ACTA MONTANA IRSM AS CR (1995)
Series A, No.6(95), 33–42

PARTICLE VELOCITY AND FREQUENCY OF SEISMIC WAVES GENERATED BY A CYLINDRICAL EXPLOSIVE SOURCE

Karel HOLUB

Institute of Geonics, Academy of Sciences of Czech Republic
Studentská 1768, 708 00 Ostrava–Poruba, Czech Republic

Abstract. Seismic measurements which were performed in the brown–coal and shale open–pit mines in the Northwest and Central Bohemia have enable to investigate relations for radial horizontal component of the particle velocity in the nearest zone of explosion. Besides the determination of critical particle velocities for sliding and failure of walls in the mines, the relations as predominant frequencies of seismic wave onsets vs. charge size and scaled distance, respectively, were ascertained. Resulting relationships are being compared with the character of sedimentary rocks in the environment of four test sites, where these experiments were carried out.

Keywords: coal and shale open–pit mines, blasting operations, seismic waves

1. Introduction

In the open–pit brown–coal mines of the Ore Mountains (Krušné hory) Miocene basin in the Northwest Bohemia, as well as in shale mines in the coal basin in Central Bohemia, blasting operations have been sometimes used before the deposits were actually exploited. At four test sites which has been different not only due to the character and degree of the rock disintegration but also by the lithology at individual localities, special seismic experiments were carried out. These experiments were aimed at correlation of influence of blasting operations on the character of macroscopic changes of the walls, thus the limitations of critical particle velocities causing either failure or sliding of the walls were described by [Holub and Tobyáš 1987; 1989]. Utilization of these field measurements allowed to carry out investigations of mutual relationship between the predominant frequencies of seismic wave onsets and charge size and local geology as well.

2. Local Geology

In the open–pit brown–coal mines in the Northwest Bohemia, two test sites were chosen. These sites were on different horizons at places which are presently no longer in operation.

The locality No 1 was situated at a place, where the coal seam was not developed. The whole block of rocks was built from overlying compact grey clays, of the tensile strength approximately 0.4 MPa, while the compressive strength was of about 2.2 MPa. The individual thin layers of the strata series were subhorizontally deposited, no obvious dislocation planes were observed.

The locality No 2 was located in the same open–pit mine but approximately 20 m above the first one. The geological cross–section was more complicated due to different sedimentary rocks existing here. The upper part of the wall was formed by subhorizontally deposited layers of compact clays. The middle and lower part of the wall was built by diagenetically consolidated sandstones partly changed by weathering into sand. The tensile strength of sandstones was amounts 0.3 MPa and the compressive strength 3.4 MPa. Besides the continuous or discontinuous fissures two conspicuous dislocation planes are presented at the test site.

For seismic experiments in the region of the Central Bohemian Coal Basin, two test sites in the shale mines in the marginal part of the Kladno–Rakovník Basin were chosen.

The test site No 3 was situated in the upper part of open–pit mine near Nové Strašecí town, where Carboniferous shale is exploited. The uppermost part of the geological profile was in general represented by a strata group of Cretaceous marl which was underlayed by facies of siltstones and compact glaucous clays, all having subhorizontal sedimentary surfaces, penetrated by more or less visible fissures. The tensile strength of glaucous clays determined on cubic specimens amounts 1.7 MPa, while the compressive strength was 7.7 MPa.

The locality No 4 of seismic measurements was situated in the shallow Carboniferous shale open–pit mine near Rakovník town. The outcrops of the Carboniferous sedimentary rocks were observed almost on the surface, nevertheless they were covered by a layer (3–4 m thick) of Quarternary clayed–sandy loam with fine rounded boulders. Due to a high content of water on the face of this superficial layer no fissures were observed, and no sampling of solid pieces for physical parameters determination was possible. A comprehensive table of the rock parameters and critical particle velocities is given in [Holub and Tobyáš 1989].

