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Seismic Waves Distribution from Blasting in a Rock Massif with One Crack or System of Parallel Fissures

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Abstract Explosive action of cylindrical charge was studied in an anisotropic rock massif which contain cracks or system of parallel fissures. Sound wave theory was used for qualitative pattern of seismic wave distribution around blasting. Results show changing of seismic waves from round to elliptical shape during distribution through rock massif with cracks.

Keywords: *blasting, charge, seismic wave, crack, rock massif, seismic hazard, rock mechanics*

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1. Introduction

Problem of seismic safety from blasting is sharp for open pit mining and civil engineering. Very often for simplifying calculation ideal isotropic medium and sphere shape charge are taken during blast design. [1,2,3,4,18] It took place in Normative Documents and Codes. The seismic safety radius is used everywhere. However, in real life we do not have ideal conditions during blasting. Real massif has fissures and it does not have same properties in all directions. In practice, if we build lines of equal velocity for oscillation process we would have ellipsoid, not circle. Such results are shown by hundreds and hundreds of measurement data. That is why seismic safety calculation need to be improve and approximated to reality. It is need to study field of equal particle velocities in rock massif with cracks.

Very deep research in this topic was provided and interesting results were received in Geophysics and Earthquake Engineering. [20,21] Models of wave propagation in the elastic medium with cracks were built on the basis of an extension of effective medium Hudson's theory, finite element method, etc. But amplitude-frequency characteristics of seismic waves from earthquakes and explosions are different [22] and research for blasting seismic should be done.

2. Materials and Methods

Investigation of wave field distributional pattern from blasting carried out by taking approximated medium model to real anisotropic massif. Homogenous and endless medium was taken as a basis model. One crack or a systems of parallel fissures with different characteristics were accepted depends of task type. Physical-mechanical properties of crack filler were different from medium properties. Blasting of cylindrical charge was taken as dynamic influence.

Detonation of charge along its length was taken as instant and seismic wave studied on big distant from explosion. All wave types, which are produced form blasting, are characterized small amplitude. Task is to find just qualitative pattern of seismic wave distribution around blasting. That is why we could use sound wave theory. [5,6,7,8,9].

To simplify problem solving of this task consider case when seismic wave from vertical charge goes through fissure. Axial of this charge is parallel to crack plane. Origin of coordinates placed on border of fissure on the opposite side to charge on the smallest distance from the one. Axial *OX* was parallel and axial OZ was perpendicular to crack plane (Figure 1) Charge (Q) in plane *XOZ* has coordinates $X = 0$, $Z = d + h$, where d is fissure width, h is a distance from charge to fissure. [10,11,12,13,14].

Let's consider a case $d < h$. Part of medium, which located beyond of fissure, takes as first (1), before of crack take as third (3), in the middle – as second (2) and consider that incident wave is sinusoidal. In this case we use Brekhovskikh's formula [19], pressure in this wave could be written down as:

$$P_{пад.} = P_0 \frac{\sqrt{r_0}}{\sqrt{r}} \exp[ik_3(x\sin\theta_3 - z\cos\theta_3) - i\omega t], \quad (1)$$

P_0 – pressure in the points, which are located on the distance z_0 from charge with radius r_0;

i – imaginary value;

k – magnitude of propagation vector, $k = \frac{2\pi}{\lambda} = \omega i$;

λ – wave length;

ω –frequency of vibration (cyclic);

θ_3 – anger of incidence wave;

t – time.

