

Flyrock model validation and application

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ABSTRACT

This paper presents a methodology whereby the maximum flyrock projection distances predicted by an historical (2009) flyrock model by the author can be validated through a series of field tests, without specialized instrumentation, for any blasthole diameter, charging configuration, and rock mass. Importantly, the validation studies do not require measurement of launch velocity, and are not based on finding the fragment projected the maximum distance, or those fragments projected beyond the test area. Data from the field studies conducted to date, involving 30 single holes fired fully-confined and more than 1000 fragment sizes and projection distances, are shown to be consistent with the 2009 flyrock model predictions for estimation of worst-case projection distances. The field validation studies, conducted under a wide range of conditions of blasthole diameter (89 to 270 mm) and scaled depth of burial (0.9 to 1.49 m/kg^{1/3}), confirm the appropriateness of the modification made in 2009 to the maximum projection distance formula proposed by Swedish researchers in the 1970s, which applied only for the specific case of crater blasting. The field studies also highlight the stochastic nature of collar flyrock projection distances, with maximum projection distances typically being no more than around 30% of the maximum calculated distance. The data analysis has considered the application of statistics using the methodology also presented by the aforementioned Swedish researchers. Consideration of the statistics of flyrock projection distances is shown to be a useful tool to assess, quantitatively, the probability of fragments being projected more than any specified distance from a blasthole of any specified charge configuration, as well as the probability of fragments landing within any specified area. That analysis suggests that a factor of safety of around 1.2, applied to the maximum calculated projection distance, can reduce the probability of damage or injury to a level equal to that of a fatal lightning strike (approximately 1×10^{-7}), and that increasing the factor of safety to 1.4 further reduces that probability by a factor of approximately 100.

1 INTRODUCTION

Despite being widely considered the greatest risk to human life from rock blasting associated with construction, quarrying and mining operations, the understanding of flyrock is lacking in terms of quantitative control procedures relating to the actual charging conditions for each and every charged blasthole, prior to the initiation of a blast. In the author's experience, most mining operations involve a range of blasthole diameters, a range of different rock conditions, a range of different explosive products, a range of different stemming processes, and a range of stemming lengths

and stemming types, all of which vary according to either lithology or rock hardness. Despite these variations, blast clearance distance at any one operation will typically be the same for all blasts. Excessive clearance distances, either for scheduled blasting or extreme weather, can have a significant and negative impact on pit productivity, and insufficient clearance distances can place operators, equipment and assets at risk of injury or damage. While all rock blasting operations known to the author have well-defined and carefully-followed protocols for clearing personnel and equipment prior to blasting, few operations check that those standard blast clearance dis-

tances are appropriate for even the designed charging configurations, much less the actual configurations of each and every blast hole. Some of the reasons that scientific or engineering checks and standards are not applied can be summarised as:

- Lack of awareness of, and access to, engineering-based flyrock models applicable to every-day blasting operations;
- The difficulty associated with validating any flyrock model for all conditions likely to be encountered within a mine site;
- The difficulty of obtaining reliable and accurate data relating to the as-charged condition of every blasthole in a pattern;
- The absence of a methodology whereby an appropriate factor of safety can be determined and applied to the estimated maximum flyrock range.

Every blasthole in a surface pattern represents a risk in terms of possible flyrock projection from the hole collars due to poor containment of blasthole pressure, and those blastholes firing to a free-face pose a double risk by virtue of a potentially-reduced state of confinement in the front-row burden. To help quantify collar flyrock risk, McKenzie (2009) proposed a series of relationships between the degree of charge confinement, blasthole diameter, and the maximum projection distance as a function of fragment size, involving the following concepts:

- (1) A size-dependent fragment launch velocity, using impulse equations based on early work by Lundborg (1974), and controlled by the Scaled Depth of Burial as defined by Chiappetta and Treleaven (1997);
- (2) Fragment trajectories based on equations of motion incorporating air resistance as a function of fragment size, as proposed by Chernigovskii (1985) and reproduced in Fig.1 below.

In addition to enabling calculation of the maximum flyrock projection distance, it is worth mentioning that Chernigovskii's trajectories enable calculation of the three dimensional "dome" surface, or "shroud", which con-

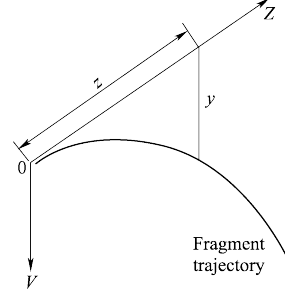


Fig. 1 Equations of motion and coordinate system presented by Chernigovskii (1985), used to construct flyrock trajectories by McKenzie (2009)

$$b_d = 0.66 \times \frac{c_x}{x_f} \times \frac{\rho_{air}}{\rho_f} \approx \frac{1.3}{x_f \times \rho_f'}, b_d \text{ is the drag factor (m}^{-1}\text{)}$$

for typical rock fragments, c_x is the dimensionless drag coefficient assumed by Chernigovskii to be 1.5, ρ_f is the density of the flyrock fragment (kg/m^3), ρ_{air} is the air density (1.29 kg/m^3 at 0°C), x_f is the fragment size (m).

$Z = \frac{1}{b_d} \times \ln(1 + b_d \times V_0 \times t)$, Z is distance measured in the original launch direction (m), V_0 is the fragment launch velocity (m/s), t is the flight time (seconds).

$y = \frac{1}{b_d} \times \ln\left(\frac{1 + \exp(2t\sqrt{b_d g})}{2 \times \exp(t\sqrt{b_d g})}\right)$, y is distance in the vertical direction (m), g is acceleration due to gravity (m/s^2).

tains all rock fragments and all possible trajectories. Intersections of the flyrock shroud and the surrounding terrain can then be undertaken.

In the context of controlling and predicting maximum flyrock range, the following points were implicit in the work presented by McKenzie (2009):

- (1) The equations of Lundborg, Chiappetta and Chernigovskii include no parameters describing stemming material properties, or rock properties, other than density (which does not affect maximum projection distance);
- (2) The equations present worst-case projection distances, and can not indicate the probability that a flyrock incident will occur for any blasthole, or within any blast pattern, nor do they predict normal projection distances.

It is therefore important to understand and separate those factors that affect maximum

projection distances, from those that affect the probability of projections occurring to the maximum calculated distances. Factors other than hole diameter and scaled depth of burial which affect the probability of a flyrock incident include the rock condition around both the charge column and the stemming column, powder factor, and delay timing, but none of these factors is considered to affect the worst-case maximum projection distance.

2 THE FLYROCK FOOTPRINT

Lundborg (1974) and Lundborg et al (1975) presented a family of curves showing maximum projection distance as a function of fragment size, for blasthole diameters in the range 0.1 inches to 10 inches, as reproduced in Fig.2.

