Explain to me why?

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ABSTRACT: This paper is presenting results obtained with digital blasting simulations. In the first part, the paper explains how the model is built and then based on case studies (fragmentation, vibration), the paper shows how accurate are the prediction, comparing digital blasting simulations and field data.

In the second part, some typical blasting situations are modeled with the digital blasting simulator. Results are analyzed and from them we are able to answer to some of frequently asked questions by blasters, such as:

- Why this guy that is located 100 m far away from the other neighbors is the only one to complain?
- Why my seismograph, always situated at the same location, shows high PPV today, but I haven't change my charge par delay?
- Why there is some coarse fragmentation in the middle of the muck-pile?

Some of the answers are not really surprising and confirmed by field experience. Some of them are really surprising because unexpected but we can certainly learn from them.

1 INTRODUCTION

Considering rock fragmentation by explosive as the ultimate goal in mines and quarries, vibrations are definitely one of the main drawbacks faced by the Industry. If we can accurately predict vibrations level and frequencies, taking into account the whole set of the involved parameters, this will bring a major benefit to each of us, in our daily production process optimization effort.

The model presented in this paper answers to this need thanks to a "holistic" approach of the vibration mechanism. By holistic, we mean that we approach the vibration effect (wave propagation) as a whole, by understanding all of the mechanisms that contributes to the process and comprehending how they are connected.

Vibration effect is a complex mechanism, to such an extend that is nearly impossible to predict its global behavior by understanding or predicting the mechanism of each elementary process involved. We can say that the value of the sum of each component is different from the sum of the value of each component.

The model is primarily based on physical equations that describe each elementary mechanism, named “gene”, involved in the vibration effect. The model is then linking the genes together, based on common parameters criteria. This is providing a "holistic" and realistic model of rock breakage, and consequently of fragmentation distribution size, taking into account all key parameters involved such as geology, explosive features, drilling pattern and timing sequence. By using physics mechanism such as thermodynamic, detonics, rock mechanic, damage principles, ballistics, the modeled vibration effect is able to directly reflect the influence of changes in input parameters value.

Field vibration measurement is compared to predicted ones to give an idea of how the model fits to the reality.

2 PRINCIPLE OF THE MODEL

Without going into details, the description of the effects of an explosion can be split up as follows (Figure 1):

1. The charge explodes and is split up into high-pressure, high-temperature gases
2. The gases are applied to the bore hole, which contains them and creates a strain field in the rock
3. This strain field, due to its impulsional aspect, creates a strain wave that is propagated in the rock and damages it
4. This damage is the centre of the cracks in the rock
5. The gas pressure is reduced via the cracks thus separating the rock fragments

6. The pressure of these gases applied to the face of the fragments, produces forces that propel the fragments
7. The fragments adopt a ballistic trajectory
8. In areas where the damage to the rock was not sufficient to create fragments, the strain wave continues its trajectory until it runs out of energy that it dissipates by making the rock vibrate.

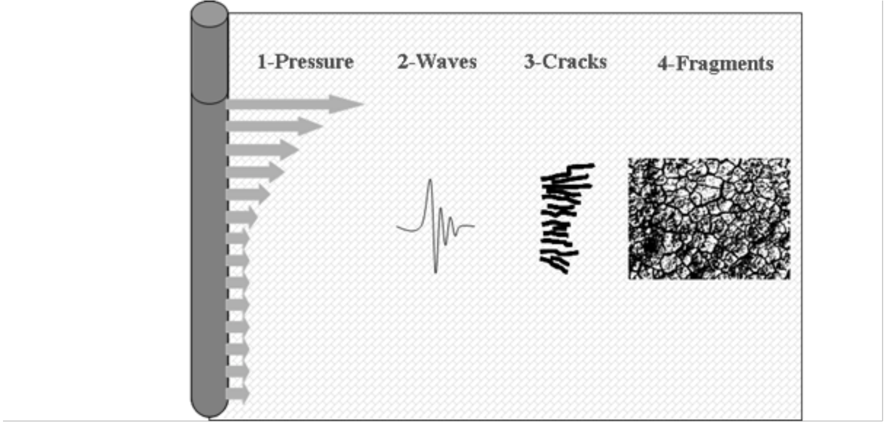

Figure 1: summary of rock breakage mechanism

The model, as explained in the introduction, is built up around elementary mechanisms (genes), each describing one of the aspects of the overall mechanism, all joined together by links explaining their interactions (Figure 2).

When studying the mechanism described above, it becomes obvious that at least with the following genes, it is possible to efficiently model the effects of an explosion:

- A detonating gene
  (that describes the evolution of the borehole pressure after a detonation)
- A strain wave propagation gene
  (resulting from a pressure field)
- A wave interference gene
  (case of several explosive charges)
- A rock damage gene
  (weakening of the characteristics of the material according to the strain)
- A fissuring gene according to the damage
- A ballistic gene *(trajectory of the fragments)*

The contemporary knowledge of these physical phenomena associated to published papers on rock breakage mechanisms and effects (see References section) enable us to define these genes easily. The model uses the following genes:

• G10- VOD Gene:	defines the detonation speed of an explosive according to its diameter
• G11- Thermo Gene:	defines the detonating pressure for an explosive of a given diameter
• G12- P(x,t) Gene:	defines the pressure field created in the face of a blasting hole according to the explosive used and the decoupling
• G20- WaveP Gene:	defines the propagation conditions of a P wave created by a pressure field on the face of a hole
• G21- WStress Gene:	defines the strain field associated with the P Wave field
• G21- WDisp Gene:	defines the displacement field associated with the P Wave field
• G22- WSpeed Gene:	defines the speed field associated with the P Wave field
• G23- WAcc Gene:	defines the acceleration field associated with the P Wave field
• G30- Damage Gene:	defines the state of the damage to the rock by a dynamic strain field
• G31- Frag Gene:	defines the bolometric distribution of a damaged rock space
• G40 -RRT:	defines the response time of a rock mass subject to a pressure field

