

Selection of inter-hole and inter-row timing for surface blasting - an approach based on burden relief analysis

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ABSTRACT: It is widely acknowledged that delay timing (inter-hole and inter-row), if optimised, can have a positive impact on blast outcomes such as fragmentation, muckpile characteristics, backbreak and ground vibrations. Available or acclaimed methods for selecting suitable timing combinations are often not conveniently packaged for direct application by site engineers during the design process. In surface free face blasting, a key parameter that should facilitate the process of selecting appropriate inter-hole and inter-row delays is the concept of minimum response time (T_{min}). This is the time which elapses between explosive detonation and rock mass movement and is a function of explosive type, rock properties and blast design parameters. This paper describes a convenient methodology for calculating the minimum response time or T_{min} to enable the estimation of optimal inter-hole and inter-row delay times for a given condition. The approach and subsequent model has been developed and validated using high speed film/video data of full scale tests gathered over a relatively wide range of blast designs, explosives and rock types. For convenience or ease of use, the model has been incorporated into an interactive computer based approach for the selection of appropriate inter-hole and inter-row delays. This approach is based on detonation simulations and a probabilistic burden relief analysis concept which is also introduced in this paper. A demonstration case study is used to describe the application of the proposed model and the burden relief analysis concept.

1 INTRODUCTION

Delay timing is an important and critical blast design parameter which may have a direct impact on fragmentation, muckpile characteristics, backbreak and ground vibrations (Lang 1979, Anderson et al. 1985; Chiappetta 1997,1998; Cunningham 2000).

As discussed by Jimeno et al. (1995), delays should permit the succession of the following events:

- Propagation of the compression and tensile waves from the blasthole to the free face.
- Readjustment of the initial field of tensions, due to the presence of radial cracks and the effect of the reflection of the shock wave on the free face.
- Acceleration of the fragmented rock by the action of gases up to a velocity that assures an adequate horizontal displacement.

The onset of rock mass movement depends on the material response in conjunction with the stress and

gas pressure stimulus generated by the explosive. There is usually a discrete element of time that has elapsed from the time of explosive detonation to mass burden displacement. This time is designated as the minimum response time (T_{min}) and is dependent on the burden mass, explosive and dynamic material response to the explosive stimulus. Generally, but not always, T_{min} can be decreased by employing small burdens, using higher energetic explosives or a combination of both.

Figure 1 illustrates the dependency of T_{min} on blast geometry given by the burden to blasthole diameter ratio and the interaction between the explosive and rock mass. This figure is a modified version of the data published by Chiappetta (1998). As shown, in surface blasting conditions, the onset of rock mass movement may range from a few milliseconds to hundreds of milliseconds depending upon the material blasted.

