ADVANCED TECHNIQUES FOR HIGH VIBRATION REDUCTION (UP TO_75%)

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ABSTRACT: The signature hole method has been developed in the nineties, electronic delayed detonators (EDD) as well. Only since ten years, EDD have become a common initiation system and computers are powerful enough to run advanced efficient simulation models to apply this theory. This paper reviews the use of the signature hole principle through case studies. The basic principle of signature hole theory in far field is analyzed and compared to advanced principle in the frequency domain applicable in near field. The paper also analyses the de-convolution theory that allows obtaining a virtual signature hole derived from the vibration record of a full blast and can provide vibration level reduction up to 75%. Finally this paper uses case studies to demonstrate the benefit of the theory applied in the field.

1. INTRODUCTION

Today, there are several methods currently used to predict the vibration level created by a blast, at a given point. Let us review first the most frequently used, i.e. the charge per delay method and then discuss strengths and weaknesses of various signature hole methods.

2 THEORY OF VIBRATION SIMULATION

2.1 REVIEW 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 analyzing the single hole 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

2.2 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.

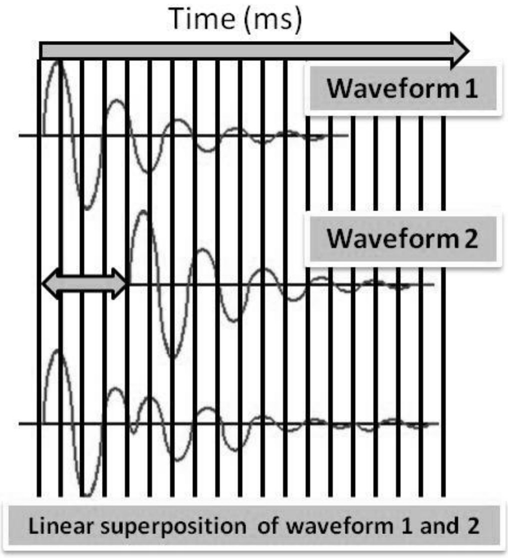


Figure 1 Signature hole method principle

<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:

$$SG(t) = \sum_{i=1}^{N} s_i(t) \quad (1) \text{ where:}$$

- $SG(t)$: 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:

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

- $S(t)$: 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 called signature hole method in the time domain as we apply linear superposition of waves recorded versus time.

2.3 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 that the signature hole has to be recorded at a distance from the blast where whatever the considered charged, the L,T,V channel recorded is the same. In another world we are far from the blast, so from the seismograph "perspective", any wave comes from the same point. We call this situation: 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 near field.

2.4 NEAR FIELD VIBRATION MODELING IN THE TIME DOMAIN

We will now deal with how we can model the vibrations in a reliable manner in 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:

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

- $S(t)$: 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 near field, as waves are coming from different direction, 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.

$$\begin{cases} SG_L(t) = \sum_{i=1}^{N} a_i (\sin(\theta) S_L(t - \Delta t_i) - \cos(\theta) S_T(t - \Delta t_i)) \\ SG_T(t) = \sum_{i=1}^{N} a_i (\cos(\theta) S_L(t - \Delta t_i) - \sin(\theta) S_T(t - \Delta t_i)) \quad (5) \text{ where} \\ SG_V(t) = \sum_{i=1}^{N} a_i S_V(t - \Delta t_i) \end{cases}$$

- 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 added of the travel time of the wave from the charge to the seismograph.

2.5 NEAR FIELD VIBRATION MODELING IN THE FREQUENCY DOMAIN

We will now deal with how we can model the vibrations in a reliable manner in 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 doesn't talk a lot 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 $F(f) = \left(\sum_{i=1}^{N} a_i \cos(2\pi f \Delta_i)\right)^2 + \left(\sum_{i=1}^{N} a_i \sin(2\pi f \Delta_i)\right)^2$ (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 point, the position of the charges and the frequency

This amplification factor will be used in such a 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 by then carrying 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 obtaining of an elementary seismic signature hole from the overall seismic signature of a blast.

