Vibration Control Using a Smartphone- Accuracy, Validation and Potentialities

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Abstract

Mine blasting is directly associated with ground vibration. If these affect critical structures (buildings pit walls, etc.) they must be mitigated to reduce the environment and social impacts. Vibration monitoring and control is one of the most important procedures in blasting because it will impact short and long term incidents associated with this blast effect. Technology moves ever forward, and today we have personal devices that are equipped with an array of sensors, for that reason the authors decided to investigate the possibility of using a personal device to do vibration control. This case study compares the same blast measured with a traditional seismograph and a smartphone. To validate this new methodology, attenuation laws were built with data from a traditional seismograph and a smartphone application. Predictions were also made prior to a set of blasts. Residual analysis was used for data validation from the two different sources. From the performed analysis, to prove the validity of this new methodology, the normality tests for statistics residues analysis proves that it is possible to infer that the model has a null residual mean and a small residual error. The achieved results show the accuracy of these devices, the authors pretend to show the potential of this equipment and open a completely new door for vibration analysis.

Introduction

The majority of raw materials are produced using explosives. Civil works, buildings and roads are dependent on explosives and rock blasting. Even the population daily food supply is dependent on the application of explosives for the production of fertilizers, metals for agriculture equipment or fishing boats (Konya & Walter, 1990). Besides all the effective energy generated by an explosive to produce the desired results after a blast (fragmentation and material movement), there might be remaining energy that is wasted as ground vibrations, air blast, fly rocks, dust and noxious gases (Bhandari, 1997).

Community complains are, in the most part, associated with vibration and damage produced by blasts, it's the responsibility of the mining or blasting engineer to control and prevent excessive vibrations when designing the blast plan (Oriard, 1999). Several regulations were developed in order to establish a relationship between the structure damages, ground particle movement velocities (PPV - peak particle velocity) and the factors that most affect vibration: distance from the blast; explosive charge per delay and vibration frequency (Hustrulid, 1999).

Every engineering projects that can produce ground vibration near communities or sensible structures is submitted to studies of terrain attenuation laws and is constantly controlled during all the activities of the project (Miranda, Leite, Jesus, & Sobral, A New Blast Vibrations Analysis Methodology, 2017). This article presents a primordial study on how the new technologies can be used to assist the blast design in terms of ground vibration control and prediction, more specific, the use of a smartphone accelerometer to estimate and manage blast vibrations.

Background

Blast Vibrations

Dowding, in 1985, refers that blasting waves can be considered as compressive, shear and surface which can be subdivided into body waves (with the capacity to travel inside the rock and soil) and surface waves (on ground surface). In one hand, P and S waves (classifyed as body waves) are characterized by its compressive and distorcional behaviour (respectivly), on the other hand the R waves (Raylaigth waves), are transmited at long distances from the blast, moving the terrain in an eliptical vertical plane - Figure 1.

