Changes of the uniaxial compressive strength of rocks under the dynamic load with different frequencies

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Změny jednoosé tlakové pevnosti hornin při statickém a dynamickém namáhání s různou frekvencí

Článek přináší výsledky měření série horninových vzorků na testovacím zařízení MTS 816 systém. Jednoosá tlaková pevnost při dynamickém namáhání byla zjišťována s frekvencí v rozsahu 0-100 Hz. Tyto dynamické pevnostní charakteristiky jsou srovnávány s pevnostními charakteristikami při statickém namáhání. Laboratorní výzkum při dynamickém namáhání by měl co nejvíce odpovídat charakteru namáhání hornin při seismických jevech v horském masivu. Z tohoto důvodu jsou v článku nejprve rozebrány seismické vlnové parametry při důlních otřesech a jiných seismických jevech v horském masivu.

Key words*: uniaxial rock strength, dynamic rock strength, rock burst*

Introduction

The research of strength and strain characteristics of rocks under a dynamic loading is aimed at evaluating these characteristics to better identify the behaviour of rocks during anomalous geomechanical events, mainly at rockbursts.

Mechanical properties of rocks were studied in the laboratory on the MTS equipment, which is a system enabling the static as well as dynamic loading of rock specimens. From the point of view of applying of measurement results, parameters of dynamic loading similar to those during seismic events in the rock mass should be used in the laboratory to recognise the rock behaviour at anomalous geomechanical events. That is why this paper deals initially with the determination of stress on the seismic wavefront first. The dynamic loading of rock specimens in the laboratory at a similar stress amplitude then simulated similar conditions as those at the occurrence of seismic events in the rock mass.

This paper describes results of the uniaxial compressive strength depending upon the frequency of dynamic loading and compares these results with the case of static loading.

The determination of stress on the seismic wavefront

This study rests upon the results of geophysical interpreting records of rockbursts made in situ. It is mainly the case of underlying data, on the basis of which the stress of the seismic wavefront is determined. Since 1989, a database of seismic events recorded by the local seismic network (Holub, 1999; Slavík, 1992) in the Ostrava-Karviná Coalfield (henceforth referred to as OKC) has existed and, in addition, analyses of rockbursts are made by the Department of Geomechanics and Geophysics, DPB Paskov, annually. Both the mentioned materials became the foundation for the data selection when evaluating the measurements in situ.

With regard to the fact that the local seismic network of OKC consists prevailingly of single-component stations equipped merely with vertical seismographs (Z component) and that for the given evaluation the complex amplitudes are required, it was decided to use digital data of the mine seismic network in the Lazy Mine (former A. Zápotocký Mine) (Knejzlík et al., 1992). In 1992-1995, four three-component stations (Z, NS and EW) were in operation there, and in the years 1996-1997 five stations were operated that by three-component registering provided required complex amplitudes of the oscillation velocity of particles of matter.

According to analyses of rockbursts from 1992 to 1997, data on rockbursts were accumulated first and, subsequently relevant seismograms were found from stations of the mine seismic network in the Lazy Mine. One criterion for the rockburst selection was the quality, i.e. the applicability of the seismograms themselves. With regard to the released seismic energy and hypocentral distances, amplitudes of induced seismic waves sometimes exceeded the dynamic range of measuring apparates, and for this reason the seismograms were inapplicable to the analyses. Altogether, 14 rockbursts by one or more stations (max. 5) were selected. Thay

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were evaluated then. However, it was found that greater accuracies of data entering the next calculations would be achieved by extending the set of selected rockbursts by significant rockburst events ($E \geq 10^5$ J), and consequently the original set was enhanced by other 18 rockburst events from the years 1996-1997. In each seismogram, particular components with the maximum amplitudes of velocity u_i ($m.s^{-1}$) of the first arrivals of the groups of P waves and S waves were found, together with the maximum complex amplitudes in both the wave groups at the given time.

From the database of rockburst events mentioned above, the coordinates of foci of these events and, the coordinates of the seismic stations were known. On the basis of the knowledge of these coordinates, corresponding hypocentral distances entering the next calculations were calculated.

