Blasting for construction
some critical aspects

OVERVIEW

When rock blasting is required for construction projects, the technique has a critical influence on overall project progress and costs. Lack of understanding of the discipline leads to unfortunate outcomes, either through excessive constraints on the operation, or else the adoption of cheap, inappropriate technology. In general, blasting systems used for mining are inappropriate for tight control of breaking, and for protection of sensitive structures. In addition, the general inability on a construction site to permit frequent or large-scale blasting operations limits productivity and asset utilisation relative to the volume of rock. Further, the tendency to specify "ultra-safe" vibration limits for blasting, results in unnecessarily slow and expensive progress.

The problems arising from the above trends can largely be avoided by applying appropriate blasting expertise well ahead of the commencement of blasting operations, excluding inappropriate technology, and ensuring that restrictions are realistic.

A real benefit of awarding tenders in this way will be the fostering of competent blasting contractors who are able to tender and deliver on the real requirements.

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INTRODUCTION

The most common sectors of commercial blasting are shown in Table 1, each with its range of typical hole lengths, hole diameters and explosives charge per hole. The wide parameter range is a consequence of the great diversity, not only within, but especially between the sectors.

Blasting personnel from other sectors, not yet exposed to the unique demands of construction blasting, are apt to incur serious and unnecessary consequences through either over- or under-blasting, as indeed are the consultants (usually with little or no training in this area) who prescribe the blasting criteria. This article attempts to define some of the more critical distinctives.

Table 1 Typical parameters for commercial blasting

Sector	Hole diameters (mm)	Hole lengths (m)	Charge/hole (kg)
Strip mining	200–345	10–40	240–3200
Opencast mining	150–311	3–15	40–1000
Quarrying	75–150	5–12	17–190
Construction	38–102	0.9–18	0.5–130
Underground massive mining	75–165	5–40	17–750
Underground narrow reef	30–65	0.9–10	0.5–30
Range	>10x	>40x	>6000x

Table 2 lists the generic explosive types used in commercial blasting. Note that these have little in common with military explosives owing to extreme differences in the requirements. All commercial explosives are based on ammonium nitrate (AN), with various additives, spanning a wide range of densities and hole diameters. The simplest is ANFO (AN prills with fuel oil added). All also lose sensitivity below a characteristic "critical" diameter, which is quite large for the bulk explosives used in large-scale mining. Note that nitroglycerine-based explosives, such as dynamite, are seldom available nowadays, owing to safety, health and cost issues. These are omitted from the list.

CARTRIDGED VERSUS BULK EXPLOSIVES

The crucial divide is between cartridged and bulk explosives. The former are provided in defined cartridge sizes and masses which enable tight control over the distribution of energy in the hole, as well as complete flexibility in application.

Bulk explosives, on the other hand, are poured or pumped into the blast hole, the mass delivered being determined by the sectional area of the hole and the column rise allowed. Many advantages accrue to the latter:

- During delivery to site, the explosive components are not yet sensitised, and thus do not travel as explosives, thereby avoiding onerous regulations affecting the transport, storage and use of cartridged explosives.
- High loading rates from mobile manufacturing units (MMUs, or "pump trucks") result in high productivity.
- Bulk explosive fills the hole section, increasing the charge mass per metre relative to cartridged explosive, so the drilling pattern can be expanded, with various important savings.
- Bulk explosives are usually of simpler and safer composition and considerably cheaper than packaged explosives.
- Bulk explosives are much more difficult to adapt for criminal acts, although ANFO, loaded into vans, has been used in various terrorist attacks.

While there are other benefits, the above are sufficient inducement for blasting contractors to make every attempt both to adopt bulk explosives, and to persuade clients that these are appropriate for every kind of application.

Most construction blasting requires both limiting the explosive mass per hole and ensuring an even breaking effect along the blast hole. Figure 1 contrasts the energy contours of bulk and cartridged explosives when the same mass of each is charged into the same diameter and length blast hole. On the same drilling pattern this would result in identical powder factors, but very different results. Since, for a given density, the column rise is inversely proportional to the square of the hole diameter, bulk explosives occupy minimum column height for the allowed charge mass. Figure 1 shows that cartridged explosive delivers a more even distribution, ensuring that adequate energy is delivered higher in the hole, and thus reducing the likelihood of slabs left after the blast.