- G41- Balist Gene: defines the trajectory of a rock fragment subject to a pressure field
- G41- MuckP Gene: defines the shape of a muck pile of fragments
- G42- StemEject Gene: defines the ejection conditions of the final stemming
- G43- CratEject Gene: defines the conditions of the crater effect of a charge near the surface
- G50- ChargeVib Gene: defines the level of vibration according to the charge per delay
- G60- SeqVib Gene: defines the level of vibration according to the initiation sequence
- G61- SeqFrag Gene: defines the granulometric distribution according to the initiation sequence
- G62- SeqMuckP Gene: defines the shape of the blasted muck pile according to the initiation sequence

All that remains is to model the interaction of the genes (Figure 2). An explosion is a dynamic phenomenon that commences when the blaster depresses the trigger button, and finishes when the rock fragments have hit the ground, and the ground has stopped vibrating. We moved from a pre-blast stable state to a post-blast stable state, having undergone a succession of transient phenomena. The time parameter is therefore part of this overall phenomenon.

To take this dynamic effect into account, once the gene interaction has been described, the model works via elementary time stages. At the end of each time stage, the interaction of the genes is updated. Each new time stage takes place, with the initial condition of the state of the previous time stage. This is how the dynamic aspect of the phenomenon is modeled.

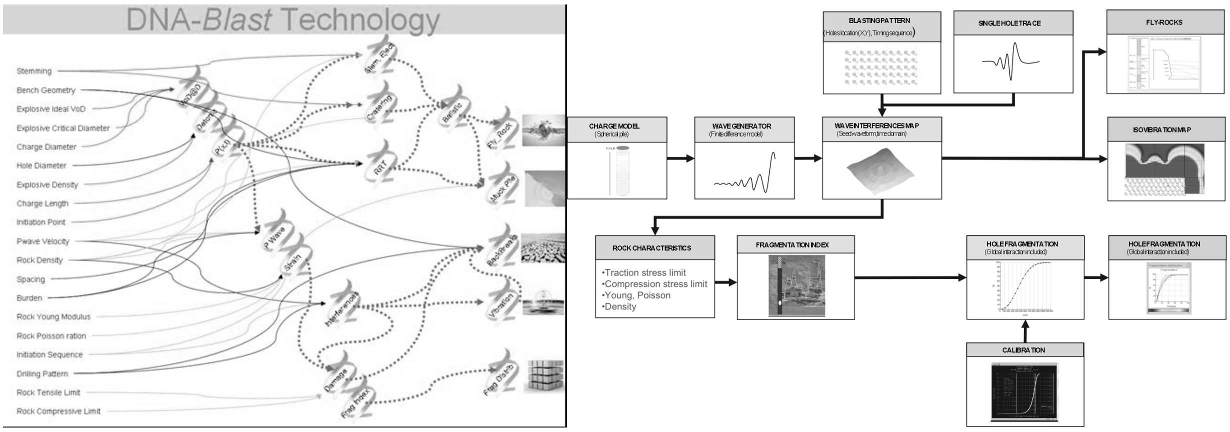

Figure 2: summary of genes interaction / structure of the model

3 PREDICTING VIBRATION

Today, there are several methods currently used to predict the vibration level created by a blast, at a given point. Let us review the two that are the most frequently used, i.e. the charge per delay method and the timing method, and analyse their strengths and weaknesses.

3.1 A brief critical analysis of the charge per delay method

The first, so-called charge per delay, or reduced distance method, recommends the theory that the vibration level at a given point is solely a function of the distance between the blast and the point in question and the charge per delay of the blast. The charge per delay is defined as being the maximum instant charge measured for all the blast charges. It is generally accepted that two charges are separated in time if the interval is over 8 ms (this value is doubtful and very controversial. Moreover, the paragraph briefly analyzing the timing method reveals its limits).

The expression retained to estimate the maximum vibration level at a given point is of the form $V = KD^{\alpha}Q^{\beta}$ where K, α, β are constants that distinguish the blast and the site configuration. This equation is also more frequently known in the form of $V = K\left(\frac{D}{\sqrt{Q}}\right)^{\alpha}$ (0) as brought to light by CHAPOT in France in the 1980s.

It should be noted that:

- The vibration level presents an axial symmetry around the blast
- The initiation sequence has no influence on the calculation
- The number and the position of the holes has no influence on the calculation

3.2 Brief critical analysis of the timing method or seed waveform method

The second so-called timing, or single trace method is based on the seismic signature of a charge measured at a given point (Figure 3).

The seismic signature of a charge is defined as the recording at a given point of the vibrations created by an isolated explosive charge (without any interaction with other charges). This seismic signature has the advantage of integrating the modifications of the source trace caused by its crossing different geological layers and the morphology of the site. A blast is made up of a series of charges delayed in time, so all you have to do, for each blast charge is to delay the elementary seismic signature of the charge, by the delay of the latter (time delay), and add together all the delayed seismic signatures, to obtain the overall seismic signature of the blast. Working from this, it is easy to obtain the maximum vibration level of the blast.