3 WAVEFORM DE-CONVOLUTION:

This word means the reverse calculation of a waveform simulation of the blast from a signature hole. In another word, having a record of a full blast, it offers the capability to obtain an average signature hole of the blast. The main interest of this method is to obtain a signature hole without shooting a single hole in the pit, which is a not very pleasant for the site.
Moreover this method allows to refresh the signature hole on a continuous basis, and consequently to benefit from the 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 from the time domain that is summarized by the equation (4) or (5):

This is a system equations with p variables where p is greater than n. In a normal situation this system has no solution. Fortunately the fact that in between the first two detonations there is only on wave propagating (the beginning the first single hole) this allows finding a solution using a gauss pivot method. The same principal applies starting from the end of the global waveform. Anyway, by experience, this technique does not give a good result as any noise on the recorded waveform is amplified by the pivot method and consequently provides a result that does not have a lot of sense.

Once again, the frequency domain is providing an elegant solution for this problem.
Equation (6) $SG(f) = F(f)S(f)$ can be written as follow: $S(f) = \frac{SG(f)}{F(f)}$ (9)

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

4 CASE STUDIES:

Let’s see how these theories work on the field looking at two typical case studies. The first one describes the single hole theory applied in far field and the second the theory applied in near field combines with the de-convolution process.

4.1 CASE STUDY ONE:

Chateauneuf les Martigues quarry in the south of France, provided by TBT
The quarry is located in the south of France, north east Marseille city. 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 reduce more the vibration level. As the column of explosive has been already cutoff into two charges to reduce the charge per delay, it was decided to use the signature hole method combining with electronic detonators to reduce vibration level.

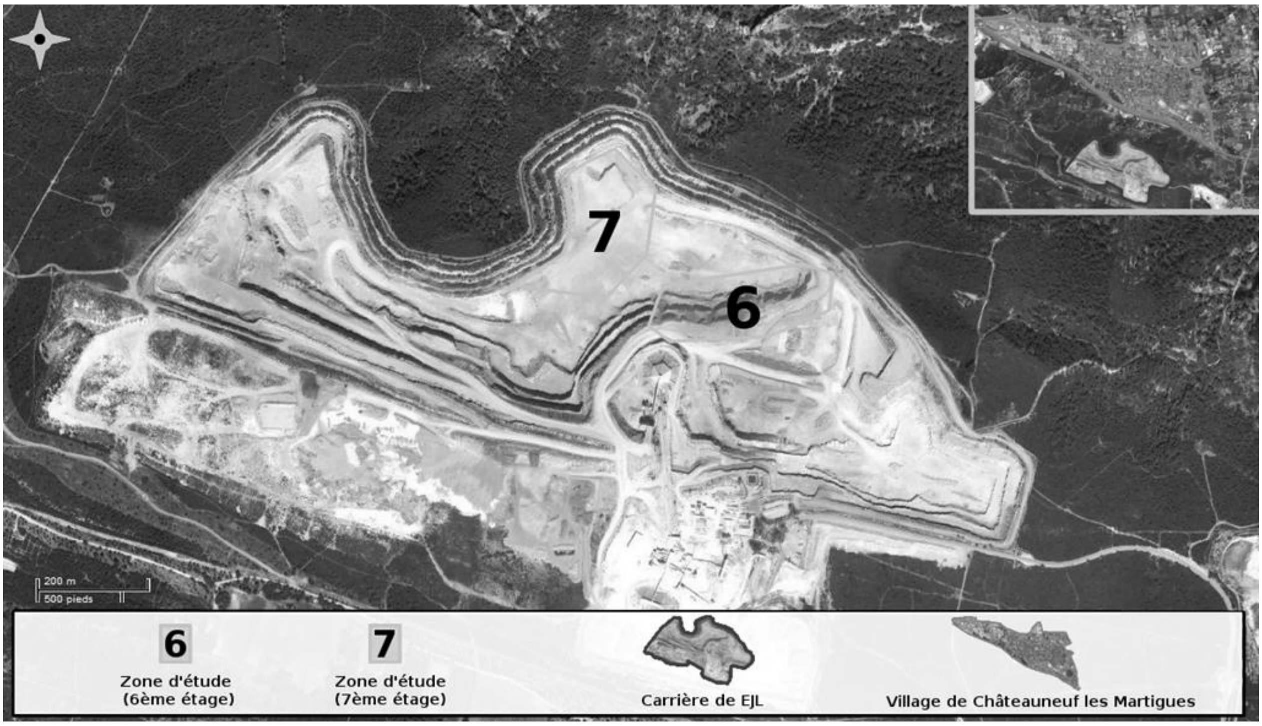


Figure 2 Plan view of the quarry and the village

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 different geology and wave travel paths. These single holes were decked with the same inter deck delay used by the quarry.