A fundamental flaw of bulk explosives in tightly controlled blasting is thus that the energy is concentrated, rather than evenly distributed.

In addition, effective hole diameters normally vary severely from nominal diameter, which is a result of:

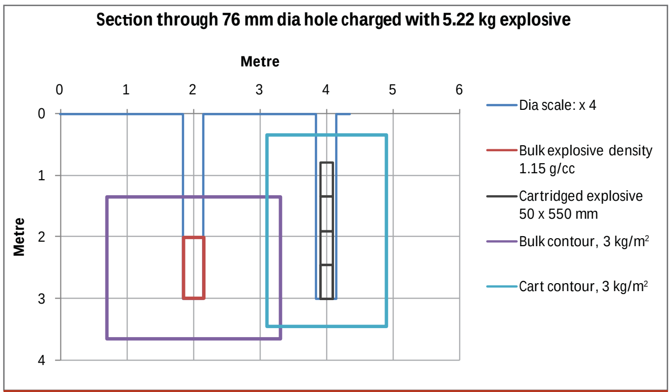

Figure 1: Bulk explosives create unfavourable geometry for controlled blasting

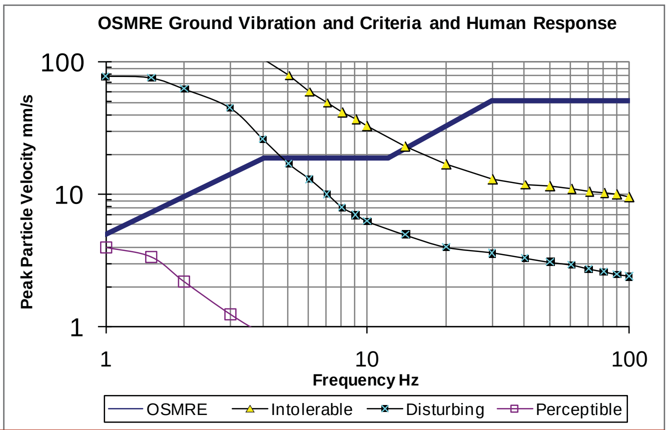

Figure 2: Blasting vibration limits from US authorities, with human response curves added

Table 2 Commercial explosives range

Explosive type	Diameter range (mm)	Comment
ANFO (poured) (ANFO = ammonium nitrate/fuel oil)	64–345	Not water resistant. Wide range of prills, mixes, delivery modes. Bulk density 0.3–0.85 kg/ℓ
ANFO (pneumatic loading)	27–100	Density 0.8–1.0, dependent on conditions
Bulk emulsion and blend (high-density, water resistant ANFO)	76–345	Wide range of blends, densities, critical diameters, mix/delivery systems: density varies with depth
Mini-bulk emulsion and water gel	30–64	New technology. Short holes: delivery, sensitising, priming and retention issues
Cartridged emulsion and water gel	22–100	Decoupling issues in air and water, sleeving may tear

Notes:
(1) Bulk explosive mass controlled by **hole diameter**
(2) Cartridged explosive coupling controlled by **hole diameter** and **cartridge spacing**

- wear on the drill bit
- cavities and caving within the hole arising from rock conditions, and
- oval and spiralling holes that result from poor drilling discipline.

This means that bulk explosive column rise is particularly variable, tending to either inadequate or excessive column length (where mass is controlled) or excessive vibration or flyrock (where column length is controlled). Cartridged explosives can be abused by overtamping, but at least the number of cartridges defines the mass per hole, enabling a much higher degree of control.

A further consideration is that the vibration impulse from bulk explosive tends to be stronger and of lower frequency in the near field, as a result of the tight coupling between explosive and rock, and the concentration of the explosive in a shorter length. Low frequencies cause more damage to structures.

