THE TRUTH ABOUT SIGNATURE HOLE METHOD

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Abstract

Since the signature hole method principle has been described in the 80's, there has always been a lot of controversy about it. The theory is easy to understand but when it comes to apply it for predicting vibration level, optimizing timing to reduce PPV or shifting frequencies, it's not always working as expected. Simulations show waveforms that don't make any sense or predictions that are far away from actual results.

From June 2009 to December 2010, about 600 blasts over 36 sites have been realized mainly in the USA. All these blasts were shot with electronic detonators. They have been carefully simulated and optimized with the signature hole principle. Vibrations have been recorded on multiples points for each blast, which build a significant database.

The paper provides some statistical analysis about how the method performs. You will also learn what makes it work, some interesting results about the 8 ms rule, the attenuation law and more.

INTRODUCTION

The signature hole method was developed in the nineties, together with electronic delayed detonators (EDD). The latter have only been a common initiation system for 10 years and computers powerful enough to run advanced efficient simulation models to apply this theory were also not available until then.
The basic principle of the signature hole theory in the far field is analyzed and compared to the advanced principle in the frequency domain applicable in the near field.
This paper reviews the use of the signature hole principle via case studies. About 600 blasts have been analyzed to demonstrate the benefit of the theory applied in the field.
Finally the paper also analyses the de-convolution theory that allows us to obtain a virtual signature hole, derived from the vibration record of a full blast, and can provide a vibration level reduction up to 75%.

THEORY OF VIBRATION SIMULATION

Today, there are several methods currently used to predict the vibration level created by a blast, at a given point. The most frequently used, i.e. the charge per delay method is not analyzed in this paper. The most advanced is the signature hole method. Let's discuss the advantages and disadvantages of various signature hole methods.

THE SIGNATURE HOLE METHOD

The second so-called signature hole or timing, or seed waveform 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.

How does the signature hole method work?
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 (Figure 1). Working from this, it is easy to obtain the maximum vibration level of the blast.

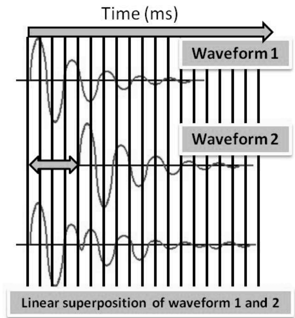


Figure 1 Signature hole method principle

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

- 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.

Mathematic formulation:
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 delayed by timing. This can be mathematically written as follows: (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, 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

This method is called the signature hole method in the time domain because we apply a linear superposition of waves recorded versus time.

FAR FIELD VERSUS NEAR FIELD

The signature hole method, as described previously, assumes that we add waves delayed by timing sequence. As waves are 3D, we measure and process waves on a referential composed of 3 axes or channels called LTV (Longitudinal, Transversal and Vertical). To make sense, this waves adding process has to be strictly the same for the 3 channels (L, T, V). This requires the signature hole to be recorded at a distance from the blast where whatever the charge considered, the L,T,V channel recorded is the same. In other words, we are far from the blast so, from the seismograph "perspective", any wave comes from the same point. We call this situation: the far field.

On the other hand, if the seismograph is located at a distance from the blast, where from its "perspective", waves from different charges are seen coming from different directions, the principle of linear superposition could not be applied. We call this situation the near field.

NEAR FIELD VIBRATION MODELLING IN THE TIME DOMAIN

We will now deal with how we can model the vibrations in a reliable manner in the near field, in the area surrounding the blast, applying the superposition model in the time domain.

To do so, we will start with the principle already mentioned in the previous paragraph, equation (2).
If we consider that each charge creates a seismic signature that is almost identical, barring the amplitude, the expression (2) becomes:

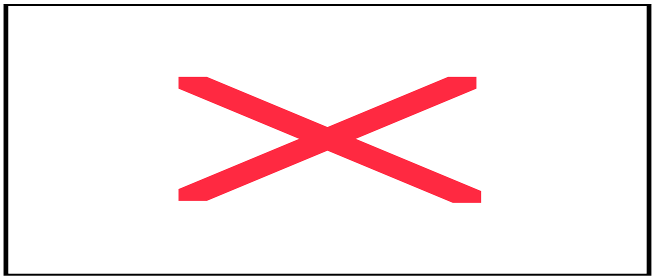
$$SG(t) = \sum_{i=1}^{N} a_i S(t - \Delta t_i) \quad (3)$$ where:

- $S(t)$: 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

If we consider the 3 channels L,T,V we have a system of 3 corresponding equations:

$$\begin{cases} SG_L(t) = \sum_{i=1}^{N} a_i S_L(t - \Delta t_i) \\ SG_T(t) = \sum_{i=1}^{N} a_i S_T(t - \Delta t_i) \quad (4) \\ SG_V(t) = \sum_{i=1}^{N} a_i S_V(t - \Delta t_i) \end{cases}$$

In the near field, as waves are coming from different directions, we need to adjust these equations taking into account the angle between the direction of the waves from the charges and the direction of the recorded signature hole.



(5) where

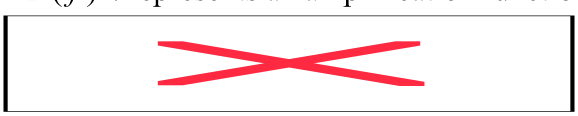
- θ : represents the angle between the direction of the waves from the charges and the direction of the recorded signature hole
- Δt_i : represents the time delay of a charge in the sequence, to which the travel time of the wave from the charge to the seismograph has been added.

NEAR FIELD VIBRATION MODELLING IN THE FREQUENCY DOMAIN

We will now deal with how we can model the vibrations in a reliable manner in the near field, 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) but using the frequency domain.
(Note: the frequency domain is a pure mathematical concept where events are not described versus time but versus frequency. This technique means little to us as it has no physical link with the real world, but it is used in physics as it helps to solve problems)

So equation (2), written in the frequency domain becomes: $SG(f) = F(f)S(f)$ (6) 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  (7)

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 attenuation 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 $a_i = \left(\frac{D_i}{D_0}\right)^{\alpha}\left(\frac{\sqrt{Q_0}}{\sqrt{Q_i}}\right)^{\alpha}$ (8)

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 given point, the position of the charges and the frequency

This amplification factor will be used in a numerical model with several aims in mind:

- Find the vibration level at a given point by multiplying it by the spectrum of the seismic signature and then carry out an inverse Fournier transform
- Look for an initiation sequence leading to a minimum vibration level in an area
- Enable an easy de-convolution of the trace and the obtention of an elementary seismic signature hole from the overall seismic signature of a blast.

WAVEFORM DE-CONVOLUTION

This word means the reverse calculation of a waveform simulation of the blast from a signature hole. In other words, having a record of a full blast, it offers the capability of obtaining an average signature hole of the blast. The main advantage of this method is to obtain a signature hole without shooting a single hole in the pit, which is a not very easy for the site to implement.
Moreover this method allows us to refresh the signature hole on a continuous basis, and consequently benefit from more accurate data everyday, to minimize vibrations.

We have seen that there are two ways to process a signature hole: one in the time domain and one in the frequency domain. Consequently, there are two ways to do the de-convolution of the signature hole.
Let's start with the time domain that is summarized by the equation (4) or (5):

This is a system of equations with p variables where p is greater than n. In a normal situation, this system has no solution. Fortunately, the fact that between the first two detonations there is only one wave propagating (the beginning of the first single hole) this allows us to find a solution using a gauss pivot method. The same principal applies starting at the end of the global waveform. Nevertheless, by experience, this technique fails to provide a good result as any noise on the recorded waveform is amplified by the pivot method and consequently provides a result that makes little sense.

Once again, the frequency domain provides an elegant solution for this problem.

Equation (6) $SG(f) = F(f)S(f)$ can be written as follows: $S(f) = \frac{SG(f)}{F(f)}$ (9)

Equation (9) directly gives the solution in the frequency. Then S(t) is obtained by an inverse Fourier transform of $S(f)$.