Data interpretation

The foci of 32 mine induced events were located in various working fields of OKC approximately in the range of distances $d \approx 300\text{-}6000$ m and, because they had an energy in the range of $E \approx 10^4\text{-}10^7$ J, it was not possible to construct any graph directly from the calculated values u_i taking into account both the hypocentral distance and the energy of the given seismic event. That is why the reduced distance was introduced as a new parameter, expressed as follows:

$$\mathrm{r_{red}} = \frac{d}{\sqrt{E}}, \tag{1}$$

where $\mathrm{r_{red}}$ is the reduced distance ($m/\sqrt{J}$), d is the hypocentral distance between the focus and the point of observation (m), $\sqrt{E}$ is the energy parameter of the seismic event ($\sqrt{J}$).

In virtue of this, the searched functional dependence accounting for the distance and the energy, may be written as $u_i = f(r_{red})$. In our case, the following limiting parameter was chosen when selecting the data from the given dependences:

$$\mathrm{r_{red}} \leq 15 \ \ (m/\sqrt{J}) \ , \tag{2}$$

By using a regression, the following equations for the complex amplitudes were found:

$$u_i = \frac{0.11625}{\mathrm{r_{red}}^{0.8943}} \qquad [m.s^{-1}] \tag{3}$$

S-waves: $$u_i = \frac{0.5361}{\mathrm{r_{red}}^{1.1093}} \qquad [m.s^{-1}] \tag{4}$$

The presented modification of the equations enables us to determine the values u_i for arbitrary values of the seismic energy of the event E (J) and the hypocentral distances between the focus and the station d (m). Graphs displaying the evaluated quantities (expressed logarithmically), including the regressions of both the relations are given in Fig. 1 and Fig. 2.

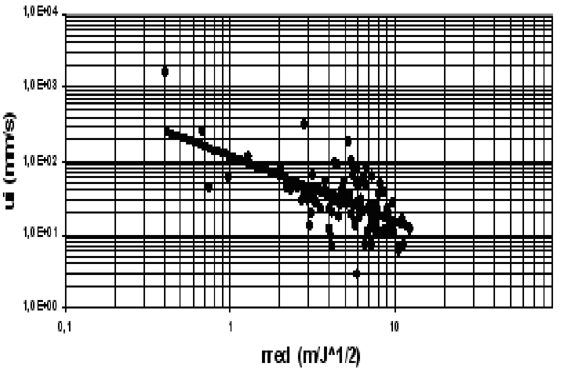

Fig. 1. Graphical dependence of ui = f(rred) for P-waves

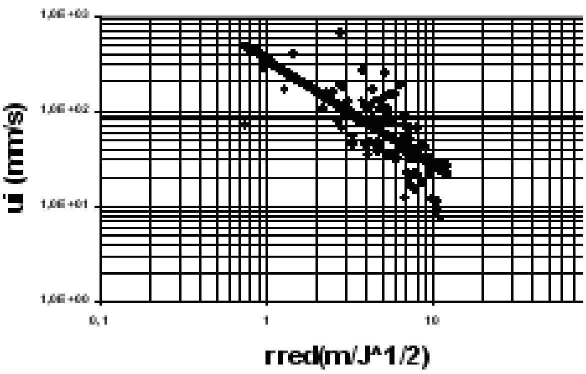

Fig. 2. Graphical dependence of ui = f(rred) for S-waves

In addition to the amplitudes of the velocity u_i, the frequencies of P waves at the first arrivals were found with the particular components as well. As shown in Fig. 3, the found frequencies changed in the range of 3-25 Hz; with the prevailing part of the frequencies concerned in the range of $f \div 3\text{-}12$ Hz, and the remaining part in partial frequencies $f = 14$, 17, 20 and 25 Hz. The presented distribution of frequencies showsthat in most cases the first arrival had a character of a low-frequency oscillation; however sometimes oscillations of higher frequencies ($f > 14$ Hz) were modulated on the carrier low-frequency oscillations.