Taking the above into account, the closer to any protected structure, the less suitable bulk explosives are. The cost of using cartridged explosives therefore has to be accepted within a given range, and tendering contractors advised of the requirement in order to qualify.

CRITERIA FOR LIMITING BLASTING VIBRATION

Vibration criteria are core to most blasting conferences nowadays, and overwhelmingly refer peak particle velocity (PPV) and frequency to various kinds of structures, and to human response. Airblast is especially important near public places, since its low frequency rattles windows and ceilings, giving the false impression of dangerous levels of ground vibration.

Figure 2 is the most widely used vibration criterion, from the US OSMRE (Office of Surface Mining, Reclamation and Enforcement), and expresses allowed PPV amplitude in terms of the frequency of any particular oscillation. Also shown are the expectations in terms of human response to vibration, derived from research using continuous vibration in 1960.

The criterion essentially stipulates that low frequencies (<4 Hz) require PPVs from 20 mm/s progressively down to 5 mm/s, while high frequencies (>12 Hz) can be tolerated at PPVs progressively up to 50 mm/s. The structures for which the criterion was developed were wooden dwellings with plaster walls near coal strip mines on weak sedimentary rock. Typical construction projects are, however, more concerned with massive and reinforced concrete, which can accept much higher amplitudes safely. PPVs of up to 120 mm/s are often acceptable for reinforced concrete, for example. Frequencies in construction blasting are also usually high (30–100 Hz), meaning that the vibration has minimal impact.

PREDICTING VIBRATION LEVELS

There is a direct link between vibration level and the mass of explosive detonating within a given interval. The interval required to ensure separation of vibration peaks depends on many factors, but 9 ms has been accepted as the minimum safe interval between holes to avoid serious reinforcement of vibration.[1]

There are various equations used to predict the maximum amplitude of vibration, and the one most commonly invoked in South Africa is derived from the old Dupont Blasters Handbook in the USA. Converted to metric units, it takes the form of Equation 1:

$$V' = 1143 \times \left(\frac{D}{\sqrt{E}}\right)^{-1.65} \qquad (1)$$

Where V' = predicted PPV, mm/s

D = distance from blast hole to point of interest, m
E = mass explosive per 8 ms interval, kg

The expression (D/√E) is known as the scaled distance, SD.

The equation can be inverted to express the charge mass limit at any distance for a given vibration amplitude, as in Equation 2:

$$E = D^2 \times \left(\frac{V'}{1143}\right)^{1.21} \qquad (2)$$

An important feature to note is that the permitted charge mass varies as the square of the distance to the structure. In close-range blasts this seriously limits rock breaking options, and choice of V' has major implications for blast design.

EFFECT OF VIBRATION CONSTRAINTS ON BLAST DESIGN

From the above, the following vital implications follow for blasts that are vibration-constrained:

1. The site vibration equation controls how much explosive is permitted to detonate during the blast in order not to exceed any given vibration PPV.
2. Once the maximum PPV criterion is fixed, this controls, through the defined equation, the permitted charge mass, and hence the maximum charge length at any distance.
3. The charge mass and length in turn determine the drilling pattern and maximum hole depth.
4. If the maximum hole depth is less than the required depth of break, then either the blasting will need to take place in more than one lift, or some form of deck charging is needed, probably with separate timing for each deck, which both increase cost and reduce productivity.
5. If the drilling pattern is reduced to accommodate light charging, this both increases the number of holes needed, and thus the number of explosive initiators, as well as reduces the size of blast that can be prepared in a given time.
6. Even if the maximum charge mass per hole is sufficient to accommodate the required hole length, blasting vibration limitation is based on charge mass per time step, usually taken to be 9 ms. Effective and efficient blasting requires blasts of larger, rather than smaller, numbers of holes, but large arrays of holes result in severe complexities and difficulties if the number of holes firing per 9 ms delay period has to be limited. This situation is exacerbated by the further requirement in public areas, that the duration of the blast be maintained at less than 1 second, as longer blasts, even of low amplitude, tend to be perceived by the public as more serious.As a consequence, the number of holes and the volume that can be blasted at one time, are limited.
7. It is usually possible to improve on the situation by, for example, resorting to electronic delay detonators, which have the capacity to reduce by up to half the lowest vibration that can be obtained with normal pyrotechnic systems, but the costs of such systems and the technical level needed to implement them have a great multiplying effect on operating costs when the volume per hole is limited by the need for reduced explosives per hole.
8. It is usually not possible to blast on any day or at any time of the day, owing to considerations of clearing the area. One blast per day is the usual restriction, and one can seldom achieve blasting on every day.
9. Thus the criterion for vibration amplitude constrains the size of the blast in terms not only of the depth, but also of the area. It also strongly affects direct costs. This can have a devastating effect on the critical path of the project.
10. The obvious alternative is to abandon blasting and instead use an expanding grout,[2] which largely eliminates the problem of rock breaking being restricted to once per day. However, these systems are both extremely expensive and not entirely dependable, so have only won favour as a last resort, and especially where small volumes are involved.
11. Alternatively the claims of the so-called "non-explosive" rock-breaking cartridges are attractive, but again, these propellant systems are expensive and have distinct limitations. High explosives (i.e. those that detonate as opposed to deflagrate) are uniquely able to deliver dependable, high-rate rock breaking in every kind of condition. This is why black powder was very rapidly replaced by dynamite when the latter became available during the late 19th century.