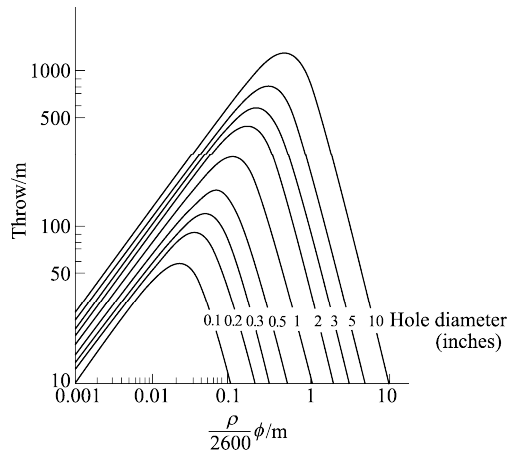


Fig. 2 Calculated maximum fragment projection distance as a function of fragment size and blasthole diameter (from Lundborg et al, 1975). Note that the abscissa represents fragment size, in metres, scaled according to the density of the fragment compared with that of granite, in which the studies by Lundborg et al were conducted

In this paper, and that by McKenzie (2009), the curves of Fig.2 are described as “flyrock footprints”, since each curve represents the limit of projection distance for fragments of different size associated with crater ejections from different diameter blastholes. In a later section of this paper, the curves will be shown not to be absolute maximum projection limits, but rather statistical limits.

Lundborg (1974) presented the empirical Eq. (1) to describe maximum throw, L'_{\max} (in metres), for all fragment sizes, as a function of hole diameter, ϕ (ϕ_{in} in inches or ϕ_{mm} in millimetres), for crater blasting as shown below.

$$L'_{\max} = 260 \times (\phi_{in})^{\frac{2}{3}} = 30 \times (\phi_{mm})^{\frac{2}{3}} \quad (1)$$

It must be stated that Eq. (1) only holds for fragments of a particular size (as given later in Eq. (6) and for all other sizes, a numerical solution is required to the Chernigovskii equations to first find the launch angle which maximises the projection distance as a function of particle size.

Lundborg (1974) also presented Eq. (2) to describe maximum throw, L'_{\max} (in metres), as a function of hole diameter, ϕ (ϕ_{in} in inches or ϕ_{mm} in millimetres), for bench blasting as shown below.

$$L'_{\max} = 40 \times (\phi_{in})^{\frac{2}{3}} = 4.6 \times (\phi_{mm})^{\frac{2}{3}} \quad (2)$$

Finally, Lundborg (1974) stated that cratering, and therefore flyrock ejection, was essentially eliminated for heavily confined blasting in which stemming length was greater than 40 times the blasthole diameter.

Lundborg (1974) presented Eq. (3) relating the launch velocity, V_0 in m/s, of ejected rock fragments to the size of those fragments, for the cratering conditions of his field tests. Note that Eq. (3) presented by Lundborg used the units of inches for hole diameter (ϕ_{in}), metres for fragment size, x_f in m, and kg/m^3 for rock density, ρ_r .

$$V_0 = 10 \times \left(\frac{\phi_{in}}{x_f - m} \right) \times \left(\frac{2600}{\rho_r} \right) \quad (3)$$

In Eq. (3), the coefficient of 10 is termed the velocity coefficient. McKenzie (2009) derived similar equations, with only the velocity coefficients being different, for the three cases of crater blasting, bench blasting and heavily confined blasting, in fully-metric form. Those coefficients (derived for blasthole diameter, ϕ_{mm} , in millimetres) were then correlated with the state of confinement of the charges as

defined by the Scaled Depth of Burial (SDoB) after Chiappetta & Treleaven (1997), as reproduced in Eq. (4) and Fig.3 below.

$$SDoB = \frac{\left(St + \frac{m}{2} \times \frac{\phi}{1000} \right)}{\sqrt[3]{W_{t_{m\phi}}}} \quad (4)$$

In Eq. (4), $SDoB$ is the Scaled Depth of Burial in $m/kg^{1/3}$, St is the stemming length in metres, ϕ_{mm} is the hole diameter in millimetres, m was assigned the value for 10 for hole diameters greater than or equal to 100 mm and 8 for smaller diameters (Chiappetta & Treleaven, 1997), and $W_{t_{m\phi}}$ is the weight of explosives, in kilograms, contained in a charge length of m times the hole diameter. Where the length of charge is less than 8 (hole diameter < 100 mm) or 10 (hole diameter \geq 100 mm), then the value of m is the ratio of charge length to hole diameter, i.e.:

$$m = \min\left(8, \frac{L_c}{\phi}\right), \text{ for } \phi < 100 \text{ mm, where } L_c$$

is the charge length, and ϕ is the hole diameter

$$m = \min\left(10, \frac{L_c}{\phi}\right), \text{ for } \phi \geq 100 \text{ mm, the}$$

term $\frac{L_c}{\phi}$ is a dimensionless ratio, i.e. L_c

and ϕ have the same units (metres or feet). Importantly, when undertaking the field tests described later in the paper, all calculations involving hole diameter, including $SDoB$, utilise the effective hole diameter, ϕ_{eff} in metres, defined as:

$$\phi_{eff} = \sqrt{(4 \times W_{t_r}) / (\pi \times \rho_{exp} \times L_c)}, \text{ where } W_{t_r}$$

is the total weight (kg) of explosive in the charge column of length L_c (metres) and ρ_{exp} is the density of the explosive in kg/m^3 .

The effective diameter therefore accounts for at least some degree of “bulling” that occurs when drilling through weak or heavily fractured rock, resulting in actual hole diameter being a little greater (typically < 10%) than the

nominal drill bit diameter.

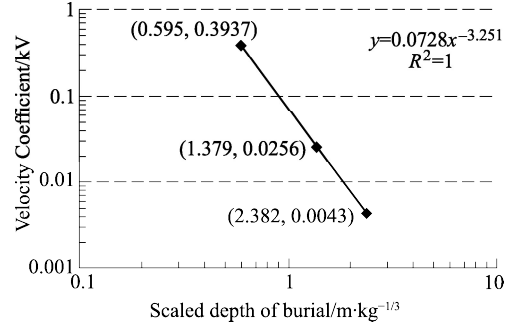


Fig. 3 Correlating the fragment velocity coefficient of Eq. (3) with Scaled Depth of Burial of the charge

McKenzie (2009) demonstrated that each of Lundborg’s observations in relation to maximum range could be covered with a single equation by the addition of a new term to Eq. (1), thereby allowing prediction of projection distance, L'_{max} in metres, from charges with any degree of confinement (crater blasting, bench blasting, and heavily-confined blasting) by incorporating the Scaled Depth of Burial term as shown in Eq. (5).

$$L'_{max} = 9.74 \times SDoB^{-2.167} \times (\phi_{mm})^{\frac{2}{3}} \quad (5)$$

McKenzie (2009) also presented Eq. (6) to estimate the size of fragment capable of being projected the distance L'_{max} for charges of any diameter and degree of confinement, and a known scaled depth of burial, $SDoB$:

$$x'_f_{mm} = 3 \times SDoB^{-2.167} \times \left(\frac{2600}{\rho_r} \right) \times (\phi_{mm})^{\frac{2}{3}} \quad (6)$$

where ρ_r is the rock density in kg/m^3 , and x'_f_{mm} is the fragment size in millimetres.

