Flyrock in surface mine blasting: understanding the basics to develop a predictive regime

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Flyrock is one of the most contentious issues in bench blasting. Unlike ground vibrations, flyrock has the propensity to cause fatality and severe injuries. Although the kinematic equations present a basis for the estimation of flyrock distance, these suffer from the drawback of ignoring the post-release effects of trajectory motion in air. Predictive models that are based on such equations not only suffer from this anomaly, but also fail in flyrock distance prediction due to the gross approximations of initial velocity calculations and shape of the fragments.

This article discusses the flyrock phenomenon, causative factors and their use in developing prediction models. Different predictive models, namely empirical and semi-empirical are reviewed and the drawbacks highlighted. The principal causative factors of flyrock namely blast-hole pressure, time of blasting impact and post-release corrections are discussed with their relevance. The study culminates into a futuristic comprehensive flyrock distance prediction methodology to predict the blast danger zone along with the probability and risk associated with flyrock.

Keywords: Basics, blast danger zone, flyrock prediction, surface blasting.

BLASTING involves the breaking of rocks using explosive (chemical) energy. The blasting process is primarily a rock–explosive interaction that entails application of pressure generated by detonation of explosives, on rock mass, over a few milliseconds. This rock–explosive interaction results in rock breakage and heaving of the broken rock mass (muck). In comparison to the mechanical methods that rely predominantly on the compressive breakage, blasting exploits the tensile strength of the rock mass. This is probably the reason that blasting is still the most prevalent and economical method for rock breakage.

Blasting, in general, results in ‘desired’ and ‘undesired’ outcomes that may be ‘regular’ or ‘random’ in nature (Table 1). These also form the objectives of the mine–mill fragmentation system (MMFS)[1].

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Any mismatch between the energy available and the work (to be) done will increase the adverse or undesired blast results[2] like excessive throw and flyrock. Flyrock and excessive throw occur due to deviations in blast design execution, use of excessive explosive energy than the required levels to fragment and throw the rock mass, and/or presence of rock mass features, not accounted for during blasting. The said rock mass and blast design anomalies favour the channelling of high-pressure gases emanating from the blast hole(s) in the direction of the weakest zone and result in fragments travelling unwanted distances than desired. Such fragments are called ‘flyrock’.

Flyrock is one of the crucial issues in bench blasting, as it is not only a safety concern but also affects the productivity. The percentage of accidents occurring due to flyrock (Table 2), justifies its importance irrespective of the fact that the problem is seldom reported[3].

Flyrock – domain definition and status of research

Fragmentation of rocks, the most desired objective of blasting, is associated with displacements of the muck that are termed as throw, excessive throw and flyrock distance (Figure 1). As defined earlier, flyrock is a rock fragment propelled from a blast face under the impact of explosive gases that travels beyond expected distances. Throw is the displacement of fragmented rock during blasting[4] that spreads to a proper distance within the bench width. Proper throw is essential for facilitation of effective loading of the muck. Excessive throw is the undesired displacement of the broken rock mass beyond the bench width or multiples of bench height. Excess throw affects the loading efficiency of excavators and reduces productivity of a mine[5].

Flyrock, arising from open-pit blasting, still eludes rock excavation engineers, despite a reasonable understanding of throw[1,6,7]. Flyrock distance predictions have witnessed a refocus in the past few years due to want of a plausible solution. Such attempts also have raised certain pertinent questions that need to be answered in order to develop a proper understanding of the flyrock phenomenon, which is expected to facilitate a better

Table 1. Blast outcome, nature and objectives

Blast result	Nature	Comments	MMFS objective(s)	Other constraints
Fragmentation	Regular	Desired	Optimize	
Throw (heave)	Regular	Desired	Optimize	Geo-mining conditions
Ground vibration	Regular	Undesired	Minimize	Presence of habitats nearby
Air overpressure and noise	Regular	Undesired	Minimize	Small working area
Toxic gases and fumes	Regular	Undesired	Minimize	Production scheduling
Flyrock and excessive throw	Random	Undesired	Eliminate	
Back break	Random	Undesired	Minimize	

Table 2. Accident statistics of reported flyrock cited by different authors

Reference	Period	Blasting injuries	Percentage of flyrock injuries in blasting related accidents
Mishra and Mallick[11]	1996–2011	30	24.19
Verakis[10]	2010–2011	18	38.00
Bajpayee *et al.*[9]	1978–1998	281	40.57
Verakis and Lobb[19]	1994–2005	168	19.05
Little[20]	1978–1998	412	68.20
Kecojevic and Radomsky[21]	1978–2001	195	27.69
Adhikari[22]	–	–	20.00

investigation regime for forthcoming R&D efforts on its prediction.

