Complexity analysis of blast-induced vibrations in underground mining, a case study

Original
Complexity analysis of blast-induced vibrations in underground mining, a case study / Cardu, Marilena; Dompieri, M.; Seccatore, J.. - In: MINING SCIENCE AND TECHNOLOGY. - ISSN 1674-5264. - STAMPA. - 22:(2012), pp. 125-131. [10.1016/j.ijmst.2011.06.013]

Publisher:
Elsevier

Published
DOI:10.1016/j.ijmst.2011.06.013

Cardu M., Dompieri M., Seccatore J. Mining Science and Technology. Complexity analysis of blast-induced vibrations in underground mining, a case study (2012), 22, pp 125-131.

Complexity analysis of blast-induced vibrations in underground mining: a case study

Marilena Cardu [a,b]***, Mauricio Dompieri*** [c,d]***, Jacopo Seccatore***[a,d]

[a] *Department of Land, Environment and Geotechnology (DITAG), 10129 Torino, Corso Duca degli Abruzzi, 24, Italy*
[b] *IGAG C.N.R., Torino, Italy, 10129 Torino, Corso Duca degli Abruzzi, 24, Italy*
[c] *Ontonix Brasil, Rua Madre Rita Amada de Jesus, 72 - cj.31b, São Paulo, Brazil*
[d] *LAPOL, Mining & Petroleum Engineering Department, University of São Paulo, Av. Prof. Mello Moraes, 2373, São Paulo, Brazil*

ABSTRACT: Blasting in geological bodies is an industrial process acting in an environment characterized by high uncertainties (natural joints, faults, voids, abrupt structural changes), which are transposed into the process parameters (e.g. energetic transfer to rock mass, hole deviations, misfires, vibrations, fly-rock...). The approach to this problem searching for the "optimum" result can be ineffective. The geological environment is marked out by too many uncertainties, to have an "optimum" suitable to different applications. Researching for "Robustness" in a blast design gives rise to much more efficiency. Robustness is the capability of the system to behave constantly under varying conditions, without leading to unexpected results. Since the geology varies from site to site, setting a robust method can grant better results in varying environments, lowering the costs and increasing benefits and safety. Complexity Analysis (C.A.) is an innovative approach to *Systems*. C.A. allows to analyze the Complexity of the *Blast System* and the criticality of each variable (drilling, charging and initiation parameters). The lower is the complexity, the more robust is the *System*, and the lower is the possibility of unexpected results.

The paper presents the results obtained thanks to the C.A. approach in an underground gypsum quarry (Italy), exploited by conventional *Rooms and Pillars* method by drilling & blasting. The application of C.A. led to a reliable solution to reduce the Charge per Delay, hence reducing the impact of ground vibration on the surrounding structures. The analysis of the correlation degree between the variables allowed to recognize empirical laws as well.

KEYWORDS: Drilling & Blasting, Complexity Analysis, Vibrations Control

1. Introduction

The underground quarry object of the present analysis is exploited by conventional room & pillars technique, a method in which rooms are opened by blasting and pillars are left to provide support [1]. The quarry is located in a quite densely anthropic context (see Fig. 1), and vibrations induced by the blasts are therefore perceived by the local population [2], [3].

"Politecnico di Torino" carried out a a detailed vibration monitoring in order to check the possible interference with buildings and neighboring structures. Some of the record exceed the thresholds established by the German standard "DIN 4150-3: Effects of vibration on Structues" [4] (see Fig. 2), a widely recognized norm in Europe. It was hence decided to perform a Complexity Analysis (C.A.) of the phenomenon, in order to analyze it under the heuristic and complexity point of view, to detect criticalities using this innovative approach.

