A "holistic" approach of blast vibration modeling and prediction

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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.

This paper, based on 15 years of field experience and research, is presenting the main genes involved in the model and their links. Field vibration measurement is compared to predicted ones to give an idea of how the model fits to the reality.

I. The Model:

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

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.

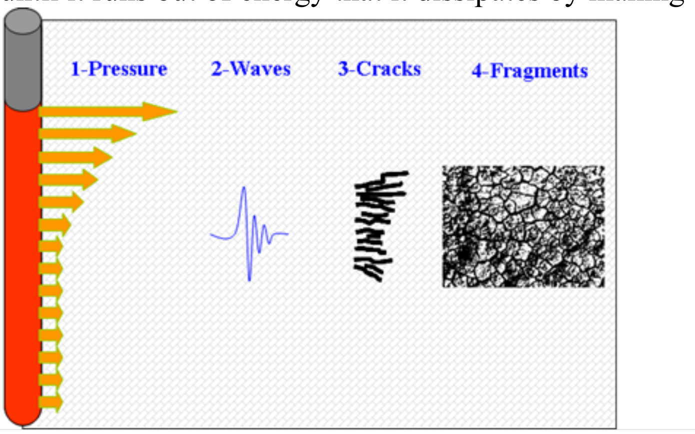

Figure 1 : summary of rock breakage mechanism

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.

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 enables us to define these genes easily. (more detail in appendix 1)

All that remains is to model the interaction of the genes. 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.

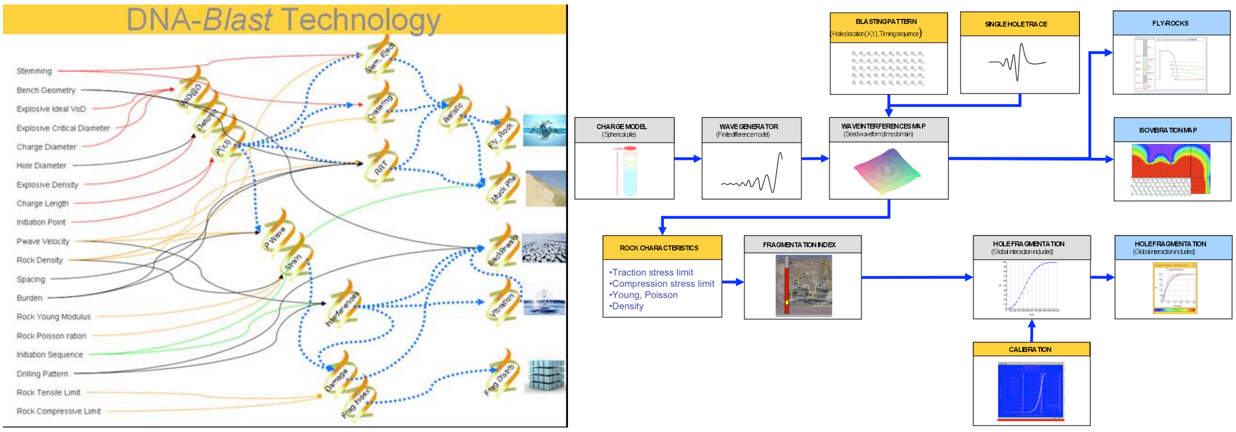

Figure 2 : summary of genes interaction / structure of the model

II. How can we model and predict the seismic conditions surrounding a blast

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.

A. 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 $V = K\left(\frac{D}{\sqrt{Q}}\right)^{\alpha}$ 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

B. 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.

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.

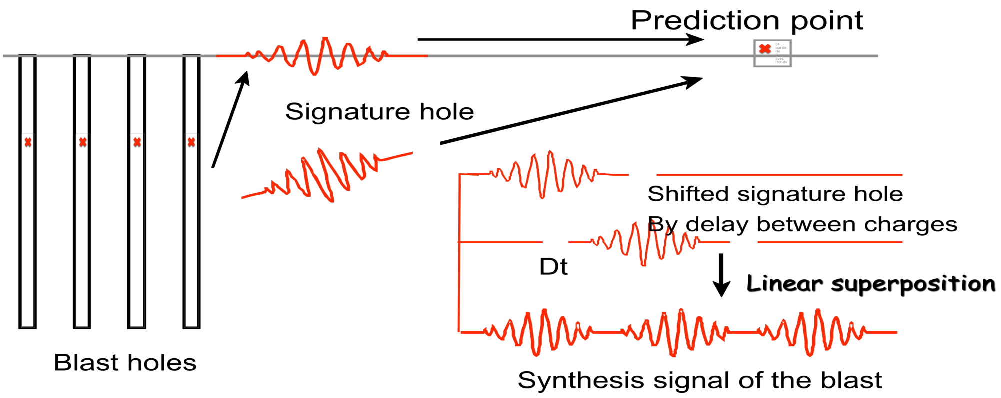

Figure 3 : the timing method or seed waveform method

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.

