METHOD OF CALCULATION OF STRAIN WAVE FIELD FOR THE BOREHOLES BLASTING CONSIDERING THE BLASTING DIRECTION

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ABSTRACT
The article presents the results of theoretical investigation of strain wave field development during the blasting of the blasthole charge pattern. A method for calculating the strain wave field is proposed. It describes a numerical simulation of the strain wave field. The influence of delay interval between rows of blasthole sand the initiation direction on the parameters of strain waves.

Keywords: crushing, blast wave factor, initiation pattern, strain field, direction of the blast, delay interval.

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1. INTRODUCTION
The analysis of blasting operations shows the need to improve the quality of rock mass preparation for its further processing. The blasting takes up to 20%-30% of share of the total cost of the final product [1]. One of the main tasks in the production of blasting operations is to obtain the rock mass with a certain particle size distribution [2, 10]. This task can be solved by performing a complete study of the medium destruction mechanism under impact loading, which allows determining the optimal parameters of an impulse in specific mining engineering conditions. An important role in the mechanism of rock destruction by an explosion is played by
strain waves, [3, 11, 12]. This article proposes the model and method for calculating the strain wave field.

2. METHODOLOGY

The method of calculating the parameters of strain waves was developed by the authors of [4, 5]. This technique was improved in the works of [6, 7, 8, 13, and 14].

The considered algorithms and programs were strongly focused on the types of computing equipment and were not designed for making many calculations.

The author of [6] tried to consider the speed of detonation and the actual loaded length. He calculated geometrical parameters of wave front around the charge of cylindrical symmetry, introduced and experimentally determined the decreasing rate of the conical section of the wave front. However, at the stage of determining the influence of the design parameters of the charge of cylindrical symmetry on the formation of a strain field in an infinite medium, he did not consider such an important parameter as the diameter of the charge. As a result, the calculation proposed by this author allows only to qualitatively estimate the shape of the wave front, depending on the loaded length and the detonation velocity.

The author of [7] eliminated these shortcomings, but he considered the process of strain field development from one extended charge, which does not fully describe the real picture of the strain impact on the destruction of rock mass, since in practice, the multiple-hole blasting is used.

In [8], they proposed the technique for numerical calculation of strain wave field parameters from four blasthole charges. However, this method did not take into account such important parameters of drilling and blasting operations as the direction and number of points of initiation. In addition, only the radial stresses or the components of the strain waves were calculated along the coordinate axes, which complicated the analysis of the entire field.

In connection with the above, this article proposes a technique that allows not only to calculate the strain state of the medium from the blasthole explosion or the simplest borehole patterns, but also to calculate main strain values based on the location of initiation points and sequence, the delay interval between charges, an unlimited number of boreholes, various types of explosives, designs, and different points of the plane.

Algorithm for calculating the strain fields consists of the following steps:

1.1. For a certain target point calculate the strain as a function of time for a single borehole charge \( k_1 \) in the coordinates \((R_{k1}, \phi)\) (Fig. 1). The strains from each elementary charge are calculated by the method presented in [4] and then they are recalculated in the coordinate system \((R_{k1}, N, Z)\) according to the formulas:

\[
\sigma_x(r, t) = \sum_{i=1}^{n} \left[ \sigma_{x1}(r_i, z, t) \cos^2 \theta_i + \sigma_{y1}(r_i, z, t) \sin^2 \theta_i \right],
\]

\[
\sigma_y(r, t) = \sum_{i=1}^{n} \sigma_{y1}(r_i, z, t),
\]

\[
\sigma_z(r, t) = \sum_{i=1}^{n} \left[ \sigma_{z1}(r_i, z, t) \sin^2 \theta_i + \sigma_{z1}(r_i, z, t) \cos^2 \theta_i \right].
\]
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1.2. Similarly, we calculate the strain field from each borehole $k_i$ in its coordinates $(R_{ki}, \varphi, Z)$ considering the delay time, points of initiation and other features of the $i^{th}$ charge. Then recalculate the strain from each blasthole in a single coordinate system $(X, Y, Z)$ - (Fig. 2) and find the total strain in this coordinate system:

$$
\sigma_z(r, t) = \sum_{j=1}^{n} \left[ \sigma_{yj}(r_j, y, t) \cos^2 \alpha_j + \sigma_{yj}(r_j, y, t) \sin^2 \alpha_j \right]
$$

$$
\sigma_x(r, t) = \sum_{j=1}^{n} \left[ \sigma_{yj}(r_j, y, t) \sin^2 \alpha_j + \sigma_{yj}(r_j, y, t) \cos^2 \alpha_j \right]
$$

$$
\sigma_z(r, t) = \sum_{j=1}^{n} \sigma_{yj}(r_j, z, t).
$$
1.3. After that we calculate the main strains. In the previous methods, they calculated projections of strains on the coordinate axes. In this method, we made a transition to the main strains for a more accurate assessment of the impact of the strain field parameters on the rock mass. This allows to directly assess the zone of destruction by the criterion of maximum tensile stresses.