EXAMPLE: CONSEQUENCES OF PPV CRITERIA CHOICE

The following example uses fairly realistic current (2012) costs to demonstrate the effect of given PPV criteria on both productivity and cost to the contractor (before adding margin, and not allowing for standing costs associated with low productivity). It is necessarily simplistic and must not be taken as definitive of price, as its sole purpose is to highlight the relative, not the absolute, consequences of different criteria.

First, the economics case, which is usually uppermost for contractors when quoting. Assume a 5 m bench height in reasonably hard rock, using cartridged explosive and pyrotechnic detonators. Figure 3 shows how explosive (and thus hole) diameter influences drilling efficiencies – BCM/m drilled (Bench Cubic Metre). Figure 4 introduces estimated costs.

It would be disastrous, as a conscientious blasting contractor, to be quoting for say 38 mm diameter explosives, while a competitor quotes on the basis of 50 mm cartridges, implying that the control will be the same. It would be more disastrous for the client when the project was under way with the lower quoting contractor, and delays and costs escalate owing to the poor control, which can never be satisfactorily compensated for by penalty clauses.

Significance of charge height above grade

Note in Figure 3 the reference to "portion charge above grade". This is an important indicator of the quality of fragmentation of the broken rock, as explosive located below grade level is basically delivering not fragmentation, but clean breaking, to avoid re-blasting. The lower the portion above grade, the more overbreak can be expected below, and the coarser the fragmentation above.

Larger holes require the charge to be lower in the hole to avoid flyrock, which means coarser fragmentation, especially if the surface rock is very hard – which is common in civil blasting (had it not been so hard, it would have been excavated mechanically).

As bench heights get lower, this becomes a serious problem, because it makes no sense to drill much deeper than specification just in order to break to grade, but create very coarse fragmentation, thus achieving not only poor digging, but also serious overbreak. Where the bench height is low, the hole diameter also needs to be small. However, few blasting contractors have access to drilling rigs for small diameter holes. Resorting to hand drilling works for small volumes, but the poor productivity, and the shallowness and poor control limit this application.

The attraction of large diameter drilling

In Figure 4, the economics seem to favour the largest explosive diameter. Unit cost is less than half the cost for the smallest explosive diameter, explaining why so few contractors have drilling rigs that can cope with small holes. However, cheap blasting has consequences for those who must handle the results of poor control.

What is often unseen until too late appears in Figure 5, showing that the allowed distance from a protected structure defines what can be used for a given charge diameter and bench height. The larger the hole and the higher the bench, the higher the vibration level and the further away any structures should be.

For a 50 mm cartridge in a 76 mm hole (normally the least offered by bulk blasting contractors with large rigs such as shown in Figure 7), if 25 mm/s is the maximum PPV (a common, somewhat arbitrary choice in contracts), the minimum distance is shown as 61 m. However, if a PPV of 50 mm/s is perfectly safe, then the minimum distance reduces to 40 m. This can have significant consequences for a project.