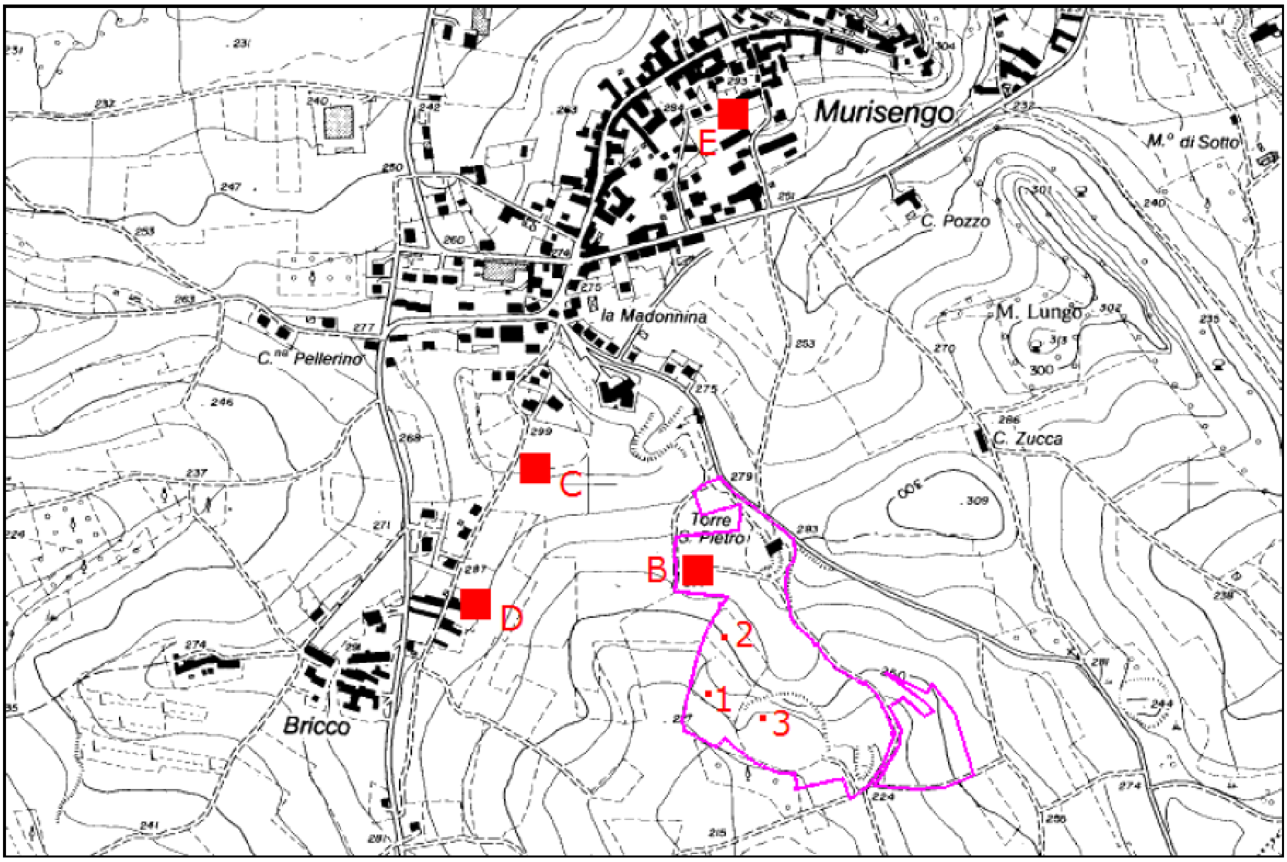


Figure 1 – Plan view of the site. Highlighted profile: location of the quarry. A, B, C, D, E: positions of preliminary vibrometric records according to the complaints of the local population. 1, 2, 3: location of the monitored blasts.

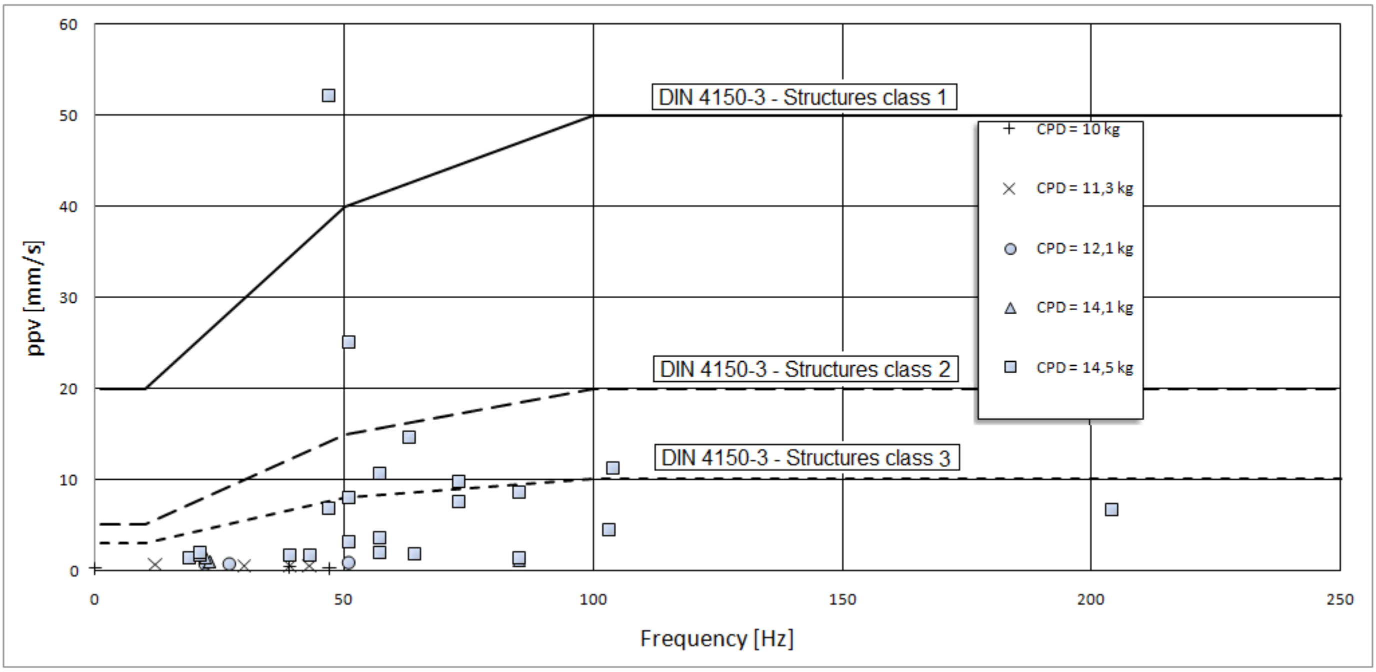


Figure 2 – ppv vs. frequency diagram obtained from the vibration monitoring, plotted on DIN 4150-3 chart where sensitivity class thresholds are highlighted

2. Complexity Analysis

Complexity Analysis (C.A.) is an innovative approach to engineering systems at its first applications in mining and explosives engineering. C.A. uses a heuristic approach to complex systems, avoiding approximation or linear regression, and allowing the evaluation of outliers in any kind of numerical dataset.