In the three-dimensional case, the equations for the transformation of the coordinate axes will have the form [9]:

\[
\sigma'_{x'} = l_1^2 \sigma_x + m_1^2 \sigma_y + n_1^2 \sigma_z + 2l_1m_1\tau_{xy} + 2m_1n_1\tau_{yz} + 2n_1l_1\tau_{zx},
\]

\[
\sigma'_{y'} = l_2^2 \sigma_x + m_2^2 \sigma_y + n_2^2 \sigma_z + 2l_2m_2\tau_{xy} + 2m_2n_2\tau_{yz} + 2n_2l_2\tau_{zx},
\]

\[
\sigma'_{z'} = l_3^2 \sigma_x + m_3^2 \sigma_y + n_3^2 \sigma_z + 2l_3m_3\tau_{xy} + 2m_3n_3\tau_{yz} + 2n_3l_3\tau_{zx},
\]

\[
\tau_{x'y'} = l_1^2 \sigma_x + m_1^2 \sigma_y + n_1^2 \sigma_z + (l_1m_2 + m_1l_2)\tau_{xy} + (m_1n_2 + n_1m_2)\tau_{yz} + (n_1l_2 + l_1n_2)\tau_{zx},
\]

\[
\tau_{y'z'} = l_2^2 \sigma_x + m_2^2 \sigma_y + n_2^2 \sigma_z + (l_2m_3 + m_2l_3)\tau_{xy} + (m_2n_3 + n_2m_3)\tau_{yz} + (n_2l_3 + l_2n_3)\tau_{zx},
\]

\[
\tau_{z'x'} = l_3^2 \sigma_x + m_3^2 \sigma_y + n_3^2 \sigma_z + (l_3m_1 + m_3l_1)\tau_{xy} + (m_3n_1 + n_3m_1)\tau_{yz} + (n_3l_1 + l_3n_1)\tau_{zx},
\]

where: \( x, y, z \) – initial coordinate axes, \( x', y', z' \) – new coordinate axes, \( l, m, n \) – directional cosines between axes.

For the strain state, there are three mutually perpendicular main areas for which the components of the normal strain have a stationary value (maximum, minimum, or minimax); the components of the shearing strain in these areas are zero. Such normal strains will be main ones.
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\[ l(\sigma_x - \sigma) + m\tau_{xy} + n\tau_{xz} = 0, \]  
\[ l\tau_{xy} + m(\sigma_x - \sigma) + n\tau_{yz} = 0, \]  
\[ l\tau_{xz} + m\tau_{yz} + n(\sigma_z - \sigma) = 0. \]

These equations allow us to determine directional cosines \( l, m, n \) for key sites. In virtue of equation \( l^2 + m^2 + n^2 = 1 \) the variables \( l, m, n \) cannot simultaneously equal to zero. The equations are homogeneous linear equations with respect to \( l, m, n \) and give non-zero solutions in the case if the determinants of these equations are zero. Calculating this determinant and equating it to zero, we arrive at the following cubic equation for:

\[
\sigma^3 - (\sigma_x + \sigma_y + \sigma_z)\sigma^2 + (\sigma_x\sigma_y + \sigma_x\sigma_z + \sigma_y\sigma_z - \tau_{xy}^2 - \tau_{yz}^2 - \tau_{xz}^2)\sigma - (\sigma_x\sigma_y\sigma_z + 2\tau_{xy}\tau_{yz}\tau_{xz} - \sigma_x\tau_{yz}^2 - \sigma_y\tau_{xz}^2 - \sigma_z\tau_{xy}^2) = 0
\]

This equation is solved by the method of half division. The three roots of this equation give the values of the three main strains.

Thus, we obtain the dependences of the main strains on time for a certain target point.

1.4. Choose the maximum values of the main strains for this point and repeat the calculation for the points in some selected cross-section. Further, when performing all the calculations, we obtain the distribution of the maximum main strains in the selected section of the rock mass. In other words, we immediately get a picture of the destruction of the rock in the selected section by the criterion of maximum tensile and compressive stresses.

3. DISCUSSION OF RESULTS

The developed method is implemented in the PASCAL software.

The initial data required for calculations: loaded length, m; explosive transformation heat, J; detonation velocity, m/s; coordinate of the upper end of the charge along the Z axis, m; charge diameter, m; longitudinal wave velocity, m/s; shear wave velocity, m/s; rock mass density, kg/m\(^3\); coordinates of a certain target point \( A \); number of charges, pcs; number of initiation points, pcs; initiation points coordinates; delay time for initiation between charges and for a charge.

After all the calculations, we obtain the numerical data of the formation of the strain field for the specified parameters of drilling and blasting operations.

Fig. 3 shows the strain wave field in the explosion of the borehole system for the conditions of the Prudyansky open-cast mine of the Prudy-Mokhovoe-Yaskinskoye deposit.
4. CONCLUSIONS

Based on the obtained results, we came to the following conclusions:

1. A method for calculating the parameters of strain waves has been developed, which makes it possible to numerically simulate the strain state of rock mass after blasting a series of borehole charges considering the sequence of their initiation.

2. The proposed method allows us to estimate the effect of each of the drilling and blasting operations parameters on the development of the strain field.

3. This method has been tested in the blasting operations at the Prudyansky open-pit mine at the Prudy-Mokhovoye-Yaskinskoye deposit and the results of calculations and experimental explosions showed satisfactory convergence.

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