On many projects, a percentage of the blasting is closer than 40 m, and it is necessary to be able to blast at any given distance, which means using a rig (as shown in Figure 6) able to drill smaller holes. If there is only work for one rig, this, rather than the large hole rig, is what must be adopted.

In every case, allowing a higher vibration criterion enables the project to progress quicker and at lower cost.

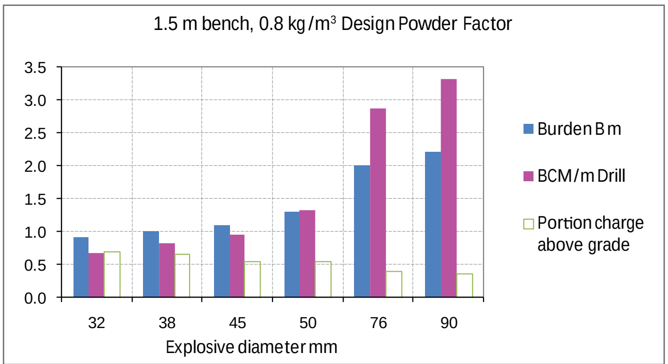

Figure 3: Drilling efficiency and explosive diameter

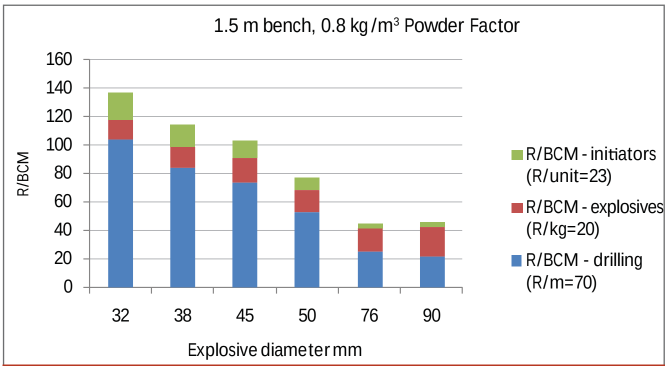

Figure 4: Drill and blast costs against explosive diameter

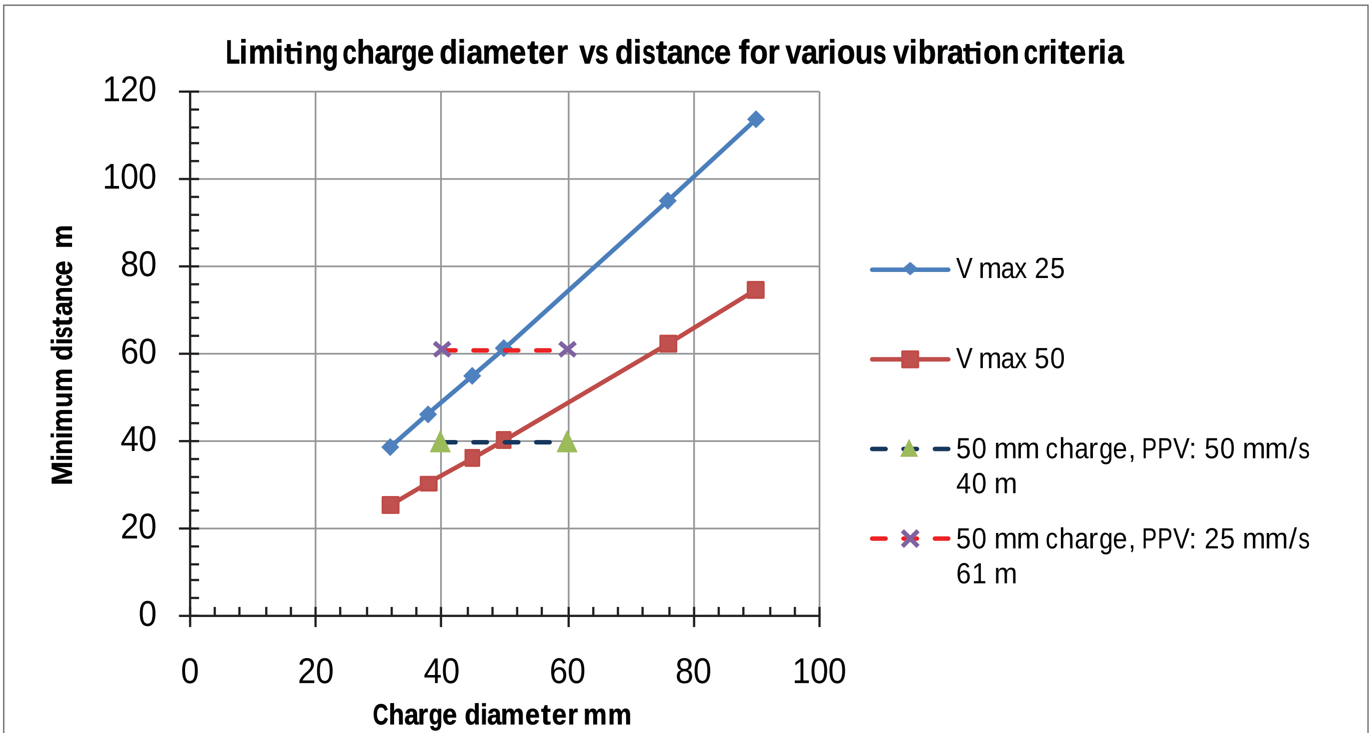

Figure 5: Higher PPV criteria enable larger, cheaper, quicker blasting to be undertaken, at closer range (5 m bench)

Figures 8 and 9 illustrate the implications when blasting within say 8 m of a structure, with 1.5 m bench height.

In Figure 9 electronic detonators have been specified, which might halve the vibration amplitude, but greatly increase blasting cost per cubic metre. For small cartridges the detonators become the most expensive item in the mix, and occasions arise where more than one detonator must be used per hole, which vastly escalates the costs.

However, it is usually only small volumes of ground that need such extreme measures, so although the cost per cubic metre is high, the overall cost to the project is small.

Clearly, if either the vibration criterion is raised, or the equation used to define the relationship between vibration and charge mass is reduced, then blasting is much more productive and less costly. In the course of a blasting project, the equation can often be modified to advantage, based on actual readings from seismographs, but not infrequently the equation used is found not to be conservative, and may even be optimistic. Therefore, the choice of a vibration criterion is a critical step with very significant cost and time implications for the whole project.