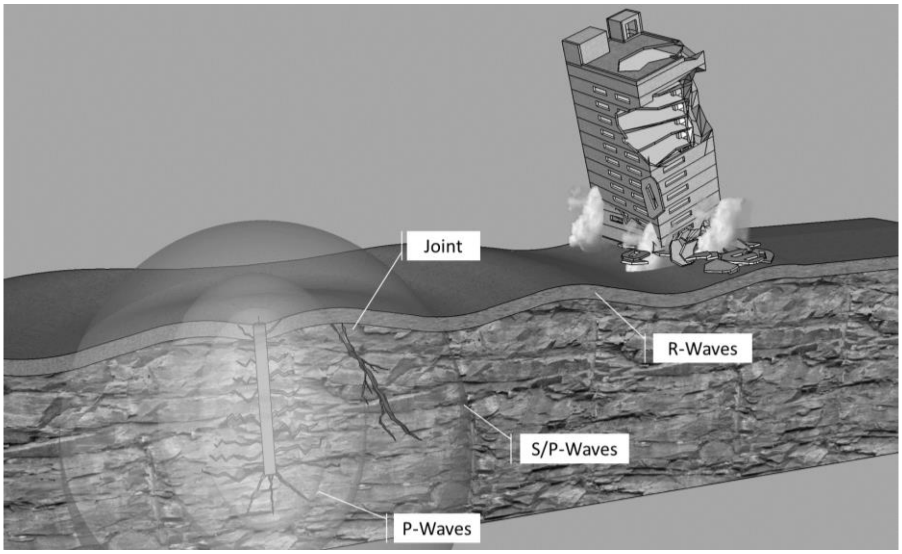


Figure 1. Seismic wave behavior

PPV is the main parameter to evaluate vibrations, comparatively to the possible damages that it might create (Hammon *et al*., 1990). In order to simplify blast vibration behavior calculations and studies, it is acceptable to compare it to seismic phenomena (sine waves) (Siskind, 2005) as represented by Equation 1.

$$\boldsymbol{u(x,t) = u_{max} \cdot \sin\left(\frac{2\pi \cdot f}{c} \cdot x + 2\pi \cdot f \cdot t\right)} \qquad \textbf{Equation 1}$$

Where:
u = **Displacement (ft) (m)**
f = **Propagation frequency (Hz)**
c = **Propagation velocity (in/s) (m/s)**
t = **Time (s)**

Regression Model

The modern interpretation of a regression, refers to the dependence of a variable (dependent variable) in respect to one or more variables (explicative variables), with the goal of estimating the average value of a population (Novales Cinca, 1993), referred by Miranda & Leite in "*A new Approach to 3D Modeling of Blast Free Faces* (2017).

Mathematically, a model, with *n* variable, is defined by Equation 2:

$$\boldsymbol{Y_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + u} \qquad \textbf{Equation 2}$$

Where:
β = Linear coefficients
X= Explicative variables
Y= Dependent variable
u = Residue: Stochastic perturbation or Stochastic error term (Gujarati & Porter, 2010, p. 40).

To determine the linear coefficients, that better adjust to our problem, is acceptable to use a technic of minimum least squares. However, using the least squares methodology, is known that a single outlier can generate a significant distortion due to the weight of the squaring of its distance to the regression model (Hamming, 1973). Some alternative propositions can be used to minimize the effect of outliers (Miranda, Validação de Modelos Lineares: Uma Análise Residual, 2016).

Attenuation law

Several affecting factors are associated with blast vibration and they can be controllable or un-controlled. Situations like blast geometry, stemming, priming, type and the amount of explosives, rock characteristics, blast direction, distance to structures and even meteorological conditions (in the case of air blast), are the main influences on vibration results. Since it is extremely complex to define the influence of each issue into a single equation or function (Bhandari, 1997), empirical approaches, relating registered PPV's with distances and charges, has been the preferred technique for a long time (since Morris - 1950 up to Dowding - 1985) to predetermine the blast charge limits in order to minimize vibration effects.

The prediction of this phenomena is a very interesting process which allows the mining or blasting engineer to control, predict and mitigate safety and environmental issues before a blast, performing the necessary actions (Miranda, Leite, Jesus, & Sobral, 2017). To better describe the blast vibration effects in a heterogenic terrain (affected by the referred factors), the best procedure is to estimate it, carrying out an experimental blast, using existent vibration data to build a prediction model, usually called – Attenuation Law (Figure 2).

The vibration attenuation is represented by Equation 3.

$$\dot{u} = a\left(\frac{R}{W^{1/2}}\right)^{m} \qquad \textbf{Equation 3}$$

Where:
$\dot{u}$ = Particle velocity (in/s) (mm/s)
R = Distance from blast (ft) (m)
W = Maximum instantaneous charge (lb) (kg)
a, m = Terrain influence factors (linear coefficients)
$\frac{R}{W^{1/2}} = SD$ = Square root scaled distance

Square root scaled distance is a function of the distance (from the blast to the PPV's measurement point and the maximum instantaneous charge) and is used to compare different field information (different distances and charges) and predict the decay of peak particle velocity. The use of the square root (and not cubic root) is based on the observation that the diameter (of a cylinder charge - Borehole) is proportional to the square root of the charge (Dowding, 1985, p. 28).