3. SEISMIC EXPERIMENTS

3.1. Instrumentation and experimental setup

For recording of the wave pattern of seismic waves in the nearest zone of cylindrical explosive source, special vibrometers type VBP–3 in connection with galvanometric portable oscillograph type POB–12M were used. The vibrometers were designed for recording of horizontal (radial) component of particle motion in the frequency range of 1–100 Hz and displacement amplitudes within the interval 1–300 mm. Details of the instrumentation are described in Holub and Tobyáš (1987).

The position of vibrometers at three places was fixed, whereas the positions of boreholes for blasting operations, as well as the shot–receiver distances varied. Depth and number of the holes depended on the height of mining walls and on the anticipated charge size used varied with respect to the necessary height of the tamping. According to the shape of the charge this explosive source as cylindrical one was denoted. For the purposes presented in this paper, only seismograms recorded at fixed positions of vibrometers placed near the wall–foot (position was denoted as "c") were analyzed. The scheme of such experimental setup is shown in Fig. 1.

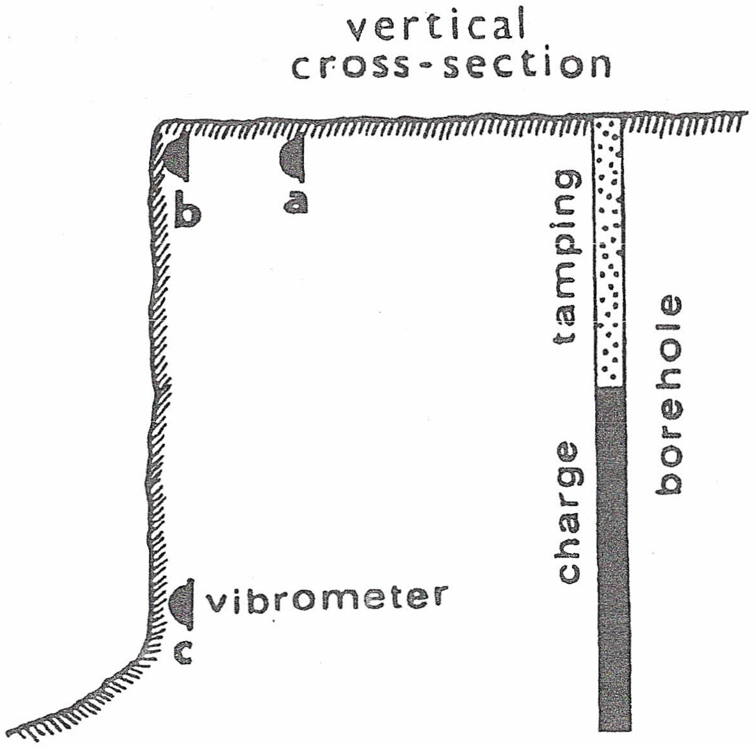

FIG. 1. Scheme of the setup at the test site.

3.2. Methods of records and data processing

In the vicinity of the explosive charge some zones due to the action of gaseous products of the explosion are usually created. These zones are characterized by different degree of deformation of the material. Naturally, the closer to the explosion source of seismic waves are recorded, the more will be the wave shape simple on the whole. Nevertheless, the interpretation of the actual wave pattern has to be performed under certain assumptions stated before.

The method of seismogram processing relies upon the evaluation of only two parameters being as follows: the amplitude (the trace deflection) A_1 of the first peak and the arrival time t_1 of this peak.

The frequency of the first cycle of ground motion is being determined using the following formula

$$f = (4\,t_1)^{-1}\,, \tag{1}$$

where t_1 in s is the arrival time of the first peak in the seismogram, which examples are given in Fig. 2.