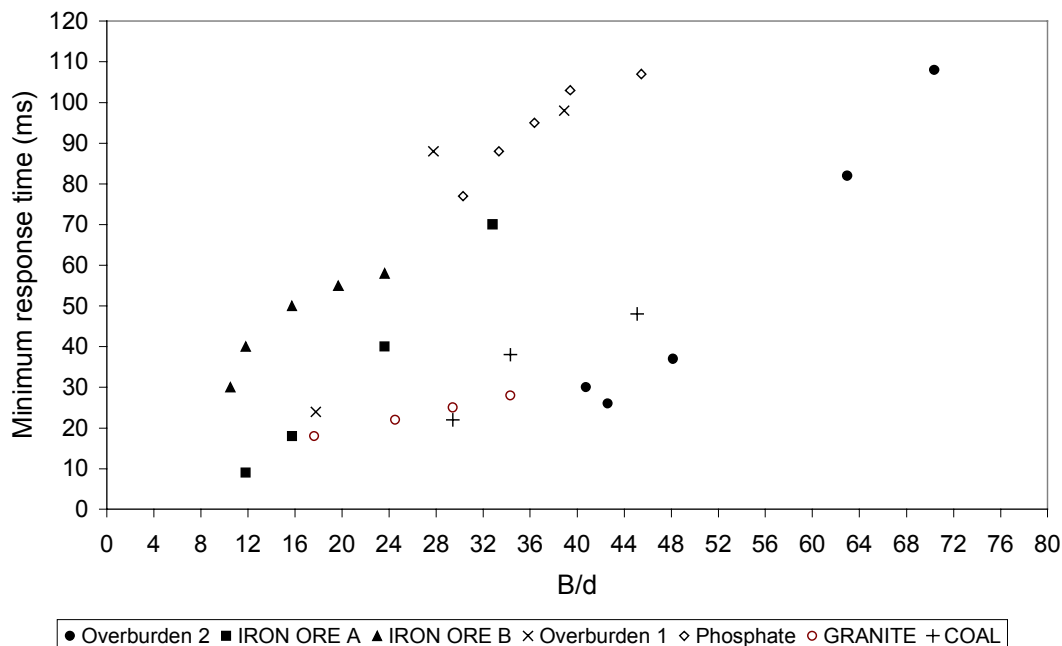


Figure 1. Minimum response time (T_{min}) versus burden to blasthole diameter ratio for a number of blasting environments (Chiappetta, 1998).

2 DELAY SEQUENCE DESIGN - CURRENT PRACTICE

In current mining practice, the selection of appropriate delay times (e.g. inter-hole and inter-row) involves the implementation of preliminary design guidelines or more quantitative methods based on knowledge of the minimum response time (T_{min}).

Preliminary design guidelines are empirical in nature and include the application of simple rules such as those documented by Jimeno et al. (1995). The list includes recommendations by Bauer who suggests delay times of 5-7 ms/m of burden in blasts with holes of 38 to 311 mm diameter; Bergman et al. and Fadeev et al. suggesting 3-6 ms/m and 4-8 ms/m, respectively and Konya & Walter proposing delay times of 6-7 ms/m, 4-5 ms/m and 3-4 ms/m of burden for low, medium and high strength rocks respectively.

As discussed by Chiappetta (1998), a more objective methodology can be adopted from knowledge of the minimum response time. For example, the delay time between holes in a row should be less or equal to the minimum response time, to encourage positive interaction for improved breakage and fragmentation. However the delay time between rows should be of the order of 1.5 to 3.0 times the minimum response time to maximise material displacement and/or create a loose muckpile.

Literature shows that there are only a handful of methods available to estimate minimum response time. These include direct measurements with the application of high-speed video analysis techniques and the use of mechanistic and numerical modelling tools. The use of high speed video analysis tech-

niques is site specific, can be both time consuming, difficult to implement and costly. Numerical codes offer a promising route but they are still evolving and are not readily available to engineers on site. This has driven the development of an empirical approach that allow engineers to make preliminary estimates of the time at which rock mass movement is expected to occur, given a particular geometry and explosive/rock mass combination. The framework of the proposed model is discussed next.

3 A MODEL TO ESTIMATE MINIMUM RESPONSE TIME

The model building process involved the compilation and back-analysis of several case studies in which comprehensive blast monitoring campaigns were undertaken. The current database is composed of 19 case studies, covering a wide range of geotechnical and blasting conditions. A detailed examination of the data available showed that minimum response time (T_{min}) is strongly dependent upon the blast geometry (i.e. burden and hole diameter), stiffness of the rock mass and explosive/rock interaction. This is in agreement with what has been previously found in the blasting literature (Lang, 1979 and Chiappetta, 1998). From this analysis, the following empirical relationship has been derived:

$$T_{min} = (K_{mass} ERI) \left[a \left(\frac{B}{d} \left(\frac{1}{K_{mass} ERI} \right) \right)^b \right] \quad (1)$$

