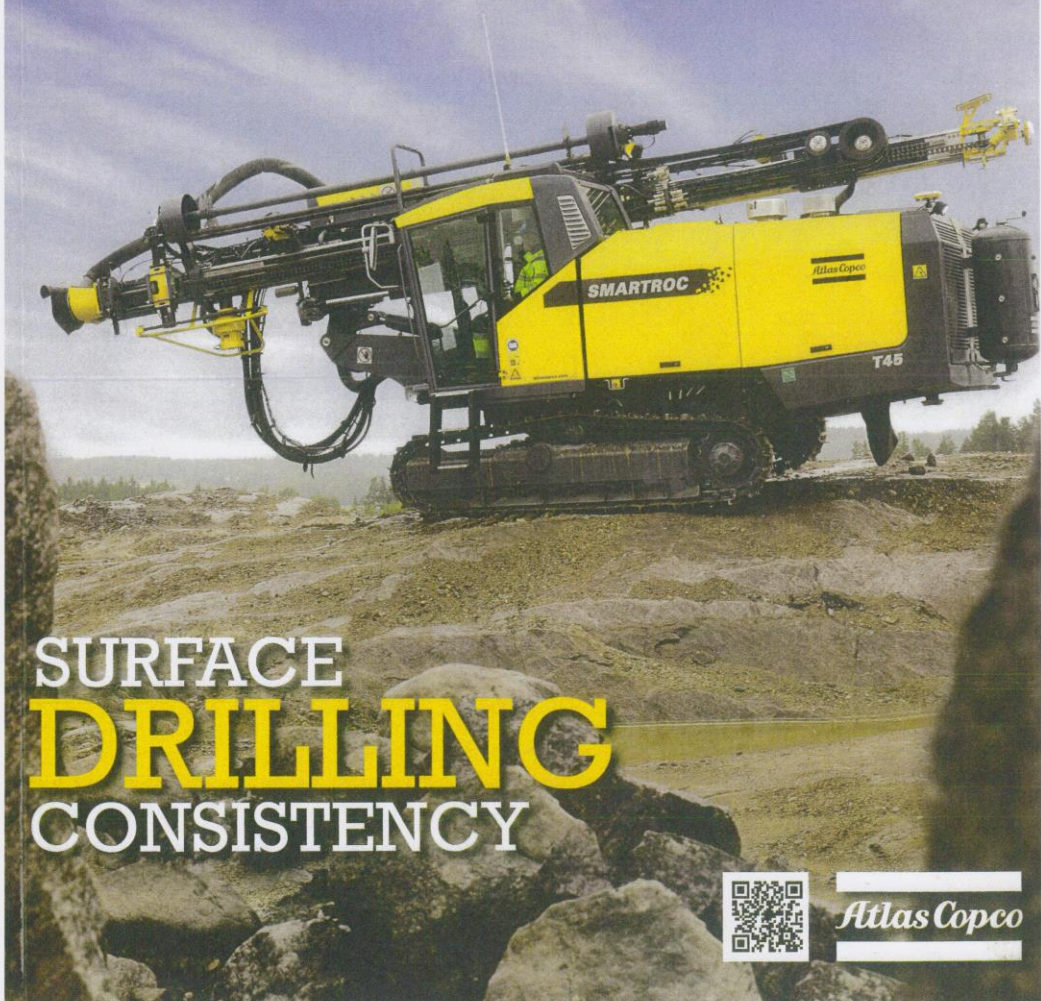


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FLYROCK PREDICTION – FROM MYSTERY TO SCIENCE

When planning blasts, flyrock remains one of the most erratic factors in the explosives process. **John Butchart** examines the predictive models that are available for estimating flyrock travel and recommended clearance zones.

Flyrock has always seemed unpredictable. One day nothing, the next day a shower of travelling stones. Traditionally, flyrock prediction and the setting of exclusion zones has been a dark art practiced by experienced shotfirers, using mysterious methods and perhaps a crystal ball.

Over the past 20 years, the art of flyrock prediction has been de-mystified and converted into science with the development of models to estimate flyrock exclusion zones. This science was discussed in *Quarry* in November 2006⁽¹⁾ but it is probably time to revisit the science and look at the latest trends.

There have been various flyrock prediction models proposed. For the most part, these have been based on trajectory theory.

TRAJECTORY MODEL OF FLYROCK

The trajectory model proposed by Workman and Calder (1994)⁽²⁾ was as follows:

$$L = (V_0^2 \times \sin 2\theta) / g \quad (1)$$

where **L** is the horizontal throw of flyrock,

in metres.