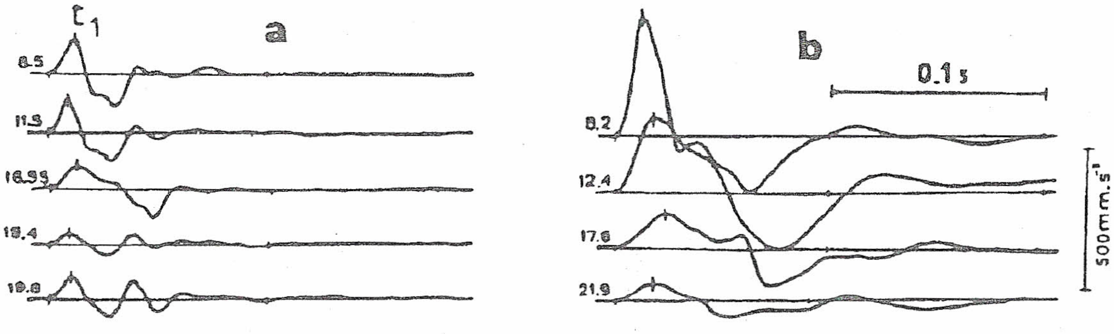

FIG. 2 Seismograms of explosions ($Q = 9\,\mathrm{kg}$) recorded at the test sites No 1 (a) and No 2 (b). The individual traces correspond to the given shot–receiver distances, t_1 denotes the first particle velocity maximum.

With the respect to elimination of changes of the shot–receiver distances r in m and the charge size Q in kg during field experiments, a new parameter – scaled distance r^* – was induced and defined as

$$r^* = r/Q^{1/3} . \tag{2}$$

For our purposes, partial sets of measured values v_i and f as well as values r^* and Q were used. These values were presented in bilogarithmic scale and the method of least squares was applied aiming at adjusting functional dependences.

Originally exponential function used for data approximation (4) had been transformed to a linear equation in the form

$$\log y = \log k \pm m \log x . \tag{3}$$

4. RESULTS OF FIELD EXPERIMENTS

The field experiments were first of all aimed at definition of critical values of particle velocities causing either sliding or failure of the wall. For this purpose, values of particle velocities observed at the fixed places located close to the upper edge of the face (formerly denoted as "b") were applied. The observations of seismic waves at fixed places located at the wall-foot, which have not been discussed yet, provided a new evidence of rock mass behaviour.

Using the experimental data v_i (mm/s) and f (Hz), three basic relations were determined as follows:

$$v_i = F(r^*) \qquad f = F(Q) \qquad f = F(r^*) . \tag{4}$$

Each of these functions are given in graphical form (see Figs 3–5) and in the form of equations (Eqs 5–7).

