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# An evaluation of precise short delay periods on fragmentation in blasting

A.J. Rorke
*bmeTech, bme (Pty) Ltd, Omnia Group, Bryanston, South Africa*

ABSTRACT: The precision available from electronic delay detonators has lead to increased and apparently successful application of very short delays in surface blasting operations worldwide. The potential for significant reduction in overall fragmentation in blasts prompted the study reported in this paper, where short delays, between 2 and 7 ms, were applied in quarry blasting and compared with conventional delays used in shocktube initiation systems (17 to about 100 ms).

The studies reported here were carried out in different operations where rock properties varied in strength and elasticity (amphibolite to calcrete). The results from the tests show clear trends in fragmentation benefit, with the harder more brittle operations being more responsive to very short delays.

A very clear reduction in overall fragmentation size has been documented. In the softer more absorbent rock types, the benefit of short precise delays was less distinguishable compared to normal less accurate shock tube initiation systems.

## 1. INTRODUCTION

Some work has been published on improved fragmentation, throw and digging rates using very short inter-hole precise (electronic) delays between holes (Rossmanith 2003) and in deck charging (Chiappetta 2007).

This paper presents data from a number of blasts at three different operations in Southern Africa, using very short inter-hole delays.

There is a short discussion on the likely mechanisms that impact on the results observed, and an observation is made about the need for a more accurate commercial electronic delay detonator.

## 2. CASE STUDIES

There is a general reluctance to try very short delays for fear that the blast may freeze up and become very difficult to dig. Very high vibration levels are another concern. Because of these concerns, many operations have only been prepared to try electronic detonators at delays that are similar to the pyrotechnic delays that they are familiar with. The result is marginal differences, illustrating only what can be achieved by applying accurate sequential firing.

The potential gains using very short delays have become evident in trial blasts at a few quarries and mines in Southern Africa, and the benefits and problems experienced from the trials are related in the case histories below.

### *2.1 Hard rock quarry*

This is a hard rock quarry that has struggled with fragmentation in the very hard amphibolites. The

Figure 1. The rock structure in this quarry has a strong influence on final fragmentation. Boulders form in the muckpile from the blocks, especially in the stemming region of each blast.

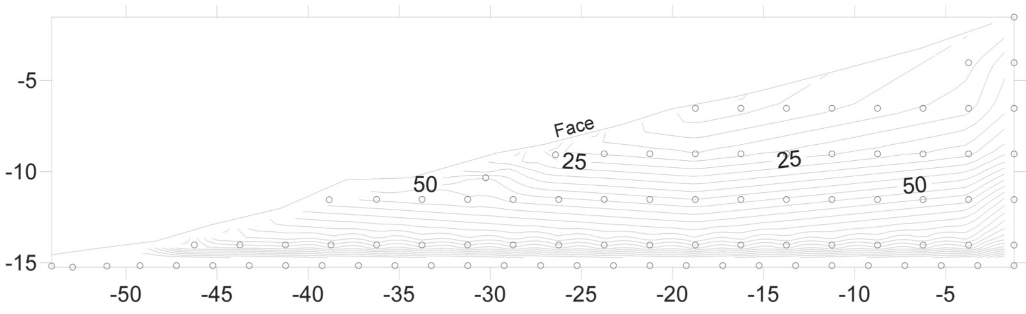


Figure 2. Typical timing contours for short inter-hole delays and longer inter-row delays to preserve the back wall.

rock is structured and results in a blocky material that tends to break into boulders along the joint planes. The in-situ rock is illustrated in Figure 1 and a typical pyrotechnic blast result is shown in Figure 3.

Subsequent to the pyrotechnic blasting, where 42 ms and 17 ms delays were used with 350 ms in-hole delays, initially a number of electronic delay blasts were used using short inter-hole delays of between 2 and 3 ms and inter-row delays of 5 and 7 ms.

These initial blasts produced much finer fragmentation, but it was difficult to control back damage. As a result, inter-row delays were increased, whilst inter-hole delays were kept short at 3 ms or less. An example of the timing contours for a recent blast is shown in Figure 2.

Some 15 blasts have been done at the quarry using short delays, and the fragmentation in each blast has been measured using the Split fragmentation analysis software. This has been


Figure 3. Typical fragmentation with pyrotechnic blasting. Large boulders were most common in the stemming region, but were also distributed within the muckpile.

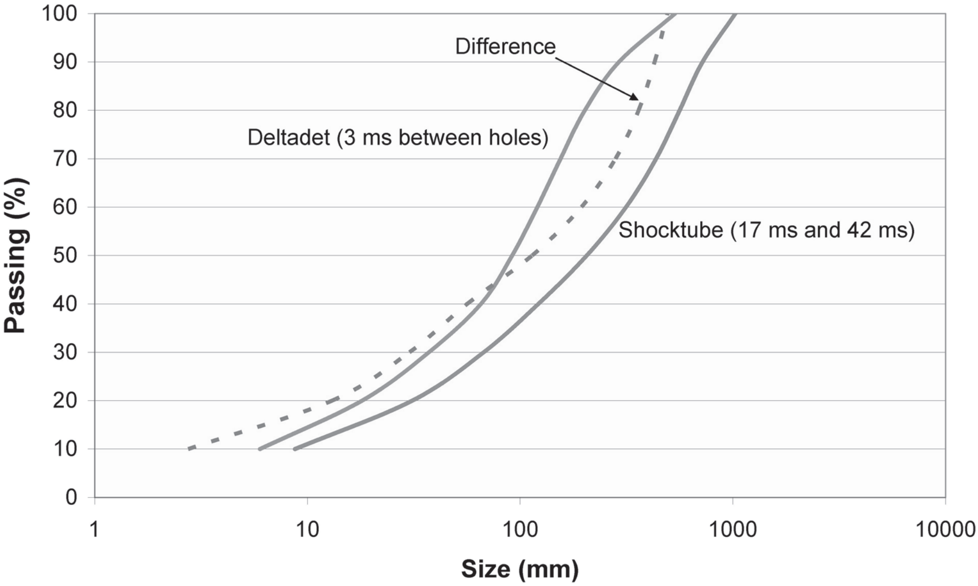


Figure 4. Combined fragmentation data from 15 electronic delay detonator blasts and two shocktube blasts in amphibolite.

compared to two pyrotechnic blasts where 17 ms and 42 ms surface delays were used with 250 ms in-hole delays. The result is provided in Figure 4.

The finer fragmentation rates have resulted in a consistently improved plant throughput rate of 10% since short delays with electronic delay detonators were introduced.

Figure 5. Fragmentation and throw after a typical electronic delay detonator blast with short inter-hole delays. There are a few large boulders just below the excavator that represent the oversize that formed along the free face of the blast.

The short inter-hole delays did not compromise blast throw, and even the initially short inter-row delays resulted in significant throw similar to the throw shown in Figure 5.

### 2.2 *Gold mine*

A study was made at a gold mine which required improved floors with better fragmentation in the floors for improved digging rates. The rock is a highly structured micaceous sandstone, with the dominant near vertical fabric striking in the same direction as the burden. The yielding nature of the rock because of the high micaceous content, the unbonded planes of weakness and the direction of the structure (Widzyk-Capehart & Lilly 2001) tends to make blasting difficult (Figure 6).

Tests were carried out with the idea that short delays would help improve fragmentation in the bottom of each blast and the floor condition, without the need for increasing explosives energy. Three electronic delay detonator blasts were carried out. The inter-hole delays were reduced from the pyrotechnic delay of 17 ms to 4 ms in the first two blasts and 2 ms in the final blast. The inter-row

Figure 6. Well developed structure in micaceous sandstone tends to inhibit fragmentation and heave in the bottom of each blast.

delays were fixed at 34 ms with the delay being increased in the final rows to reduce back damage. The effective inter-row pyrotechnic delay was 59 ms.

Fragmentation results were improved in the precise detonators, but not as significantly as in the very hard amphibolite rock of the hard rock quarry. The fragmentation results from two of the electronic delay detonators blasts are illustrated in Figure 7.

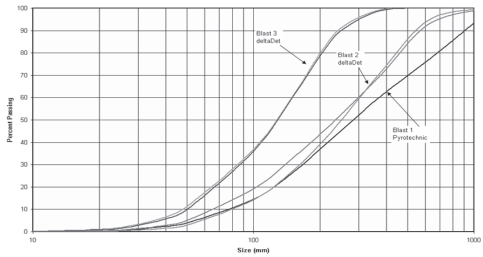


Figure 7. Fragmentation achieved using deltaDet detonators and short delays between holes in closely structured micaceous sandstone. Fragmentation in two of the electronic delay detonator blasts is compared with a pyrotechnic blast that was fired in the same area of the mine containing similar rock.

### 2.3 *Uranium mine*

The rock in this mine comprises a calcrete that contains horizontal layering with differing strength. The rock yields under dynamic load, and tends to fragment very coarsely, especially in the stemming area of each blast. It is believed that the horizontal planes act as transmission channels for high pressure gasses that could negatively impact unfired charges. The typical rock and its structure are shown in Figure 8. The obvious solution appeared to be very short delays between holes and between rows of holes.

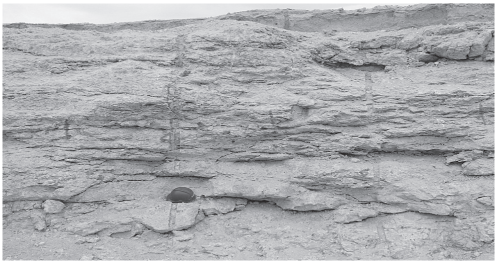

Figure 8. Calcrete rock containing unbonded irregular but relatively extensive horizontal planes.

A number of electronic delay detonator blasts were fired with delays equivalent to 3 ms/m with a tight V cut in each blast. The fragmentation results were disappointing (Figure 9). In subsequent blasts, delays were first shortened more, and then slowly increased. Currently, there appears to be little difference to fragmentation, regardless of the delay periods. In this type of rock, changes in stemming length and hole distribution appear to have a more significant impact on fragmentation outcome.

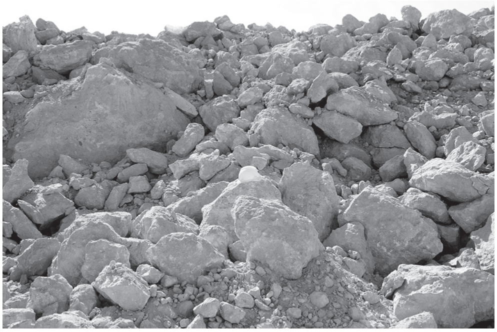

Figure 9. Typical coarse fragmentation, especially in the stemming zone of each blast.

## 3. DISCUSSION

### 3.1 *Rock type*

In each of the three cases outlined in this paper, explosive type, drill patterns, energy and stemming lengths were kept constant. However, there was a marked difference in the success of applying short delays between holes using precise detonators. The harder more brittle rock responded best with a marked decrease in fragment size and an increase in uniformity. In the much softer, but traditionally difficult to blast calcrete, the rock responded poorly to short delay periods.

### 3.2 *Mechanism of short delays*

The mechanism of short delays is thought to be the result of interference between wave fronts to achieve increased amplitudes and therefore more damage in the form of micro-cracks to the rock. Two kinds of interference are envisaged:

- Collision of compressive waves. Wave fronts travelling out from simultaneously detonating

Table 1. Calculated delay values (D) using Equation 1 that will result in simple sinusoidal waves being in phase.

| C (m/s) | Frequency (Hz) | Hole Spacing (m) | λ (m) | D (ms) (n=0) | D (ms) (n=1) |
|---|---|---|---|---|---|
| 6000 | 500 | 3 | 12.0 | 0.50 | 2.50 |
| 6000 | 400 | 3 | 15.0 | 0.50 | 3.00 |
| 6000 | 300 | 3 | 20.0 | 0.50 | 3.83 |
| 6000 | 200 | 3 | 30.0 | 0.50 | 5.50 |
| 6000 | 100 | 3 | 60.0 | 0.50 | 10.50 |

holes meet with increased amplitudes in the zones of convergence. This collision can also occur as a result of reflection off surfaces such as the free face or planar structures within the rock mass (Rossmanith 2003)

- Build-up of wave amplitudes. Holes firing sequentially along a line can be timed so that the shockwaves radiating form each hole is in phase with the wave passing through from the previous hole. Figure 10 shows this principle in an illustration where the wavefronts are superimposed on one side of line of sequentially firing holes

Essentially, the build-up of wave amplitudes is the limiting case of the collision of compressive waves. It is achieved at longer inter-hole delays than would be the case for the collision of waves and therefore represents the case for the longest inter-hole delays that can effectively result in increased amplitudes through constructive wave interference.

A progressive build-up of wave amplitudes down a line of holes would require delays that are specific to the rock transmission velocity and the distance between holes. If one wave cycle is considered, the optimal delay between holes for waves from each hole to be in phase is:

$$D = \frac{B + \lambda n}{C} \times 1000 \qquad (1)$$

$B$ is the distance between holes (m), $\lambda$ the wave length (m) and c the wave velocity (m/s). To benefit from constructive interference and achieve significant amplitude gain, the number of wavelengths, $n$ should remain small (<2) as the waveform will have a very short duration close to the blasthole.

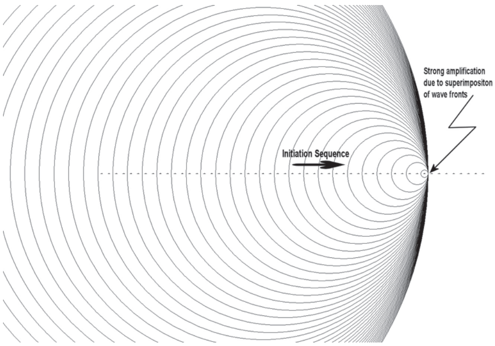


Figure 10. Simple illustration of the concentration of wavefronts ahead of a line of sequentially firing holes. The optimal inter-hole delay to achieve this depends on the wavefront velocity and the physical distance between the holes.

Assuming a typical wave velocity of 6000 m/s and a hole spacing of 3 m, for waves to be perfectly in phase, the inter-hole delay would need to be 0.5 ms. The frequency impacts the delay if waves are separated by one wavelength (n=1) or a multiple thereof. This is illustrated in Table 1

### *3.3 Delay accuracy*

The important point is that the precision required to achieve the necessary delays for optimal constructive interference will be fractions of a millisecond. This is not possible when using current electronic delay technology with accuracies that are generally a function of delay period.

Most current electronic delay detonators have firing-time accuracies that are within 1 ms, when overall delay periods are less than about 500 ms. This is still too coarse an accuracy, when considering superimposition of waves in blasts. The problem becomes even more evident as overall delay period increases (Table 2).

Table 2. Estimates of firing time scatter as a function of delay period according to test information (Greyvenstein, 2007). The scatter is estimated to be about six times the coefficient of variance.

| Delay Period | deltaDet .01% ms maximum deviation | System 1 0.01% coefficient of variance | System 2 0.06% coefficient of variance |
|---|---|---|---|
| 100 | 0.18 | 0.18 | 0.36 |
| 1000 | 1.80 | 1.80 | 3.60 |
| 5000 | 9.00 | 9.00 | 18.00 |
| 10000 | 18.00 | 18.00 | 36.00 |

Because of the relatively long wavelengths, compared to inter-hole spacings, it should be possible to achieve a certain amount of constructive interference, within the scatter range of 0.5 ms, even though it may not be optimal. When firing-time accuracy falls below this, the chance of achieving constructive interference by design decreases rapidly.

It can be concluded, that, although firing time accuracies of electronic delay detonators are greatly improved compared to pyrotechnic systems, there is still a need to improve accuracy by an order of magnitude to take full advantage of constructive interference in the blast.

It is also clear, that as the absolute delay periods in a blast increase above about 100 ms, with most electronic delay systems, the benefit from compressive wave collisions or constructive interference using short inter-hole delays will disappear and out of sequence firing may in fact become a problem when short relative firing times are applied.

## 4. CONCLUSIONS

From field results, the use of short accurate delays provide significant possibilities for reducing fragment sizes for blasts in hard brittle rock. The benefit decreases as rock becomes more yielding.

With most electronic delay detonators, there is a decrease in firing time accuracy with increase in delay time. Therefore, the use of short inter-hole delays to achieve a theoretical increase in shock or vibration wave amplitude to do added damage to the rock is likely to be most successful only if absolute delays are relatively short (less than about 100 ms).

The use of short delays between holes in hard rock blasts that have been reported here, and others that the author has been involved in, have produced very encouraging results. However, if the full impact of wave interference close to the energy source is to be achieved, better accuracy will be needed than is currently available from commercial electronic delay detonators.

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# Electronic initiation technique - state of the art and its application in Austria

J. Plank & F. Hammelmann
*W&P Austria & Orica Europe*

ABSTRACT: After 4 years of development in 1986 the first electronic detonator - Dynatronic - was introduced by Dynamit Nobel. This electronic initiation system - following the design of an electric initiation system - was based on delay numbers. Since then, a lot of experience has been gained in different applications (underground and surface) and in designing electronic initiation systems themselves.

