5. Management covering blast design

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Blast optimisation with impedance matching using surface-wave tomography at an opencast coal mine

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ABSTRACT: Multichannel analysis of surface waves (MASW) method is one of the advanced geophysical techniques for determination of in-situ compressional wave velocity of rock mass. This technique was applied at sandstone benches of a coal mine for rock mass characterisation and blast optimisation by impedance matching of explosives. Field experiments were conducted on seismic profiling to characterise sandstone rock mass on the basis of P-wave velocity (V_p) measurements. The running benches were selected for the experimentation so as to cross check the results of the V_p with the exposed faces of the benches. The instrument used for seismic profiling contains 24 geophones of 14 Hz frequency. The mode of survey was 'refraction method' which could give the V_p profile upto 50-60m depth and about 100m stretch. The source of vibration generation was by hammering of specific Sledge hammer. The raw seismic data collected in the field was analyzed by software called 'Seismic imager' for generating V_p profile of rock strata upto a depth of 50-60m from the surface. The V_p profiles of each bench were initially analysed for the composite layers and smooth layering was done afterwards for general rock mass characterisation. The V_p profiles were determined for three benches of the mine, which include weak, medium and hard types of rock mass. The rock impedance was calculated based on the V_p determined by seismic profiling. This data was used for the selection of explosive with desired velocity of detonation and density, so as to match the impedance and of rock mass. The blast performance with the suitable explosives with impedance matching was obviously better than that of impedance mismatching. The optimisation studies resulted in reduction of back break by 50-75% and reduction of mean fragment size by 15-47%. The paper stresses the need for conducting impedance matching exercises for all blast sites for blast optimisation and improved productivity.
Keywords: Seismic Profiling, Rock Characterisation, Impedance, Blast Optimisation

1. INTRODUCTION

Productivity in opencast mines depends heavily on the degree of fragmentation. Various unit operations like drilling, blasting, loading and transportation are influenced by fragmentation and jointly contribute to the overall productivity. It is often observed that practising engineers indiscriminately use explosive charges to improve fragmentation with scant regard to rock formations and explosive properties. This may not be in the best interest of overall mine productivity. It calls for a study of the proper selection of explosives for various rock properties. The best matching for optimum shock wave transmission to the rock occurs when the detonation impedance of the explosive is equal to the impedance of the rock material (Atchison 1964). Impedance is the product of compressional wave velocity and density of the material. Impedance calculation requires the determination of in-situ P-wave velocity (V_p) and density of rock mass. Therefore MASW technique of seismic profiling was applied for rock mass characterisation of sandstone overburden in this study.

Surface-wave tomography is an efficient way to obtain images of the group velocity at a test area of rock formation, because Rayleigh-wave group velocity depends on frequency. There are separate images for each frequency and at each point in these images the group velocities define a dispersion curve, a curve that relates group velocity to frequency. Extending the common use of surface wave analysis techniques from estimating shear wave velocities and compressional wave velocities for detection and/or imaging required a multichannel approach to data acquisition and processing. Integrating the multichannel analysis of surface waves (MASW) method with a common mid-point (CMP)-style data acquisition permits the generation of a laterally continuous two dimensional (2-D) shear wave velocity field cross-section (Park *et al.* 1999; Xia *et al*. 1999). The MASW method as used here requires minimal processing and is relatively insensitive to cultural interference. Mating MASW with the redundant sampling approach used in CMP data acquisition provides a non-invasive method of delineating horizontal and vertical variations in near-surface material properties.

Continuous acquisition of multichannel surface wave data along linear transects has recently shown great promise in detecting shallow voids and tunnels, mapping the bedrock surface, locating remnants of underground mines and delineating fracture systems (Park *et al*. 1999). Extending this technology from sporadic sampling to continuous imaging required the incorporation of MASW with concepts from the CDP method (Mayne 1962). Integrating these two methodologies resulted in the generation of a laterally continuous 2-D cross-section of the shear wave velocity field. Cross-sections generated in this fashion contain specific information about the horizontal and vertical continuity and physical properties of materials as shallow as a few inches to over 300 ft. Seismic reflection surveys are generally designed to image structural and stratigraphic features with a high degree of resolution and accuracy. On such surveys, surface waves are considered noise. For our application, however, it is possible to exploit the sensitivity of the surface wave to changes in material velocities that make up the half-space it travels through. Surface wave propagation depends on frequency (depth of penetration), phase velocity (compressional and shear), and density. Each of these properties will affect the surface wave dispersion curve (phase velocity vs. frequency) in a predictable fashion. Since shear wave velocity has the greatest impact on the properties of a surface wave, we can invert the dispersion curve in such a way as to obtain the shear wave velocity as a function of depth (Xia *et al*. 1999). Borton (2007) says that the phenomena of seismic anisotrophy giving lower stiffness perpendicular to layering than in parallel, has been used since the nineteenth century for investigating fractured rock at depth. Disturbances in the shear wave velocity field will show up as anomalies in the otherwise uniform contours of the shear wave velocity field for a layered earth. The same analogy holds good for compressional wave velocity also. The objective of this experimental work has been to find out the shear-wave and compressional-wave (V_p) structure and from these dispersion curves and to get the inferences regarding the structural quality of the strata. This paper deals with the application of seismic profiling for rock mass characterisation for optimisation of blast parameters of various rock formations.

2. ADVANTAGE WITH THE MASW METHOD OF PROFILING

Earlier P and S-wave velocities were determined using laboratory estimates, which seldom reflect the in-situ conditions. Moreover the researchers found that the shear waves penetrate with less attenuation than compressional waves. Shear waves were also found to be less affected by noise compared to compressional wave reflections (Dasios *et al*. 1999). Several key characteristics of surface waves and surface wave imaging make application of this technique possible in areas and at sites where other geophysical tools have failed or provided inadequate results. First and probably foremost is the ease with which surface waves can be generated. The relative high amplitude nature of surface waves (in comparison to body waves) makes possible their application in areas with elevated levels of mechanical/acoustic noise. A layer over half space is all that is necessary to propagate surface waves. It is one of the few acoustic methods not requiring velocity to increase with depth and/or a contrast (i.e., velocity, density, or combination [acoustic impedance]).

Conductivity of soils, rocks, electrical noise, conductive structures, and buried utilities all represent significant problems or at least important considerations for electrical methods. These have little or no impact on the generation or propagation and generally have no influence on the processing or interpretation of surface wave data. This flexibility in acquisition and insensitivity to environmental noise allows successful use of shear wave velocity profiling in areas where other geophysical methods might be limited. Surface waves, when used to image the earth, provide a rapid and relatively straightforward method of examining the shallow subsurface. Unfortunately, interpretations of the two-dimensional shear wave velocity field derived from the inversion of the surface wave dispersion curve are much lower resolution than seismic reflection sections. However, the shear wave velocity field derived in this fashion is quite sensitive to abrupt changes in shear wave velocity. In this setting, it is reasonable to expect voids, caverns, or collapse features to be associated with an abrupt change in shear wave velocity (Miller 1999).

Areas with pits, trenches, or underground utilities are likely targets for this type of imaging. Subsidence-prone areas also are likely targets for this type of imaging. Decreases in the shear wave velocity related to decreases in compaction or localised increases in shear wave velocity associated with the tension dome surrounding subsurface cavities are key indicators of either subsidence activity or areas with a strong potential for roof collapse. In situations where gradual subsidence is or has been active, a dramatic drop in shear wave velocity will be characteristic of earth materials that have begun to collapse into voids formed at depth. This low velocity zone generally produces a characteristic signature in the shear wave velocity field. Since the shear wave velocity of earth materials changes when the strain on those materials becomes 'large,' load-bearing roof rock above mines or dissolution voids may experience elevated shear wave velocities due to loading between pillars, or, in the case of voids, loading between supporting sidewalls. Key to exploiting surface waves as a site characterisation tool is their sensitivity to shear wave velocity, compressional wave velocity, density, and layering in the half space.

3. MASW TECHNIQUE FOR ROCK MASS CHARACTERISATION

3.1 Data acquisition

The instrument called Geode (Geometrics controllers Inc., USA) was used for acquiring the data for surface wave analysis using Multi Channel Analysis of Surface Waves (MASW) technique. The sensors used were of 14 Hz frequency and 24 in number. The MASW system with various components is shown in Figure 1. The sensors were spread at 1m spacing and the seismic source was at 5m distance in all the experiments. A sludge hammer of 10 lb weight was used as the seismic source. Each site will have specific characteristics affecting data properties. Optimising parameters and equipment is critical to maximising the accuracy, analysis format, and potential of the resultant processed sections. Data acquired for surface wave analysis using the MASW technique are generally broadband (i.e., 4 Hz to 64 Hz), with offsets designed based on target dimensions and depths. Standard CMP roll-along techniques are used in conjunction with 24-channel recording systems. The array of geophones and seismic source for a survey are shown in Figure 2. Shot and receiver spacing as well as near and far source offsets depend on the number of recording channels and maximum and minimum depth of interest.

Ground cover (soil, cement, gravel, grass, etc) has no significant influence on the accuracy of the recorded surface wave energy (Miller 1999). Generation of surface waves is quite easily accomplished with weight drop style sources, with the particular specifications of the source only limited by the dominant frequency band of interest. For deeper penetration a large and heavy source is optimum. Receivers need to be low frequency (< 8Hz) and broadband. With cost consideration,

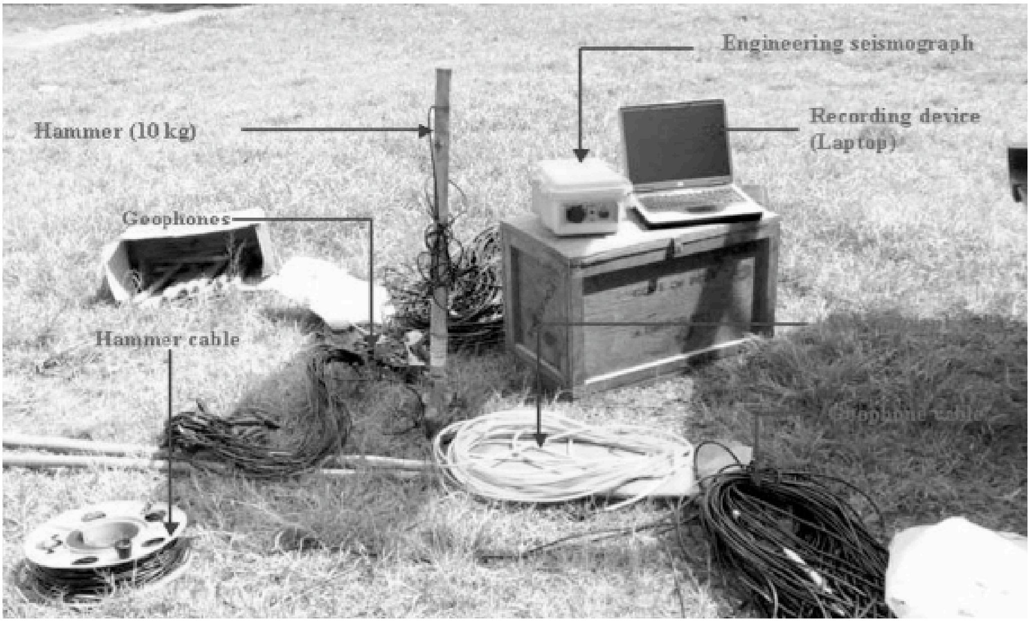

Figure 1. Various components of the MASW system.

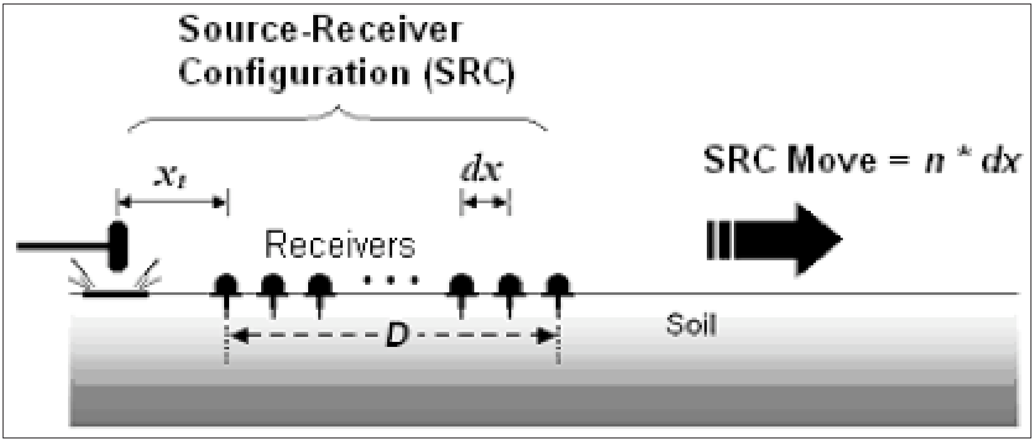

Figure 2. Array of geophones and source for a seismic survey.

the optimum geophone has a natural frequency of around 4.5 Hz and can be outfitted with either flat baseplates or short spikes depending on the surface to be surveyed. Recording geometries and frequency ranges of data examples presented here provided optimum data characteristics for examining earth materials in the depth range from about 1 to over 50m below ground surface. Many studies have shown that receiver-ground coupling is critical for high-resolution body wave surveys (Hewitt 1980). Maximising frequency response and recorded body waves normally requires longer spikes, well seated into competent earth. Coupling experiments at various sites have suggested receivers only require simple ground contact to record broad-spectrum surface wave energy. Little or no improvement is evident in response (frequency vs. amplitude) when geophones are 'planted' using spikes, placed on the ground using plates, or held to the ground with sandbags (Miller 1999). The arrival wave trains with different geophone deployments are shown in Figure 2. Comparison of wave trains due to different geophone deployment methods on the surface were shown in Figure 3.

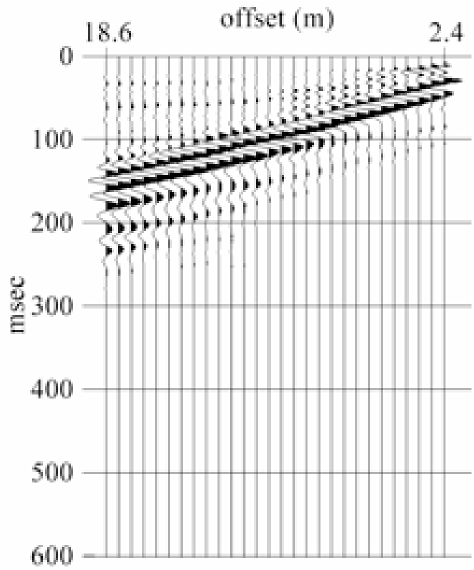

Figure 3a. Comparison of geophone deployment methods – Spikes.