C. 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:

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

- $S(t)$: 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 $F(f) = \left(\sum_{i=1}^{N} a_i \cos(2\pi f \Delta_i)\right)^2 + \left(\sum_{i=1}^{N} a_i \sin(2\pi f \Delta_i)\right)^2$

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 $\left(V = K\left(\frac{D}{\sqrt{Q}}\right)^{\alpha}\right)$ of the decrease in the amplitude for a single hole, we obtain:

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

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

It should also be noted that $\Delta t_i = \Delta_i + \frac{D_i}{V_p}$ 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 at any point around the blast.

It should be noted that:

- 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 will be used in the model with several aims in mind:

- Find the vibration level at a given point by multiplying it by the spectre 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 modelling or optimising the fragmentation. This factor enables the wave amplitude generated by each hole to be corrected in the fragmentation model

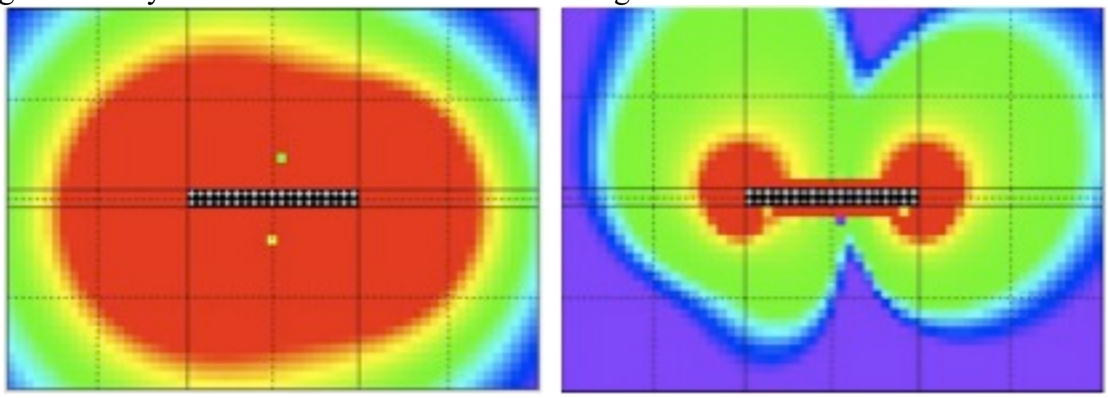

Figure 4 : example of amplification factor at 10Hz and 40 Hz surrounding a blast

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.

III. 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.

Each 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 model is consistent and sound.

Nevertheless, we have launched multiple field validation campaigns with the help some quarries and mines and some of the results will be available and presented in February. The two examples below give a good idea of its degree of validity. In the mean, just to give a good feel about the global model validity, the case study below, about fragmentation prediction, is a good illustration of the ability to predict vibration level as the fragmentation prediction is based on the P wave amplification factor in the blasted block itself (for more information, please refer to paper published in 2008 ASIEX conference: *A "holistic" approach for blast fragmentation modelling*

Case study: Fragmentation modeling

At mine A[1], three blasts 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. The measurement concerns the areas situated at the centre of the blast.
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
   (The calibration is based on average measured and simulated curves)
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
6. Comparison of the modeled and measured results for blast N°3

The graphs below respectively represent the blocometric distribution of the measured (dashed lines) and simulated (solid lines) values. The Y-axis represents the passing percentages, and on the X-axis the sizes are in millimetres.

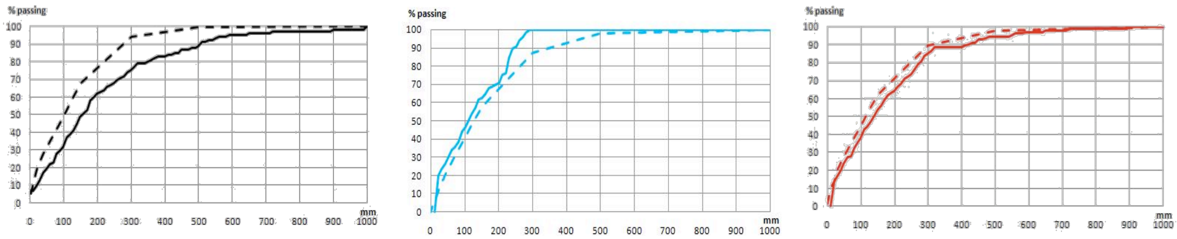

Figure 5: Blocometric distribution of blast n°1,2,3

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).