The kind of operation where electronic initiation is applied has a huge influence on system demands and design. Today an electronic initiation system has to be fit for surface and underground applications, for small quarry blasts and for huge open cast operations with up to 4,800 detonators and 1,000 t of explosives in one blast. The i-kon™ electronic initiation system offers several options tailored to different type of applications and blast sizes.

The optimisation process for environmental demands in production of raw materials at Wietersdorfer & Peggauer Zementwerke GmbH [W&P] is described in the second part of this paper. A major element of this optimisation process is the operation adapted application of Orica's i-kon electronic initiation system. In contrast to this, experience during the transition of quarrying by traditional drill and blast operation to direct extraction by means of a heavy hydraulic excavator in marl mining are described.

## 1. ELECTRONIC INITIATION

The first part of this paper describes the early days of electronic initiation, starting in the 80s and ending with the introduction of the status of Orica's current i-kon electronic initiation system.

### *1.1 History of electronic initiation*

Development work for the first electronic initiation system was started in the early 80s. Some electronic initiation systems had already been developed for military purposes. In contrast to military needs the technical demands for an initiation system for civil use are fairly different. The key demands for developing Dynamit Nobel's first electronic initiation system - Dynatronic - had been:

- design of a 2-wire based initiation system
- connecting circuit comparable to traditional electric circuit
- safe against stray current, electrostatic & electromagnetic power
- 60 delay numbers
- maximal delay time up to 6,000 ms
- high accuracy up to the maximum delay time (deviation < 1 ‰)
- 'test firing circuit' feature

The traditional functionality of the pyrotechnic delay element - carrying the *information* of delay time and carrying the *energy* for independent operation - had to be divided into 2 parts; a chip being responsible for communication / processing and a capacitor for energy storage / supply.

The first approach brought a system following closely the design of an electric circuit, being connected in series. With a consumption of 10 - 15 Volts per detonator a blast with 500 boreholes (2 detonators / borehole) would have been charged up to 15,000 Volts. Leakage became a serious problem, and the probability of a high rate of misfires was unacceptable. Considering the high resistance of an electronic Detonator it was obvious to change the main design from serial connection to parallel connection; this decision was made in November 1982. The next challenge was, that at this time electrolyte capacitors - required to establish the energy supply for the processor and finally to initiate the fusehead - were fairly big. To stay inside the geometric boundaries of traditional Detonators, it was decided to divide the prototype in 2 major parts:

– one part inside the explosives carrying the fusehead, the primary charge and the base charge
– one part outside the borehole containing the electronic processor and the "Power-Station" to supply the processor and fusehead with energy after the circuit is armed and the timers are counting

This 'Macro-Model' was designed to gather experiences with electronic initiation in general; 10 of these systems were in use. Some of these boxes - which had to be placed very close to the blast - got lost during blasting.

The next step was to keep away electromagnetic power [EMP] - which is generated by the blast itself - from the electronic parts of the detonator. EMP affected the blast box or hit the shotfirer while he was pushing the button. Therefore, it became essential to merge both parts of the detonator (Figure 1), to establish a 100 % independent operation of every detonator after the blast was initiated.

In 1986 the Dynatronic System (Figure 2) was introduced to the marketplace. The first Blaster (ZG N 1) was fairly big and displayed the current operating status via different coloured lights. The interval between the delay numbers could have been chosen freely; this increment was valid for all delay numbers. The tester Dynatest was an analogue device and had to be compensated manually, according to the resistance of the firing circuit.

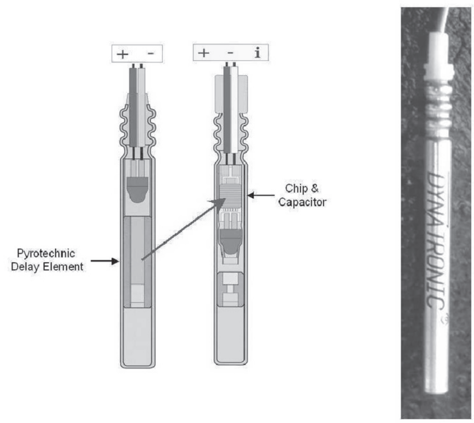


Figure 1. Dynatronic.

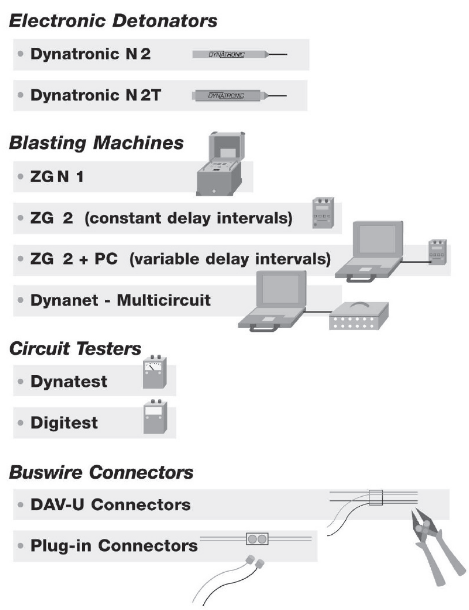


Figure 2. System components Dynatronic.

10 years later ZG 2 and Digitest were introduced with dimensions like today's i-kon™ Logger or Blaster 400. They were operating with a 2 line LCD Display and ZG 2 was prepared to be programmed alternatively via external Software (TIUS = Timing Interval User Software). TIUS was designed to

generate individual delay times between delay numbers. Dynatronic had to follow its delay number fixed sequence, always. For connecting the detonators to harness (buswire), two different systems were available: the standard DAV-U system where an additional tool (DAV-U pliers) was required, or a plug-in system where the female part of the connector was already part of the harness wire. Depending on blast pattern, harness with different spacings of the connectors was available (e.g.: 0.8 m spacing for contour/perimeter in tunnel or a connector-pair each 3,0 m for standard quarry operation).

Figure 3. The i-kon system.

### 1.2 *The i-kon electronic initiation system*

In 2000 the i-kon system was launched and started to replace the Dynatronic system.

The i-kon electronic initiation system has broken barriers in civil explosives technology. Its handling, safety and initiation precision opens up new opportunities. The system consists of 3 main components: the Detonator, Logger and Blaster (Figure 3).

#### *1.2.1 The i-kon detonator*

Every detonator can be programmed in 1 ms increments between 0 ms and 15,000 ms. Up to 4,800 detonators can be used in one blast. Thanks to the 2-way communication between all the components of the initiation system, functionality can be checked at any time. Since the user has to stock only one type of detonator, storage is considerably simplified. The detonators have a clip connector for easy hook up to the harness wire, which is available in 200 m coils and is carried in a customised sling bag for easy handling on the blast. Different wire length (5 - 80 m) and wire properties are available; from standard to extra tough for rough charging conditions or long sleeping times.

#### *1.2.2 The i-kon logger*

All the detonator relevant data are generated and saved in the logger. It can save data from up to 200 detonators. As soon as the detonator is connected to the harness, the logger registers this detonator in the firing circuit (reading and saving its unique ID number). Functionality of the electronic components

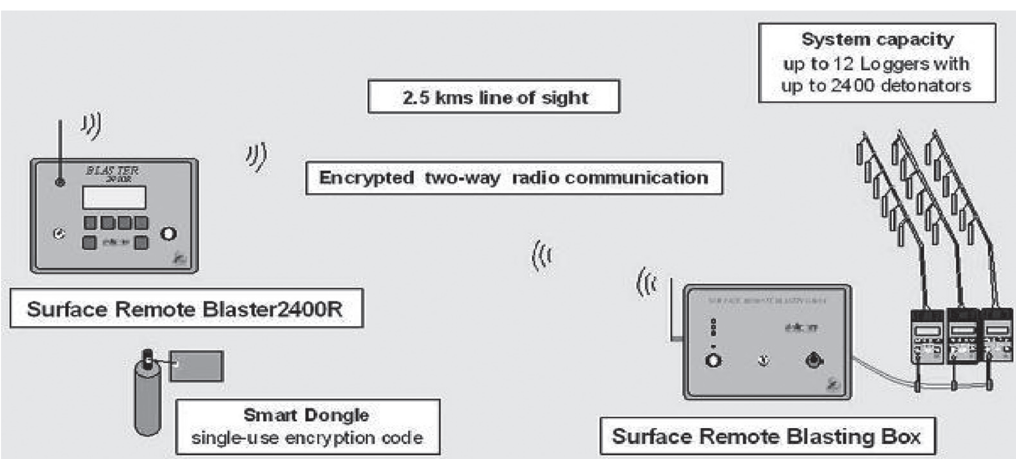


Figure 4. Surface remote blasting system.

of each detonator is checked and the entire firing circuit is tested for short circuit and leakage current. The logger is inherently safe due to low voltage and low current and can be used to address detonators on the blast pattern.

### *1.2.3 The i-kon blaster*

The blasters are the exploders that control the programming, arming and triggering of the firing circuit. They are available with different system capacities and application related functionality (e.g.: communication via buswire, telephone modem or radio transmission).

### *1.2.4 The i-kon SURBS*

The i-kon™ Surface Remote Blasting System (SURBS) is designed to program, arm and initiate surface blasts wireless from the point of safety. The system consists of the Surface Remote Blaster2400R, the surface remote blasting box (SRBB) and the proven detonator and logger technology of the current i-kon system (Figure 4). A sophisticated and patented safety technology guarantees the highest safety standards for application of the SURBS.

The maximum system capacity is 2,400 detonators (via 12 Loggers) in a single blast.

The Blaster2400R is the control unit of the SURBS which controls the SRBB via radio; the SRBB supplies the firing energy to the attached loggers and detonators. The communication between Blaster2400R and SRBB is encoded with a unique one-time digital encryption code. Furthermore all radio signals contain the unique serial number of the SRBB. Each command is checked for data corruption. At the beginning of the blasting sequence a ‘keep alive’ timer is started in the SRBB. The timer must be continuously reset by Blaster2400R commands during the whole blasting sequence. If the reset command is not received by the SRBB (e.g. the data transfer is disrupted) it will automatically default to standby mode. During operation of the system the SRBB must confirm receipt and execution of all radio commands, before the Blaster2400R can proceed with the blasting sequence (Figure 5).

Each time the system is used, a new unique digital encryption code is generated by the SRBB and written to the smart dongle. For any operation of the system the digital key code must be read and checked by the Blaster2400R. Without valid digital encryption code the SRBB cannot be remotely controlled by the Blaster2400R and the blast cannot be fired.

Figure 5. SURBS in operation.

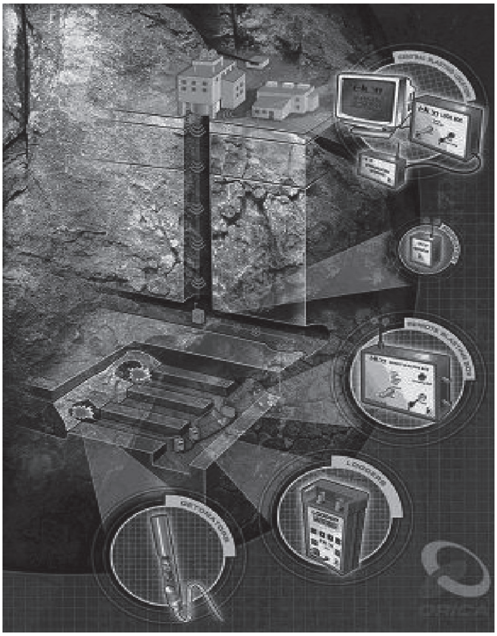

Figure 6. CEBS components.

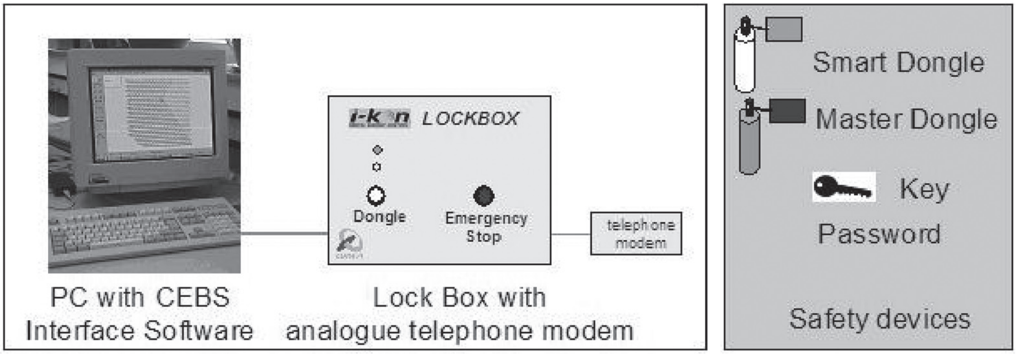


Figure 7. System components in central blasting location (Mine office).

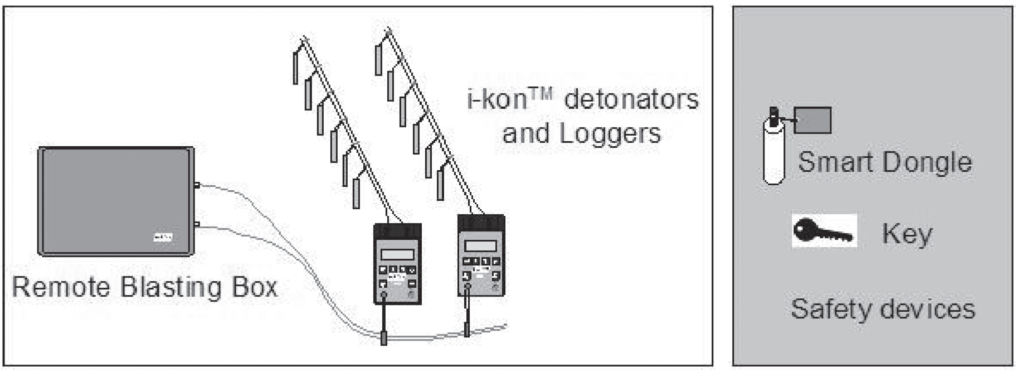


Figure 8. System components near blast site.

*1.2.5 The i-kon CEBS*

The i-kon™ Central Blasting System (CEBS) is designed to program, arm and initiate underground blasts from a central point of safety (Blasting location = surface or underground mine office). The system (Figure 6) consists of components for use at the central blasting location of the mine (Figure 7) and for use at the blast site (Figure 8). The system can make already use of an analogue mine telephone network; LAN and W-LAN access will be available in future also.

The system components at the blast site consist of the Remote Blasting Box (RBB) and the proven detonator and logger technology of the current i-kon system. The RBB can only be activated with a key and a smart dongle by an authorised operators. To proceed with the blast the initialised smart dongle must be taken to the central blasting location and placed in the dongle port.

The system components for use at the central blasting location (e.g.: mine office) consists of a PC based centralised blasting interface software and the master control unit 'Lockbox' with the attached communication interface (e.g.: telephone modem). Several sophisticated features & devices guarantee the highest safety & security standards for application of the i-kon CEBS.

*1.2.6 SHOTPlus-i*

In addition to the hardware, the SHOTPlus-i software can be used to plan, document and analyse the entire blast (Figure 9). The planning data generated in the office can be transferred into the firing circuit via the logger (Figure 10). After the blast has been carried out, all the detonator and firing circuit related data can be uploaded to SHOTPlus-i again. In addition to the programmed delay time, the uploaded data contain name and status of each individual detonator. SHOTPlus-i is the main platform for different blast based

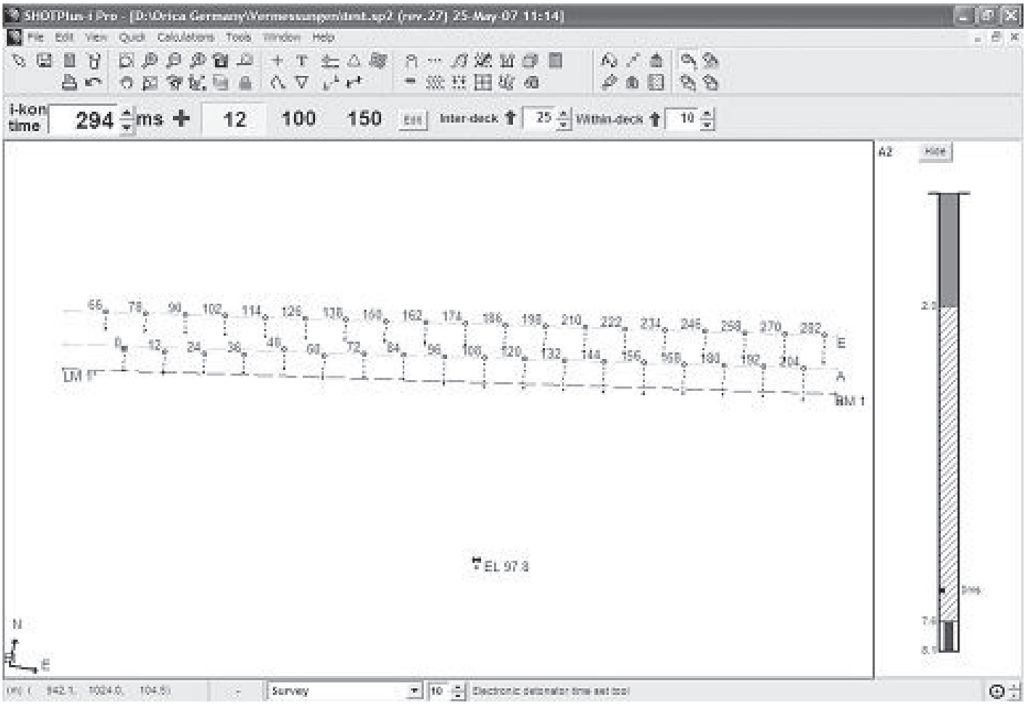


Figure 9. Timing & charging tool inside SHOTPlus-i.

services (e.g.: blast survey, operation management & documentation, initiation optimisation, vibration prediction).


