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SOME FEATURES OF SEISMIC WAVES OBSERVED IN THE TERRITORY OF NORTHERN MORAVIA AND SILESIA

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ABSTRACT

A grant project for the period 2003-2005, supported by the Grant Agency of the Czech Republic, was set up to determine properties of seismic waves and the structure of the uppermost part of the Earth´s crust in the territory of northern Moravia and Silesia. Quarry blasts and mining induced seismic events served as seismic sources. Permanent, temporary and portable seismic stations were used for the monitoring of these seismic events. During the experiments local microearthquakes were also detected and localized. For the complex evaluation of seismic wave features, data of the CELEBRATION 2000 and SUDETES 2003 refraction experiments were incorporated, as well. The velocity-depth dependence of body waves was searched by joint inversions of travel times of Pg/Sg phases. A special feature of the wave trains, generated by quarry blasts, was a pronounced dispersive character of short-period Rayleigh surface waves. These waves enabled us to establish their dispersion curves, on the basis of which the structure of superficial layers was determined down to a depth of several hundreds of meters.

KEYWORDS: Moravo-Silesian region, body waves, surface waves, quarry blast, microearthquake, crustal structure

1. INTRODUCTION

The subject of the three-year grant project (2003-2005) was to determine properties of seismic waves and the structure of the uppermost part of the Earth´s crust in the territory of northern Moravia and Silesia using quarry blasts and mining-induced seismic events. The seismic station Ostrava-Krásné Pole (OKC) and the regional network operating in the vicinity of Frenštát pod Radhoštěm, which consisted of 5 seismic stations, were initially assumed to serve as basic sources of seismic data (Holub et al., 2004). Unfortunately, the operation of this network was discontinued at the end of 2002, and a new solution had to be accepted. As a replacement of this monitoring system, another network consisting of 5 temporary seismic stations was afterwards erected to the west of this location (Růžek et al., 2004).

Quarry blasts as well as selected mining-induced seismic events were recorded at the OKC station and at temporary stations. While in case of quarry blasts the absolute time of their origin was checked by a special device, basic data of rockbursts (coordinates and time) were quoted in the database of mining-induced seismic events. It is worthwhile to mention that both the coordinates and the time resulted from the localizing procedure. Borehole shots carried out during international seismic experiments CELEBRATION 2000 and SUDETES 2003 (Guterch et al., 2003; Grad et al., 2003; Holub et al., 2005) served as another source of information. When constructing travel time curves, exact firing times and coordinates of explosions were available. Moreover, weak seismic activity was also observed and individual tectonic events were used as another source of elastic waves aimed to investigate seismic wave velocities within the area of 49.00°N - 51.00°N x 16.00°E - 18.75°E. In addition to the observations at permanent and temporary stations, measurement was also carried out along a short refraction profile between the Jakubčovice nad Odrou quarry and the OKC seismic station.

All available data gradually gathered in the course of the grant project solution was analyzed in various ways. The following characteristics and results were determined: travel time curves, 3D models of seismic velocities based on a kinematic inversion of Pg/Sg travel times, 1D vertically inhomogeneous models of superficial layers,

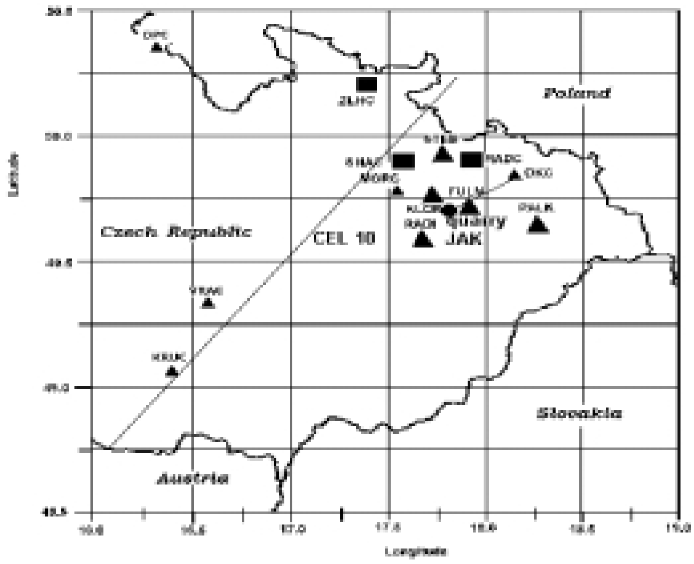

Fig. 1 Network of temporary seismic stations (▲, ■) situated on the territory of northern Moravia, along with some of stations of the Czech national seismological network (▲).Two straight lines display the courses of refraction profiles CEL 10 and quarry Jakubčovice nad Odrou - the OKC seismic station.

dispersion of short-period Rayleigh waves, spectra of seismic waves, and laboratory measurements of rock samples. These results are summarized in the present paper.

2. SEISMIC STATIONS

2.1. PERMANENT STATIONS

By permanent stations we mean the seismic stations that create the Czech Regional Seismic Network (CRSN), which consists of ten stations. For our data assessment purposes, only readings from five stations were used, namely OKC, MORC, DPC, KRUC and VRAC; their layout is displayed in Fig. 1. The specification of the CRSN station instrumentation is available at www.ig.cas.cz .

