M. RAMULU
A. K. RAINA
and
A. SINHA

New blasting techniques for productivity enhancement in underground coal mines

The pace of developments in underground blasting technology is insignificant in contrast to developments in opencast blasting. Blasting practices in underground mines has limited flexibility due to many safety criteria, statutory and field constraints. This has narrowed the scope of major modifications in the solid blasting design vis-à-vis the efficiency and yield per round. However, it is high time to balance the opencast and underground mine production, in view of the exhausting reserves in shallow depth and socio-environmental problems due to opencast mining. With this back-drop, Central Institute of Mining & Fuel Research (CIMFR), Regional Centre, Nagpur developed two new underground blasting techniques with simple modifications in explosive loading patterns. They are: (i) in-hole delay solid blasting technique (ii) bottom hole decking technique. The first technique was in-hole delay solid blasting technique by inserting multiple delay detonators in cut holes to improve the solid blasting efficiency. The conventionally available resources are used in this technique without violating the statutory guidelines. The trial blast results indicated improvements in all the parameters like pull, yield per round, powder factor and detonator factor. The overall improvement in pull per round was 49% with 1.5m deep rounds and 40% with 1.8 m deep rounds. The technique also resulted in reduction of ground vibration intensity by 32-37%.

Another blasting method developed was bottom hole decking technique by inserting air-deck at the bottom of the blastholes. In this technique a spacer is to be placed at the bottom of the hole and remaining portion of the hole is conventionally charged. The length of spacer is equal to 10-12% of depth of blasthole. A wooden spacer or any anti-static plastic pipe can also be used for decking. The technique was also applied in both soft and medium hard coal formations while exploiting the thin coal seams. The trial blast results indicated improvements in pull, yield per round and powder factor. The overall progress/pull per round observed was 36% with 1.5m deep rounds and it was up to 22% with 1.8m deep rounds with the powder factor (ton/kg) improvement up to 70%. The technique was also resulted in reduction of ground vibrations by 20-26%. The experimental results also reveal that the in-hole delay solid blasting and bottom hole decking techniques are suitable for relatively harder and softer formations respectively for improving blasting productivity.

Introduction

It is high time to concentrate upon underground mining vis-à-vis blasting, as the cost of opencast mining is going to increase in near future due to higher stripping ratio. Moreover major share of the good quality of coal in India is presently available in thin and deeper seams which can be exploited by underground mining. Larger output in a blasting round is essential to improve the utilisation of mechanical excavators. However, many restrictions in solid blasting design in coal mines due to safety considerations have narrowed the possibility of larger output.

Underground coal mine blasting is different than all other types of rock blasting because of two important issues. Firstly, the operation takes place in a dangerous environment containing methane gas and coal dust. Secondly, the coal is much easier to break than rocks. Hence, the blasting in coal must be conducted fulfilling all the prevailing safety regulations.

The Mine Safety and Health Administration (MSHA) of USA specifies that for solid blasting in coal mine the maximum charge weight in a hole should not exceed 3 lb (USBM 8925d). Further, it insists that a minimum burden of 18 inches and a maximum of 20 holes per round must be maintained. Moreover, the guidelines restrict the leg wire length of the detonators within 16 ft or such a length having equivalent resistance and also do not permit the use of "0" delay detonators in the circuit with milli-second delay detonators.

The chance of explosive malfunctioning is high in solid blasting due to close proximity of charges. Mainereo (1986) observed that the desensitization of blastholes was very frequent in coal mine when the blastholes were closer than 0.6 m. Katsabanis and Ghorbani (1995) found that the sympathetic detonation might occur if different charges are

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Dr. M. Ramulu and Dr. A. K. Raina, Scientists, Central Institute of Mining & Fuel Research, Regional Centre, 3rd Floor, MECL Complex, Seminary Hills, Nagpur 440 006 and Dr. A. Sinha, Director, CIMFR, Dhanbad, e-mail: more.ramulu@gmail.com; cmrirc@dataone.in

separated at less than 8 times the hole diameter.