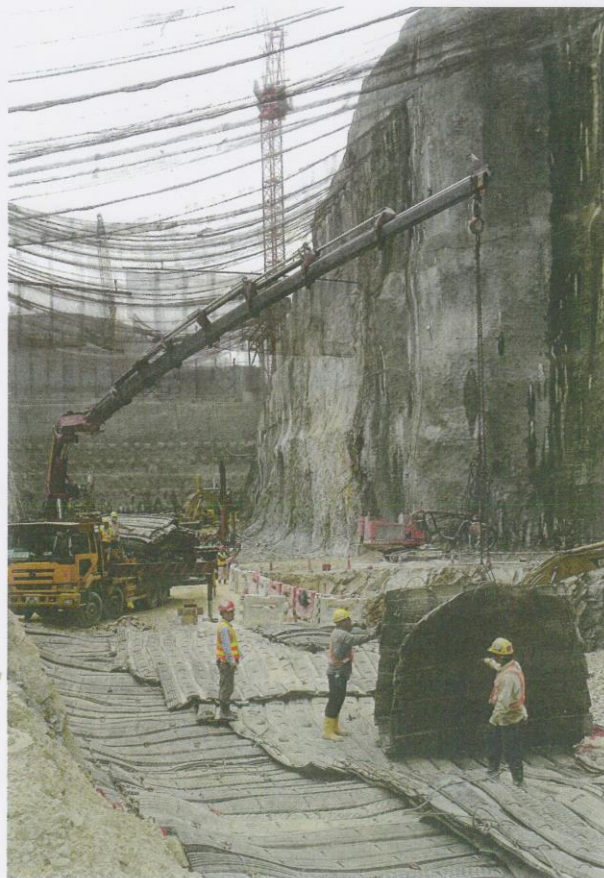
V₀ is the launch velocity in metres/second.

θ is the launch angle from horizontal, in degrees.

g is the gravitational constant, in m.s⁻².

This formula ignores drag, which is a reasonable approximation in the range of launch velocities commonly found with blasting. Drag becomes a significant factor when approaching supersonic velocities, but is difficult to model due to the need to assign a coefficient of drag to a large number of irregular rock fragments.

As the sine function is greatest when the



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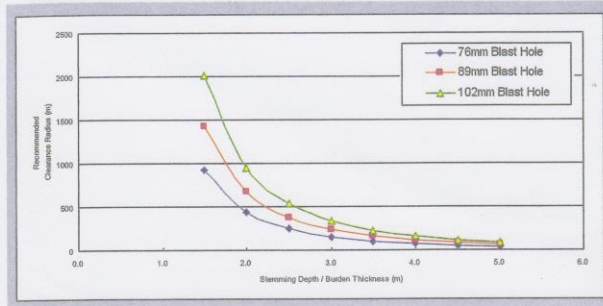


Figure 1. Graph showing the effect of blast hole diameter on recommended clearance radius.

angle is 90° (Sin 2θ = 1.0), it follows that flyrock travel is furthest when the launch angle θ is 45°:

$$L_{max} = V^2 / g \quad (2)$$

where L_{max} is the maximum horizontal flyrock throw, in metres.

This formula also ignores the elevation difference between the launch site and the target receptor, so it is reasonable to improve the formula by adding +/- H:

$$L = (V^2 / g) +/- H \quad (3)$$

where H is the elevation difference between launch and landing sites, in metres.

This formula assumes the trajectory is at 45° in a straight line, which is not quite accurate, but is again a reasonable approximation which aids in simplicity without introducing significant error.

Workman and Calder (1994)¹⁹ also proposed a methodology to calculate launch velocity. This model used a scaled burden approach:

$$V = K \times (m^{0.5} / B)^{1.5} \quad (4)$$

where K is a site constant which must be

determined empirically.
 m is the charge mass per metre of blasthole, in kilograms.
 B is the burden thickness or stemming depth, in metres.
 M^{0.5} / B is known as the "scaled burden".