2.2. MONITORING ARRAY SPF

The aim of this array was to monitor induced seismicity using five surface seismic stations distributed in the broad vicinity of the Frenštát Mine in the southern part of the Ostrava-Karviná Coal Basin (OKCB). Their continuous operation started in January 1992 and a substantial part of recordings was represented by seismograms of induced seismic events from the central part of OKCB. Some blasts from nearby quarries were recorded, too. In 2000, several borehole shots fired along the CEL10 profile during the seismic experiment CELEBRATION 2000 were recorded by the array (Holub and Rušajová, 2002). Comprehensive information on the Frenštát seismic network (SPF) can be found in the paper by Holub et al. (2004a). The operation of this array terminated in December 2002, but data from the CEL10 profile was interpreted and included in the experimental database for the investigation of seismic velocities under the present grant project.

2.3. TEMPORARY STATIONS

Two groups of temporary stations were used. The first group was represented by the stations ZLHC, RADC and SHAC, equipped with short-period seismometers SM-3 (f_0 = 0.5 Hz, and the damping constant D ≈ 0.7), and the data acquisition system PCM3-EP, which operated in the triggered regime (Knejzlík, 2000). The positions of these stations are designated in Fig. 1 by the symbol (■).

The second group was represented by the stations FULN, KLOK, RADI, STEB and PALK, which were deployed within the grant project. These stations, designated in Fig. 1 by the symbol (▲), were equipped with the portable data acquisition system GAIA and broadband seismometers STS-2 (till April 2004), which were later substituted by three-component short-period seismometers LE-3D (f_0 = 1 Hz) (Růžek et al., 2004). The data acquisition system GAIA and the seismometers LE-3D were substituted again in 2005, namely by the VISTEC system and seismometers VEGIK and SM-3 (f_0 = 0.5 Hz and D_S ≈ 0.7), respectively. The sampling frequency was 100 Hz in all cases. These stations operated in a continuous regime, opposite to the triggered one as described above. The permanent breakdown of this network occurred during December 2005.

The names, codes and coordinates of the aforementioned stations are given in Table 1.

Table 1 An overview of data related to seismic stations specification.

Name	Code	φ_N (°)	λ_E(°)	H (m)
Ostrava-Krásné Pole	OKC	49.8353	18.1423	250
Moravský Beroun	MORC	49.7768	17.5425	742
Dobruška	DPC	50.3502	16.3222	748
Moravský Krumlov	KRUC	49.0619	16.3952	341
Vranov u Brna	VRAC	49.3084	16.5933	470
Radíkov	RADI	49.5958	17.6744	572
Fulnek	FULN	49.7125	17.9081	330
Klokočov	KLOK	49.7564	17.7192	624
Stěbořice	STEB	49.9344	17.7739	375
Palkovice	PALK	49.6406	18.2719	628
Zlaté Hory	ZLHC	50.2232	17.4063	517
Raduň	RADC	49.8931	17.9412	295
Slezská Harta	SHAC	49.8892	17.5839	478

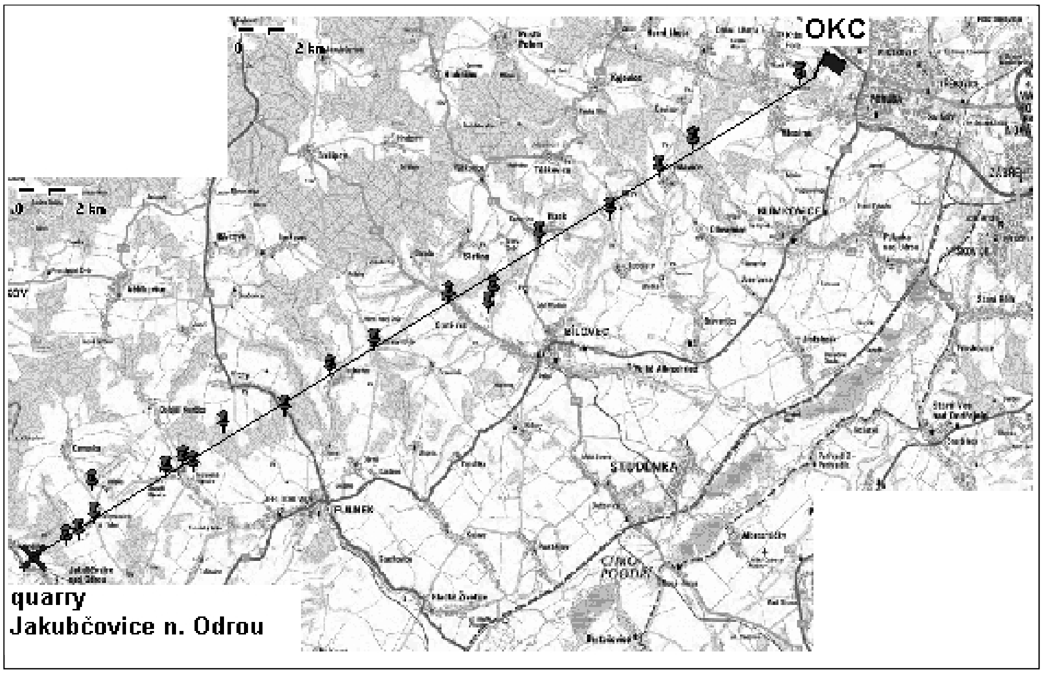

Fig. 2 Position of the short refraction profile between quarry Jakubčovice nad Odrou and the OKC seismic station and distribution of site of observations along it.