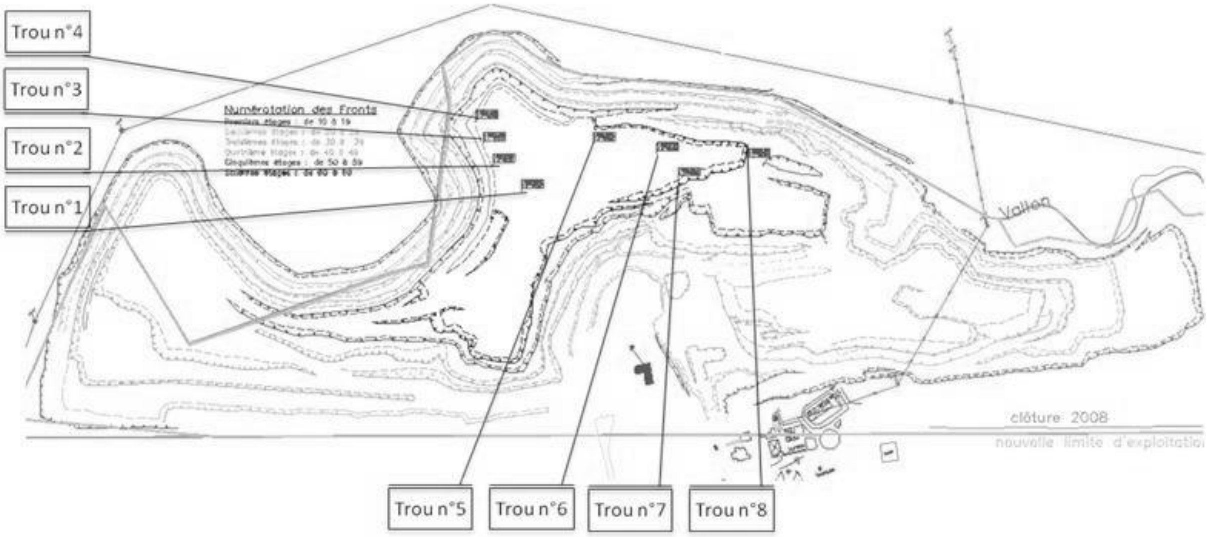
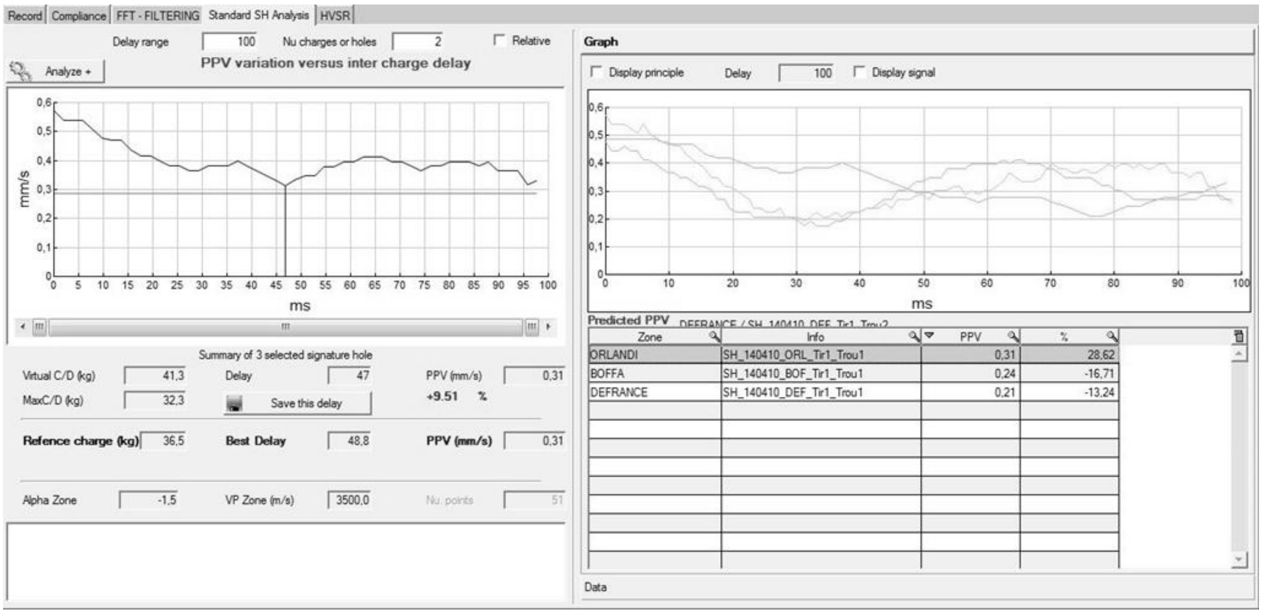