Changes in frequencies depending on changes in the hypocentral distance or the released energy of particular events have not been proved in the virtue of geophysical data interpretation.

When calculating the stress on the seismic wavefront, the following average velocities of seismic wave propagation are found and considered: $v_P = 4200$ m.s^{-1} and $v_S = 2100$ m.s^{-1} according to (Holub et al., 1987).

Assessment of stress on the seismic wavefront

The stress on the seismic wavefront is determined according to Brepta and Prokopec (1972) by the following relation:

$$\sigma_s = \rho_h \,.\, v_i \,.\, u_i \qquad [\mathrm{Pa}] \qquad (5)$$

where ρ_h is the volume weight of rock [kg.m^{-3}], v_i is the velocity of seismic wave propagation [m.s^{-1}], u_i is the mass velocity [m.s^{-1}].

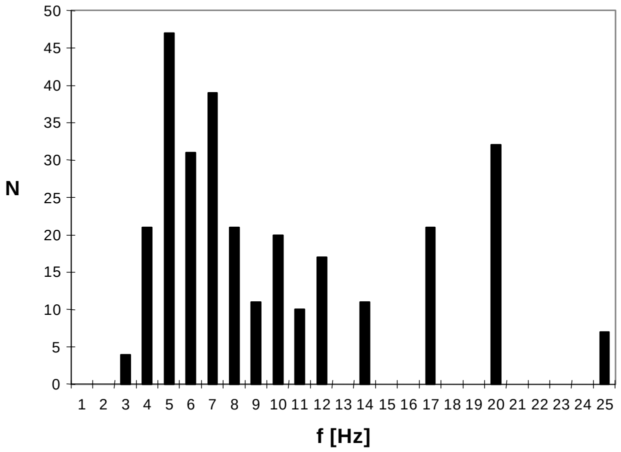

Fig. 3. Histogram of frequency rates in the first arrivals of P waves

The average volume weight of Carboniferous surrounding rocks is about 2600 kg.m^{-3}. The velocity of seismic longitudinal wave propagation is 4200 m.s^{-1}. The mass velocity u_i was assessed in the previous chapter. It follows from Fig. 1 that it is in the range of 0,012 – 0,26 m.s^{-1} with longitudinal waves; the maximum value determined being 1,2 m.s^{-1}. Thus, on the basis of relation (5), the stress on the longitudinal wavefront σ_s ranges from 0,13 to 2,8 MPa and the maximum value of the given measurement is 19,7 MPa.

With transversal waves, the velocity of wave propagation is lower (2100 m.s^{-1}) and the mass velocity is in the range of 0,02 – 0,5 m.s^{-1}; the maximum value being 0,66 m.s^{-1}. These values correspond to, stresses on transversal seismic wavefronts of 0,11 – 2,7 MPa and the maximum value of 3,6 MPa correspond.

Partial conclusion

With the observed rockbursts and strong seismic events, the established values of stresses on the seismic wavefronts were prevailingly lesser than 3 MPa. The only ascertained value of 19,7 MPa is an exception.

The frequency of longitudinal waves is in the range from 3 to 25 Hz; however, it is prevailingly 3 – 12 Hz.

This evaluation was used in the laboratory measurement of mechanical characteristics of rocks under dynamic load.

Evaluation of strength properties of rocks under the static and dynamic loading

The mechanical rock characteristic affects, to a considerable extent, the behaviour of rock mass during the mining activity, especially the origin of anomalous geomechanical events. Up to now, mechanical properties of rocks have been studied under a static loading owing to the unavailability of a testing device for the dynamic loading. The Laboratory of Rock Mechanics at the VŠB – Technical University of Ostrava is nowequipped with such a device (MTS 816 Rock Test System) that enables the static as well as the dynamic loading of rocks. Thus, it is possible to study the mechanical characteristics of rocks in conditions similar to these of the rock mass at the occurrence of seismic events, mainly of rockbursts.

For studying the properties of rocks under various modes of loading, it is necessary to ensure a rather large number of test specimens of the same rock. Because this study is orientated towards the conditions of the Ostrava-Karviná Coalfield, samples from thick layers of Carboniferous surrounding rocks were taken.

