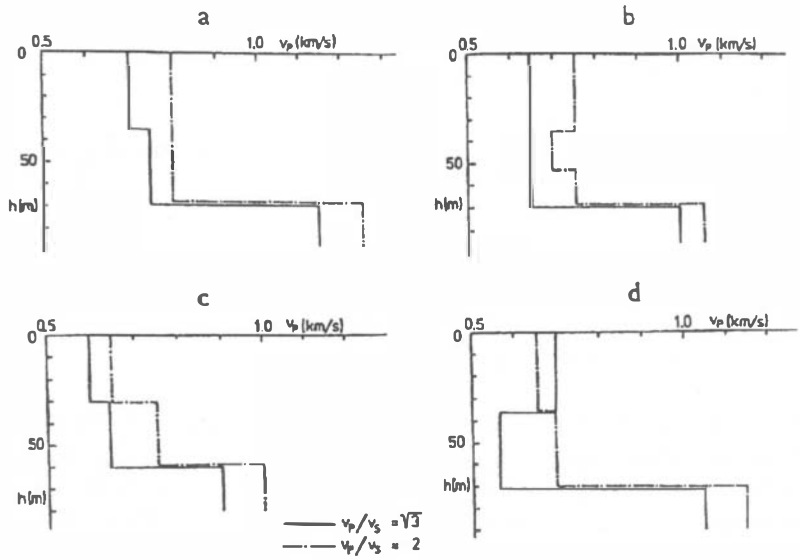

FIG. 6. Models for the profile between the shot point Báb and observation sites Jarok (a), Dvorníky (b), Malý Báb (c) and Boleráz (d)

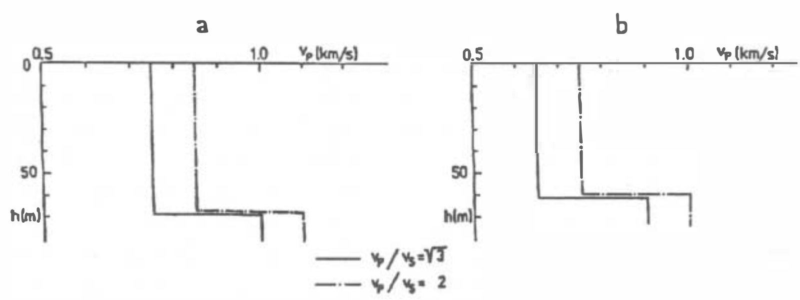

FIG. 7. Models for the profile between the shot point Sikenička and observation sites Čata (a) and Čaka (b)

material has a smaller thickness. For example, the thickness of the low-velocity layer in the Dubnice depression in the Danubian Lowland (wider surroundings of the site Čaka) varies within the depth interval of 5–10 m (Novák et al., 1966). Analogously, the velocity interface in our models does not correspond to the underground water level, which was found near the shot point Mušov at a depth of only several meters under the surface. Therefore, we should rather assume that the pronounced velocity increase in the uppermost 50–70 m could be connected with lithological and facial development of sedimentary cycle in the Danubian Lowland

and in the Carpathian foredeep.

5. Conclusions

The interpretation of the observed dispersion curves, described above, leads to the following general conclusions.

Relatively simple models are usually sufficient to explain the observed dispersion of the short–period Rayleigh waves. Multilayered models would probably characterize the real structures better, but for their determination some supplementary data or constraints would be necessary, such as data from shallow seismic measurements or well–logging. The observed dispersion curves themselves, as a consequence of their limited accuracy and period range, do not contain information sufficient for constructing more complicated models.

The velocity interface at depths of 50–70 m probably does not correspond to the boundary of the low–velocity weathered layer, nor to the level of underground water. Therefore, it would be desirable to use a borehole for its more accurate verification. The borehole could allow to correlate lithological and facial development of the sedimentary filling with the seismic results.

Two values of the compressional to shear wave velocity ratios, namely $v_P/v_S = \sqrt{3}$ and $v_P/v_S = 2$, were used in the interpretations. Since some recent investigations indicate even higher values of this ratio, v_P/v_S = 2–5, these higher values should also be considered in future investigations.

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