Vibration assessing model: comparison between methods

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Abstract

The aim of blasting operations is rock fragmentation. It provides an appropriate rock material granulation or size that is suitable for loading and transportation. However, the blasting process and usage of explosives remain a potential source of numerous human and environmental hazards. The aim of this paper is, first of all, to provide models (and models comparison) concerning one of the major environmental issues related to blasting operations in mining and civil engineering projects: ground vibration propagation. The study displays an assessment of ground vibrations caused by blasting experiments at a whinstone quarry. The vibration source is the blasting of a fixed quantity of explosive burden (200 Kg of an Ammonium Nitrate Slurry Watergel – Tutagex 110, fragmented in 8 different parallel blast holes with a fixed 2 meter spacing). The primary goal of this study was to estimate the peak particle velocity (PPV) of the vibration, in order to protect the dwelling area adjacent to the quarry. Based on the data obtained from field measurements, a new equation was proposed: to achieve this objective we use geostatistical modelling, the branch of statistics that studies the phenomena that are developed on space-based, starting from the information derived from the sampling. The decision to describe the phenomenon with geostatistical modelling stems from having a limited number of samples and a vibration source difficult to repeat, which makes the geostatistics suitable for this purpose. In fact, it is often used to study phenomena characterized by a limited availability of samples. The final goal is the comparative analysis between the results obtained by the geostatistical equation and common empirical predictors currently used in blasting practice. The analysis of the comparison between these two approaches shows that the geostatistical tool seems to be suitable to the purposed scope.
Keywords: geostatistics, vibrations, quarries, blast.

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1 Introduction

The purpose of blasting operations is rock fragmentation. It provides appropriate rock material granulation or size that is suitable for loading and transportation. The blasting process and usage of explosives, however, remain a potential source of numerous human and environmental hazards. Singh and Singh [1] indicate that fragmentation accounts for only 20-30% of the total amount of explosive energy used. The remainder of the energy is wasted away in the form of ground vibrations, air-overpressure and flyrock. All of them can, under some circumstances, cause damage to structures nearby and, apart from this, be the source of permanent conflict with inhabitants who live close to the operation. A recent study completed by Raina *et al*. [2] indicates the degree of human response to blast vibrations and air-overpressure.

Ground vibrations are acoustic waves that propagate through the rocks [3, 13]. They differ from the round vibrations caused by earthquakes in terms of seismic source, amount of available energy and travelled distances [4]. Usually, parameters such as velocity, displacement and acceleration of particles are recorded during the vibration measurements, but several studies achieved that the most important parameter, that has to be studied, is the Particle velocity. Many scientists and engineers investigated on PPV prediction and published their findings. The first significant PPV predictor equation was proposed by the US Bureau of Mines [5]. There are also modified predictors from other researchers or institutions such as Langefors and Kihlström [6], Ambraseys and Hendron [7], Indian Standard Institute [8], Daemen *et al.* [9], Pal Roy of CMRI [10], etc. However, the PPV predictor established by USBM is still the most widely used equation in the literature. To the knowledge of the author, no work has been reported in the literature that addresses the application of geostatistical approach for the estimation of ground vibration. This paper explains the usage of geostatistical modeling for estimation of ground vibration and comparison between principal common vibration predictors including geostatistical one. To reach these goals measurements were performed of vibrations at Basalt Quarry in central Italy, Rome.

2 Instrumentation and measurement on site

Measurement campaign was carried out at Dark-Grey Basalt Quarry, nearby Roma. The quarry was created in the early years of the century, with the purpose of providing Basalt to Rome-Ostia railway line, and still continues its activities extracting Granite for B1 line of Rome subway. The instrumentations used to measurement complies with IEC 60651, IEC 60804, IEC 61672-1, IEC 60260 and IEC 61260 Class 0 and consisted of 4 Sinus Soundbook units, on which have been connected accelerometer terns.

Due to instrumentation availability, it was possible to estimate the value of the vibrations in 4 different points simultaneously. Table 1 shows points P1, P2, P3, P4 coordinates (X is the perpendicular distance from the blast face, Y is the parallel distance starting from midst of bench edge, D is the X-Y sum vector.