Solid blasting practice in coal is regulated in India by Coal Mines Regulations 1957 and the related circulars issued by the Director General of Mines Safety, Dhanbad. Several restrictions are imposed in solid blasting due to gassy conditions. Therefore longer rounds, which are practiced in rock tunnels or drifts, are not possible in coal. However, plenty of new ideas and efforts are being experimented to improve the yield per blast and are sometimes permitted on case to case basis.

It is known that in solid blasting, a cut is blasted initially towards which the rest of the shots are fired. The confinement, which is maximum in the cut holes in absence of any free face, is released to a great extent once the cut is developed and hence, the balance holes are blasted with minimised confinement. The efficiency of a blasting round vastly depends on the success of cut development. Wedge type cut prevails over others in India. The restrictions in solid blasting towards total firing time as 150 ms in case of degree II and 100 ms in case of degree III coal mines (Deshmukh, 1991) do not permit application of long delays in the cut holes. Further, the distance between the charges in two shots is fixed as no less than 0.6 m. This has restricted closer spacing of holes or larger charge concentration in the cut holes. Hence, scopes to counter the larger confinement in the cut holes are limited. Moreover, the restrictions on the type explosive charge, delay between the two consecutive delays, charge per hole as per gassy conditions are the constraints towards development of deeper or larger cut resulting in poor pull per round. Innovations in various explosive accessories like relays, shock tubes and others are applied in opencast blasting not yet permitted in the underground coal mines. Hence, rounds deeper than 1.5 m, are not common in India considering the prevalent restrictions. The pull ratio also lies in a mediocre range of 0.6-0.7.

In-hole delay solid blasting

In view of the above conditions, an innovative in-hole delay pattern was evolved by the authors to improve the solid blasting efficiency in the coal mines. This essentially includes the use of multiple delay detonators in a single hole so that total permissible explosive quantity is distributed or segmented in different delays which are fired sequentially from the top, where the confinement is originally smaller, to provide less confinement to the charge being fired in the next delay situated in the bottom part of the hole and having originally a larger confinement. Further, multiple delays provide additional time for the burden to be displaced more efficiently. Though this type of delay arrangement may be tried in all the holes for better fragmentation and output, but is especially useful in the cut holes or toe holes, where the confinement is larger than other holes in a round, to reap the major benefits in case of limited availability of delay detonators. The technique is briefly explained in Fig.1, which resembles to the in-hole delay initiation method used in opencast blasting using shock tubes.

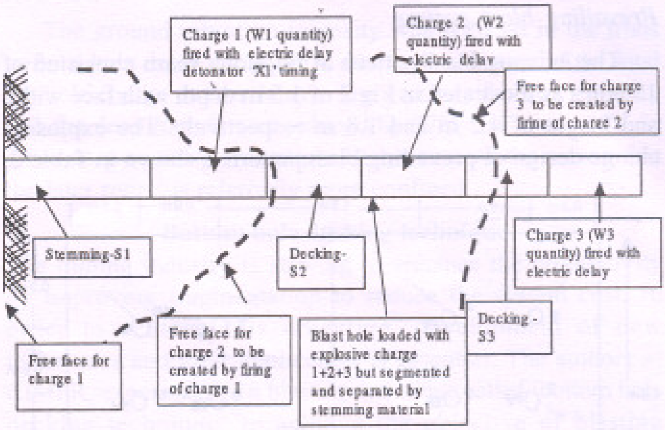


Fig.1 In-hole delay solid blasting technique – a schematic diagram

This novel technique has been filed for patent and it was granted recently (IPMD, 2004). The uniqueness of the technique is that it abides by all the existing safety criteria and uses the conventional electric delay detonators, without demanding for extra resources.

FIELD APPLICATION OF THE TECHNIQUE

Field application of the in-hole delay solid blasting at coal mines

This in-hole delay solid blasting technique was applied at Bagdona seam of Tawa underground mine of Pathakhera area, Western Coalfield Limited (WCL). The Tawa mine is located in the district of Betul of Madhya Pradesh. The mine has three seams namely upper workable seam, lower workable seams and Bagdona seam. All the workable seams were classified as Degree II gassy seams. The maximum permissible charge per hole in such gassy condition is 0.565 kg. The average daily production of the mine was 1628 t. Geological disturbances such as dyke, fault and sill makes are observed in the mine. The geo-technical details are given in Table 1.