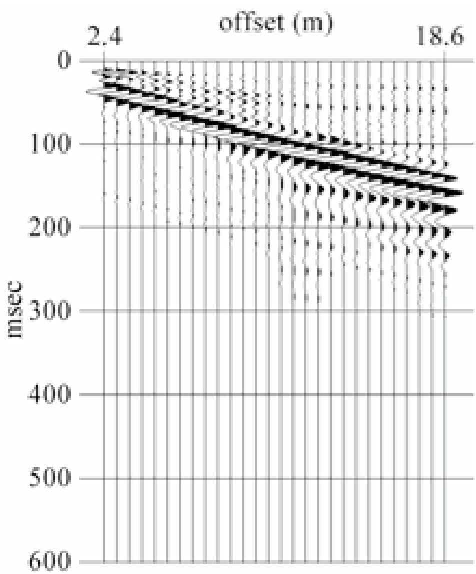

Figure 3b. Comparison of geophone deployment methods – Base Plates.

3.2 Data processing

Each multi-channel shot gather was recorded with all live receivers within the optimum offset window for surface wave sampling of subsurface materials within the target window. Multichannel records

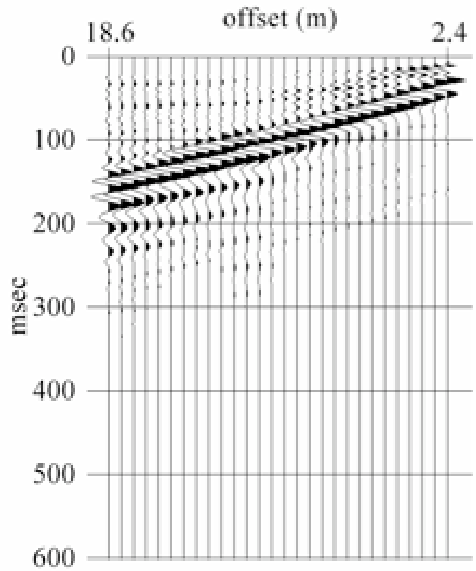

Figure 3c. Comparison of geophone deployment methods – Base Plates with Weights.

were analysed with *SurfSeis* (a proprietary software package of the Kansas Geological Survey), which facilitates use of MASW under continuous profiling configurations. During processing, each shot gather will generate one dispersion curve. Care must be taken to insure the spectral properties of the data (shot gathers) are consistent with the maximum and minimum f-vc values (f is the frequency, vc is phase velocities of surface waves) contained in the dispersion curve. Each dispersion curve is individually inverted into an x-vs trace. Gathering all x-vs traces into shot station sequential order forms a 2-D grid of the shear wave velocity field. The shear wave velocity field generated in this fashion does 'smear', to a limited extent, the velocity value for a specific point in space. This distortion requires a good understanding of the resolution and accuracy of the specific data set analysed before making any interpretation.

4. FIELD APPLICATION OF THE SEISMIC PROFILING

4.1 Mine Details

The field experiments on seismic profiling and impedance matching were conducted at KOCP of Western Coalfield Ltd (WCL), Coal India

Ltd. The KOCP mine is situated about 25 km from Nagpur town on Nagpur-Jabalpur National Highway No. 7. The area is characterised with flat topography having elevations ranging from 980 ft. to 1000 ft. above mean sea level. The drainage of the colliery is controlled by perennial Kanhan river flowing on the southern side of the colliery. Kamptee underground colliery of Nagpur area in the WCL was started in 1954. There are five coal seams namely, I, II, III, IVA, VA, VB and VC in the leasehold area of the colliery. All the coal seams were developed on pillars and depillared or splitted with stowing. Developed pillars are also standing over some patches of the underground leasehold area of the colliery in different coal seams. This underground colliery was abandoned in 1999. Opencast mining is being carried out to extract the developed pillars in the underground mining. Many of such standing pillars have been caught fire and blasting for extraction of these pillars poses problems. There is also a problem of optimum blast fragmentation, which may be due to mismatching of rock mass properties and explosive selection.

4.2 Geology

The exposures of Lower Gondwana rocks around Tekadi-Silewara-Patansaongi-Bokhara-Khapa-Saoner belt located about 25-30 kms west of Nagpur is referred to as Kamptee Coalfield. Kamptee Coalfield is a horse-shoe shaped basin aligned in a NW-SE direction. The coalfield is blanketed by the detrital mantle. The generalised stratigraphy of the coalfield is shown in Table 1.

The Barakars overlie the Talchirs and underlie the Moturs conformably. They consist of fine, medium and coarse grained sandstone, intercalations of shale and sandstones, sandy shale, carbonaceous shale and coal seams and are around 300 m in thickness. Kamthis are a good aquifer and overlap directly above Barakars. The dip of the seams is about 1 in 4.5 on the rise side and about 1 in 5 to 1 in 6 on the dip-side. It shows a tendency to further flatten beyond the existing limit of working. Five coal seams namely I, II, III, IVA, IVB, VA, VB and VC are present in the leasehold area of the colliery.

The coal seams are numbered from the top downward, thus seam I is the top-most coal horizon whereas seam V is the bottommost seam. The rock properties of all the three benches, where tests were conducted are shown in Table 1. The intact rock P-wave velocity was tested by ultrasonic device as shown in Figure 4. The laboratory evaluation of P-wave velocity and density are given in Table 2.

Table 1. Stratigraphical sequence of Kamptee coalfield.

Age	Formations	Lithology	Thickness (m)
Recent to sub-recent	Alluvium	Black cotton soil, sand, boulder and clay	7.75 –41.25
-- Unconformity--------------------------------------			
Upper Permian	Kamthis	Coarse grained ferruginous sandstones with clay beds and rare thin coal / carbonaceous shale bands	6.10 – 74.60
-- Unconformity--------------------------------------			
Middle Permian	Moturs	Variegated clays and green chloritic sandstones	36.90 – 210.53
Lower Permian	Barakars	Fine grained sandstones, medium to coarse grained sandstones with shale bands and coal seams	75 – 300
Upper carboniferous	Talchirs	Greenish grey fine grained sandstones and needle shalers	> 300
-- Unconformity--------------------------------------			
Archaeans	Metamorphics	Metamorphic gneisses and granites	

Table 2. Intact rock properties of all the test sites.

Site	Rock density	Laboratory measurement of P-wave velocity, m/s
Bench-I	2550	2380
Bench-III	2600	2640
Bench-IV	2675	3125

4.3 Seismic profiling at KOCP, WCL

The authors conducted a seismic profiling survey to characterise sandstone rock mass on the basis of P-wave velocity measurements. The survey was conducted at the surface of sandstone rock mass towards the North East direction of the mine. The survey was conducted at three locations of the mine covering hard, soft and medium rock mass. The running benches were selected for the experimentation so as to cross check the results of the P-Wave velocity profile (V_p) with the exposed faces of the benches. The experimental set up is shown in Figure 5. The rock samples were collected from middle and bottom layers of bench-I for laboratory testing of P-wave velocity. The faces of exposed benches are shown in Figure 6.

Figure 4. P-wave velocity determination of sandstone samples from Laboratory testing.

Figure 5a. Seismic profiler experimental set up at KOCP, WCL – hammering point.

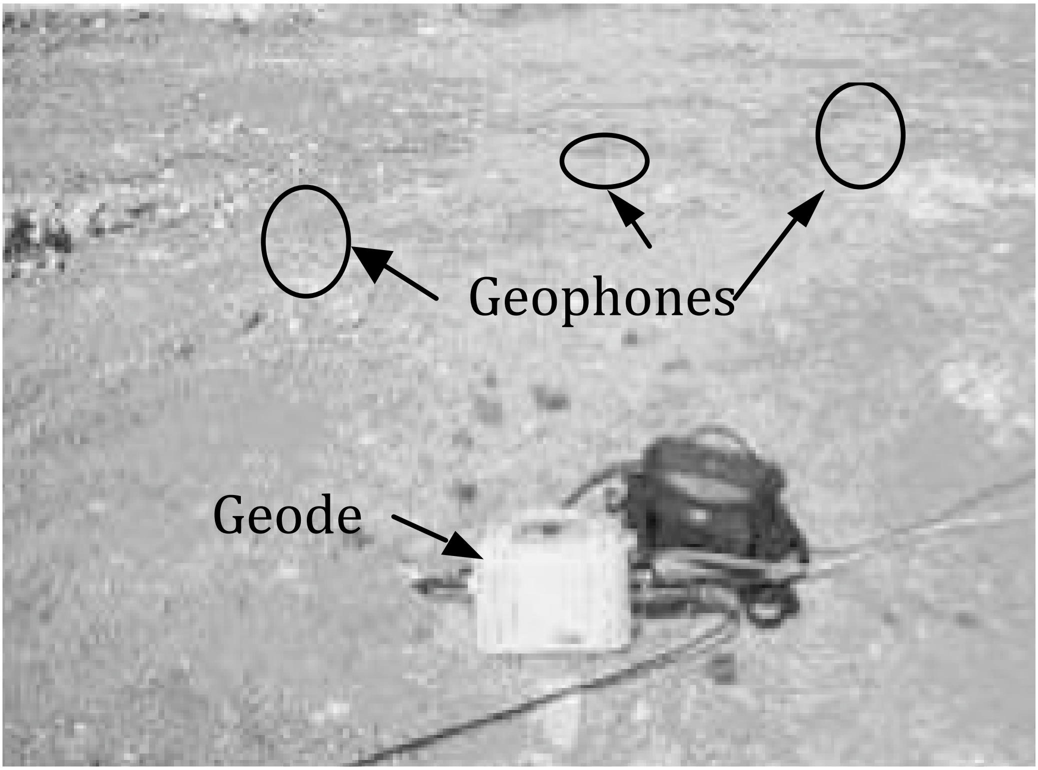

Figure 5b. Seismic profiler experimental set up at KOCP, WCL - Geode and geophones.

Figure 6. Exposed face of a test site at KOCP mine, WCL.

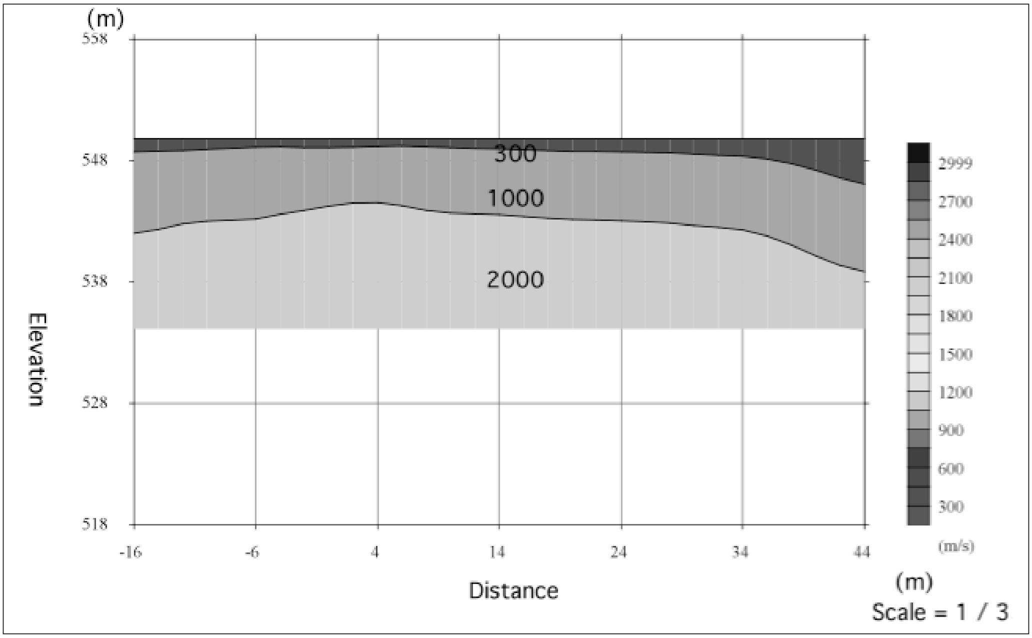

Figure 7. V_p profile of major cluster of layers of sand stone strata at bench-I.

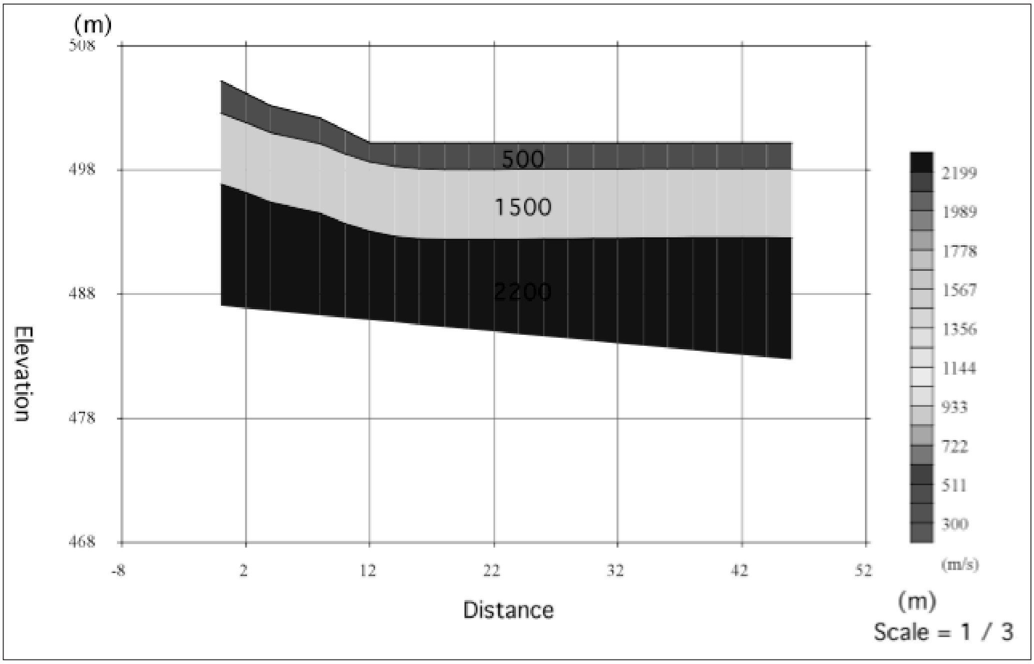

Figure 8. V_p profile of major cluster of layers of sand stone strata at bench-III.