Figure 10. Upload/download feature in SHOTPlus-i.

## 2. THE W&P OPERATION IN AUSTRIA

In the following sections the Wietersdorfer & Peggauer Zementwerke GmbH [W&P] is introduced. Production optimisation in 3 different quarries is described. Part of this is the operation adapted application of electronic initiation, which is a major tool inside the optimisation process at the Peggau operation for more than 10 years now. In contrast to the application of the latest state of the art drill and blast techniques, also direct mechanical extraction has gained over the past years. Operating experience in marl mining during the transition of quarrying from traditional drill and blast operation to direct extraction by means of a heavy hydraulic excavator are described.

Currently, the workforce at the company Wietersdorfer & Peggauer Zementwerke GmbH is about 420 employees, producing approx. 750,000 t of cement and binders, 80,000 t of lime, 260,000 t of plaster and 150,000 t of other construction materials (e.g. aggregates, …). Operations are in Wietersdorf (Figure 11), Peggau (Figure 12) and Leoben (Figure 13). For this, approximately 1.7 to

1.8 million tons of raw material are quarried at ten different locations at these three operations every year. In some of these operations raw materials have been produced for more than 114 years now. Due to the long operation time, they have now reached the immediate vicinity of settlement areas.

Since 2000, the company has been certified according to ISO 9001, ISO 14001 and the EMAS regulation.

Over the past few years the following major parameters inside the production process of cement were changed:

– composition & mixture of different raw material qualities
– adjusting substitute fuels to the process and
– updating processing plants to the latest state-of-the-art technique by conversion and/or retrofitting, according to market demands

Figure 11. Wietersdorf operation including the limestone and marl quarries.

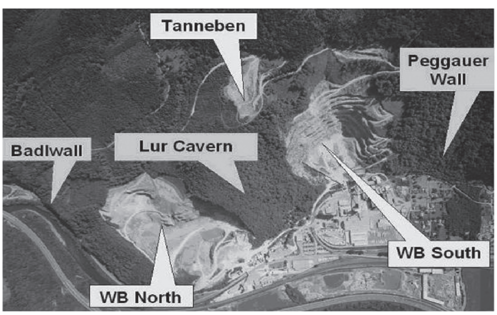


Figure 12. Limestone quarries at Peggau.

## 2.1 *Limestone & marl production at the Wietersdorf operation.*

The Wietersdorf operation is situated in Carinthia in the Görtschitz Valley about 30 km north of Klagenfurt. Two mining locations – the limestone quarry in the south and the marl quarry in the north – have opened up the deposit.

Figure 13. Dolomite quarry at Leoben.

The marl of Klein St. Paul is assigned to the Upper Cretaceous. The nummulitic limestone (Eocene) in the upper layer of the deposit has a thickness of 50 to 100 m. Depending on the content of $CaCO_3$, the entire succession from lime via marl, clay marl to clay exists in the marl quarry. The material is quarried by multiple benching, the bench height being 5 m only, but its length is up to 800 m. Due to the inhomogeneous stratification in the marl quarry (i.e. thin-stratified inter-bedding of marl and carbonate layers with fairly different chemical composition) comprehensive quality control is vital, taking into account the varying $SO_3$ content.

The limestone quarry is located 1.5 km to the south of the factory at 785 m above sea level. The material is quarried in one bench with a height of approx. 22 m and a length of approx. 280 m. The limestone is extracted by drill and blast operation; technology is comparable to the Peggau operation, which will be explained more detailed later in this paper.

The crusher is situated in the middle between the lime and marl quarries at 780 m above sea level. Therefore, the average conveying distance is up to 1,000 m. The material is hauled to the primary crusher by heavy trucks (60 t payload). Then belt conveyors lead the pre-crushed raw material to the raw material store of the cement plant.

New options for raw material production were tested at the Wietersdorf operation in 1996. During the replacement investment for loading equipment, a conversion took place in the marl quarry from traditional drill and blast operation to direct extraction by means of a heavy hydraulic excavator (Figure 14) with a power output of 500 kW at 2,100 rpm. The hydraulic excavator (Type: Liebherr R 984 B) is equipped with a hydraulic quick-change device enabling the excavator to operate with a backhoe dipper or alternatively with a ripper (Figure 15). It takes only one minute to change the backhoe dipper (volume of 5.5 $m_3$) to the ripper. Depending on rock properties, the digging and loading capacity of the hydraulic excavator varies between 500 and 700 t per operating hour, diesel consumption is approx. 65–75 litres per operating hour.


Figure 14. Hydraulic excavator Liebherr R 984 B.

Furthermore, the way of taking samples had to be changed due to this technological transition. Since drill fines are no longer available for the quality management, samples are taken manually from the corresponding layers for the purpose of quality control. The raw material extraction is directed on basis of the main raw material properties (selective mining); the resulting mixing ratio is steered by a customised management system.

The general geological conditions enable economic efficiency of this mining technology. Approximately 95 % of the solid raw material can be extracted by this way in the marl quarry. In areas with compact layers of more than 80 cm thickness, overburden blasting is practised for breaking the rock, keeping wear out of the hydraulic excavator in an acceptable range. To maintain high availability of the hydraulic excavator, inspections are carried out including wear measurements as well as oil analyses on a regular basis.

The major advantages for transition from a traditional drill and blast operation to selective, mechanical mining – justifying the investment of the heavy hydraulic excavator also from an economic point of view – are:

- accurate selective mining leading to maximise homogenisation of product quality
- reduced bench height: higher number of digging points opens up huge potential for quality management
- reduced bench height: increased labour safety
- increased crusher throughput because of lower raw material moisture and less fines
- very effective noise and visual protection barriers
- high flexibility due to quick setting up of connecting ramps (easy site development)
- use of the hydraulic excavator for high-cut and deep-cut, enabling intermediate storage of the raw material close to the digging point (in situ quality management)

Figure 15. Use of the ripper during extraction.

The transition to direct extraction in the marl quarry of the Wietersdorf operation brought a significant reduction of emissions to the neighbours. In the past about 60 to 70 production blasts per year were carried out in the marl quarry; nowadays only 5 to 10 overburden blasts – with 3 to 5 boreholes each – are required per year.

The requirements for the raw material homogeneity, which have been increased in the meantime, led to the result that the raw material extraction in the marl quarry has to be carried out even more selectively. In December 2003, the wheel loader was replaced by another hydraulic excavator from Liebherr with an ever higher break-out force (Type: 984 C; payload: 118 t; power output: 523 kW at 2,100 rpm).

*2.2 Limestone production at the Peggau operation*

The Peggau operation is situated in Styria in the Mur Valley about 15 km to the north of Graz. Raw material has been produced in the southern and northern company-owned quarries (Figure 16) for about 114 years. The limestone quarry at Tanneben (Figure 17) including slip shaft (vertical ore pass) and subsequent underground belt conveyor system was commissioned in 1992. There are numerous conservation areas (cavern preserve, natural reserve and Natura 2000 – area 'Peggau Wall') around the site. Furthermore, the factory premises are situated in a protected landscape area and water reservoir area of the municipal utilities of Graz (Drinking-water). The centre of the town Peggau is located at a distance of about 400 to 700 m south from production.

Figure 16. Peggau operation (North & South) & Conservation area Lur-Cavern (Middle).

The only tourist attraction of the town Peggau is the Lur-Cavern dividing the traditional mining region into the southern and northern quarry (Figure 16). The Lur-Cavern with a length of approx. 6 km connects the towns Semriach and Peggau, which have a difference in level of approx. 300 m. Being the largest waterflowing stalactite cavern of Austria, the Lur-Cavern is frequently visited; both from Peggau and Semriach.

For all blasting operations the business hours of the Lur-Cavern Company have to be taken into account. Blasting activities can only be carried out, outside the business hours. Irrespective the precise position and shape of the Lur-Cavern, options to expand both quarries are fairly limited.

There are no tangible limit values on ground vibration emissions; nor are there any corresponding standards for the nature sanctuary Lur-Cavern with respect to blast vibration. It is prohibited to affect or damage the cavern due to its legal categorisation as a nature sanctuary. The stalactites (Figure 18) are crucial points in this connection, in particular the small tubes of calcareous sinter at the roof of the Lur-Cavern which have a wall thickness of only a few tenths of a millimetre.

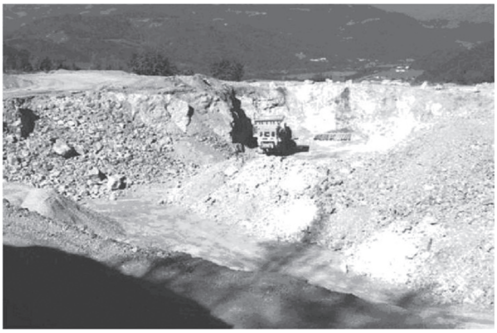

Figure 17. Mobile crusher at the quarry Tanneben.

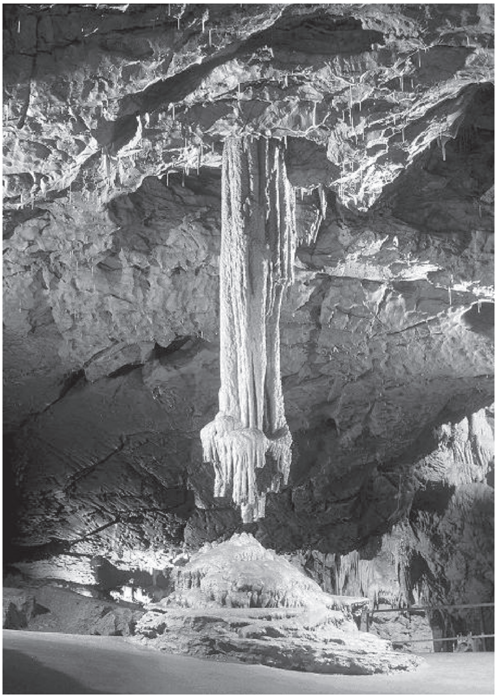

Figure 18. Stalagmite and stalactite (The 'Prince').

### 2.2.1 Limestone quarrying

The limestone quarried in Peggau can be assigned to the Devonian and is distinguished by a high degree of purity and the most different coloration. Due to the age of the limestone, there are comprehensive karst phenomena, in part filled with clays (e.g.: joints, cracks, ...).

A continuous 'step by step' optimisation process is carried out in the Peggau operation to achieve acceptance of raw material production by the neighbours and inhabitants of Peggau. With this process it is intended to reduce emissions to a sustainable level considering the general economic situation. Therefore, the mining method in the northern and southern quarries was converted to benching with bench heights of 25 m.

In the Tanneben limestone quarry the material is extracted from one bench with a height of approx. 12 m; protected by a noise and sight barrier.

### 2.2.2 Drill and blast operations

A drill rig from Sandvik BPI (Type TR 119) is used to prepare the boreholes with a diameter of 90 mm. In the 1990s head and toe boreholes were drilled but nowadays normally only head boreholes are usual. An exception are in homogeneous geological areas (e.g. karst, ...) where due to technical reasons drilling of the head boreholes is difficult or impossible. The spacing of the headers is up to 4.5 m; depending on the geological conditions. Burden in the first row is approx. 5.0 m (Figure 19). The average consumption of explosives per year and ton is up to approx. 100 g/t raw material.

The whole blasting set up was changed significantly at the Peggau operation in 1996:

- the column inside the vertical boreholes (headers) was divided into 2 decks
- Length of the intermediate stemming is at least 2 m
- the upper deck was initiated at the beginning from the top but nowadays from the bottom
- the lower deck is initiated from the bottom of the borehole (Area of best confinement)

The higher amount of time spent for charging is justified by a considerable reduction of the blasting vibrations at bench heights of more than 20 m. Additionally, when using electric initiation (due to the limited amount of delay numbers) the size of the blast has to be divided into two or even more individual blasts. Using electronic initiation the number of blasts is reduced significantly.

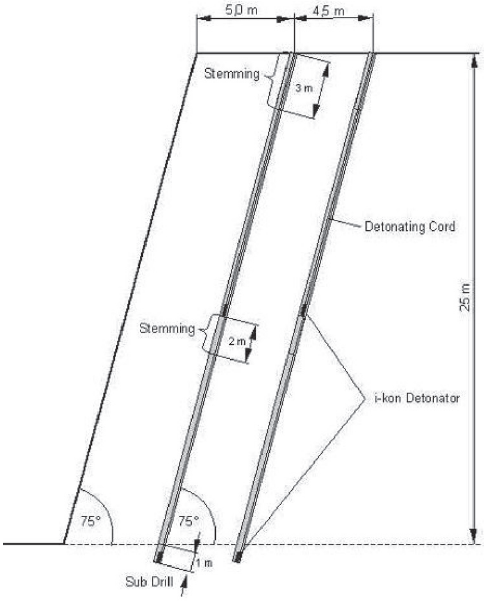


Figure 19. Two row blast with divided column (2 decks) and electronic initiation.

### 2.2.3 Optimisation process

An empirical, but systematic step-by-step approach (Figure 20) was chosen to find the best timing for improving blast result (fragmentation) and reducing ground vibration (Figure 21). The vibrations measured in the area of the neighbours as well as in the Lur-Cavern prove that it is possible to reduce the resulting velocity of vibration down to 60 % with an associating increase of the frequency to approx. 16 to 22 Hz. In the area of the Lur-Cavern and the neighbours (distance 100 to 400 m) 90 % of the recorded values (250 vibration records) ground vibration velocity were below 0.7 mm/s with a reliable increase of the associated frequency.

As a further result of the optimisation process it was possible to increase the charge per delay considerably at the same time.

On the first view, the higher costs for the electronic initiation seem to be a disadvantage. At the Peggau site these additional costs for the electronic initiation are approx. 5 cent per ton of mined rock. However, to determine the total drill and blast costs the operating advantages have to be considered also. The following items can be taken

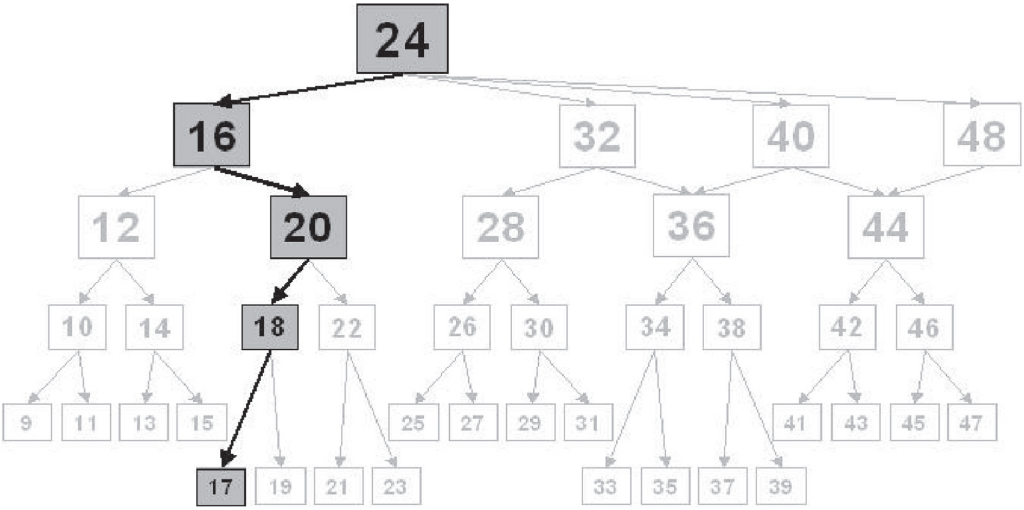


Figure 20. Empirical 'step by step' approach to find best timing (Example).