2.4. MOBILE STATIONS

In addition to the observations at permanent and temporary stations, the first series of refraction measurements began, in April 2004, also along the profile directed from the Jakubčovice nad Odrou quarry to the OKC seismic station, the length of which was approximately 30 km, situation of this profile is displayed in Fig. 2. This seismic experiment was completed between May and June 2005. At the same time, several blasts at quarries Bohučovice and Podhůra were recorded at a discrete site of observations. Only the portable data acquisition system GAIA and the three-component short-period seismometers LE-3D were employed in field experiments.

3. SOURCES OF SEISMIC WAVES

Deep seismic sounding represents a traditional method of the detailed study of crustal structure. In the former Czechoslovakia, seismic experiments using this method started in the 1960s (Beránek et al., 1971). During these experiments, only hole shots along three international refraction profiles were fired. Quarry blasts were later used for planar mapping of the Moho discontinuity and in the course of regional refraction measurements (Beránek and Zátopek, 1981; Mayerová et al., 1994).

3.1. HOLE SHOTS ALONG REFRACTION PROFILES

In 1997, seismic refraction experiment POLONAISE ´97 was realized on the territory of Poland (Guterch et al., 1999), which was followed by another experiment CELEBRATION 2000 (Guterch et al., 2003; Guterch et al., 2003a). The latter was a large-scale project, which involved not only measurements along refraction profiles through the Carpathians towards the Panonian Basin, but also measurements along the profile CEL09 intersecting the territory of Bohemia from southeast to northwest, and along the profile CEL10 crossing Moravia from northeast to southwest. There were four shot points (No.1-4) along the profile CEL10; one of them was situated on the Polish territory, while three shot points were distributed on the territory of Moravia. As for the profile CEL09, only hole shots from two shot points (No. 5 and 6) were included into our data set for interpretation. Between June 23 and June 25, 2000, eight explosions were fired and almost all were recorded at permanent seismic stations, while seismic stations of the SPF array recorded only explosions from shot points No. 1-4. The single charge of 700 kg of explosives was fired on the shot point No. 1, while the rest of explosions had a unique charge of 210 kg (Holub and Rušajová, 2002).

In 2003, the former international cooperation continued during another seismic experiment - SUDETES 2003 - which linked to the previous field experiments (Guterch et al., 2003; Grad et al., 2003). Measurements were carried out along the profiles S01 through S06, along which 10 shot points were distributed and where 10 explosions were fired. While eight shots were represented by borehole shots, only two useful explosions on the profile S04 were quarry blasts. The scheme of this experiment setup, i.e. the situation of profiles and shot points on the territory under investigation is given in (Holub et al., 2005), see Fig. 1. Charges of 400 kg were used at quarries, while in case of hole shots the charges varied between 50 and 250 kg. During this passive seismic experiment, mainly explosions blasted on the territory of Poland were detected at the permanent as well as temporary seismic stations located in northern Moravia and Silesia. Moreover, these explosions were also recorded at a solitary seismic station in southern Moravia in the epicentral distance of 233 km from the shot point.

3.2. QUARRY BLASTS

During the proposed project, quarry blasts were considered as the main seismic sources. Therefore, the management of quarries was asked for basic information concerning the blasting operation plans in the near future. In this way, during the time period 2003-2005, we gradually created a database of quarry blasts from 22 quarries, which contained data such as charges of explosives, approximate times of blasting operations and coordinates of the quarry. Later on, the analysis of input data proved that the prevailing part of quarries either used relatively small charges, or the blasting operations were seldom performed. It was found out that in the epicentral distances under consideration quarry blasts using less than about 1,000 kg of explosives usually did not generate seismic waves of sufficient energy. Therefore, due to the unfavourable signal-to-noise ratio, these blasts were not included into our programme. Finally, only eight quarries were chosen as suitable seismic sources.

The absolute time of the quarry blast was determined by means of devices BR-1 (Brož, 2000) or PCM3-NB (Holub et al., 2004). Considering that this instrument had to be placed at a safe distance (tens of meters) from the hole shot, the measured time was corrected in order to obtain the accurate origin time. Since laboratory experiments showed that the ultrasonic velocity is v_P = 3300 m/s in greywacke samples, we used the same velocity in the time corrections mentioned above.

A detailed analysis of records of quarry blasts carried out on the territory of northern Moravia and Silesia proved the existence of very expressive surface waves displaying a pronounced dispersion. Therefore, it was concluded that this property should be used as a very helpful tool in subsurface mapping.

3.3. INDUCED SEISMIC EVENTS

Not only quarry blasts, but also mining induced seismic events were taken into account as possible sources of seismic waves. This possibility was based on the experience in seismological observations at the OKC seismic station. This station very often records induced events not only from the Ostrava-Karviná coal mines, but also from Polish coal mines. However, the accurate timing in case of Polish mines was not reliable at all. Consequently, we could not use Polish data to extend our database of induced seismic events.

Induced events in Czech coal mines are detected not only by regional, but also by local seismographic networks, as well as by seismoacoustic arrays. These measurements ensure a reliable location of induced events, i.e. a reliable determination of their coordinates and origin times. Data from seismoacoustic arrays has especially high accuracy, because the measuring bases are usually close to foci. These hypocentral parameters of induced events were at our disposal for further study.