Despite the fact that flyrock consumes only 1% of the explosive energy used in a blast[8], it is more serious in nature, in comparison to ground vibrations, as it can inflict damages, injuries and fatalities. Several authors have reported that 20–40% of the blasting related accidents are due to flyrock[9–11]. The research on flyrock is, however, abysmal[12] and considering the above-mentioned facts, the problem deserves more attention from the researchers.

Hence, it is essential to identify the reasons for lack of R&D on flyrock. Under or non-reporting of flyrock[3] probably due to heavy penalties imposed by regulatory agencies, high cost of experimentation, and the random nature of flyrock are some of the reasons identified for inadequate R&D on flyrock. Such limitations are the cause for low confidence with regard to the existing predictive models of flyrock distance.

One of the downers in flyrock prediction is its random nature, as one cannot generate a flyrock and need to rely on chance. Modelling of random flyrock with regular variables poses a challenge to the researchers. There have been attempts to predict the flyrock using throw or heave prediction routines but these suffer from the perils of gross generalization. Since flyrock is a potential threat to property and life, one cannot risk under-prediction. Over-prediction on the other hand, may adversely impede the production of a mine.

A survey of the literature also points to a departure in identified causative variables and those used for prediction (Table 3). One of the important observations from Table 3 is that despite the fact that improper burden, geology and associated anomalies are identified as major causes of flyrock, these do not find place in predictive models as parameters.

Table 3 gives an idea about the fact that the geology and many other variables do not find place in the prediction of flyrock distance despite the fact that stemming and specific charge assume importance in predictions.

Based on the above comparison (Table 3), the following conclusions can be drawn and major factors and research gaps in flyrock prediction identified:

1. Rock mass properties are mentioned as a cause but find little place in predictive models.
2. Specific charge q, a ratio of explosive quantity in a blast hole to the product of blast geometry, viz. burden B, spacing S and bench height H_b, i.e. $(B \times S \times H_b)$. Some models still use q and B, S, H_b in a single equation despite the fact that these are in-built in the specific charge. The conditions in which blast geometry was varied keeping specific charge constant are not mentioned in the derivation of such models. Under such circumstances the repetition of influencing factors in the flyrock predictive models is obvious. This makes the models statistically redundant. There are possibilities to combine different variables of rock mass and blast design in a better manner to reduce the number of variables in a flyrock distance prediction model.
3. Density of the explosive has been used in a few models only, but the actual borehole pressure has not been modelled and estimated for prediction of flyrock distance.

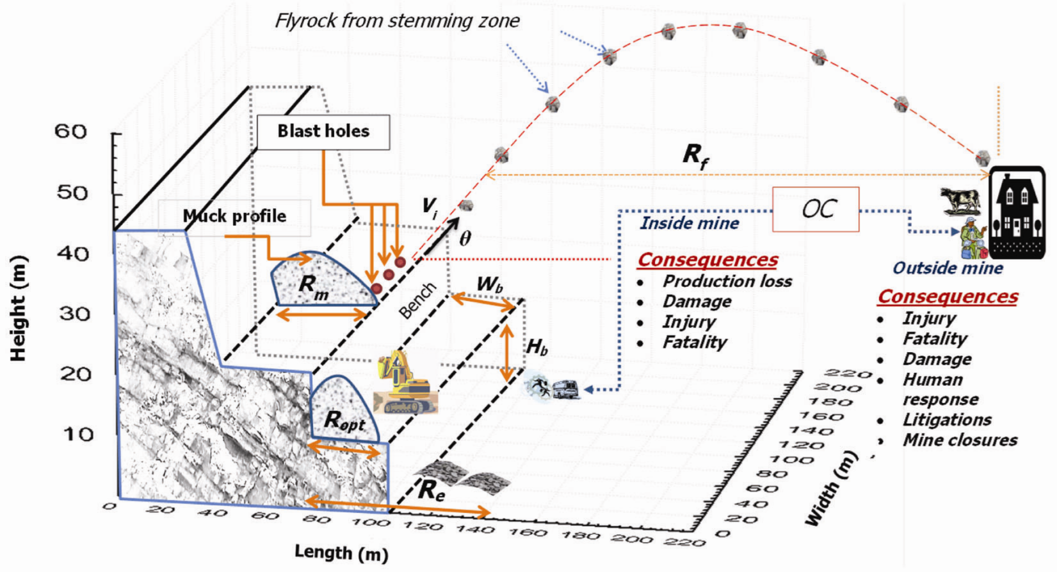

Figure 1. Description of throw, excessive throw and flyrock. H_b, *Bench height;* W_b, Bench width; R_e, Excess throw; R_f, Flyrock distance; R_{opt}, Optimum throw for loading efficiency; V_e, Exit or maximum velocity of flyrock; θ, Launch angle of flyrock and OC, Objects of concern.