Figure 3 Signature hole location

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 at two different section of the pit. 47 ms between holes in the north part and 96 ms between holes in the south part.



Delay range 100
Nu charges or holes 2
☐ Relative

Summary of 3 selected signature hole

Virtual C/D (kg) 41,3
Delay 47
PPV (mm/s) 0,31
MaxC/D (kg) 32,3
+9.51 %

Refence charge (kg) 36,5
Best Delay 48,8
PPV (mm/s) 0,31

Alpha Zone -1,5
VP Zone (m/s) 3500,0
Nu. points 51

☐ Display principle
Delay 100
☐ Display signal

Predicted PPV DEFRANCE / SH_140410_DEF_Tir1_Trou2

Zone	Info	PPV	%
ORLANDI	SH_140410_ORL_Tir1_Trou1	0,31	28,62
BOFFA	SH_140410_BOF_Tir1_Trou1	0,24	-16,71
DEFRANCE	SH_140410_DEF_Tir1_Trou1	0,21	-13,24

Figure 4 **Screen shot of I-Blast far fiel timing optimization**

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 next 6 months (Figure 5).
As the bench was “moving” toward the village 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.

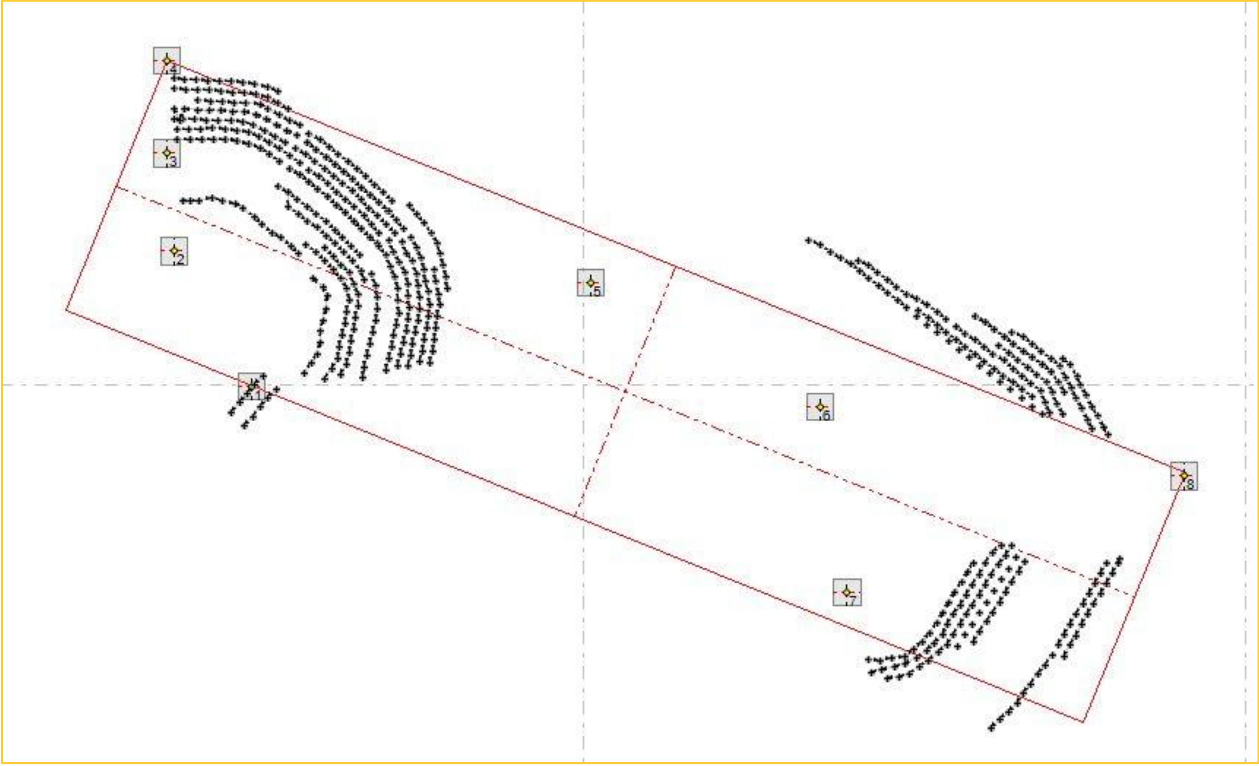


Figure 5 **Electronic blasts during 6 months**

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