For the special case where the launch elevation is the same as the impact elevation, Eq. (6) can be re-written:

$$x'_f_{mm} = 0.31 \times L'_{max} \times \left(\frac{2600}{\rho_r} \right) \quad (7)$$

Note that the equation to calculate maximum

projection distance does not involve the fragment density, but the size of fragment capable of being projected the maximum distance does involve the fragment density.

The transformations by McKenzie (2009) effectively enabled the family of flyrock footprints presented by Lundborg (1974) in Fig.2 to describe the collar flyrock footprints for any blasthole diameter under any state of confine

ment, i.e. by simply adjusting the scaled depth of burial, or the stemming length, the flyrock footprint can be controlled to any maximum specified distance, as demonstrated in Fig.4. The values x'_f_mm and L'_{max} for each curve (shown as the solid circles) represent the coordinates of the peak of each of the flyrock footprints.

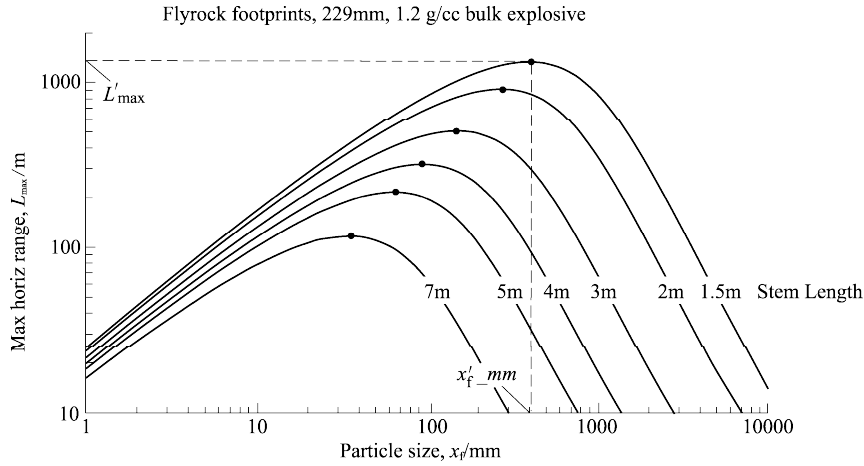


Fig. 4 Effect of variable stemming length on flyrock footprint for fixed hole diameter (229 mm), bulk explosive product density (1.2 g/cc), and rock density (2.7 g/cc)

The similarity in shape of the individual elements in the family of curves in Fig.4, and of Lundborg's family of curves of Fig.2, hints at the possibility to parameterise the curves and reduce them to a single, "universal" footprint. This appears to be possible by defining a Normalised Maximum Range for each fragment size, $L^*(x_f_mm)$, and a Scaled Fragment Size, x'_f_mm , according to Eq. (8) and Eq.(9) respectively, below.

$$\begin{aligned} \text{Normalised Range, } L^*(x_f_mm) \\ = \frac{L(x_f_mm)}{L'_{max}} \end{aligned} \quad (8)$$

$$\text{Scaled Fragment Size, } x'_f_mm = \frac{x_f_mm}{x'_f_mm} \quad (9)$$

When scaled in the above manner, the entire family of curves in Fig.2 and Fig.4 collapses to a single, scaled curve which describes the

worst-case collar flyrock footprint for any rock type, any blasthole diameter, any bulk explosive product, and any length of stemming. The peak of this monotonic function has the coordinates (1,1), and the abscissa and ordinate values for all points forming the curve in Fig.5 are expressed as percentages of x'_f_mm and L'_{max} respectively. The universal footprint can be derived by appropriate scaling, as above, of any SDoB-specific flyrock footprint, and the curve coordinates are presented in the appendix to this paper.

The important property of all flyrock footprints is that they define the maximum projection distance for rocks of all sizes, though it is necessary to define "size" in relation to flyrock fragments, as used in this study. A rock fragment is considered to have three dimensions according to the following definitions:

- Minimum dimension is the narrowest gap

of infinite length through which the fragment can be made to pass;

- Intermediate dimension is the minimum circular opening through which the fragment can be made to pass;
- Maximum fragment dimension is the greatest distance between any two points.

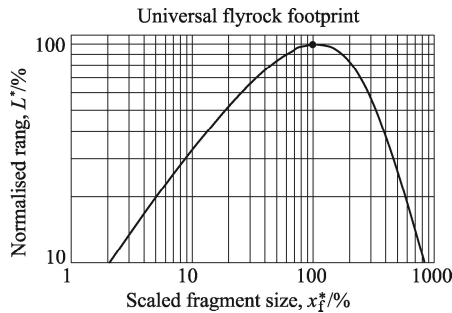


Fig. 5 The universal flyrock footprint applicable for all rocks, all blasthole diameters, all bulk explosive products, and all stemming lengths

Chernigovskii (1985) considers fragment size in his trajectory equations to be “the size of the edge of a cube of a volume equal to the volume of a parallelepiped which circumscribes the given fragment.”, and further states that the ratios of maximum to intermediate to minimum dimensions for rock fragments are typically 1.6 : 1.0 : 0.6. The size of fragments as presented in this paper is taken to be the intermediate fragment dimension, or 0.6 times the maximum fragment dimension.

3 VALIDATING THE MODEL

One possible method of validation is to use Eq. (5) relating the maximum projection distance to the scaled depth of burial. A series of single hole tests could be arranged in which the stemming height is varied, and the maximum fragment projection distance is plotted against the scaled depth of burial. The problem with this method of validation is that it requires firstly that the rock which travels the maximum distance be unambiguously identified, found, and surveyed, and secondly that the same rock should be of the optimum size which maximises the projection distance. Many repeat tests would be required before

such validation could be achieved.

A more practical validation process recognises that the flyrock footprint defines the maximum limit of projection for fragments of any defined size, under worst-case conditions, for a known scaled depth of burial. It should therefore be possible to validate the model by measuring the size and projection distance for the larger rock fragments located relatively close to a single, fully-confined blasthole with a known scaled depth of burial. Fig.6, for example, shows the expected worst-case flyrock radiation pattern from a Monte Carlo simulation of 5000 fragment projections of random size between 150 and 350 mm, using Chernigovskii’s equations, for a 229 mm diameter hole with 4.5 metres of stemming and charged with a bulk explosive of average in-hole density 1.1 g/cc, and a SDoB value of $1.19 \text{ m/kg}^{1/3}$. While the flyrock model for this case estimates a maximum projection distance of 248 metres for a fragment of size 69 mm, fragments in the size range 150 to 200 mm are not predicted to be projected more than approximately 200 metres, and fragments in the range 300 to 350 mm are not expected to be projected more than approximately 100 metres. While it may not be possible to establish the maximum projection