The device, MTS 816 Rock Test System, enables a considerable variability in loading modes. Testing has to performed merely with a certain variable, while the other parameters should be constant.

Test equipment and testing modes

The test machine, MTS 816 Rock Test System has a range of the compressive loads of up to 1015 kN, the stiffness of 26 x 10^8 N.m^{-1}, the optional static or cyclic (dynamical) load, the possibility of sensing the stress-strain characteristic behind the strength limit, the scanning of strains of test pieces and the possibility of measuring under the rheological mode, and others.

At the static strength testing of rocks, the systems for test control either by a force gain or by a strain gain are used. When controlling the test by the strain gain, we also obtain the curve of the stress-strain diagram behind the strength limit. Simultaneously, this mode of loading better corresponds to the loading of rocks in the rock mass and for this reason it is preferred. The main control parameter of the test is then the set rate of strain [mm.s^{-1}].

At the cyclic loading, a control quantity must be chosen as well – a force or strain. Further, the frequency of cyclic loading, the loading curve type, the amplitude of cyclic loading and the mean value of the control quantity, in the vicinity of which oscillations occur, are set. The following loading curves may be chosen: sinusoidal, rectangular, triangular, and variously modulated basic curves mentioned.

This machine is not equipped with the program ensuring the strength at the dynamic loading. This means the program with a gradually increasing load with the acting force (strain) oscillation. According to servicemen of the firm MTS, who put the machine into operation and provided training, the ensuring of strength under the cyclic loading must be separately programmed. The device enables the proper programming of any testing procedure, but the program for the strength testing under the dynamic loading would contain programming steps of the order of tens of thousands without any possibility of a simple modification.

However, the control computer of the device enables changes in testing parameters in the course of the test run. The parameters of the test may be entered numerically; by mouse-controlled buttons it is possible to change them continuously. In this way, a mean value of the quantity at which the oscillation occurs may be continuously raised. The rate of this increase is adjustable as well. Thus, it is possible to conduct the strength testing of rocks under the dynamic loading. After the setting relevant parameters, these tests are fully reproducible – they are performed under the same conditions. A disadvantage is the fact that in the whole duration of the test the button of increasing the mean value of the control quantity must be mouse-controlled.

As a control quantity, the deformation is selected because it better corresponds to the loading of rocks in the mass. The 0,1 mm amplitude of dynamic loading was determined. With this test machine, the deformation is measured from the movement of the test cylinder piston. It means that the deformation shown covers both the deformation of the test piece and the deformation of the test device.

Therefore, all measured deformations must be reduced depending upon the stiffness of the machine and the real acting force.

The 0,1 mm amplitude of dynamic load was taken. According to the stiffness of the device, 0,0144 mm of it falls to the deformation of the device itself and 0,0856 falls to the deformation of the test specimen itself. From the deformation modulus of the rock and the dimensions of the testing specimen, we may calculate that a the selected deformation amplitude, the amplitude of the acting force is 32,7 kN, to which the amplitude of the acting stress of 18,5 MPa corresponds.

Then, the selected loading corresponds, according to the Chapter 2, to the maximum values of stress on the seismic wavefront during the rockbursts assessed.

With all tests, the rate of deformation was chosen so that after the reduction of the loading rate this might change within the prescribed limits of 0,5 – 1,0 MPa.s^{-1}, i.e. of course, in the area of a roughly linear part of the loading phase of the strain-stress diagram. The setting corresponding to the rate of deformation requires a preliminary testing of the test piece of the given sample because the keeping of the prescribed rate of stress gain related to the rate of deformation depends on the modulus of deformation of the rock and the dimensions of the test specimens.

For the primary study of the mechanical characteristics of rocks under the dynamic loading we chose the frequency ranging from 0 to 100 Hz. The shape of the oscillation curve was sinusoidal. To make parameters of comparing measurements of the static loading consistent with corresponding parameters of the dynamic loading, we selected the same mode for testing (cyclic loading) with the option of zero frequency or amplitude. In this way, the cyclic loading became the static loading. The other parameters being crucial to the rate of loading were not changed.