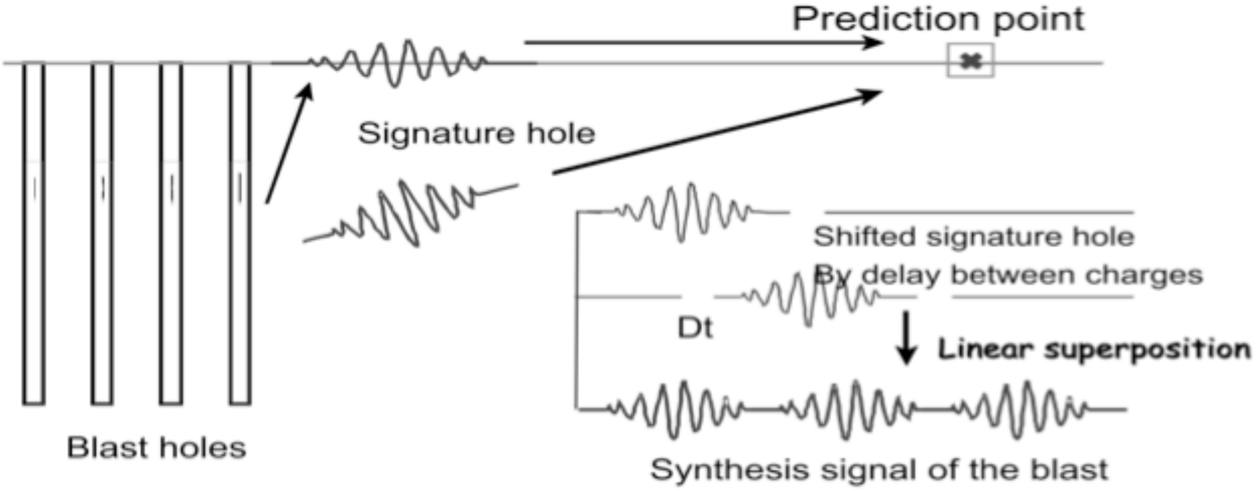

Figure 3: the timing method or seed waveform method

It should be noted that:

- The method takes the initiating sequence into account.
- The method requires a seismic signature per type of charge.
- It is possible to take into account the relative position of the holes amongst themselves compared with the measurement point, by correcting the time delay between the charges by the travel time between the charge and the measurement point.
- The vibration level is only estimated at a distance equal to that separating the single hole blast from the measurement point of the elementary seismic signature.
- By applying this principle, the rule of 8 ms previously mentioned no longer makes sense, because each time delay corresponds to a different vibration level, even though the rule of 8 ms insists that beyond 8 ms the vibration level is constant.

3.3 The seismic model approach

We will now deal with how we can model the vibrations in a reliable manner with the model, in the area surrounding the blast, whilst taking into account all the key parameters (geology, position of the holes, the charges in the holes and, of course, the initiation sequence).

To do so, we will start with the principle already mentioned in the previous paragraph, but that is generalised i.e. the seismic signature of a blast, measured at a given point, is the sum of all the seismic signatures generated by all the blast charges. This can be mathematically written as follows: $SG(t) = \sum_{i=1}^{N} s_i(t)$ (1) where:

- $SG(t)$: represents the seismic signature of a blast (expressed in the time domain)
- $s_i(t)$: represents the elementary seismic signature of each blast charge (expressed in the time domain)
- N: the number of charges in the blast

If we consider that each charge creates a seismic signature that is almost identical, barring the amplitude, the expression (1) becomes:

$SG(t) = \sum_{i=1}^{N} a_i S(t - \Delta t_i)$ (2) where

- $S(t)$: represents the elementary seismic signature of a typical blast charge (expressed in the time domain)
- Δt_i : represents the time delay of a charge in the sequence
- a_i : represents the amplitude coefficient of the elementary seismic signature

This equation, written in the frequency domain becomes: $SG(f) = F(f)S(f)$ (3) where

- $SG(f)$: represents the amplitude of the Fourier transform of SG(t)
- $S(f)$: represents the amplitude of the Fourier transform of S(t)
- $F(f)$: represents an amplification function

with $F(f) = \left(\sum_{i=1}^{N} a_i \cos(2\pi f \Delta_i) \right)^2 + \left(\sum_{i=1}^{N} a_i \sin(2\pi f \Delta_i) \right)^2$ (4)

In addition if we call D_0 the reference distance between the charge per delay and the measurement point of the seismic signature and by applying the classic law $\left(V = K \left(\frac{D}{\sqrt{Q}} \right)^{\alpha} \right)$ (5) of the decrease in the amplitude for a single hole, we obtain:

$V_0 = K \left(\frac{D_0}{\sqrt{Q}} \right)^{\alpha}$ (6) and $V_i = K \left(\frac{D_i}{\sqrt{Q}} \right)^{\alpha}$ (7) so $V_i = \left(\frac{D_i}{D_0} \right)^{\alpha} \left(\frac{\sqrt{Q_0}}{\sqrt{Q_i}} \right)^{\alpha} V_0 = a_i V_0$ (8)

Hence $a_i = \left(\frac{D_i}{D_0} \right)^{\alpha} \left(\frac{\sqrt{Q_0}}{\sqrt{Q_i}} \right)^{\alpha}$ (9)

It should also be noted that $\Delta t_i = \Delta_i + \frac{D_i}{V_p}$ (10) with:

- Δ_i : represents the time delay of the initiation sequence
- $\frac{D_i}{V_p}$: represents the time delay of the trajectory of the seismic wave between the charge and the point of measurement.

On the assumption that the frequency domain of the seismic signature of a charge is identical for all charges, it is therefore possible to calculate a seismic amplification factor (Figure 4) at any point around the blast.

<u>It should be noted that:</u>

- The amplification factor takes into account the position of the holes, the initiation sequence and the charge in each hole
- The amplification factor is solely dependent on the arrival time of the trace at a point, the position of the charges and the frequency

This amplification factor (Figure 4) will be used in the model with several aims in mind:

- Find the vibration level at a given point by multiplying it by the spectra of the seismic signature and by then carrying out an inverse Fournier transform
- Look for an initiation sequence leading to a minimum vibration level in an area
- When modeling or optimizing the fragmentation. This factor enables the wave amplitude generated by each hole to be corrected in the fragmentation model