4. TRAVEL TIMES OF BODY WAVES

An extensive database of travel times was completed as part of the grant project. The database contains travel times for 1301 rays from 63 different seismic sources, covering a broader area of Moravia and Silesia. In particular, the data includes 516 readings from the CELEBRATION 2000 experiment, 183 readings from the SUDETES 2003 experiment, 161 measurements of quarry blasts performed in 2004-2005, 63 mining induced events (using the seismic bulletin of the mines), and 125 local tectonic events (a location procedure was a part of the computation). Starting with a simple 1D structural model, the data set was finally inverted for 3D velocity models. The rays in the 3D models were computed by the bending method, and the corresponding inverse problem was solved with evolution algorithms. The velocity model seems to be consistent with the concepts of the geological structure of the region. The model reaches to a maximum depth of about 18 km. The lowest surface velocities of 4.4 km/s were found in the Neogene sedimentary basins. The structure at greater depths follows the Sudetes directions of NWW-SEE. We shall not give further details here considering a special paper is in preparation. Final velocity model will be presented in a user friendly digital form at http://www.ig.cas.cz in a short time. The computing method is briefly outlined in (Růžek et al., 2005). Undoubtedly, the database of travel-time measurements in the Moravo-Silesian region will also be valuable in future structural studies.

The surface velocities inferred from standard refraction measurements, and also the surface velocity of 4.4 km/s, as mentioned above, represent certain simplifications of the velocity profile at shallow depths. Namely, the actual *P*-wave velocities at the surface are usually low, but increase rapidly within the uppermost layers to a depth of about 1 km. To obtain details of this superficial structure, detailed refraction measurements at short epicentral distances are needed (Málek et al., 2004, 2004a). Consequently, we have also performed detailed measurements along several profiles in the Moravo-Silesian region.

Let us describe briefly the detailed measurements along the profile from the quarry at Jakubčovice nad Odrou toward the OKC station, and their interpretations using the classical Wiechert-Herglotz method. The length of the profile was nearly 30 km, and *P*-wave travel times at 17 epicentral distances were obtained (the next three measurements were less accurate due to technical or local conditions, and had to be eliminated). Figure 3 shows the observed travel times by the isolated points. The solid line in the figure represents their approximation with a rational function, i.e. a quotient of two polynomials, in the simple form

$$t(r) = \frac{a_1 r + a_2 r^2}{b_0 + r} \quad , \tag{1}$$

t being the travel time and r the epicentral distance (Málek et al., 2004a; Novotný et al., 2004). The coefficients of the best approximation, a_1, a_2, and b_0, were obtained by a gradient method. The smoothed travel-time curve in the form (1) was then interpreted by the Wiechert-Herglotz method. The resultant velocity cross-section is shown in Fig. 4 as the solid line. The dashed lines in the figure indicate the approximate bound of the velocity distributions determined by the method of delete-one jackknifing; see Málek et al. (2004). The mean *P*-wave velocity at the surface, of about 3.5 km/s, seems to be in a good accordance with laboratory measurements and with studies of short-period surface waves.

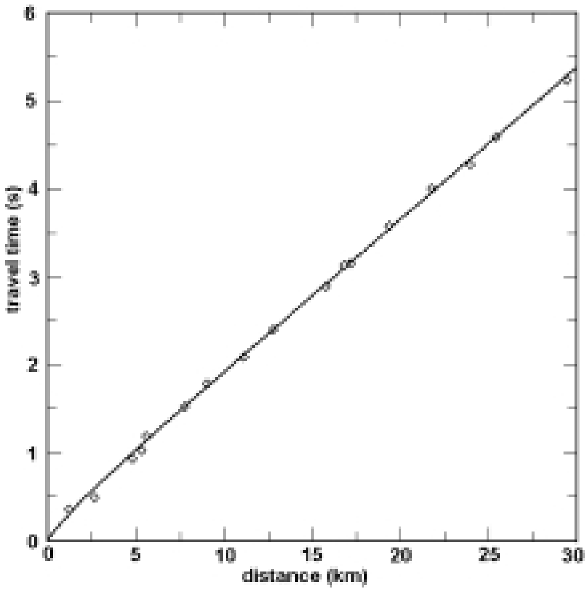

Fig. 3 Travel times along a selected refraction profile (diamonds) and their rational approximation (solid line).

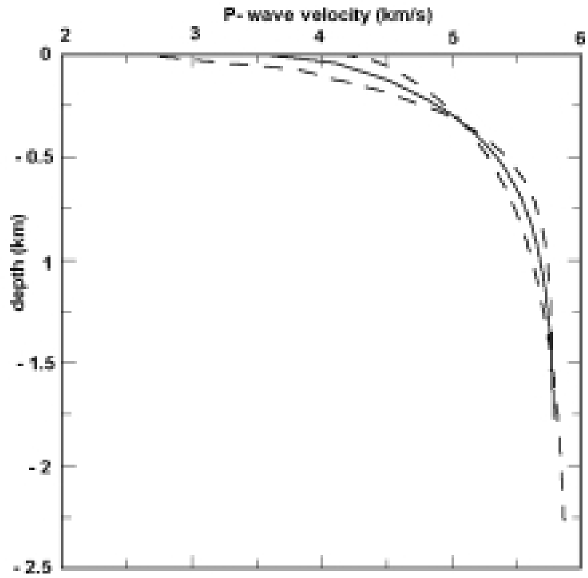

Fig. 4 Velocity model (solid line) corresponding to the smoothed travel-time curve in Fig. 3. The dashed lines show two most extreme variations of the velocity model obtained by the method of delete-one jackknifing.