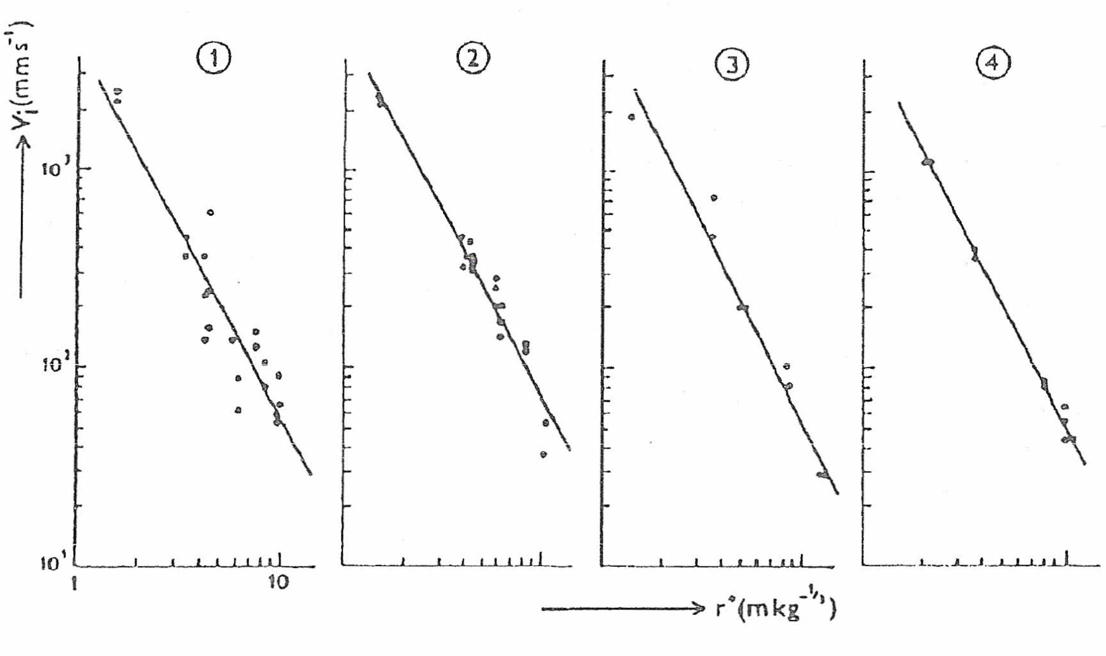

FIG. 3. Maximum particle velocity v_i of the seismic wave (radial horizontal component) vs. scaled distance r^* valid for the test sites Nos 1–4.

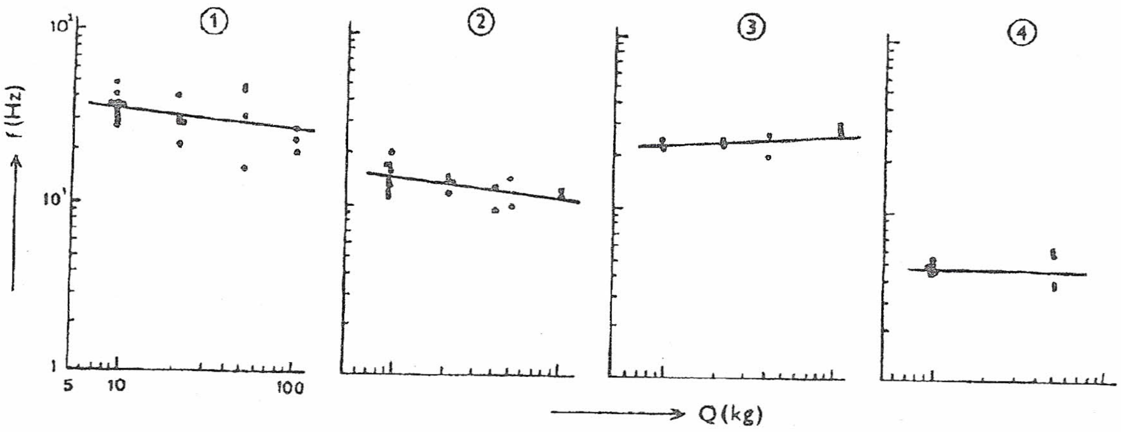

FIG. 4. Frequency f of the seismic wave (radial horizontal component) vs. charge size Q valid for the test sites Nos 1–4.

4.1. Particle velocity vs. scaled distance

The experimental data obtained in processing of seismograms enabled to create for test sites Nos 1–4 v_i vs. r^* graphs presented in Fig. 3. The approximation was performed using straight lines which are determined by linear equations obtained by the least square solution; the shape of equations corresponds to separate test