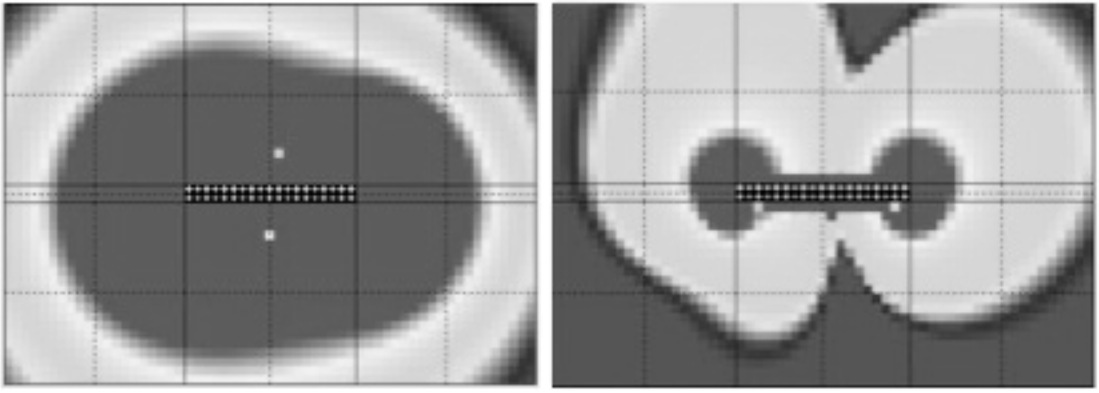

Figure 4: example of amplification factor at 10Hz and 40 Hz surrounding a blast

Finally, it should be noted that the amplification factor enables an easy deconvolution of the trace and the obtaining of an elementary seismic signature from the overall seismic signature of a blast.

4 MODELING FRAGMENTATION

4.1 <u>Rock breakage mechanism</u>

Fragmentation is the result of cutting the matter into elementary blocks along preferential fragile lines between the damage points of the rocky matrix.

These damage points are created by the strain waves that are propagated in the rock and, according to their intensity and the state of the matter, lead to damaging or locally destroying the latter. The force that separates the fragments from each other along these lines is caused by the gas pressure when it enters into the fissures and comes to rest on the faces of the fragments.

Therefore, the mechanism is very similar to that which a child uses to cut out a shape in a piece of paper with a needle. The child begins by pricking a line of holes in the paper that form the edge of the shape. This is the equivalent of the strain wave that spreads out causing damage (small holes) in the matter (sheet of paper). Then, he holds the paper at each end, and with his hands he exerts a force on either side of the paper. This is the equivalent of the gas pressure. The sheet of paper tears along the line that links all the holes (fragile zone).

Thus, we can construct a fragmentation model based on this principle by propagating a strain wave, created by the pressure field in the blasting hole in the rock, and by defining all the fragile points created by this wave, then by linking them together in order to define the blocks thus obtained. This method raises no technical study, or digital solution problems, but, in order to have a realistic result, it requires accurate knowledge of the state of the matter surrounding the hole.

Indeed, the fragile points (holes in the sheet of paper) only appear when the strain wave passes because on a microscopic scale, the matter is not homogenous. It has structure variations, which mean that one zone may or may not resist better to the strain state created by the wave than another. These zone variations, with different degrees of resistance and weakness, will be the source of the network of "holes" within the rocky matrix.

The result is that although the mechanism as described, enables us to model the fragmentation phenomenon theoretically, it is only with a very accurate and detailed measurement on a microscopic scale of the mechanical state of the rock that it can be applied. Now we know that although it is possible in a laboratory on a small scale, today it is impossible to carry out this measurement on an operational site, even more so on a larger scale.

For all that, should we abandon the principle for modeling the fragmentation of a blast?

4.2 The fragmentation model approach

Not necessarily! The microscopic approach to the phenomenon shows us that the rock has structure variations randomly distributed throughout the matrix. Here, we are faced with a phenomenon that can be described statistically. This is how we will describe the fragmentation mechanism of a rocky matrix with a strain wave.

Let us take an elementary cube of matter. We know that, when looked at through a magnifying glass, the inside is not homogenous and has variations in structure, but that, when viewed from outside (macro view), this cube seems to be homogenous or even isotropic. For example, we can characterize it with the following values: Young's Modulus, Poisson ratio, and tensile and compressive strength. Therefore, we have to find a description of the macroscopic damage that takes into account the microscopic state.

To do so, let us study the damage created by a wave. One of the best comparisons to describe a wave is undoubtedly the waves in the sea. If we watch the waves breaking against a sea wall, throughout time, they will damage the wall at it's weakest points. It is possible to link the damage to the sea wall to different characteristics of the waves.

- The height of the wave (amplitude of the wave). Very large amplitudes damage the sea wall quicker. A very large amplitude can even lead to it being destroyed, in one go.
- The repetition of the waves on the wall or their cyclic or alternating feature (frequency of the wave). The hammering effect weakens the wall that will give way in time.
- The length of each wave (wavelength). The longer the wave, the longer it will exert its force on the sea wall.

We suggest constructing the fragmentation model of the rock based on these characteristics (amplitude, frequency, wavelength).

Let us take an elementary cube of matter and submit it to the passage of a strain wave for time T.

Let us look for a very short time dt at the effect of the part of the wave that is in the elementary cube. It has an amplitude "A" that we compare with the limit strength Sigma limit ($\sigma_{\lim}$) of the rock according to the state of the wave.

The elementary fragmentation index is defined $if(dt) = \frac{A}{\sigma_{\lim}}$ if ≥1, if not $if(dt) = 0$ (11)

and $[If]^{-1} = \sum_{dt=0}^{ct=T} if(dt)$ (12)

It should be noted that this index increases with the application time of a wave whose amplitude is higher than the rock's strength. Therefore, it is directly correlatable to the number of fragile zones created (holes) by the wave, and, consequently, inversely correlatable to the size of the fragments created.

The value $If = \left[\sum_{dt=0}^{ct=T} if(dt)\right]^{-1}$ (13) is the value we shall retain as the fragmentation index and that directly correlates to the size of the fragments that will be created in the elementary cube.

How can we move from If to the blocometric distribution of a hole?

The space around a hole is split into elementary volumes. The time T necessary for the strain wave from the blasting hole is split into sections dt

For each elementary volume (n) we calculate If(n). After having sorted the If(n) from the smallest to the largest, we split the range of values $\left[If(n)_{\min}, If(n)_{\max}\right]$ into intervals that we call "blocometric classes".