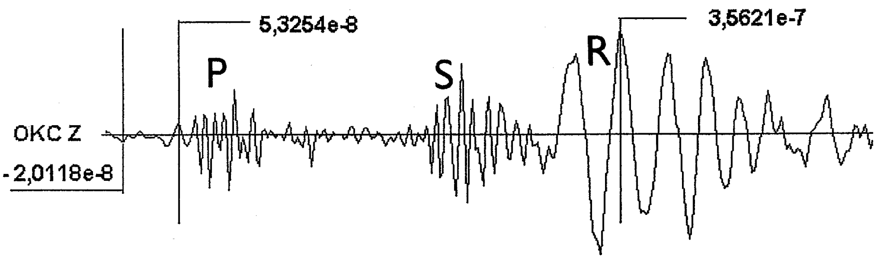

Fig. 5 Comparison of seismic noise level with amplitudes of some useful signals during a quarry blast recorded at the seismic station OKC; d ≈ 30 km, Q = 5315 kg.

5. SURFACE WAVES DISPERSION

Apart from seismic reflection and refraction experiments, the analysis of short-period surface wave dispersion is also a method of investigating the uppermost part of the Earth´s crust structure (Xia et al., 1999 and 2004).

The existence of short-period Rayleigh waves was documented on seismograms of the OKC seismic station. An example of wave trains of body waves, as well as surface waves generated by a quarry blast is given in Fig. 5. The records at OKC enabled to study special features of these waves, and to use them in structural studies of the superficial part of the Earth´s crust in the territory of northern Moravia and Silesia. It is well known that shallow seismic sources generate more intensive surface waves than deeper sources. This explains the fact that Rayleigh waves generated by some quarry blasts are rather intensive. Moreover, these waves display dispersion, which is a consequence of the stratified overburden of the Lower Carboniferous Culm facies sediments, e.g., greywackes, shales, claystones and siltstones.

Structural studies using surface waves are based on a construction of observed dispersion curves and their interpretation. Let us describe the propagation of Rayleigh waves along the profile from the quarry Jakubčovice nad Odrou to the OKC seismic station. For this purpose, 11 records with well-developed Rayleigh waves were selected, and the group-velocity dispersion curves were calculated from them using the standard graphical-numerical method proposed by Savarenskiy (1959). The average curve of these 11 dispersion curves was then determined (Holub and Rušajová, 2003); see Fig. 6.

The average dispersion curve was first interpreted in terms of a simple structural model that was composed of a layer on a half-space. Both the layer and the half-space were assumed to be homogeneous and isotropic. (Note that more complicated models are usually applied in many structural studies at present, but this simple model of the medium is still useful in studies of shallow structures). The interpretation was performed by a gradient method. The partial derivatives of the group velocity with respect to the parameters of the medium,

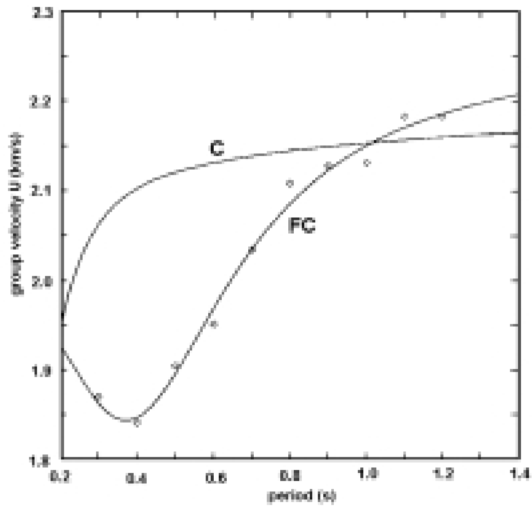

Fig. 6 Group velocities of Rayleigh waves for the selected profile: the isolated points represent the observed data; curve C is the theoretical dispersion curve for an initial model, curve FC for the final model.

needed in the gradient method, were calculated analytically using the implicit function theorem. The parameters of the initial model (C), and the parameters of the final model (FC) are given in Table 2; see details in (Novotný et al., 2005).

The corresponding dispersion curves are shown in Fig. 6. It can be seen that the final model satisfies the observed data much better than the initial one. It should be pointed out that the thickness of the effective layer is nearly 400 m. Moreover, the *P*-wave velocity in the layer, of about 3.5 km/s, is very close to the surface velocity derived from the refraction data (Fig. 4).

Recently, we have interpreted the same dispersion curve in terms of a layered medium that was composed of five layers on a half-space. Each layer was 100 m thick, and this value was kept fixed during the interpretation. The initial *P*-wave velocities increased linearly from 3.4 km/s in the first layer to

Table 2 Parameters for dispersion curves computation: C – starting model, FC – resulting model of a layer on the half-space.

MODEL	a_1(m/s)	a_2 (m/s)	b_1 (m/s)	b_2 (m/s)	ρ_2/ρ_1	H (m)
C	3500	4200	2000	2400	1050	100
FC	3530	4207	2150	2565	1027	383

a_1, b_1 and ρ_1…..velocities of P- and S-wave and density in the upper layer
a_2, b_2 and ρ_2 ….velocities of P- and S-wave and density in the half-space
H ..thickness of the layer on the half-space.