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Table 1: Measurement points.

Measurement point	X(m)	Y(m)	D(m)
P1	40	0	40,00
P2	23	9	24,70
P3	41	3	41,11
P4	32	6	32,55

The accelerometer terns were placed radially, transversely and vertically from the edge of bench. The data were acquired using 1000Hz sampling frequency; accelerometers have been buried 40cm depth (figure 1).

Figure 1: Bench edge and accelerometer tern.

The blast design and characteristics are set out below.

Explosive: NITRAM; charge weight: 200kg; bench height: 18m; bench width: 20m; bench thickness: 2m; number of blast holes: 8; last hole array: single row; spacing: 1m; delay: 25ms; burden: 1 (burden and explosive ratio).

Data collected were processed by SAMURAI 2.0 (Sinus Acoustic Multi-channel Universal Real-time Analysis Instrument); integrating the acceleration has been obtained the velocity and its PPV. Table 2 reports PPV_i associated to *i* measurement points.

Table 2: PPV associated to measurement points.

Measurement point	X(m)	Y(m)	D(m)	PPV_i(mm/s)	Axle
P1	40	0	40,00	142,08	Z
P2	23	9	24,70	246,93	Z
P3	41	3	41,11	138,49	Z
P4	32	6	32,55	181,63	Z

3 Processing of physical model

Simultaneously, with the implementation of geostatistical model, a theoretical model was used to predict ground vibrations in our interest area. Thanks to the knowledge of the explosive used and characteristic rock parameter, a grid of PPV values was calculated.

To reach this goal, a theoretical model developed by Berta [11] was used. Berta considered that the seismic energy transmitted to the rock by the explosive can be evaluated with the two following equations:

$$E_s = 2\pi A^2 f^2 \, 2\pi {D_S}^2 \, \rho_r V_C \, T_v \, 10^{-6}$$

$$E_s = n_t \, n_1 \, n_2 \, E_T \, Q$$

where A = displacement (m), f = frequency (Hz), D_S = distance from the explosion point (m), ρ_r = density of the rock (kg/m^3), V_C = seismic velocity (m/s), T_v = duration of the vibration(s), n_t = breaking factor (charges laid on the ground n_t<0.4; charges without a free face n_t>0.4), E_T = energy per unit of mass, Q = amount of explosive. n_1 and n_2 are, respectively, impedance factor and coupling factor shown which are represented by the following formulas:

$$n_1 = 1 - \frac{(Z_e - Z_r)^2}{(Z_e + Z_r)^2}$$

$$n_2 = \frac{1}{E^{D/d} - 1{,}72}$$

where Z_e = impedance of explosive (kg $m^{-1}s^{-2}$), Z_e = impedance of rock (kg $m^{-1}s^{-2}$), D = blast hole diameter (mm), d = charge diameter (mm). From previous equations the following is obtained:

$$A(m) = \sqrt{\frac{n_t \, n_1 \, n_2 \, E_T \, Q \, 10^6}{4\pi^3 f^2 \, {D_S}^2 \, \rho_r V_C \, T_v}} \tag{1}$$

The significant duration of vibrations is considered to be five times the period: $T_v = 5T_s = \frac{5}{f}$, and the ground frequency is calculated with:

$$f = (kf \, \log D_S)^{-1}$$

where kf is a characteristic ground constant which influences the reduction of frequency with distance. As a result, equation (1) can now be written as follows:

$$A(m) = \sqrt{\frac{n_t \, n_1 \, n_2 \, E_T \, Q \, kf \, \log D_S \, 10^6}{20\,\pi^3 \, {D_S}^2 \, \rho_r V_C \, T_v}} \tag{2}$$

Integrating equation (2),

$$V(m/s) = \frac{\sqrt{Q}}{D_S} \sqrt{\frac{n_t \, n_1 \, n_2 \, 10^6}{5\, kf \, \pi \, log D_S \, \rho_r \, V_C}} \tag{3}$$

Table 3 shows explosive characteristics and rock parameters referring to our case, considering measurement point number 1.

Solving equation (3), using values listed in Table 3, PPV in P1 result 0.14477 (m/s), so 144.77(mm/s).