The number of If(n) values per class represents the elementary blocometric distribution of a hole.

It should be noted that :

- The scale of the blocometric classes is completely arbitrary
- The scale of the Y-axis is expressed as a % of the total number n of elementary blocks
- The same result, represented in cumulative values, gives the traditional representation of a blocometric distribution.

5 A FEW COMMENTES REGARDING THE MODEL

- **This model takes into account all the key parameters of a blast (quality of the explosive, geology, position of the holes (drilling pattern), and blasting sequence).**

The characteristics of the explosive (critical diameter, ideal detonation speed, density, length and diameter of the charge) are taken into account in order to calculate the pressure field in the borehole. The mechanical characteristics of the rock (Young's modulus, Poisson ratio, tensile and compressive strength, and density) that are necessary to propagate the strain wave, are also included in the model.

To do so, a finite differences calculation process is used, which enables us to take into account the variations in the characteristics of the rock in space and time. Each elementary rock cube of the model can be given its own characteristics. For example: one of the DNA-Blast software modules enables us to specify the geology surrounding a hole based on the log of the hole obtained during drilling.

The model used to describe the strain wave created by a cylindrical charge of finite length is based on the splitting of the said charge into elementary cylinders of a length equal to the diameter of the hole. For each elementary charge, a model for the wave propagation with a spherical source is applied. The interaction of the waves from each source is carried out by linear superposition, by staggering each one by a period of time equal to the diameter of the hole divided by the detonation speed.

- **How rock mass is taken into account?**

Rock mass parameters (joints, cracks, …) are taken into account by the macroscopic approach of the model as the mechanical characteristics of the rock (Young's modulus, Poisson ratio, tensile and compressive strength, and density, P-wave velocity) used to propagate the strain wave, are the characteristics of the rock mass itself and not those of the rock matrix. Different rock mass parameters, described by macroscopic mechanical characteristics, can be used in the model around each hole or on each area where vibrations want to be modeled, to describe a non-uniform geology.

- **This model gives the blocometric distribution of each hole, and enables the overall distribution of the blast to be obtained, as well as a dispersion cone by concatenation of all the elementary curves.**

The model allows us to obtain a blocometric distribution for each blasting hole (explosive charge per hole, local geology at the hole and volume concerned defined by its drilling pattern associated with its initiation time – it is to be noted that the drilling pattern used is real not theoretical, that is to say the distance to the free face created by the detonation of the preceding holes). The blocometric distribution of the blast is obtained by adding the elementary distributions of each hole per class, then constructing the overall cumulative distribution of the blast.

- **The model can easily be calibrated afterwards, based on the site measurements obtained with part or all of the muck pile.**

The model, as we saw, enables us to obtain a blocometric distribution on a relative scale, each blasting hole having its own distribution. To calibrate the model, all you have to do is to adjust the horizontal scale (size of the blocometric classes) of a hole or group of holes. This adjustment is carried out by simply altering the size of the largest class, i.e. the class where there is 100% passing size. We should note K the proportionality coefficient between the simulated size and the real size of the largest class.

It is also possible to accurately adjust the shape of the curve to take into account the non-linearity of the fragmentation mechanism, if the latter is too great. To do so, we calculate the transfer function

$$F(class) = \frac{Real\_Distribution(class)}{Theoretical\_Distribution(class)} \quad (14)$$

The knowledge of these two coefficients K and F(class) enables the model to be calibrated for future simulation. It should be noted that this calibration does not modify the influence of the parameters and that it is carried out once the simulation is finished. Therefore, it is not detrimental and can be carried out afterwards, which corresponds to the reality of a site: the blocometric result of a blast is only known once it has been carried out and dug.

- **The model takes into account the initiation sequence and its influence on the wave inferences**

One of the most important aspects of the model is that it takes into account the firing sequence. The fragmentation model for a hole is based on the effects of the strain wave that spreads through the volume of rock around the said hole. Therefore, you simply have to replace the elementary wave, for each hole, with the resultant of the waves of the whole blast at the hole to obtain the influence of the initiation sequence on the volume of the hole in question. If we take the analogy of the sea wall damaged by the wave, the damage is created by a combination of all the waves that break against the wall.

6 VALIDATION OF THE MODEL

The first question that comes to mind immediately when an approach such as this is presented is to know its validity. In other words, the predictions of a model such as this are close to reality and, being given that the model has imperfections, how much will it deviate from reality.

6.1 Validation of the mechanism (genes)

Each DNA-Blast gene has been validated using on site measurements or laboratory data in order to guarantee the validity of its model. A gene is considered to be valid when the deviations between the values measured and those simulated are below 30%. Due to the type of model, split up into a set of genes, with a behaviour deviating no more than 30% from the data measured, the DNA-Blast model is consistent and sound.

6.2 Validation of Fragmentation and vibration prediction

The example below gives a good idea of its degree of validity. The case study below, about fragmentation prediction, is a good illustration of the ability to predict vibration level and fragmentation distribution as the fragmentation prediction is based on the P wave amplification factor in the blasted block itself (please refer to upper paragraph)

At mine A[1], three blasts (Figure 5) were the subject of special monitoring and in situ fragmentation measurement thanks to an image analysis, as well as “manual” screening of some parts of the muck pile, in order in particular to fine tune the quantification of the fine particles. It should be noted that the in situ fragmentation measurement for these blasts was only carried out on part of the muck pile and not for the whole volume. The measurement concerns the areas situated at the centre of the blast. The blocometric distributions obtained are only therefore representative of part of the (blasted) broken volume.

Note 1 : For confidentiality reasons the name of the mines has been replaced by a letter.