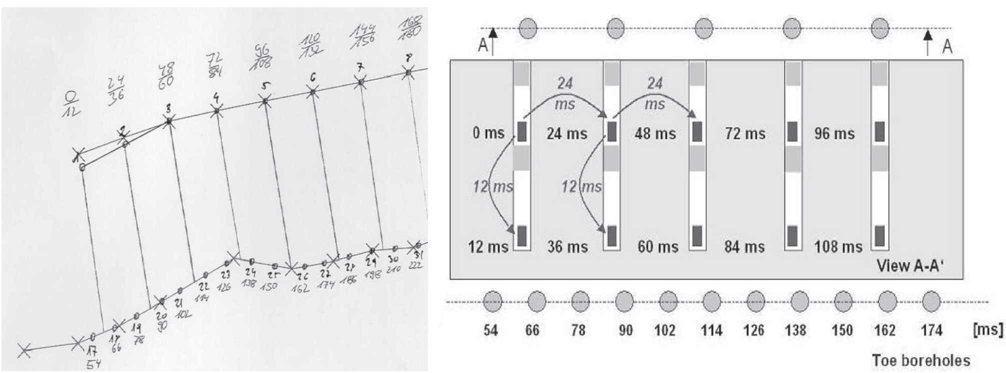


Figure 21. Ground vibration optimised initiation pattern (in a blast with head and toe boreholes).

into account for calculating the value of electronic initiation:

- The extended size of the production blasts (Figure 22) and the increase of charge per delay at the Peggau operation enable a reduction in the amount of blasts per year by 50 %. By this the proportion set-up costs for the whole drill and blast operation per year are decreased significantly:
  - surveying the wall face
  - checking deviation of boreholes
  - planning & documenting the entire blast
  - transport of drill rig to the intended blasting area
  - announcement of blast to the responsible federal authorities
  - matching the time of blasting with the neighbours
  - matching the time of blasting with the Lur-Cavern company, the Austrian Federal Railways, owners of real estate to the north and south of the site
  - placing blasting guards at the federal road to close the road while blasting
  - all other activities on site have to be stopped during the blasting procedure and
  - after blasting bench crest and face have to be scaled by means of an hydraulic excavator

– Fragmentation analysis and assessing diggability of the muck pile is essential for evaluating the blast result in total. Based on a subjective evaluation, the grain size distribution has been improved and percentage of fines and boulder has been reduced. This leads to well-balanced quantities of the limestone fractions available for further processing
– The complete production of already released parts of the deposit became possible again and mining losses in sensitive areas are avoided
– It is not necessary to change the mining method to mechanical production; thus avoiding higher costs for development and production activities

Figure 22. Production blast at the Peggau operation.

## 3. FINAL REMARKS

In the early 80s development of the first Dynatronic electronic initiation system was started. In 1986 Dynamit Nobel introduced this delay-number based electronic initiation system, which followed the design of an electric initiation system. Since then, a lot of experience has been gained in all kinds of civil applications and in the design of electronic initiation systems themselves. Today electronic initiation systems have to be fit for surface and underground applications, for small quarry blasts and for huge open cast operations with up to 4,800 Detonators and 1,000 t of explosives in one blast. The i-kon™ electronic initiation system, described above, offers several options adjusted to a wide range of applications and blast dimensions.

The consistent implementation of the latest state of the art production technology led to the fact that Wietersdorfer & Peggauer Zementwerke GmbH can continue raw material extraction at their different sites. Production is accepted by the neighbours and authorities despite the difficult general environmental conditions. After adapting production technique to the mine's specific needs, a sustainable reduction of emissions has been achieved. There have been no further complaints by the neighbours since 2001. Consequently, in the future the raw material quarrying will be possible even in sensitive areas, for which the permission has already been received. There is no further need for changing mining method. The transition of the production technology from drill and blast operations to direct extraction by means of a heavy hydraulic excavator has proved a success in the marl quarry of the Wietersdorf operation. New opportunities have been opened up to the Peggau operation by introducing electronic initiation more than 10 years ago. An empirical, but systematic approach brought the best timing with respect to a significant reduction of ground vibration, the improved fragmentation and increase of the charge per delay at the same time. The higher costs for the electronic detonator itself are more than compensated by various operational advantages and brought an extra value to the operation.

Drawing the 'Bottom Line', electronic initiation is part of the daily work at the Peggau operation.

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# How to control the frequency content of blast vibrations with electronic detonator

F. Platre
*Director, Pyrénées Minage, Pau, France*

C. Mut
*Operation manager, Pyrénées Minage, Pau, France*

Y. Bleuzen
*Engineer, Technical Assistance Department, Nitro-Bickford, Paris, France*

R. Puntous
*Blasting Expert, IMI, Paris, France.*

ABSTRACT: Réunion is currently a dynamic region in terms of road construction. One of the projects underway is the construction of the south bypass of St Denis de la Réunion which consists in the south part of a cut and cover trench. The materials to be extracted partially consisted of basalt, requiring blasting. Given the presence of many residential buildings the company Pyrénées Minage, with the technical assistance of IMI and Nitro-Bickford, proposed the usage of electronic detonators.

The analysis of the results from the first blasts indicated high values in one of the measurement points, which was partly due to a resonance phenomenon. After a series of blasts, the electronic firing sequences were adjusted so as to generate precise frequencies sufficiently removed from the structure's resonance frequency to attempt to reduce vibration. This article presents the vibratory analyses carried out in order to detect this phenomenon and the obtained vibration results.

## 1. PRESENTATION OF THE WORKSITE

### *1.1 The operation's objectives*

Prepared within the framework of a regional development plan, the South Boulevard is part of a road development plan covering the northern part of Réunion. Its construction meets specific traffic issues in the city of St Denis de la Réunion. It provides a high capacity urban artery which connects with the streets that fan out into the city. It will serve to restructure a network that primarily runs from the heights of the city of St Denis to the ocean, and to redesign the city around this axis.

It will provide the population with quicker and more direct connections between districts. It will help to improve the access to the University, increase the value of the commercial activities along the urban boulevard, and provide a closer connection between the island's two economic hubs, namely the Roland Garros airport and the port of Pointe des Galets.

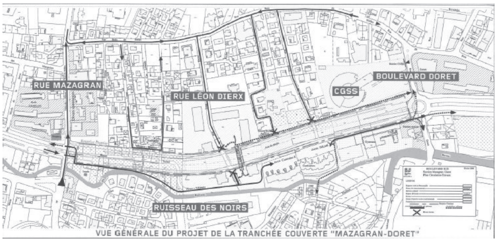


Figure 1. General view of the cut and cover trench.

This operation's completion will provide for the continuation of the South boulevard between the two sections already open to traffic on either side of it: Source-Mazagran to the west and Doret-Digue to the east.

### *1.2 The project's participants*

This project is financed by the Réunion region and the city of St. Denis. The project management is provided by Scetauroute and Société du métro de Marseille.

The contracting firms are the companies PICO for the preliminary works on the cut and cover trench and SBTPC (VINCI group) for the earthworks and civil engineering of the cut and cover trench.

The company Pyrénées Minage is a subcontractor of SBTPC for the rock breaking works.

The total amount of the works is 43 million euros.

### *1.3 General characteristics*

Running for 670 m out of the 8 km of the South boulevard, the "Mazagran Doret" section stretches from the rue Mazagran to the Boulevard Doret. This layout with two lanes each way separated by a central reserve includes, on the one hand, the realisation of lateral frontage roads and the local access for public transport and, on the other hand, the construction of a cut and cover trench structure 297 m long, 8 m deep equipped with underpass approaches measuring 75 m on the east side and 115 m on the west side.

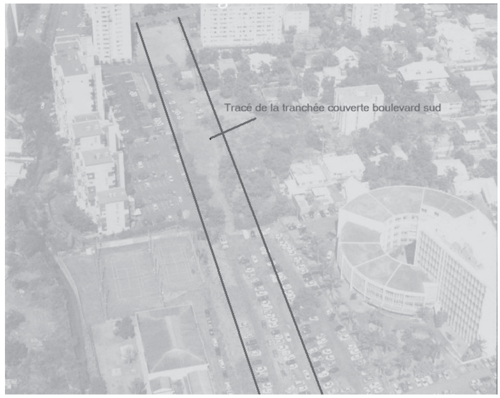


Figure 2. Upper view of the cut and cover trench.

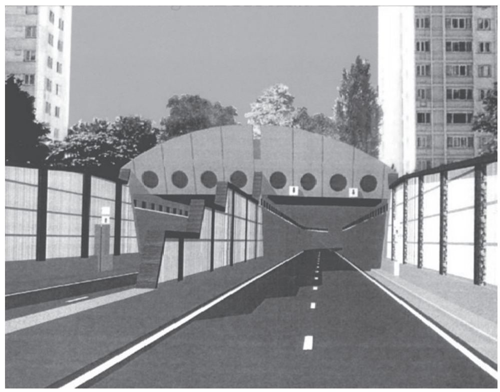

Figure 3. Front view of the cut and cover trench.

The cut and cover trench consists of a double reinforced concrete unit, for which the separation is a solid wall. The transversal characteristics are the following: total length of 21 m, width of the lanes per direction of 8.25 m (2 main lanes measuring 3.5 m).

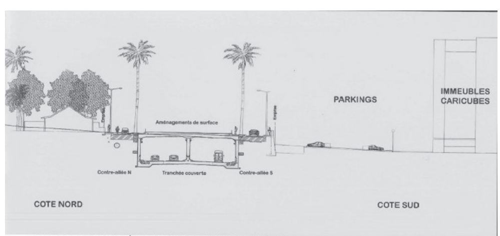


Figure 4. Diagram of cut and cover trench.

The cut and cover trench serves to limit the sound nuisance linked to automobile traffic. The construction will be illuminated and provided with traffic surveillance cameras.

### 1.4 Technical constraints

The material to be removed on the 8 m deep of the trench is partially consisted of basalt that required extraction by blasting. The proximity of many structures, a majority of which are multi-story residential buildings, prompted the project owner to install seismographs at 19 points in the worksite's surroundings in order to control vibration generated by blasting.


Figure 5. View of the trench, South direction.

Figure 6. View of the trench, North direction.


Figure 7. View of the trench, North direction.

### 1.5 Location of the vibration sensors

The sensors were placed on the ground floor and on the upper floors of the buildings in order to very precisely monitor the impact of the vibrations from the blasting. The geophone sensors were connected to various recording units that completely recorded the blast signals as time elapsed. In this way, the seismic traces could be precisely analysed in the event of the vibration threshold being exceeded.

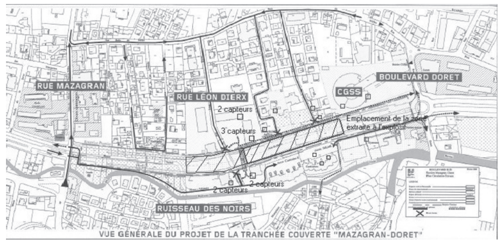


Figure 8. Location of the seismographs.

## 2. BLAST TECHNIQUES

After clearing of the topsoil over approximately 2 m, the encountered materials were extracted using explosives. The trench's earthworks required the usage of two blasting techniques:

### 2.1 Pre-split of the exterior walls

The pre-split blast is carried out over the trench's total height, i.e. over 6 m with a loading of 40 g/m detonating cord and a 30 mm cartridge, 125 g at the bottom of the hole. The blasts use short delay electrical detonators (25 ms between holes), initiated by a sequential 10-line blaster (REO). The unit charge per hole amounted to 325 g (5 m of 40 g cord and a 125 g emulsion cartridge). Each hole was initiated at a different time, thanks to the use of a sequential blaster. Pre-split lengths of 30 to 40 m were blasted per round.

### 2.2 Mass blast to break the rock from the trench's central zone

For these blasts, preliminary vibration studies had defined the maximum unit charge to be used on the basis of the position of the holes relative to the buildings that were being monitored. This charge varied from 0.500 kg to 2 kg in order to comply with the vibratory constraints included in the specifications. The blast plan was prepared in order to comply with the limits, by adapting the pattern and depth of the drilling. As such, for a limit charge of 1 kg, the blast plan was the following:

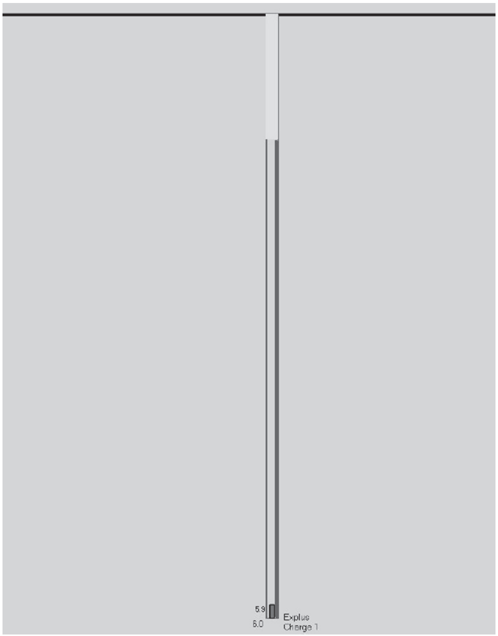


Figure 9. Pre-split blasting plan.

The initiation was provided by electronic detonators in order to take advantage of programming flexibility (in steps of 1 ms) and the precision of the initiation time. Thanks to these two characteristics, the sequence plans were adapted, insofar as possible, to the site's vibratory constraints while carrying out consecutive blasts in 100 to 300 holes, i.e. 50 to 200 kg of total explosive charge.

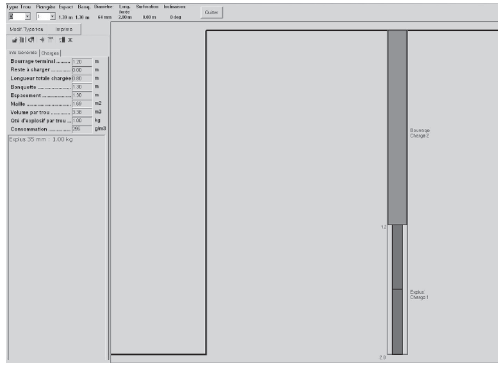

Figure 10. Central zone blasting plan.

## 3. TEST SET: ADAPTATION OF THE BLAST PLANS

The rock breaking works began in September 2006 with the performance of a series of test blasts intended to confirm the preliminary study's results and to determine an optimum electronic sequence for the mass blasts. The initial blasts were carried out using the following configurations:

The installed seismic instrumentation (19 sensors) served to determine the vibratory values generated by each blast, as well as each signal's frequency content. From the very first blast, two particularities came to light:

– With a majority of the sensors, the frequency content of the signals, i.e. the main frequencies

Table 1. Technical data from the 7 first blasts.

| Blast number | Date | Unit charge | Time between holes | Time between rows | Minimum time between holes |
|---|---|---|---|---|---|
| 1 | 07/09/06 | 1 kg | 20 ms | 65 ms | 5 ms |
| 2 | 12/09/06 | 1 kg | 13 ms | 48 ms | 4 ms |
| 3 | 08/10/06 | 0.5 kg | 25 ms | 67 ms | 8 ms |
| 4 | 12/10/06 | 0.5 kg | 20 ms | 85 ms | 5 ms |
| 5 | 16/10/06 | 0.5 kg | 20 ms | 85 ms | 5 ms |
| 6 | 23/10/06 | 0.75 kg | 16 ms | 36 ms | 4 ms |
| 7 | 24/10/06 | 0.5 kg | 16 ms | 36 ms | 4 ms |

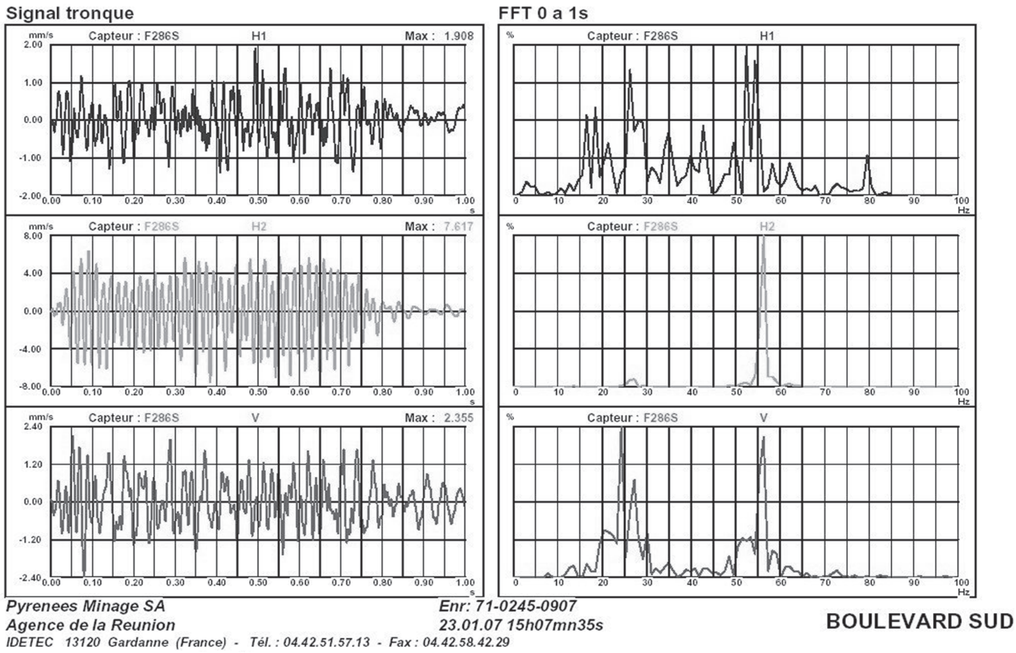


Figure 11. Example of the vibratory result for blast 32, sequence 18 ms between holes (56 Hz), 40 ms between rows (25 Hz) for sensor F286S.