There are many strategies that can be adopted to achieve effective blasting within safe limits despite the above problems, but these need very careful assessment and cooperation between client, blasting contractor, and blasting specialist.

DISCUSSION

In practice, situations are frequently more critical than those shown in these examples, and the algorithms used to produce the diagrams only illustrate the trends rather than giving precise guidelines.

Blast design is strongly situation-dependent: the closer to any protected area or structure, and the lower the bench height, the less valid are general blast design equations. However, when tendering, it is these general design equations that tend to be adopted by contractors, and because there is such emphasis on price, and because most of the drills are really quarry rigs rather than construction rigs, and because it is so convenient to use bulk explosive like ANFO or bulk emulsion, these are the ingredients behind the tenders.

As a result, blasting contractors may well be appointed when there is an intrinsic impossibility that they will fulfil the real requirements of the work. The usual outcome of this is that, if vibration is under control, then (a) breaking is poor, resulting in serious production delays, and (b) remedial work and excess concrete are necessitated, usually attributed to "ground conditions", when in fact the correct hole size and blasting technique would have much reduced such situations. Alternatively, violations of the vibration, flyrock and airblast requirements result in (a) serious disruption due to damage control, disputes, the accommodation of complainants, and (b) either re-negotiation of blasting contracts or changing of contractors, with little assurance that the new contractors will do better, unless the lesson has been well learned.

The blasting cost is usually a small component of overall project costs, so the saving achieved by focusing on tendered cost rather than on competence is meaningless relative to delays and remedial work, not to mention the aggravation factors.