TERROCK FLYROCK MODEL

Richards and Moore (2004)²⁰ of Terrock Consulting Engineers in Eltham, Victoria, combined formulae (2) and (4) above to produce the Terrock Flyrock Model:

$$L_{max} = (K^2 / g) \times (m^3 / B)^{2.25} \quad (5)$$

This again ignores elevation difference, so we may modify it accordingly:

$$L_{max} = (K^2 / g) \times (m^3 / B)^{2.25} +/- H \quad (6)$$

Richards and Moore found that K varied from blast to blast, but was generally not more than 27 in competent rock. If we adopt this value, we can simplify (K² / g) to a numerical constant of 74.39, giving us a working formula as follows:

$$L_{max} = 74.39 \times (m^3 / B)^{2.25} +/- H \quad (7)$$

This working formula assumes that K = 27. Although this is a reasonable starting point for initial estimations, it must always be remembered that K is a site constant, and must be verified independently for each new site by empirical measurements. The final part of the Terrock Flyrock Model is the clearance zones. Terrock recommends an equipment safety radius of 2 x L_{max} and a personnel safety radius of 4 x L_{max}. For the rest of this article we will ignore the less-restrictive equipment safety radius and concentrate on the personnel safety radius. The Terrock Flyrock Model was presented by its authors in *Quarry* in 2006²¹.

Using a computer-based spreadsheet, formula (7) can readily be turned into a table and graph, using 89mm holes charged at a density of 1.2g.cm³:

Table 1: Flyrock table – Bulk emulsion in 89mm holes. For 89mm holes with column charge of 7.5kg.m⁻¹, and no elevation difference.

Burden thickness / stemming depth	Ratio of blasthole diameters	Maximum likely flyrock travel	Recommended clearance radius
1.5	20.2	221.5	886
2.0	22.5	168.4	674
2.2	24.7	131.5	526
2.4	27.0	104.8	419
2.6	29.2	83.1	341
2.8	31.5	70.2	281
3.0	33.7	59.7	235
3.2	36.0	49.6	199
3.4	38.2	42.4	170
3.6	40.4	36.5	146
3.8	42.7	31.7	127
4.0	44.9	27.8	111
4.2	47.2	24.5	98
4.4	49.4	21.7	87
4.6	51.7	19.3	77
4.8	53.9	17.3	69

To see the above table plotted as a graph, refer to Figure 3 on page 17.

ROLE OF STEMMING AND BURDEN

It can be seen from the table that flyrock travel starts to increase greatly once stemming or burden get below about 40 blast hole diameters. Indeed, this is a good rule of thumb for urban or close-proximity blasting situations, and allows a clearance radius of about 150 metres, assuming flat ground.

Australian Standard AS2187.2 *Explosives – Storage and use – Use of explosives* recommends that stemming should be at least 25 times the hole diameter. From Table 1, it can be seen that this would require a clearance radius of over 500 metres. The AS2187.2 recommendation should be taken as a minimum, and be reviewed in terms of actual site conditions.

The 40 x diameter rule and the 150m clearance radius apply regardless of hole diameter, as shown by the bold numbers in Table 2. To see Table 2 plotted as a graph, refer to Figure 1 above.

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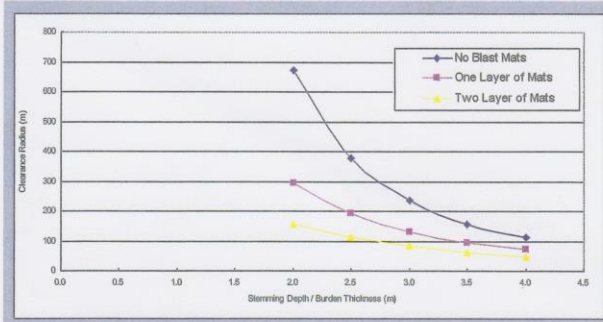


Figure 2. Graph showing the effect of stemming on clearance radius, and the reduction achieved by using blast mats.



Blast mats are constructed from steel-belted treads of used car tyres, woven with steel cable.

Table 2. Effect of hole ratio on clearance radius. For blastholes with column charge of bulk emulsion @ density 1.2g.cm⁻³ and no elevation difference.

Burden thickness or stemming depth (metres)	76mm blastholes		89mm blastholes		102mm blastholes	
	Hole ratio	Clearance radius	Hole ratio	Clearance radius	Hole ratio	Clearance radius
1.5	19.7	928.6	16.9	1423.4	14.7	2015.3
2.0	26.3	439.6	22.5	673.7	19.6	953.9
2.5	32.9	246.1	28.1	377.1	24.5	534.0
3.0	39.5	153.2	33.7	234.8	29.4	332.4
3.5	46.1	102.6	39.3	157.2	34.3	222.6
4.0	52.6	72.5	44.9	111.1	39.2	157.3
4.5	59.2	53.4	50.6	81.8	44.1	115.8
5.0	65.8	40.6	56.2	62.2	49.0	88.1

In some older textbooks there are references to stemming depth being at least 20 times the hole diameter. This refers to the minimum amount of stemming necessary to contain the explosive gases long enough to do useful work. It was never intended as a flyrock mitigation recommendation, and it isn't.