Testing material

For studying the given dependences, it is necessary to ensure a rather large number of testing specimens of the same rock. For this study, a sample from the borehole Darkov 265/01 was selected.

The sample No. č.265/01-1 comes from a layer of rocks between the seam 561-35a and the seam 605-33 lower bench – the Saddle Seams, at the depth ranging from 588 to 607 m below the sea level. It is the case of light grey to grey, medium-grained subgraywacke containing coal detritus with a coal laminae whose thickness is of up to 2 mm on fractured surfaces. In the sample, muscovite flakes are visible macroscopically.

The slenderness ratio of the test specimens is 1 and the diameter is about 47,5 mm.

Measurement results

The modes of measurement presented in Chapter 3.1. were used. Results of measurements of the uniaxial compressive strength and the modulus of deformation under the static loading are given in Tab. 1. The results of measurements of the uniaxial compressive strength and the modulus of deformation depending upon the frequency of loading at the amplitude of deformation 0,0856 mm, (which corresponds to about 18,5 Mpa), are shown in Tab. 2. The dependence of the uniaxial compressive strength on the frequency of dynamic loading can be seen in Fig. 4. The dependence of the modulus of deformation on the frequency of dynamic loading can be seen in Fig. 5.

Conclusion

From the Fig. 4. an increase in the uniaxial compressive strength under otherwise equal conditions is obvious.

With the modulus of deformation, any dependence on the frequency of loading cannot be observed.

Tab. 1.

Values of uniaxial compressive strength and modulus of deformation under static loading		
Sample designation	**Uniaxial compressive strength** [Mpa]	**Modulus of deformation** [Mpa]
Darkov 265/01-1-21	78.9	10319
Darkov 265/01-1-24	96.2	8899
Darkov 265/01-1-27	96.2	8910
Darkov 265/01-1-30	83.3	9609
Darkov 265/01-1-33	109.2	12067
Darkov 265/01-1-36	116.8	11766
Mean	96.8	10262

Tab. 2.

Values of uniaxial compressive strength and modulus of deformation depending on frequency under dynamic loading (0.1 mm amplitude)			
Sample designation	**Frequency** [Hz]	**Uniaxial compressive strength** [Mpa]	**Modulus of deformation** (MPa)
Darkov 265/01-1-16	20	83.8	10504
Darkov 265/01-1-19	30	71.2	11985
Darkov 265/01-1-22	40	98.5	12745
Darkov 265/01-1-25	50	82.1	9814
Darkov 265/01-1-31	70	113.1	11945
Darkov 265/01-1-34	80	94.9	10661
Darkov 265/01-1-35	90	99.7	9847
Darkov 265/01-1-40	100	103.9	13607

This is a first study of the stress-strain behaviour of rocks under the dynamic load. In these first tests, some measurement problems connected with itself and the evaluation of measured parameters had to be solved.

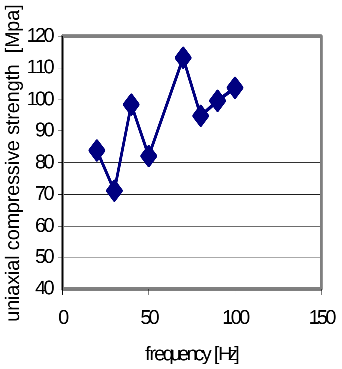

Fig. 4. Dependence of the uniaxial compressive strength on the frequency of dynamic loading

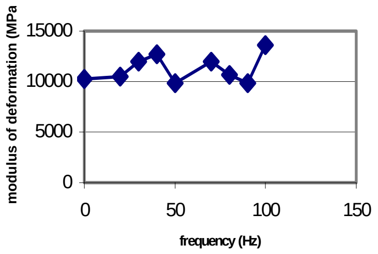

Fig. 5. Dependence of the modulus of deformation on the frequency of dynamic loading

The research continues to assess samples from various rock layers and with a higher number of test pieces.

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