where T_{min} is the minimum response time assumed to occur at the centre of the explosive charge (ms); K_{mass} is the rock mass stiffness (GPa) which is a function of the rock mass dynamic Young's modulus (E_d) and Poisson's ratio (ν_d): $K_{mass}=E_d/(1+\nu_d)$; B is the burden (m); d the hole diameter (m) and ERI is an explosive rock interaction term. This term has been based on the explosive performance term introduced by Bergmann (1983) and is given by the following expression:

$$ERI = (0.36 + \rho_e) \left(\frac{D^2}{1 + \frac{D^2}{v_p^2} - \frac{D}{v_p}} \right) \left(\frac{D}{D_{CJ}} \right) \rho_e \quad (2)$$

where ERI is the explosive-rock interaction term; ρ_e is the density of the explosive (g/cm^3); D is the actual (non-ideal) detonation velocity (km/s); v_p is the P-wave velocity of the intact rock (km/s) and D_{CJ} is the CJ detonation velocity (km/s).

In Equation 1, there are two fitting constants, namely a and b. For the current database, they are determined as 2.408 and 1.465, respectively. In recognising the empirical nature of the proposed model, predictions are restricted to geometries covering B/d ratios of 12 to 45 and assume that blastholes are fully coupled and properly stemmed.

Preliminary validations of the proposed approach have shown encouraging results. For example evidence documented by Guest et al. (1995) and Vassie (1991) suggested that the minimum response time of trough rings fired in Tuffisitic Kimberlite Breccia (TKB) was of the order of 30 ms. This corresponded to a ring geometry consisting of 102 mm diameter

blastholes on a 3.6 m burden configuration, charged with a pumpable emulsion product.

For similar conditions, the proposed model estimates the minimum response time to be in the range of 22ms to 33ms with the most likely time calculated at 27ms. These estimates were based on a pumpable emulsion product with a density of 1.18 g/cm^3 ; Ideal VOD of 5438 m/s and an estimated confined VOD of 4916 m/s. TKB properties included an unconfined compressive strength (σ_c) of 32 MPa, Dynamic Young's modulus (E_d) of 17 GPa and a rock mass stiffness (K_{mass}) of 10.2 GPa.

The proposed model has also been tested for its ability to realistically predict changes of minimum response time given by changes in geometry (i.e. namely burden distance). Measurements documented by Mishra & Gupta (2001) were used in this assessment. Because rock mass parameters were not provided, K_{mass} was estimated to be 4 GPa, from assumptions of P- and S-wave velocities of the order of 2100 and 1100 m/s respectively and a rock density of 2000 kg/m^3 . This rock mass can be classified as a low strength and energy absorbing overburden. Blasting parameters were given by Mishra & Gupta (2001) and these allowed the estimation of the explosive-rock interaction term (ERI).

The estimation of rock mass stiffness (K_{mass}) did not affect the ability to check whether the model was sensitive to changes in burden, as this was kept constant. Results from this particular analysis are shown in Figure 2. From an engineering point of view and based on the data collected by Mishra & Gupta (2001), modelling results appear to effectively capture the dependency of minimum response time on burden for a constant explosive/rock mass combination.