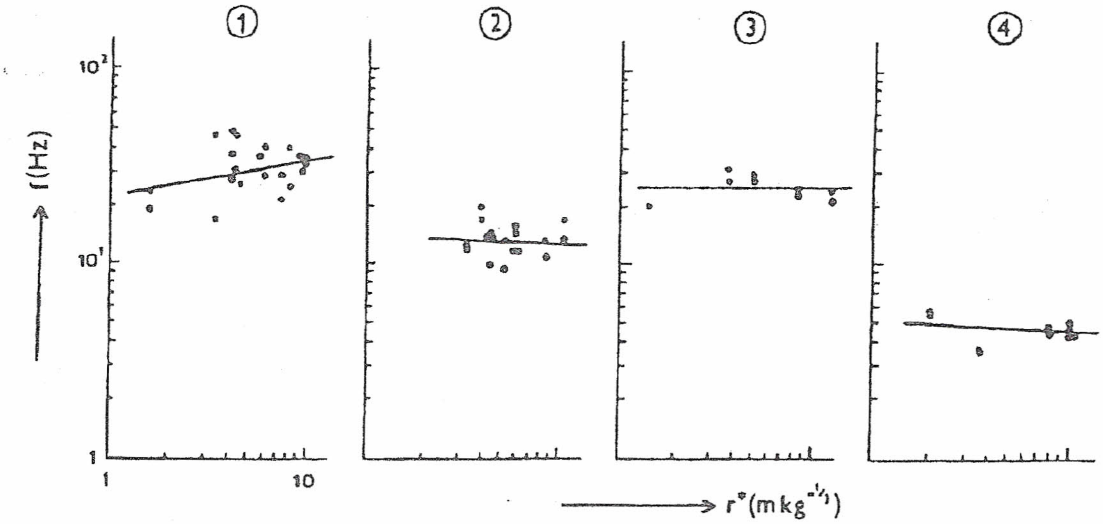

FIG. 5. Frequency f of seismic wave (radial horizontal component) vs. scaled distance r^* valid for the test sites Nos 1–4.

sites Nos 1–4.

$$\log v_i = (-1.895 \pm 0.175) \log r^* \pm (3.615 \pm 0.130)\,, \quad r = 0.928 \qquad (5.1)$$
$$\log v_i = (-1.843 \pm 0.098) \log r^* \pm (3.715 \pm 0.071)\,, \quad r = 0.976 \qquad (5.2)$$
$$\log v_i = (-2.017 \pm 0.158) \log r^* \pm (3.744 \pm 0.125)\,, \quad r = 0.979 \qquad (5.3)$$
$$\log v_i = (-1.944 \pm 0.061) \log r^* \pm (3.642 \pm 0.053)\,, \quad r = 0.996\,. \qquad (5.4)$$

The slopes of approximating straight lines differ slightly each of other, having the values in the range of $m \doteq 1.8 - 2.0$. If we compare the standard deviations of parameters $\log k$ and m determined (see Eq.3), there could be seen that their deviations are relatively small, i.e. it implies, that the conditions for recording as well as for blasting operations in boreholes were practically maintained at the same level and any adjoining negative factors (e.g. misfire or reduced explosion efficiency due to bad tamping of charge) probably did not occurred.

4.2. Frequency vs. charge size

The procedure of investigation of the above mentioned function was similar to investigation of particle velocities. The resulting graphs are presented in Fig.4, whereas the linear equations of approximating straight lines are described by formulae:

$$\log f = (-0.117 \pm 0.069) \log Q \pm (1.652 \pm 0.095)\,, \quad r = 0.361 \qquad (6.1)$$
$$\log f = (-0.101 \pm 0.048) \log Q \pm (1.258 \pm 0.065)\,, \quad r = 0.467 \qquad (6.2)$$
$$\log f = (0.053 \pm 0.045) \log Q \pm (1.317 \pm 0.058)\,, \quad r = 0.407 \qquad (6.3)$$
$$\log f = (-0.013 \pm 0.080) \log Q \pm (0.683 \pm 0.071)\,, \quad r = 0.072\,. \qquad (6.4)$$