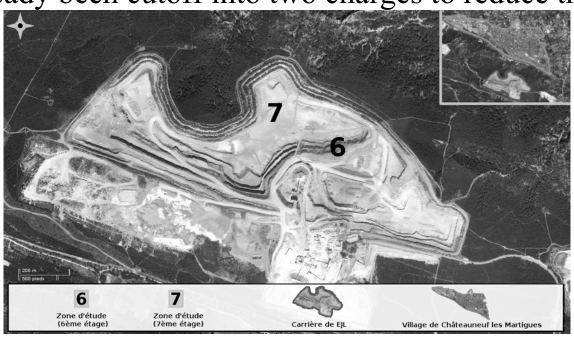
CASE STUDIES

Let's see how these theories work in the field looking at three typical case studies. The first describes the signature hole theory applied in the far field in a French quarry and the second, the theory applied in the near and far field in a significant number of quarries in the USA. The last one describes the signature hole theory combined with the de-convolution process.

CASE STUDY ONE

Chateauneuf les Martigues quarry in the south of France, data provided by TBT

The quarry is located in the south of France, north east of the city of Marseille. The village of Chateauneuf les Martigues is located at 850 m from the quarry (Figure 2) and the average vibration level was 0.9 mm/s. Even with this very low level, there were still a lot of complaints from the inhabitants. There was no low frequency identified whether in the ground vibration or in the air blast. The manager of the quarry decided to tentatively further reduce the vibration level. It was decided to use the signature hole method combined with electronic detonators to reduce vibration level, as the column of explosive had already been cutoff into two charges to reduce the charge per delay.



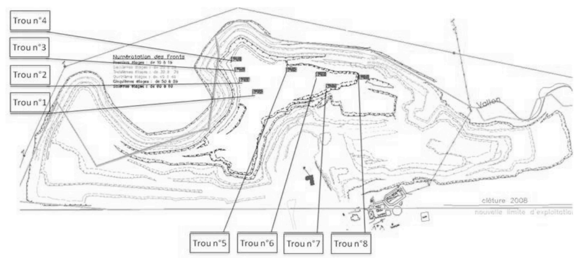
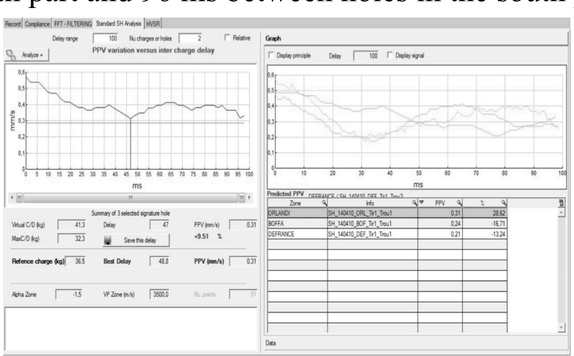


Figure 2 **Plan view of the quarry and the village / Figure 3 Signature hole location**

The first stage was to conduct signature hole measurement. A set of 8 single holes were shot in various places (Figure 3) in the pit to cover all the different geology and wave travel paths. These single holes were decked with the same inter deck delay used by the quarry.

The DNA-Blast model and the I-Blast software (Figure 4) was used to simulate the effect of inter row timing using the advanced far field signature hole module (850 m is considered as far field). Two types of timing were selected corresponding to two different sections of the pit, with 47 ms between holes in the north part and 96 ms between holes in the south part.



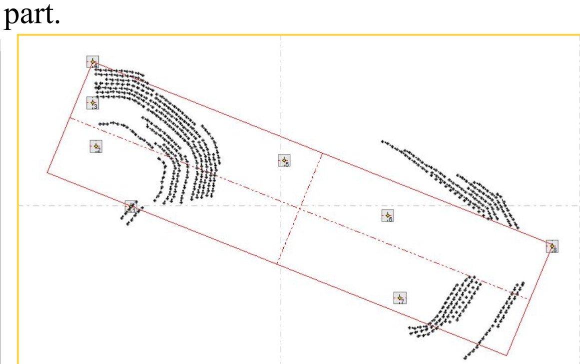
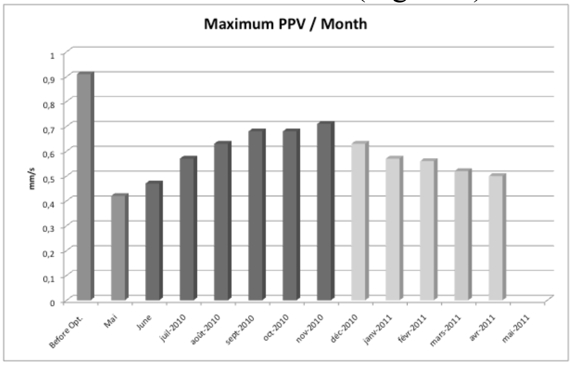


