CHANGES OF ANISOTROPY OF P-WAVE VELOCITY PROPAGATION DURING DEFORMATION PROCESS OF ROCK SAMPLES

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Abstract

Laboratory loading of migmatite cylindrical samples was carried out under various loading direction relative to rock foliation. The sparse net of 8 sensors was used for ultrasound time-of-flight measurement at discrete time intervals during loading up to sample strength limit. The P-wave velocity was determined in 28 directions (all combinations of sensors). This enabled us to calculate velocity ellipsoid. Velocity ellipsoid calculation was successfully used for determination of P-wave velocity anisotropy and for investigation of its changes during sample loading. The changes of size and orientation of the main axes of velocity ellipsoid were analyzed for separate experiments with regard to loading level. It was found, that independently on mutual orientation between rock foliation and loading direction, the minimum velocity vector turns perpendicularly to final rupture plane and maximum velocity vector turns to the plane of final rupture. This new velocity anisotropy ellipsoid method developed is a suitable tool for characterization of rock fracturing process. Acoustic emission indicates new crack formation during loading.

Introduction

Rocks often exhibit a macroscopic anisotropy of mechanical properties, e.g. [1]. This anisotropy can be caused by crystal structure of single minerals, arrangement of mineral grains and orientation of cracks or microcrack systems. Anisotropy of mechanical properties depends also on the stress level and on the system of acting forces, uniaxial force, confining pressure, etc. Anisotropy has effect to rock behavior during its loading and a way of final failure. It also causes anisotropy of elastic wave propagation in rocks.

Elastic wave velocity anisotropy can reveal valuable information about rock structure. The relationship between velocity anisotropy and rock structure can therefore be used for interpretation of geophysical measurements. However, for successful application it is essential to know influence of stress-strain state of rock to velocity anisotropy.

A method for estimation of elastic wave velocity anisotropy based on ultrasonic transmission data during rock sample loading was developed. The method is approximation of ultrasonic transmission data by triaxial velocity ellipsoid. The mutual relations between velocity anisotropy, rock structure, loading direction and rupture plane were further observed in dependence to the loading level.

Laboratory Investigation of Ultrasound Velocity Anisotropy

Rock elastic parameters can be determined by means of static or dynamic methods. The static methods are based on the Hooke’s law, which states the linear relation between acting force and deformation. In the case of presence of open cracks in rock, acting force can induce their closing and relation between force and strain is not linear.

Applied dynamic methods were based on ultrasonic transmission. These methods consist in determination of elastic wave propagation time through the sample along the known path. Dynamic methods, in contrast to static methods, result from application of small deformations and short-time acting force. The overall values of seismic velocities in rocks can be according to Ji et
al. [2] calculated based on elastic constants of individual crystals and volume fractions of the constituent minerals of the rock. Babuška [3] studied velocity anisotropy of minerals and rocks with respect to its application for deep structure research of the lithosphere. He supposed that the anisotropy caused by effect of cracks disappears at depths of 5-6 km. Přikryl et al. [4] demonstrated that hydrostatic pressure can cause closing the cracks in volcanic rocks. Therefore the anisotropy of intact rocks is caused only by their structure and anisotropy is almost constant and independent on the changes of hydrostatic pressure. Hydrostatic pressure of approximately 200 MPa [5] corresponds to depths of 5-6 km, assumed by Babuška.

If the rock shows anisotropy caused by the combination of both effects of the mineral grains arrangement and the preferential crack orientation, then the anisotropy changes depend on the mutual orientation of both these structure elements. In the case of diverse orientation of mineral grains and cracks anisotropy, the changes of hydrostatic pressure induce not only changes of anisotropy value, but also cause changes in the anisotropy orientation.

**Processing of Ultrasonic Transmission Data**

The results of ultrasonic transmission were transformed to the velocity ellipsoid. The ellipsoid is constructed as a quadric passing through the end points of velocity vectors. The origin of each velocity vector is situated in the midpoint of the ellipsoid. Direction of velocity vector is determined by the source and receiver positions (Fig. 1). The amplitude of velocity vector is the velocity value corresponding source - receiver positions.