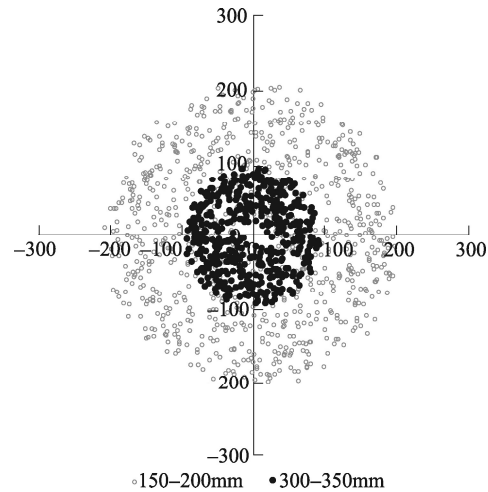


Fig. 6 Projection footprints for fragments in the size range 150 to 200 mm, and 300 to 350 mm, for 229 mm diameter blasthole and Scaled Depth of Burial of $1.19 \text{ m/kg}^{1/3}$
(Axes show distance in metres)

distance for fragments in the size range 150 to 200 mm if they are projected beyond the cleared test area, the maximum projection distance for those rocks can be deduced from measurement of the maximum projection distances of the 300-350 mm fragments located closer to the blasthole collar. Importantly, it is considered neither necessary nor practical to attempt to validate the model by trying to find the furthest-projected fragments.

Data reported in this paper were obtained from a series of single-hole firings in vertical holes of varying diameter (89 to 270 mm), drilled to depths of 15 to 20 metres with a minimum charge length of approximately 10 metres, and with aggregate stemming lengths varying from a minimum of 1.5 metres at 89 mm diameter to a maximum of 5 metres at 270 mm diameter, consistent with the minimum stemming lengths deployed at the different mine sites. Single holes were fired, without a free face, with a separation distance of approximately 200 metres on a very carefully cleaned and prepared bench so that flyrock fragments as small as approximately 60 mm (intermediate dimension) could be readily identified and assigned to a specific test blasthole. Efforts were made to video-record each test using multiple drones, but the critical data collected were the intermediate dimension and the projection distance for multiple (~10 to 200) fragments per hole from those tests which generated significant flyrock ejections. Fragments identified for tagging were the larger fragments (up to a maximum size of approximately 1 metre) which tended to be located within 50 to 150 metres of the hole collar. In general, it was not possible to correct the measured projection distance for fragment rolling after impact, though for the large and heavy fragments it was often possible to identify the impact location due to significant “divots” in the bench surface. Both video records and “divots” suggest that rolling of up to about 10 metres after impact is not uncommon.

An important observation during the field work was that on many occasions, flyrock was restricted to less than a 20 metre radius of projection around the hole, despite the relatively

short stemming lengths used and the fully confined nature of the charges. In competent ground, and at scaled depth of burial around 1.1 to 1.2 $\text{m/kg}^{1/3}$, flyrock projection distance was often minimal, especially if the rock condition around the hole collar was competent. Flyrock ejections to the maximum expected projection distance do not always occur even for fully-confined charges. This could at least partially explain the flyrock occurrence statistics presented by Little (2007), and is consistent with Lundborg’s field studies in which the maximum measured projection distance was only 25 metres, compared with his maximum calculated projection distance of 260 metres.

For each test, the blasthole loading conditions were carefully controlled in terms of hole depth, weight of bulk explosives (ANFO or 1.2 g/cc heavy ANFO) loaded, and stemming length. In competent rock and with scaled depth of burial greater than 1.1 $\text{m/kg}^{1/3}$, flyrock projection distances tend not to exceed approximately 20% to 30% of the worst-case distance calculated by the flyrock model. Flyrock distances were considerably greater in holes where the collar conditions were poor, due either to inherent rock condition (e.g. weak, oxidised coal), or due to sub-drill damage from the previous bench. Examples of the more energetic responses of holes in the test programme are shown in the photographs of Fig.7.

Tests were also conducted in holes which had been charged but not stemmed, since such conditions sometimes occur on patterns in the process of being loaded, but which have been evacuated due to approaching electrical storms. More work is required with these hole conditions since the Scaled Depth of Burial term assumes the presence of collar stemming.

Since loading conditions were precisely known, the scaled depth of burial was accurately determined for each test and the scaling and normalising terms (x'_f mm and L'_{\max} respectively) of Eq. (5) and Eq. (6) were reliably calculated. The tests involved scaled depth of burial values in the range 0.9 to 1.49 $\text{m/kg}^{1/3}$, and the results are presented in Fig.4 below. Attempts were made to also include the data in

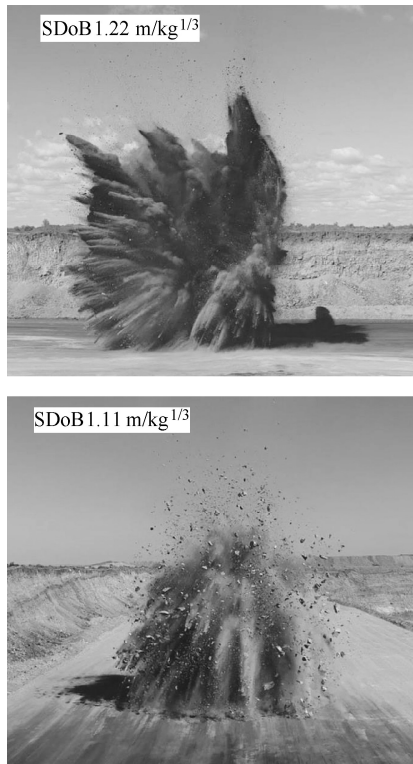


Fig. 7 Frames from drone video records for two flyrock tests in a coal mine

Fig. 4 from the paper by Lundborg (1974), but that author did not report the critical details of

the linear charge load (kg/m), or stemming/uncharged collar lengths, thereby making it impossible to determine the scaled depth of burial for the data reported. Back analysis using the flyrock model proposed here suggests that the stemming lengths were not longer than approximately 0.3 metres in Lundborg's field tests with holes of 1 inch diameter.

The following important observations are worth noting from Fig. 8:

- All points, representing easily-identified flyrock fragments within the test area, lie within the universal footprint, for all tests, even assuming no fragment rolling on most occasions. If fragment rolling distances could be subtracted from all measured distances (i.e. the points in Fig. 8 moved vertically downwards), there would be a small increase in the amount of white space between the measured points and the normalised footprint.
- Scaled Depth of Burial was not necessarily the factor having the controlling influence on maximum projection distance—the condition of the rock around the stemming zone appears to also have a strong influence (the grey-shaded squares in Fig. 8, with $SDoB$ 1.22 m/kg^{1/3})