Figure 4 **I-Blast far field timing optimization / Figure 5 Electronic blasts for 6 months**

These delays provided a significant vibration level reduction of about 40%, bringing PPV from 0.9 to 0.45 mm/s and were used for the following 6 months (Figure 5).

The bench was "moving" toward the village so the vibration level started to increase (that is a normal situation). When they reached 0.7 mm/s, it was decided to conduct a second analysis and to optimize the inter deck delay.

The same process was applied, shooting a single deck instead of a single hole. According to the single deck record and I-Blast process, the inter deck delay was set to 45 ms and the inter row delay to 35 ms. Vibration moved back to 0.5 mm/s (Figure 6)



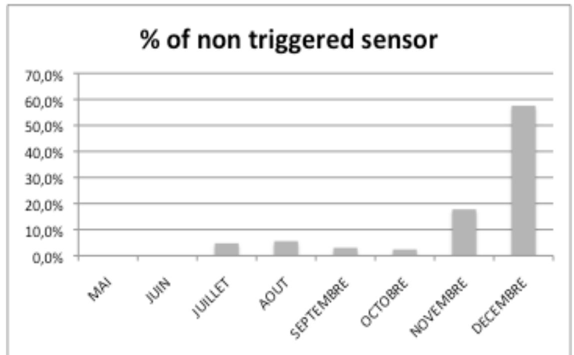


Figure 6 Vibration history during the optimization process / **Figure 7 percentages of non-triggered sensors**

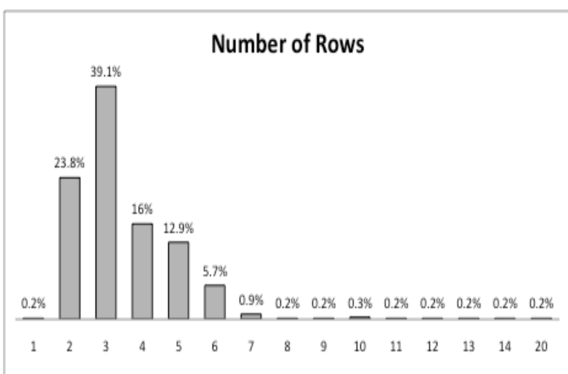
To conclude, we can say that the signature hole method in the far field, combined with electronic detonators, provides very good results. It reduces the vibration level without changing the charge per delay (Figure 6),. The number of blasts below the seismic trigger also increased considerably (Figure 7), providing a huge benefit with regard to inhabitant complaints.

CASE STUDY TWO

South Technical Services (STS) provides advanced technical services to the drilling, blasting, construction and mining industries in the U.S. STS customers in this case were mainly quarries in the East part of USA.

574 blasts over 35 sites have been realized in the USA mainly in 2010. All these blasts were shot with electronic detonators. They have been carefully simulated and optimized with the signature hole principle. Vibrations have been recorded on multiples points for each blast, which build a significant database. These data are analyzed below.

Blast configuration:



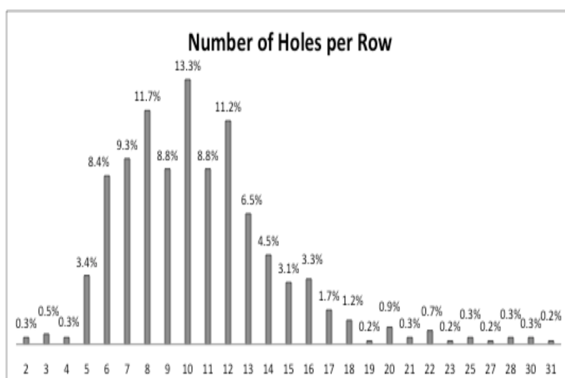


Figure 8 : Average number of rows per blast / Average number of holes per row

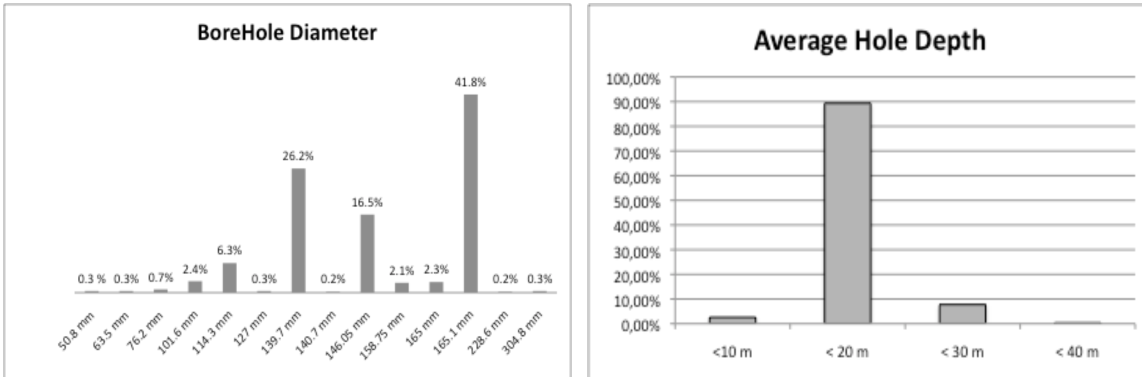


Figure 9 : distribution of borehole diameter / Average hole depth

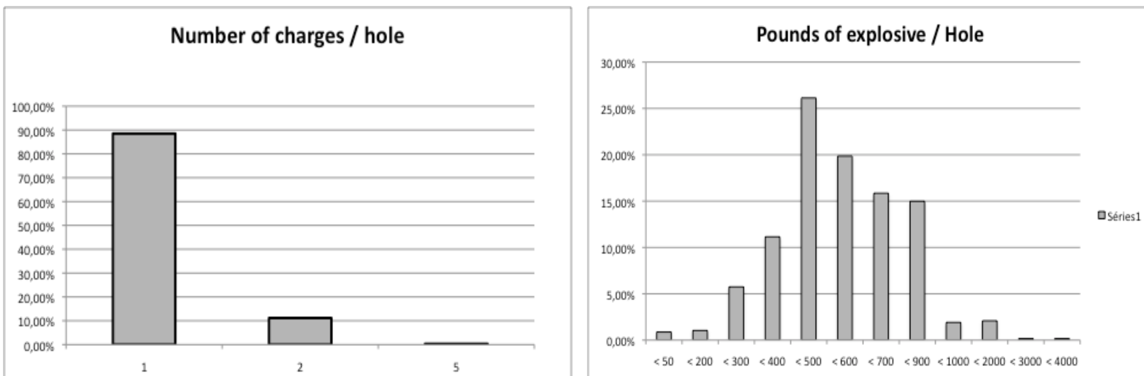


Figure 10 : distribution of number of charges per hole / pounds of explosive per hole

From that we draw the average blast configuration:

Number of rows	: 3
Number of holes per row	: 10
Borehole diameter	: 165 mm
Hole depth	: 15 – 20 m
Charge per hole	: 500 pounds

We also notice that the spectrum of these parameters is very large. The signature hole method has been applied to small shots (2 row, few holes per hole) as well to large shot (7 rows, 15 holes per row).