TABLE 1: DETAILS OF GEO-TECHNICAL INFORMATION OF COAL SEAMS

	Name of seam	Thickness (m)	In-situ compressive strength (MPa) obtained by Schmidt rebound hammer	Direction and average dip of seam
1.	Upper workable seam	0.75-2.34	Not tested	N 50° W, 1 in 7-12
2.	Lower workable seam	2-3	30	N 50° W, 1 in 7-12
3.	Bagdona seam	0.8-2.32	40	N 50° W, 1 in 7-12

The extraction method includes manual drilling and blasting with LHD loading and belt conveyor transportation. Owing to smaller thickness, the yield per blast of Bagdona and upper workable seams is very low.

Prevailing blast pattern

The existing blast pattern at Bagdona seam consisted of 13 holes as illustrated in Fig.2 of 1.5 m depth with face width and height of 4.2 m and 1.8 m respectively. The explosive charge design of prevailing blast pattern is shown in Table 2.

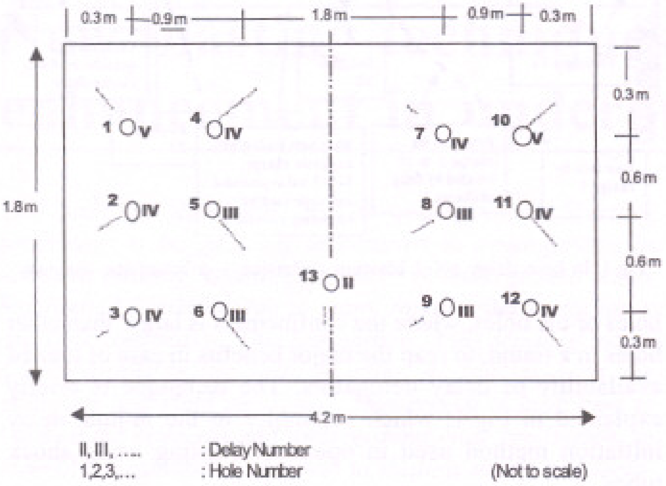


Fig.2 Existing blast pattern of Bagdona seam

TABLE 2: CHARGE DISTRIBUTION WITH EXISTING PATTERN

Delay no.	No. of holes	Total explosive charge/delay, (kg)
II	1 (centre)	0.37
III	4	1.85
IV	7	2.59
V	2	0.74
Total	13	5.55

The average pull per blast round was 0.7m with the existing pattern by 1.5m blasthole depth and yield was 8 ton/round. The average powder factor, drilling factor and detonator factor are 1.43 tonnes/kg, 0.4 tonne/m and 0.61 tonne/detonator respectively.

Experiments with in-hole delay solid blasting

In order to assess the efficacy of the technique, initially cut holes were drilled and blasted with in-hole delay as explained in Fig.1. As the results were encouraging, the full face blasting trials were conducted with in-hole delay. The step by step procedure of charging the cut holes is as follows:

Step-1: Inserting primer cartridge of 0.185 kg with higher delay number into blasthole

Step-2: Decking of the hole after first primer up to 0.6 m with stemming capsules

Step-3: Inserting two cartridges amounting to 0.37 kg with smaller delay number

Step-4: Packing of the remaining hole length by stemming material

Step-5: Connecting the leg wires of two delay detonators in series

The maximum charge per hole was kept as 0.555 kg which is within permissible limit as per the statutory conditions. The gallery size, where experimentation were carried out, was almost same for all the test blasts.

The in-hole delay charge configuration is shown in Fig.3.

The blast pattern and hole geometry and direction of angle of in-hole delay cut pattern is shown in Fig.4 and the charge details are given in Table 3.