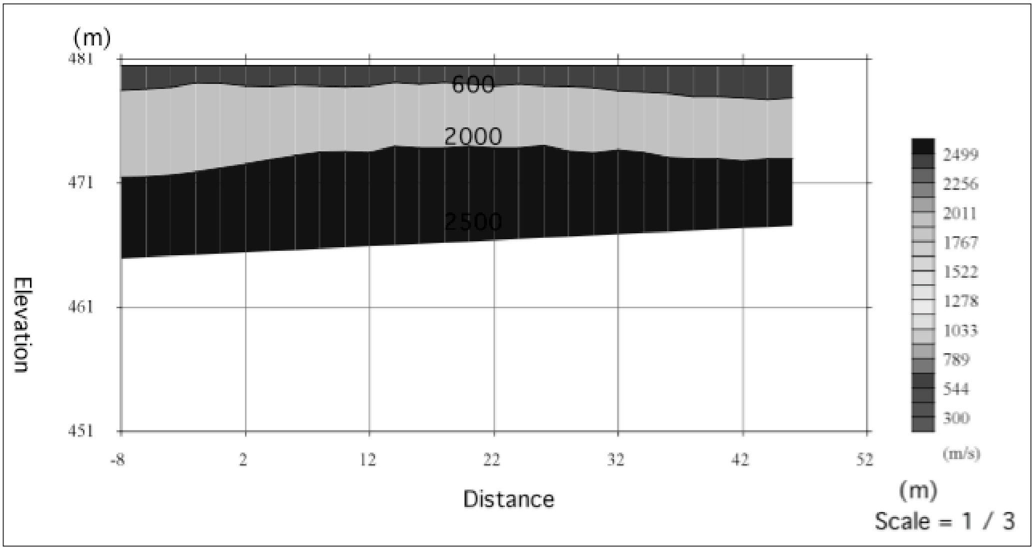

Figure 9. V_p profile of major cluster of layers of sand stone strata at bench-IV.

The mode of survey was 'refraction method' which could give the V_p profile of 50-60m depth and about 100m stretch. The source of vibration generation was by hammering by means of a 10 pound weight Sledge hammer with 5-10 numbers of stacks. The seismic raw data generated in the field was stored in a laptop computer connected to Geode while surveying. The raw data collected in the field was analysed by software called 'Seismic imager'. The processed data generated a V_p profile of rock strata upto a depth of 25m from the surface. The P-wave velocity profiles of the each bench

Table 3. In-situ and laboratory P-wave velocities of sandstone rock.

Site	Field P-wave velocity, m/s	Laboratory P-wave velocity, m/s
Bench-I	2000	2380
Bench-III	2200	2640
Bench-IV	2500	3125

were initially analysed for the composite layers and smooth layering was done afterwards for generalisation of rock mass characterisation. The V_p profiles of Bench-I, which is comparatively soft formation is shown Figure 7. The P-wave velocities of individual layers were varying from 240m/s to 2200m/s from top to bottom. The poor V_p at the top might be because of fractures generated due to the weathering of the rock mass. The V_p profiles of Bench -III is shown in Figure 8. The P-wave velocities were varying from 500m/s to 2314m/s and the poor V_p at the top might be because of fractures generated due to the production blasting in the past. The V_p profiles of bench-IV is shown in Figure 9. The P-wave velocities in smooth layered analysis were varying from 500m/s to 2500m/s from top to bottom and the here also the top layer gives poor V_p, which might be because of fractures due to previous blast rounds. The in-situ and laboratory P-wave velocities of sandstone rock for all the test sites are given in Table 3.

The P-wave velocities indicate that there is 19-25% increase in laboratory V_p values in comparison to field V_p values at all the test sites. This indicates that the field V_p profiles are realistic measurements by the seismic profiling surveys as reported by Barton (2007).

5. OPTIMISATION OF BLAST FRAGMENTATION BY IMPEDANCE MATCHING

5.1 Blasting practice at Kamptee mine, WCL

The prevailing blasting practice at KOCP mine was carried out with cartridged explosives of fixed velocity of detonation (VOD) for all the benches, irrespective of various rock properties. A typical image of blasting at the mine is shown in Figure 10. The blast results like fragmentation, throw and peak particle velocity of vibration were monitored using high resolution video camera and seismographs. Fragmentation size distribution analysis was carried out by image analysis software called FRAGALYST. The blast design parameters and the blast results are given in Table 4 and Table 5 respectively.

Figure 10. Image of blasting at the KOCP mine recorded in the high-resolution camera.

Table 4. Existing blast design parameter at KOCP mine, WCL.

Blast No.	1	2	3	4	5	6	7	8	9
Location	OB bench-I	OB bench-I	OB bench-I	OB bench-III	OB bench-III	OB bench-III	OB bench-IV	OB bench-IV	OB bench-IV
Drilling pattern	Staggered	Staggered	Staggered	Staggered	Staggered	Staggered	Staggered	Staggered	Rectangular
Initiation pattern	H-H*	H-H	H-H	H-H	H-H	H-H	H-H	H-H	H-H
No. of rows	4	4	4	4	4	4	4	4	2
Hole diameter, mm	150	150	150	150	150	150	150	150	150
Bench height, m	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	4.5
Hole depth, m	7	7	7	7	7	7	7	7	7
Burden, m	4	4	4	4	4	4	4	4	4
Spacing, m	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Stemming, m	3	3	3	3	3	3	3	3	3
Initiation by	DF**	DF	DF	DF	DF	DF	DF	DF	DF
Delay used, ms	25	25	25	25	25	25	25	25	25
Charge/hole, kg	50	50	50	50	50	50	50	50	50
VOD of explosive, m/s	3000	3000	3000	3000	3000	3000	3000	3000	3000
Density of explosive, kg/m^3	1100	1100	1100	1100	1100	1100	1100	1100	1100
Specific charge, kg/m^3	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
H-H* - Hole to hole DF** - Detonating Fuse									

5.2 Blast Optimisation by impedance matching

The best matching for optimum shock wave transmission to the rock occurs when the detonation impedance of explosive is equal to the impedance of the rock material. According to the theory of impedance matching, the explosive impedance should be as nearer to the rock impedance as possible to couple the explosive induced stress waves through the rock mass. The impedance matching expression is given below (Persson and Holmberg 1994).

$$\rho_e C_d = Zr \ \rho_r C_p \quad (1)$$

where,

ρ_e = explosive density, C_d = VOD of explosive, ρ_r = rock density, C_p= P-wave velocity and Z_r = impedance ratio

It is very clear from the rock mass properties of the sandstone that the compressional wave velocity is varying from 2000-2500m/s from Bench-I to Bench-IV, however there is no change in the explosive properties, especially VOD. Substituting the values of rock and explosive parameters given in Table 3 and Table 4, in the equation (1), the impedance ratio (Z_r)values were calculated as 0.65, 0.58 and 0.49 for Bench-I, Bench-III and Bench-IV, respectively. These Z_r values are considered as poor from impedance matching point of view (Persson and Holmberg 1994). This indicates that the explosive which was used for blast fragmentation is relatively suitable for Bench-I, but not for Bench-III and Bench-IV.

Table 5. Blast results with existing impedance values.

Blast No.	Location	Throw, m	Back break, m	Mean Fragment size, m	PPV at 55m distance, mm/s
1	Bench-I	10	1.0	0.46	15.8
2	Bench-I	8	2.0	0.38	17.2
3	Bench-I	9	1.0	0.52	16.6
4	Bench-III	8	3.0	0.41	17.2
5	Bench-III	10	3.0	0.36	15.9
6	Bench-III	9	2.0	0.42	16.3
7	Bench-IV	8	2.5	0.45	15.5
8	Bench-IV	10	1.0	0.53	17.3
9	Bench-IV	10	2.0	0.51	16.0

Table 6. Blast results with modified VOD values.

Blast No.	Location	Throw, m	Back break, m	Mean Fragment size, m	PPV at 55m distance, mm/s
1	Bench-I	6	0.50	0.39	11.3
2	Bench-I	7	1.00	0.31	12.4
3	Bench-I	9	1.00	0.41	14.3
4	Bench-III	9	0.75	0.30	12.5
5	Bench-III	6	1.25	0.32	12.2
6	Bench-III	9	1.00	0.31	14.5
7	Bench-IV	9	0.50	0.28	11.5
8	Bench-IV	7	0.75	0.31	9.6
9	Bench-IV	6	0.50	0.27	10.7

Based on the impedance values of various rock mass at all the three benches, best possible explosive impedance was calculated and shown in Table 6. As there was some technical limitations on the increase of density of explosive beyond 1100 kg/m^3, only VOD values were adjusted as 3400m/s, 3700m/s and 4100m/s for Bench-I, Bench-III and Bench-IV, respectively. This combination of explosives resulted in the Z_r value of above 0.7 for all the benches. The modified VOD values were applied in all the three test sites and the blast results with modified explosive parameters i.e. impedance matching.

The improvements in blast performance due to impedance matching are given in Table 7. The results clearly indicate that the selection of proper explosives with impedance matching to the rock impedance result in improving the blast fragmentation, reducing the throw and reducing of blast vibrations. The overall throw in the modified blast rounds was reduced by about 25%. The back break was reduced by about 50% at Bench-I and upto 75% at both Bench-III and Bench-IV. The mean fragment size of blast fragmentation was reduced by 15-21% at Bench-I, 11-26% at Bench-III and it was 37-47 % reduction at Bench-IV. Earlier works on the relation between VOD and damage by Singh and Xavier (2005) also indicate that the high VOD explosives produce less damage due to the reason that generally the high VOD explosives yield higher shock energy and less gas energy.

Table 7. Improvements in blast performance due to impedance matching.

Blast No.	Location	Percentage reduction in throw, m	Percentage reduction in back break, m	Percentage reduction in Mean Fragment size, m	Percentage reduction in PPV at 55m distance, mm/s
1	Bench-I	40	50	15.22	28.48
2	Bench-I	12.5	50	18.42	27.91
3	Bench-I	0	0	21.15	13.86
4	Bench-III	-12.5	75	26.83	27.33
5	Bench-III	40	58	11.11	23.27
6	Bench-III	0	50	26.19	11.04
7	Bench-IV	-12.5	80	37.78	25.81
8	Bench-IV	30	25	41.51	44.51
9	Bench-IV	40	75	47.06	33.13

6. CONCLUSIONS

The improvements in blast performance due to impedance matching were substantial in terms of blast fragmentation and vibration as well as damage control. The overall throw in the modified blast rounds was reduced by about 25%. The back break was reduced by about 50% at Bench-I and upto 75% at both Bench-III and Bench-IV. The mean fragment size of blast fragmentation was reduced by 15-21% and Bench-I, 11-26% at Bench-III and it was 37-47 % at Bench-IV. The vibration intensity was also reduced by 14-45% with increase of impedance matching of explosives. The blast results shown in this study, clearly indicate that the selection of proper explosives with impedance matching to the rock impedance result in improving the blast fragmentation, reducing the throw and reducing blast vibrations. Therefore, impedance matching should be given adequate importance while selection of explosive for improving blasting productivity and safety.

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Improved blast results from the implementation of a business intelligence system

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ABSTRACT: A business intelligence system has been developed within an explosive company to monitor the blasting process and track the layout of the blast, and other parameters such as drilling accuracy, re-drilling attempts, charging of the holes and stemming by linking blast design software into decision support systems using open source Enterprise Information Integration and Business Intelligence software. Handheld computers collect real time data at the points of interaction, i.e. the blaster and the explosive mobile manufacturing units, and transmit this via mine-wide wireless networks to a mine control room where it is correlated with the designs in the blast planning software. Increased productivity is achieved by providing the explosive truck with the GPS co-ordinates of each hole and the relevant explosive mass. The system is described and the benefits, which include increased productivity, improved fragmentation, prevention of fly rock, quick identification of uncharged holes and predictability of supply times, due to better consistency of drilling and charging are explained using case studies where the knowledge of the actual on-bench information has contributed to significant benefits to both the explosive company and the mines.

1. INTRODUCTION

Blasting is a very practical operation that is often seen as a simple process of filling boreholes with explosives and detonating them in sequence. A higher level overview suggests that blasting is the main productive process in a mining operation and that the quality of the output significantly affects the productivity of the mine. In turn, that quality is derived from attention to detail in a sequence of highly technical processes that are applied in diverse and difficult environments often with minimal supervision. A successful blast relies on a good design that has been optimised based on local and general experience and the accurate realisation of that design on the bench.

A business intelligence system is a set of computer programs that gathers data on the business process, maintains a record that can be used to produce historical reports, dashboards showing the current status of whether targets are being met and also allows data mining for knowledge development and process prediction (Olszak and Ziemba 2007). Such a system has been developed within an explosive company to monitor the blasting process and track the layout of the blast, and other parameters such as drilling accuracy, re-drilling attempts, charging of the holes and stemming. The blast is designed using laser surveying or 3D stereophotogrammetry so that appropriate burdens can be evaluated. The timing is allocated and investigated using simulation software. The mass per hole is determined and transmitted by wireless network to the explosive trucks. Handheld computers collect real time data at the points of interaction, i.e. the blaster and the explosive trucks, and transmit this via mine-wide wireless networks to a mine control room where it is correlated with the designs in the blast planning software. Increased productivity is achieved by providing the explosive truck with the GPS co-ordinates of each hole and the relevant explosive mass. Discrepancies between actual and planned parameters can be identified immediately. The information from the various regional supervisory centres is relayed to a monitoring centre at the head office to provide dashboards that represent the current status of the service delivery.

This paper briefly describes the system and some studies where the knowledge of the actual on-bench information has contributed to significant benefits to both the explosive company and the mines. The benefits shown include increased productivity, prevention of fly rock incidents, quick identification of uncharged holes and improved fragmentation due to better consistency of drilling and charging.

2. BUSINESS INTELLIGENCE TO BLASTING INTELLIGENCE

"Business intelligence (BI) refers to technologies, applications and practices for the collection, integration, analysis, and presentation of business information and sometimes to the information itself. The purpose of business intelligence - a term that dates at least to 1958 - is to support better business decision making. Thus, BI is also described as a decision support system (DSS)," Wikipedia.

The business intelligence game has fundamentally changed since 2005, with the availability of good open source business intelligence packages, systems or solutions. Open source Business Intelligence allows small to medium-sized businesses to take advantage of the integration, dashboard and reporting functionality usually only available to large organisations due to high license fees. The core problems of business intelligence are the extraction of data, the accumulation of data in a form that allows easy analysis and the presentation of reports of key performance indicators relevant to the decision maker that needs to act on the information.