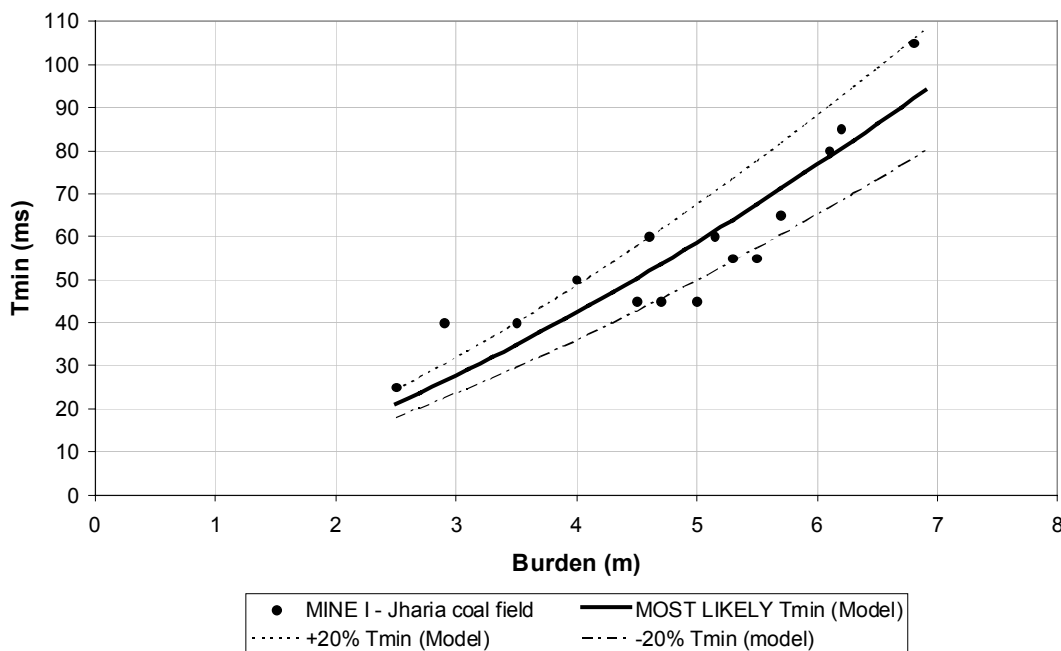


Figure 2. Comparison between measured minimum response time and model predictions for a constant explosive/rock mass combination.

4 APPLICATION OF THE T_{MIN} MODEL

Minimum response time can be used as a key input in the definition of inter-hole and inter-row delay sequences in a free face blast. As discussed earlier, guidelines such as those proposed by Chiappetta (1998) can be directly applied (e.g. 1.5 to 3.0 times the minimum response time to maximise material displacement). There are, however, limitations to this approach, as the choice of delay times will also depend on the precision of the available down-hole and surface delay detonators.

To assist with the selection of inter-hole and inter-row delays, taking into account both T_{min} and delay scatter, the concept of burden relief was developed by research engineers from the Julius Kruttschnitt Mineral Research Centre (JKMRC, 1990 & Riihioja, 2003). The approach is based on the assumption that for an explosive deck to be successful, as far as fragmentation and displacement is concerned, a free face towards which the rock can be blasted must be available. For a free face to be available, it is required that at least two adjacent holes in front of the hole in question have detonated at a defined time earlier, to provide sufficient burden relief.

4.1 Burden relief analysis

Figure 3 illustrates the burden relief analysis concept for a staggered pattern. For hole 4 to be considered as having detonated successfully, holes 1 and 2 or 1 and 3, need already to have detonated successfully at an earlier time interval, given in this case by the expected minimum response time (T_{min}).

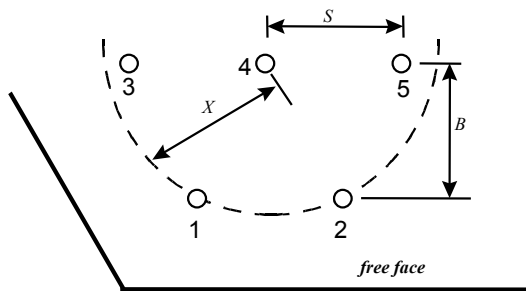


Figure 3. Staggered pattern hole layout.

In general, the approach simply estimates the likelihood of a deck being over-burdened at the instant of detonation. To estimate the probabilities of success or failure of a blasthole, a simple “burden relief” criteria is checked for a number of detonation simulations. The criteria follows that for a given relief distance (i.e. the largest distance between holes, “x” in Figure 3), there is a minimum number of explosive charges that must go off before a hole can detonate successfully (two is the default number), these charges should have also detonated at an earlier time interval defined by the relief time or expected minimum response time.

In order to compile the statistics necessary to estimate detonation scatter and probabilities of success or failure, it is necessary to run a number of detonation simulations. For a given simulation, an explosive deck is 100% successful when the whole criteria is met, if one fails, then the deck is assumed to fail and subsequent detonations which rely on this hole will also fail. Experience has shown that it is possible to choke a whole section of a blast if just one hole fires out of sequence.