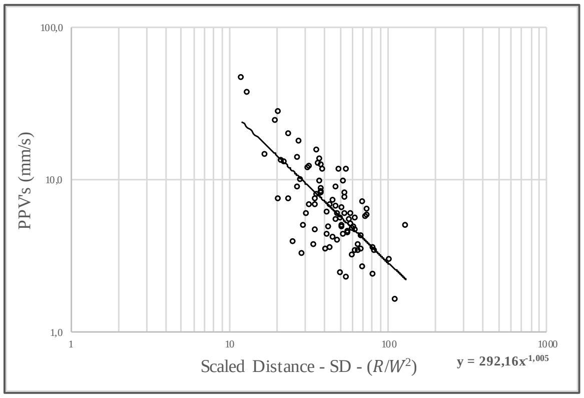


Figure 2. PPV based attenuation law (adapted from Miranda, Leite, Jesus, & Sobral, 2017)

Seismograph features

There are several systems for the interpretation of ground movements. In blasting, the most widely used vibration sensors are the electromagnetic transducers that are based on the emission of an electrical tension proportional to the vibration velocity of the ground (Jimeno, Jimeno, & Carcedo, 1995). A magnetic mass suspended in a geophone's interior (mobile coil), remains fixed during the ground movement and the relative movement between it and the case (attached to the ground), produces electrical signals (Sanchidrián & Muñiz, 2000). Modern equipment, uses a digital recorder to register the variation of the electrical signal over time, identifying the peak levels (Bhandari, 1997).

Smartphone characteristics and accelerometer

This investigation was based on the technology present on the iPhone 5S, announced and released in 2013 (Lashinsky, 2012). Some of the characteristics of this equipment are presented on Table 1.

Table 1. Phone Characteristics (Apple, 2016)

Body	Dimensions	123.8 x 58.6 x 7.6 mm
	Weight	112 g
Display	Type	LED-backlit IPS LCD, capacitive touchscreen, 16M colors
	Size	4.0 inches
	Resolution	640 x 1136 pixels
Platform	OS	iOS 7, upgradable to iOS 10.3.3
	Chip	Apple A7
	CPU	Dual-core 1.3 GHz Cyclone (ARM v8-based)
Memory	Internal	16/32/64 GB, 1 GB RAM DDR3
Sensors		Fingerprint (front-mounted), accelerometer, gyro, proximity, compass
Battery	Stand-by	Li-Po 1560 mAh battery (5.92 Wh)

The authors decided to investigate the results of a vibration analysis using the accelerometer LIS331DL (produced by STMicroelectronics). This electronic element is a low-voltage 3-axis digital output linear MEMS accelerometer housed in a LGA package (STMicroelectronics). This accelerometer is able to register accelerations between ±2g and ±8g with an output data rate of 100Hz to 400Hz and operates on a temperature range from -40ºC/-40ºF to +85ºC/185ºF.

Mathematical data Treatment

A particle acceleration can be understood as a velocity variation of a particle, this means, if one particle suffers any kind of velocity variation it is suffering an acceleration (Halliday, Resnick, & Walker, 2008). Therefore, the instantaneous acceleration (or simply acceleration) is given by Equation 4:

$$\boldsymbol{a = \frac{d_v}{d_t}}$$ **Equation 4**

This way, the particle velocity can be obtained by the acceleration integration.

Indefinite Integral

There is one difference between the calculation of a defined integral $\int_a^b f(x)dx$ and an indefinite integral which can be defined in the way $\int_a^x f(x)dx$. The first situation gives us a number (that can be interpreted as an area), the second one generates a table of numbers (Hamming, 1973).