Out of 10 test blasts, 5 trial blasts were conducted with 1.5 m deep holes and the rest of the 5 trials with 1.8 m deep holes. The charge details of the trial blasts and the blast results are given in Table 4.

Trial blast results and performance improvement

The blast results and performance improvement achieved with in-hole delay cut pattern is summarised in Table 5.

TABLE 3: EXPLOSIVE CHARGE DETAILS WITH IN-HOLE DELAY CUT PATTERN

Delay no.	Name of blastholes	No. of holes	Explosive charge delay, (kg)
0	Centre holes	2	0.74
I & II	Cut holes	6	3.33
III	Support holes	4	2.22
IV	Top corner holes	2	1.11
Total	14	14	7.4

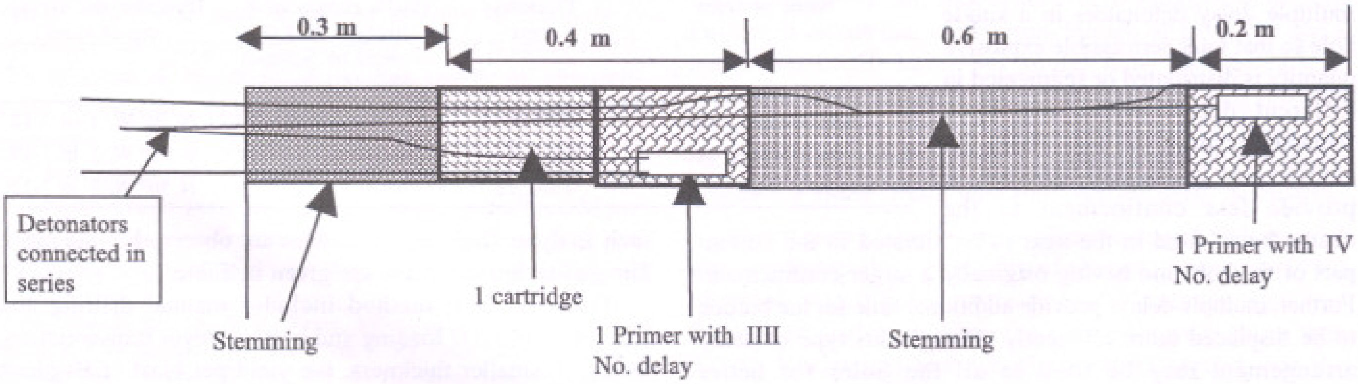


Fig.3 Charge design of the cut holes with in-hole delay pattern (figure not to scale)

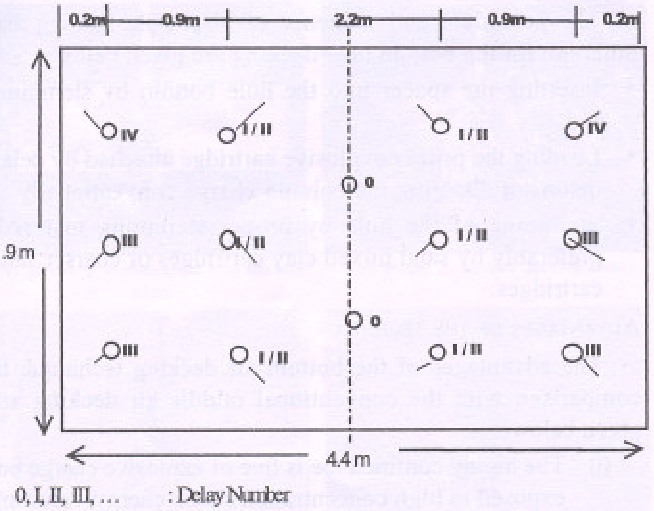


Fig.4 Full face blast design with in-hole delay cut pattern

From the test blast results it is clear that the average pull was increased to 49% with 1.5m deep rounds and 40% with 1.8m deep rounds, which obviously resulted in increase of yield per round. The coal production per round was increased up to 63% with 1.5m deep rounds. The test blast results also indicate the increase of powder factor by 26% and 64% in test blasts with 1.5m and 1.8m deep rounds, respectively. The increase of detonator factor was very meagre as comparatively more number of detonators were consumed in in-hole delay blast pattern.