In order to perform an analysis of the complexity of a system multi-dimensional maps have to be realized: images that report the raw measured data plotting:

$$x_i \text{ against } x_j \ \forall x_{i,j} \in \text{ variables of the system, with } i \neq j.$$

Each map is divided into cells. On each cell an image analysis is performed. From the shape and the density of the cloud of points with coordinates (x_i, x_j), the presence of a connection (link), and the noise of this interaction are detected. The strength of the connection is known as *correlation degree*. This is done for each couple of variables of the system. Through this image analysis technique, multi-dimensional data are transformed into *process maps*.

The complexity, then, appears as a measure of the structure of the interconnections and the noise between the variables.

Any system has:

- a minimum level of complexity C_{min}, under which it behaves totally deterministic
- an operative level of complexity C at which it works at the moment of the analysis
- a critical level of complexity C_{CR}, beyond which it becomes unstable, being able to change behavior unexpectedly and cause surprises.

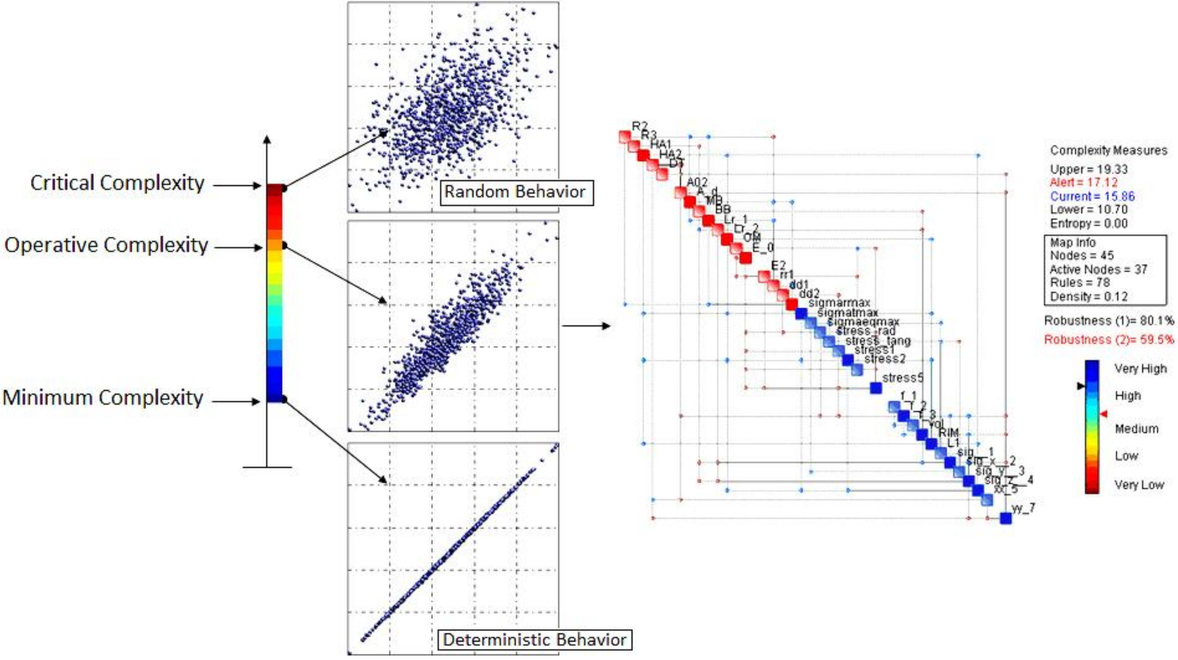


Figure 3 – Example of the functioning of Complexity Analysis. Levels of complexity (left), corresponding multidimensional maps (center) and system map (right).

The margin between operative and critical complexity is known as topological *robustness*: the capability to withstand a degree of uncertainty in the input without greatly influencing the output results. Inversely proportional to robustness is the *fragility* of the system, i.e. its capability of abrupt rupture (output of unexpected results) without signals of breaking, and due to apparently innocent causes.

Any variable has an individual contribution to the total complexity of the system. This contribution is calculated by taking the variable off and calculating the consequent drop of total complexity. This measure of *contribution to total complexity* is an indicator of how critical the variable is for the whole system.

Additional and more specific references on the operation of C.A. can be found in Marczyk, 2006 [5], Marczyk, 2008 [6], in Ottino, 2004 [7], in Dellino *et al.* , 2008 [8] and, in relation to the first application of C.A. to the excavations by drilling and blasting, in Seccatore *et al.*, 2010 [9].

3. Case Study

The exploited orebody is a sedimentary deposit, approximately 100 meters wide and 40 meters deep, dipping approximately 50 degrees to the SW. The waste cover is about 20m deep, consisting of loose colluvial debris, laying on a bed of marl and calcareous sandstone. The orebody develops in E-W direction, with interlayers of marlin the same direction. Two main discontinuities, consisting of marl layers up to some decimeters thick, dip parallel to the orebody, with the joints filled with silt and clay.