There are several formulae for the calculation of indefinite integrals. *Hamming* (1973) gives us some of these options. The authors quote, the widely used, *Simpson's* formulae (Equation 5):

$$\boldsymbol{y_{n+1} = y_{n-1} + \frac{h}{3}(y'_{n-1} + 4y'_{n} + y'_{n+1})}$$ **Equation 5**

Where h, is the step chosen for the sample gathering.

Smartphone Seismograph App

O-Pitblast developed an app, using Swift 3 and Xcode 8. The algorithm constantly registers the acceleration and stores the last seconds of the measurement. When the acceleration reaches the trigger limit, the algorithm starts storing the data during a certain time that can be defined by the user. A numerical integration is applied to the acceleration data to obtain the PPV data (Simpson's method, for example, has an associated error in the order of $0.01 \times h^5$), and the highest value is gathered in each of the axes.

Casing Characteristics

An initial prototype was developed in order to attach the phone into the ground and register its movement (Figure 3). The structure was built from aluminum, composed by four aluminum legs, to be buried into the ground, and a flat platform with a Dual Lock 3M Velcro fixing the equipment.

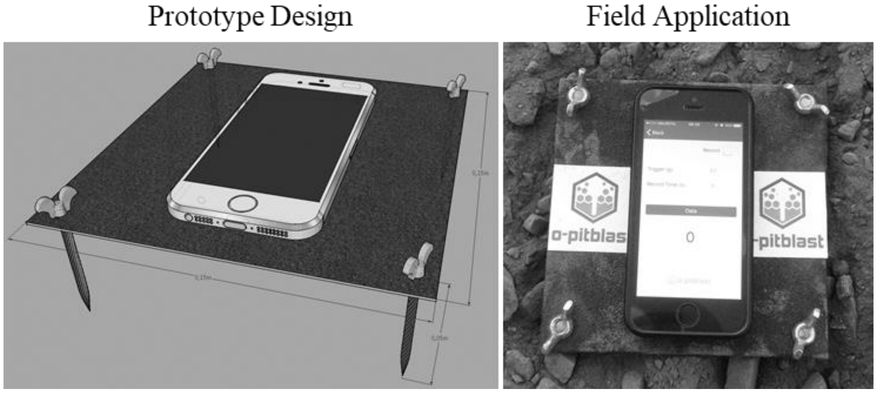


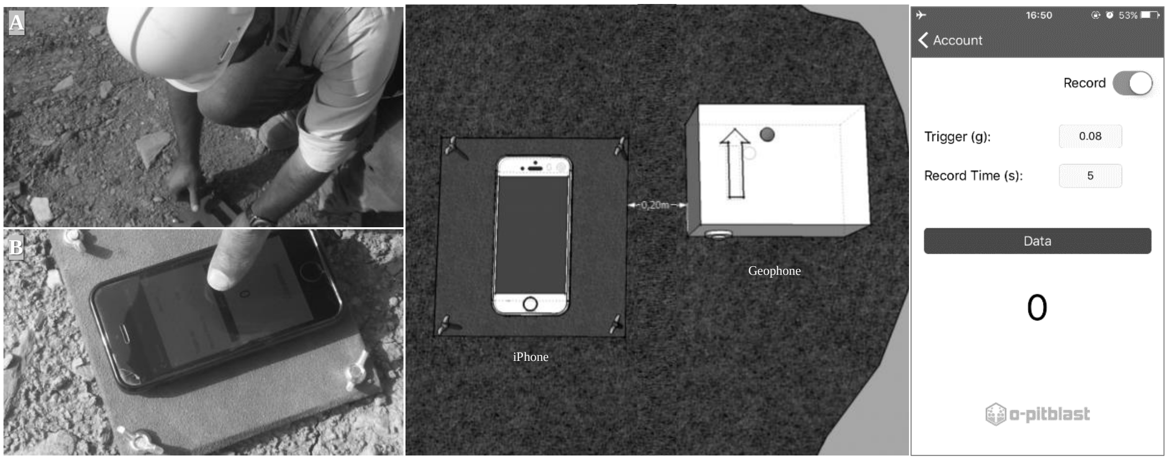
Figure 3 - Prototype design and application

