DEVELOPING A MEASUREMENT PLAN TO STUDY BLASTING STRESS WAVES INDUCED BY THE EXPLOSIVE BREAKAGE OF ROCK IN THE CHELOPECH UNDERGROUND MINE

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ABSTRACT. Determining the peak particle velocity (PPV) in the near-blast impact zone is a key factor in explosive breakage management. The most reliable way is to obtain actual PPV data through in-situ measurements. Such measurements, however, are difficult to conduct and have features of their own. Therefore, it is necessary to review the current practical experience, select appropriate instruments and create an optimal measurements plan. This study reflects the experience from PPV measurements in the world's leading mining countries such as Australia, Canada and the USA, and in Bulgaria as well, to clarify the mechanism of explosive breakage in the near-blast zone. The objective is to conduct, based on the international experience, successful measurements and obtain real l values for the Chelopech mine. From the resulting shape of the stress wave and the PPV values the parameters of the stress waves, the duration of the compression phase, and the blast energy and impulse will be derived. These data will enable management of the blasting effect to improve ore production.

Keywords: blasting effect, stress waves, parameters, measurements

РАЗРАБОТВАНЕ НА ИЗМЕРИТЕЛНА СХЕМА ЗА ИЗСЛЕДВАНЕ ПАРАМЕТРИТЕ НА ВЪЛНИТЕ НА НАПРЕЖЕНИЯ ПРИ ВЗРИВНОТО РАЗРУШАВАНЕ НА МАСИВА ЗА УСЛОВИЯТА НА РУДНИК ЧЕЛОПЕЧ

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РЕЗЮМЕ. Установяването на пиковата скорост (PPV) на частиците в близката зона на действие на взрива е ключов фактор за управление на взривното разрушаване. Най-сигурният начин да се получат реални данни за PPV е чрез измервания *in situ*. Тези измервания обаче са трудни и имат своите особености. Поради това, е необходимо да се проучи опитът от практиката, да се изберат подходящи измерителни уреди и да се състави оптимална схема на измерване. В настоящото изследване е отразен опитът от измервания на PPV във водещи в минното дело страни в света – Австралия, Канада, САЩ, както и в България, по изясняване на процеса на взривното разрушаване в близката зона. Целта е, въз основа на световния опит да се извършат успешни измервания и се получат реални резултати за условията на рудник Челопеч. От получената форма на вълната на напрежения и от стойностите на пиковата скорост ще бъдат определени параметрите на вълните на напрежения продължителност на фазата на натиск, енергия и импулс на взрива. С тези данни става възможно действието на взрива да бъде управлявано за постигане на по-добри производствени резултати.

Ключови думи: действие на взрива, вълни на напрежения, параметри, измервания

Introduction

Knowing the peak particle velocity (PPV), especially in the near-blast impact zone − within the line of the least resistance, allows for assessment of the operation of each individual charge in the line or fan-pattern, and of the distribution of energy within the breakage zone. Therefore, measuring it and obtaining its actual values *in situ* are of key significance in explosive-breakage management. Such measurements have their specific features and, therefore, it is necessary to review the current practical experience, select appropriate instruments and create an optimal measurement plan. Furthermore, adequate results require pre-defining of the expected velocity in order to select a suitably sensitive recipient of seismic fluctuations, to determine the method for its fastening onto the rock surface or in a borehole, and to ensure that the direction of movement coincides with the direction of response of the unit.

While various devices, referred to as geophones, used for measuring of the far-zone blast-seismic fluctuations, are present on the market, no near-zone measurement sensors were available on the market during the studies.

This study reflects the experience from studies in the world's leading mining countries such as Australia, Canada and the USA, and in Bulgaria as well, to clarify the mechanism of explosive breakage in the near-centre blast zone. The aim is to use the global experience in order to obtain *in-situ* results specific to the Chelopech-mine about the stress wave forms and the PPV values which can be used to determine the duration of the compression phase and the blast energy and impulse. These data will enable management of the blasting effect to improve ore production.

A study of the US Bureau of Mining (USBM) to determine the effect of charge diameter on explosive performance

The US Bureau of Mines carried out a large-scale study (Nicholls, 1966) on the effect of the charge diameter on explosive performance. Three different explosives were detonated in three different charge diameters. Three linear arrays of holes were drilled with 13 holes in each. Each array contained six shot holes, and the remaining were gauge holes with strain gauges suspended in them (Fig. 1). The experiment was used to measure relative deformation (microinch/inch). The shot-to-gage wave arrival time was measured, as well as the time of entry of the signal into the gauge, the deformation rise and fall times, the compression phase length, and the maximum compression and strain amplitudes. These data were used to infer the pulse types. Three wave types were registered (Fig. 2). It was concluded from the processing of the data that small-diameter charges are much less effective in producing strain waves in rock than larger diameter charges of the same explosive.