r – distance from charge to viewpoint of medium with coordinates $x = X_1$, $z = d$:

$$r = \sqrt{X_1^2 + h^2}. \qquad (2)$$

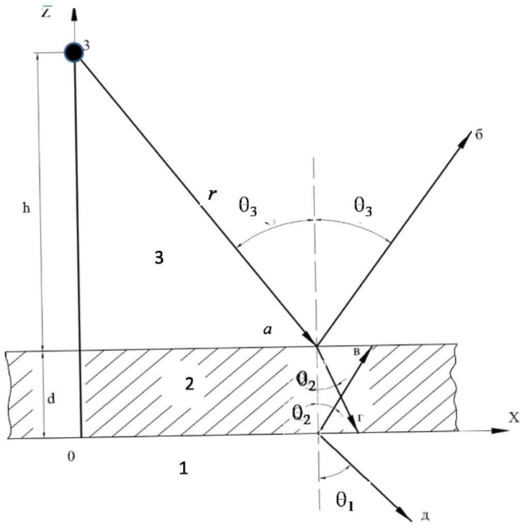

Figure 1. Seismic wave passing through fissure from blasting of vertical borehole charge

3 – charge; a –wave, which is down coming on fissure; б – reflected wave from nearest crack to charge; в – refracted waves from nearest crack to charge; г – reflected wave from the remotest charge to crack; д – wave that passes through the crack; θ1, θ2, θ3 – angle of wave refraction, angle of wave reflection and angle of wave falling, correspondingly; 1, 2, 3 – medium behind a crack, a crack and the crack front, respectively.

Along with down coming wave in the medium, reflected pressure wave arises behind the crack. [15,16,17]

$$P_{відб.} = P_0 \frac{\sqrt{r_0}}{\sqrt{r}} K_{відб.} \exp[ik_3 \begin{pmatrix} x\sin\theta_3 \\ -z\cos\theta_3 \end{pmatrix} - i\omega\, t]. \qquad (3)$$

Complex reflection coefficient $K_{відб.}$ is inputted in the first part of equality (3). It is expressed through impedances z_1, z_2, z_3 of examined medium parts.

$$\begin{gathered} K_{відб.} = (z_2^2 - z_1^2)\ (z_1^2 + z_2^2 + 2iz_1z_2\text{ctg}\theta_3)^{-1}; \\ z_1 = \rho_1 c_1 \cos^{-1}\theta_1; z_2 = \rho_2 c_2 \cos^{-1}\theta_2; z_3 = z_1; \\ \gamma = k_2 d\cos\theta_2 = c_2^{-1}\omega d\cos\theta_2, \end{gathered} \qquad (4)$$

де ρ_1, ρ_2, ρ_3 –density of medium 1, 2, 3;
c_1, c_2, c_3 – wave distribution velocity in these mediums.

As far as crack is thin then condition is met

$$d << c_2\omega^{-1}, \qquad (5)$$

Whence

$$\gamma << 1. \qquad (6)$$

Pressure in the wave which came in medium 1 could be calculated due to transparence coefficient $K_{проз.}$:

$$\hat{P}_1 = P_0 \frac{\sqrt{r_0}}{\sqrt{r}} K_{проз.} \exp[ik_1 \begin{pmatrix} x\sin\theta_1 \\ -z\cos\theta_1 \end{pmatrix} - i\omega\, t]. \qquad (7)$$

Transparence coefficient might be represented through impedances z_1 i z_2:

$$K_{проз.} = 4z_1z_2 \begin{bmatrix} -(z_1 - z_2)^2 \exp(i\gamma) \\ +(z_1 + z_2)^2 \exp(-i\gamma) \end{bmatrix}^{-1} \qquad (8)$$

The dependence of the magnitude of the pressure was taken into account during the mass velocity U determining in the environment for a crack in general formula:

$$U = grad\ \hat{P}_1 / i\omega\rho. \qquad (9)$$

Expressions (1), (3), (9) give

$$\begin{gathered} \hat{U}_{1x} = \hat{P}_1 (c_1\rho_1)^{-1} \sin\theta_1; \\ \hat{U}_{1z} = \hat{P}_1 (c_1\rho_1)^{-1} \cos\theta_1 \end{gathered} \qquad (10)$$

Hence the value of mass velocity:

$$U_1 = \sqrt{|\hat{U}_{1x}|^2 + |\hat{U}_{1z}|^2} = (\rho_1 c_1)^{-1} (|\hat{P}_1|^2)^{0,5}. \qquad (11)$$