Field Application

The procedure carried out in this experiment is composed by several steps. Since the authors are proving the use of a smartphone to build an attenuation law (in comparison with a usual seismograph) the first step was to get a standard triaxial geophone to be the comparison point. The used geophone (Vibracord DX System) with capacity of recording 2048 S/s from a frequency range of 1Hz to 350Hz. The aluminum structure was compressed in to the ground, ensuring a perfect coupling between the two elements (Figure 4). A total of six blasts were accompanied using the phone structure in conjunction with the buried geophone (20 cm / 7,87 in away). From each blast, MIC (Maximum Instantaneous Charge), distance to the measurement point and both measurements from the phone and seismograph were recorded.

A minimum trigger level of 0,08g and a record time of five seconds where defined in the phone application settings.

Since the expected vibration was under 1,0 g ($9,81 m/s^2$), the smartphone structure was spiked on the ground, at a distance of less that 3,05 meters (10 feet) from the nearest building in agreement with the ISEE standards (ISEE, 2015).

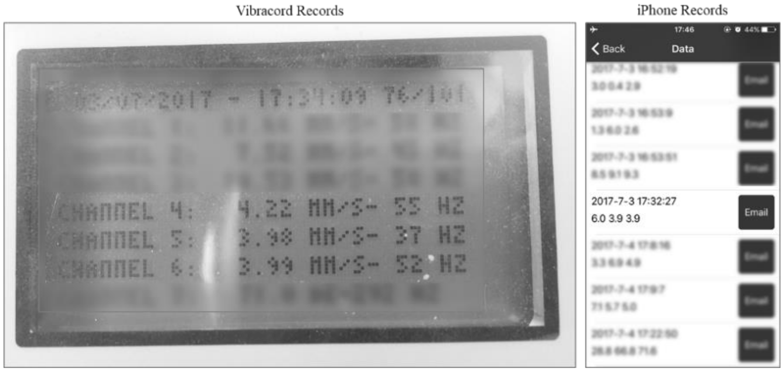


Record
Trigger (g): 0.08
Record Time (s): 5
0

Figure 4 - Installation of the phone on field and App Settings

Results analysis

The main objective of this research was not to replace a seismograph in a daily monitoring procedure but to test the use of a smartphone in the process of building an attenuation law. However, in order to prove that a comparison between the two equipment's was made. Table 2 presents the obtained values from the two procedures and Figure 5 shows one example of the measurements given by both instruments. Another example of the behavior over time of the vibration waves can be observed on Figure 6 showing a direct relation between the two signals.


Vibracord Records

```
CHANNEL 4:   4.22 MM/S- 55 HZ
CHANNEL 5:   3.98 MM/S- 37 HZ
CHANNEL 6:   3.99 MM/S- 52 HZ
```