The ground vibration intensity was reduced in the trials with in-hole delay cut pattern, due to distribution of the total cut hole charge in two delays. The ground vibration intensity at 1.5m deep rounds was reduced by 37% and it was 32% in 1.8m deep rounds. This might be because of the reason that the later round is relatively more confined.

Bottom hole decking technique

The mining industry is striving to enhance the productivity by improving fragmentation to reduce the system cost. In order to achieve this objective, development of new techniques and their application is essential. The authors at CIMFR, experimented a blasting technique called 'bottom hole decking technique' to achieve the objective of blasting productivity improvement of the mining industry. The technique consists of air decking at the bottom of the blasthole in dry holes by means of a wooden spacer or a closed PVC pipe. Although, practice of air decking is not new thing in blastholes, the concept of inserting bottom hole decking below the explosive column is relatively new. Explosives provide a very concentrated source of energy, which is often well in excess of that required to adequately fragment the surrounding rock material. Blast design, environmental requirements and production requirement limits the degree to which the explosive energy distribution within the blasthole can be significantly altered using variable loading techniques. Use of air-decks provide an increased flexibility in alteration and distribution of explosive charge in blastholes.

TABLE 4: EXPERIMENTAL BLAST DETAILS CONDUCTED AT TAWA UNDERGROUND MINE, WCL

Blast No. depth, m	Max. hole /round, kg	Total charge	Max. charge/ delay, kg	Av. pull, m	Yield/round, tonne	Powder factor, t/Kg	Detonator factor, t/d
1	1.5	7.03	1.48	0.95	11.9	1.69	0.66
2	1.5	7.4	1.665	0.95	11.9	1.61	0.66
3	1.5	7.4	1.48	1.10	13.8	1.86	0.77
4	1.5	7.4	1.11	1.10	13.8	1.86	0.77
5	1.5	7.03	1.11	1.10	13.8	1.96	0.77
6	1.8	7.22	1.665	1.40	15.7	2.17	0.87
7	1.8	6.66	1.48	1.50	14.4	2.16	0.80
8	1.8	6.66	1.48	1.45	14.4	2.16	0.80
9	1.8	6.66	1.48	1.45	15.0	2.25	0.83
10	1.8	6.66	1.11	1.40	15.7	2.36	0.87

TABLE 5: IMPROVEMENT IN BLASTING EFFICIENCY USING IN-HOLE DELAY CUT PATTERN

Parameter	Prevailing blast pattern		In-hole delay technique		% improvement	
	1.5 m depth	1.8 m depth	1.5 m depth	1.8 m depth	1.5 m depth	1.8 m depth
Av. pull, m	0.7	1	1.04	1.4	49	40
Av. yield/round, tonne	8	10	13	15	63	50
Av.powder factor, tonne/kg	1.43	1.35	1.8	2.22	26	64
Av. detonator factor, tonne/detonator	0.61	0.571	0.65	0.76	7	33
Av. ground vibrations, mm/s at 30m from face	9.5	11	6	7.5	37	32

The air-decks are, conventionally, inserted within the explosive column of a blast hole, which is also called as middle air decking. Literature shows that middle column air-decking was first used by Mel'Nikov (1940) and Marchenko (1954) for fragmentation improvement and increased burden movement. The middle air decking has some limitations and cannot be universally applicable to all types of rock mass and materials (Mead et al, 1993). Instead of middle air decking, top decking resulted in improvement of blast performance in terms of better fracturing (Chiapetta, 1987; Moxon, 1993; Sastry, 2001). Attempts were made by Indian researchers to apply the air-decking technique to improve the blast fragmentation and to reduce the ill-effects of blasting (Chakraborty, 1996; Jhanwar, 1999; Sastry, 2001; Ramulu, 2005). Chiapetta (2004) conducted experiments with bottom air-decking by means of a specially designed spacer and got good blast results of fragmentation, reduced vibration and toe. He developed a device called ' Power Deck' to facilitate bottom hole decking in vertical blastholes in opencast mines. Collinsworth (1997) also used bottom hole air decking for preventing coal damage and loss in cast blasting. The paper deals with laboratory and field investigations with bottom hole air decking and discusses the results obtained.