A basic approach of calculating the effects of the joint sets was used to evaluate the influence of parting planes and frequency of occurrence, for roughly estimating the rock mass behavior: an RQD of 80% has been found, while a Rock Mass Rating (RMR) of 52 gives rise to a class III rock, according to Bieniawski [10].

The quarry is located in a hilly countryside, approximately 300m above the sea level. The area is especially devoted to agriculture, and is well known for its famous wineyards. Rural houses and warehouses located in the closest neighborhood belong to class 1 and 2 according to DIN 4150-3. Some historical monuments and structures located in the same area, and in the medieval village of Murisengo, belong to class 3.

With room and pillar mining, the orebody is excavated as completely as possible, leaving sections of ore as pillars to support the hanging wall. Room and pillar is the most common method of mining flat deposits of limited thickness, and it is to a great extent used for rocks of sedimentary origin, such as gypsum. The dimensioning of stopes and pillars depends on the stability of the hanging wall and the ore itself, the thickness of the deposit and the rock pressure [11], [12], [13]. Pillars are arranged after a regular pattern, shaped as elongated walls, separating the stopes: the usual thickness of the pillar is the same as the width of the stope. The drilling and blasting operations are organized with the objective to perform up to three blasts per day, generally at the same time, with short intervals (max. five minutes) between them.

The opening cut is performed with horizontal holes, according to different geometries, V-cut and fan cut respectively. Three schemes are adopted for blasts, as shown in Fig.4.

3.1 Blast Schemes

Scheme n.1 consists in a V-cut placed in the middle of the cross section and quite low down; each V in the cut, consisting of 6 holes, is fired with the same interval number, using 25 ms delay electrc detonators, to ensure a good coordination between the blastholes with respect to breakage. The charge concentration in the cut holes is 2.4 kg/hole, resulting in a CPD (charge per delay) of 14.5 kg. Total consumption of explosive per blast is 210 kg, divided into 18 delays. 1 cartridge of dynamite is placed in each hole as bottom charge, while the column charge consists in 3 cartridges of emulsion.

Scheme 2 adopts a fan cut (Fig.4); total consumption of explosive per blast is 90 kg, divided in 10 delays, with a CPD of 14.1 kg.

Scheme 3 is quite uncommon, and is just adopted to rearrange the floor of the quarry; also in this case a fan cut is adopted, while all the stoping holes are drilled following an almost squared pattern with the same inclination (Fig.4). Each row consists in 8 blastholes, simultaneously fired. Total consumption of explosive per blast is approximately 120 kg, divided into 10 delays, with a CPD of 11,3 kg.

Charging geometry, both for scheme 2 and 3, consists of 2.5 cartridges of dynamite in each hole as a bottom charge, and of 2 cartridges of emulsion as a column charge.
Stemming is not adopted and the firing pattern is designed according to the employment of 25 ms detonators.

Table 1 – Parameters of the blast schemes

Symbol	Parameter	Unit	Scheme 1	Scheme 2	Scheme 3
L_d	Design pull	[m]	3.10	2.50	2.50
L_a	Actual pull	[m]	2.80	2.25	2.25
H	Efficiency	-	0.91	0.90	0.90
V	Blasted volume	[m^3]	180	118	142
Q	Total charge	[kg]	213	83	124
PF	Powder Factor	[kg/m^3]	1.18	0.71	0.87
N	Holes number	-	88	61	88
S	Cross section	[m^2]	58	47	63
CPD_{max}	Maximum charge per delay	[kg]	14.5	14.1	11.3