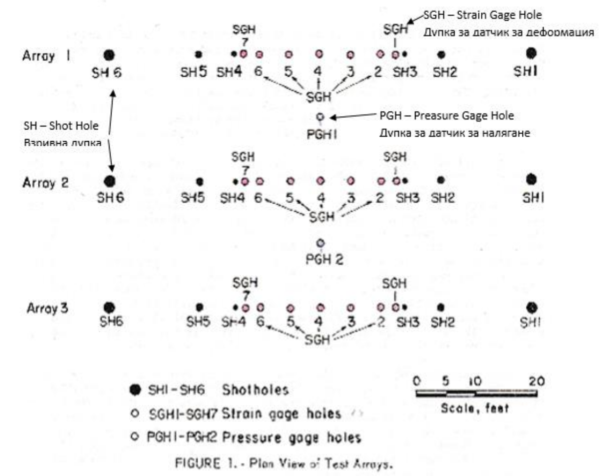


Fig. 1. Test borehole location layout

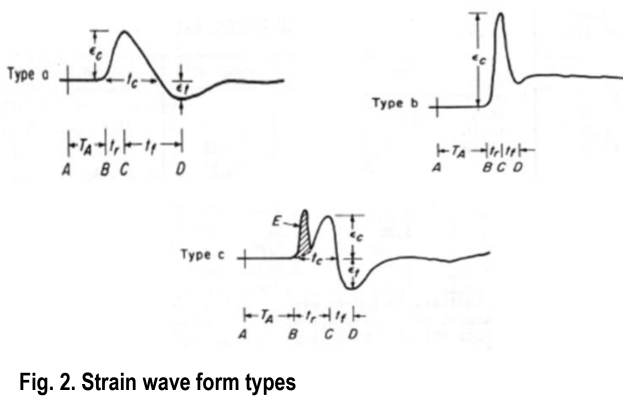


Fig. 2. Strain wave form types

Legend

A	Charge detonation time	t_r	Rise time
B	Beginning of strain pulse	t_c	Compression time
C	Pressure deformation peak	t_f	Fall time
D	End of strain deformation	ε_c	Peak compression deformation
E	Part of the booster-explosive pulse	ε_t	Strain deformation
T_A	Initiation time		

Studying of strain-wave parameters during ore blasting in Bulgaria

In 1990, a study of stress wave parameters was carried out (Stefanov, 1993) in the S. Stefanov shaft mine of the GORUBSO-Zlatograd company. The aim was to determine the stress wave parameters during production blasting *in situ* and to use the study results to optimise the explosion patterns.

The explosive breakage effect in and outside the near-blast zone and, also, the effect of energy dissipation at distance were determined by measuring the peak particle velocity at different distances from the explosion centre. The particle velocity and stress in the near-blast zone are high and the gauges, which were subject to high loads, had to be specially designed.

While various devices (geophones) used for measuring of the far-zone blast-seismic fluctuations, are present on the market, no near-zone measurement sensors were available on the market during the studies. Such a gauge, converting the mechanical motion to electrical signals, can be of an induction type in which case it should ensure that the measured value is proportional to the induced electromotive voltage. Such a gauge was designed for the study (Stefanov, 1993).

When installed, the gauge must be rigidly connected to the rock. As the blast wave reaches the gauge, its body is dragged along with the moving media. Inertia and reduced friction leave the magnet immobile but move the coil, whereby electromotive voltage is generated. The special coil ensures that the resulting electromotive voltage is proportional to the *movement velocity.*

A H117 magneto-electric light-ray oscilloscope (rotating-mirror oscillograph) was used as a measuring instrument. It transformed the electrical signal from the gauge through a reflecting galvanometer (the rotating mirror) into a light ray tracing a photographic film or light-sensitive paper moving at a certain speed.

When studying single fast-flowing processes such as explosions, it is important to synchronise the measuring instrument with the time of explosion. After the oscilloscope is energised, recording the studied signal requires time for the film to reach the required speed, before the explosion pulse is sent. A synchronisation device comprising a time-setting, a power supplying and an implementing unit and with the relevant signalling capabilities was constructed for this purpose.

The schematic diagram of the measuring system is shown on Figure 3.