During the simulation of the detonation sequence, the inherent variability of pyrotechnic delays is modelled with a normal probability distribution function given by the nominal detonation time (mean) and a scatter factor which defines the standard deviation. For each simulation, Monte Carlo sampling is used to estimate the likely detonation time of each deck. The simulations also consider the velocity of detonation of the explosive charge, down-hole shock tubes and any type of surface connectors (i.e. shock tube or detonating cord).

To demonstrate the use of the burden relief analysis concept for design and optimisation purposes, a simple case study is presented in the following section.

4.2 Demonstration case study

This section demonstrates the use of the burden relief analysis concept. All algorithms have been coded into a blast design package designated as JKSimBlast (JKTech, 2003). As will be shown, the output of the burden relief concept is graphical, different colour scales are used to identify the probability of success or failure of a deck for a pre-defined number of simulations. This graphical output allows the engineer to quickly assess areas of a blast that could be affected by over-confinement and thus take controlling measures. The process is done interactively by selecting delays from a pre-defined set of accessories with unique characteristics (i.e. depending upon supplier). If pyrotechnic delays are being used, the engineer is able to run what if scenarios for any number of scatter (variability) factors and thus identify the risks of adopting a specific tie-up configuration using pyrotechnics and at the same time assess the benefits of increased detonator precision.

The following demonstration case study is based on a regular staggered pattern of eight rows with approximately 20 holes each. Nominal design parameters are described in Table 1.

Table 1. Nominal design parameters.

Burden (m)	8
Spacing (m)	9
Blasthole diameter (mm)	241
Blasthole length (m)	15.2
Charged length (m)	9.1
Explosive type	WRANFO
Explosive density (g/cm ³)	0.99
Ideal VOD (m/s)	5829
Confined VOD (m/s)	5029
P-wave velocity (intact) (m/s)	2902
Rock mass stiffness (GPa)	3.2

Table 2. Proposed delay configurations.

	Design 1	Design 2
Inter-hole (ms)	42	65
Inter-row (ms)	65	150
Down-hole (ms)	500	500

Based on the parameters summarised in Table 1 and by applying the empirical approach described earlier, the estimated minimum response time is 57ms to 86 ms, with the most likely time being 71ms.

For this case, the following “burden relief” criterion was established: For a blasthole to be 100% successful, two charges that are within a distance of 10m must detonate successfully at a time interval within 71ms.

For demonstration purposes, the analysis has involved the assessment of two design sequences (Table 2).

The design 1 configuration was based on the “rule of thumb” of 6-7 ms/m of spacing for low strength rock environments and design 2 on the premise that 0.9 times the minimum response (T_{min}) would be adequate to increase the likelihood of inter-hole cooperation for breakage, and that 2 times T_{min} would be adequate for effective burden relief to take place. In both cases, downhole delays of 500ms were considered necessary in order to allow the initiation front to precede the detonation front, and thus reduce the likelihood of surface cut offs. This can be visually assessed during the playback of the detonation sequence in the JKSimBlast software.

In the above design sequences, 1000 Monte Carlo simulations were conducted with an assumed delay scatter of 4 %, which as discussed earlier, defines the standard deviation to be 4% of the nominal delay. Results from these two simulations are given in Figures 4 and 5 for designs 1 and 2, respectively.