Table 3. Comparison of causative factors and their use in flyrock distance prediction

Causative parameters		Prediction parameters	
Parameter	Citations	Parameter	Citations
Burden	13	Stemming	10
Geology	13	Specific charge	8
Stemming	10	Hole depth	7
Excessive explosive	6	Burden	6
Inadequate delay	6	Spacing	6
Improper blast layout	5	Blasthole diameter	6
Poor confinement	4	Density of rock	5

4. Ambiguity exists in throw, excessive throw and flyrock in most of the recent publications of 2011–2013.
5. Stemming is used a major factor in prediction of flyrock distance. The nature of stemming which is different from the rock being blasted is altogether ignored.

This brings us to the question about our understanding of the flyrock problem. In this context, it is important to remember that flyrock distance prediction involves two scientific domains, viz. (a) the impetus imparted by the explosive pressures to the fragment under the influence of confinement, and (b) the trajectory physics of uneven shapes travelling in air and their rebound from the landing surface. These two domains are detailed further.

(A) Impetus in terms of the initial velocity of flyrock is dependent on: (i) Blast geometry and its departure from the design; (ii) Rock type; (iii) Rock mass and its anomalies.

(B) Post-release trajectory physics defined by: (i) Launch angle of the flyrock; (ii) Shape of the flyrock; (iii) Size and weight of the flyrock; (iv) Magnus effect; (v) Rebound from the surface of landing.

Thus, it is imperative to lay down the basis for flyrock distance prediction and in support of which McKenzie[13] mentions ‘A reliable flyrock model must be able to provide reasonably accurate estimations of both projection velocity and projection distance, ideally as a function of the fragment size and blast design’. It is assumed that rock mass conditions are included in the blast design for flyrock distance predictions.

Flyrock prediction methods

The prediction of flyrock as is evident in the literature has been attempted by two methods, viz. (i) empirical and (ii) semi-empirical/trajectory physics based equations.

Empirical

Several models have been proposed recently to predict the flyrock based on the design variables and the explosive properties. These models have inherent errors and do not incorporate the rock mass properties which are important in determining the flyrock distance. The empirical methods demand analysis of the rock, explosive and blast design variables through a comprehensive database to arrive at a feasible solution for flyrock distance prediction. Since the same set of variables assumes importance in prediction of throw and flyrock distance, a clear distinction and correction for factors responsible for flyrock needs to be incorporated in such models.

Some of the models based on artificial neural networking (ANN) do predict flyrock with better accuracy but the scope of these is limited to the sites of investigation only. However, the ANN method provides a good basis for identification of variables dominating the flyrock distance.

Semi-empirical trajectory physics-based models

The initial velocity (V_0) of flyrock is the focus of such models. Hence such models are the most sought after. One of the models by St. George and Gibson[2], and questioned by Little and Blair[14] and later modified by Stojadinović *et al.*[15] is given in eq. (1)

$$V_0 = \frac{3\rho_e C_d^2 \Delta t}{32\phi\rho_r}, \tag{1}$$

where ρ_e is the density of the explosive (g/cm^3), C_d the velocity of detonation (m/s), Δt the length of impulse time, ρ_r the density of rock (g/cm^3) and ϕ is the diameter of the particle.

The drawbacks of such models are as follows:

1. The definitions of velocity of detonation (c_d) and density of the explosive (ρ_e) used for determination of the blast-hole pressure and impact are not explicit. There is sufficient evidence to suggest that the generalized equations do not necessarily reflect the of blast-hole pressure generated as propounded by Cunningham[16]: 'The rule of thumb that Detonation Pressure, $P_{cj} = (\rho_e \times c_d^2/4)$ is only an approximation, and becomes increasingly incorrect with non-ideality. Using the detonation velocity to estimate pressure in the borehole for blasting calculations is therefore futile. This pressure is in any case not exerted on the borehole walls'. Any predictions based on such premise are thus questionable.
2. The time of impact used in such equations is assumed from empirical observations and not from actual monitoring. Such time of impact, assumed to be of the order of 10^{-6} s, is doubtful as the flyrock emerges some time later after breakage of the rock that takes the order of 10^{-4}–10^{-2} s (as also shown by Yu *et al.*[17]). This implies that the flyrock impact is for longer duration but with lesser pressures in contrast to that assumed in such equations.
3. The post-release mechanism is complex in nature and is assumed to be just dependent on the air drag assuming fragments of spherical shape, while there are several other factors detailed below that have strong influence on the flyrock distance.