The parameters of above velocity ellipsoid were found by optimization procedure of solving the over-determined problem. The resulting surface represents therefore smoothed approximation of directional velocity distribution. The differences between measured data and their approximation by ellipsoid can be caused for example by internal inhomogeneity of rock material, inaccuracies in determined propagation time and also by the simplified model of velocity anisotropy used. The root mean square value $RMS$ was used for the quantitative evaluation of differences between measured velocity vectors and established velocity ellipsoid.

**Experiment**

**Confining load experiment**

Migmatite from the locality of Skalka (Czech Republic) was chosen for the experiment as a material with distinct, macroscopic visible plane-parallel structure. Ultrasonic transmission for P-wave velocity anisotropy determination was carried out on the spherical migmatite sample under several levels of hydrostatic pressure. Time of flight of P-wave through spherical samples was measured at 132 independent directions at each level of hydrostatic pressure in a range from 0 to 200 MPa [6-8]. The minimum velocity direction is perpendicular to the migmatite foliation and the maximum velocity direction lies in the foliation plane.

Anisotropy can be quantitatively described by the value of anisotropy coefficient $k$, defined by the relation:

$$k = 100\% \frac{v_{\text{MAX}} - v_{\text{MIN}}}{v_{\text{MAX}}},$$

where $v_{\text{MAX}}$ is maximum and $v_{\text{MIN}}$ is minimum velocity value. This definition is a modification of anisotropy coefficient introduced by Birch [9]. The anisotropy orientation does not change during loading up to 200 MPa. The coefficient of anisotropy $k$ decreases with increasing hydrostatic pressure from 41.1% to 12.6%. The anisotropy coefficient and the velocity values return to its original values after unloading. Substantial decrease of anisotropy coefficient, together with fact that the orientation of velocity anisotropy does not change during loading, indicate the presence of crack system with orientation parallel to foliation plane. It was caused by a reversible process of closing this crack system during the sample loading.
Uniaxial loading experiments

The migmatite cylindrical samples (height 100 mm, diameter 50 mm) were used. Experiments were carried out under different mutual orientations between the loading direction and the migmatite foliation (parallel, angular 45° and perpendicular). The computer controlled MTS loading system was used for samples loading. There was applied uniaxial loading regime with constant loading rate of 0.5 MPa/min.

There were eight wideband acoustic emission (AE) sensors (WD, PAC, USA) attached on sample surface (Fig. 1). All sensors were used for both, ultrasonic transmission, and monitoring of acoustic emission. Eight-channel transient recorder AMSY-5 (Vallen Systeme) was used. Sampling frequency was 10 MHz and the record length was 2048 points.

Ultrasonic transmission was realized in consequent cycles at selected load levels (see Figs. 2 to 4). Every transmission cycle includes eight steps – every sensor act as an ultrasonic transmitter and the others were receivers in the individual step. From the recorded ultrasonic signals, the corresponding velocities were calculated. Due to large dimensions of sensors (diameter 10 mm), special measurement on glass cylinder was conducted and obtained data were used for corrections of measured times, namely in dependence on direction of ray path.

Results and Discussion

The velocity ellipsoid parameters were used for interpretation of ultrasonic transmission measurement. They were: the size of its semi-axes ($v_{\text{MAX}}$, $v_{\text{MEAN}}$, $v_{\text{MIN}}$) and their directions ($\alpha_{\text{MAX}}$, $\alpha_{\text{MEAN}}$, $\alpha_{\text{MIN}}$) and anisotropy coefficient $k$. The developed method of velocity ellipsoid calculation enables the evaluation of ultrasonic transmission realized on cylindrical samples under uniaxial stress by the similar way as the velocity anisotropy measurement on spherical sample under hydrostatic pressure. This makes possible to mutually compare results obtained during uniaxial loading of cylindrical samples with results from hydrostatically loaded spherical samples.

Acting force perpendicular to the foliation

In this configuration the minimum velocity performs the maximum changes during the loading (Fig. 2A). The values of mean and maximum velocities do not significantly change. Anisotropy coefficient $k$ decreases up to 70% of the ultimate strength. Above this loading level up to the ultimate strength, $k$ increases with loading (Fig. 2B). Decrease of $k$ in the first part of loading to 70% strength is probably caused by closing of primary microcracks. The increase of $k$ in the final part of loading could be induced by formation of new microcrack system in direction of ultimate failure plane.
Fig. 2. Loading: direction perpendicular to foliation; ultimate strength: 111.8 MPa [10]. A. Three velocities, $v_{\text{MAX}}$ (shown with circles), $v_{\text{MEAN}}$ (shown with squares), $v_{\text{MIN}}$ (shown with triangles); B. AE, RMS and k values; C. Stereographic projection of the orientations of velocity vectors during loading to failure.