The aim of the key performance indicators (KPI) is to boil the working of a business down to a few numbers that encapsulate the bulk of a business. The decision makers in any industry typically know what these numbers are, but it is always a challenge to measure them in a relevant fashion, and ensure that they are measured correctly. Blasting audits have shown their worth for controlling and optimising productions (Giltner and Koski 2010) although our experience suggests that the data tends to be a static picture of the mining operation and remains in the files produced by the auditors. By selection of the appropriate KPIs, the business intelligence approach allows for continual logging, monitoring and reporting of the data that would arise from a static blast audit and will eventually develop the mine into a knowledge based operation (Olszak and Ziemba 2007). Such KPIs need to be agreed between the mine, the explosive supplier and the mining contractor. The parameters can be based on service levels such as amount of product delivered or technical data such as average powder factor. Preferably, these KPIs are presented in the form of dashboards to have all the relevant information a decision maker needs available on a single page, with the ability to drill-down into the information as required. A dashboard would typically comprise several inter-connected graphs or reports that allow a problem to be understood with a few mouse-clicks.

Where disparate systems need to use each other's information as soon as it becomes available, this is called Enterprise Information Integration (EII). Although not strictly part of BI, good EII open source software is widely available. The biggest challenge in producing the relevant reports needed to make decisions is obtaining the data from the various sources. In most businesses, the data typically comes from Excel spreadsheets, but may come from databases or other applications. Most

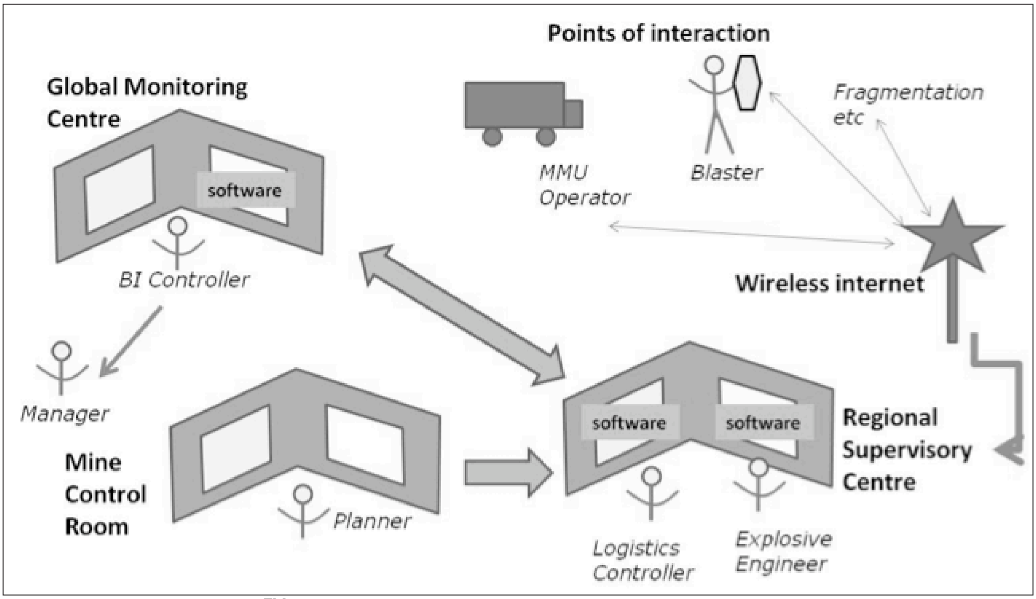

Figure 1. Schematic of Blast-i^{TM} blasting intelligence system.

mining operations, especially the smaller ones, are still paper based and therefore the implementation requires adding information gathering systems along with the processing systems. Data for analysis is typically stored in a separate database so that using the analysis tools on the data does not interfere with the functioning of the source systems. In order to do a detailed analysis, the data needs to be transformed into a format that allows easy and flexible analysis. The tools that allow the data to be fetched from disparate sources, such as excel spreadsheets, other systems' reports, other databases or web services, are called ETL tools. These tools can also be used for data integration where the information can be transferred in batches. For the explosive supplier this implies integration of financial and strategic reporting tools such as a SAP system with the technical information to provide the inputs for a complete mine to mill reporting system.

Data for analysis is typically stored in a separate database from the system in which it is generated. The data is stored in a way that allows for easy and flexible analysis. Often this is done in an 'analysis cube' that can be effectively queried using a specialized language. More data than is strictly necessary is stored, allowing a type of 'snapshot' or historical analysis of the source data. This data would then be the underlying data for statistical trends analyses. In the blasting context this analysis cube contains information such as the accumulated explosive charge per truck with the GPS position of the charge that can then be analysed to determine truck efficiencies and produce reports on how much explosive is provided to each mine and where it was placed. Once integrated into the entire mining cycle, dashboards can be used to improve operational excellence of the blasting as well as the explosive supply chain, accounting for input and output process relations in terms of safety, environment, productivity and behaviour (Lurf *et al*. 2007).

3. BLAST-i^{TM} BLASTING INTELLIGENCE SYSTEM

The main components of the Blast-i^{TM} system are shown in Figure 1 and described in detail in the subsequent sections. The roles of the people interacting with the system are named for their typical interaction with the system and may differ between different implementations and mine operations.

3.1 Points of interaction

The entry points to the blasting intelligence system are the people who perform the daily activities of charging the blast. These can be divided into two sub categories, namely the blasters and the Mobile Manufacturer Unit (MMU) operators.

The blaster is in charge of ensuring that the pattern is filled to plan. This involves checking the lengths of the blast holes, ensuring that the correct charge is placed into each hole, that all the holes are filled and that the stemming lengths are correct and the stemming is placed properly. The blaster also places the initiation system and determines the timing. In practice these tasks may be undertaken by more than one person on a bench. The system has been designed so that the blaster loads and checks the holes according to the digital plan received on a GPS enabled PDA called the Personal Blast Assistant (PBA). Details of the charging can be recorded on the PBA, such as missed holes, stemming lengths, over-filled or under-filled holes, initiation systems, timing and any additional information that could affect the blast. The system recognises that the explosive engineer needs to make decisions and that these need to be recorded to schedule the relevant actions. The form on the PBA allows the blaster to record their observation and enter an action. For example, if the hole is too short, the blaster can record the length and request a re-drill. The blaster can return at any stage to identify the holes that require further action and to ascertain whether the actions have been completed satisfactorily.

The operator of the MMU controls the amount and type of explosive placed into each hole via the PLC on board the truck. The system can supply the operator with a plan of the blast showing the mass of explosive. If the MMU charges directly into the hole the MMU is equipped with an onboard GPS. Where the MMU is at some distance from the hole, the hose operator carries a backpack with a powerful GPS to locate the position within 1 metre accuracy (Figure 2) and snap to the position provided by the survey department or the drill monitoring system. The system records the GPS position and mass of all explosives pumped into each hole and the operator can visualise the state of the bench on an onboard screen. Any new MMU entering the bench receives the updated plan and can start charging immediately without having to infer where charging has been done previously. It is important not to remove the operator’s ability to control the MMU and the system only records and provides advice on the mass for each hole. In many mines the holes are filled to the estimated stemming length as a short cut for the proper design of the blast. In this case the system can record the mass pumped. If the mass is calculated beforehand then the exact mass can be immediately charged into the hole. This improves efficiencies and controls the mass of explosive in any one section of the blast, preventing overfilling and the associated hazards such as flyrock.

3.2 Remote wireless internet access

The system is best applied where there is remote wireless access on the mine. Mines these days often have their own WIFI mesh networks or are situated in regions that have cell phone coverage with the ability to transfer data. The development of the system has tracked the improvements in mine-wide wireless infrastructure and linking in with the continual improvements in these emerging technologies has been the most challenging part of the system development. The system has had to be designed to be robust against loss of data and loss of wireless signal. This has been done by storing the data at the points of interaction and transmitting them only when the signal is assured. In the worst case scenario this needs to be achieved by returning to a base station with a known signal quality at regular intervals. This can be done in the ordinary schedule of the mining operation as for example returning to their vehicles or when the MMU returns to refill.

3.3 Regional Supervisory Centres

The data from the blasts is analysed at the Regional Supervisory Centres, which are local control rooms managed by an explosive engineer who supervises a number of blasters. On large mines this will be a specially designed control room on site. For smaller mines and quarries the operations can be grouped at a single convenient hub near to the operations. In some cases, the data is analysed at head office and control is achieved by telephone interaction.

The explosive engineer interacts with the patented Active Loading System which is a database-driven operating system facilitates a two-way real-time communication platform between the teams at the points of interaction (i.e. the blasters and the Mobile Manufacturing Units) and the regional supervisory centre. The benefit of this system is that the explosives engineer receives up-to-date information on what's happening on the bench, allowing immediate, corrective intervention and communication with the blaster before initiating the blast. This two-way interactive communication between the bench and office

Figure 2. MMU and hose operator with GPS backpack.

empowers the blasting team to deliver the most cost efficient blast that is as close to the plan as possible.

At this stage, the data can be integrated with other information for example, the final fragmentation obtained from online systems for fragmentation analysis (Palangio *et al*. 2005, Chow *et al*. 2010) and linked into simulation tools (Everett 2010) that permit the simulation of the effect of the blast output on the rest of the mine to mill process (Workman and Eloranto 2003).

The logistics controller interacts with the same data in a different role. They can monitor information such as the truck locations, the amount of product remaining in each truck, the charging efficiencies and can optimise the delivery of explosives to the mine to maximise productivity. They can keep track of breakdowns, turnaround times and other data that assists with planning of the supply operation.

3.4 Shared interface with mine control rooms

The Regional supervisory centre shares an interface with the mine to obtain electronic blast plans and to deliver reports. The electronic blast plans contain the position of each of the blast holes. The position can be as reported by advanced drill logging systems, or by direct surveying, or can be as planned in typical mine planning or surveying software. Good relationships are required between the IT departments of the mine and the supplier in order to implement secure systems to transfer the data.

3.5 Monitoring room at Head Office

Often in order to understand a particular problem, it is necessary to look at the information in a variety of ways and summarize in different ways. Once the data has been stored in an analysis cube in the right way, it can be presented as a pivot table and analyzed according to many different criteria, shown both as a graph, as a report or with the relevant details contained in a particular pivot cell. It was soon realised that views of the data from the Regional Supervisory Centres can be collated into knowledge for the whole company by creating dashboards that provide pictures of the history of the interactions and, even more importantly, provide some predictive capacity.

This forms the BI 'consumption' stage (Olszak and Ziemba 2007), which derives mainly from the interaction with the end users. Olszak and Ziemba (2007) also noted that this

Figure 3 Monitoring room.

stage 'shows its major role in popularising and promoting practices that are related to data analyses and BI systems'. The compilation of this information into knowledge is where the company performance can be significantly improved and interactions with customers facilitated. The reporting is, however, highly dependent on the requirements of specific users and the system must be flexible enough to allow for a variety of report formats.

In order to do this in the blasting intelligence system, certain data is compiled and transmitted securely back to a main database at the head office and can be viewed on multiple screens (Figure 3) by the global blasting intelligence controller. By correct selection of the business analysis toolkit, in this case using Pentaho, the appropriate reports can be constructed relatively quickly and easily via the World Wide Web to mangers within the explosive company or at customer sites. Modern software developments have provided off-the-shelf applications that have enabled this reporting to be presented as dashboards and distributed by email, sms or as interactive websites.

3.6 Knowledge based software

Software for the Blasting Intelligence System has been developed from the points of view of the two main users – the explosive engineer and the logistics controller.

Firstly, the explosive engineers need to be able to obtain a blast plan, determine a suitable design, apply timing and simulate the blast and specify the mass of explosive in each hole. Whilst the blasts are being charged the information must be available to enable the explosive engineer to determine if the charging is happening to plan and to be able to let mine management know when the bench will be ready to blast. The system is designed to be able to apply the outputs of any blasting software, though a specific set of software has been developed to have separate, but consistent, interfaces to enable users to specialise in the application of the software that is most relevant to their job requirements. The interaction of the three software components and their unified internal data base with the blast process is shown schematically in Figure 4.

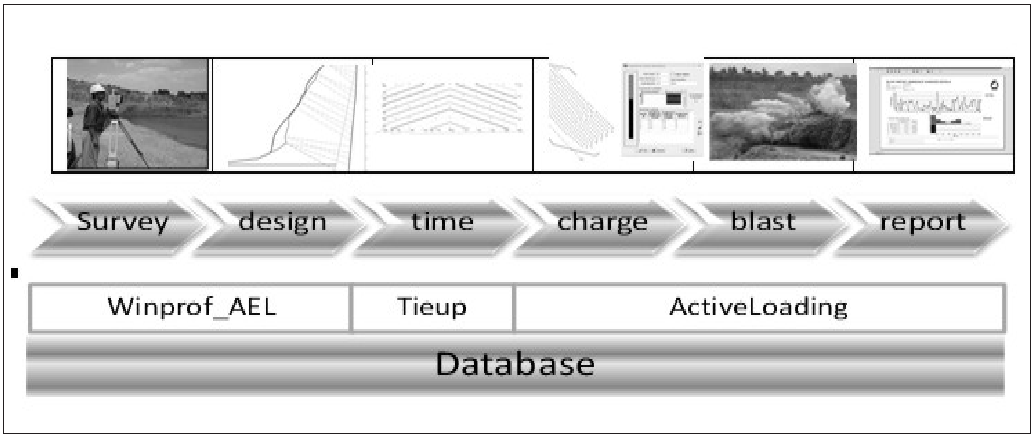

Figure 4. Software process flow.