iPhone Records

2017-7-3 17:32:27
6.0 3.9 3.9

Figure 5 – Vibracord® Measurements vs. Smarphone Measurements

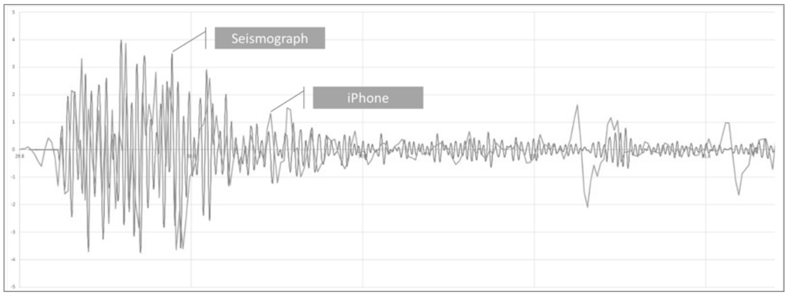
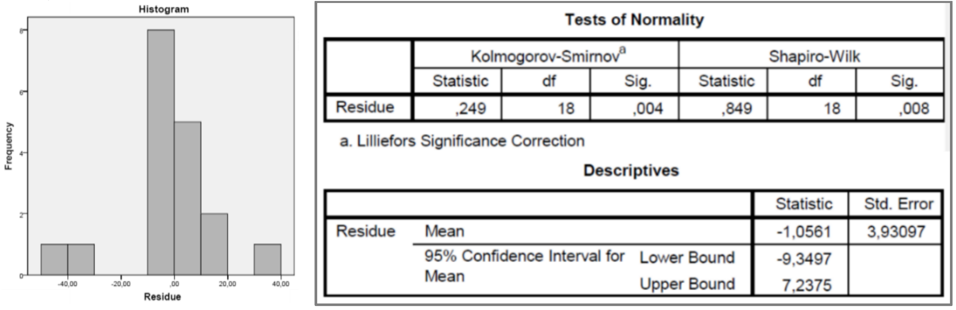


Figure 6. Seismograph behavior over time (Seismograph vs. Smartphone)

Table 2 - PPV Measurements

Vibration Information					
Smartphone			Seismograph		
PPV Horizontal	PPV Transversal	PPV Vertical	PPV Horizontal	PPV Transversal	PPV Vertical
24 mm/s	42,6 mm/s	52,7 mm/s	33,37 mm/s	48,62 mm/s	33,73 mm/s
6 mm/s	3,9 mm/s	3,9 mm/s	4,22 mm/s	3,98 mm/s	3,99 mm/s
28,8 mm/s	66,8 mm/s	71,6 mm/s	61,62 mm/s	32,07 mm/s	56,79 mm/s
7,7 mm/s	8,3 mm/s	5,7 mm/s	6,51 mm/s	10,27 mm/s	5,88 mm/s
1,1 mm/s	3 mm/s	2,3 mm/s	42,76 mm/s	3,15 mm/s	2,04 mm/s
3,8 mm/s	5,3 mm/s	8,8 mm/s	6,04 mm/s	5,04 mm/s	5,23 mm/s

When analyzing the residuals between the two sources it is possible to observe a slight normal distribution tendency (Figure 7)



Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Residue	,249	18	,004	,849	18	,008

a. Lilliefors Significance Correction

Descriptives

			Statistic	Std. Error
Residue	Mean		-1,0561	3,93097
	95% Confidence Interval for Mean	Lower Bound	-9,3497	
		Upper Bound	7,2375	

Figure 7. Residuals Analysis and Normality Tests and Statistic Descriptive (SPSS output)

Analyzing the normality test, the data shows a certain tendency to be validated. P-Value presents a movement demonstrating a predisposition to normality (Shapiro-Wilk moving to 5%) - Figure 7. This is not sufficient to prove the normality of the data, however it is indicative that it follows that tendency (more tests need to be done). Also, the zero is contained within the confidence interval.

In the next phase, the results of the attenuation law using both methodologies were compared. Figure 8 shows the attenuation laws generated in the three directions of measurement.