The orientation of the maximum velocity vector is given by the migmatite structure and it does not change during the whole loading. Maximum velocity lies in the foliation plane. During loading the orientation of minimum velocity vector changes from the direction perpendicular to migmatite foliation to the direction perpendicular to the plane of final rupture (Fig. 2C).

The acoustic emission (solid curve) slowly increases up to 80% of the ultimate strength and after reaching this value it increases rapidly (Fig. 2B). This is caused by creation of new microcracks. Up to 60% of the ultimate strength, the value of $RMS$ (shown with triangles) decreases and has a similar trend as $k$ (shown with circles). After reaching this loading level, the $RMS$ value slightly increases until sample rupture.

*Acting force parallel to foliation*

In this configuration the maximum velocity is almost constant during the whole loading experiment. The minimum velocity does not change up to 70% of the ultimate strength, after which
it decreases to sample failure (Fig. 3A). Differences between behavior of minimum velocities during perpendicular and parallel loading arise from the fact that most of primary cracks is oriented parallel to the foliation. Closing of these cracks takes place only in the beginning of perpendicular loading. After reaching approximately 70% strength, new cracks form in both loading tests and this is reflected in the changes of minimum velocities and of $k$. From the changes of maximum and minimum velocities, it follows that anisotropy coefficient is almost constant up to 70% strength and then increases up to total sample failure (Fig. 3B). During this experiment the minimum velocity direction is perpendicular to the migmatite foliation, and in this case is also perpendicular to the plane of final sample rupture (Fig. 3C). The maximum velocity direction lies in the foliation plane and it turns to the direction of uniaxial loading.

The AE number slowly increases up to 80% of ultimate strength. At higher loading levels, the AE increase is faster (Fig. 3B). That can be related to the sample fracturing process. The $RMS$ value increases during whole loading experiment and it has a similar trend as anisotropy coefficient and AE number.

Acting force along 45° to foliation

No substantial changes in velocity values and velocity vector directions occur in this configuration. Obtained results can be explained as follows: neither closing nor widening of primary microcracks nor formation of new microcrack system occurs. The orientations of minimum and maximum velocity vectors correspond to the plane of final rupture parallel with migmatite foliation. In this case, the sample deformation is realized by sliding along the predisposed foliation planes.

The AE only slowly increases up to 90% of the ultimate strength. At higher loading level the AE increase is faster (Fig. 4B). The final AE number is much lower than those in other experimental configurations.

![Graphs](Fig. 4. Loading: direction along 45º to foliation; ultimate strength: 125.7 MPa [10]. A. Three velocities, $v_{\text{MAX}}$ (shown with circles), $v_{\text{MEAN}}$ (shown with squares), $v_{\text{MIN}}$ (shown with triangles); B. AE, RMS and $k$ values; C. Stereographic projection of the orientations of velocity vectors during loading to failure.

Conclusions

The ellipsoid approximation method was used for processing of velocity anisotropy. This approach is feasible using ultrasonic transmission with monitoring by a sensor network usually used for monitoring acoustic emission. It was proven that for this method the sparse network with only eight sensors is sufficient to determine a velocity ellipsoid. The accuracy of velocity ellipsoid
approximation was tested by root-mean-square method (RMS). The RMS values are smaller then 10% of P-wave velocity values for all experiments.

Application of the velocity ellipsoid method makes it possible to study the influence of mutual orientation of acting load and rock foliation on the changes of velocity vectors and anisotropy during loading.

Values of velocity vectors determined on the cylindrical samples by the velocity ellipsoid method correspond well to the velocities measured on spherical samples under atmospheric stress.

The velocity ellipsoid method was successfully used for the determination of P-wave velocity anisotropy during uniaxial sample loading. This is shown as a suitable tool for characterization of rock fracturing process.

For anisotropic rocks (migmatite), it was found that the minimum velocity vector turns perpendicularly to final rupture plane. The maximum velocity vector lies in the plane of final rupture during the whole sample loading. These results are independent on mutual orientation between rock foliation and loading direction.

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