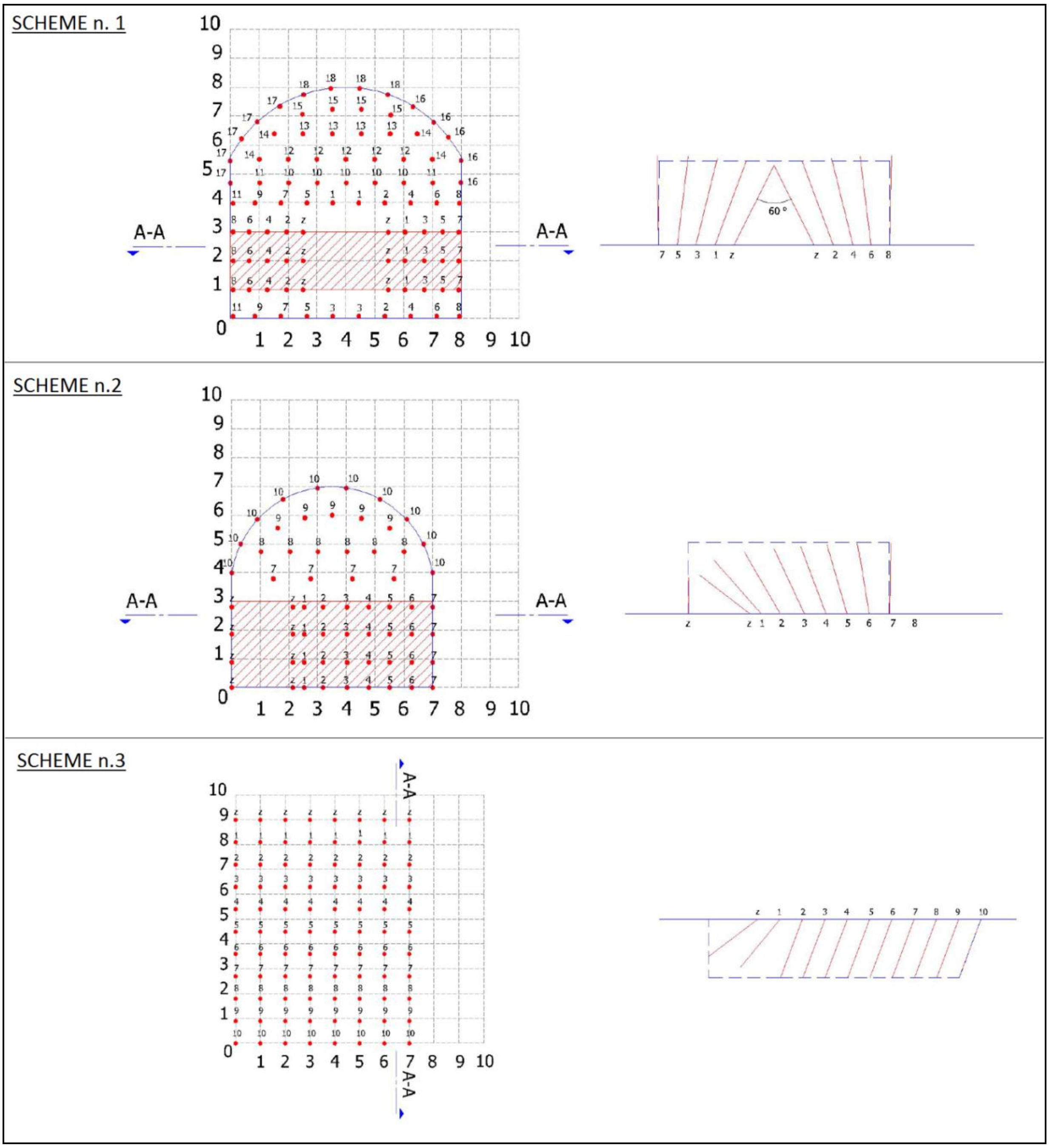


Figure 4 – Schemes of the blasts adopted in the quarry

The most relevant data on blasts geometry and explosive consumption are given in Table 1.

4. Complexity Analysis of the data

The C.A. was made considering the following groups of variables:

- Vibrometric records: peak particle velocity (ppv) and frequency, using triaxial geophones and considering the distances from the blasting site and the instruments;
- Drilling parameters: diameter, length, number of the blastholes;

- Charging parameters: charge per hole, charge per type of explosive, charge per delay (CPD);
- Firing sequence: time and number of delays.

All blasts, during the experimental campaign, were recorded thanks to four traxial geophones, coming from different firms. To perform C.A., data obtained from each instrument have been separately analyzed. If data coming from different instruments (each one having its own systematical error) would have been considered, an artificial complexity should have been generated.

4.1 Contribution to total complexity

The contribution to total complexity of the main parameters is shown in Fig. 5. The maximum number of holes per delay is a critical parameter in most cases. Then its influence has been analyzed against critical vibrometric records. The results, given in figure 5, show that when 6 blastholes are simultaneously fired (scheme 1), the most critical conditions are reached (in terms of high ppv and low frequencies): it can give reason of significant damage to nearby buildings or various structures.

Scheme 1, to be noticed, presents the highest CPD, and the highest number of holes and delays. Contributions to total complexity of these parameters are shown in figure 4.The CPD max that was found in scheme 1 can be ascribed to the 6 zero-delay cut holes, which are simultaneously ignited. The results of C.A. suggest the way to solve the problem: either a greater number of delays or a lower number of rows has to be employed while performing the V-cut, reducing the CPD max (by reducing the number of holes per delay) and the peak particle velocity.