With help of (7) the (11) could be written down as:

$$U_1 = (\rho_1 c_1 r)^{-1} \sqrt{|K_{проз.}|^2}, U_1 = \frac{P_0}{\rho_1 c_1} \sqrt{r_0 r |K_{проз.}|^2}. \qquad (12)$$

Formula (12) with (8) gives opportunity to calculate square modulus of transparency ratio:

$$|K_{проз.}|^2 = (8z_1^2 z_2^2) / \begin{bmatrix} z_1^4 + 6z_1^2 z_2^2 + z_2^4 \\ -(z_1^2 - z_2^2)\cos 2\gamma \end{bmatrix} \qquad (13)$$

The resulting expression (13) might be converted using identity $\cos 2\gamma = 1 - 2\sin^2\gamma$. Than:

$$\left|K_{проз.}\right|^2 = 1 + 0,85\ (z_1/z_2 - z_2/z_1)\ \sin^2\gamma. \qquad (14)$$

Let's confine ourselves to the consideration of incidence angles for which

$$(z_1/z_2 - z_2/z_1)\sin^2\gamma << 1, \qquad (15)$$

That is $\gamma << 1$. After a series of expansions of $\sin^2\gamma$ in formula

$$(1 + x)^n = 1 + n[1 + nx] \qquad (16)$$

with $nx << 1$, equation (14) looks like

$$\begin{gathered} \left|K_{проз.}\right|^2 = 1 + 0,85A(\theta_1)\gamma^2, \\ A(\theta_1) = (z_1/z_2 - z_2/z_1)^2. \end{gathered} \qquad (17)$$

Based on the above, the mass velocity of the wave calculated by the formula:

$$U_1 = \frac{P_0\sqrt{r_0}}{\rho_1 c_1 \sqrt{r}} \cdot \left(1 + 0,125A(\theta_1)X^2\right). \qquad (18)$$

We accepted that the crack width d and the impedance difference z1 – z2 heading to zero in the isotropic medium. Then, based on dependencies (4) and (17) it can be written that

$$A(\theta_1) = 0, \gamma = 0. \qquad (19)$$

A fallen on the crack mass velocity (18) takes the form of:

$$U_1 = \frac{P_0\sqrt{r_0}}{\rho_1 c_1 \sqrt{r}}. \quad (20)$$

Consider the case of the seismic waves falling at a distance R from the charge when the wavelength λ is bigger more than the distance a between parallel cracks: λ >>a and R >>a (Figure 2).

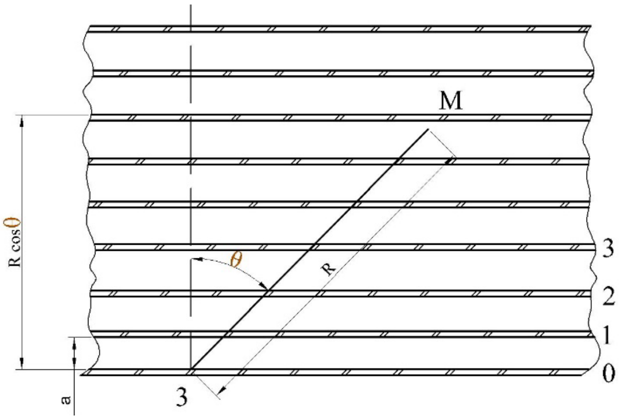

Figure 2. The scheme of seismic waves distribution in anisotropic medium with parallel fracture system

Parameters of cracks and filler of environment can be considered the same for all fissures which are plane parallel and thin: d<<a. Medium between the cracks is taken homogeneous and isotropic. Values that characterize them are marked by index 1, medium variables (aggregate) - by index 2. If crack are numbered in the distance from the charge Q, assuming that the charge is located at the 0th crack and $\theta = 0$ (Figure 2), the number of cracks can be determined by the formula:

$$N = (R/a)\cos\theta, \quad (21)$$

where θ – the angle between the direction to the observation point M and the normal to the crack (the angle of the blast wave falling on the crack). If cosθ > 0,1, then $N >> 1$.