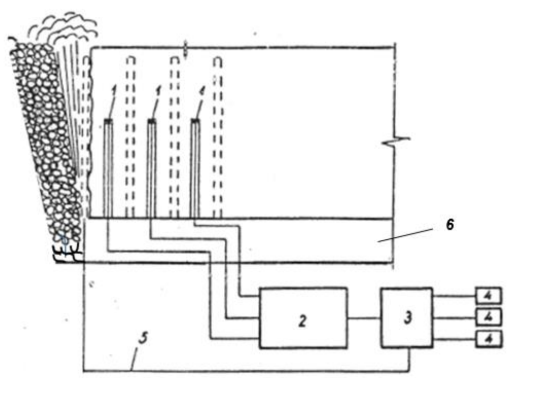


Fig. 3. A system for direct measurement of stress-waves in rocks. 1 – Gauge; 2 – Measuring instrument (rotating-mirror oscillograph); 3 – Synchronisation device; 4 – Power-supply unit; 5 – Explosion circuit; 6 – Sub-level gallery

The studies were conducted during production blasting of boreholes in a fan arrangement with one sequential and one diagonal cut-shots. The gauges were positioned at increasing distances from the blast centre: 0.5*W*, 1*W*, 1.5*W* (*W* – line of the least resistance), along an axis perpendicular to the fan plane, at the level of the blast centre.

One resulting seismogram is shown on Figure 4. The signal-recording equipment (using film reel, below ground) does not always allow for good recording quality but the resulting record is readable and usable. The film shows the stress wave emitted from the borehole in the centre of the fan and registered by 3 consecutively positioned gauges, as shown on Figure 3. The record allows for measurement of the amplitudes (A_1, A_2 and A_3) which are the peak particle velocity at three different distances, the duration of the compression phase (t_1, t_2 and t_3), and, also, the time of entry of the wave into the second and the third gauges (T_{1-2} and $T_{2.3}$). The stress rising and falling times can also be read.

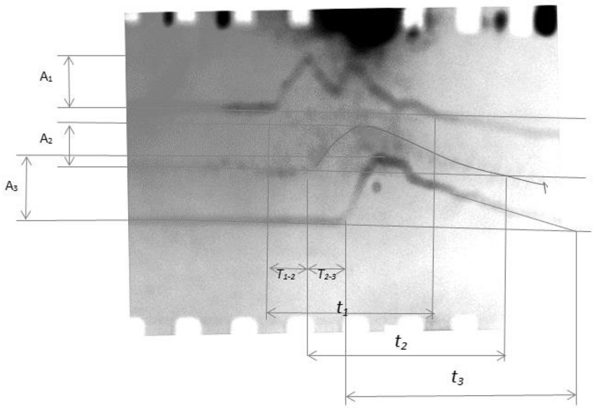


Fig. 4. A record of the stress wave emitted from the central fan borehole

Peak velocities ranging between 0.20 m/s and 4.12 m/s were registered, with a positive phase duration of 1 ms to 4 ms.

These results underlie the dependency between the peak particle velocities and the distance from the blast centre in both blasting patterns used during the study.

A study by the Australian Centre of Geomechanics of the stress wave parameters to determine their effect on support systems

In 2006, the Australian Centre for Geomechanics published an article (Heal, D., et al. 2004) with results from a study of the performance of underground support systems subjected to rockbursts simulated by explosives. The energy absorbed by the support systems was assessed by a study of the explosion effect.

The rockburst simulation layout is presented on Figure 5. A discontinuous line shows the test wall to which two support systems and measuring instruments are attached.

Three blastholes are drilled parallel to and 5 m from the wall for the rockburst simulation.

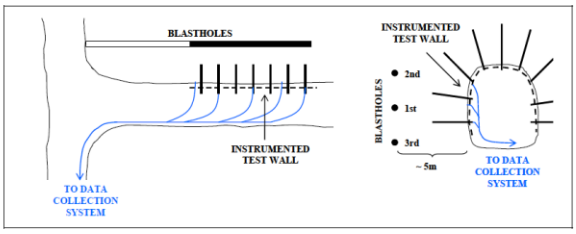


Fig. 5. Rockburst simulation layout

The measurement was conducted using 14 Hz SM6 geophones (25.4 mm in diameter and 35 mm long) connected to a 16 channel monitoring system. Sixteen geophones (2 three-axial and 14 uniaxial) were installed in different places relative to the source of energy. The two triaxial geophones were cemented into 64 mm wide and 2 m deep boreholes drilled perpendicular to the test wall. Six horizontal uniaxial geophones were mounted on the surface of the test wall to measure the stress waves at the rock-air interface. Eight horizontal uniaxial geophones were end-mounted onto 2.4 m long conical rockbolts of one of the support systems. This is a method to assess the dynamic response of the rockbolts and the rock mass.