Figure 6: High-performance small hole rig for good control and production in a tight situation

Figure 7: Oversize rig, inefficiently producing (left) and overbreak and oversize (right)

Blasting is a difficult and to some extent veiled technology, but it influences the morale, cost and progress of any project. Being a small part of overall cost, usually assigned to the earthmoving contractors as a sub-contract, it tends to receive little attention during tendering and planning. This of course rewards blasting contractors who are poorly equipped to do what is required, and forces competent contractors to operate at high risk at reduced margins.

CONCLUSION

As shown in the simplified blast design sequence in Figure 10, four critical choices determine the ability of a blasting contractor to deliver effective, on-time, well-costed blasting results in the demanding environment of civil projects. These are the vibration criteria, the vibration equation (including the seismic monitoring and supervision associated with this), the hole diameter, and the explosive type.

Rock breaking operations for construction projects have unique demands which cut across the insistence of many large and small blasting contractors on using quarrying drill rigs, bulk explosives and cheap and easy initiation systems. If blasting is only a part of the earthworks contract, this is likely to create remoteness between client and blasting contractor. There is much to gain by making the blasting a separate contract, which elevates this critical activity to clear accountability and transparency of costs. It is important that the priorities and internal costing of the earthworks contractor do not distort understanding and limit options for the

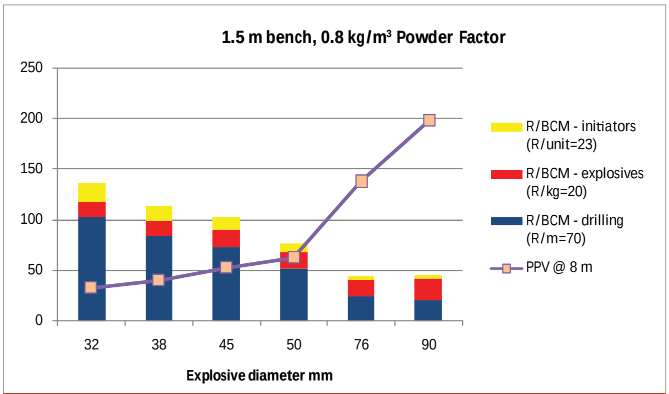

Figure 8: Close-range blasting with pyrotechnic detonators

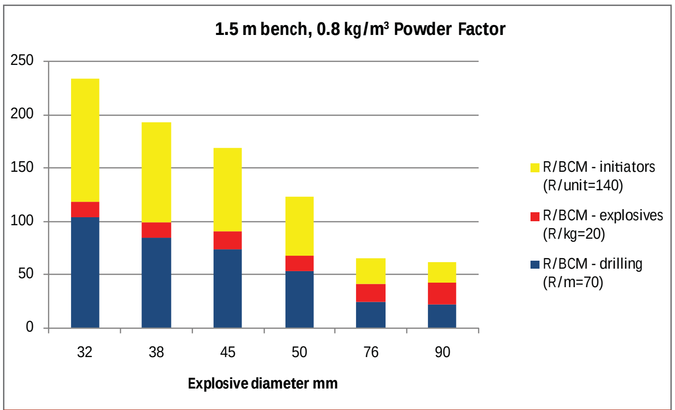

Figure 9: Effect of using electronic detonators on blasting costs

client. For the same reason, in-house or favoured blasting contractors of the earthworks contractor need to be carefully vetted. The more critical the blasting requirements, the less is cost per cubic metre a useful way of judging a tender.

If the blasting is considered well before a project gets under way, the scheduling of the activities, the appropriate blasting technology and the contractors can be brought together to facilitate a happy rock breaking experience.

The author is deeply grateful to the many consultants, blasting contractors, earthworks contractors and principals who offered me invaluable exposure to very critical and difficult situations over the past six years.