   (a) Launch angle – strongly controls the overall range and direction of the flyrock.
   (b) Air drag – determined by the fragment shape, size and weight and its initial velocity of the fragment.
   (c) The wind velocity.
   (d) Magnus effect – the translation of fragments during their travel in air.
   (e) Rebound of the fragments after their landing on the surface.
   (f) The overall topography of the mine, including altitude of the blast and landing place.

Flyrock and blast danger zone

Assuming that the flyrock distance is predicted with reasonable accuracy, the objectives of the prediction mechanims do not end, since the regulatory authorities will be interested in the risk involved and back calculations of the range of a flyrock to define the blast danger zone (BDZ).

Before elucidating BDZ, it is important to define the objects of concern. There are several subjects which come into picture with respect to flyrock in and around the mines. These subjects are designated as 'objects of concern' (OC) and are classified as given in Table 4.

OC assume importance since the consequences of flyrock entail similar cost of damages irrespective of structures, persons, livestock and equipment belonging and not belonging to the owner of a mine. The definition of OC thus lays foundation for definition of a BDZ.

In order to define BDZ, it is essential to work out the probabilities of an event and its consequences, which define the risk involved. Equation (2) defines the method to evaluate the risk.

$$\text{Risk} = \text{Probability of an event } p(E) \times \text{consequence of an event } C(E),$$

or

$$\text{Risk} = p(E) \times C(E). \tag{2}$$

Probability of a flyrock range exceeding the permissible limit, at a particular mine, can be worked out from monitored data of a mine and its probability density function that generally assumes a Weibull distribution. However, the consequence (cost and/or penalties) of the flyrock event is not known or is difficult to estimate (since it involves fatalities also), a threat ratio (T_r) representing $C(E)$ as shown in eq. (3), was defined by Raina *et al.*[18] to represent the consequence.

$$C(E) = T_r = \frac{R_{perm}}{R_{obj}}, \tag{3}$$

where R_{perm} is the permissible or acceptable range of flyrock, R_{obj} the distance of OC from the blast site and T_r threat ratio.

Table 4. Definition of objects of concern with respect to flyrock risk domain

Object of concern	Concern	Nature with respect to blast	Penalty level
Residents in nearby dwellings	Injury	Static	High
Personnel within the mine or blasting zone	Injury or fatality	Shifting	High
Structures outside the mine area	Damage	Static	High
Structures within the mine area	Damage	Shifting	Low
Equipment belonging to the mine	Damage	Shifting	Low
Equipment not belonging to the mine	Damage	Static	High
Livestock not belonging to the mine	Injury, fatality	Static	High