As can be seen from the above table, stemming that is only 20 x hole diameter requires a clearance zone of over 900 metres, which can be achieved on most mine sites but in very few quarries.

BLAST MATS AS ADDITIONAL PROTECTION

Adopting a stemming depth of 40 x hole diameter can lead to excessive oversize in the stemming zone, with secondary breakage costs. This can be overcome by using blasting mats as a secondary form of protection, to replace some, but never all,

of the stemming. There are many types of blasting mats available, made variously from woven rope, woven steel cables, rubber conveyor belt, plate steel, or woven tyres.

Blast mats supplied by Flintstone Group Australia are made from the steel-belted treads of used truck tyres, held together in two overlapping layers by interwoven steel cables.

These rubber tyre tread mats weigh at least 60 kg.m⁻² and come in sizes up to 6m x 3m. A typical mat will weigh between 400kg and 1200kg.

To quantify the effectiveness of a blasting mat, it is useful to look at its equivalence in stemming, ie how much the stemming column can be shortened with a layer of blasting mats on the surface.

Flintstone Group recommends that, as a conservative estimate, divide the unit weight of a blasting mat per square metre by 80 to derive the stemming equivalence. For example, a mat weighing 60 kg.m⁻² would have a stemming equivalence of 60/80, or 0.75m (750mm). For a given stemming depth, this can halve the recommended clearance zone, or more:

Table 3: Effect of blast mats on clearance radius.

Burden thickness or stemming depth (metres)	89mm holes with emulsion @ 7.5 kg/m charge		Layers of blast mats	Equivalent stemming	Revised Clearance
	Hole ratio	Clearance radius			
2.0	22.5	673.7	1	2.75	254.4
2.5	28.1	377.1	1	3.25	190.7
3.0	33.7	234.8	1	3.75	131.4
3.5	39.3	157.2	1	4.25	94.9
4.0	44.9	111.1	1	4.75	71.1
2.0	22.5	673.7	2	3.50	157.2
2.5	28.1	377.1	2	4.00	111.1
3.0	33.7	234.8	2	4.50	81.8
3.5	39.3	157.2	2	5.00	62.2
4.0	44.9	111.1	2	5.50	48.6

To see Table 3 plotted as a graph, refer to Figure 2 above.

Similar tables can be constructed for other hole diameters and other column charges, but the message is the same: blasting mats as recommended by the Australian Standard can reduce the recommended clearance

IS FLYROCK THE QUARRY PROFESSIONAL'S CURSE?

In the blasting industry, flyrock causes more deaths, injuries and asset damage than all other causes put together. A surprising statistic? A North American study of 412 lethal and non-lethal accidents in 2001 found that 27.7 per cent of these accidents were caused by wild flyrock outside the clearance zone and 45.6 per cent were due to localised flyrock within the clearance zone. A study done today in Australia would probably produce similar results.

The fact that nearly half of all accidents occurred within a zone from which people and assets were supposedly excluded is indeed interesting; it suggests that the clearance procedures might have been less than foolproof in many cases. No doubt, many of these accidents occurred to the firing party, suggesting that even our most experienced shotfirers are not bulletproof.

With flyrock being such a prominent cause of accidents, one might think that, as an industry, we would have got it all together by now. A brief scan of the incident alerts issued by the various state authorities over the past few years tells us that this is not so. We don't even seem to be making any gradual improvement.

Part of the problem may be the oft-chanted mantra that "blasting is both a science and an art". The truth may be that we invoke the "art of blasting" as a cover when we don't know or don't understand the science.

Flyrock prediction and control is a science. Flyrock follows the laws of physics and derives its energy from the laws of chemistry. There are various predictive models in existence, one of the better ones being a model derived by Victorian firm Terrock Consulting Engineers, based on numerous field measurements at various locations.

Flyrock can originate from the face of the blast, if the face is unavoidably facing in a sensitive direction, in which case careful burden measurement and control is required. It can also originate from cratering around the blast hole collar. This type of flyrock can fly in any direction and tends to have a higher launch angle.

To avoid the arithmetic, the model can be depicted as a table or as a graph (see Figure 3 above). This shows that likely flyrock throw is heavily influenced by stemming depth or burden thickness, with small decreases leading to much larger increases in likely flyrock travel distance.