DESIGN OF THE BOTTOM DECKING TECHNIQUE

The bottom hole air-decking was developed to avoid the general disadvantages of middle air decking and to simplify the complex charging procedure, associated with it. The design aspects of the technique are explained in the following sections.

COMPONENTS AND PROCEDURE OF APPLICATION

The bottom hole decking consists of air decking at the bottom of the hole in dry holes by means of a spacer or a closed PVC pipe, covered at the upper end. The fume characteristics of the spacer are to be tested before applying in underground coal mine. If blastholes are wet, water decking will be created at the bottom by means of a spacer with a weight attached to it for sinking to the bottom. The diameter of the spacer should be preferably one third of the blasthole diameter for easy lowering and not allowing the charge to go to bottom side while loading. The reported values of air-deck length was taken as basis for optimum bottom deck length which was about 10% of the hole depth (Mead et al, 1993). The hole contains explosive and stemming column as in conventional loading but with a spacer at the bottom. The principle of bottom hole air decking in achieving optimum explosive energy interaction on rock mass is given below:

- Reduced shock energy around the blast hole due to cushioning effect of air decking, which otherwise would result in crushing
- Explosive energy-rock interaction is more at the bottom due to relative relief zone existing at that zone.
- Effective toe breakage is due to striking and reflection of shock waves at the bottom face of hole

The procedure and sequence of blast hole loading and initiation for the bottom hole decking are given below:

- Inserting the spacer into the hole bottom by stemming rod.
- Loading the primer explosive cartridge attached by delay detonator charging the column charge conventionally
- Stemming of the hole by proper stemming material, preferably by sand mixed clay cartridges or coarser sand cartridges.

ADVANTAGES OF THE TECHNIQUE

The advantages of the bottom air decking technique in comparison with the conventional middle air decking are given below:

(i) The highly confined toe is free of explosive charge but exposed to high concentration shock energy, resulting in good toe breakage and low vibration intensity.

(ii) The reduced overall peak shock reduces the back break and damage.

LABORATORY SCALE EXPERIMENTS

Small scale laboratory experiments were conducted in Plexiglas models to test the efficacy of the technique and full scale field tests were conducted on the basis of blast performance of laboratory experiments.

Plexiglas model preparation

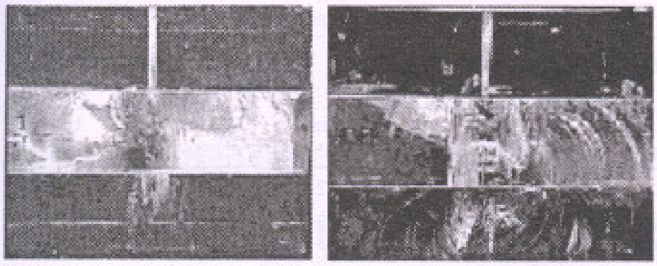
In order to conduct laboratory experiments, it was required to select a transparent material so that the post-blast fractures can be calculated accurately by visual observations. Plexiglas material was the right choice for this purpose and its properties are given in Table 6. Considering the availability and economy of the Plexiglas, the size of the models was 0.3 (width) × 0.3m (breadth) × 0.076m (thickness). Three pieces of Plexiglas were glued together with an adhesive to form a single block to simulate the general joints in rock mass. The adhesive used did not affect the strength, clarity and transparency of the material. The blast hole of 8mm diameter drilled at the centre of the block to a depth of 0.15 m, which was constant for all the 4 models. The holes were drilled with the help of a lathe machine and blasted with a detonator, which may be regarded as a 10 gm spherical charge.