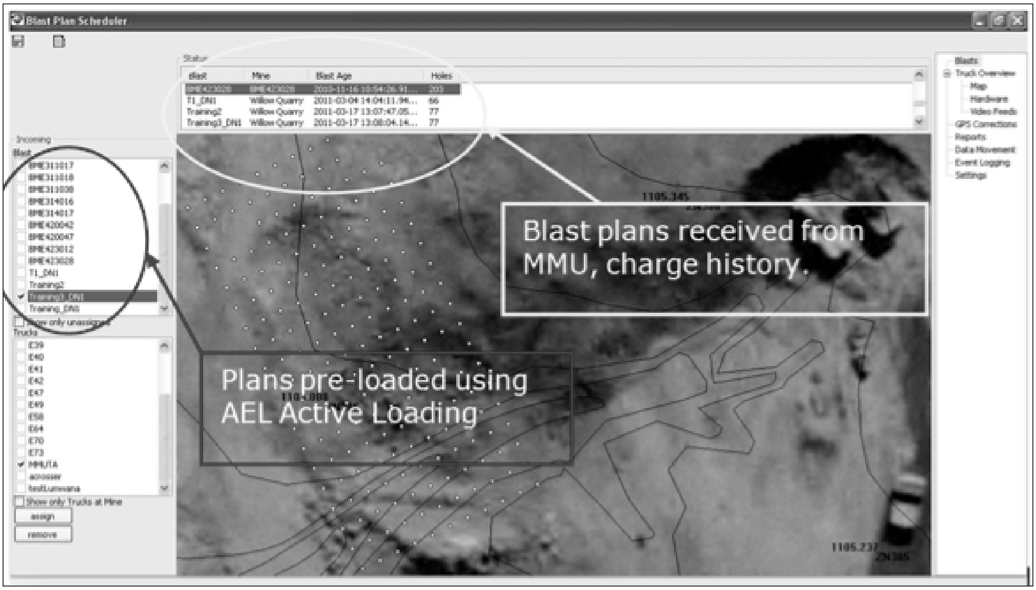

Figure 5. Blast plan scheduler.

The Winprof-AEL software imports the layout of blasts from three dimensional bench profiles obtained using laser profiling or stereophotography. The code enables the explosive engineer to visualise the hole positions to ensure consistent burdens and hence prevent excess toes or unwanted flyrock. The planned design can be compared with the actual drilled pattern. The explosive engineer then applies the AEL Tie-Up software to open the same blast from the common database and times the blasts. Alternatively, the software can import layouts exported from the mine databases and supplied via the shared interface with the mine control room. The timing can be directly exported to the electronic detonation systems. The Active Loading System is the final component of the software trio and is a total blast management system that produces the electronic charging plans for each blast, collects explosive charging data automatically from suitably equipped Mobile Manufacturing Units in the field and manages the data being entered into electronic clipboards on

Personal Blasting Assistant devices on the bench.

Secondly, the logistics controller at the mine must be able to know where each explosive truck is situated at any time, how much it has pumped and be able to evaluate the efficiencies of each truck. The Blast Plan Scheduler (Figure 5) allows the logistics controller to see which plans have been submitted by the explosive engineer for charging, to allocate these to the relevant MMU and then to evaluate which have been acted upon. The logistics controller can view when the trucks are actively charging on the bench and has a symbolic display of whether the GPS system are connected, when the PLCs are turned on, and when the MMU is charging each hole. If the status is not to plan, the logistics controller can then send messages to request the relevant operators to fix the problem. The logistic controller can log any breakdowns on the MMUs and keep a history of the issues of each of the trucks.

4. CASE STUDIES

A number of example case studies are presented to illustrate the benefits of the Blasting Intelligence software.

4.1 Blast pattern consistency

An issue that causes considerable conflict between an explosive company and the mines it supplies occurs if a blast has been fired and the outcome is not as expected. Occasionally, a blast will have a section of unbroken rock and then an investigation is required to determine the root cause. The mine will tend to say that the explosive was of poor quality and did not detonate, however there may have been no holes drilled at that point, if holes were drilled, they may have collapsed and have had insufficient explosive pumped into them, or they may have been drilled, but forgotten during the charging process. In this case, the quarry had charged a small blast based on a manual layout of the drill hole pattern. The plan of the pattern as produced by the GPS carried by the hose handler shown in Figure 6 indicated considerable variation between the hole positions and the desired burden and spacing. This indicated that there would be significant deviation from the planned rock fragmentation. In addition, a zone of mud and water filling a depression had completely hidden one hole. This was not charged at the time of the plot and once the explosive engineer was alerted to the lack of charge in the hole. This was particularly important because the holes in the surrounding area had been undercharged, probably as result of mud in the holes. Had this blast been fired as it was charged in Figure 6, there is no doubt that a pillar of solid rock would have been left in the centre of the muckpile. This would have impeded the muckpile heave and would have been very hard to dig out and may have required secondary blasting in difficult and unsafe conditions.

The poor layout of holes has almost doubled the burden and the effect of this can be illustrated using the Kuz-Ram Fragmentation model (Cunningham 2005). Figure 7 shows some fragmentation data obtained from the mine and analysed using the SPLIT optical analysis programme. The rock factor A is fitted to this data for the relevant design burden of 3.0m and the design spacing of 2.5m on 15m holes 102mm in diameter. This fit is also shown in Figure 7. The fitted curve shows more fines than observed in the optical analysis and this is due to the scaling of the photographs taken, as they were intended for an oversize minimisation project. The effect of the poor hole distribution is shown by the curve denoted 'Missing holes' in Figure 7. This indicates that the characteristic size increases from the initial 405mm to 622mm. The maximum size increases to nearly 3m as the uniformity drops significantly from 1.33 to 0.89. The lower uniformity co-efficient also indicates an increased fines component. Thus, the poor layout of the blast will contribute to considerably more secondary breaking, more energy used in the crusher with lower throughput and increased wastage of material as fines.

Conversely, Figure 7, can be interpreted as demonstrating how much improvement can be obtained if the blasting patterns are improved. The benefit of the blasting intelligence system is that once the blasters become aware of the system and how it can monitor the progress the quality of the blasting improves and so the system can also be used for quality assurance.

4.2 Flyrock prevention

The second study involves blasting on the top benches of a local quarry. In these benches the degree of weathering varies considerably and so the rock mass has formed into a series of solid cones interspersed with a weak, boulder strewn conglomerate as shown in Figure 8.

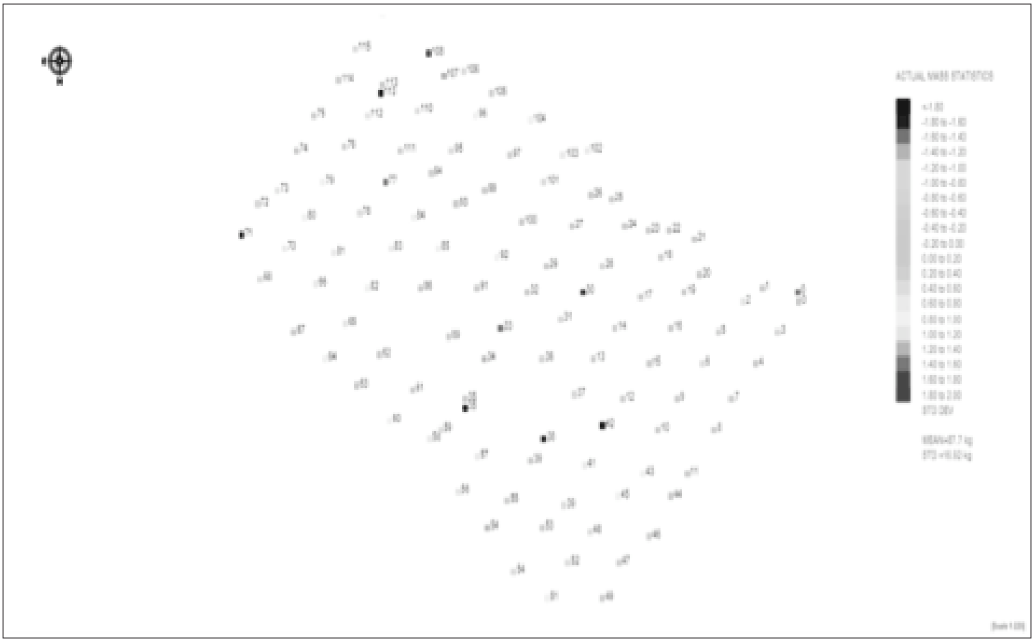

Figure 6. Explosive charge plan showing irregular pattern and missing holes.

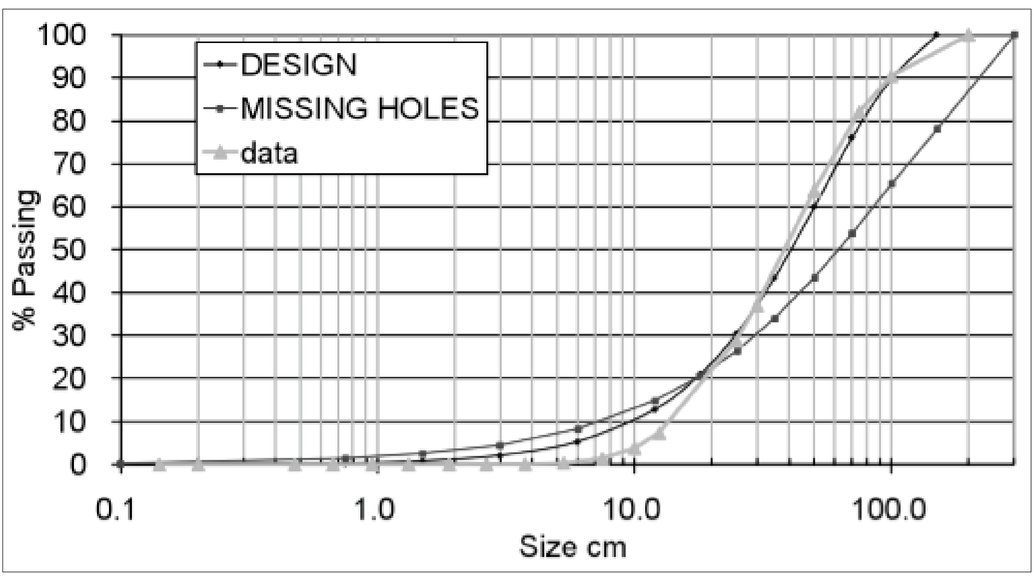

Figure 6. Explosive charge plan showing irregular pattern and missing holes.

Figure 8a. Photograph of top benches being charged.

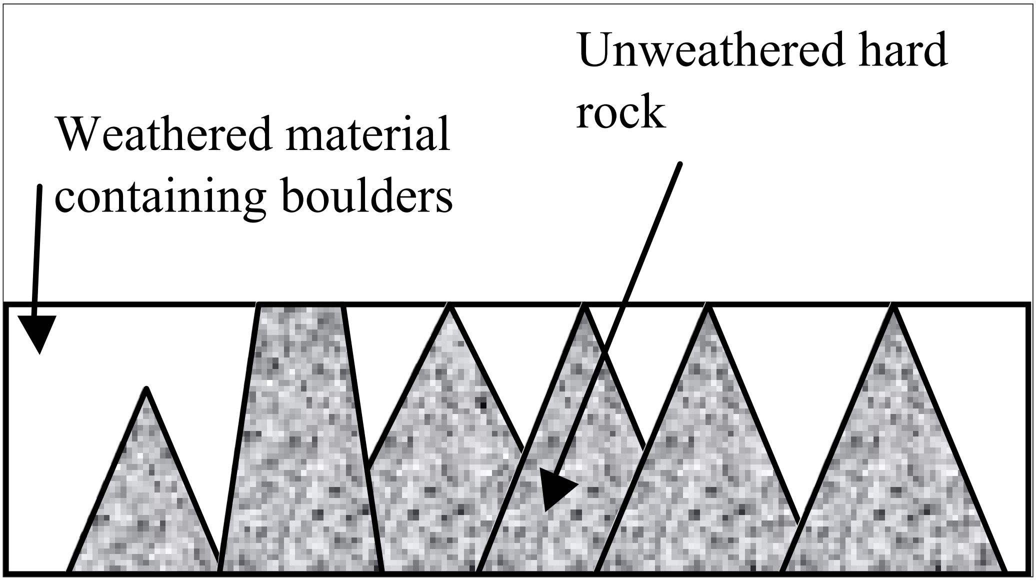

Figure 8b. Schematic of rock cones interspersed with boulder material.

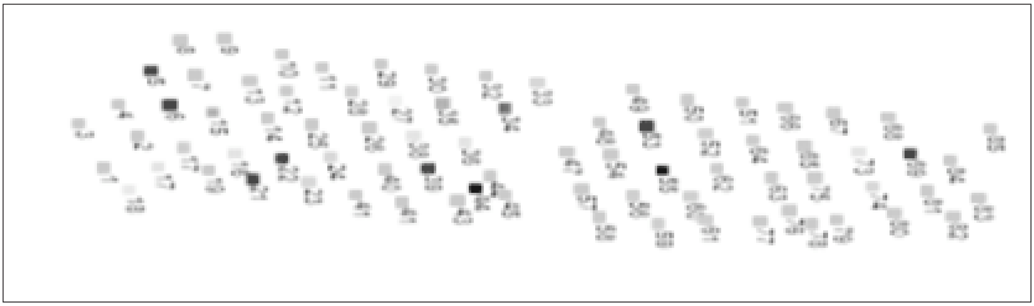

Figure 9. 'Spot plot' of explosive charge plan with arrows indicating missing lines of holes.

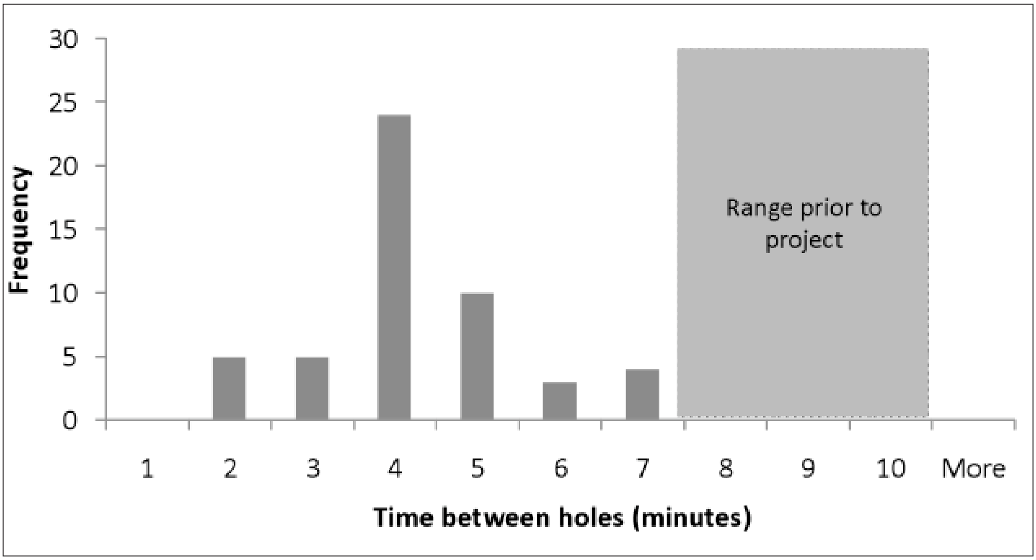

Figure10. Improved charging cycle times due to automated blast loading (after Joseph 2009)

Figure 9 shows the 'spot plot' of the charge masses produced by the ActiveLoading programme and indicates that a line of holes has not been charged. On closer inspection, it was found that the holes had not been drilled. Without the system, a poor blast outcome would most likely have been blamed on poor explosive product performance. However, the data provides a record of the actual reason. The missing holes occurred right where the harder rock intersected the bench surface. This is the worst possible place to miss out holes as the lack of explosive in the hard rock would have left a pillar of hard rock standing in the middle of the muck pile.