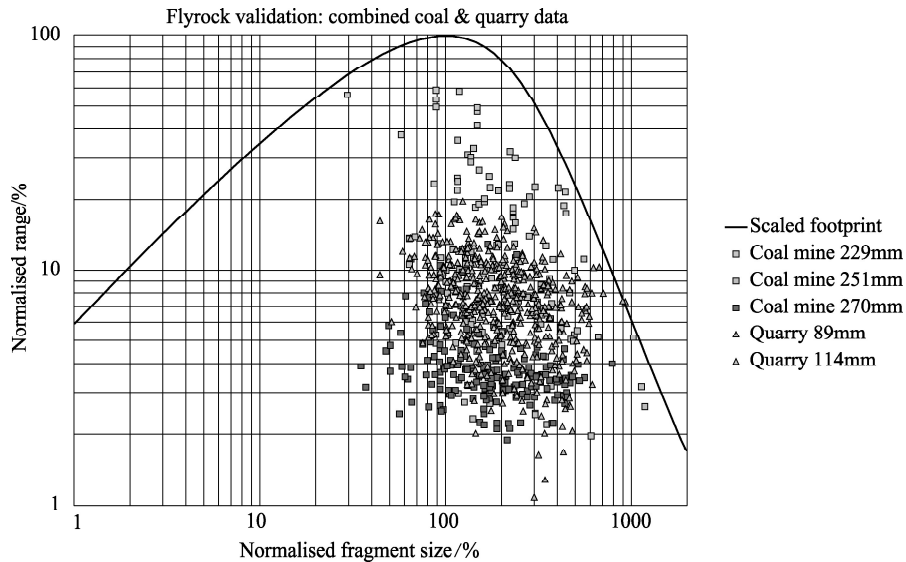


Fig. 8 Overlay of test data, with varying scaled depth of burial ($SDoB$) and hole diameter, on the universal flyrock footprint

involved oxidised coal for almost the entire stemming zone, and the condition of the rock around the charge may also have a strong influence, with ejection being suppressed if the rock surrounding the charge is soft and easily deformed;

- Even where rock condition in the hole collars was poor, maximum measured flyrock projection distance did not exceed the distance calculated by the flyrock model. The maximum projection distances derived using the model appear to represent worst-case outcomes;
- In one test without stemming, and explosive loaded to 4 metres of the collar in a 251 mm diameter hole ($1.015 \text{ m/kg}^{1/3}$), ejection was predominantly vertical, with a maximum horizontal projection distance of only 52 metres;
- While thousands more data points could have been added to the graph for each test (see the images in Fig.7), they would all have been positioned below the existing point clusters, and would have added no additional value to the validation process.

4 APPLYING THE MODEL

Once it has been demonstrated that the flyrock model can reasonably-easily be validated through field tests under actual site conditions, the next task is to consider how the model can be applied, taking into consideration the probability of a flyrock accident, in the form of either human injury or equipment damage. This requires an assessment of the extent to which the probability of damage can be reduced to an acceptable level by applying a Factor of Safety to the calculated projection range using Eq. (6). The US Office of Surface Mining (2012), focused on flyrock control in US coal mining operations, for example, effectively requires a Factor of Safety of 2 in the statement “*Flyrock travelling in the air or along the ground shall not be cast from the blasting site more than one-half the distance to the nearest dwelling or other occupied structure*”. But, what do we really know about the probability of rock travelling beyond the calculated maximum range,

and by how much does a factor of safety of 2 reduce the probability of injury or damage?

Lundborg (1979) essentially reported that his flyrock range equation (Eq. (1)) published in 1974 is not an absolute maximum range, and presented a methodology to determine the probability that one or more rock fragments would be projected a distance greater than the distance determined from that equation. The methodology was based on field data which showed that the distribution of the number of flyrock fragments with projection distance followed a Weibull curve, Eq. (10), for which the parameter values R_0 and m were determined by curve fitting.

$$S = 1 - \text{Exp} \left(- \left(\frac{R}{R_0} \right)^m \right) \quad (10)$$

In Eq. (10), R is the distance, in metres, from the blasthole collar, and S is the cumulative fraction of the total number of projected fragments projected a distance equal to or less than R . It is assumed that Lundborg only considered fragments which were easily identifiable and that the fragment count was constrained to those particles easily found and identified, and that fine particles were ignored. Consideration of Chernigovkii’s equations of motion and Lundborg’s original flyrock footprint curves, both suggest that the motion of small fragments is strongly retarded by air resistance and that such fragments do not generally represent a significant flyrock risk.

With reference to the Weibull curve and its parameters, Lundborg (1979) presented both everyday death statistics (suicide, motor vehicle deaths, accidental drowning, and a fatal lightning strike) and flyrock projection statistics associated with the maximum calculated projection distance of 260 metres for field tests with a 1 inch diameter blasthole:

- (1) For a single fragment to be ejected and travel beyond the calculated maximum distance (i.e. beyond a factor of safety of 1.0), the probability is 1 in $10^{8.5}$, or approximately 1 in 316 million;

(2) For a single fragment to be projected and land within a specific 1 square metre area beyond the maximum calculated distance (i.e. beyond a factor of safety of 1.0) is 10^{-13} , or 1 in 10 trillion;

(3) For 10^9 fragments ejected (suggested by Lundborg, 1979, as possibly representing all ejections over the course of one year of blasting at a particular site), the probability of one or more fragments being projected beyond the calculated maximum distance (i.e. beyond a factor of safety of 1.0) is 90%;

(4) For 10^9 fragments ejected (e.g. all ejections over the course of 1 year of blasting at a particular site), the probability of one or more fragments landing within a specific 1 square metre area beyond the maximum calculated distance of 260 metres (i.e. beyond a factor of safety of 1.0) is 1 in $10^{3.95}$, or 1 in 8900.

Lundborg (1979) proposed that for a cumulative probability function of the form of Eq. (10), the probability that N fragments ejected from a single hole should all fall inside the maximum calculated distance, R_{\max} is given by Eq. (11), and therefore the probability that one or more fragments will fall outside the maximum distance is given by Eq. (12).

$$P(< R_{\max}) = \left[1 - \text{Exp} \left(- \left(\frac{R_{\max}}{R_0} \right)^m \right) \right]^N \quad (11)$$

$$P(> R_{\max}) = 1 - \left[1 - \text{Exp} \left(- \left(\frac{R_{\max}}{R_0} \right)^m \right) \right]^N \quad (12)$$

Lundborg (1979) further proposed that the probability, ΔP , of a single fragment falling between a distance R and $R+\Delta R$ (i.e. an annulus of area of width ΔR), for $\Delta R \ll R$, can be derived from differentiation of the Weibull equation, as presented in Eq. (13):

$$\Delta P = \frac{dP}{dR} \times \Delta R = \Delta R \times \frac{m}{R_0} \left(\frac{R}{R_0} \right)^{m-1} \times \text{Exp} \left(- \left(\frac{R}{R_0} \right)^m \right) \quad (13)$$

and that the probability, $P(\Delta A)$, of one or more rocks, from a total of N rocks ejected, falling within an area, ΔA , within the annulus ($\Delta A = \Delta L \times \Delta R$, the shaded area in Fig.9) is given by Eq. (14).

$$P(\Delta A) = 1 - \left[1 - \left(\frac{\Delta L}{2\pi R} \right) \times \Delta R \times \left(\frac{m}{R_0} \right) \left(\frac{R}{R_0} \right)^{m-1} \times \text{Exp} \left(- \left(\frac{R}{R_0} \right)^m \right) \right]^N \quad (14)$$

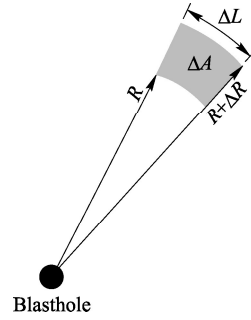


Fig. 9 Area of potential impact remote from blasthole collar.