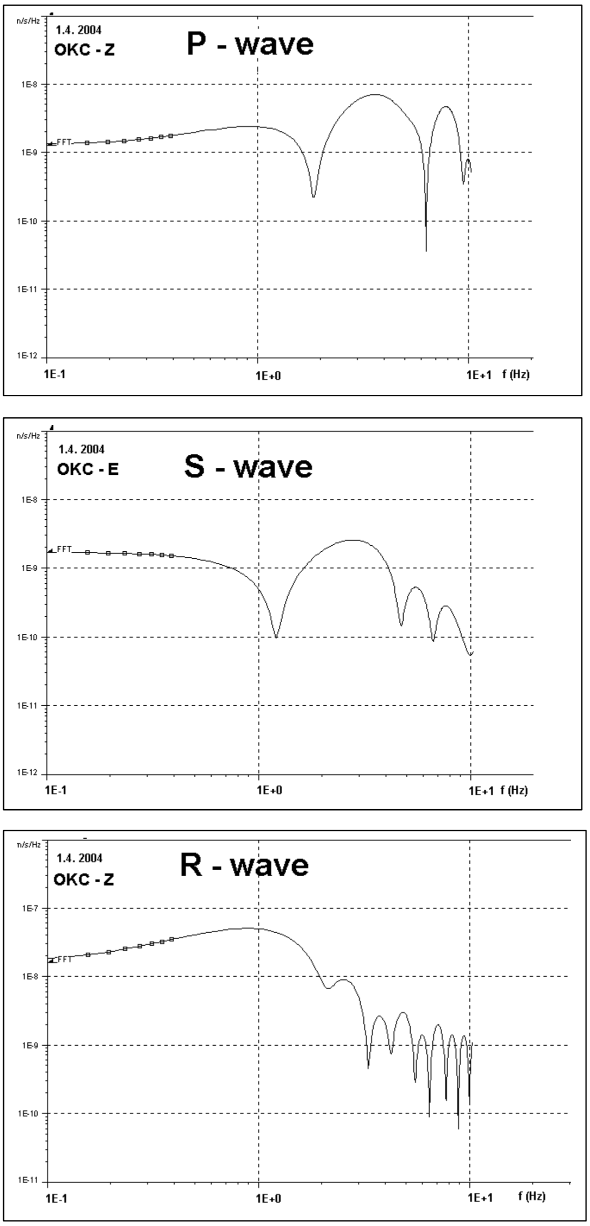

Fig. 7 FFT spectra of seismic waves generated by an explosion in quarry Jakubčovice nad Odrou and recorded at OKC seismic station; d ≈ 30 km, Q = 6630 kg.

4.4 km/s in the half-space (the Poisson´s ratio was assumed to be between the *P*- and *S*-wave velocities). The interpretation was performed by a variant of the method of single-parameter variation (Novotný et al., 2001). The final model was again very close to the simple model given in Table 2, i.e. a nearly homogeneous, 400-m-thick layer on a half-space. This means that the dispersion data requires a pronounced velocity discontinuity at a depth of about 400 m.

From the viewpoint of the geological structure of the area it seems that the velocity discontinuity at an approximate depth of 400 m probably corresponds to facial boundary having a smooth transition between the Hradec greywacke and Kyjovice shale, which consist of rocks with different petrographical composition. While the Kyjovice shale consists of intensively folded layers of claystones and siltstones, the Hradec greywacke, which represents a medium with higher seismic velocities, is formed by greywackes, if appropriate, by fine to medium grained greywacke conglomerates, eventually by fine to medium grained greywacke conglomerates; the thickness of the whole formation is about 500-600 m.

6. SPECTRAL PROPERTIES OF SEISMIC WAVES

The database of parameters of rockbursts recorded at three seismic stations situated in underground mines of the OKCB was used for the investigation of prevailing frequencies of ground vibrations. The hypocentral distances inside the Karviná coal basin varied within the limits of 0.5 – 6 km. The amplitude spectra of *P*-wave particle velocities had a broad maximum in the frequency interval $f_P \approx$ 3-12 Hz, the weighted average frequency being $f_P^* = 5.8$ Hz. Analogous values for *S*-wave velocities were as follows: $f_S \approx$ 2-9 Hz and $f_S^* = 4.2$ Hz. These values were typical for rockbursts with energies of 10^4-10^7 J. However, one can expect that the values of predominant frequencies can be influenced by the amount of the released energy, in accordance with the assumption that the higher energy of a rockburst, the lower frequency of generated vibrations. In case of quarry blasts, predominant frequencies of vibrations at individual sites were observed within the following intervals: $f_P \approx$ 10 –15 Hz, $f_S \approx 5$ Hz and $f_R \approx$ 0.8 – 3 Hz (for Rayleigh waves). A set of spectra for *Pg*, *Sg* and *R*- waves is shown in Fig. 7.

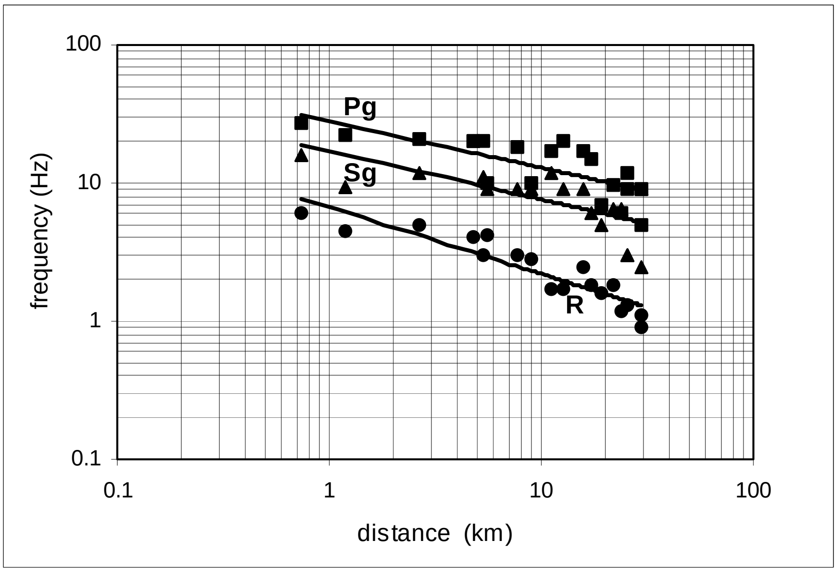

Fig. 8 Set of dependences f (Hz) for body and surface waves vs. epicentral distance d (km) along profile: quarry Jakubčovice nad Odrou – the OKC seismic station.