The chart clearly shows that once stemming gets much below 40 times the hole diameter, the flyrock potential starts to increase very quickly.

If the science is clear, why are we still having flyrock incidents? As an industry, we don't seem to have improved over the years.

Part of the reason might be suburban creep, which

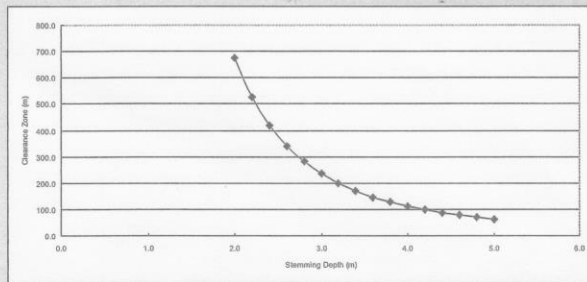


Figure 3. Stemming depth vs. recommended clearance zone for 89mm blastholes loaded with bulk emulsion at a density of 1.2 kg/m³ (courtesy of Terrock Consulting Engineers, Eltham, Victoria).

brings sensitive assets ever closer to our quarry boundaries, thus reducing the feasible exclusion zone which we can establish around each blast. A more likely reason is that increasing either stemming or burden will lead to increases in the percentage of oversize rock in the muckpile, which is expensive to reduce to a lump size acceptable as crusher feedstock. The considerable cost of secondary breaking provides a powerful incentive to reduce burden and stemming as much as possible in order to minimise the production of oversize lumps in the stemming zone.

How do we resolve these conflicting requirements? Australian Standard AS2187.2 specifies that "where protection from the possibility of fly is necessary, blasting mats or other suitable controls shall be used".

BLAST MATS

Blasting mats made from used truck tyres were first used about 50 years ago in Scandinavia, and their use has spread throughout Europe and North America. Surprisingly, they are not so commonly used in Australia, despite their availability, and despite the fact that various state regulators recommend them.

Flinstone Mining Services is importing Flinestone blast mats for use in urban blasting and sensitive areas. These mats are constructed from the steel-belted treads of used truck tyres, woven together with steel cable to make mats of various sizes, but with sufficient weight to resist the upward movement of rock, and with excellent resistance to penetration. A typical mat weighs about 60 kilograms per square metre.

Using blasting mats to cover the face or surface of a blasting area has the same effect as increasing the

burden or the stemming. Quarry professionals are advised to divide the weight per square metre by 80 to get an estimate of stemming equivalence, ie at 60 kg/m², the stemming equivalence is 60/80, or 750mm. A quick look at Figure 3 shows that an increase in stemming from 3.25m to 4.0m will halve the recommended clearance zone from 200m to 100m.

For more information, make sure you read the main feature of this section.

As an industry, we come under increasing pressure from various consumer groups and stakeholders and our extractive industries are defensible only if we operate to the highest standards of safety and community acceptability. Our regulators (and the community) require us to take all reasonable and necessary steps to avoid creating environmental hazards.

When blasting near a sensitive urban area, if we choose to minimise our stemming and we choose not to use blast mats or similar protection, we can hardly claim that we took all reasonable and necessary steps.

Perhaps it is time we stopped treating blasting as an "art" and relying on our judgement which is subject to human error. The science for flyrock prediction exists and we should use it, together with remedial protective measures where necessary.

There is no acceptable level of flyrock incidents. To embrace the science and take all protective measures will ensure the best possible outcomes for the industry and help us move forward to a "zero tolerance" policy for flyrock.

Source: Flinestone Mining Services

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A typical blast mat weighs about 60 kilograms per square metre.

zones, and reduce the risk of an unwanted and possibly tragic incident.

A final word of caution: these predictive formulae are based on measurements of worst case scenarios of flyrock throw.

Flyrock is notoriously inconsistent and a prediction of 200m does not mean that flyrock will travel 200m from every blast.

Worst case occurrences generally happen when a blast hole intersects a fault zone or is collared in broken rock which has been fractured during previous blasting.

It is easy to use an observational approach and keep on incrementally reducing the stemming.

This might work for dozens of blasts, and then there will be that one rogue blast hole that proves the formulae correct. It only takes one hole to create enough wild flyrock to create a possibly tragic situation, and at the same time risk the loss of the quarry licence, the shotfirer's licence and the company's insurance policy.

The science for predicting flyrock travel is there and we should all be using it. With the available knowledge, there is simply no excuse to prefer mystery over science. •

John Butchart is technical director of Flintstone Mining Services Pty Ltd.

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