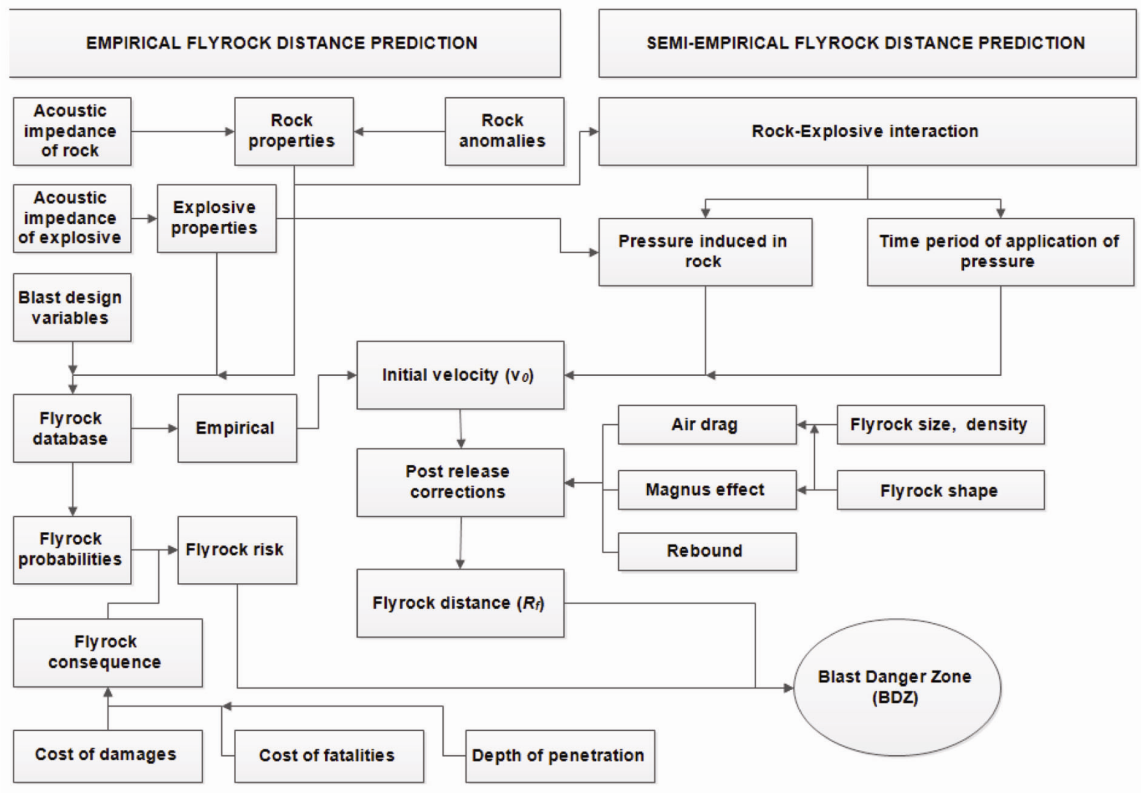

Figure 2. Flyrock and Blast Danger Zone prediction mechanism.

C(*E*) is a measure that can provide a method to define BDZ in a dynamic manner while evaluating the risk due to flyrock.

Focus of research – the way forward

In light of the above discussions, it is imperative to have a rethinking to resolve the issue of flyrock. This will require action on several fronts, viz.

1. Generating a significant sized database to establish a probability density function of flyrock.
2. Understanding the rock explosive interaction in definite terms while deliberating comprehensively on explosive properties, rock properties and eliminating ambiguities in rock and explosive characterization. This should include proper weightage to anomalies in rock mass that results in flyrock.
3. Developing a predictive mechanism with focus on the physics of flyrock generation based on specifics of point 2 above and differentiation of throw, excessive throw and flyrock.
4. Definition and quantification of consequences relevant to flyrock and a plausible solution for risk in conjunction with the probability of occurrence of flyrock in a particular geo-mining condition.

In line with the above, Figure 2 depicts a brief futuristic approach to the problem of flyrock distance prediction and definition of BDZ.

Figure 2 explains two comprehensive methods to approach the flyrock distance prediction and BDZ definition.

The first approach is to generate a significant database incorporating the rock, explosive and blast design variables to predict flyrock with a better degree of confidence. A correction for anomalies is suggested as these are the major causes for occurrence of flyrock. The second approach is to determine the rock–explosive interaction through direct measurements, which can define the amount of pressure received by a flyrock and the time over which the pressure is applied on the flyrock. Thus the pressure can be used directly while replacing the initial velocity of the flyrock in kinematic trajectory models. This can be achieved by monitoring the pressure induced in rock mass through standard pressure probes.

Figure 2 also defines the research that is currently lacking in determination of the post-release effects of various influencing variables on the flyrock distance. These can be taken up independently and researched for possible solutions through extensive experimentation.

The estimation of probability and risk as explained can be possible through a comprehensive database of the flyrock distances measured and the penalties imposed on the mines on account of flyrock. Experimentation on depth of penetration of flyrock can also provide an idea of the flyrock damage. Once the above issues are resolved, a proper scheme for defining the BDZ can be evolved with a scientific basis.

Conclusion

The need for differentiation in different modes of displacement of rock due to blasting, to evolve a logical method of flyrock prediction, has been stressed in this article. The lacunae of existing flyrock predictions models have been identified. Understanding the rock–explosive interaction during blasting and projectile motion in fluid is pertinent for evolving a better model for flyrock range determination. The risk due to flyrock that is a subject of consequence and probability should define the ultimate aim of a prediction mechanism.