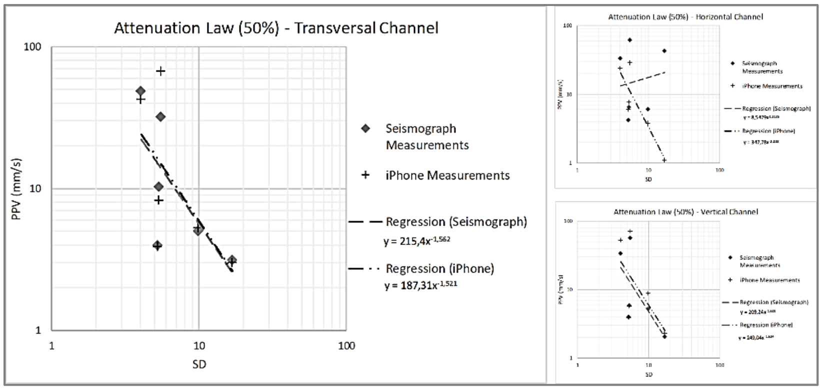
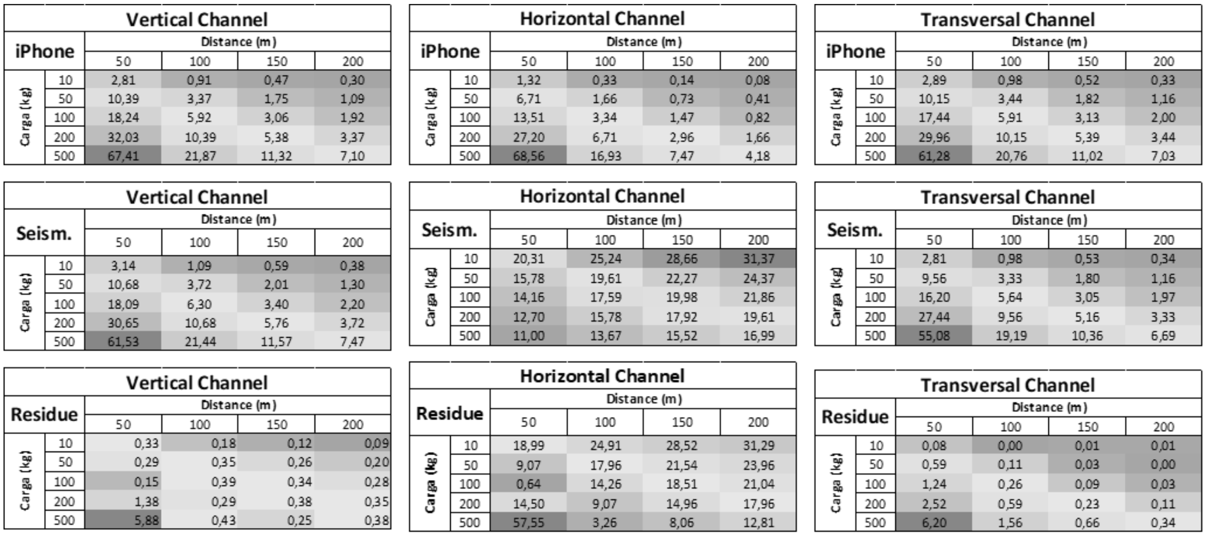


Figure 8 - Attenuation Law – Transversal, Horizontal and Vertical (Phone and Seismograph)

The reader can observe a very interesting similitude between the two sets of data. The differences observed in the individual measurements (PPV's) are absorbed by the linear regression (based on the minimization of the square residue) and a quite accurate attenuation law was achieved.

Some comments must be made in relation to the attenuation law generated with the horizontal measurements. A presence of an outlier was noticed on the seismographs measurements which turn out to be an issue with the definition of the attenuation law for this situation. However, the behavior of the smartphone seismograph remains constant. The reason of this abnormal value can be justified by a possible problem on the fixation of the seismograph to the ground (human error/application error) or in can be related with the charge/distance prediction tables (Table 3) some interesting findings appear when comparing the values of each channels.

Table 3 - Charge vs. Distance Tables (associated residues)



Vertical Channel					
iPhone		Distance (m)			
		50	100	150	200
Carga (kg)	10	2,81	0,91	0,47	0,30
	50	10,39	3,37	1,75	1,09
	100	18,24	5,92	3,06	1,92
	200	32,03	10,39	5,38	3,37
	500	67,41	21,87	11,32	7,10

Horizontal Channel					
iPhone		Distance (m)			
		50	100	150	200
Carga (kg)	10	1,32	0,33	0,14	0,08
	50	6,71	1,66	0,73	0,41
	100	13,51	3,34	1,47	0,82
	200	27,20	6,71	2,96	1,66
	500	68,56	16,93	7,47	4,18