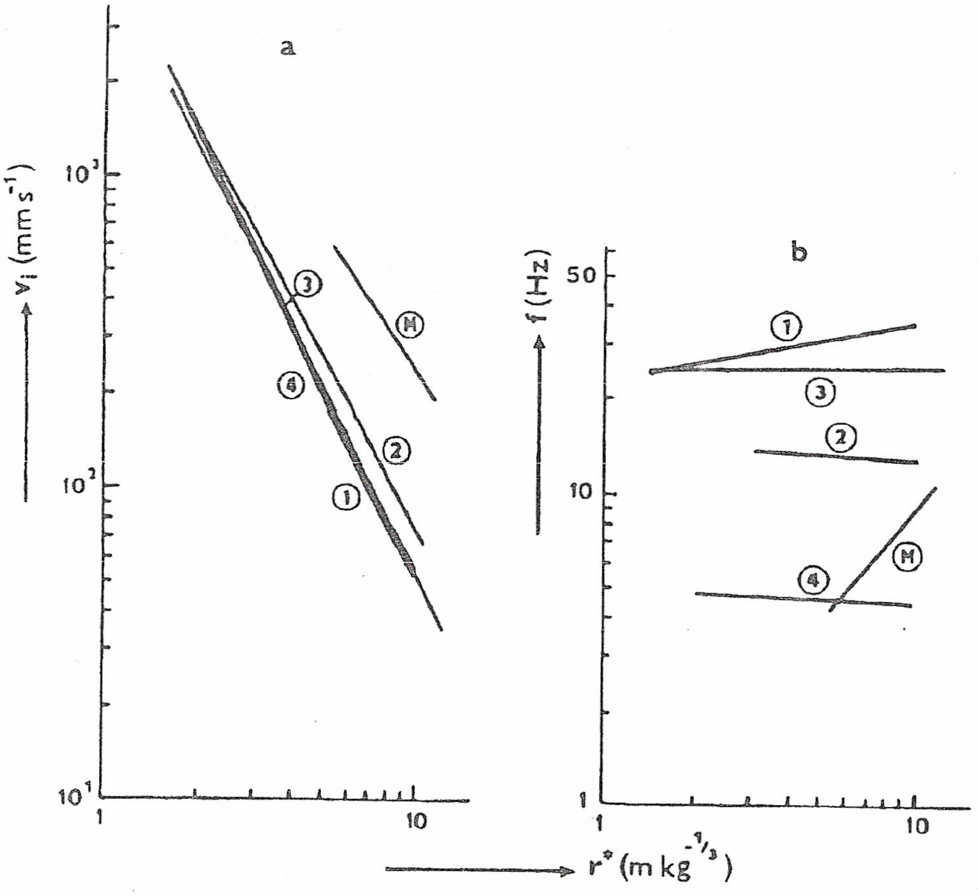

FIG. 6. Sets of straight lines approximating the relationships: a – particle velocity v_i vs. scaled distance r^*, b – predominant frequency f vs. scaled distance r^* valid for the test sites Nos 1–4 and M.

In course of judging of the accuracy of parameters $\log k$ and m, given in Eqs 6.1–6.4, some features occurred. Although standard deviations of the parameter $\log k$ are relatively small, errors in slopes of straight lines determination display substantially higher values which exceed absolute values of the slopes. In general, slopes vary between $m \doteq 0.05$ and the value $m \doteq -0.12$. Thus, there was proved that within the interval of charge size $Q \doteq 10$–100 kg almost any evident dependence did not exist. In contradiction to graphs in Fig. 3, where relatively small scatter of experimental values of particle velocities was observed, the scatter of input data frequencies in Fig. 4 was more considerable. There should be stated, that the negative factors (probably wave pattern disturbances due to tiny discontinuities in the rock mass) affecting the field experiments were much more pronounced in determination of the frequency content of seismic waves than in particle velocity investigations. Therefore it implies that this parameter should be more sensitive to the changes of conditions during the field experiments. Without respect to a minimum correlation between both parameters investigated, the frequencies are being grouped for individual test sites within a relatively narrow bands limited by values: $f \doteq 15$–50 Hz

(No 1), $f \doteq 10$–$20\,\mathrm{Hz}$ (No 2), $f \doteq 20$–$30\,\mathrm{Hz}$ (No 3) and $f \doteq 3.5$–$6.0\,\mathrm{Hz}$ (No 4).