The impact area $\Delta A = \Delta R \times \Delta L$

In relation to the number, N , of rock fragments ejected from a single hole, an upper value could be considered to be the volume of the crater with internal angle of 90 degrees, divided by the volume of a fragment of size x'_f , namely:

$$N = \frac{\pi r^2 h}{3} \times \frac{2.2}{(x'_f)^3}$$

Where h is the depth of the crater (m), r is the crater radius (m), x'_f is the fragment dimension (m) of Eq. (7), and $\frac{2.2}{(x'_f)^3}$ is the

volume (m^3) of the rock fragment capable of achieving maximum projection distance as presented by Chernigovskii (1985).

For a hole of diameter 229 mm, with 4 metres of stemming, and a bulk explosive of density 1.1 g/cc ($SDoB = 1.09 \text{ m/kg}^{1/3}$), the maximum crater depth is expected to be approximately 5

metres (stem length plus 5 times hole diameter), the crater radius is expected to also be around 5 metres (90° cone angle), and the volume of the fragment capable of achieving the maximum projection distance (Eq.(7)) is approximately $\frac{0.092^3}{2.2} = 0.00035\text{m}^3$. Under

these conditions, the maximum possible value of N is estimated to be around 4×10^5 . The value of N decreases to around 1×10^5 for a hole diameter of 102 mm with $SDoB$ $1.09 \text{ m/kg}^{1/3}$, and as stemming length is reduced with this hole diameter, to a value less than 1000 for scaled depth of burial of $0.6 \text{ m/kg}^{1/3}$ (cratering conditions).

Probability curves have been created, following the principles presented by Lundborg (1979), with the everyday death statistics updated according to more modern published data (Insurance Information Institute, 2016), in Fig.10 below, for the case of one or more fragments falling within an area of ten square metres, and a hole diameter of 229 mm. The area of ten square metres is considered to conservatively represent the exposure of the cabin of a mine vehicle.

Of interest in Fig.10 are the following observations:

(1) At a factor of safety of 1 (i.e. at a distance equal to the calculated maximum projection distance) and 0.4×10^6 ejected flyrock fragments, the probability that one or more fragments will strike a specific area of 10 square metres is approximately 4×10^{-6} , or 1 in 250,000 (point A), which is approximately 40 times more likely than a fatal lightning strike (approximately 10^{-7} , Insurance Information Institute, 2016);

(2) For an increase in the Factor of Safety of 20% (i.e. for an increase of clearance distance by 20% of the maximum calculated distance), the probability that one or more fragments will strike a specific area of ten square metres is reduced by a factor of approximately 100. Similarly, a reduction in distance by 20% of the maximum calculated distance will increase the probability by a factor of approximately 100. These trends are independent of the number of fragments ejected;

(3) The above calculations assume all fragments to be ejected from the same location, i.e. a single blasthole collar. Using the statistics of

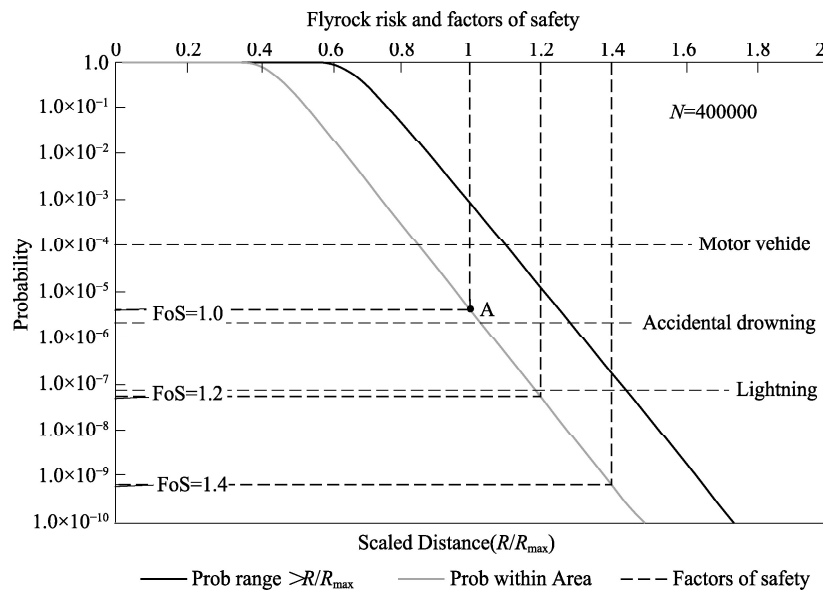


Fig. 10 The probability of one or more rock fragments being projected over different scaled distances, (upper curve) and to fall within an area of ten square metres beyond the maximum calculated projection range (lower curve)
(The parameter N is the assumed number of ejected fragments)

Fig.10, the probability of one or more fragments striking a specific area of ten square metres at a distance double the calculated maximum projection distance (i.e. factor of safety = 2) is around 1×10^{-15} . This is approximately one hundred million times less likely than a fatal lightning strike, though the statistics have assumed an omnidirectional flyrock radiation pattern. The probability could be increased by anything up to a factor of ten (i.e. preferential projection within a cone angle of 36 degrees) to account for the possibility that fragments could be ejected preferentially in a specific direction.

However, it has not been established that the Weibull distribution remains applicable to all collar flyrock ejections, or that the parameters

presented by Lundborg (1979) can be applied by simple scaling to blastholes of diameter other than 1 inch. While the task of counting the rock fragments ejected during a flyrock event is daunting to the point of being impractical, a look at Lundborg's Weibull curve (Fig.11) shows that more than 80% of the rock fragments ejected in his tests were projected less than 10% of the maximum calculated distance, and only around 0.2% of the fragments were projected more than one third of the maximum calculated distance. Stated differently, for every thousand fragments projected, no more than 2 are expected to be projected more than one third of the calculated maximum projection distance, based on Lundborg's (1974) field tests.