4 Geostatistical modelling

Geostatistics is the branch of statistics that studies the space-based developed phenomena, starting from the information derived from their sampling.

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Table 3: Explosive characteristics and rock parameter.

Q	200 kg
E_T	3,3 [MJ/kg]
kf	0.015
D_S	40 [m]
ρ_r	2900 [Kg/m³]
V_C	5400 [m/s]
n_t	0.4
n_1	0.83
n_2	0.9

The aim of geostatistical analysis is to assign a value to the regionalized variable at the points where it is not known. In this study as regionalized variable has been considered, according to literature, the highest value among X, Y and Z peak particle velocity (PPV). There are several methods for effecting such estimates that depends on the characteristics of the phenomenon under investigation, stationary or non-stationary. For stationary phenomena, the best estimation method, which provides the best results, is the Ordinary Kriging, whereas for non-stationary phenomena is generally used the Universal Kriging estimator. The choice of the right method to estimate, is often difficult to detect. To reach this goal, variograms are exploited, covariance and generalized covariance, this is a process for attempts based on statistical assumptions. In practice these discrete functions are calculated using available samples, then these data are pooled by continuous functions, obtaining full information about variability of the phenomenon. This is the main tool that estimator use to calculate the regionalized variable at the points where it is not known.

4.1 Stationary model

The starting point has been geostatistical modeling, by using the software *Multigeo*, assuming a stationary phenomenon, and then estimating a regionalized variable using Ordinary Kriging. Initially the model has been implemented using the grid points found with theoretical physics model, so considering those points as sampled values: it was decided to interpolate the main direction, 90°, that was approximated by Gaussian function with range 110 m from blast point. Figure 2 shows the PPV map obtained and Table 4 lists the cross validation analysis results.

To further improve the model reliability, it was proceeded to apply an external drift to the model, directly interpolating some measured PPV values (Table 5).

4.2 Non-stationary model

Stationary geostatistical analyses are based on the assumption of studying a phenomenon whose average does not present a trend.

The next step was to work out non-stationary geostatistical modeling, so assuming that the average of the regionalized variable presents a trend.

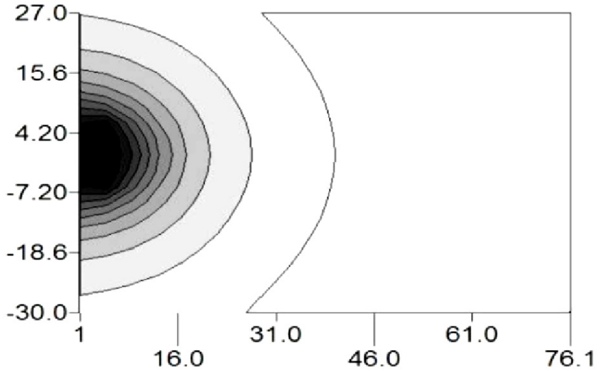

Figure 2: PPV geostatistical map arising from stationary modeling.

Table 4: Cross validation results.

Errors	Values
Mean error	-0.00044
Mean square error	0.00073
Sqrt (mean square error)	0.00271
Mean standard error	0.00311
Mean square standard error	0.16471
Sqrt (mean square standard error)	0.40958

Table 5: Geostatistical results summary table.

			PPV1(mm/s)	ΔPPV	ΔPPV %
Stationary	Drift free		142,93	0.85	0.59
	With external drift	**P2**	142,62	0.54	0.38
		P3	142,21	0.13	0.09
		P4	142,54	0.46	0.32
Non-Stationary	Drift free		142,73	0.65	0.45
	With external drift	**P2**	142,52	0.44	0.30
		P3	142,005	-0.075	-0.05
		P4	142,20	0.12	0.08

The software used has been *FAIPACK*, which is a tool that allows us to study a phenomenon assuming it is a non-stationary, analyzing it with random intrinsic functions of order K (FAI-K). The FAI-k substantially filters the trend of the phenomenon through flat surfaces or quadric surfaces, which brings us back to the study of stationary increments; that is to say, average constant along the surface. The type of surface available is indicated with k: k=0 is a horizontal surface, k=1 is an inclined surface, k=2 is a quadratic surface, k=3 is a cubic surface. In current practice it does not exceed grade 2.