NOTES

1. The ">8 ms rule" has been widely challenged over the years, and has flaws, but is still the best general criterion in the absence of site-specific investigation.
2. Expanding grouts are basically compositions of Quicklime (CaO) which, when wetted, expand and crack the ground around the hole. ☐

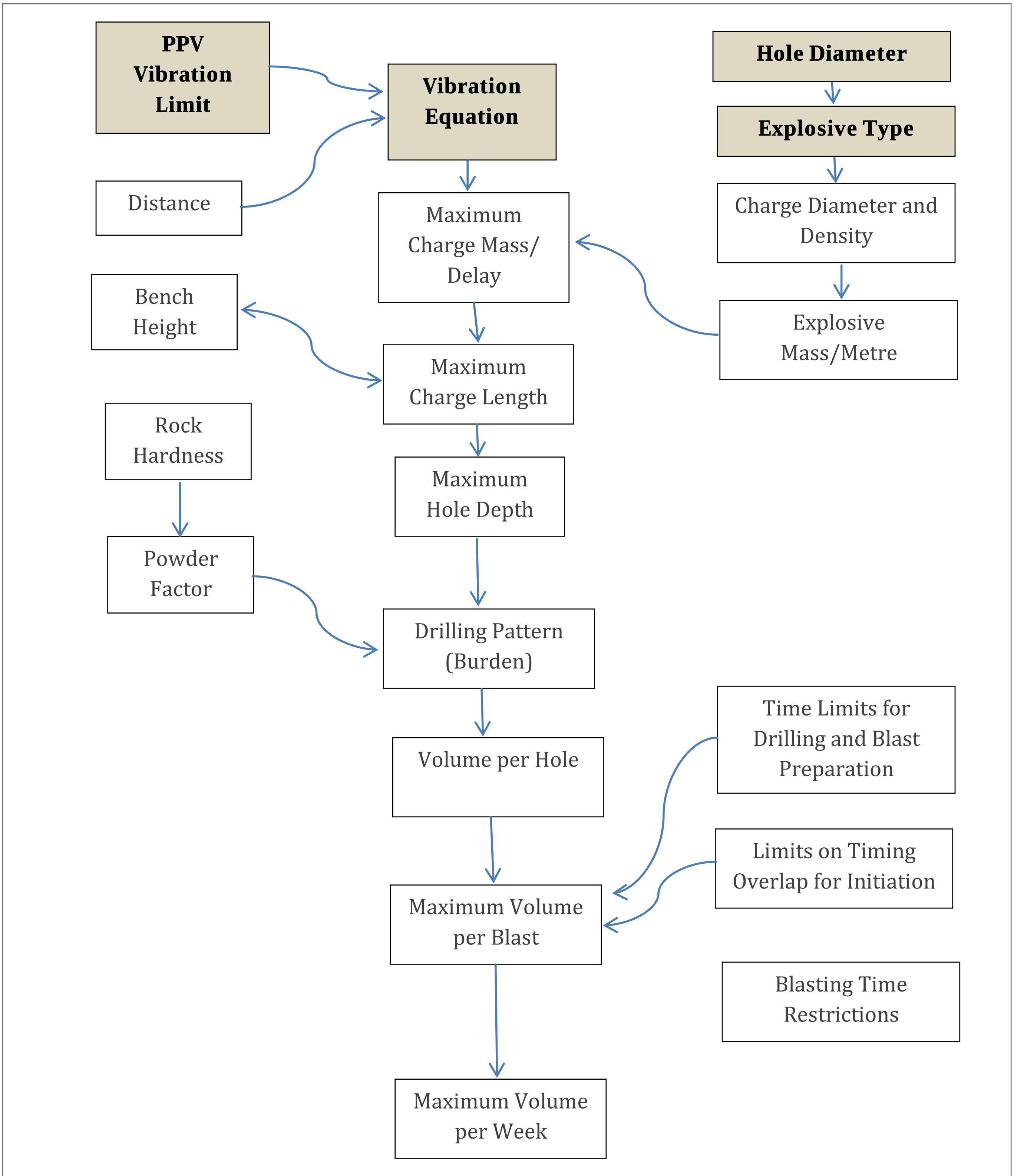

Figure 10: Simplified Blast Logic Tree

Source:
http://www.saice.org.za/downloads/monthly_publications/2013/2013-Civil-Engineering-July/#/0