TABLE 6: STATIC AND DYNAMIC PROPERTIES OF THE PLEXIGLAS MATERIAL

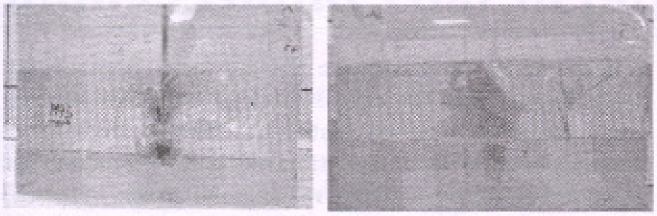
	Property of Plexiglas	Value
1	Density	1400 kg/m^3 (14 kN/m^3)
2	Compressive strength	262.5 MPa
3	Tensile strength	96.0 MPa
4	P-wave velocity	2862 m/s
5	S-wave velocity	2308 m/s

Blast results in Plexiglas models

The experiments in Plexiglas models are shown Fig.5. It was observed that the crushed zone in the conventional model blast was 10 times the blast hole diameter, whereas it



(a) Model 1: conventional non decking blast (b) Model 2: bottom decking blast



(a) Model 3: conventional non decking blast (b) Model 4: bottom decking blast

Fig.5 Laboratory scale experiments in Plexiglas models with conventional charging (a) and with bottom decking (b)

was 5 times the hole diameter in the bottom deck model blast. This indicates that more energy was not spent for crushing, which is considered as wastage in general production blasts. Specific surface area (SSA), a measure of explosive energy utilisation, was considered as one of the parameters of blast performance assessment (Ramulu, 2002). SSA (extra surface area created per unit volume, m^2/m^3) observed in the conventional model blast was 0.09 m^{-1}, where as it was 0.1 m^{-1} in the bottom deck model blast, which is the 10% increase in SSA.

From the model results it is clear that the model with bottom decking created fractures almost uniformly from top to bottom of the model (Fig.5), whereas the model without decking created more fractures at the middle and very little fracturing at top and bottom portion of the model. This indicates that, with bottom decking the explosive energy was uniformly acted throughout the blast hole and resulted in uniform fracture distribution.

FIELD APPLICATION OF BOTTOM DECKING TECHNIQUE

A total of ten number of field tests were conducted at Tawa underground mine to corroborate the blast performance achieved in model scale blasts. The details of the field experiments at two different test locations of the mine i.e. thin seam and thick seam are explained in the following sections. The site description and geological properties of the mine were already explained in the previous sections. The blast pattern and the charge details are hole geometry was same as shown in Fig.4 and Table 3, respectively. The bottom decking in all the trials was achieved by inserting a closed PVC pipe (spacer). The fume characteristics of the spacer were tested before applying in underground coal mine and not found any noxious fumes, stipulated by statutory conditions. Blast hole charge design for production blasts with bottom air-decking is shown in Fig.6. Out of 10 trials, 5 trial blasts were conducted with 1.5 m deep holes and the rest of 5 with 1.8 m deep holes. The details of the trial blasts and the blast results are provided in Table 7. The charge per round was reduced in 1.8 m deep rounds by reducing the charge in the periphery holes.

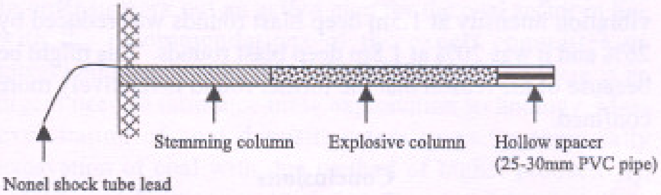


Fig.6 Blasthole charge design for production blasts with bottom air-decking

Trial blast results and performance improvement

The blast results and performance improvement achieved with bottom decking technique is summarised in Table 8.