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Under these assumptions, we have analyzed the variability of the phenomenon with the Generalized Covariance, and the estimation has been done using the Universal Kriging.

As result, has been identified the k order of the function, and according to the results obtained with the various orders, has been chosen $k = 1$.

Then, has been calculated the Generalized covariance and interpolated with the function with the best approximation (Table 5 shows the values obtained).

4.3 Non-stationary model conclusion

Even using non-stationary simulations there were improvements and best result by using external drift (Table 5).

4.4 Geostatistical model conclusion

Table 5 reports the PPV1 (PPV value obtained at P1) and errors related to the evaluation at point P1. Values related to points P2, P3, P4, are obtained by direct measurements in three different points (Table 1).

As reported, it is clear as adding one external drift in this geostatistical model (in both stationary and non-stationary cases), the error related to the evaluations are lower.

It is evident, moreover, how non-stationary analysis is one that gives best results, in all four simulations (drift-free and with external drift), showing that the phenomenon of vibrations produced by blasting operation, is a phenomenon that, using geostatistical modeling, has to be studied assuming a *non-stationary statistical framework*, so assuming that the random variable average is not constant.

So far, even if we are allowed to claim that theoretical Berta's model is close to reality, it generates results with 1.9% of error, because Berta's model ignores some borders effects. By using geostatistical modeling is possible to correct, partially, the theoretical Berta model's errors. Indeed, using the correct geostatistical model, and in particular an external drift with only one real value which contribute significantly to correct the error of modeling, it is possible to have some predictive results with more accuracy.

5 Comparison between models

The next step has been to evaluate PPV on point P1 by experimental equations [11, 12], and after that to compare models results with geostatistical results.

5.1 Common predictors

Among the massive literature regarding blasting operations, it was considered to analyze only 6 models, the ones that best fit for this case. The most accredited predictor is Duval and Fogelson's of the US Bureau of Mines. They performed 10 years of experimentations, 171 blasts in 26 different quarries across the US, and they gave birth to a new equation in 1963, able to connect PPV values and structural damages. This equation has been the first PPV predictor and is still the most used. In particular assuming cylindrical explosive geometry for long cylindrical charges, they concluded that any linear dimension should be scaled with the square root of the explosive charge weight based on dimensional analysis. The equation proposed by USBM is:

$$\mathrm{PPV} = \mathrm{K}\left(\frac{\mathrm{D}}{\sqrt{\mathrm{W}}}\right)^{-\mathrm{n}}$$

where,
PPV is peak particle velocity (mm/s), D is the distance between blast face and monitoring point (m), W is maximum explosive charge used per delay (kg), and K, n are site constants which can be determined by multiple regression analysis.
Later, Langefors and Kihlstrom [6] proposed the following relationships to estimate PPV:

$$\mathrm{PPV} = \mathrm{K}\left(\frac{\mathrm{W}^{\frac{1}{2}}}{\mathrm{D}^{\frac{2}{3}}}\right)^{\mathrm{n}}$$

In 1968, Ambraseys and Hendron [7] suggested that any linear dimension should be scaled to the cube root of the explosive charge weight for spherical geometry. An inverse power law was suggested to relate amplitude of seismic waves and scaled distance to obtain the following relationship:

$$\mathrm{PPV} = \mathrm{K}\left(\frac{\mathrm{D}}{\mathrm{W}^{\frac{1}{3}}}\right)^{-\mathrm{n}}$$

Indian Standard [8] suggested that the blast should be scaled to the equivalent distance or the scaled distance, defined as the explosive charge weight divided by cube root of square of real distance. The proposed equation is:

$$\mathrm{PPV} = \mathrm{K}\left(\frac{\mathrm{W}}{\mathrm{D}^{\frac{2}{3}}}\right)^{\mathrm{n}}$$

The Ghosh–Daemon predictor [9] proposed that various inelastic effects cause energy losses during wave propagation in various medium. This inelastic effect leads to a decrease in amplitude in addition to those due to geometrical spreading. They modified the propagation relations of USBM in terms of adding inelastic attenuation factor (α). The equation proposed is:

$$\mathrm{PPV} = \mathrm{K}\left(\frac{\mathrm{D}}{\sqrt{\mathrm{W}}}\right)^{-\mathrm{n}} \mathrm{e}^{(-\alpha)\mathrm{D}}$$

where,
PPV is peak particle velocity (mm/s),
D is the distance between blast face and monitoring point (m),
W is the maximum explosive charge used per delay (kg), and
K, B and α are the site constants which can be determined by multiple regression analysis.