Of further concern is the significant overcharging observed in the holes in between the harder rock regions and indicated by colouring the individual holes based on ratio of the actual to planned charge mass. This suggests that explosive was being filled into cavities or joints in the softer weathered material and raises the potential for flyrock considerably, particularly since the rock was weak and contained larger boulders. The benefit of having the blasting intelligence system installed on the MMU is that when this plot is viewed by the explosive engineer at the quarry, remedial actions can be taken prior to blasting and hence avoid costly mistakes and environmental and safety hazards. The graphical representation of over and under-filled holes adds significantly to the understanding of the blasters on the bench and the reporting will drive behaviour to improve the quality of the bench preparation.

4.3 Improved production efficiency

A case study at Jwaneng Diamond Mine, approximately 160km west of the capital city

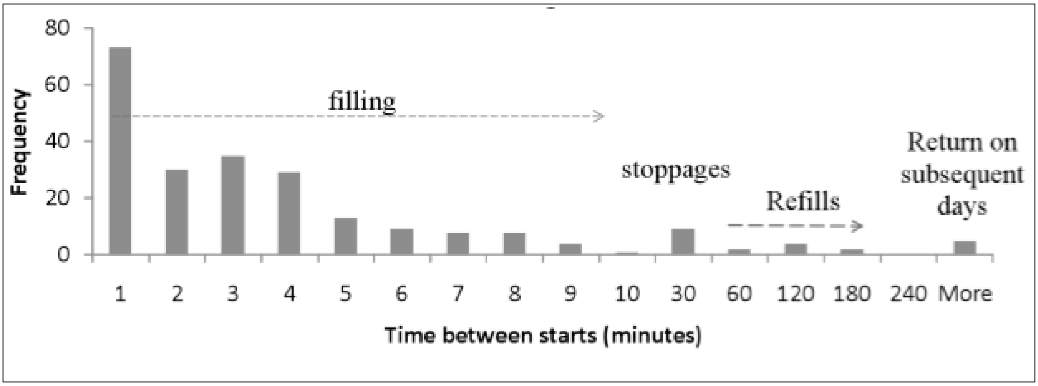

Figure 11. Frequency distribution of time between holes for a MMU over 77 days.

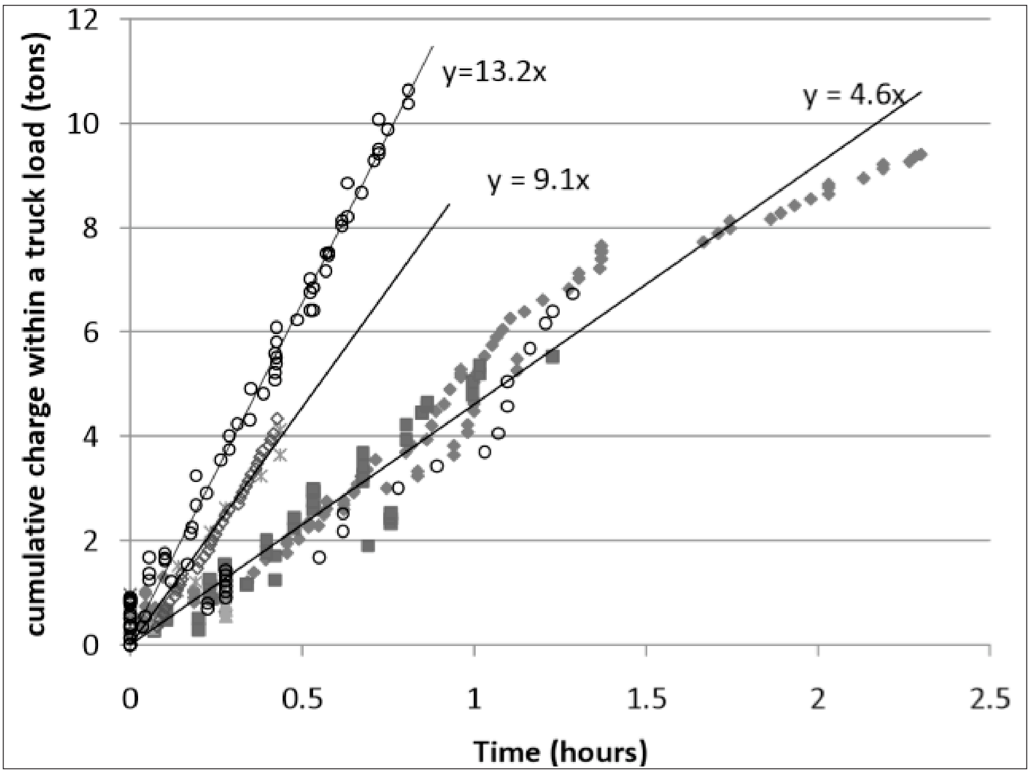

Figure 12. Plot of rate of explosive delivery for various benches logged.

of Gaborone, Botswana was reported by Joseph (2009). The base case was started in 2006 as there was a problem of drilling control that led to borehole depths that were either too deep or too short. A drill depth monitoring exercise was implemented to ensure that all holes were drilled to within 30cm of the target depth and positions just before being loaded with explosives. While this exercise, which was conducted by both Jwaneng Mine and AEL, improved the drilling results from about 70% to more than 95% accuracy, the charging cycle times per hole increased to very high levels of about 7 to 10 minutes per blasthole. At the time, the same amount of explosive was required to be charged into each hole, causing an inconsistent energy distribution into the rock mass. After implementation of the automated blast loading system, an improvement to less than 50% of cycle time per blasthole was observed compared to the original practices. The graph of the total cycle time per hole for a single blast is shown in Figure 10 in comparison to the range of original cycle times.

4.4 Production performance prediction

To date, nearly 3 million tons of explosives loading has been monitored since 2005 through the system in its various phases. This case study takes some data from a single MMU on a large open pit mine and analyses the time taken between holes in order to develop some models for predicting product performance. On a mine that is placing 800 to 1400 tons of explosive into a blast, involving 50 to 90 truck loads each blast will takes a number of weeks to prepare. The ability to know more exactly when each block is ready to fire becomes vital for short term planning on the mine. This predictability requires the development of models of the length of time that it takes each MMU to actually change the explosive that it carries to the bench. The histogram of times taken between start of charging one hole and the start of charging the next hole has been plotted in Figure 11for a set of 77 days of monitoring of a single truck at a large open pit mine. It can be seen that there are four different time periods shown on the graph, which has a nonlinear x axis. The time between holes is roughly 1 to 10 minutes. Then, there is a set of data around 30 minutes that indicate short on-bench stoppages for various reasons such as inspections, waiting for drilling and minor repairs. The third data region involves travelling to and from the bench to refill the truck, which could take anything from 1 to 3 hours per round trip on this mine, depending on the distance to the silos. The final set of data involves overnight gaps, services, and gaps when other trucks charged the bench and this truck only returned to the original bench some days later.

The time between holes, with delays removed, can be analysed on a cumulative basis to determine the maximum charging rates that are determined for the specific mining conditions and on-bench work procedures. The cumulative time on the bench and associated mass of explosive pumped is shown in Figure 12. The plots indicate three different actual charging rates. The slower rates are due to charging smaller diameter holes. This requires the pump to be set on a slow rate and because the holes require smaller charges, there must be more accuracy with the stemming measurements and hence this takes longer. Pumping large holes at a fast rate is the most efficient means of delivering the product.

The prediction of the time that the bench can be ready to blast can now be analysed in more detail. At this stage, a simple equation that takes into account the charging rate R in tons per hour, the average number of stoppages T_s and the round trip duration T_r is applied. More work is being done to include a statistical analysis that applies the variation in the data to provide best and worst case estimates.

5. CONCLUSIONS

A business intelligence system has been developed within an explosive company to monitor the blasting process and track the layout of the blast, and other parameters such as drilling accuracy, re-drilling attempts, charging of the holes and stemming by linking blast design software into decision support systems using open source Enterprise Information Integration and Business Intelligence software. The system is described and the benefits are explained using case studies where the knowledge of the actual on-bench information has contributed to significant benefits to both the explosive company and the mines

The mine benefits by knowing the exact distribution of explosive charge and saves on drilling and re-drilling costs. Production delays due to excavating in hard digging conditions as a result of having uncharged regions are eliminated by identify missing holes. The application of less safe working practices to blast out pillars of rock within the muck pile can be eliminated. Flyrock issues that are a safety hazard and deteriorate relationships with neighbours can be eliminated. The system builds up knowledge of problem areas and these can be blasted more effectively when similar conditions occur on lower benches. Systematic reporting and predictive capabilities improve the production scheduling and hence the overall mine productivity. The explosive company benefits by the elimination of claims and the improvement of drill and blast planning and scheduling. This improves the business productivity and the relationships with the customers.

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Mathematical model and software for the design of blasting

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ABSTRACT: Creation of the software for basic mining works is very important task. That is motivated by considerable IT-technology progress and application of automatic projecting systems and automatic controlling systems in mining. This paper introduces an applied computer program intended for the calculation of blasting parameters for open-cast mines. The 'Bench blasting' program is based on a mathematic model of rock blasting by charges in the holes and on the method of calculating the blasting parameters. Both model and method have been developed at the Moscow state mining university by the blasting craft department. The model of blasting-rock is founded on particular value Weibull fragmentation distribution, on deformation zones in the bench, and on experimentally confirmed dependence of average muckpile pieces on charge parameters and physical rock properties. The calculation leads in automatic mode with the usage of the data set at the beginning of the program work.

1. THE MATHEMATICAL MODEL OF BLASTING

The urgency of working out of new software for modeling the basic mining processes is predetermined by universal introduction of the automatic projecting systems and the automatic control systems in mining connected with considerable IT technologies progress.

It is necessary to choose or develop a mathematic model of blasting in order to begin working out the software. This model will be the basis for the developed software. The quality of such a model is greatly affected on the quality of the accuracy of rock fragmentation forecasting and the reliability of the definition of rational blasting parameters.

1.1 The analysis of existing mathematical models

One of the first models was developed by Dr. V.K. Rubtcov in 1968. He used sedate dependence of the volume of muckpile pieces on linear parameters:

$$v^{-} = (d / d_{\max})^{c} \tag{1}$$

Where d_{max} – is the maximum size of muckpile pieces, d_{max}=d97, c denotes– an exponent, c=0,33

Thus the average size of muckpile pieces equals:

$$d_c = \frac{c}{c+1} d_{\max} = 0{,}25 d_{max} = 2 d_{50} \text{ .(2)}$$

The dependence of fragmentation on parameters of physical properties of rock looks like:

$$v_н^+ = v_e^+(1-kq) \quad (3)$$

Where q denotes the - specific charge, kg/m^3, $v_н$, and v_e – the boulders, in the muck pile and in the virgin rock mass.

Cunningham (1987) has suggested using an exponent as function of distribution of rock fragmentation volumes from linear sizes:

$$v^+ = \exp(-d/d_c)^n \quad (4)$$

Cunningham has used a formula by Kuznecov V.M. for definition of the average diameter of muckpile pieces:

$$d_c = A\left(\frac{V}{Q}\right)^{0,8} Q^{0,17}\left(\frac{1,15}{e}\right)^{0,63} \quad (5)$$

Where A is - a constant defining properties of rock; V is – the rock volume blasted by one charge, м^3; Q is - the mass of an individual charge, kg; and e denotes - bulk strength of explosive in equivalent ANFO (the given factor is entered into the initial formula by Cunningham C.V.B)

Cunningham C.V.B. has suggested to use the following expression for definition of the second parameter of distribution:

$$n = (2,2-0,014\frac{w}{d_з})(1-\frac{\xi}{w})(\frac{1+m}{2})^{0,5}\frac{l_{oз}}{h} \quad (6)$$

Where w, $d_з$, $lo_з$ - accordingly, Burden, diameter and length of the basic charge (above a bottom bench), m - relative distance between charges, m = a/w, h - bench height, and ξ - An average deviation of the charge location from the designed one (‘accuracy of drilling’).

The model of Cunningham C.V.B. was entitled ‘Kuz-Ram’ (Kuznecov-Rammler).This model is widely applied for elaboration of corresponding computer programs, for example by Precision Blasting Service (Konya 1995). One should also mention the model ‘SAROBLAST’ (Kou & Rustan 1992).

Weibull’s distribution is used for the analytical description of rock fragmentation. According to it, yield of fractions will equal:

$$v^- = 1-\exp(kd/d^*)^n \quad (7)$$

The concrete definition of Weibull's distribution in model SAROBLAST is accepted in the form of the generalized equation of rock fragmentation, offered by Holmberg R.(1981):

$$v^- = 1-\exp(-0,76d/d_{50})^{1,35} \quad (8)$$

In the model ‘SAROBLAST’ the equation is accepted for calculation d_{50}:

$$d_{50} = 0,14[w^2(1,25w/a)^{0,5}]^{0,29}(c/qe)^{1,35} \quad (9)$$

Where q is - the specific charge, kg/m^3 and c is - the parametrical complex defined by parity:

$$c = \sigma_c / 2E\eta\theta \quad \text{Kg/m3}, \quad (10)$$

Where σ_c and E denotes the uniaxial compressive – strength of rock and the module of elasticity, θ is - heat of explosion, kJ/kg, is – the factor of blast energy transmission to rock, η = 0,2.

General faults of existing models of rock blasting and the models mentioned above, are the considerable physical uncertainty and the incompleteness that influence negatively on the accuracy of results. Models ‘Kuz-Ram’ and ‘SAROBLAST’ don't consider structural characteristics of rock massif in an explicit form.

The generalised character of the given models, excludes the possibility to count for the quality of the deformation zones influencing the rock fragmentation parameters. Therefore the model above can be compared to the simplified nondeterministic models that don’t open up the physical sense of processes of rock fragmentation by blast.