Problem field involves the study of mass velocity fluctuations in the points of medium, which are separated from charging more cracks number.

Using expression (18) for each series of cracks between charge Q and the point M , we obtain the formula for determining the mass velocity U(θ) at the point of the medium:

$$U(\theta) = \frac{P_0\sqrt{r_0}}{\rho_1 c_1 \sqrt{R}} \cdot \left(1 + 0{,}125 A(\theta)\gamma^2(\theta)\right)^{N(\theta)}. \quad (22)$$

Using (3.21), we have:

$$U(\theta) = \frac{P_0\sqrt{r_0}}{\rho_1 c_1 \sqrt{R}} \cdot \left(1 + 0{,}125 A(\theta)\gamma^2(\theta)\right)^{(r/a)\cos\theta}. \quad (23)$$

Isoseismic line is characterized by the same mass velocity, it is mean that:

$$U(\theta) = const, \quad (24)$$

in the direction perpendicular to the exposed cracks (where $\theta = 0$) isoseismic line is located in the distance R0 from the source of explosion (Figure 3). Distance from anywhere isoseismic line when $\theta \neq 0$ taking into account the expressions (23) and (24) is defined as

$$r = R_0 \cdot \frac{1 + \frac{R_0}{4a}\left(\frac{\rho_1 c_1}{\rho_2 c_2} - \frac{\rho_2 c_2}{\rho_1 c_1}\right)^2 \left(\frac{\omega d}{c_2}\right)^2}{1 + \frac{R_0}{4a}\left(\frac{z_1}{z_2} - \frac{z_2}{z_1}\right)^2 \gamma^2 \cos\theta}. \quad (25)$$

Equation (18) (23) (25) describe the distribution of seismic waves in the rock with cracks. Using these equations by the inverse problem of frequency analysis of incident and reflected waves can be solved, rocks structure and factor anisotropy can be determined. Distances to isoseismal line in the fractured massif around the explosion are defined by the formula (25) and obtained their distribution pattern is shown in Figure 3.

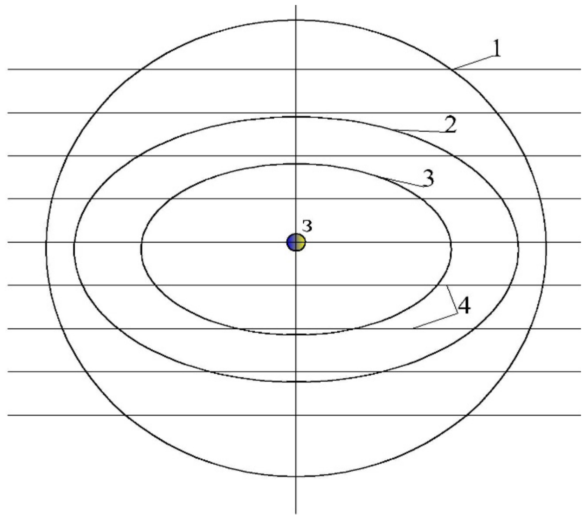

Figure 3. Seismic waves distribution in fractured massif around the explosion

1-3 - isoseismic lines;
"3" - the epicenter of the explosion;
4 - a system of parallel cracks

3. Results and Conclusion

Numerical data analysis shows that the border isoseismic lines varies from elliptical shapes to form a circle. It was found that modifying of the isoseismic lines has an impact parameter $\omega d / c_2$ which is included in the formula (25).

When specified parameter is decreasing the elliptical shape isoseismic lines moves in a circle shape. This transition should be expected in the peripheral area of the explosion because of high-frequency components are damping with increasing distance from the explosion to the observation point in the oscillation spectrum. Analytical proof of this fact is the decrease parameter $\omega d / c_2$ when $d = const$ and $c_2 = const$.

Cracks are not parallel in a real massif, they are not filled, or filled unevenly. That is why theoretical research results may differ from experimental data. However, results of this article shows that crack influence on the shape of seismic waves. Understanding of the impact can help to predict seismic hazard from blasting and to control waves for best using the energy of explosions.

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