In order, Pal Roy [10] of the Central Mining Research Institute proposed a new predictor equation based on the data collected from different Indian geo-mining conditions. This equation is only valid in the zone of disturbance, when W>0 and PPV>0.

$$\mathrm{PPV} = \mathrm{n} + \mathrm{K}\left(\frac{\sqrt{\mathrm{W}}}{\mathrm{D}}\right)$$

Table 6 summarizes all the above described equations.

Table 6: Common predictor equations.

Agency/institution and authors	**Predictor equation**
USBM predictor equation (Duval and Fogelson, 1962)	$PPV = K\left(\frac{\mathrm{D}}{\sqrt{W}}\right)^{-n}$
Langefors *et al*. (1963)	$PPV = K\left(\frac{\sqrt{W}}{D^{\frac{2}{3}}}\right)^{n}$
Ambraseys-Hendron equation (1968)	$PPV = K\left(\frac{D}{W^{\frac{1}{3}}}\right)^{-n}$
Indian standard (1973)	$PPV = K\left(\frac{W}{D^{\frac{2}{3}}}\right)^{n}$
Ghosh–Daemen (1983)	$PPV = K\left(\frac{D}{\sqrt{W}}\right)^{-n} \boldsymbol{e}^{(-\alpha)D}$
CMRI equation (Pal Roy, 1991)	$PPV = n + K\left(\frac{\sqrt{W}}{D}\right)$

5.2 Common predictors comparison

To obtain values of PPV in a given point, using common predictors, it is necessary to find out values of K, n andα. To do this the equations have to be solved by setting systems of 2 or 3 equations in 2 or 3 variables. Thanks to the availability of the measures in P2, P3 and P4 has been possible to solve systems of equations, to calculate the value of the PPV1 by each predictor, and then to compare the results obtained using the 6 equations and those obtained with the geostatistical modeling. Table 7 shows values of K, n and α that solve the equations systems.

Table 7: K, n and α values.

	Ghosh–Daemen	***USBM***	***Langefors***	***Ambraseys–Hendron***	***Indian Standard***	***CMRI***
K	0.316	1.402	0.541	2.645	0.031	1.255
n	0.815	1.135	1.702	1.135	1.70	0.024
α	0.060					

Therefore PPV1 has been calculated (value of the PPV obtained in P1) by using each predictor.

Table 8 shows values of PPV1, errors and percentage errors, compared to the measured value of PPV1

Table 8: PPV1 by common predictors, errors and percentage errors.

	Ghosh–Daemen	*USBM*	*Langefors*	*Ambraseys –Hendron*	*Indian Standard*	*CMRI*
PPV 1(mm/s)	144.85	142.86	142.86	142.86	142.86	143,02
ΔPPV1(mm/s)	2.77	0.78	0.78	0.78	0.78	0.94
ΔPPV1%	1.94	0.55	0.55	0.55	0.55	0.66

From the results is possible to see that using the predictors USBM, Langefors, Ambraseys and Indian standard, the result does not change. Using the equations of Gosh and CMRI, the PPV1 differ from the previous ones, in particular the best prediction is achieved by the use of the USBM, Langefors, Ambraseys and Indian standard formulas, while the predictor processed by Gosh-Daemen has calculated a very different result from the true value.

6 Comparison between common predictors and geostatistical models

Table 9 summarizes the results of all the simulations performed with geostatistical modeling and those obtained using common predictors.

The results have been listed in table in descending order. As we can see from the table, results obtained with geostatistics are considerably better than those obtained by use of the common predictors. In fact, apart from the 0.55% error obtained with the formulas (USBM, Langefors, Ambraseys and Indian Standard, which rank between the two geostatistical solutions without the use of drift) all the geostatistical simulations have provided better results.