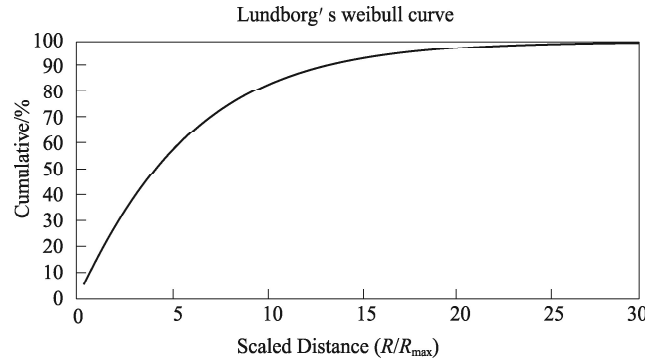


Fig. 11 Lundborg's Weibull Curve with abscissa scaled to maximum calculated projection distance, R_{max} , of 260 metres

As an indication of the possible applicability of the same Weibull parameters to, for example, the 229 mm diameter blastholes used in this field study, Fig.12 presents a plan view of the radiation pattern of rock fragments around the field test with scaled depth of burial = $1.11 \text{ m/kg}^{1/3}$. Fig.12 includes a series of markers showing the scaled distance for the test, from which it appears that very few rock fragments have been projected more than approximately 10% of the maximum calculated projection distance of 290 metres. It is proposed that scaling of Lundborg's Weibull parameter, R_0 , for different hole diameters and scaled depth of burial, can be done by:

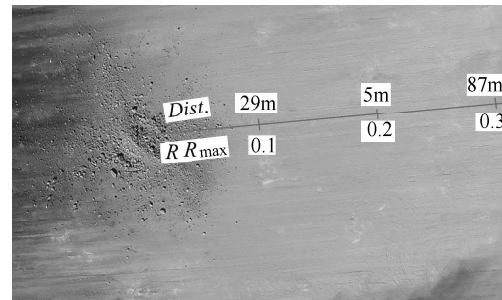


Fig. 12 Aerial view of flyrock radiation pattern around a charge with $SDoB = 1.11 \text{ m/kg}^{1/3}$

$$R'_0 = 15.309 \times \frac{L'_{max}}{260} \quad (15)$$

where 15.309 is the value for the Weibull coefficient, R_0 , obtained by Lundborg (1979) from tests with 1 inch diameter holes and a maximum projection distance of 260 m, and L'_{\max} is the maximum calculated projection distance for any other charge configuration defined in Eq. (5).

5 APPROPRIATE FACTOR OF SAFETY

Using the statistics of Fig.10, an appropriate factor of safety to be applied to the maximum calculated flyrock range for personnel safety could be considered to be as low as 1.2 (i.e. clearance distance = 1.2 times the maximum calculated flyrock range), on the basis that at this distance, the probability of any ten square metre area being struck by flyrock from a single hole which ejects 4×10^5 rock fragments is approximately the same as that of a fatal lightning strike. If the Factor of Safety is increased to 1.4, that probability reduces to be approximately 100 times lower. That is, an appropriate personnel clearance distance could be taken to be 1.2 to 1.4 times the maximum calculated projection range derived from this flyrock model, provided that calculations use the as-charged condition of every blasthole, rather than the as-designed information. A lower factor, perhaps in the range 0.5 to 0.8, could reasonably be used as the equipment clearance distance, depending perhaps on the footprint area of the equipment.

When deciding personnel blast clearance distances based on maximum calculated projection distances, it is considered imperative to use as-loaded charge configurations rather than as-designed. Small errors in stemming length, or effective hole diameter due to bulging of holes, can significantly increase maximum projection distances, especially in cases where as-designed stemming lengths are already short in order to reduce oversize generation in the stemming zone.

6 CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the studies reported in this paper, the predictions of the model pro-

posed by McKenzie (2009) appear to be worst-case projection distances likely to occur either for aggressive stemming practices (i.e. with scaled depth of burial less than approximately $0.9 \text{ m/kg}^{1/3}$), or in blastholes where the rock in the collar stemming zone is disturbed and heavily fractured. Where rock condition in the stemming zone is competent, flyrock projection distances are typically no more than approximately one third of the maximum calculated projection distances.

Validation of the model has been demonstrated to be quite straightforward, requiring minimal resources. The model reproduces Lundborg's (1974) curves when the scaled depth of burial is approximately $0.6 \text{ m/kg}^{1/3}$, effectively validating the model for his field conditions (1 inch diameter holes in granite). Recent validation has also demonstrated that the model describes very well the worst-case ejections observed in field testing with 89 to 270 mm diameter blastholes in materials ranging from soft sedimentary materials to granite, with the scaled depth of burial ranging from 0.9 to $1.49 \text{ m/kg}^{1/3}$. More work is considered necessary to confirm the model's validity over a wider range of rock type and blasthole diameter. Validation does not require all ejected rock fragments to be surveyed, or even to find the furthest-projected rock fragments.

By scaling the flyrock footprint derived for any scaled depth of burial and hole diameter, using the methodology described in this paper, it appears possible to define a universal flyrock footprint upon which data from tests in any rock type, with any bulk explosive, with any blasthole diameter and with any length of stemming, can be plotted to test the validity of the proposed model.

While the model in this paper provides estimates of the probability that an ejected fragment will be projected the maximum possible distance, it cannot provide estimation of the probability that any particular hole will exhibit the necessary intensity of cratering to cause a flyrock incident. Other published works have suggested that probability to be of the order of approximately 1 in 1,000 blasts, though this

would have to be heavily dependent on the aggressiveness of the particular blasting operation, i.e. the minimum length of stemming required to achieve desired fragmentation.

Once a reliable estimate is made of the maximum projection distance of fragments, it does not appear to be necessary to apply a large factor of safety in order to provide an acceptable level of risk to the operation. The methodology presented by Lundborg (1979) appears to be a reasonable way to arrive at any risk level considered appropriate to the blasting operation, and suggests that a Factor of Safety of 2, when applied to the model presented in this paper, produces an extremely conservative clearance distance which may adversely impact on a site's mining operations. It remains to be demonstrated, however, that the Weibull fragment distribution function derived by Lundborg can be scaled to apply to different hole diameters and different *SDoB* values.

While the field work conducted to date has confirmed the validity of the model proposed by McKenzie (2009), it is not yet considered to be sufficient to convincingly validate the fly-rock model under all conditions. The studies indicate the ease with which field work can be planned and undertaken to either support the model, or to identify the need for parameter adjustment. Importantly, validation does not require tracking of lone fragments, measurement of fragment launch velocities, or the use of expensive high-speed cameras, and model adjustment is easily accomplished if needed.

Parameter adjustment would be required if maximum measured projection distances were either consistently greater or consistently less than the maximum distances calculated by the equations presented in this paper. Appropriate adjustments would focus on the correlation in Fig. 3 between launch velocity and scaled depth of burial, or adjustment to the drag coefficient assumed by Chernigovskii (1985) to be 1.5 (affecting the value of the b_d term of Fig. 1).

Additional field work is required to allow estimation of maximum projection range for blastholes without stemming (e.g. pre-split holes or holes un-stemmed at the time of

evacuation due to approaching lightning) and blastholes with decoupled charges, including both air decks and blastholes in which the charge diameter is less than the hole diameter. Studies are also required for the case of a known electronic misfire within a blasted muckpile, potentially susceptible to lightning-induced detonation. In these situations, the rock condition around the charge is likely to be heavily disturbed and fractured, and factors including velocity of detonation and charge confinement are likely to significantly reduce maximum projection distances.