The validation protocol for the model is as follows:

1. Modeling blast N°1
2. Calibration of the model with the help of the in situ measurements of blast N°1 (Figure 6)
   (The calibration is based on average measured and simulated curves)

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[1] *For confidentiality reasons the name of the mines has been replaced by a letter.*

3. Modeling blast N°2 using the calibration obtained thanks to blast N°1
4. Modeling blast N°3 using the calibration obtained thanks to blast N°1
5. Comparison of the modeled and measured results for blast N°2 (Figure 6)
6. Comparison of the modeled and measured results for blast N°3 (Figure 6)

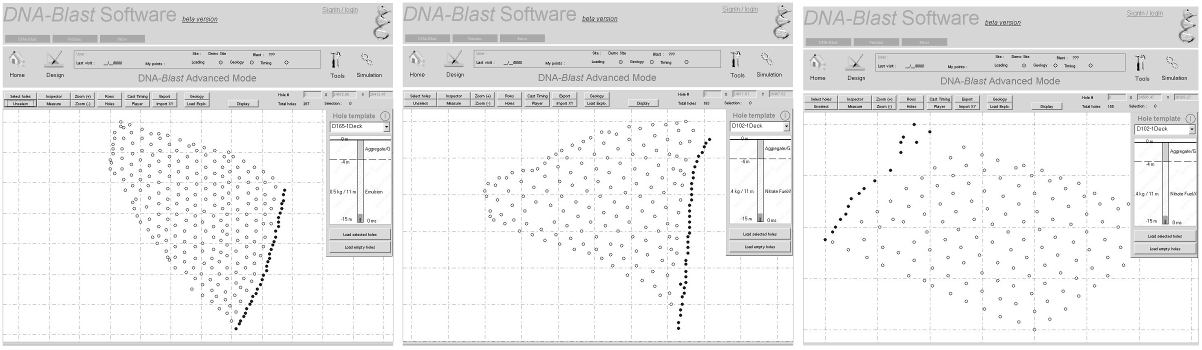


Figure 5: blasts involved in case study A

The graphs below (Figure 6) respectively represent the blocometric distribution of the measured (dot line) and simulated (plain line) values.

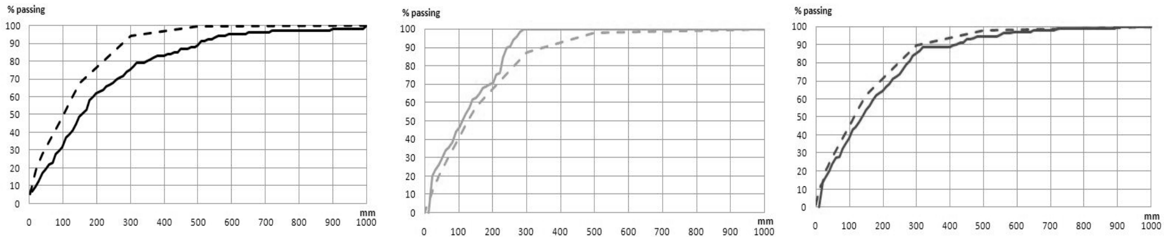


Figure 6: blocometric distribution of blast n°1,2,3

When analysing the calibration effect (obtained from the average values measured) of the high and low values of the simulated distribution, we noted that the curves are very similar and the difference in percentage of the range of the size of fragments is less than 16%. This difference is confirmed by the simulations of blasts N°2 and N°3 compared with the values measured for the high and low values of the distribution; it is in fact lower (10%) for the average value. This deviation is very acceptable. Therefore, the model provides unprecedented results and is validated including the vibration prediction (part of the mechanism).

7 WHAT APPLICATION ARE THERE FOR THE MODEL?

7.1.1 PREVENTING FIELD TRIALS AND ERRORS.

A digital simulation with a reliable result is a tool that for example permits strategic choices to be made, exploring the different configurations, without undertaking tests in situ, which are costly, because they require substantial instrumentation to compare the results. Therefore, the traditional trials and errors process can be avoided, so that configurations that are sometimes risky or could become dangerous can also be avoided.

7.1.2 ANSWERING TO FREQUENTLY ASKED QUESTIONS BY BLASTERS

- ***Why this guy that is located 100 m far away from the other neighbors is the only one to complain?***

When you have some neighbors close to the pit, the common sense tells us to monitor vibrations at the closest point from the blast or at the boundary of the pit. As we know that vibration level decreases versus distance, if your vibration readings at the boundary at the pit are fine, they should be fine far away.

In the example below we can see that it's not so obvious. At a given distance, the model display different vibration amplification factors due to the interferences of waves. If you have a seismograph located where it's blue on the graph, the vibration level is very low. Unfortunately at the same distance we can see that there is some area where the amplification factor is high (Figure 7-2). More than that, at a far distance (Figure 7-3) from point (Figure 7-1) amplification factor is higher!
That is the reason why you can have a neighbor located far away from your closest seismograph, but complaining even if the vibration readings are fine!!