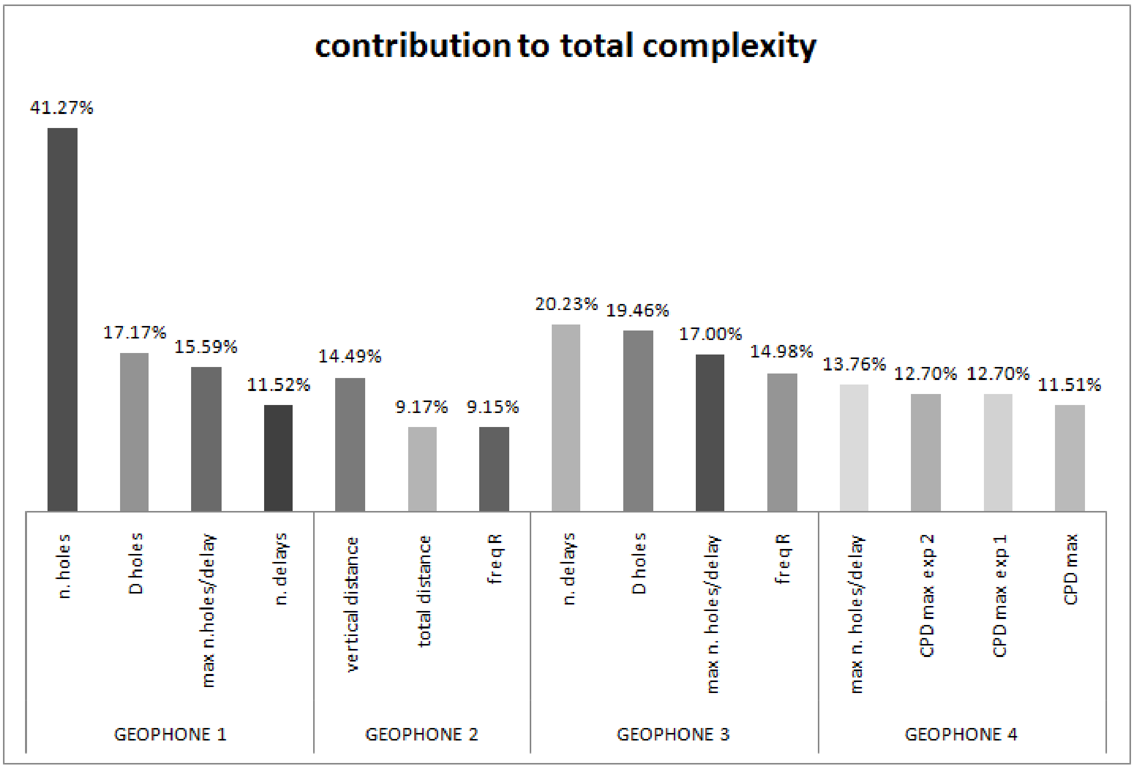


Figure 5 – Main contributions to total complexity of the variables, separately considered for each instrument

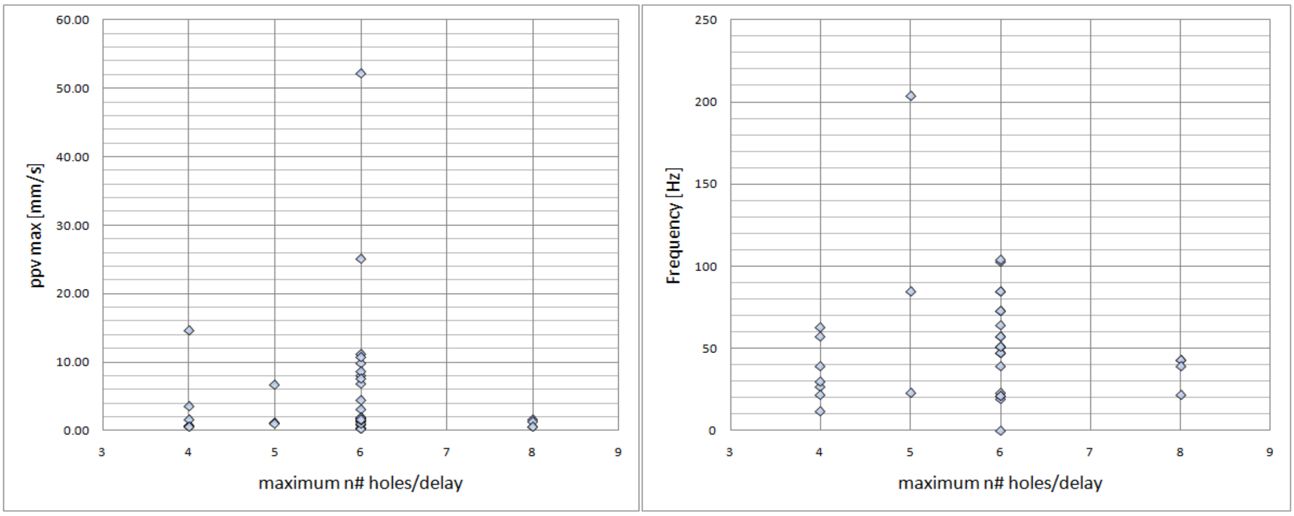


Figure 6 – Influence of the number of blastholes per delay on peak prticle velocity and frequency

4.2 Temporal complexity analysis

Temporal analysis of complexity and robustness behaviors supplied the results shown in Figure 7. According to the time discretization shown in Figure 8, the first four steps include only blasts of Scheme 1: their complexity C is very close to critical level C_{CR}, then the robustness is very low. As the time rolls by, and blasts of the second and third scheme are included, C_{CR} increases more than C, giving rise to a higher robustness. This is in agreement with the above mentioned results: Scheme 1 is more critical and more fragile at the same time.

Blast schemes n.2 and 3, from the Complexity point of view, are as well more robust and reliable and have lower probability of unexpected results.