From the test blast results it is clear that the average pull was increased to 36% with 1.5m deep rounds and 22% with 1.8m deep rounds, which obviously resulted in increase of yield per round. The coal production per round was increased up to 50% with 1.5m deep rounds. The test blast results also

TABLE 7: EXPERIMENTAL BLAST DETAILS CONDUCTED BOTTOM DECKING AT TAWA UNDERGROUND MINE

Blast No. depth, m	Max. hole /round, kg	Total charge	Max. charge/ delay, kg	Av. pull, m	Yield/round, tonne	Powder factor, t/Kg	Detonator factor, t/d
1	1.5	7.4	1.48	1.1	13.79	1.69	0.99
2	1.5	7.4	1.48	1.05	13.17	1.61	0.94
3	1.5	7.4	1.48	0.95	11.91	1.86	0.85
4	1.5	7.4	1.48	1.1	13.79	1.86	0.99
5	1.5	7.4	1.48	0.9	11.29	1.96	0.81
6	1.8	6.66	1.48	1.25	15.68	2.17	1.12
7	1.8	6.66	1.48	1.3	16.30	2.17	1.16
8	1.8	6.66	1.48	1.15	14.42	2.17	1.03
9	1.8	6.66	1.48	1.25	15.68	2.26	1.12
10	1.8	6.66	1.48	1.3	16.30	2.35	1.16

TABLE 8: IMPROVEMENT IN BLASTING EFFICIENCY USING BOTTOM DECKING TECHNIQUE

Parameter	Prevailing blast pattern		Bottom decking technique		% improvement	
	1.5 m depth	1.8 m depth	1.5 m depth	1.8 m depth	1.5 m depth	1.8 m depth
Av. pull, m	0.7	1	0.95	1.22	36	22
Av. yield/round, tonne	8	10	12.0	15.30	50	29
Av.powder factor, tonne/kg	1.43	1.35	1.61	2.30	13	70
Av. detonator factor, tonne/detonator	0.61	0.571	0.85	1.09	39	91
Av. ground vibrations, mm/s at 30m from face	9.5	11	7	8.75	26	20

indicate the increase of powder factor by 13% and 70% in test blasts with 1.5m and 1.8m deep rounds, respectively. It was also observed that the detonator factor was also increased by 39% and 90% in test blasts with 1.5m and 1.8m deep rounds, respectively. The increase of detonator factor was very predominant in case of tests with bottom decking in comparison with tests with in-hole delay blast pattern.

The ground vibration intensity was substantially reduced in the trials with bottom decking blast pattern, due to the cushioning effect of blastholes in perimeter holes. The ground vibration intensity at 1.5m deep blast rounds was reduced by 26% and it was 20% at 1.8m deep blast rounds. This might be because of the reason that the former round is relatively more confined.

Conclusions

Due to several safety restrictions on account of dangerous environment, there is hardly any flexibility in coal mine solid blasting for a major change in the blast design to obtain significant improvement in the blast efficiency and yield. To counter the problem, the CIMFR developed and applied an innovative in-hole delay cut pattern in Tawa underground coal mine of WCL using electric delay detonators without violating the existing safety criteria. The technique deploys multiple electric delay detonators in a hole, which adds time for the burden displacement, to partition the total charge and firing sequentially from collar to bottom in order to provide less confinement for the bottom charge to pull a greater depth. A total of 10 numbers of trials were conducted at the Bagdona seam. The improvements observed in all the blast performance indicators like pull, yield per round and powder factor, except in detonator factor, with both 1.5m and 1.8m deep rounds. There was an added advantage of reduction in ground vibration intensity by 32-37%, which obviously results in improving ground control and roof support aspects of underground mine.

The bottom air decking experiments in Plexiglas models proved that the explosive energy was effectively used in uniform fracturing and more breakage in comparison with the conventional charging. The field experiments at two test sites corroborated the blast results obtained in Plexiglas models. The bottom air decking also resulted in the overall progress/pull per round of 36% with 1.5 deep rounds and 22% with 1.8 m deep rounds even with the powder factor improvement (ton/kg) up to 70%. The increase of detonator factor was very predominant in case of tests with bottom decking in comparison to tests with bottom decking technique. The technique was also resulted in reduction of ground vibrations by 20-26%. The laboratory and field experimental results prove that the bottom-hole air decking is an effective technique for improving the opencast blasting productivity as well as safety.

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(Continued on page 95)