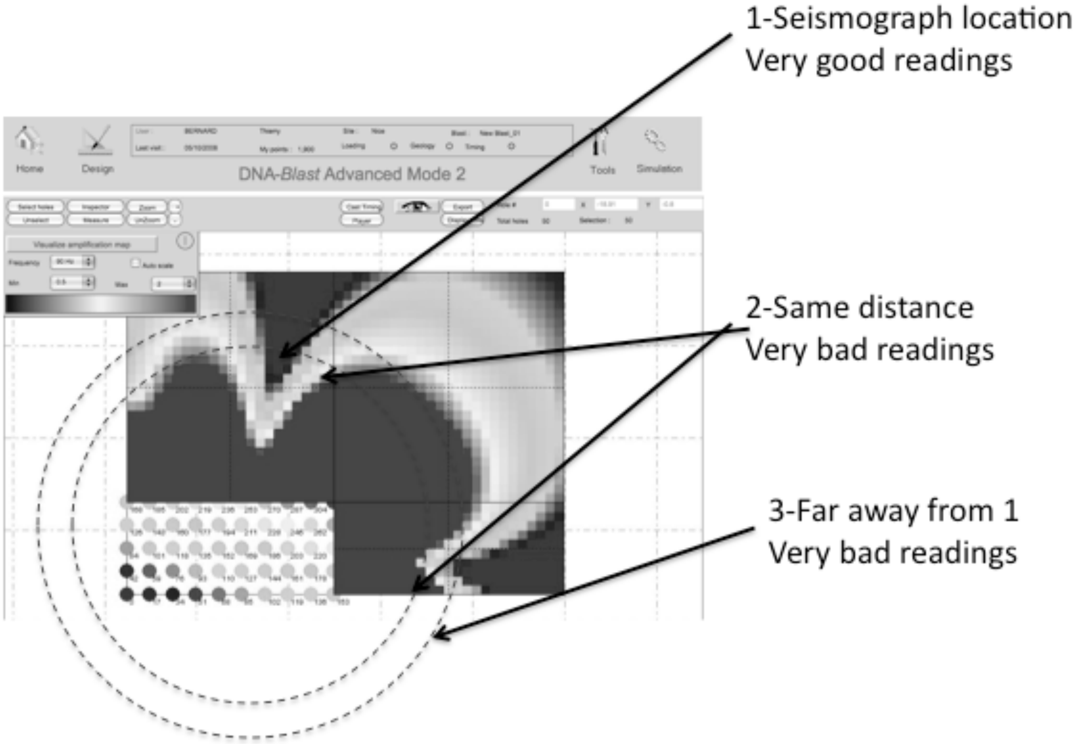


Figure 7: influence on seismograph on PPV

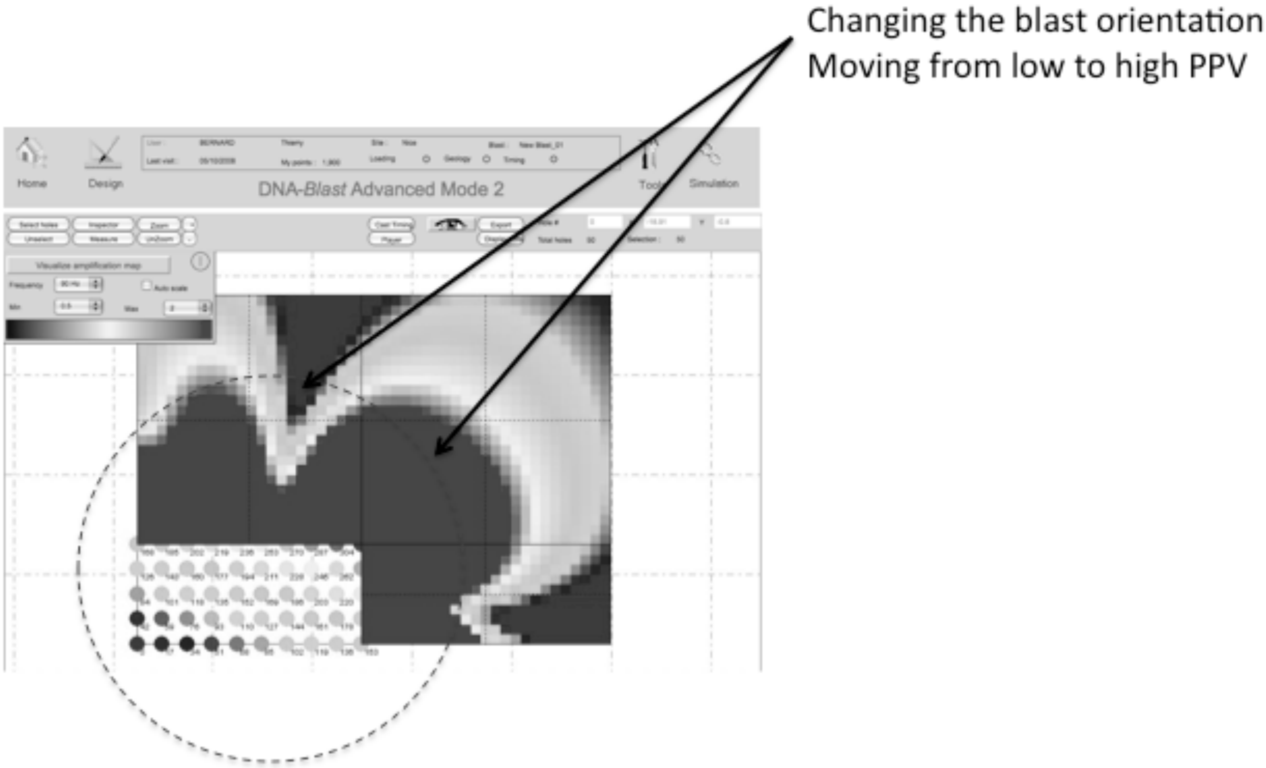
- ***Why my seismograph, always situated at the same location, shows high PPV today, but I haven't change my charge par delay?***

To answer to this question, let's assume we keep the same blasting configuration as above. We have seen that the vibration amplification factors around the blast are not circular (previous case). This is mainly due to the initiation sequence associated to the drilling pattern that creates a wave interference pattern.

In the case we are blasting at the same distance from the seismograph, with the same charge per delay, there are two main parameters that could change:
1. The orientation of the blast
2. The initiation sequence.

1. Simulating a different orientation of the blast is very easy and can be obtain, just by rotating the blast itself and keeping the seismograph at the same location. We can also rotate the seismograph location around the blast that will give exactly the same result.

In that case we can see (Figure 8) that the vibration amplification factor is not constant on a circle around the blast that means that the PPV will change according to the blast orientation, even with a constant distance from the seismograph and a constant charge per delay!



Changing the blast orientation
Moving from low to high PPV

Figure 8: influence of blast direction on PPV

2. A different initiation sequence, with a blast located at the same place and the same orientation versus the seismograph is giving a different vibration amplification factor map. This is once again due to the interference pattern that is strongly influenced by the initiation sequence. The two simulations below demonstrate the influence of the initiation sequence on the vibration amplification factor map. On the left simulation (Figure 9) , the opening point is on the left corner of the blast with a standard 17ms between holes and 42 ms between rows; on the right simulation (Figure 9) , the opening point is on the middle of the first row, with a V shaped sequence with short delays (3ms) between holes.