Transversal Channel					
iPhone		Distance (m)			
		50	100	150	200
Carga (kg)	10	2,89	0,98	0,52	0,33
	50	10,15	3,44	1,82	1,16
	100	17,44	5,91	3,13	2,00
	200	29,96	10,15	5,39	3,44
	500	61,28	20,76	11,02	7,03

Vertical Channel					
Seism.		Distance (m)			
		50	100	150	200
Carga (kg)	10	3,14	1,09	0,59	0,38
	50	10,68	3,72	2,01	1,30
	100	18,09	6,30	3,40	2,20
	200	30,65	10,68	5,76	3,72
	500	61,53	21,44	11,57	7,47

Horizontal Channel					
Seism.		Distance (m)			
		50	100	150	200
Carga (kg)	10	20,31	25,24	28,66	31,37
	50	15,78	19,61	22,27	24,37
	100	14,16	17,59	19,98	21,86
	200	12,70	15,78	17,92	19,61
	500	11,00	13,67	15,52	16,99

Transversal Channel					
Seism.		Distance (m)			
		50	100	150	200
Carga (kg)	10	2,81	0,98	0,53	0,34
	50	9,56	3,33	1,80	1,16
	100	16,20	5,64	3,05	1,97
	200	27,44	9,56	5,16	3,33
	500	55,08	19,19	10,36	6,69

Vertical Channel					
Residue		Distance (m)			
		50	100	150	200
Carga (kg)	10	0,33	0,18	0,12	0,09
	50	0,29	0,35	0,26	0,20
	100	0,15	0,39	0,34	0,28
	200	1,38	0,29	0,38	0,35
	500	5,88	0,43	0,25	0,38

Horizontal Channel					
Residue		Distance (m)			
		50	100	150	200
Carga (kg)	10	18,99	24,91	28,52	31,29
	50	9,07	17,96	21,54	23,96
	100	0,64	14,26	18,51	21,04
	200	14,50	9,07	14,96	17,96
	500	57,55	3,26	8,06	12,81

Transversal Channel					
Residue		Distance (m)			
		50	100	150	200
Carga (kg)	10	0,08	0,00	0,01	0,01
	50	0,59	0,11	0,03	0,00
	100	1,24	0,26	0,09	0,03
	200	2,52	0,59	0,23	0,11
	500	6,20	1,56	0,66	0,34

Limitations

Besides the good results presented until this point, the authors feel the need to point out some limitations associated with this research and mention that this document is the first on a series articles testing this new technology. Even though potential normal distribution on the residual data evaluated was obtained, there is the **need to continue testing** and analyze other type of blasts at different distances, MIC, different terrains, frequencies, smartphones from the same model and other smartphone models. The sample rate of a normal seismograph can be from 512 to 65,536 S/s (Instantel, 2016), and is known that the ISEE Digital Sampling Rate required is at least 1000 S/s (Performance Specifications For Blasting Seismographs, 2016) though, due to smartphone limitations, **a sample rate of 100 S/s was used**. However, the authors reiterate that this methodology doesn't have the intention to replace a seismograph but rather to develop a procedure and a new method that can produce accurate attenuation laws.

Conclusion

This research intends to show an under-explored area within the subject of vibration control and analysis. It has been proven that it is possible to build an attenuation law using ordinary equipment such as smartphones. The authors believe that further studies will have to be carried out to ensure the correct functioning in all areas that involve rock blasting. The errors and differences associated with the values obtained on the field, between the seismograph and the smartphone, were not relevant when calculating the regression line by minimum least squares. It is believed that applying the methodology of Absolute Minimum Residues (Miranda, Leite, Jesus, & Sobral, A new Approach to 3D Modeling of Blast Free Faces, 2017) more accurate values will be obtained. The developed prototype structure was proved to be reliable since it was there is a similarity between the behavior of the two datasets coming from different equipment's. Despite the results that were presented, there is an obvious necessity to continue this research in order to find out if it can fulfil the ISEE specifications. The authors think that there is an big potential, and that alone, justifies the continue research going forward.

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