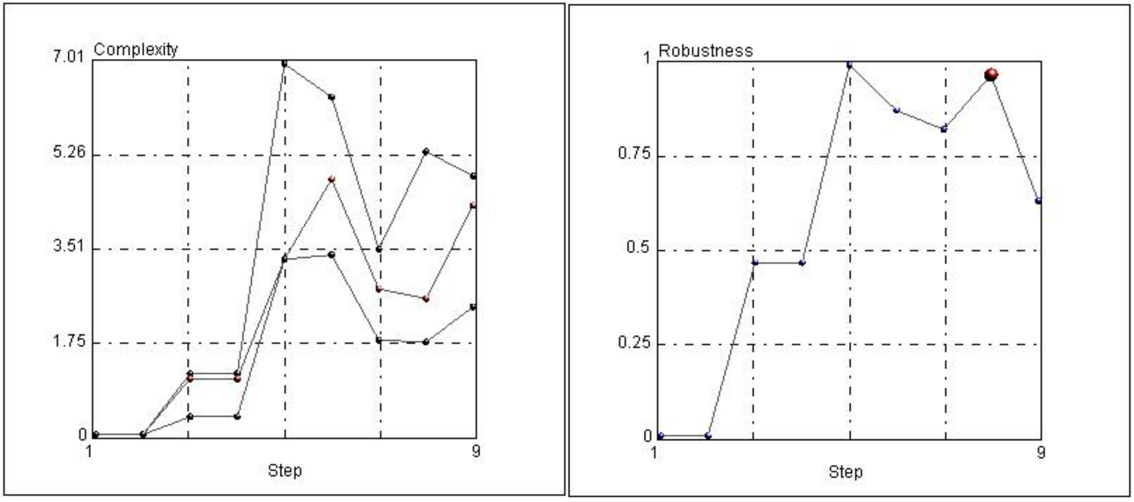
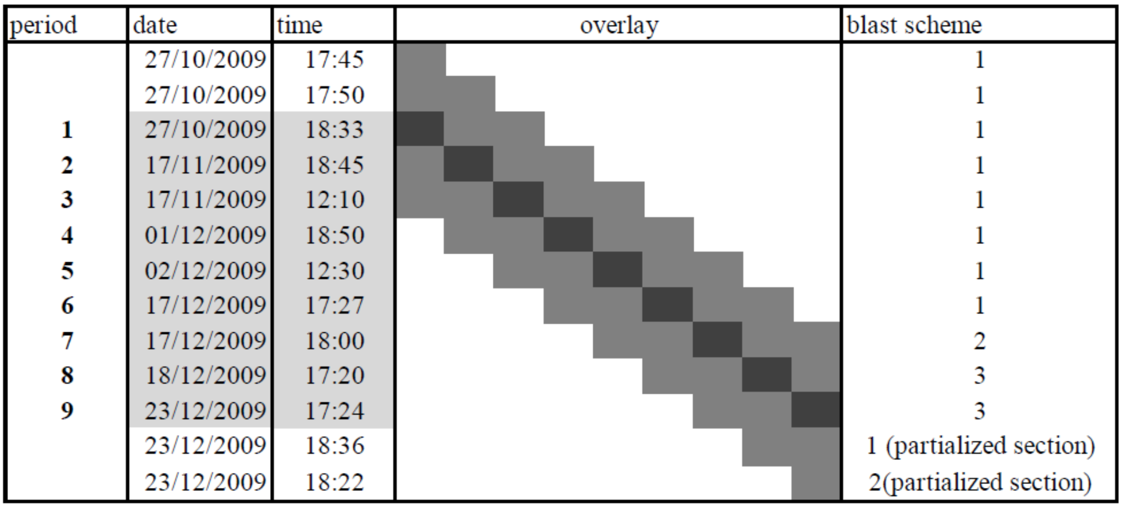


Figure 7 – Temporal complexity analysis. Left: evolution of complexity in time (upper line: critical complexity; middle line: operational complexity; lower line: minimum complexity). Right: evolution of robustness in time.



period	date	time	overlay									blast scheme
	27/10/2009	17:45	▨									1
	27/10/2009	17:50	▨	▨								1
1	27/10/2009	18:33	■	▨	▨							1
2	17/11/2009	18:45	▨	■	▨	▨						1
3	17/11/2009	12:10	▨	▨	■	▨	▨					1
4	01/12/2009	18:50		▨	▨	■	▨	▨				1
5	02/12/2009	12:30			▨	▨	■	▨	▨			1
6	17/12/2009	17:27				▨	▨	■	▨	▨		1
7	17/12/2009	18:00					▨	▨	■	▨	▨	2
8	18/12/2009	17:20						▨	▨	■	▨	3
9	23/12/2009	17:24							▨	▨	■	3
	23/12/2009	18:36								▨	▨	1 (partialized section)
	23/12/2009	18:22									▨	2(partialized section)

Figure 8 – Time discretization of the steps used to perform temporal analysis: central dates of the steps are highlighted in dark grey, time overlays in light grey; the blast schemes adopted are given in the last column

5. How C.A. detects empirical relationships

As mentioned above, when performing C.A. the presence of links and their strength is measured as the *correlation degree*.

A strong correlation degree has been detected amongst the three components of frequency and the CPD of each explosive, as shown in Figure 9. This correlation has been recognized as Sadowskij´s empirical law [14]:

$$\mathbf{f} = \frac{\mathbf{1}}{\mathbf{K_f}\ \mathbf{logR}} \qquad (1)$$

Where *f* is the frequency of vibrations, *R* the distance between the blast and the geophones and K_f a coefficient, depending on the type of soil. In Figure 10 the minimal frequencies have been plotted versus the scaled distance (distance reduced by the squared root of the minimal CPD), therefore including the two variables whose correlation has been detected by C.A., and Sadowskij´s law has been plotted as follows:

$$\mathbf{f} = \frac{\mathbf{1}}{\mathbf{K_f}\ \mathbf{log}\left(\frac{\mathbf{d}}{\sqrt{\mathbf{CPD_{min}}}}\right)} \qquad (2)$$

where *d* is the distance between the blast and the geophones and CPD_{min} is the minimum CPD used in the quarry. A $K_f = 0.02$ has been used, being valid for compact rocks, as the gypsum is.