IV. <u>What new usage and what applications are there for the model?</u>

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 trial and error process can be avoided, so that configurations that are sometimes risky or could become dangerous can also be avoided.

The example below shows how the model can be used to obtain an idea of the vibration map around the blast. The simulation is done with first an initiation sequence of 17 ms between holes and 42 ms between rows. Initiation point is on the bottom left corner of the blast. The grid is the mapping area for vibration.

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

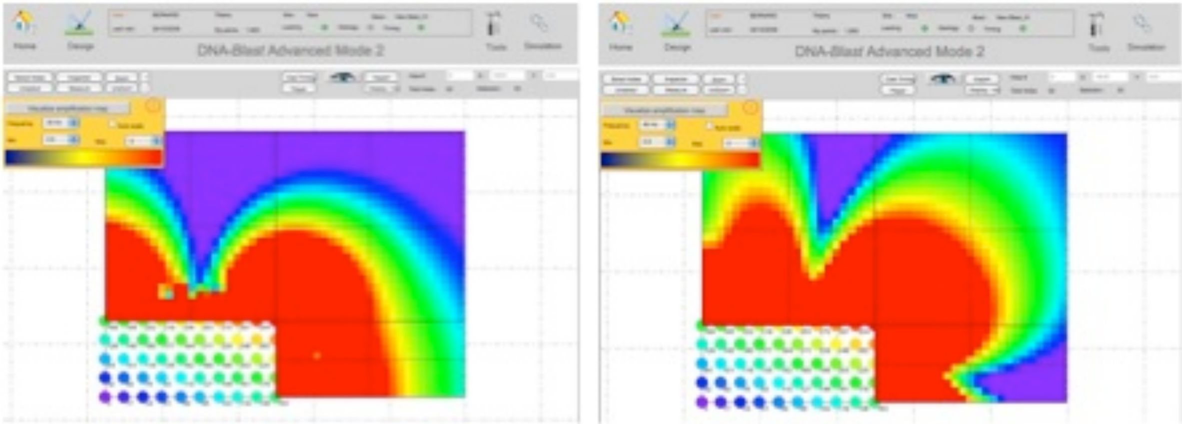

Figure 6 : Map Amplification factor for a 30 Hz and 90 Hz signal

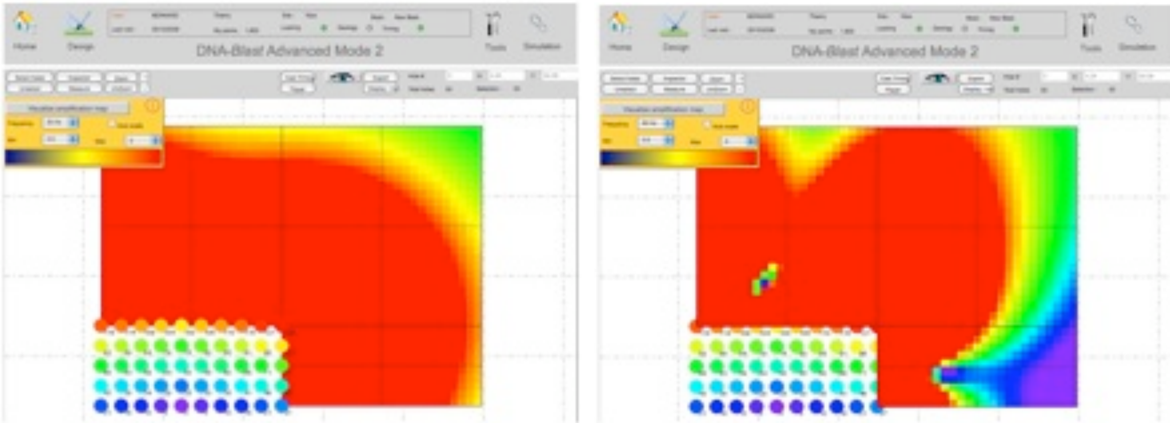

Figure 7 : Map Amplification factor for a 30 and 90 Hz signal with V shape initiation sequence and short delays

V. 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 and fly-rocks

Each elementary "gene" of the model have 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.

Today, this model is a unique model 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, that is seriously lacking in the present models.

This opens up new horizons for optimizing blasts. Therefore, each blaster, shift supervisor, or manager can now assess the effects of a blasting configuration in terms of the technical result or safety, as well as the financial impact.

VI. Appendix

A. Appendix 1 – List of genes modelled

- 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

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