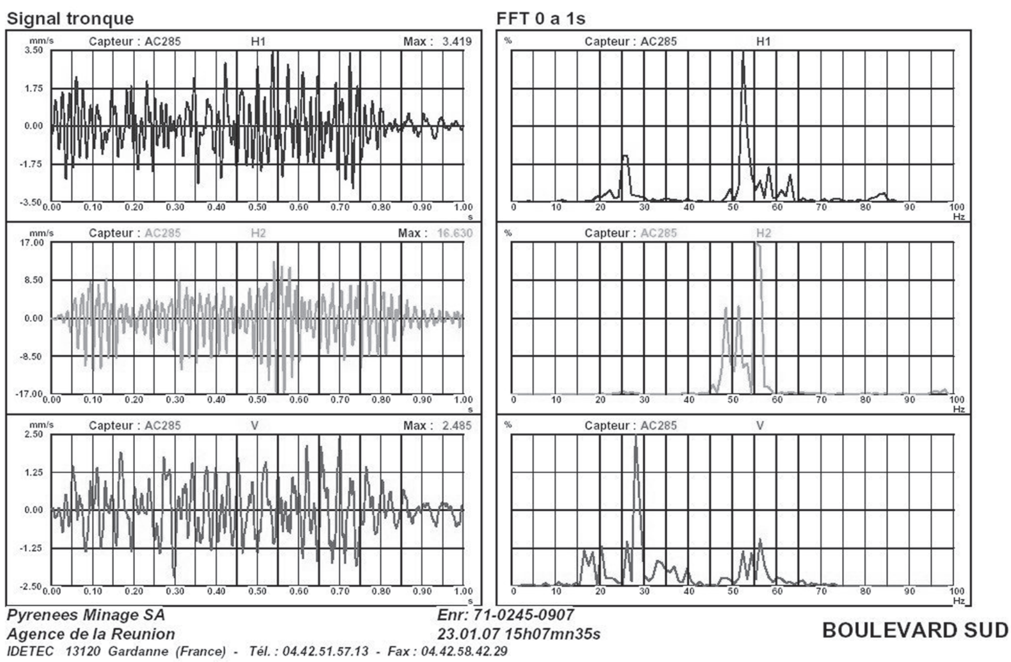


Figure 12. Example of the vibratory result for blast 32, sequence 18 ms between holes (56 Hz), 40 ms between rows (25 Hz) for sensor AC285.

calculated by the FFT, was in relation with the implemented electronic blast sequence. For an interval between holes of 20 ms and an interval between lines of 65 ms, the main frequencies measured at the control points were 1/20 ms = 50 Hz and 1/65 ms = 15 Hz. For an interval between holes of 18 ms and an interval between lines of 40 ms, the main frequencies measured at the control points were 1/18 ms = 55 Hz and 1/40 ms = 25 Hz

– With sensor C44MA, located at the top of an elevator shaft, the values measured on the vertical track were 3 to 4 times higher than the values anticipated by the preliminary seismic study. On this point, the main frequencies measured in the vertical direction fell between 18 and 22 Hz, for the first blasts

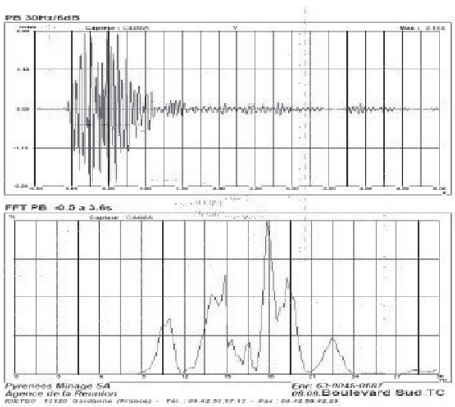


Figure 13. Vibration result on sensor C44MA -18 Hz main frequency

In order to understand this unexpected phenomenon, additional vibratory measurements were taken at this point, with the elevator in operation.

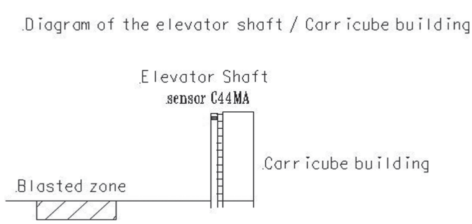


Figure 14. Diagram of the elevator shaft, sensor C44MA.

The control point was located at the top of an independent elevator shaft, connected to the main structure of the Carricube building by a series of iron bridges located on each floor. Measurements of the structure's vibrations were carried out while the elevator was in operation: it came to light that the structure was reacting to a characteristic frequency of its own, varying from 18 to 22 Hz on the vertical track.

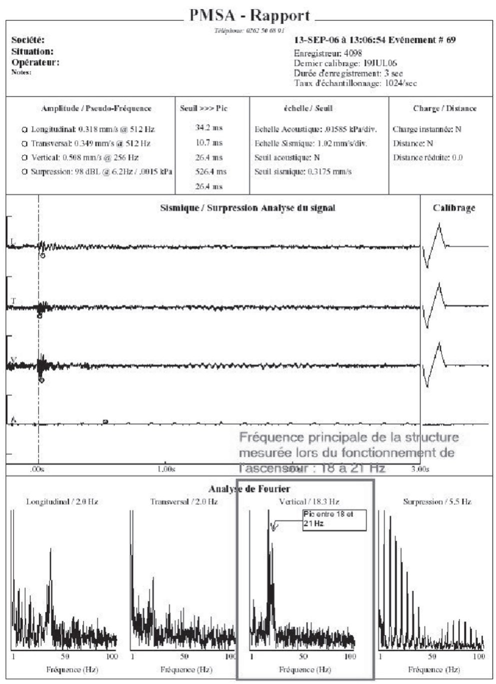


Figure 15. Example of the seismic signal recorded with the elevator in operation.

This was exactly one of the main frequencies generated by the electronic sequence during the initial blasts, due to the interval between rows: one of the hypotheses adopted in order to explain the high values at this point was the correspondence between the structure's probable resonance frequency between 18 and 22 Hz and the frequency generated by the interval between rows.

Sequence modifications were then carried out, either toward lower frequencies by increasing the time between rows, or toward higher frequencies by reducing the time between rows. The most favourable results were measured while reducing the interval between rows, thereby increasing the

Table 2. General blasts characteristic.

| Unit charge | Usual total charge | Number of holes | Blast volume | Minimum distance in m | Vibrations measured in mm/s |
|---|---|---|---|---|---|
| 0.5 kg | 150 kg | 300 | 450 $m^3$ | 20 m | 2.5 to 5 mm/s |
| 1.0 kg | 200 kg | 200 | 575 $m^3$ | 35 to 40 m | 3 to 5 mm/s |

frequency generated in the elevator shaft. At the end of the test set, the following sequences were adopted for the mass blasts:

- Time between holes: 18 ms, i.e. an associated frequency of 56 Hz
- Interval between rows: 40 ms, i.e. an associated frequency of 25 Hz
- Starting of the blast: at the centre

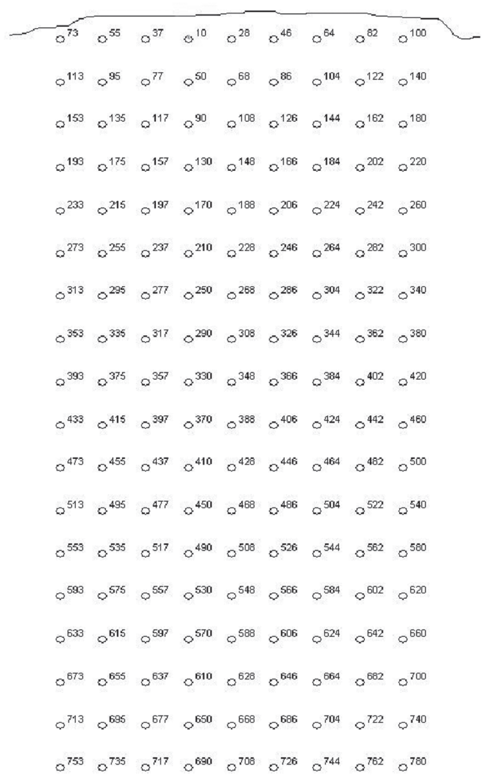

Figure 16. Standard blasting sequence.

The unit charges were placed according to the position of the blasts relative to the control points and their vibratory responses.

## 4. PROGRESS OF THE WORKS

Based on the results of the test set, the characteristics of the blasts were changed only very slightly relative to the sequence.

Table 2 summarizes the main parameters for all of the production blasts:

The vibration values were variable depending on the points being measured. The indicated values corresponded with the range of vibrations measured at an equivalent distance and equivalent charge, for different points.

The usual prediction calculation for the vibrations generated by the blasts was carried out using the following general formula, known as the Chapot law

Equation 1. Vibration prediction formula.

$$V = K\left(\frac{D}{\sqrt{Q}}\right)^{-1.8}$$

with:
V = particle speed in mm/s.
K = wave attenuation coefficient.
D = distance in metres between the blast and the measurement point.
Q = instantaneous unit charge of explosives in kg.
The coefficients calculated on the basis of the measured results generally fell between 1500 and 3000.

The average volume blasted each week amounted to 800 $m^3$, in keeping with the initial schedule's forecasts. The project ran from September 2006 to January 2007 (4.5 months with a one-month stoppage), for a total volume of 10,000 $m^3$.

The continuous vibration measurements served to confirm the test set's results, notably in the most sensitive structure (elevator shaft), and for the main frequencies measured at the other points.

These results serve to validate an aspect that is still poorly described with regard to the potential for electronic initiation: the frequency generated in surrounding structures in the general environment can be imposed by the blast sequence. This opens interesting prospects for resolving vibratory problems by being able to impose frequencies that are as harmless to the environment as possible.

### *4.1 Blast preparation with packaged explosives and electronic detonators*

Figure 17. Loading of the blast.

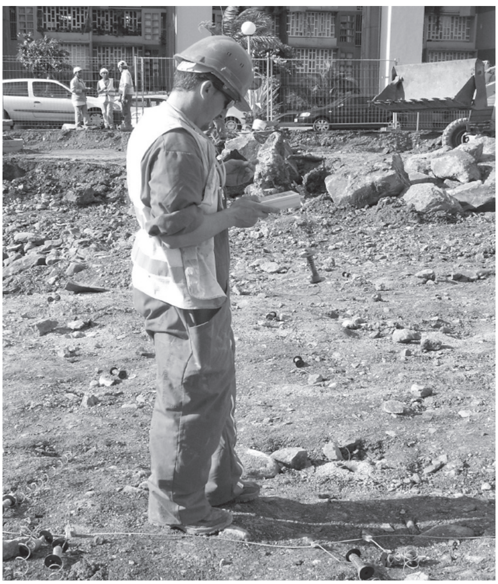

Figure 18. Programming and connection of the blast.

### *4.2 Blast protection against projection risks*

The projection risk was controlled through the use of crushed 6/10 mm gravel stemming of a minimum 1.3 m, and by covering the blasts with a triple layer system of high density geotextile, netting and high density geotextile. There were no projections throughout all of the works.

Figure 19. Connexion of detonators.


Figure 20. Setting the netting for protection.

Figure 21. Final protection with high density geotextile.

Figure 22. Blast coverage: geotextile, netting, geotextile.

### 4.3 Drilling example and blast results near one of the sensitive buildings


Figure 23. Drilling close to Carricube building.


Figure 24. Result of blast close to Carricube building.

### 4.4 Blast results: pre-split and excavation

Figure 25. Pre-split result.


Figure 26. Blast earthworks.

### 4.5 Progress of the works from September 2006 to February 2007


Figure 27. Trench in September 2006.

Figure 28. Trench in November 2006.

Figure 29. Trench in January 2007.

Figure 30. Trench in February 2007.

## 5. CONCLUSION

The earthworks for the Mazagran-Boulevard Doret cut and cover trench in the South Boulevard of St Denis de la Réunion, Réunion, Indian Ocean, were carried out successfully with the use of electronic initiation. This technique made it possible to adopt an optimum sequence by imposing primary frequencies that would be as harmless as possible to the monitored structures. This project's results can be transposed to all outdoor blasting applications (public works, mines, quarries) in sensitive areas.

## 6. ACKNOWLEDGMENT

The authors want to thank the companies Scetauroute and SBTPC for their confidence and their acceptance for the innovating technical solutions proposed and adopted for the blasting of this trench in a very sensitive environment.

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# Studying the contribution of electronic detonator to the quality of blast

J.-P. Tshibangu K., E. Lefebvre
*Faculté Polytechnique de Mons, Mons Belgium*

J-C. Libouton, N. Contardi
*Nobel Explosifs Belgique, Châtelet Belgium*

ABSTRACT: An experimental study has been carried out in the region of Tournai into two limestone quarries: Gaurain-Ramecroix and Milieu to try to understand the contribution of the electronic detonator on blasts. This paper will focus on the results obtained on the Gaurain-Ramecroix quarry and will deal only with generated vibrations. We used a constant 10 to 18 ms delay per blast in one or two rows of shots. An alternating firing sequence has been implemented to avoid explosive sensibility problems between adjacent holes; the technique led sometimes to delays as low as 7 ms, especially when working in two rows. The site is instrumented with vibration transducers situated at distances ranging from 40 m to about 700 m; the collected signals have been processed to yield peak particle velocities and frequencies. An interpretation of the time history of the signals is also given to try understanding the wave propagation mechanisms with respect to delay and distance.

## 1. INTRODUCTION

In production blasting the electronic detonator is a promising initiation system, the use of which is spreading out in the global mining field. In Belgium many quarries are adopting this firing method to try to improve the block size of the blast and manage the ground vibrations. In this study we will focus mainly on this second aspect. The field application concerns a big limestone quarry in the Tournai region of Belgium.

Many people who have shifted from classical initiation systems, i.e. electric or Nonel, claim that the process of rock breaking has been improved. During the early use of electronic detonators in Belgium, people were enthusiastic to apply the hybrid method (Hinzen 1988) by convolving unit signals to model the production blast. But, when looking to published results in Europe during recent years, it seems that the results are not as satisfactory as wished for and developing a practical design tool for miners is still a challenge. We need first to understand the effect of a few blast parameters by trying to maintain some others constant before moving forward in modelling. By performing some simple shooting schemes in the study (i.e. by imposing constant delays during the shot) we will try in this paper to understand the wave propagation mechanisms and draw some conclusions that we can use in further treatments.

2. GENERAL CONSIDERATIONS

It is generally admitted that the production blast in the mining field has an objective of fragmenting as large as possible volume of rock mass in order to minimise the costs. But the drawback of such an approach, especially when mining inhabited areas, is the inconvenience caused by the generated vibrations. Many factors influence the vibration level among which the detonating charge and the distance to the measuring point can be considered as the most important that can be controlled by the blasting technician. This is proven by the wide use of the attenuation equations calculating the maximum vibration velocity as a function of the scaled distance (Dowding 1985, Hustrulid 1999, Les techniques de l'Industrie Minérale 2002). These equations, known as square root or cube root scaling laws, are to be built by using a statistical approach applied on a series of experimental measurements. The relationship between the scaled distance and the peak particle velocity in the log-log diagram is linear and can be characterised by an intercept and a slope depending on the characteristics of the region and type of blasts.

Since the appearance of the millisecond delays initiation systems on the market, the volume of the rock masses to be mined has increased considerably due to the division of the shot into several small detonations. The technology used in the classical initiation millisecond-delays caps (i.e. electric or Nonel) gives an inherent error on the detonating time that can be as high as 10% as described by Dowding (1985 p. 243). This error can give an overlap of detonations and one must be careful when estimating the unit explosive charge.

The electronic detonator technology, as claimed by manufacturers, allows a more accurate definition of the delays and, hence, can lead to more scientific approaches in the assessment of the effect of delays on the vibrations. This goal could be achieved by developing numerical modelling. Experiments that can check the accuracy of the electronic caps require measurements that can be performed in the very nearby field with respect to shots and using synchronised transducers, this was not the case in our study. As suggested by some authors, indirect methods can be used to show the high reliability of the electronic detonator in comparison to the electric one. Among the published results, Chavez & Chantry (2003) used the same delay on both electronic and electric blasts as presented on Figure 1; the resulting measured Peak Particle Velocity shows a more stable value for the electronic caps.

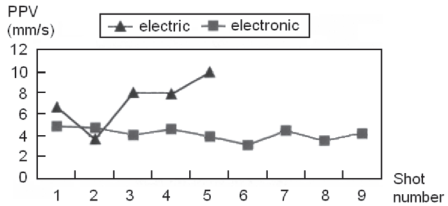


Figure 1. Comparison of Peak Particle Velocity (PPV) obtained during 12 ms blasts initiated by electric caps on one hand and by electronic ones on the other hand (after Chavez and Chantry 2003).

The accuracy and free delays that can be programmed on the electronic cap present two obvious advantages: blasting of more voluminous rock masses thanks to short delays between consecutive holes, and avoiding structures resonance frequencies by numerical modelling (Dowding 1985).

The development of electronic detonator technology brought a promising numerical approach to model the result in terms of peak particle and frequency of vibrations. The so named 'hybrid approach' is one of the most wide-spread ideas (Hinzen 1988). It relies on unit blast to get a typical response of the rock mass and, then, use a series of impulses (i.e. Dirac impulse) to model a production blast. During the early use of the electronic cap technology in Belgium people tried to perform unit blast as did for instance the Nobel Explosive Belgium company in the Gaurain-Ramecroix quarry in 1996 (Ollinger 1998). The treatment of the collected data by the hybrid method to build production blasts gave poor results. In fact, as widely admitted, the vibrations due to quarry and mine blasts are very difficult to model because of the complicated geology and geometry, multiple pulses and the overlapping wave effect. This means that the concept of building production blasts by numerical modelling (using the linear superposition) from unit blasts is still a challenge for researchers.