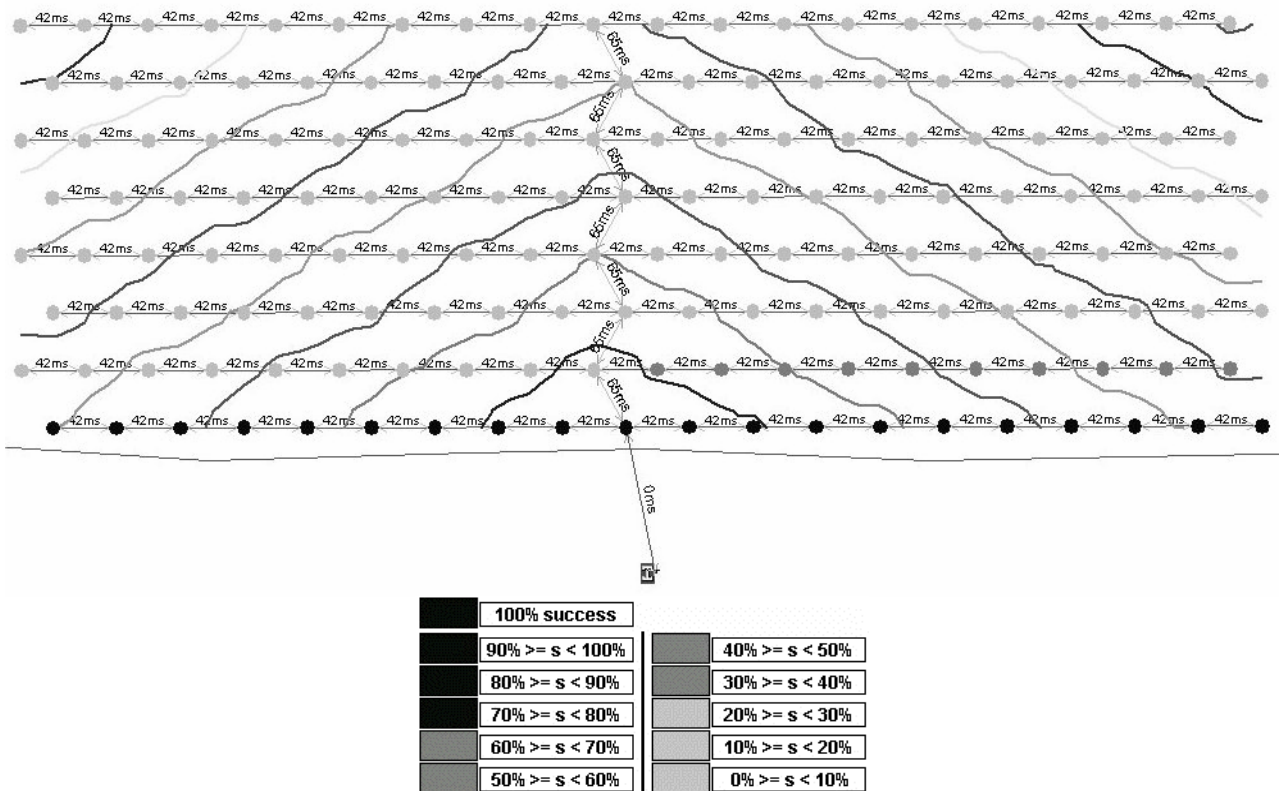


Figure 4. Simulation results for design 1: Inter-hole = 42ms, Inter-row = 65ms, Down hole = 500ms; Simulations = 1000. Scatter factor = 4%.