4.3. Frequency vs. distance

As mentioned before, the parameter r^* (scaled distance) is usually induced in effort to enable a representation of two sets of two different variable parameters in the form of one variable quantity graph according to Eq.2.

The graphs for individual test sites are given in Fig. 5. Utilization of the least square method solution resulted in determination of linear equations, the expression of which are as follows:

$$\log f = (0.198 \pm 0.114) \log r^* \pm (1.351 \pm 0.085)\,, \qquad r = 0.393 \tag{7.1}$$

$$\log f = (-0.050 \pm 0.141) \log r^* \pm (1.165 \pm 0.108)\,, \qquad r = 0.102 \tag{7.2}$$

$$\log f = (0.006 \pm 0.076) \log r^* \pm (1.399 \pm 0.065)\,, \qquad r = 0.029 \tag{7.3}$$

$$\log f = (-0.045 \pm 0.085) \log r^* \pm (0.700 \pm 0.073)\,, \qquad r = 0.200\,. \tag{7.4}$$

Comparing frequency vs. scaled distance and frequency vs. charge size, as well as the parameters $\log k$ and m in linear equations, there is obvious that a certain similarity does exist. Besides comparable values of the standard deviations of parameters $\log k$ and m (see Eqs 6.1–6.4 and 7.1–7.4), a very tiny correlation between the predominant frequencies and scaled distance within the interval of values $r^* = 1$–$10\,\mathrm{m\,kg}^{-1/3}$ occurred. During seismic experiments, the shot–receiver distances varied approximately in the range $r \doteq 3.5$–$25.0\,\mathrm{m}$ and the charge sizes $Q \doteq 10$–$100\,\mathrm{kg}$ as well.

5. DISCUSSION OF RESULTS AND CONCLUSIONS

Seismic measurements which were performed in brown–coal and shale open–pit mines confirmed their benefit and necessity. Using stripping of overburden, sometimes blasting operations are being used for destruction of hard interbeds. Such type of measurement can help in decisions as to the further progress of blasting operations, aimed at nonoccurrence of sliding or failure of walls in mines.

In course of comparing of the absolute value of parameters m and $\log k$ in linear equations of particle velocities valid for the former fixed place "b" close to the upper edge of the wall (see Holub and Tobyáš 1987, 1989) and the present applied place at the wall–foot, a similarity was found. For the test sites Nos 1,2 and 4, the differences of parameters m and $\log k$ determined in setups for the test sites "b" and "c" did not exceed 11 % and 8 % at minimum, respectively; for the test site No 3 the differences reached almost 48 % and 38 %, respectively. A relatively good agreement of the parameters m and $\log k$ in both data sets for sites Nos 1,2 and 4 corresponds to minimum natural conditions changes in course of experiments. On the other hand, the experimental values observed at the test site No 3 were probably affected by different degree of failure of the upper and lower part of the mine wall.

In Fig. 6a, the resulting straight lines of data sets approximation for the test sites Nos 1–4 are presented. The length of these lines corresponds to the interval of parameters v_i, f and r^* induced. The straight line denoted by M represents the results of field measurements which were carried out in the fluvial plain of the Dyje river in South Moravia. During the hole shots explosions, there was recorded the vertical component of particle motion (see Holub 1980). In comparing straight lines 1 and 2 with the line M, it is obvious that the efficiency of explosions, represented by higher values of particle velocities, differ more than 5– or 3–times, respectively, in benefit of sedimentary rocks in the area of the fluvial plain.