The parameterised equations in this paper provide estimates of maximum projection distances for the specific case where a flyrock fragment's impact elevation is the same as its launch elevation. The general equations, however, can be applied to any case where the impact elevation is either greater than or less than the launch elevation, and to account for any local pit topography.

Application of the model to determine safe clearance distances for blasts requires the use of actual as-loaded charge configurations for each hole in the pattern. Blast clearance distances based on as-designed charge configurations should use a higher factor of safety than those established using actual charge configurations.

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REFERENCES

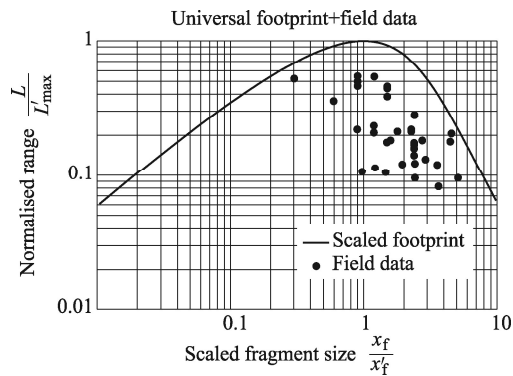
- Chernigovskii A.A., (1985) Application of directional blasting in mining and civil engineering, Chapter 4, Movement of Flyrock Subject to Air Drag, pp 91-100, second revised and enlarged edition, Nedra publishers, Moscow, 1976, published for the United States Department of the Interior and National Science Foundation, Washington DC, 1985, by Amerind Publishing Company, New Delhi.
- Chiappetta R.F., Treleaven, T., (1997) Expansion of the Panama Canal, Seventh High Tech Seminar Blasting Technology, Instrumentation and Explosives Applications, (2): 867-910.
- Little T.N. (2007) Flyrock Risk, Australasian Institute of Mining and Metallurgy, EXPLO 2007 Conference, Wollongong, NSW, 3-4 Sep., pp 35-43.
- Lundborg N. (1974) The Hazard of Flyrock in Rock Blasting, Swedish Detonic Research Foundation, Stockholm, report DS 1974:12.
- Lundborg N. (1979) The Probability of Flyrock Damage, Swedish Detonic Research Foundation, Stockholm, report DS 1979: 10.
- Lundborg N., Persson P-A., Ladegaard-Pedersen, A., et al. (1975) Keeping the Lid on Flyrock in Open Pit Blasting, Engineering Mining Journal, May, pp 95-100.
- McKenzie C. (2009) Flyrock Range & Fragment Size Prediction, 35th Annual Conference on Explosives and Blasting Technique, International Society of Explosives Engineers, Vol 2, Denver, CO.
- Office of Surface Mining Reclamation and Enforcement, National Archives and Records Administration, Code of Federal Regulations, USA, Title 30, revised as of 01 July, 2012, 30 CFR 700.1, Chapter VII, 816.67.

Appendix: Scaled Flyrock Footprint (Universal Footprint), with some Field Data

Scaled Size $\frac{x_f}{x'_f}$	Normalised Range $\frac{L}{L'_{max}}$	Eff Dia/ mm	$SDoB/ m \cdot kg^{-1/3}$	Max Calc Range/m	X_f/mm	Measured Frag Size/ mm	Measured Dist/m	Scaled Size	Normalised Range
0.01039	0.0610	232	1.110	310	102.9	250	37.8	2.43	0.12
0.02077	0.1069	232	1.110	310	102.9	300	40.8	2.92	0.13
0.05193	0.2167	232	1.110	310	102.9	200	37.3	1.94	0.12
0.08308	0.3050	232	1.110	310	102.9	375	25.5	3.65	0.08
0.10385	0.3563	232	1.110	310	102.9	125	35.1	1.22	0.11
0.15578	0.4664	232	1.110	310	102.9	150	32.6	1.46	0.11
0.20771	0.5571	232	1.110	310	102.9	100	33.0	0.97	0.11
0.25963	0.6334	232	1.110	310	102.9	250	29.4	2.43	0.09
0.41541	0.8012								
0.62312	0.9295	232	1.220	253	83.8	100	59.0	1.19	0.23
0.83082	0.9877	232	1.220	253	83.8	75	55.7	0.89	0.22
1.03853	0.9994	232	1.220	253	83.8	230	45.9	2.74	0.18
1.29816	0.9715	232	1.220	253	83.8	200	35.6	2.39	0.14
1.55780	0.9146	232	1.220	253	83.8	300	30.2	3.58	0.12
1.81743	0.8429	232	1.220	253	83.8	200	42.7	2.39	0.17
2.07706	0.7655	232	1.220	253	83.8	100	52.4	1.19	0.21
2.59633	0.6163	232	1.220	253	83.8	150	53.7	1.79	0.21
3.11559	0.4905	232	1.220	253	83.8	200	44.1	2.39	0.17
3.63486	0.3916	232	1.220	253	83.8	125	44.3	1.49	0.18
4.15412	0.3160	232	1.220	253	83.8	200	39.9	2.39	0.16

Continued

Scaled Size $\frac{x_f}{x'_f}$	Normalised Range $\frac{L}{L'_{max}}$	Eff Dia/ mm	$SDoB/ m \cdot kg^{-1/3}$	Max Calc Range/m	X_f/mm	Measured Frag Size/ mm	Measured Dist/m	Scaled Size	Normalised Range
4.67339	0.2584	232	1.220	253	83.8	375	45.0	4.47	0.18
5.19265	0.2142	232	1.220	253	83.8	50	90.0	0.60	0.36
6.23118	0.1530								
7.26971	0.1144	232	0.890	500	166.0	400	140.2	2.41	0.28
8.30824	0.0888	232	0.890	500	166.0	250	192.6	1.51	0.38
10.38530	0.0585	232	0.890	500	166.0	250	220.3	1.51	0.44
12.98163	0.0392	232	0.890	500	166.0	250	229.1	1.51	0.46
15.57795	0.0288	232	0.890	500	166.0	150	273.4	0.90	0.55
18.17428	0.0226	232	0.890	500	166.0	200	270.2	1.20	0.54
20.77060	0.0184	232	0.890	500	166.0	50	260.6	0.30	0.52
25.96325	0.0135	232	0.890	500	166.0	150	249.0	0.90	0.50
31.15591	0.0106	232	0.890	500	166.0	150	230.5	0.90	0.46
36.34856	0.0088								
41.54121	0.0075	229	1.193	263	88.0	140	48.0	1.59	0.18
51.92651	0.0058	229	1.193	263	88.0	200	58.0	2.27	0.22
103.85302	0.0028	229	1.193	263	88.0	450	25.0	5.11	0.10
		229	1.193	263	88.0	400	54.0	4.55	0.21
		229	1.193	263	88.0	200	56.0	2.27	0.21



In the above Table, the effective hole diameter (Eff Dia) was determined on the basis of the measured length, density and weight of charge in the test blastholes. In all cases the nominal hole diameter was either 229 or 251 mm. Rock was a soft sedimentary material ($UCS < 30$ MPa) which down-hole cameras revealed to sometimes display significant bulging.