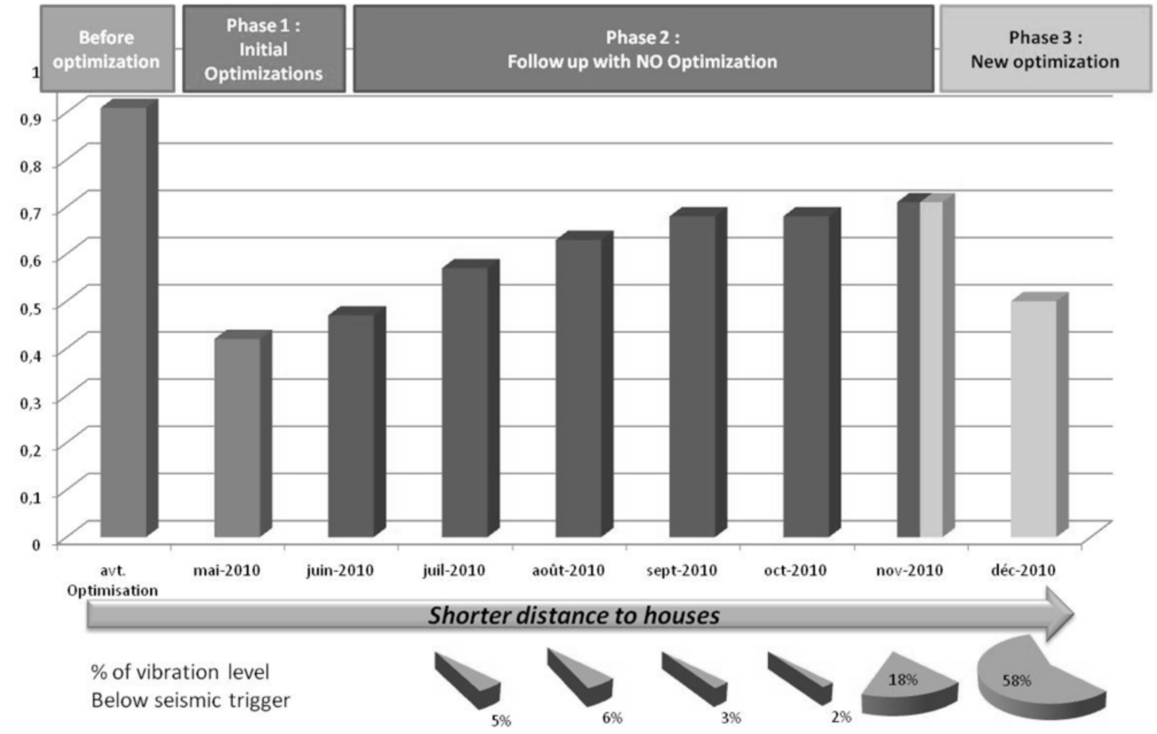


Figure 6 Vibration history during optimization process

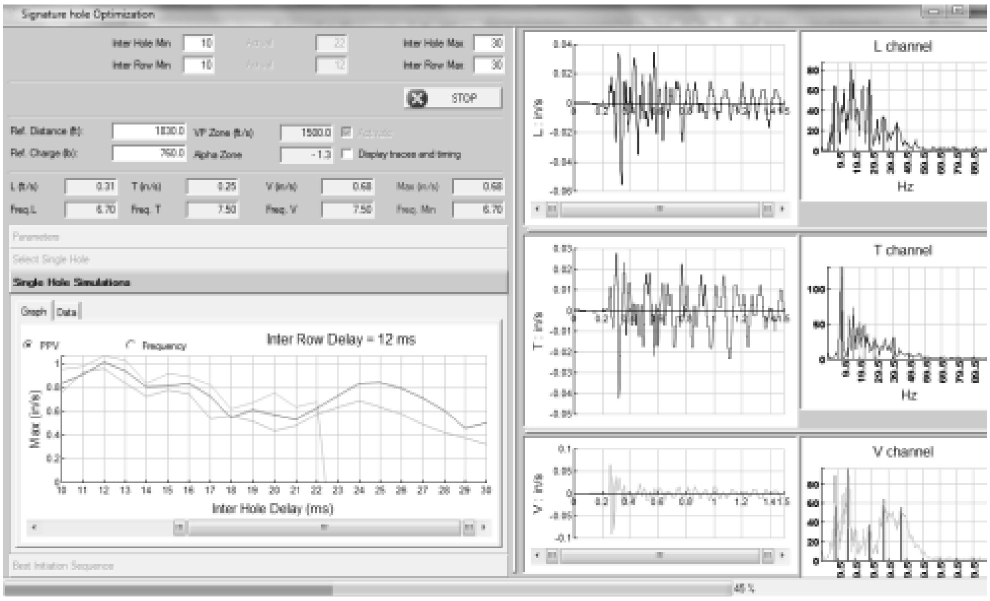
As a conclusion, we can say that the signature hole method in far field, combined with electronic detonators, provides very good results. It allows reducing vibration level without changing the charge per delay. The number of blast below the seismic trigger also increased a lot (Figure 6), providing a huge benefit as regard inhabitant complaints.

4.2 CASE STUDY TWO:
Culpeper quarry, USA, provided by STS
STS provides advanced technical services to the drilling, blasting, construction and mining industries in the U.S. STS customer in this case was a quarry in Virginia. Previous shot was done at 6-10 inches in this part of the quarry close to power lines. (less than 200 feet)

The challenge was to reduce vibration level below 2.00 inch/s at the power lines (Figure 7). 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 got 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 8)
*"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 9)

Figure 7 Top view of the power line close to the pit



Inter Hole Min 10 Actual 22 Inter Hole Max 30
Inter Row Min 10 Actual 12 Inter Row Max 30
Ref. Distance (ft): 1830.0 VP Zone (ft/s) 1500.0 ☑ Activate
Ref. Charge (lb): 750.0 Alpha Zone -1.3 ☐ Display traces and timing
L (in/s) 0.31 T (in/s) 0.25 V (in/s) 0.68 Max (in/s) 0.68
Freq.L 6.70 Freq. T 7.50 Freq. V 7.50 Freq. Min 6.70
Inter Row Delay = 12 ms

Figure 8 Screen shot of I-Blast PPV optimization module

Then a second shot was done, 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% from before and this shot was closer and more holes.
Pretty awesome……” said John Babcok, blasting specialist at STS.

Figure 9 **Shot number 1**

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

5 CONCLUSIONS:

The signature hole method is not only a nice 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.

Moreover recent developments and powerful computers allow us to obtain a signature hole record by a de-convolution from a 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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