Table 9: PPV1 summary table.

	PPV1(mm/s)	**ΔPPV**	**ΔPPV%**
Non- Stationary with external drift **P3**	142,005	-0.075	-0.05
Non- Stationary with external drift **P4**	142,20	0.12	0.08
Stationary with external drift **P3**	142,21	0.13	0.09
Non- Stationary with external drift **P2**	142,52	0.44	0.30
Stationary with external drift **P4**	142,54	0.46	0.32
Stationary with external drift **P2**	142,62	0.54	0.38
Non- Stationary drift free	142,73	0.65	0.45
USBM, Langefors, Ambreseys, Indian	142.86	0.78	0.55
Stationary drift free	142,93	0.85	0.59
CMRI	143,02	0.94	0.66
Gosh	144.85	2.77	1.94

7 Conclusions

The purpose of this study has been to verify whether and how the geostatistical modeling lends itself to the prediction of the phenomenon of vibrations caused by blasting operation.

The results show that geostatistics, is not only a valid tool for assessing these phenomena, but it also allows a prediction considerably more efficient than those already used. Using only the knowledge on the characteristics of the site under examination, the parameters associated to the firing procedures, and, performing a single measurement on site, it is possible to implement a geostatistical model with external drift, which significantly reduces the estimation error made by common predictors. The error passes from 0.55% resulting from the use of the model USBM to -0.05% by implementing a non-stationary geostatistical model with external drift.

References

[1] Singh, T.N. and Singh, V. An intelligent approach to prediction and control ground vibration in mines, Geotech. Geologic. Eng., 23: 249–262, 2005.
[2] Raina, A.K., Haldar, A., Chakraborty, A.K., Choudhury, P.B. and Bandyopadhyay, R.M. Human response to blast-induced vibration and air overpressure. Bull. Eng. Geol. Environ., 63: 209–214, 2004.
[3] Berry P., Dantini, E.M., Blasting Techniques Used in the 1950's and their Probable Effects on Mechanical Characteristics of Rock Vis-à-Vis Current Methods, Proc. Int. Conf. on Rock Eng. and Excav. in an Urban Environment, IMM, pp. 517–521, Hong Kong, 1986.
[4] Oriard, L.L., The scale of effects in evaluating vibration damage potential, Society of Explosives Engineers, pp. 161–176, 1989.
[5] Duvall, W.I. and Fogelson D.E., review of criteria to estimating damage to residences from blasting vibrations, USBM-I, 5968, 1962.
[6] Langefors, U., Kihlström, B., The modern technique of rock blasting, 1963.
[7] Ambraseys, N.R., Hendron, A.J., Dynamic behaviour of rock masses, Rock mechanics in engineering practices, p. 203–7, 1968.
[8] Indian Standard Institute. Criteria for safety and design of structures subjected to underground blast, ISI Bull, 1973.
[9] Daemen, J.J.K., Barkley, R.C., Ghosh, A., Morlock, C.R., and Shoop, S.A., Ground and air vibrations from caused by surface blasting., Vol. 1,1983 (http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=6613826)
[10] Pal Roy, P., Vibration control in an opencast mine based on improved blast vibration predictors, Mining Science and Technology, Volume 12, Pages 157–165, 1991.
[11] Berta, G., L'esplosivo strumento di lavoro. Italesplosivi (Mi), 1985.
[12] Mancini, R., Cardu, M., Scavi in roccia: gli esplosivi, Hevelius, Aprile 2002. ISBN: 8886977484, ISBN-13: 9788886977487
[13] Giraudi, A., Cardu, M., Kecojevic, V., An Assessment of Blasting Vibrations: A Case Study on Quarry Operation, American Journal of Environmental Sciences 5 (4): 467–473, 2009. ISSN 1553-345X
[14] Berry P., Dantini, E.M., Sismicità indotta da volate in galleria. II Congr. Italo-Brasileiro de Engenharia de minas, Vol. 1, pp. 283–295, San Paolo, Brazil, 1993.