Attention was also paid to the relation between maximum spectral amplitudes of *P, S* and *R*-waves vs. distance. For this purpose, measurements along the profile passing from the quarry at Jakubčovice nad Odrou to the OKC seismic station, the length of which was approximately 30 km, were used. Nineteen sites of observations were deployed along this profile; the closest location was 740 m from the explosion. The prevailing spans of observed frequencies were as follows: $f_P \approx$ 28-8 Hz, $f_S \approx$16-5 Hz and $f_R \approx$ 7-1.3 Hz. These values were approximated by a regression function according to the formula

$$f = f_0 \cdot r^{-n}\,, \tag{2}$$

where r is the epicentral distance in kilometres, and coefficient n characterizes the decrease of frequency with increasing epicentral distance r (Fig. 8). It was found out that the exponent n for body waves was almost the same, namely n = 0.33 (for *P*-waves) and n = 0.35 (*S*-waves), whereas n = 0.49 for Rayleigh waves. The absolute term of the regression straight line, f_0, for individual types of waves equals approximately to the following values: 27.8 Hz (*P*), 17.0 Hz (*S*) and 6.7 Hz (*R*).

7. LABORATORY EXPERIMENTS

Quarry blasts were used as major seismic sources in our studies of the superficial structure in the territory of northern Moravia and Silesia. The quarry Jakubčovice nad Odrou, which was of our primary interest, is situated in the Lower Carboniferous Culm facies, where outcrops of greywacke, sandstones and conglomerates were predominantly documented. Research into physical and mechanical properties of greywacke rock specimens was, therefore, undertaken as part of a complex program of laboratory experiments. Experiments were carried out independently under controlled laboratory conditions in two laboratories, namely in the Laboratory of Mechanical Properties of the Institute of Geonics (IG) AS CR in Ostrava and the Geotechnical Laboratory of the Institute of Rock Structure and Mechanics (IRSM) AS CR in Prague.

Two types of cylindrical cores were prepared from an irregular shape of blocks of greywacke taken in the quarry Jakubčovice nad Odrou. The size of the cores was 96 mm and 24.8 mm in length, having a diameter of 46 mm, so the length-to-diameter ratio was about 2 and 0.5, respectively. Considering that the laboratory setup in the IRSM needed a different size of specimens, the original cylindrical cores were re-drilled to a diameter of about 30 mm, and their length shortened to 60 mm.

The stress-strain measurements and ultrasonic velocities determination of greywacke samples in a triaxial chamber were performed in the IG AS laboratory on the mechanical press ZWICK 1494 that has stepping motors and the maximum force of 600 kN. The triaxial chamber is equipped with strain gauges for measurements of longitudinal and lateral deformation. The measuring complex also includes a lot of electronic supplementary devices, e.g. ultrasonic receivers and transmitters, a PC for ultrasound and deformation, a data acquisition system and controlling electronics of the press (Konečný et al., 2004). In

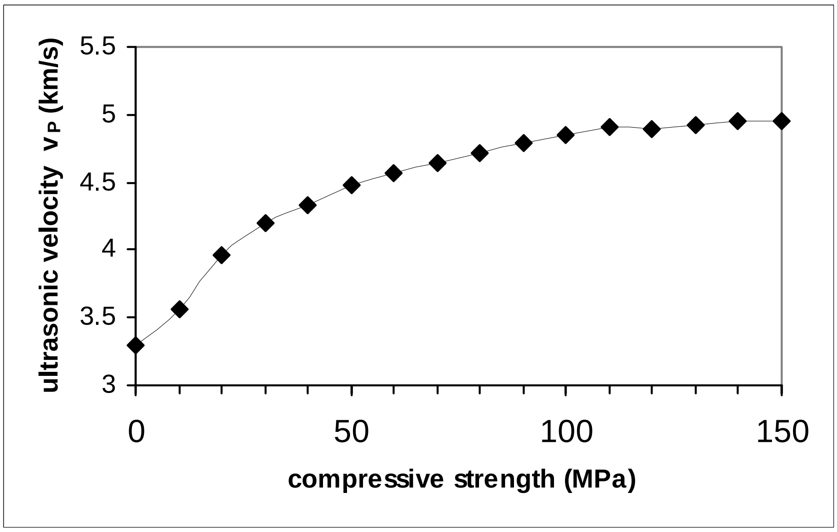

Fig. 9 Ultrasonic velocity v_P of greywacke cylindrical samples vs. compressive strength.

addition to basic measurements of stress-strain characteristics of the rock samples, which are not the subject of this paper, some physical parameters of our interest were also investigated. In particular, the following average values were obtained for six samples of Lower Carboniferous greywacke: bulk density $\rho \approx 2580$ kg/m^3, ultrasonic velocity $v_P \approx 3350$ m/s, simple compressive strength $\sigma_D \approx 99$ MPa, Poisson´s ratio $\nu \approx 0.16$ and Young´s modulus $E \approx 15480$ MPa.