The highest PPVs, of 2,65 m/s and 3.14 m/s, were produced by exploding of an 8 kg emulsion charge and a 16 kg charge, respectively. Also, the duration of the positive wave phases produced by blast 1 at around 4 ms and blast 2 at 2.5 ms were recorded by the seismographs.

Measurement of stress wave parameters in rocks and in paste fill stopes at Cannington Mine in Australia

In 2006, a study (van Gool, Bronwyn, 2007) of PPV in ore rocks and in a paste-fill stope was carried out in the Cannington Mine in Western Australia. The study was intended to determine the critical peak velocities at which the artificial massif remains stable and involved two cycles. The first cycle entailed recording of production blasting in adjacent stopes, i.e. blasting in the remote zone. The measuring instruments were positioned so that the geophones could measure the PPV both in the paste fill and in the ore.

The second cycle entailed blasting the holes drilled into a gallery specially made into the paste fill, and the geophones were used to measure peak velocities from explosions in the near-impact zone.

Six three-axial geophones connected to a Blastronics BMX monitor were used. Four geophones were installed into the shot hole. The two remaining geophones were cemented in holes drilled from the side of the gallery, one in the wall adjacent to the blast holes, and the other in the rock, also near the blast holes but at a depth of 1 m.

The resulting data show that the PPVs from the same blast and at the same distances from the blast location vary. In this case this is caused by the reflection and refraction of the wave at the ore/paste-fill interface where two materials with different densities meet.

It is a known fact that waves are partially reflected and refracted at such interfaces. The higher the difference in densities between the two materials, the larger the portion of refracted or reflected wave energy will be. Paste fill is far less dense than the ore and, therefore, much of the wave energy (up to 90% according to the Cannington Mine study) released from a blast inside it, will reflect and remain in the paste fill and only a small part will enter the rocks. If the blast occurs into the rocks, then much of the wave will reflect back into it and a small part will move into the paste fill.

The PPV results and predicted values at the ore - paste fill interface show that the paste fill is expected to cave from a blast impact with PPV above 2.5 m/s.

Measuring of fan borehole blast energy in the INCO Mine in Canada

The performance of individual charges in the fan-pattern at the INCO shaft mine in Canada was studied to determine the extent to which charges release their energy (Mohanty B., et al., 2013). Instantel Minimate units, available on the market, were employed to record the blasting fluctuations together with three-component seismographs (geophones) and accelerometers. The recording data were extracted using a data collection analogue system.

The geophones and accelerometers were installed into galleries at certain distances from the blast location which was within the near-impact zone. As required, the units were attached to the rock surface by solid connection.

Summarised results from multiple blasts show that 56% of all shot holes release less than 20% of the expected explosive energy and that only 44% release nearly all of their energy.

Discussion

Understanding the blast effect and determining the method of its management requires obtaining of *in situ* measurement data of the following blast-induced stress wave parameters: a) Duration of positive phase (compression), τ, s; b) Wave length, λ *m*; c) maximal radial velocity of particle fluctuation behind the wave front (peak velocity) v_r, m/s; d) maximum radial stress σ_r, Pa; d) displacement of particles *u* during the positive wave phase τ: e) relative positive phase pulse, *Pa.s*; f) relative energy, J/m^2.

The maximum radial velocity of particle fluctuations behind the wave front (peak velocity) and the duration of the positive phase (compression) are determined directly from the seismogram, while the relocation and the relative energy are derived by graphic integration.