Unit blasts are very expensive for mines because the amount of fragmented rocks is very small for normal loading operations. For quarries located in the high density inhabited regions like Belgium;

the inconvenience is obvious on the production rate because one needs to shot everyday a given amount of rocks. In order to avoid disturbing the normal rate of production, the present study used only multi-detonation blasts by varying the firing sequence in a way that will be described in next sections.

Transducers were placed both in the nearby and far fields to understand the effect of distance and direction (with respect to geology). In fact, it is admitted that one can speak about the nearby field when the distance to the row of blast holes is in a ratio of less than one to the wavelength, while this ratio should be a lot of wavelengths to deal with far field. As reported by Cording (in Dowding 1985), the wavelength ranges from 30 m to 1500 m for typical blasts. One must also be aware of the effect of the charge length on the vibrations measured in the very nearby field as proven by the USBM experiments as reported by Hustrulid (1999).

In this study the signals will be processed by Fourrier's Fast Transforms to assess the values of both peak particule velocity and the associated principal or dominant frequency. The computations have been carried out on specific software developed by Nobel Explosive Belgium (after Libouton 1994). The software allows the display of the signal time history and the calculation of both Fourrier's Transform and its integral.

## 3. EXPERIMENTAL SITE AND WORKING METHOD

### *3.1. Site and parameters*

The study was performed in the Gaurain-Ramecroix quarry in the Tournai region (Belgium). The quarry is worked by the Italcimenti Group for limestone that is used both for cement and crushed materials; the overall production is about 11 millions tons per year.

The Tournai limestone outcrop belongs to the Carboniferous formations of the northern border of Namur's Synclinorium (Belgium). This is a strip lying from eastern Namur to western Lille in France. In the Western part of this synclinorium the structure is characterised by the Roubaix's synclinal followed by the Mélantois-tournaisis anticline in which the quarries of the tournasian basin have been opened. The outcrop is characterised by argillaceous limestones which sometimes contain hard silica nodules (Hennebert & Doremus 1997).

The limestone is generally covered by sandy and clayey sand formations. The top of the limestone is generally horizontal but is affected by caves and other weathering phenomenon. The Tournai limestone deposit is intersected by a series of sub-vertical joints that divide the body into different blocks, the two identified fracture directions measured in the region are N30°E and N100°E.
The Gaurain-Ramecroix quarry is 230 m deep and extends horizontally to one kilometre. It is mined in 13 benches of varying heights (10 to 25 m) depending on the chemical and mechanical properties of the layers to be exploited. The blast experiments presented in this study were performed on the 5th bench of 10.5 m height that we selected for reasons of homogeneity (Figure 2).

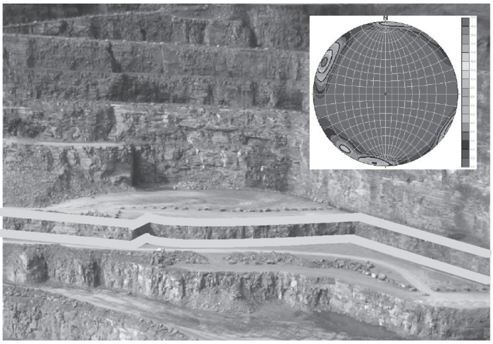

Figure 2. A view of the Gaurain-Ramecroix quarry showing the position of bench 5. A pole diagram of the regional fracturing is also superimposed.

The production blasting operations use vertical drill holes of 165 mm diameter loaded generally with Anfo and/or Emulsions. The drilling pattern is 5 m x 5.5 m and the number of rows ranges from 1 to 4 (in the study we will use 1 or 2 rows). The quarry is surrounded by inhabited areas that require the blast operations to take care in terms of vibration.

In order to understand the influence of different parameters each blast concerned by the study has been preceded by site measurements to ensure about the accuracy of drilling: the drilling pattern has been verified by a decametre and the burden of each drill hole has been surveyed by a 'Laser Ace' theodolite. Figure 3 gives an example of the burden profiles measurement on the face for shot CC118.

A total of 5 shots were carried out, 3 were

Table 1. Blast parameters of the 5 shots of the study.

| Parameters of the blast | CC118 | CC112 | CC110 | CC210 | CC215 |
|---|---|---|---|---|---|
| Delay [ms] | 18 | 12 | 10 | 10 | 15 |
| Orientation of the face | N 30° E | N 30° E | N 30° E | N 30° E | N 30° E |
| Mean height of the holes [m] | 10.22 | 10.24 | 10.21 | 10.03 | 10.65 |
| Mean burden [m] | 4.74 | 4.66 | 5.86 | 3.64 | 4.96 |
| Mean spacing [m] | 5.38 | 5.41 | 5.51 | 5.51 | 5.48 |
| | | | | | |
| Priming charge [kg] | 47.5 | 45 | 214.5 | 70 | 278.5 |
| Alufo charge [kg] | 1425 | 1350 | 1125 | 2175 | 1700 |
| Anfo charge [kg] | 1150 | 913 | 686 | 1840 | 1450 |
| Total charge [kg] | 2622.5 | 2308 | 2025.5 | 4085 | 3428.5 |
| Maximum charge per hole [kg] | 140 | 137.5 | 126.5 | 149.5 | 142.5 |
| Number of holes | 19 | 18 | 16 | 29 | 25 |
| Number of rows | 1 | 1 | 1 | 2 | 2 |
| Powder factor [g/t] | 144 | 145 | 142 | 156 | 166 |
| Tonnage to be blast [t] | 18171 | 15889 | 14256 | 26055 | 20599 |
| Total charge per delay [kg/ms] | 145.69 | 192.33 | 202.55 | 408.50 | 228.57 |

performed on one row and two on 2 rows. Table 1 summarises the parameters of the blasts. For naming the shots we used two first letters to identify the site (CC for Gaurain-Ramecroix), one digit gives the number of rows and the two others the delay. The firing sequence will be described with the presentation of results.

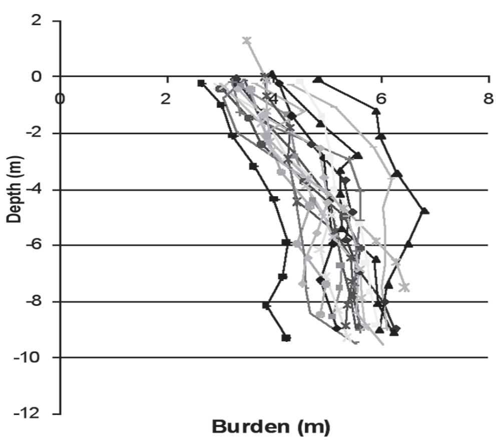


Figure 3. Variation of burden as surveyed by a laser theodolite on shot CC118.

### 3.2. *Instrumentation*

Vibration transducers were placed both in the nearby (the closest was about 40 m away) and in the far field (see Figure 4 and Table 2). G is a one component transducer (vertical) that has been placed in a hole of 1m depth filled with crushed rock in the vicinity of M. It is synchronised with transducers M and B situated in the nearby field. Transducers NLB, NM300 and NB300 are also situated in the quarry's area with NB300 being on the same bench than the shot. To trigger the synchronised transducers a 'Watson probe' (carbon electric resistance) has been placed 1 m depth in the stemming of the first drill hole. The blast has also been recorded by a high speed camera (500 images per second).

For the far field, some recording devices have been installed in the closest houses: Estas, Delcroix and Pattine.

Notice also on Figure 4 that the orientation of the face (lying along transducers B and M) corresponds to N30°E, one of the two main fracture directions.

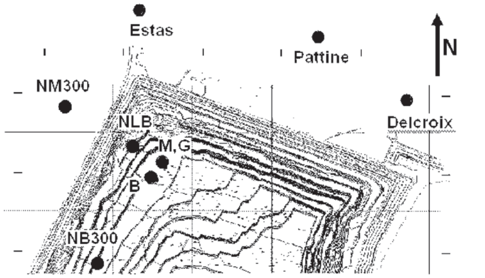


Figure 4. Position of transducers used all during the study at the Gaurain-Ramecroix quarry : G is uniaxial geophone, B & M are triaxial, NLB – NB300 – NM300 are Nomis seismographes, and Estas – Patteine – Delcroix are resident's seismographes.

Table 2. Estimated distances of velocity transducers to the studied face in the Gaurain-Ramecroix quarry.

| Transducer | distance to row (m) |
|---|---|
| M (3D) | 44.50 |
| B (3D) | 41.00 |
| NLB | 84.50 |
| NM300 | 287.50 |
| NB300 | 262.00 |
| Delcroix | 657.50 |
| Estas | 414.00 |
| Pattine | 533.00 |

## 4. EFFECT OF THE DELAY

### *4.1. Collected signals*

We collected a great amount of data among which we selected some to be presented in this paper; some others need a more in depth analysis and, even, complimentary experiments.

As described earlier the signals given by the different shots have been processed by means of the FFT technique; we Particle Velocity (PPV) and Principal Frequency (PF).

Because of the attenuation and interferences of signals in the far field, we will focus on the geophones placed in the nearby field to show the influence of the delay. The two graphs on Figure 5 give two typical signals recorded on transducer M during the 10 and 18 ms delay shots respectively both for the longitudinal component of velocity. The collected and/or calculated data are as follows:

- Shot CC110: duration of the shot = 150 ms, Principal Frequency = 54 hz, PPV = 174 mm/s
- Shot CC118: duration = 330 ms, Principal Frequency = 26 Hz, PPV = 178 mm/s

The Shooting sequences are also given. One can notice the alternate firing sequence: the first hole to be shot is in the middle of the face and the delay between the first and the second holes is a bit longer than normal to avoid explosive densification problems in adjacent holes.

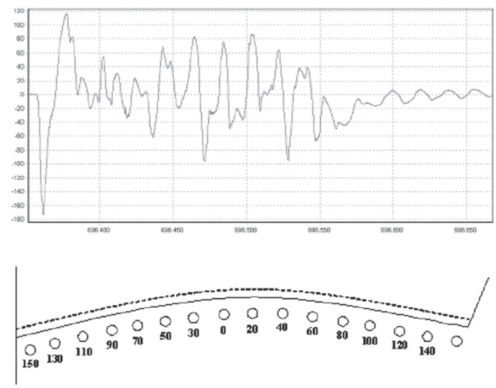


Figure 5a.

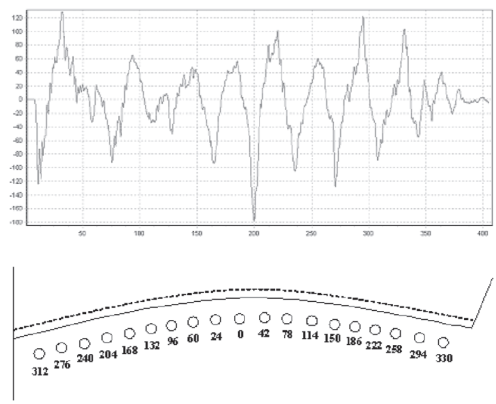


Figure 5b.

Figure 5. Longitudinal wave registered on the transducer M situated 45 m from the firing row - (a) Shot CC110ML – 10 ms delay. (b) Shot CC118ML – 18 ms delay (one x coordinate subdivision is 50 ms on both graphs).

As can be observed on the graphs the duration of the signal is a bit longer than the shot. One can see that the ratio of the 10 ms Principal Frequency (PF) to the 18 ms one is about 2 while the delay ratio is 0.55. This is an indication about the relationship between the delay and the resulting Principal Frequency in the nearby field for the production blast. But, as will be shown further, such a relationship is not obvious in the far field, so we can consider that the registered waves on transducer M is an image of the blast.

### 4.2. *Effect of delay on the Peak Particle Velocity (PPV)*

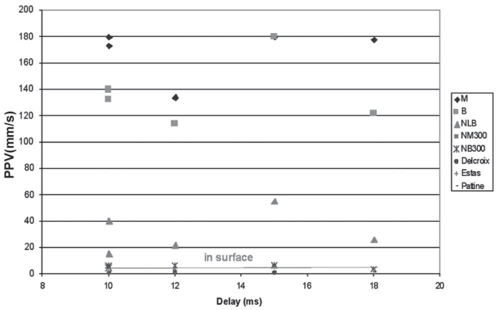


Figure 6. Evolution of the Peak Particle Velocity with the firing delay for all transducers.

The plot on Figure 6 synthesises the effect of the delay on the PPV for the longitudinal signal for all the five blasts and all transducers. It can be observed that the PPV variation with respect to the delay does not have a clear trend. The interpretation of the results is complicated by the sequence of firing in the two rows blasts. In fact, for the 10 ms delay two rows blast, the first row was fired before the second one; this resulted in a large heave, rear effects and the saturation of the M transducer (180 mm/s). To avoid these effects, the equivalent 15 ms blast has been fired in a way such that the holes of the second row were fired a few seconds after the first one (see Figure 7). The alternating sequence was intended to avoid short delays between adjacent holes. As a result, the M transducer has also been saturated but, when looking to the firing sequence one sees that from the 98 ms hole to the 195 ms one (the last hole on the first row) the bulk delay was sometime as short as 3 ms (i.e. holes 170 and 173 ms). This overall or bulk delay calculation is valid when we consider the whole blast as situated to a constant distance with respect to the transducer. This can help understand the saturation of the M transducer in the so named 15 ms blast. For the NLB transducer which is a bit further than the M one, if we move the experimental point leftward between 0 and 10 ms, one can see that the trend would be a decrease of the PPV with the delay. Such results need to be verified by further tests.

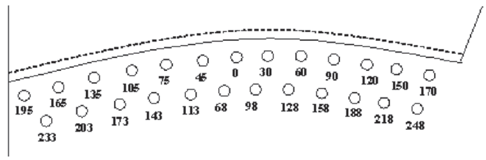


Figure 7. The firing sequence in the CC215 shot (2 rows, 15 ms between two consecutive holes of a row).

### 4.3 *Effect of delay on the Principal Frequency*

If we assume that the principal or dominant frequency (PF) of the signal depends only on the delay, then this parameter should be equal to the reverse of the time elapsed between two successive explosive charges. We name the so calculated principal frequency, the theoretical frequency, and one must be aware on the fact that it could be realistic only in the very close area of the detonating holes. The theoretical frequency can be assessed as:

$$f_{th} = \frac{1000}{\tau} \qquad (1)$$

With τ[ms] being the delay between 2 consecutive blast holes.

Table 3 summarises the theoretical frequencies corresponding to the delays experimented in the study.

| Delay (ms) | fth (Hz) |
|---|---|
| 18 | 55.56 |
| 15 | 66.67 |
| 12 | 83.33 |
| 10 | 100.00 |

We plot on Figure 8 the variation of the principal frequencies versus the delay for the longitudinal signal. In the nearby field (transducers M, B and NLB) the PF decays when the delay increases. This trend is also observed on the NB300 transducer situated 260 m away but on the same bench than the blast. We modelled this variation with a power law curve; the good correlation coefficients prove the relationship between the two parameters.

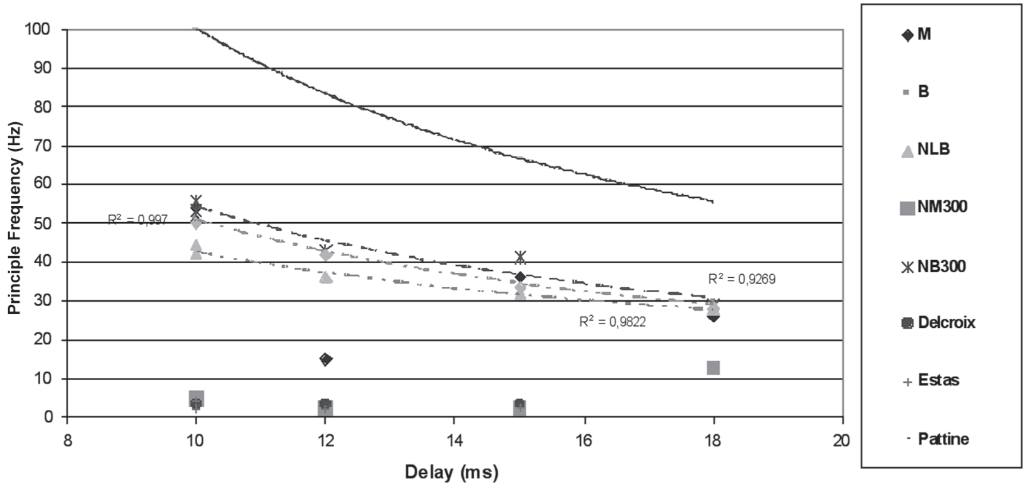


Figure 8. Principal Frequencies versus the detonating delay.

In the far field on the other hand (transducers Delcroix, Estas and Pattine) it seems that there is no clear influence of the delay because the PF remains low and of the order of about 5 Hz. This trend is also observed for the NM300 transducer situated 290 m away, a comparable horizontal distance than NB300. The difference between NM300 and NB300 can be explained in terms of the anisotropy of rock mass structure as stated further in the paper.