The Geotechnical laboratory of the IRSM measured ultrasonic velocities v_P using three samples of the same rock material as mentioned above, and, moreover, changes of v_P under increasing triaxial loading. For these experiments, a hydraulic frame with a maximum axial compression force of 3000 kN and a device with a fluid-confining pressure of up to 150 MPa were used (Živor and Trčková, 2004). At the beginning of the experiment, i.e. when the loading was not applied, the average value of velocity $v_P \approx 3289$ m/s was obtained. The experiment then continued under increasing loading, and changes in ultrasonic longitudinal velocities were measured. The gradual increase of ultrasonic velocities is displayed in Fig. 9. The steepest increase of the curve up to the loading of 30 MPa is obvious. Furthermore, the increment in velocity is gradually lower, and, finally, between the values of 110-150 MPa the increment represents only about 1%. At this high loading, the average velocity reaches a value of 4955 m/s, and the deviations from this average for three rock samples are less than 2%.

The laboratory experiments served especially as independent tests of the results of refraction measurements. Moreover, velocity of longitudinal waves was taken into account in a more precise determination of the firing time in quarries. Finally, certain estimates of bulk density and longitudinal wave velocity were needed in interpreting the dispersion curves in order to reduce the number of unknown parameters (fixed relations of these quantities to shear-wave velocities were assumed).

8. MICROEARTHQUAKES

In addition to quarry blasts and induced seismic events, the temporary and permanent stations also recorded weak seismic events of tectonic origin that occurred in the Moravo-Silesian region and its vicinity.

Sporadic tectonic events of regional origin had been recorded at the OKC seismic station for many years. More than sixty microearthquakes were recorded from the beginning of the temporary network operation in May 2003 up to December 2005. The first two microearthquakes, recorded in July 15 and 17, 2003, were localized and the accuracy of foci determination was also verified using the same location procedure that was used for a quarry blast at Jakubčovice nad Odrou (Růžek et al., 2004). Foci of 15 microeartquakes were sometimes localized by also using data from stations of the CRSN. Isolated microearthquakes were concentrated mainly to the environs of Opava, Vizovice, Budišov nad Budišovkou, Hranice, Dolní Benešov, Mohelnice and Prostějov, while microearthquakes near Šternberk na Moravě and Odry occurred repeatedly during several days (Holub, 2005).

The tectonic development of the investigated area displays a lot of fault zones. The main fault systems of the Sudetic direction in the Moravo-Silesian region include, for instance, the Marginal Sudetic Fault, faults of Bělá, Opavice, Klepáčov, Temenice, Konice etc. A fault denoted as the Marginal Jeseníky Fault (Kumpera, 1994) is also very important. Unlike the abovementioned faults, it has approximately east-west orientation.

It seems that most foci can be related to the aforementioned significant faults. It is also interesting that the depth of these foci ranged within the interval of 5-18 km. However, it was difficult to determine their further parameters, such as focal mechanisms, as the most tectonic events were very weak. Note that the strongest earthquake occurred on December 31, 2005. This event, detected by seismic stations included into the CRSN, as well as stations situated in Slovakia, was localized to the environs of Šternberk na Moravě. Its focal depth was around 12 km, and its magnitude was estimated at M = 1.8.

9. CONCLUSIONS

The paper analyzes representative features of seismic waves recorded at permanent, temporary and mobile stations in the territory of northern Moravia and Silesia during three years of observations. Quarry blasts, hole shots, mining induced seismic events and microearthquakes were used as sources of seismic waves. The following conclusions can be made:

(i) A database of about 1300 travel times from 63 different seismic sources was completed. A 3-D velocity model of the upper crust was derived from the travel times using the ray bending method and inverse evolution algorithms. The model is consistent with the concepts of the geological structure of the region. The structure at greater depths follows the Sudetes directions of the NWW-SEE. Special detailed measurements were performed along a short refraction profile to derive a 1-D model of the uppermost crustal structure by using the Wiechert-Herglotz method. This structural model is characterized by a rather low superficial velocity of about 3.5 km/s for *P* waves, but by a high velocity gradient to a depth of about 1 km.

(ii) Some quarry blasts generated intensive Rayleigh surface waves with distinct dispersion. Observed dispersion curves were compared to theoretical ones for a simple model of the medium, composed of a layer on a half-space. The layer was about 400 m thick, which could be associated with the Kyjovice shale, and the half-space with a somewhat higher velocity could be associated with the Hradec greywacke.

(iii) Spectra of body waves were investigated in the near zone of rockbursts. The predominant frequencies were about 6 Hz for *P* waves and 4 Hz for *S* waves. Changes of the frequency contents of body and surface waves along the short refraction profile were also studied.

(iv) Laboratory measurements of stress-strain relations and ultrasonic velocities were carried out on cylindrical-shaped samples of Lower Carboniferous Culm greywacke.

(v) It was documented that a lot of microearthquake foci traced the well-known faults with the Sudetic orientation, e.g. the Marginal Sudetic Fault, faults of Bělá, Opavice, Klepáčov, Temenice, Konice, etc. Only the significant Marginal Jeseníky Fault has approximately E-W orientation.

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