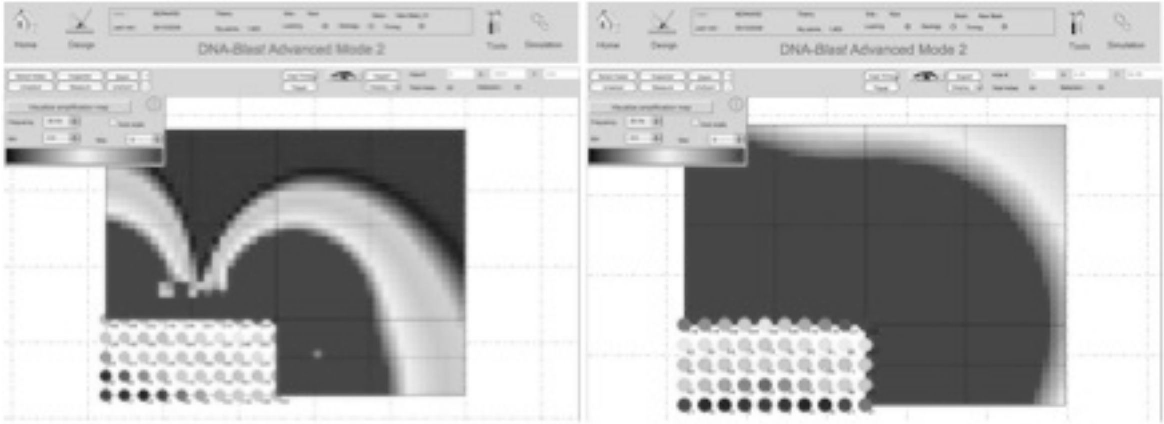


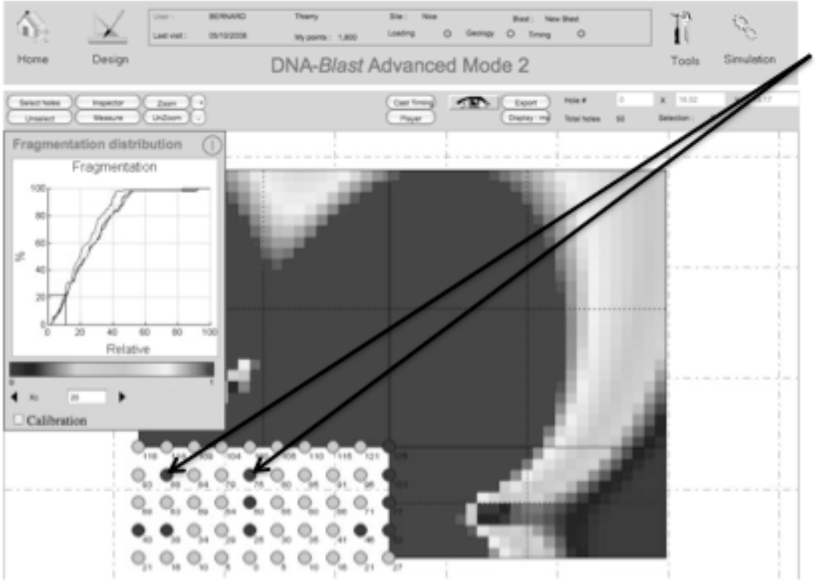
Figure 9: comparing the influence of the initiation sequence on vibration map

- ***Why there is some coarse fragmentation in the middle of the muck-pile?***

When digging in a muck pile, it might happen that we find some coarse fragmentation. If the drilling pattern was very good (same burden and spacing for each hole, no significant drilling deviation) and the powder factor constant for each hole, we always think that it is because of the geology! What else could it be?

Let's have a look to a fragmentation distribution predicted with a blasting effect simulator, where fragmentation is based on the rock damage created by P-wave in the block. As the P-waves interferes into the block itself depending on the initiation sequence and the drilling pattern, the damage around each hole varies according the interference pattern. As a consequence, the damage is not uniform and varies accordingly to the interference pattern.

The model shows us the fragmentation distribution curve but also colors each hole with a color that is proportional to the contribution of the hole to the global fragmentation distribution.
In the example below (Figure 10), hole fragmentation contribution are colored from blue (fine fragmentation) to red (coarse fragmentation). We can clearly see that two holes, in the middle of the muck pile are providing a coarse fragmentation.



Holes contribution to a coarse fragmentation

Figure 10: influence of initiation sequence of fragmentation distribution

8 SUMMARY AND CONCLUSION

Modeling all the effects of a mine blast, something we have dreamed of for a long time, is a reality today. The model predicts the overall effects of a blast, based on a set of elementary mechanisms (genes) interconnected by their common physical parameters, according to time.

Consequently, the model offers an approach to blast vibration prediction, whilst simultaneously modeling the other effects, such as the rock fragmentation mechanism, taking into account all the key parameters in a mine blast: Geology, drilling pattern, hole loading, with the quality of the explosive and stemming, and above all the initiation or firing sequence.

The model has been validated with real configurations and also some real blast. They only deviate by a few percent from the values measured, which enables us to consider that the model is reliable and useful.

To key questions such as:

- Why this guy that is located 100 m far away from the other neighbors is the only one to complain?
- Why my seismograph, always situated at the same location, shows high PPV today, but I haven't change my charge par delay?
- Why there is some coarse fragmentation in the middle of the muck-pile?
- Why…

We can answer that simulations teach us that wave interference patterns are responsible of most unexpected results.

- PPV are not uniform at a given distance form a blast
- Orientation of a block is affecting the PPV at a given distance, regardless the charge per delay.
- Fragmentation distribution is not uniform from hole to hole and strongly depends on the initiation sequence.

This opens up new horizons for optimizing blasts as the prediction of a vibration amplification factor map helps us to understand both vibration levels and fragmentation distribution.

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