On figure 8 we also have to point out that the measured PF in the nearby field are about half of the theoretical ones as calculated by equation (1), this is a result that deserves to be studied in depth because we have the effect of distance, alternating firing sequence and overlapping of waves.

## 5. EFFECT OF DISTANCE AND FACE ORIENTATION

### *5.1. General results*

As presented in the description of the site under study, the limestone rock mass exploited in the Tournai region is intersected by two near vertical dipping sets of joints, one of the sets has a more close joint spacing (about N30°East) than the second one (N100°East). The velocity transducers have then been placed in order to measure the propagation of waves in both of the two directions as shown in Figure 4.

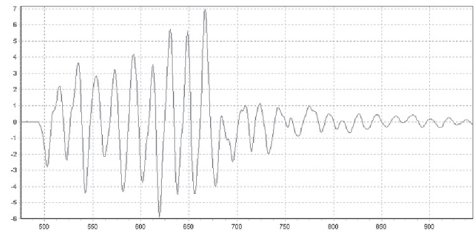

Figure 9a.

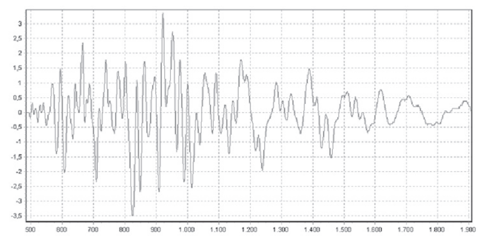

Figure 9b.

Figure 9. Transverse waves recorded on transducers NB300. 9a and NM300 9b for shot CC110 (1 row and 10ms delay).

For the nearby field, typical signals have been presented in Figure 5. Considering the close position of transducer M with respect to the face and the duration of the recorded data, one can say that the signals are dominated by volumetric waves.

For a medium distance let us look on Figure 9 to signals from shot CC110 on transducers NB300 (260 m away on the same bench) and NM300 (about 290 m away on surface). The two transducers are located at comparable horizontal distances, but one is situated on the same quarry bench in the less fractured direction (NB300) while the other is situated on surface in the most fractured direction (NM300).

When comparing the transverse waves on the two transducers, one sees a difference. On NB300 the signal (PF = 52 Hz, PPV = 7 mm/s) is divided into two parts: the first one is characterised by an increasing value of the peak particle velocity and lasts about 170 ms, while the second one shows a sharp drop and a slow decay. The pseudo-frequency seems to be constant all along the duration. The NM300 signal (PF = 5 Hz, PPV = 3.5 mm/s) is also characterised by an increasing first stage lasting about 400 ms (more than twice the duration of the shot) and a decaying second one with the transition being smoother than on the NB300.

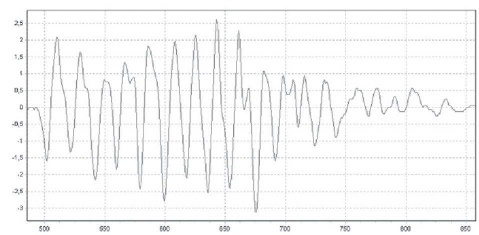

Figure 10a

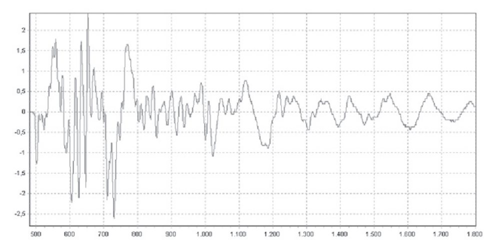

Figure 10b

Figure 10. Vertical waves recorded on transducers NB300 and NM300 for shot CC110 (1 row and 10ms delay).

The calculations showed that the NB300 transducer recorded higher values both for Principal Frequency and Peak Particle Velocity with respect to NM300. These higher values can be attributed to the volumetric waves and belong to the first part of the signal. On NM300 on the other hand the signal is characterised by a lot of noises and a longer duration that we can attribute to refractions and reflections on joint surfaces occurring in the rock mass (near vertical joints and stratification).

When looking to the equivalent vertical signals as shown on Figure 10, we still have two stages that can be attributed to at least two trains of waves. On the NB300 subsurface transducer (PF = 53 Hz, PPV = 3 mm/s) the transition between the two identified stages is smooth and the decay is progressive. On the other hand, the NM300 surface transducer (PF = 9 Hz, PPV = 2.6 mm/s) presents a second phase characterised by a constant magnitude of velocity for a long period (about 800 ms); this is certainly a train of surface waves due to the low speed overburden material and reflections/refractions on joints.

Furthermore, Figure 11 giving a transverse signal of the Delcroix transducer (650 m away) shows duration of about 4000 ms or nearly 200 times the duration of the originating shot. The calculated Principal Frequency is low (3.4 Hz) as does the Peak Particle Velocity (0.6 mm/s), and the second stage of the signal has a quasi constant amplitude for a duration of 2000 ms.

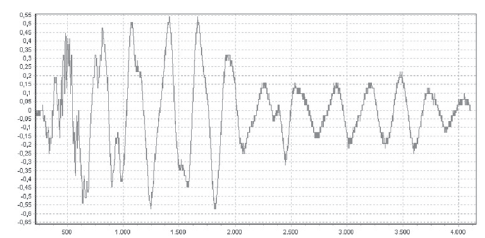

Figure 11. Transverse wave generated by the 10 ms shot at 650 m (transducer Delcroix).

### 5.2. *Variation of parameters with distance*

When plotting all calculated longitudinal values of PPV versus the absolute distance (Figure 12-a), one notices that the PPV decays rapidly with distance and correlation coefficients range from 0.97 to 0.99. It seems that 100 m is the critical distance at which the PPV drops to less than 20 mm/s while under this distance the velocity can increase very sharply to values as high as 200 mm/s. Dowding (1985) reported 500 mm/s in the very nearby field.

Beyond 400 m the PPV becomes very low and one can use the result with respect to the security norm to assess the distance allowed for the first inhabited houses. The same conclusion can be drawn for the other components of the waves (i.e. transverse and vertical).

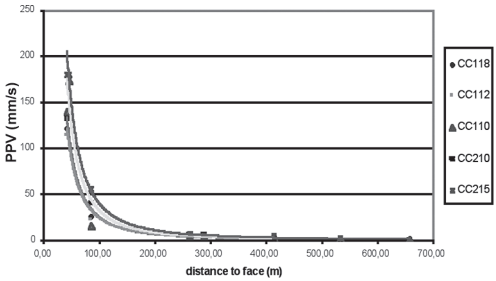


Figure 12a

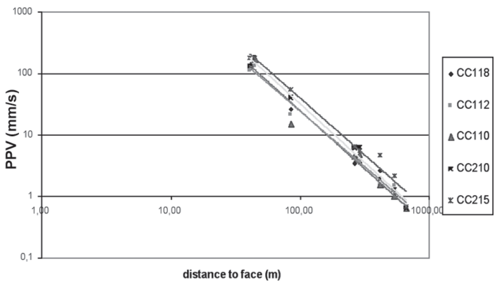


Figure 12b

Figure 12. Variation of the PPV with distance for longitudinal waves: (a) in decimal scale and (b) in a logarithmic scale.

As for PPV, we plotted the principal frequency versus distance as shown on Figure 13 for the vertical waves. The evolution of the PF with absolute distance is not obvious even if the general trend is the record of low frequencies at long distances. The 18 ms shot gave almost constant value of PF for distances ranging from 300 m to 700 m. We can also point out the drop in the PF value between transducers NB300 and NM300 situated at comparable horizontal distances.

When we presented the data recorded in the far field we showed that typical signals have two stages (point 5.1) and we assumed that the second stage could be attributed only to surface waves. Using this assumption we assessed the characteristics of the surface waves as follows in Table 4. Most of the results come from the transducers placed in the nearest residents.

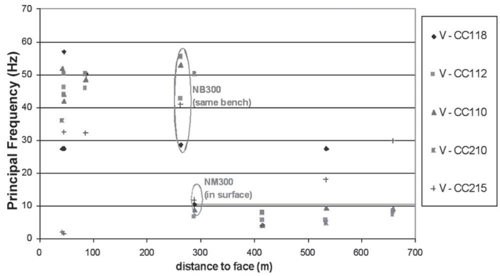


Figure 13. Variation of the Principal Frequency with distance for vertical waves.

Table 4. Graphically assessed frequencies of surface waves and corresponding durations.

| Waves | interval of frequency (Hz) | Corresponding duration (ms) |
|---|---|---|
| L | [3.3 . 5] | [300 . 200] |
| V | [5 . 8] | [125 . 200] |
| T | [2 . 4] | [250 . 500] |

## 6. CONCLUSIONS

An in situ experimental study is presented in this paper to understand the response of the rock mass to blasts initiated by electronic detonator technology. The main objective of the study being the control of ground vibration, a prediction has to be developed for practical use. Among the approaches the numerical modelling by the hybrid method is a promising technique, but we need reliable data on the rock mass. Because of the complexity of the problem and the great number of parameters, especially when working on fractured rock masses, we focussed in this paper on understanding the propagation and attenuation mechanisms of the waves. The alternate firing system tried gave results that deserve to be verified in further tests before proceeding to modelling as planned.

The main results have been presented in terms of Peak Particle Velocity (PPV) and Principal Frequency (PF) after FFT processing of the signals. This verifies the classical PPV attenuation laws with respect to distance and also the fact that at the nearest houses, the signals are composed mainly by surface waves. The anisotropic behaviour of the rock mass characteristic of the Tournai region has also been emphasised by the use of transducers lying in two perpendicular directions. Devices situated at comparable horizontal distances gave different results in terms of PPV and PF. An in depth study has to be carried out to understand the propagation mechanisms from unit detonations.

## 7. ACKNOWLEDGEMENT

The authors would to like to acknowledge the board of Nobel Explosives Belgium for supplying both equipment and people to carry out the field tests; and also the SCT Company exploiting the Gaurain-Ramecroix and Milieu quarries for accepting the disturbance of experimental blasts on the rate of production.

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# Three Gorges cofferdam demolition using electronic initiation

L. Simpson
*Electronic Blasting Systems Specialist, Orica Mining Services (Australia)*

ABSTRACT: Since the introduction of Orica's i-kon™ electronic blasting system in 1999, many quarry and mine operations have successfully deployed the technology to enjoy significant benefits in productivity, safety and environmental compliance. More recently, the advantages of electronic initiation such as security, precision, flexibility and testability, in combination with blast management software, have also been recognised and utilised in the demolition industry. As a result, a number of inner urban building demolitions have been successfully completed using electronic initiation. This paper describes the first application of the i-kon electronic blasting system in a challenging and complex dam demolition, utilising more than 2500 electronic detonators, at the Three Gorges cofferdam on the Yangtze River in mainland China.

Detail will be given on the selection process, design, how the electronic blasting system was deployed, the demolition method and outcomes. The paper will also discuss some complications encountered and make recommendations for future blasts of this kind.

Strict time constraints, attendance of live media and high national importance required the blast to be fired on schedule. This resulted in an effective and controlled demolition, however some issues were encountered that required remediation for total completion. The paper discusses the outcome, circumstances and actions taken to complete the task.

## 1. INTRODUCTION

The Three Gorges Dam project is located on the Yangtze River at Yichang in Hubei province. The project was originally proposed in 1919 by Dr. Sun Yat-Sen, as a means of controlling flooding of the Yangtze River and to generate hydroelectric power.

The project was finally approved and with construction starting in 1993, completion is expected in 2008/9 when the final turbines are installed and operational.

In brief, the Three Gorges Dam is a concrete gravity dam measuring 2309m long, 183m high and 84m wide at the causeway.

The final reservoir will stretch some 600km to the west with the dam designed to support water levels to 175m. When complete the dam will contain 26 hydroelectric turbines, with a generating capacity of 18.2 Gigawatts. An additional six turbines will be installed underground by 2010.

The construction of the cofferdam was finished in 2003, which saw the completion of Phase 2 of the project and allowed filling the reservoir while construction continued on the main wall.

Completion of the structural works at the southern end of the main dam on May 20th 2006 meant that cofferdam demolition could now proceed.

This paper will discuss the application of the i-kon electronic blasting system to precisely control demolition of the cofferdam.


Figure 1. Three Gorges Dam and Ship Locks.


Figure 2. Dam location map.

## 2. PRODUCT TESTING AND EVALUATION

Throughout 2005 and early 2006 the Yangtze Design Institute (responsible for the demolition design) and Chongqing Gezhouba Yipuli Chemical Co. (responsible for manufacturing and supplying explosives), conducted a series of tests, trials and simulations to select the initiation system.

Tests were conducted on a range of conventional and electronic initiation systems to determine which could provide the required reliability, robustness and accuracy for the task. These included function and firing accuracy for:

- Pressure testing
  5 days at 35m water depth
  7 days at 40m water depth
- Temperature testing
  60° after 12 hour exposure
  80° after 1.5 hour exposure

Trials and simulations were conducted including:

- Scale model simulation
  Used to test detonator function, accuracy and theproposed demolition method
- Quarry firing test
  Used to test the proposed explosive for suitability and determine loading characteristics
- i-kon firing simulation Full-scale field simulation using the actual delay times to test actual detonators quantities and circuit configuration as would be used in the demolition

These evaluations resulted in the i-kon system being chosen for the demolition project.

## 3. DEMOLITION DESIGN

The cofferdam was designed and built to include requirements for its eventual demolition.

During construction, a series of blasting chambers and post-split holes were installed. The blasting chambers were connected by an internal tunnel, which would allow access to the chambers for charging and firing.

Prior to the demolition, additional blastholes were drilled to improve explosive distribution at critical points in the dam wall.

The cofferdam was constructed entirely of concrete, standing roughly 115m high at its deepest point. The section to be demolished had a total length of 480m. The top 30.3m would be cut from the dam, leaving what remains of the concrete embankment at about 66m below the water level when the dam fills to capacity. The remaining embankment will act as a silt trap, protecting the hydroelectric turbines from silt build up near the turbine intakes.

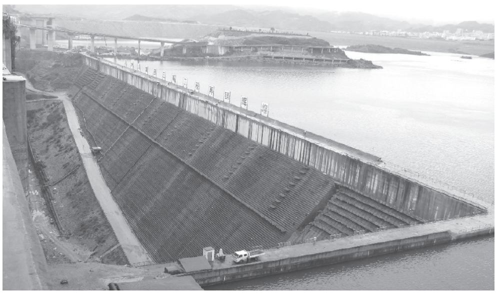

Figure 3. Three Gorges Cofferdam.

Blast designers sectioned the dam into sixteen (16) blocks.

Blocks one (1) through to four (4) would not be demolished.

Blocks 5, 6 and 16 would be blasted to a depth of 45m, to fragment and demolish the concrete structure. The demolition of the dam ends was likely to present the greatest environmental impact on the surroundings.

The demolition design for blocks 7 through to 15 was intended to cause minimal environmental impact, by the use of a unique design to split and topple the blocks away from the main dam wall. The nine (9) blocks in this section were 340m in total length, each block measuring 40m in length, except block 15 which measured 20m. The access tunnel and blasting chambers were located internally in these blocks. A section through the dam is displayed in Fig.5, showing the access tunnel and the orientation of the blasting chambers. In plan view the chambers are staggered with extra vertical blast holes added between.

The effect was to provide good explosives distribution at the pivot point, through which the blocks would topple. The chambers would be fired in the correct sequence to cut a large wedge from the front of the dam at the pivot point.

This would be followed by the sequenced initiation of horizontal post-split holes, to complete the 23.2m cut through to the back of the dam wall. The sequenced initiation of vertical post-split blast holes would then cut the 40m sections free, resulting in each block to toppling into the river away from the main dam wall.

The demolition would begin at block 16, followed by the toppling of blocks 15 to 7 and finish with the demolition of blocks 6 and 5. All the internal blasting chambers were located between 31.3m and 38.5m, the horizontal post-split blast hole that complete the cut were located at 30.3m, below the top of the dam.

## 4. ENVIRONMENTAL CONSIDERATIONS

At the time of the blast, it was estimated the explosives chambers would be approximately 26m to 33m below water level. The chambers would fire upriver away from the main dam wall protected by the bulk of the cofferdam.

The two ends of the cofferdam, blasted to a depth of 45m, were the most critical in terms of environmental impact. Both ends were heavily sand-

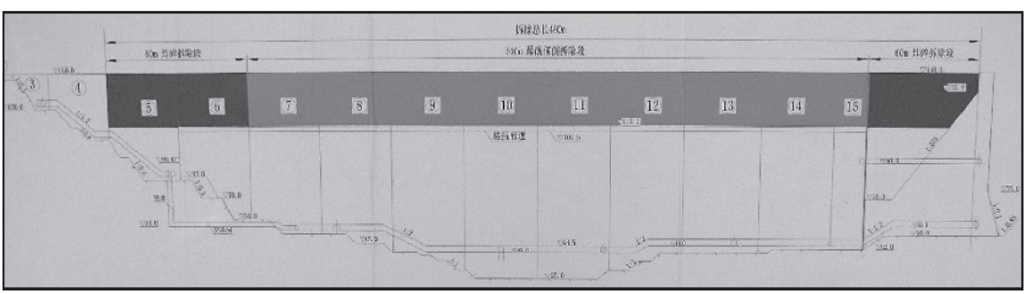


Figure 4. Drawing of Cofferdam showing block locations.