1.2 Offered mathematical model

The analysis of results of the long-term experimental works executed on domestic open-cast mines and building of hydroelectric power plants, allows to simplify the equation used in model ‘SAROBLAST’ for the analytical description of rock blasting fragmentation, taking a total yield of fractions ‘from above’:

$$v^{+} = \exp(-0{,}7\, d \big/ d_{50}) \tag{11}$$

And yield ‘from below’:

$$v^{-} = 1 - \exp(-0{,}7\, d \big/ d_{50}) \tag{12}$$

Where d50 – is 50% of total yield of fractions.

From (12) it is possible to express muckpile pieces:

$$d = -1{,}43 d_{50} \ln v^{+} \tag{13}$$

In this case the average diameter of muckpile pieces:

$$d_c = \int_o^1 d(v^{+}) dv^{+} = -1{,}43 d_{50} \int_0^1 \ln v^{+} dv^{+} \tag{14}$$

$$d_c = -1{,}43 d_{50} \left| v^{+} \ln v^{+} - v^{+} \right|_0^1 = 1{,}43 d_{50} \tag{15}$$

Median diameter of muckpile pieces equals:

$$d_{50} = 0{,}7 d_c \tag{16}$$

From (14) and (16) follows:

$$d = -d_c \cdot \ln v^{+} \tag{17}$$

The last expression allows to determine the average muckpile piece both through the yield of boulders, and through a yield of any key fraction that is especially actual in hydraulic engineering building and by working out of deposits of nonmetallic building materials:

$$d_c = -d_н \big/ \ln v_н = d_н \big/ \left| \ln v_н \right| \tag{18}$$

$$d_c = -d \big/ \ln v^{+} = d \big/ \left| \ln v^{+} \right| \tag{19}$$

Total yield ‘from above’ corresponding to average diameter of muckpile pieces equals:

$$v_{dc}^{+} = 0{,}37; (v_{dc}^{+} = 37\%) \tag{20}$$

Total yield ‘from below’ corresponding to average diameter of muckpile pieces equals:

$$v_{dc}^{-} = 1 - v_{dc}^{+} = 0{,}63; (v_{dc}^{-} = 63\%) \tag{21}$$

Taking into account deformation zoning, it is possible to execute a look-ahead estimation of an average and median sizes (diameters) of muckpile pieces according to actual blasting parameters.

$$d_c = \kappa \cdot d_{c2}(k_1 V_1 + V_2 + k_3 V_3 + \ldots + k_6 V_6) = 0{,}1\kappa \cdot (\gamma d_e)^{0,5}$$
$$(fd)^{0,33} \cdot q^{-1}(k_1 V_1 + V_2 + k_3 V_3 + \ldots + k_6 V_6)$$
$$d_c = \kappa \cdot d_{c2}(0{,}12 V_1 + 1 \cdot V_2 + 0{,}4 V_3 + 1{,}8 V_4 + 1{,}5 V_5 + 1{,}4 V_6) \tag{22}$$

$$d_{50} = \kappa \cdot d_{50-2}(0{,}12 V_1 + 1 \cdot V_2 + 0{,}9 V_3 + 1{,}8 V_4 + 1{,}5 V_5 + 1{,}4 V_6) \tag{23}$$

As a result the median values on diameter of rock equals:

$$d_{50} = 0{,}07 (\gamma d_e)^{0,5} (fd)^{0,33} / q \tag{24}$$

In a general view the offered model of blasting rock is shown in Figure 1.

2. SOFTWARE FOR CALCULATION OF BLASTING PARAMETERS

On the basis of the above given rock blasting model a design procedure for the rational parameters of bench blasting rocks (Table 1) and the computer program ‘Bench blasting’ intended for automated designing of blasting works was developed. The program allows to calculate quickly and qualitatively the blasting parameters. Distinctive features of ‘Bench Blasting’ are the simplicity of development, the simple intuitive interface, the presentation of all calculations, and also the possibility to connect all of available databases of physical characteristics of rocks, explosives, ignitions and parameters of rig.

The design procedure of rational blasting parameters realized in the given program is reflected in Table 1.

Analytical approximation of fragmentation:

$$v^{+} = \exp(-0{,}7 d / d_{50})$$

$$v^{-} = 1 - \exp(-0{,}7 d / d_{50}) \tag{25}$$

$$v^{-} = 1 - 0{,}5^{d/d_{50}}$$

$$d_c = \int_o^1 d(v^+)dv^+ = -1{,}43d_{50}\int_0^1 \ln v^+ dv^+ =$$

$$-1{,}43d_{50}\left|v^+ \ln v^+ - v^+\right|_0^1 = 1{,}43d_{50} \qquad (26)$$

$$d_{50} = 0{,}7d_c d = -d_c \cdot \ln v^+ ; d_и = -d_c \cdot \ln v_и \qquad (27)$$

Fragmentation formation in muckpile from the polydisperse mixes of the deformation zones:

$$d_{50} = d_1^{50}v_1 + d_2^{50}v_2 + \ldots\ldots + d_n^{50}v_n \qquad (28)$$

$$d_c = d_{c1}v_1 + d_{c2}v_2 + \ldots\ldots + d_{cn}v_n \qquad (29)$$

Analytical estimation of fragmentation:

- Without deformation zones:

$$d_{50} = 0{,}07(\gamma d_e)^{0,5}(fd)^{0,33} \cdot q^{-1} \le 0{,}7d_e \qquad (30)$$

$$d_c = 0{,}1(\gamma d_e)^{0,5}(fd)^{0,33} \cdot q^{-1} \le d_e \qquad (31)$$

$$d_c = \kappa \cdot d_{c2}(k_1V_1 + V_2 + k_3V_3 + \ldots\ldots + k_6V_6) = 0{,}1\kappa \cdot (\gamma d_e)^{0,5}(fd)^{0,33} \cdot q^{-1}(k_1V_1 + V_2 + k_3V_3 + \ldots\ldots + k_6V_6) \qquad (32)$$

$$d_c = \kappa \cdot d_{c2}(0{,}12V_1 + 1 \cdot V_2 + 0{,}8V_3 + 1{,}8V_4 + 1{,}5V_5 + 1{,}4V_6) \qquad (33)$$

$$d_{50} = \kappa \cdot d_{50-2}(0{,}12V_1 + 1 \cdot V_2 + 0{,}8V_3 + 1{,}8V_4 + 1{,}5V_5 + 1{,}4V_6) \qquad (34)$$

k1 , k2 …k6 - Factors of fragmentation degree of deformation zones;

v1, v2 .....v6 - Relative volumes of deformation zones;

f, γ, de - coefficient of rock's strength by prof. Protodjakonov M. M, density and the average linear size of natural joint in massif; d – deameter of charge, *м; q* – specific charge; *κ*- The factor considers influence of the detonation pattern on the results of blasting; *κ=1* - At in-line pattern without cut, *κ=0,85-0,95* at diagonal pattern or pattern with cut.

Specific charge depends on:

- average diameter of muckpile pieces $q = \dfrac{0{,}1(\gamma \cdot d_e)^{0,5}(f \cdot d)^{0,33}}{d_c}$;

-yield of boulder $q = \dfrac{0{,}1(\gamma \cdot d_e)^{0,5}(f; \cdot d)^{0,33}}{d_c}$;

-yield of key fraction $q = \dfrac{0{,}1(\gamma \cdot d_e)^{0,5}(f \cdot d)^{0,33}}{d_c}$;

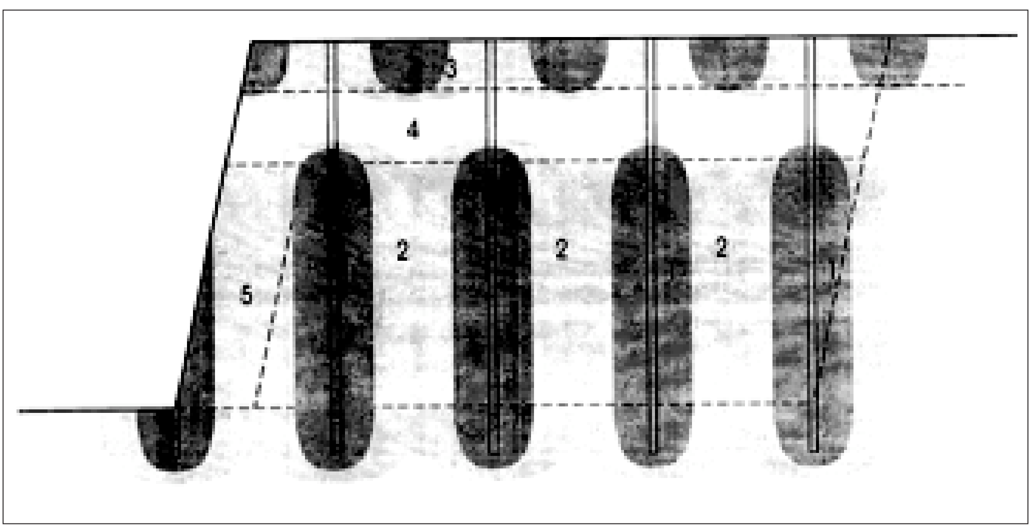

Figure 1. General view of mathematical model of blast rock. 1-fragmentation zone, 2-Joint formation zone, 3-near-surface zone, 4-passive fragmentation zone, 5-near-slope zone.

Table 1. Rational parameters of a charge in bench blasting.

№	Parameters	measure	Settlement formulas
1	The bench's height		$50d < h < 0,8l_м$
2	Diameter of a charge	m	$d = (0,01 \dots 0,02)h$
		m	$d = 0,2 \cdot \sqrt[4]{П / d_e}$
3	Specific charge	kg/m^3	$q = 0,1 \cdot \frac{(d_e \cdot \gamma)^{0,5}(f \cdot d)^{0,33}}{d_c}$
4	depth of subdrilling	m	$q = \frac{0,1(\gamma \cdot d_e)^{0,5}(f \cdot d)^{0,33} \lvert \ln V_n \rvert}{d_n}$
5	height of blasthole		
	-vertical	m	$l_н = 4(f \cdot d_e)^{0,33} d / q^{0,5} = (7 \dots 15)d$
	Slant	m	
6	Length of stemming	m	$l = h + l_н$
7	Length of charge		
8	Loading density	m	$l = (h + l_н)\sin\alpha$
9	Mass of charge		
10	Drilling pattern:	kg/m	$l_{зб} = (46 - 15d_e)d / f^{0,17} = (15 \dots 30)d$
	-Burden, w & b	kg	
	-spacing	m	$l_з = l - l_{зб}$
	-limited burden	m	$p = 785\, d^2 \Delta$
		m	$Q = pl_з = p(l - l_{зб})$
	-safety burden		$w = b = \sqrt{\frac{p}{q} \cdot \frac{l_з}{hm}}$
11	Check on burden:		
	-to working out of bottom bench		$a = \sqrt{\frac{p}{q} \cdot \frac{l_з m}{h}}$
	-for condition of safety	m	
		m	
		m	
12	Delay time:		$w_м = \frac{60\, d}{d_e^{0,125}} \left(\frac{\Delta e}{\gamma} \right)^{0,5} \kappa_1 \kappa_в$
	-for seismic normalization	ms	
	-for exception of detonative cord blasting	ms	$\kappa_1 = 0,32\, l_{зб}^{0,33}$, $\kappa_в = 1,45 - 0,45m$
			$w_б = 2 + h \cdot ctg\, \alpha$
			$w(= b) < w_м$
			$w > w_б$
			$t = 60d(\gamma\Delta)^{0,5} / eq$
			$t_б = 1,1(a/d)_{min}$

The basic window of the program consists of four tabs (working forms 1-4), each of them unites a certain stage of calculation. There are fields for fill in with the data and buttons for calculation of parameters, on each of the tabs.

The first tab (the working form 1), is presented on Figure 2. It is intended for calculation of charge diameters and the specific charge. Physical properties of rocks, the ledge parameters, the demanded size of muckpile fragmentation size are set on it, calculation of rational charge diameter and the specific charge providing desirable result is made. The first tab provides the viewer with the graph of the specific charge on an average muckpile piece. The user can correct the received value.

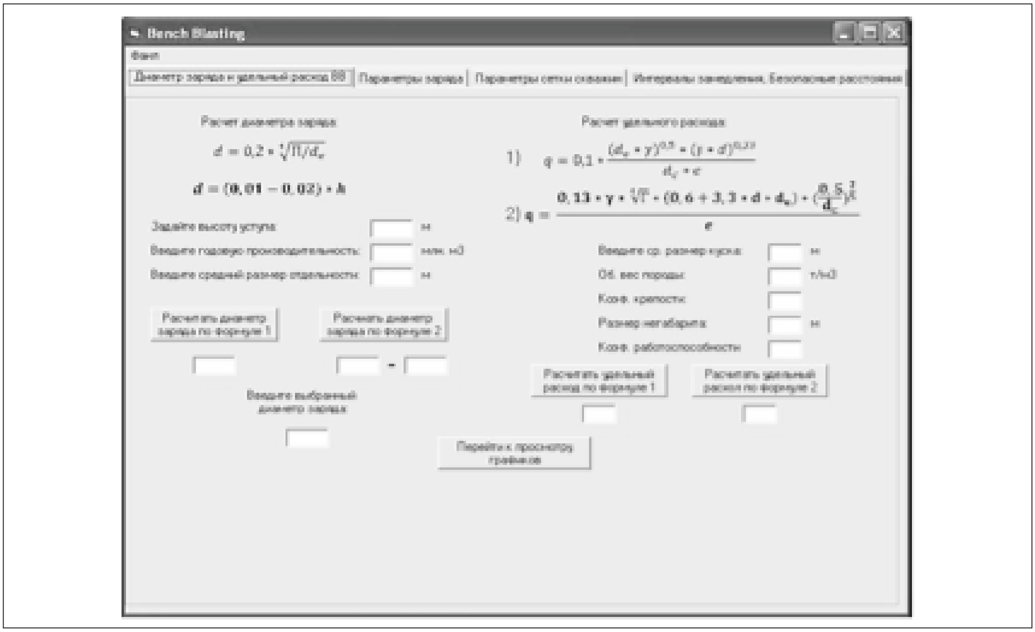

Figure 2. The working form 1: Calculation of diameter of charges and specific charge.