When comparing our values of m in Eqs 5.1–5.4 with results of experimental performed in cohesive soils [Kuzmina et al. 1962] a relatively good agreement was obtained ($m \doteq 2.2$). Similar results in parameter m determination were reported by Schenk (1974 and 1974a) for stress waves recorded in the near zone of explosion. For explosions carried out in limestone within the range of scaled distance of $r^* \doteq 3.4$–$17.7\,\mathrm{m\,kg^{-1/3}}$, $m \doteq -1.9$, while in loess for the range of $r^* \doteq 2.1$–$17.8\,\mathrm{m\,kg^{-1/3}}$, $m \doteq -1.6$ were ascertained.

Set of straight lines in Fig. 6b indicates very similar course of slopes for the test sites Nos 1–4. On the contrary, the straight line M has quite another shape being represented by a steep slope ($m \doteq 1.5$) within the interval of scaled distance $r^* =$ 5.4–$11.5\,\mathrm{m\,kg^{-1/3}}$. It seems that under the conditions of seismic waves propagation in the plane parallel with the planes of strata series at the test sites Nos 1–4, the changes of parameters r and Q within one order of units are not sufficient for ascertaining any close correlation in frequency vs. scaled distance dependence. It testifies to the fact as though the seismic waves are propagating through the rock mass material the physical properties of which are near the properties of homogeneous medium. Therefore functions $f = F(Q)$ or $f = F(r^*)$, with respect to setup in general reflect the influence of layered rock material on the appereance of frequencies which are being limited within a relatively narrow frequency range.

In comparison to this, the steep slope of the straight line M for this data set from the fluvial plain mentioned above, could be explained in the following way. The explosions were carried out in the boreholes, the depth of which varied within the limits $h \div 15$–60 m. The short–receiver distance $r \div 40$–52 m was always related to the center of the charge and therefore with increasing charge size the center of cylindrical charge moved towards the Earth's surface. This fact caused that seismic waves gradually propagated through sedimentary layers with lower and lower velocities. These changes of propagation velocities, as well the increasing charge size displayed in gradual lowering of seismic waves predominant frequencies.

Comprising the local geology and summarizing graph in Fig. 6b following conclusions imply:

- the lowest frequencies ($f \div 3.5$–6 Hz) at the test site No 4 were observed. The local geology was represented by a Quarternary clayed–sandy loam;
- rather higher frequencies ($f \div 10$–20 Hz) were recorded at the test site No 2, where sandstones partly changed into sands due to weathering occurred;
- the relatively highest frequencies of seismic waves ($f \div 15$–50 Hz) were obtained at the test sites Nos 1 and 3, where compact clays and glaceous clays, respectively, occurred;

- former seismic experiments at the site M in the area of fluvial plain proved that the predominant frequencies of seismic waves ($f \div 4.5$–12 Hz) were affected by changing charge size as well as by the properties of unconsolidated sedimentary rocks, the uppermost part of which was water saturated.

REFERENCES

Holub K. (1980), *Explosive source and its influence on ground motion dynamics*, Studia geoph. et geod. **24**, 414–418.

Holub K., Tobyáš V. (1987), *Velocity of ground motion near blasts in the open-pit mine*, Travaux Géophysiques XXXII (1984), No 594, Academia, Praha, 261–280.

Holub K., Tobyáš V. (1989), *Particle velocities near blasts in shale open-pit mine*, Travaux Géophysiques XXXIV (1986), No 621, Academia, Praha, 43–53.

Kuzmina N.V. et al. (1962), *Sejsmicheskij effekt vzryvov na vybros v neskalnych svjaznych gruntach*, Tr. IFZ AN SSSR **21**(188), 3–72. (in Russian)

Schenk V. (1974), *Stress waves produced by a spherical explosive source in clay shale*, Travaux Inst. Géophys. Acad. Tchécosl. Sci. No 377, Geofyzikální sborník 1972, Academia, Praha, 333–342.

Schenk V. (1974a), *Stress waves and particle velocities produced by a spherical explosive source in limestone*, Travaux Inst. Géophys. Acad. Tchécosl. Sci. No 378, Geofyzikální sborník 1972, Academia, Praha, 343–362.