<u>About the optimized timing used:</u>

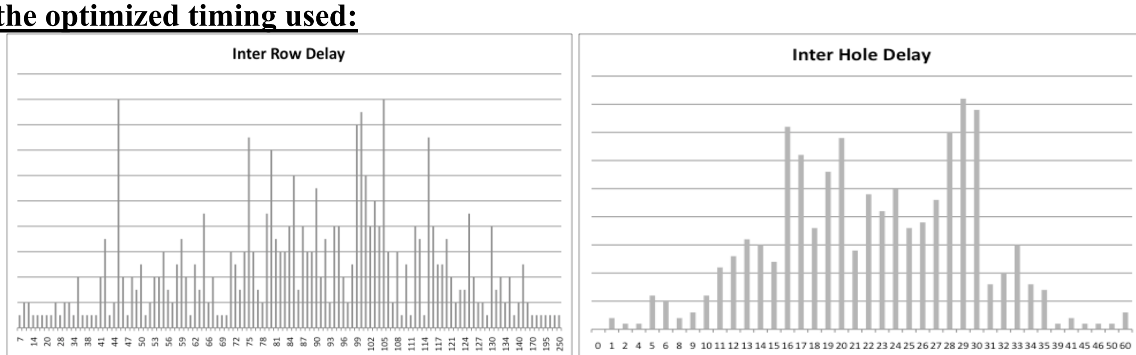


Figure 11: distribution of inter row delay / inter hole delay

Looking at figures 11, it should be noticed that there is no dominant timing. Inter hole delay varies from 1 to 60 ms and inter row delay varies from 7 to 250 ms. This makes a lot of sense as the optimized timing, based on signature hole method, is mainly a function of the signature hole itself, holes locations and the geology. They are obviously different for each blast.

We use to assume that the signature hole is intrinsically identical for a given type of hole in a given rock. This assumption is very strong and needs to be revisited when the signature hole method does not provide good results, mainly because of the geology (See next case study about the de-convolution process)

About the vibration results:

For confidentiality reasons vibration level are not disclosed.

The graph below shows the accuracy of the predicted vibration levels simulated with the signature hole method.

It should be noticed that 50 % of the blasts have been simulated with an accuracy of 10% (versus measured vibration) and 22 % of accuracy over 10% with the following results (meaning the vibration might be half what was predicted or 1/3 less than predicted).

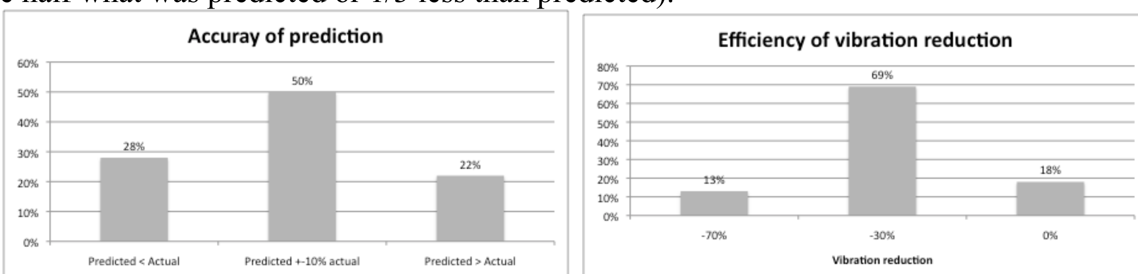


Figure 12: accuracy of predicted vibration levels / efficiency of vibration reduction

The graph below show the efficiency of vibration reduction using optimized timing provided by the signature hole principle. 69 % of the blasts shot with an optimized timing show a vibration level reduced by 30% versus standard timing. For 13%, vibration level could be reduced by 70%.

"I will say that 98% of the time, the vibration trends in the predictions are accurate. This means that if the vibration is over by 0.10 in/sec, it will always be that way. If I predict low by 0.20 in/sec, it will be low by that every time. Sometimes I will take the time to re-calibrate the model if it is critical, other times I will just accept the "error" rate knowing it is consistent every time." said John Babcok, blasting specialist at STS

<u>About the optimized timing used:</u>

The graph below (figure 13) shows the minimum inter hole delay in a shot. It should be noticed (figure 13, right graph) that in 71,7 % of the blasts, the minimum inter hole delay in below 8 ms. The 8 ms rule is definitively broken according the vibration results described in the next paragraph.