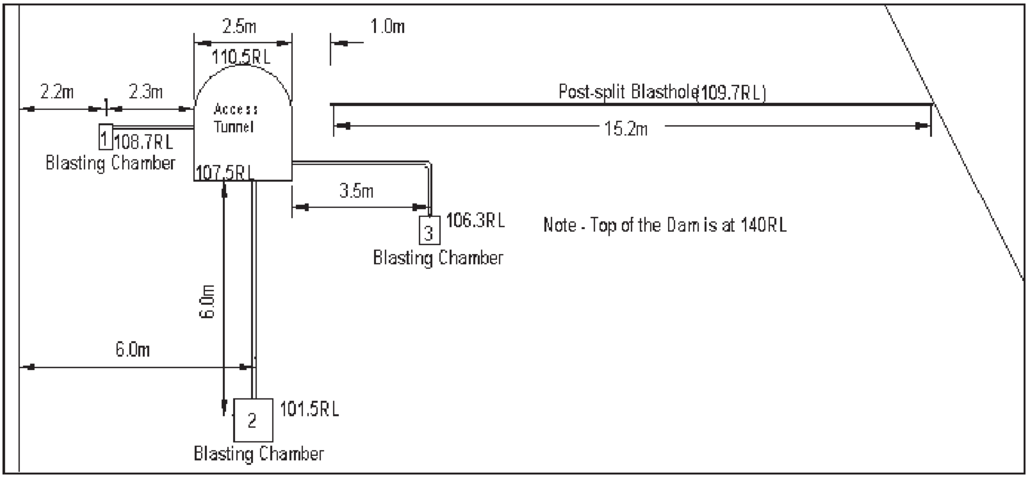


Figure 5. Internal access tunnel and associated blasting chambers.

bagged and all free faces had been covered with conveyor belt screens to prevent flying debris. All blastholes where accurately stemmed with concrete to retain explosives energy.

A compressed air curtain was established between the cofferdam and the main dam to limit energy transmitted to the main wall.

Fish stocks and wildlife were driven from the area. An effort that was later reported as being successful, since there was no reported fish kill.

The Yangtze Design Institute established a network of vibration monitoring stations that report acceptable levels of vibration.

## 5. PLANNING FOR AND DEPLOYING THE ELECTRONIC BLASTING SYSTEM

Initial planning for deploying the i-kon system was based on best practices developed over a number of years usage in various applications. The Three Gorges cofferdam demolition, however, presented several new challenges. These included language difficulties, differing priorities between various groups, adjusting to the unexpected and technical issues associated with most of the detonator leads being underwater at the time of logging and programming.

Loading and priming blastholes and chambers was the responsibility of EXPL/Yipuli, who supplied the bulk explosive. The work was carried out to a high standard by large work crews lead by local shotfirers and engineers.

Orica Mining Services provided general technical support during loading and stemming to ensure the trouble free application of the i-kon system. The Orica i-kon team tested the detonators during and after the loading and stemming operations, to ensure that system leakage was kept to a minimum and all detonators were functioning.

EXPL and Chongping Gezhouba Yipuli Chemical Co. provided overall management of loading and design implementation. Their project engineers supervised the blast crews and conducted a continuous audit during loading and detonator testing.

When detonators were loaded, the EXPL/Yipuli team would record the detonator IDs used in each blast hole or chamber. They then produced a label with was attached to each detonator lead wire indicating the blast hole or chamber number, the unique detonator ID number and the required delay time to be applied at logging

At the completion of loading, all lead wires would be drawn up to the causeway railing at the top of the cofferdam. This meant that the labels and data records were extremely important as once the void between the cofferdam and the main dam was flooded it would not be possible to identify which detonator belonged to which blast hole or chamber. Given the detonator ID, EXPL could advise which blast hole or chamber the detonator was from and it's required delay time.

This process proved very successful in tracking the location of detonators and blast hole or chamber locations. The detonator IDs became integral to the control process, once recorded they could be used to locate blast hole or chamber locations.

## 6. LOGGING OPTIONS AND PLANNING

During the planning for how to best log and manage the data collection process three logging options were considered.

### *6.1 Option 1*

Full use of Orica's SHOTPlus®-i software and the SHOTPlus-i logging function whereby delay times are pre-loaded to the loggers from the blast design software. This is the most accurate and efficient method of logging large complex blasts. SHOT-Plus-i also generate logging sheets that help the operator record the logging process thus ensuring that delay times and detonators are not missed or logged incorrectly.

The SHOTPlus-i option would require that all the lead wires should be drawn up to the causeway railing directly from their individual blast hole collars, so they could be logged in their correct place in the logging route. This process worked very well during the detonator simulation earlier in May.

### *6.2 Option 2*

Use both SHOTPlus-i and manual logging modes to log the detonators.

This option would employ the speed and accuracy of SHOTPlus-i to log the sections of the dam, where the lead wires could be arranged in order according to their rows and location.

The flexibility of manual mode would be used to log detonators from the explosive chambers. The lead wires from the internal explosive chambers would be bunched together and pulled to the surface via 102mm diameter ventilation holes. It would be simpler to log these detonators in manual mode using the delay time recorded on their tags.

This option would still require logging sheets and plans as with SHOTPlus-i, which would allow a high degree of reliability during logging and checking.

### *6.3 Option 3*

Full use of manual mode to log the blast. Manual mode is flexible and relatively operator friendly, however reliant on operator accuracy for entry of delay times. Operating procedures would eliminate the occurrence of data entry errors by use of logging sheets with appropriate checks and balances. Lead wires would need to be placed in some sort of order according to their point of origin within the dam.

The entry of delay times proved to be an issue during logging as the style of handwriting on the tags was not always easy to understand. The technicians writing the delay times to the tags and some of the operators that logged the detonators had English as a second language. This meant that some mistakes occurred due to misinterpretation of written details.

### *6.4 Selecting the final logging option*

The logging plan was developed around the assumption that Option 1 would be used to log the detonators in the cofferdam.

This would require that the lead wires would each be drawn up to the railing (top of the dam) from their individual hole collars or at least together with other detonator leads from the same row or chamber.

As the logging date approached and the lead wires were lifted to the railings, the following observations were made:

- The wires were collected together in bunches of many lead wires, from various levels of the dam wall and not in any particular order
- It became apparent that it would be difficult and time consuming to search amongst the connectors of each bunch to conform to a logging route for SHOTPlus-i logging
- It also became apparent that the use of the detonator I.D tags would be very time consuming and difficult and still require searching through the bunches of leads when looking for subsequent detonator labels

As a result logging Option 1 was dropped as a practical means of logging. Instead it now seemed Option 3, using full manual mode would be the most practical and efficient means of logging.

This method still required logging plans as a minimum to record position on harness, logging direction and detonator locations for use during troubleshooting if required.

Option 3 was tested on the cofferdam late on the 3rd of June, what was discovered resulted in the introduction of Option 4, as follows:

### 6.5 *Option 4 -freestyle*

Due to the way the detonator leads had been collected into bunches from multiple points of origin, in no particular order and tied as multi-lead bunches to the dam railing, it was very difficult and time consuming to log to a pre-determined logging path.

Option 4, was introduced, which called for the i-kon operators to log a specified number of detonators to each logger. They would not follow a pre-determined logging path and would not be able to record a position on harness.

Both these changes are normally seen as risky deviations from normal i-kon logging practice. However, there was no other option, which would see the logging completed within the time available.

This approach would rely on the fact that detonator identification number had been recorded previously during loading and could be used to identify their origin from within the dam. Option 4 would require the logged detonator identification numbers to be up-loaded to the computer running the blast design software, matched to their recorded position within the dam, their delay times could be edited if required, and then re-loaded to the logger.

This meant a complex arrangement whereby sheets of detonator data were supplied by the loading teams and crosschecked against design. A complex addition to an already complex situation.

## 7. 6TH OF JUNE – COFFERDAM DEMOLITION

It cannot be understated how important the success of this demolition was to the Three Gorges management team and officials. It would be billed as the world's largest dam demolition and an example of excellence in engineering and project management. The event would be a showcase, broadcast live both nationally and to the world.

Throughout the loading and logging process, there had been a steady stream of media, photographs and interviews. On the 6th of June, the intensity of the occasion was evident, working to an unmovable deadline, based on live television programming and intense media interest.

The days plan required that the team would:

- connect the harness extensions to each harness
- conduct final logger tests at the logger location on the job
- establish the loggers and harness extensions in the final logger position
- conduct the final detonator tally session with the audit team
- conduct a pre-blast programming test run, and finally
- fire the blast on time

### 7.1 *Detonator final tally, audit session*

While the harness extensions were being attached and final logger checks were conducted. EXPL/ Yipuli called a meeting to agree on the final detonator tally. During this meeting a few final delay corrections where made and final detonator tallies per logger were agreed.

The final figure announced by the audit team was 2506 detonators. This tally differed by one detonator to the tally conducted by the logging team on the previous day after logging was complete.

The logging team had calculated that they logged 2505 detonators. Both parties were in close agreement on the final tally and given the time, pressures and barriers to clear communication the slight difference in tallies were accepted.

The logging team tally midday on the 5th of June was as follows:

- master 1368
- slave 1137 =
- total 2505 detonators

This would be a synchronised blast using two B2400S i-kon blasters working together as master (10 loggers) and slave (9 loggers). There were 19 loggers with 2505 detonators logged to them.

### 7.2 *Pre-blast programming test run*

Since the blast site was to be cleared by 11.00am, in preparation for the demolition blast in the afternoon, permission had been given for the i-kon team to power up and run a full program sequence.

This pre-blast programming session had been requested so that the i-kon team could verify that the system was good to go for the main event.

The i-kon B2400S blasters and loggers programmed all the detonators without a single pause in the process, no errors, programming was successful. There were no communications issues, the system had preformed flawlessly.

*7.3 42 missing detonators*

With approximately 90 minutes to firing time, after uploading the data from the two B2400S blasters used in the pre-blast test. It was discovered that their detonator tallies were as follows:

- Master Blaster = 1327
- Slave Blaster = 1137
- Total = 2464

The tally should have been 2505, there were 42 detonators missing with none of the loggers showing any errors.

Back at the logger position, the logger count agreed with the blasters. By this time, there was 30 minutes to firing time. A quick review was undertaken in light of the new information with the likely cause isolated to one section of the dam.

In the end, the decision was taken by the project team to fire the blast with 42 detonators missing. The two B2400S blasters programmed the logged detonators flawlessly, finding no issues or no errors. The blast was fired at the required time.

## 8. BLOCK 15

The demolition of the cofferdam was a spectacular sight. The design preformed flawlessly as did the i-kon system.

Unfortunately, block 15 remained standing Block 15 was the smallest of the blocks designed to topple into the river. It was the first block that should have toppled and it contained the 42 detonators in the internal blasting chambers.

*8.1 Why were 42 detonators missing?*

The method of deploying and timing the detonators required application of a new technique, as the location of the detonators within the dam could not be verified in the field. This technique required the use of hand written tags on each lead wire, which carried the delay time and blast hole reference number.

The once logged data was cross-matched with data collected during loading, using the detonator identification number to verify that the delay time and location were correct. Occasionally errors were found in the data matching process requiring that the data should be edited.

In order to retrofit the delay times, another capability of the i-kon system was used to 'upload – edit – reload' the detonator delay times using a personal computer (p.c.).

This process required the collection of detonator identification numbers during logging, being uploaded to a p.c., matching detonator identification numbers from the charging records, editing the times and reloading back to the loggers.

Unfortunately, this process deviated from normal (proven) procedure and added a new complexity to an already complex situation.

There is much that could be written about the process, but in short, the data on logger #2 was over-written by an incorrect file, effectively deleting 42 detonator identification numbers from the logger. Due to the complexity of the checking arrangements, this was not picked up in the audit process until the 'test' programming conducted just prior to the main event.

Unfortunately, time was running short and to rectify the situation meant the firing deadline would need to be pushed back. The demolition was fired knowing that 42 dets. were missing resulting in block 15 being left standing.

## 9. BLOCK 15 DEMOLITION

Investigation revealed that of the 42 detonators in the explosives chambers of block 15, 21 detonators could still be logged. Most these detonators now registered some leakage, likely due to insulation damage on their lead wires.

There were 17 explosives chambers in block 15; each had been double primed. The explosives chambers contained 34 detonators in all. The other eight detonators were in single primed easer blast holes and not considered critical to demolition of the block.

All the horizontal post split blast hole had fired as designed, so block 15 was cut through to the access tunnel. If the explosive chambers could be fired then the demolition was likely to be satisfactorily completed.

By logging the 21 detonators that responded, it was possible to determine which explosives chambers contained functional detonators. It was ascertained that roughly two thirds of the chambers could be fired, except those in the back left hand corner of block 15.

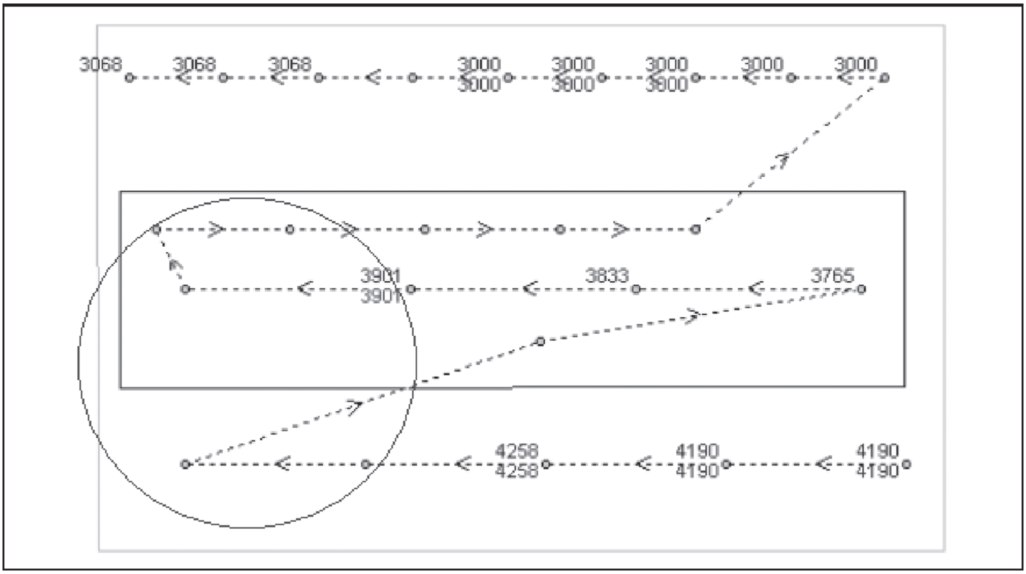

Figure 6. Block 15 showing 21 responsive detonators and location of critical non-responsive detonators.

Firing only the available detonators was considered a risk, since there was some concern that a portion of the structure may be left in place. Communications needed to be established with the non-responding detonators in the back corner of block 15.

It was suggested that divers could be used to investigate the situation in the access tunnel and to reconnect the lead wires. Investigation using a bucket of water taken from the Yangtze River, showed that we could make lead wire connections underwater with minimal leakage. A team of salvage divers was recruited and shown how to reconnect the i-kon lead wires. The access chamber was located under 26m of water thus restricting the time each diver could spend in the chamber. It was not easy work, visibility was poor and rubble had been deposited in the access tunnel.

On descending to the access tunnel the diver would take with him one end of a new lead wire, with a logger attached to the surface end. When the lead wire was found in the access tunnel, they would clip the lead to it, allowing the ID to be checked and determine if it was in one of the required explosives chambers. By mi day on the 9th of June, four additional i-kon detonators in critical chambers had been reconnected and could be logged. There were now enough explosives chambers available to ensure a successful demolition.

Although the system reported high levels of leakage, 93mA at programming voltage, the detonators were programmed and block 15 was successful toppled into the Yangtze River.

## 10. CONCLUSION

The demolition of the Three Gorges cofferdam was a tremendous success for the Three Gorges management team, the Yangtze River Design Institute and for EXPL/Yipuli and Orica Mining Services. The unique design to topple the dam wall via underwater demolition, proved to be very successful. As a result, the structure has been re-engineered to serve as an underwater silt dam.

The i-kon electronic blasting system proved its worth as a reliable and flexible tool for use on complex and demanding projects such as this. There is little doubt that employed with a well run system of checks and balances, this system will deliver a high level of confidence to the most demanding of projects.

Two-way communication in an electronic blasting system cannot be undervalued; on this occasion, it proved to be a decisive factor in the successful demolition cofferdam and block 15.

There are a number of lessons here but the most compelling would be that a simple, open and accessible system of checks and balances is essential on such a complex and critical undertaking.

## 11. ACKNOWLEDGEMENTS

Finally I would like to extend my thanks to the Three Gorges Project management team for the opportunity to play a small part in The Three Gorges Project and the Yangtze River Design Institute for their support and help while onsite.