1. Hustrulid, W., *Blasting Principles for Open Pit Mining, Vol. 1, General Design Concepts*, A.A. Balkema, Rotterdam, 1999, pp. 285–289.
2. St. George, J. D. and Gibson, M. F. L., Estimation of flyrock travel distances: a probabilistic approach. In AusIMM EXPLO 2001 Conference, Hunter Valley, 2001, pp. 409–415.
3. Davies, P. A., Risk based approach to setting of flyrock danger zones for blasting sites. *Trans. Inst. Mines Met.*, May–August 1995, 96–100.
4. Konya, C. J. and Walter, E. J., *Surface Blast Design*, Prentice Hall Inc, New Jersey, 1990, p. 297.
5. Favreau, R. F., The prediction of blast-induced swell by means of computer simulations. *Bull. Can. Inst. Min. Metall.*, 1993, **86**, 69–72.
6. Chernigovskii, A. A., *Application of Directional Blasting in Mining and Civil Engineering*, Oxidian Press India Private Ltd., New Delhi, 1985, pp. 91–112.
7. Carter, C. L., A proposed standard for the objective measurement of muck pile profiles. In Third International Symposium on Rock Fragmentation by Blasting, ISEE, Brisbane, 1990, pp. 59–162.
8. Berta, G. L., *Esplosivo strumento di lavoro* (*Explosives: An Engineering Tool*), Italesplosivi, Milan, 1990, pp. 31–64.
9. Bajpayee, T. S., Rehak, T. R., Mowrey, G. L. and Ingram, D. K., Blasting injuries in surface mining with emphasis on flyrock and blast area security. *J. Saf. Res.*, 2004, **35**(1), 47–57.
10. Verakis, H., Flyrock: a continuing blast safety threat, 2011; http://docs.isee.org/ISEE/Support/Proceed/General/11GENV1/11v161g.pdf
11. Mishra, A. K. and Mallick, D. K., Analysis of blasting related accidents with emphasis on flyrock and its mitigation in surface mines. In *Rock Fragmentation by Blasting* (eds Singh, P. K. and Sinha, A.), Taylor and Francis, London, 2013, pp. 555–561.
12. Raina, A. K., Soni, A. K. and Murthy, V. M. S. R., Spatial distribution of flyrock using EDA: An insight from concrete model tests. In *Rock Fragmentation by Blasting* (eds Singh, P. K. and Sinha, A.), Taylor and Francis, London, 2013, pp. 563–570.
13. McKenzie, C. K., Flyrock range and fragment size prediction, 2009; http://docs.isee.org/ISEE/Support/Proceed/General/09GENV2/09v206g.pdf.
14. Little, T. N. and Blair, D. P., Mechanistic Monte Carlo models for analysis of flyrock risk. In *Rock Fragmentation by Blasting* (ed. Sanchidrián, J. A.), CRC Press, Boca Raton, Fla, 2010, pp. 641–647.
15. Stojadinović, S., Pantović, R. and Žikić, M., Prediction of flyrock trajectories for forensic applications using ballistic flight equations. *Int. J. Rock Mech. Min. Sci.*, 2011, **48**, 1086–1094.
16. Cunningham, C. V. B., Assessment of detonation codes for blast engineering. In Third High-Tech Seminar on Blasting Technology, Instrumentation and Explosives Applications, San Diego, 2–7 June 2011, p. 14.
17. Yu, Y., Qi, J. and Zhao, M., On the characteristics of rock and energy under high strain rate. Proceedings of the 5th International Symposium on Rock Fragmentation by Blasting – FRAGBLAST-5, Montreal, 25–29 August 1996, pp. 279–283.
18. Raina, A. K., Chakraborty, A. K., Choudhury, P. B. and Sinha, A., Flyrock danger zone demarcation in opencast mines: a risk based approach. *Bull. Eng. Geol. Environ*., 2011, **70**, 163–172.
19. Verakis, H. and Lobb, T., Flyrock revisited an ever present danger in mine blasting, 2007; http://docs.isee.org/ISEE/Support/Proceed/General/07GENV1/07v109g .pdf.
20. Little, T. N., Flyrock risk. In Proceedings of EXPLO Conference, Wollongong, NSW, 3–4 September 2007, pp. 35–43.
21. Kecojevic, V. and Radomsky, M., Flyrock phenomena and area security in blasting-related accidents. *Saf. Sci.*, 2005, **43**(9), 739–750.
22. Adhikari, G. R., Studies on flyrock at limestone quarries. *Rock Mech. Rock Eng*., 1999, **32**(4), 291–301.

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