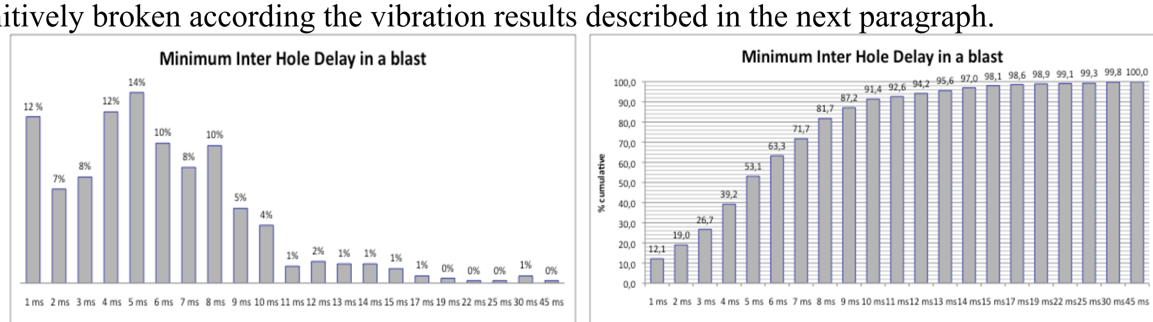


Figure 13: distribution of minimum inter hole delay in a blast

CASE STUDY THREE

South Technical Services (STS) provides advanced technical services to the drilling, blasting, construction and mining industries in the U.S. STS customers in this case were mainly quarries in the East part of USA.

The previous shot was carried out at 6-10 inches in this part of the quarry close to power lines. (Less than 200 feet). The challenge was to reduce the vibration level below 2.00 inch/s at the power lines (Figure 14). The next shot was located close to the power lines (less than 150 feet). Quarry management stipulated that STS could NOT do a signature hole. The blast configuration had to be: full column 74 foot face with 6.5 inch holes and no decking.

"*I took one of their blasts from two years ago (with digital detonators) and a seismic waveform recorded at the power lines. I entered all the data including some very detailed rock info that the quarry obtained for me. I "de-convoluted" the signature hole, based on the blast using DNA-Blast software corresponding module. I shot the next shot at the Quarry using the Derived Signature Hole Waveform and the optimized timing provided by I-Blast software*." (Figure 15)
"The derived signature waveform was picture PERFECT – I was blown away by how good it looked (AWESOME). I timed the next shot (which was the closest yet) based on the simulation, and I got a 50% reduction at double my Hertz. So, I won't be doing a signature hole at that quarry which saves me a lot of time and work." said John Babcok, blasting specialist at STS.

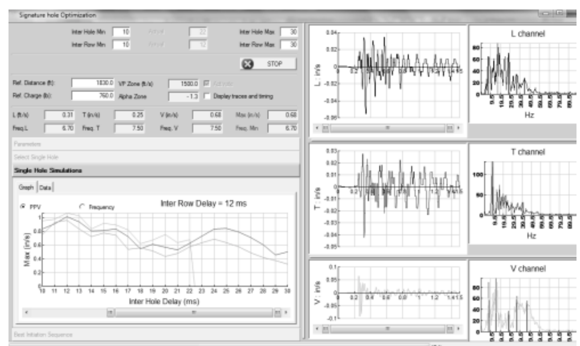


Figure 14 Top view of the power line close to the pit / **Figure 15 Screen shot of the I-Blast PPV optimization module**

Then a second shot was made, in the same area close to the previous one.

I just shot the second shot at the Quarry using the Derived Signature Hole Waveform. I re-analyzed the data using the seismograph info from the previous shot (when the readings were reduced by 50%) and the shot today the readings were reduced another 50% compared to previously, and this shot was closer with more holes.
Pretty awesome……" said John Babcok, blasting specialist at STS.

Figure 16 Shot number 1

To conclude, we can say that the signature hole method in the near field, combined with electronic detonators, and an advanced modeling capability is able to provide awesome results. It reduces the vibration level without changing the charge per delay. The signature hole can also be obtained by a de-convolution of a full blast record saving considerable time and work in the field.

CONCLUSIONS:

The signature hole method is not only an interesting theory, it works in the field. Combined with electronic detonators and advanced modeling software, it provides a huge benefit in vibration level reduction. Without changing the charge per delay, results between 30% and 70% of PPV reduction can be achieved with an accuracy of prediction of 10%.

Moreover recent developments and powerful computers allow us to obtain a signature hole record by a de-convolution from the record of a full blast. This is a great opportunity to automate timing sequence optimization by processing seismic records on a daily basis.

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