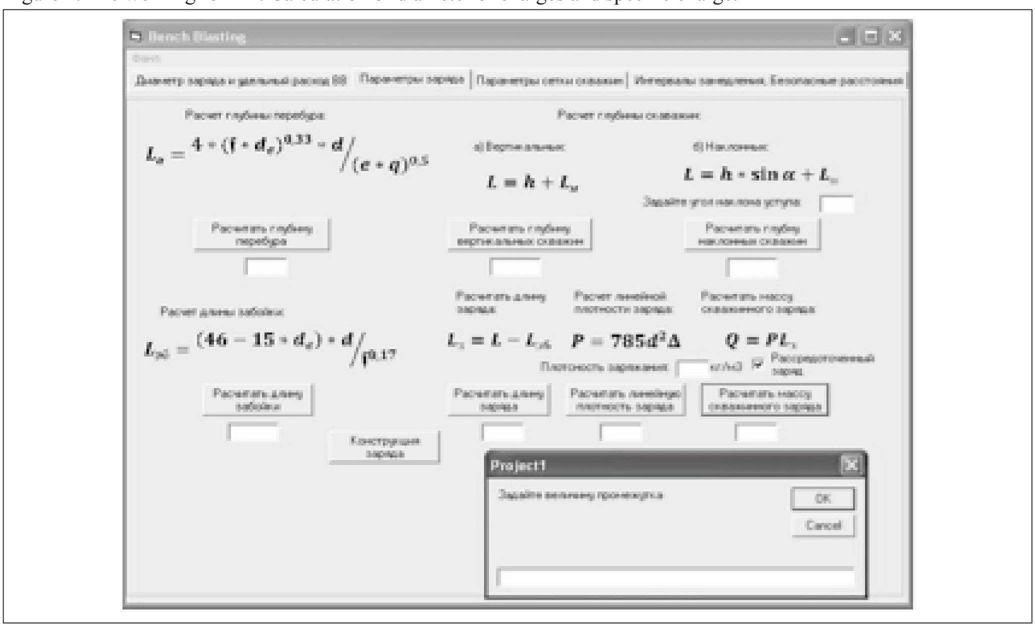

Figure 3. The working form 2: Calculation of blasthole parameters.

The second tab (the working form 2), is presented on Figure 3.

This tab is intended for calculation of key parameters for individual blastholes: depth of subdrilling, length of blasthole, sizes of stemming, lengths of a charging column (length of a charge), loading density and weight of a charge. The calculation is based on the values set on the first tab. These values can be corrected manually. There is a button which is needed for viewing a design of a charge on this tab.

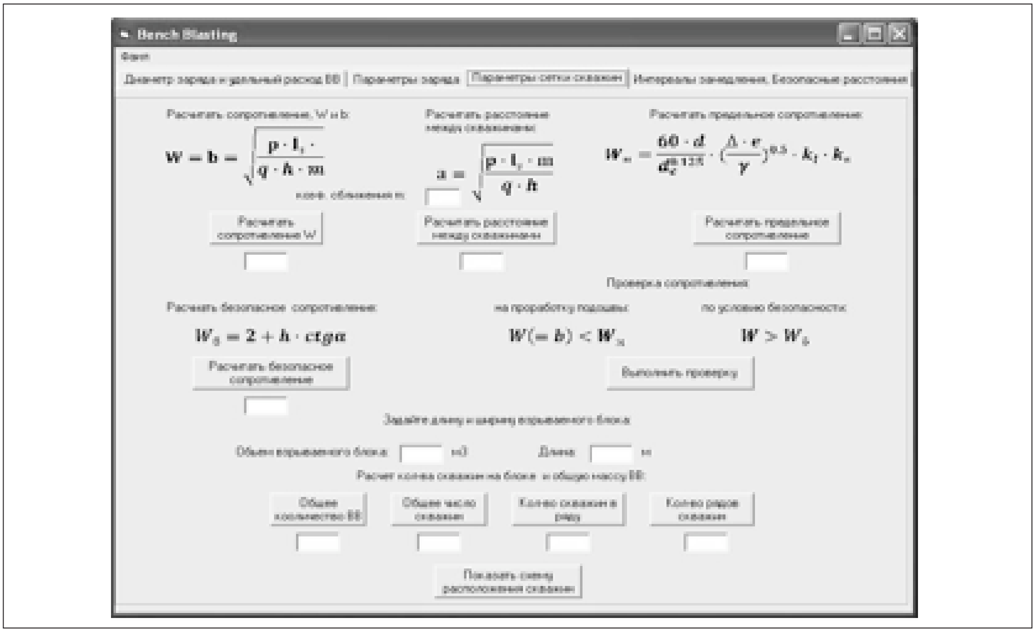

Figure 4. The form 3: Calculation of drilling pattern parameters.

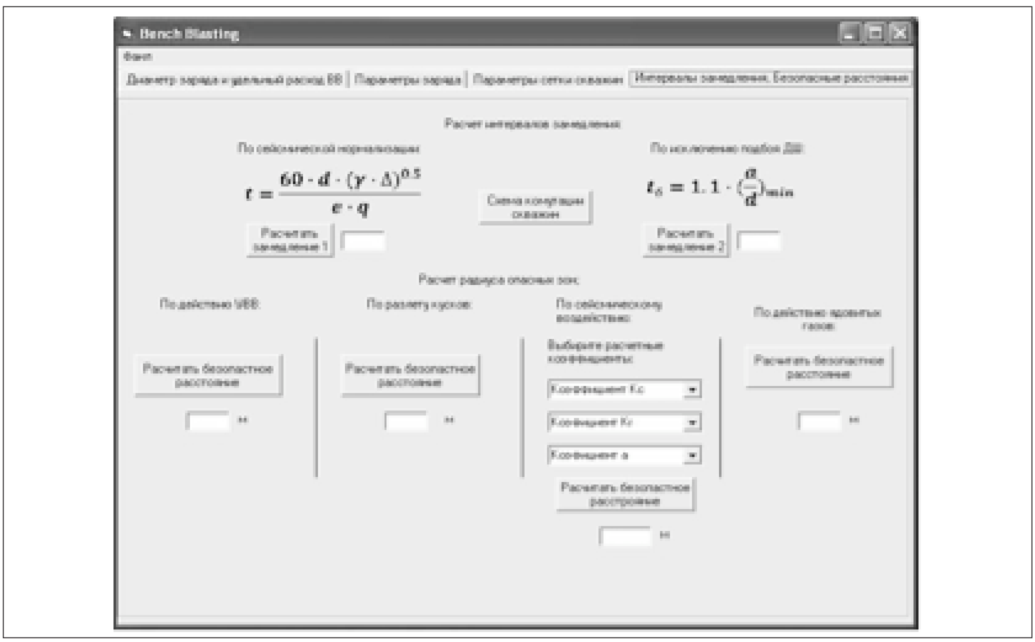

Figure 5. The form 4: Delay times and blast area.

The third tab (Figure 4) is devoted to calculation of drilling pattern parameters.

On that tab calculation is based on the parameters calculated or set on the previous tabs, and on values set at work with this tab.It is possible to execute calculated burden check on limiting (maximum) value for the set conditions, and on a safe distance to the bench edge of the rig. There is a button of transition to other working forms for viewing of the drilling pattern.

On the following tab (the working form 4) calculation is carried out of delays time between groups of charges, calculation of blast area (for example: flyrock area, airblast action area) according to 'Uniform safety rules at blasting' (Figure 5).

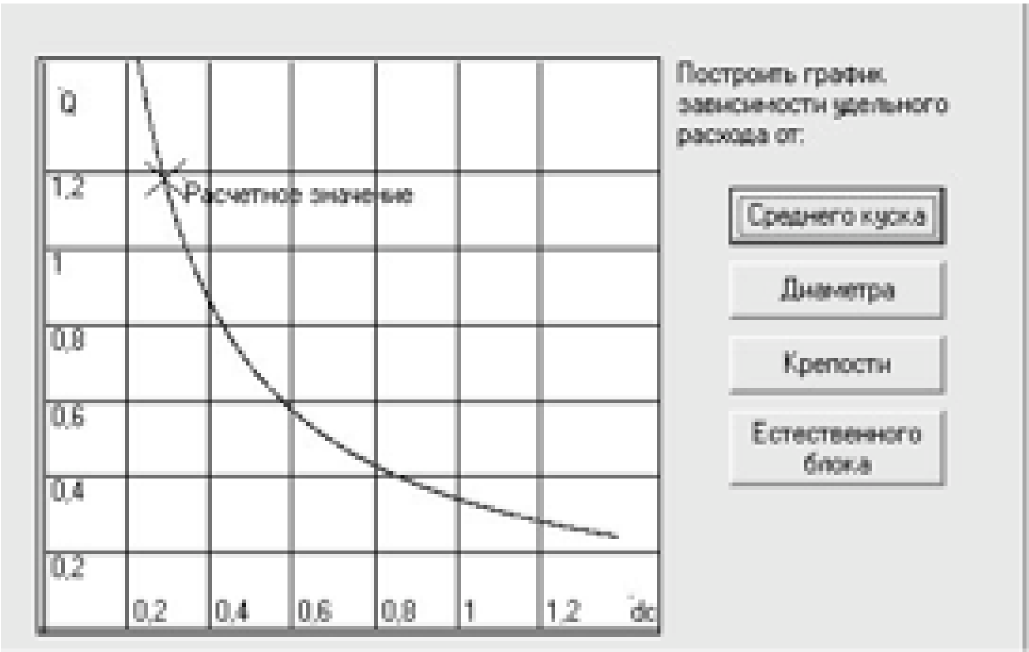

Figure 6a. Graph of specific charge on defined parameters.

Figure 6b. Graph of specific charge on defined parameters.

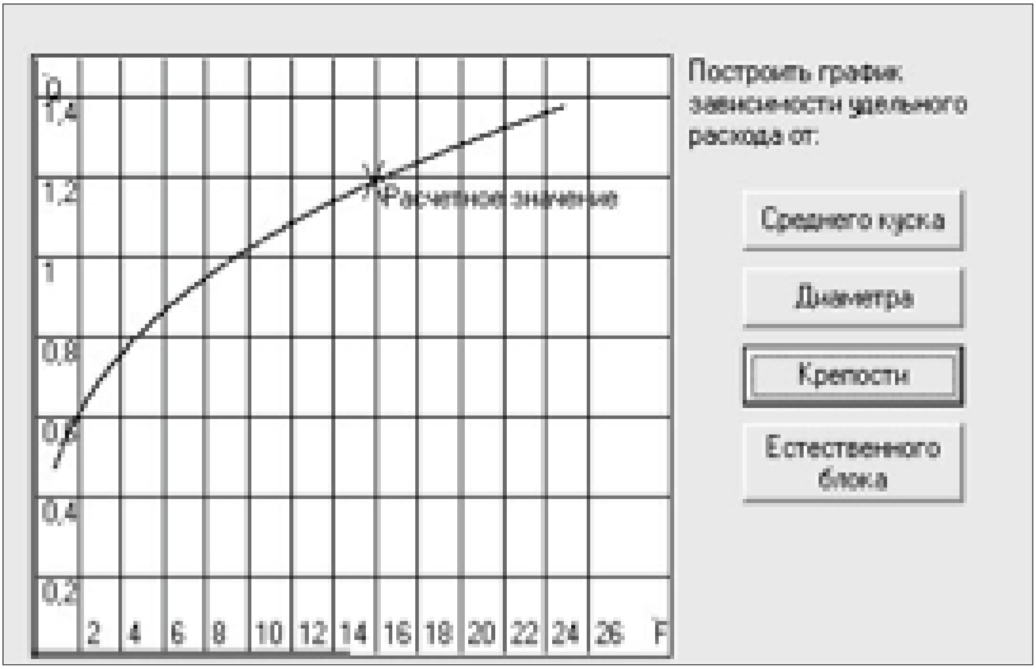

Figure 6c. Graph of specific charge on defined parameters.

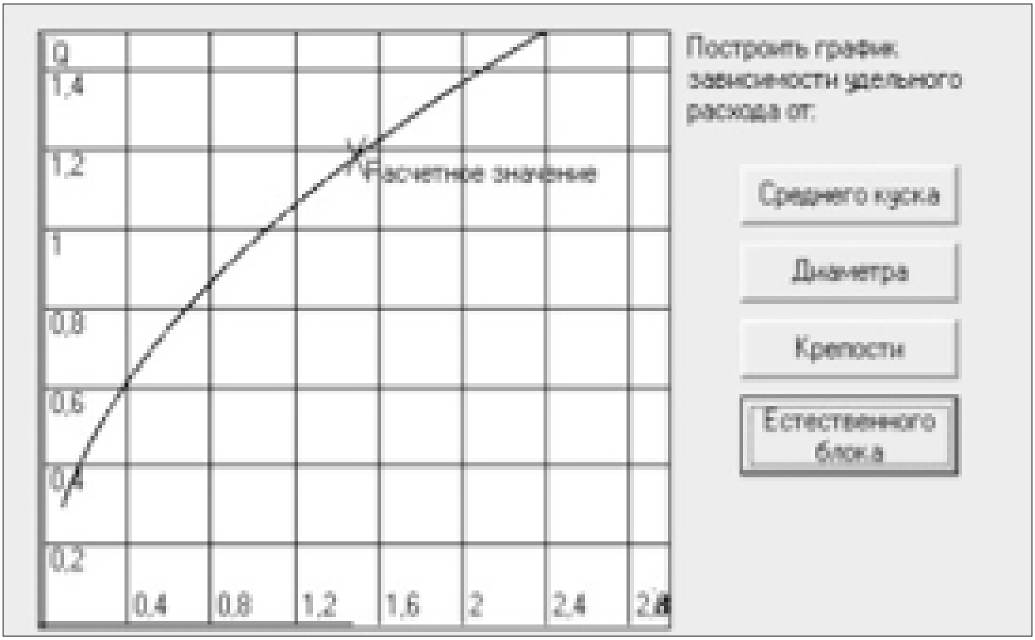

Figure 6d. Graphs of specific charge on defined parameters.

Graphs show a general view of dependences and the calculated value. This function allows to analyze the data and to correct blasting parameters. Transition to viewing of schedules is carried out from the working form 1.

3. CONCLUSIONS

The carried out analysis of existing mathematical model of blasting has allowed both to reveal items lacking, and to define the criteria what mathematical model of blasting should consist of:

- Dependence of the volume of muckpile pieces on their linear parameters.
- The Equation defining dependence of one of the most significant scale fragmentation parameters on blasting parameters and on indicators of physical properties of rock.

  Average or median diameters of rock's pieces are used as such scale parameter. The new mathematical model of blasting has been constructed as a result.

The model considers the established criteria, and also deformation zoning of massif.

The program 'Bench blasting' for the computerized calculations of blasting parameters is developed on the basis of the model. The program allows to simplify the process of blast designing. And the built in functions allows to analyse the settlement values. It should promote improvement of the quality of the blast.

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