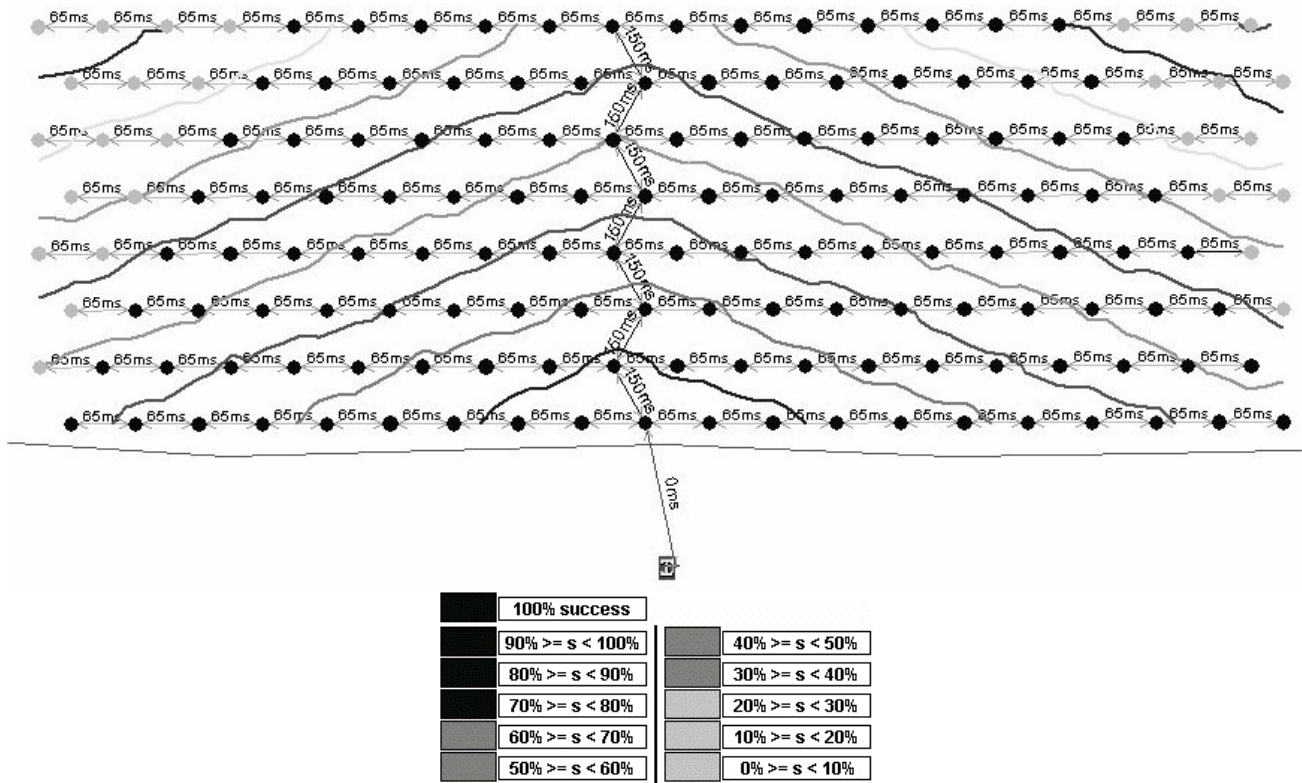


Figure 6. Simulation results for design 2: Inter-hole = 65ms, Inter-row = 150ms, Down hole = 500ms; Simulations = 1000. Scatter factor = 0.1%.

5 CONCLUSIONS

Minimum response time can be used as a key input parameter in the design of appropriate inter-hole and inter-row delays under free face blasting conditions.

An empirical model that allows the estimation of minimum response time has been introduced. Preliminary validations show that the model is able to capture the dependency of minimum response time on burden, explosive type and rock mass conditions. It is however recognised that further validation work is still required to improve its predictive capabilities.

The concept of burden relief analysis has been introduced. The application of minimum response time and burden relief analysis as a tool to assist in the selection inter-hole and inter-row delays has been demonstrated with a simple case study.

Burden relief analysis has shown that when a theoretically acceptable delay sequence is chosen, the inherent variability of pyrotechnics can still influence the final outcome. When precision is improved, then the burden relief criterion is clearly met. This highlights the benefits of delay precision as a way of having true control over the sequence of detonation of a blast. This allows greater control over the degree of confinement (relief) of blastholes, prior to detonation. In practice, the provision of adequate relief has been shown to have a marked impact on the final degree of uniformity of fragmentation, muckpile looseness and back-break.

In terms of controlling ground vibration amplitudes and frequencies, the choice of delay times is also crucial. For conditions in which vibration must be controlled, the burden relief analysis should be supplemented with analyses conducted with specific vibration modelling and monitoring methods.

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