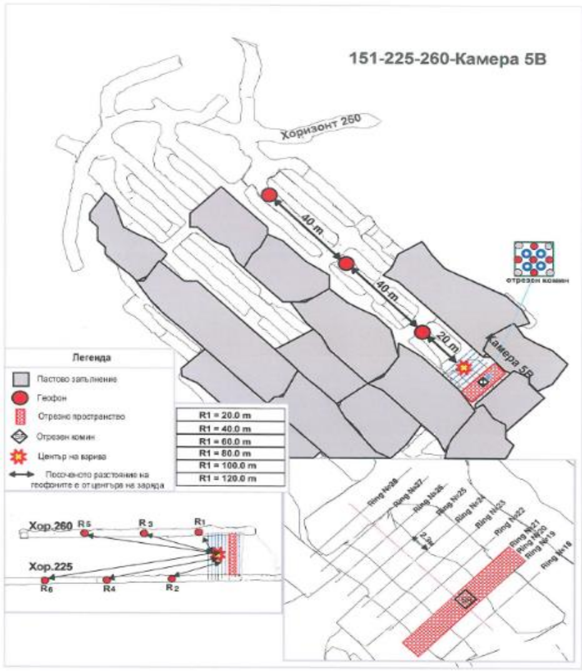
The summarised results from the above studies show that peak particle values v=(4.12÷0.2) *m/s* have been measured in strong rocks at relative distances of R/R_0 = (30÷200) (where *R* is the distance from the blast centre, and R_0 is the charge radius). The positive phase of the wave varies - τ=(1÷4) *ms*. The particle movement velocities were measured at 2.65 m/s for an 8 kg of explosive charge and 3.14 m/s for a 16 kg charge. A study of PPV in ore rocks and in paste fill using 69 mm wide production shot holes, each charged with approximately 98 kg of explosive, showed peak values measured at 32 to 55 m from the blast centre of 19.2 mm/s to 32.5 mm/s in rocks and 13.6 mm/s to 78.1 mm/s in paste fill. The higher velocities in the paste fill may be explained with the interference of the stress wave from the first shot hole with those of the subsequently blasted shot holes. PPVs of 80 to 90 mm/s were obtained from other studies, at a distance of approximately 60 m from the blast centre.

Good-quality results during field studies require rigid connection of the gauge to the rock, consistency of the signal-receiving gauges and the measuring equipment with the expected stress-wave parameters, and, also, consideration of the local geological conditions of the locations in which the studies take place.

A measurement pattern for the Chelopech Mine in Bulgaria

The analysis of such measurements practised worldwide underlies the pattern for the forthcoming measurements in the Chelopech Mine (Fig. 6).

a)



b)

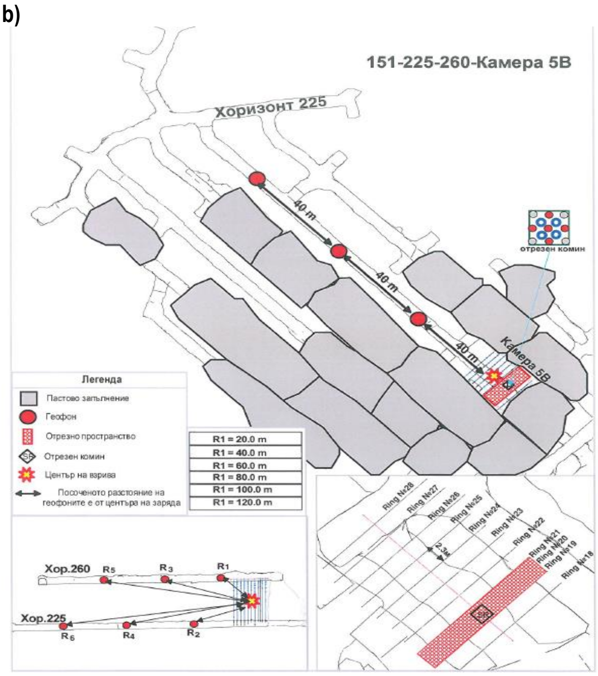


Fig. 6. Location of the geophones at levels 225 a) and 260 b)

This pattern features six geophones, of which three are installed at an upper level and three at a lower level. Each geophone will measure the particle displacement velocity and, being placed at varying distances from the blast centre, the geophones will allow determination of the energy dissipation law. The measurement will be carried out during the end stope forming stage, at which time the highest stress will be transferred through the rocks whose integrity will not have been disrupted by other blasting. The geophones will be positioned at a distance of 20 m from the charge centre. The stope will be positioned between mined and subsequently paste-filled spaces. The fans within the end stope will be positioned 1.3 m apart, and the remaining fans will be 2.3 m apart. This decision was imposed by the need for more rock-fracturing energy when opening up the end stope.

Conclusion

The PPV study is key for the understanding of the blast effect and for the necessary management measures. According to the global experience of such practices, gauges capable of resisting high acceleration are used in the near blast-impact zone, or breakage zone, and geophones are used at different distances from the near and far zones to measure the seismic effect.

The analysis of such measurements practised worldwide underlies the pattern for the forthcoming measurements in the Chelopech Mine, where also geophones will be used at different distances from the blast centre. This will enable measuring the particle displacement velocity and determining the energy dissipation law in the Chelopech Mine conditions.

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