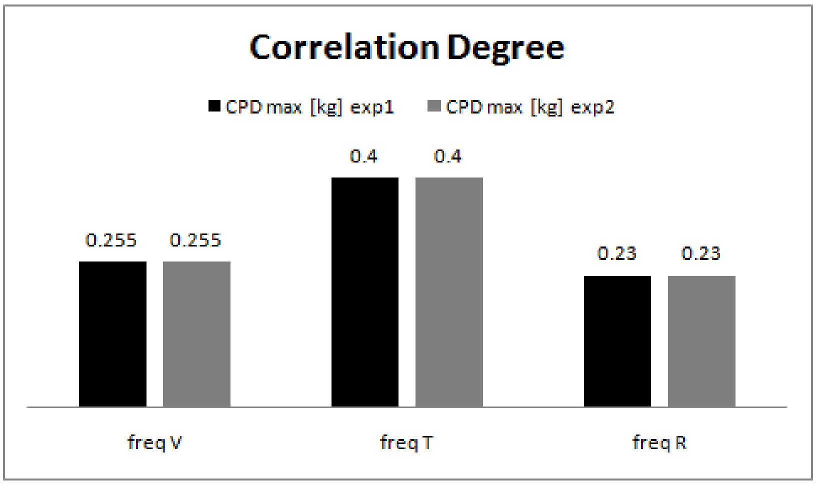


Figure 9 – Correlation degrees depending on frequency components with CPD max both for dynamite (exp 1) and emulsion (exp 2) explosives. To be noticed, no differences were found between the two kind of explosives in terms of influence on vibrations frequency

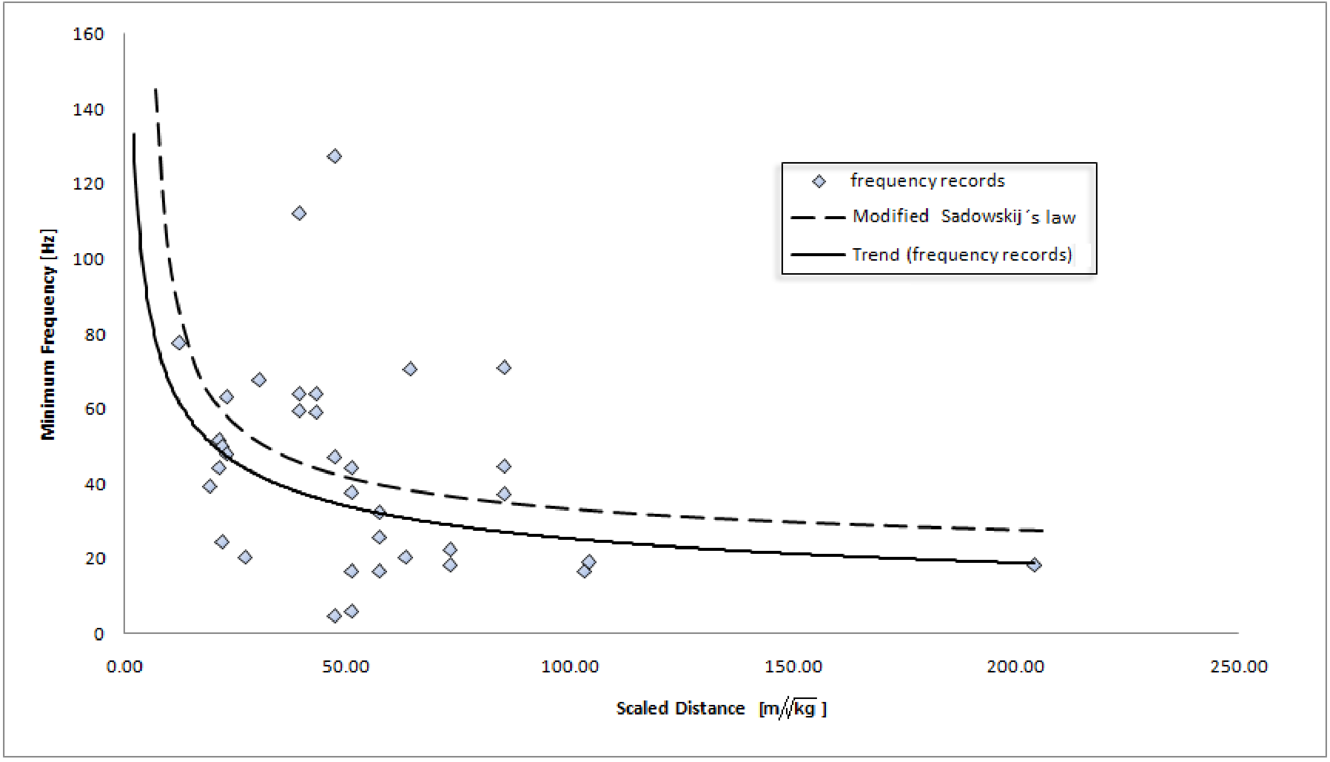


Figure 10 – Trend of the frequency vs. scaled distance: a good accordance with respect to Sadowskij´s modified law (see Eq. 2) is clearly observable

C.A. is still at its first steps in explosives applications, and its employment as an engineering tool is still under evaluation. From the results here obtained, C.A., having recognized a kind of correlation confirmed by empirical rules widely accepted, appears to be an effective tool to analyze such complex systems as blast-induced vibrations.

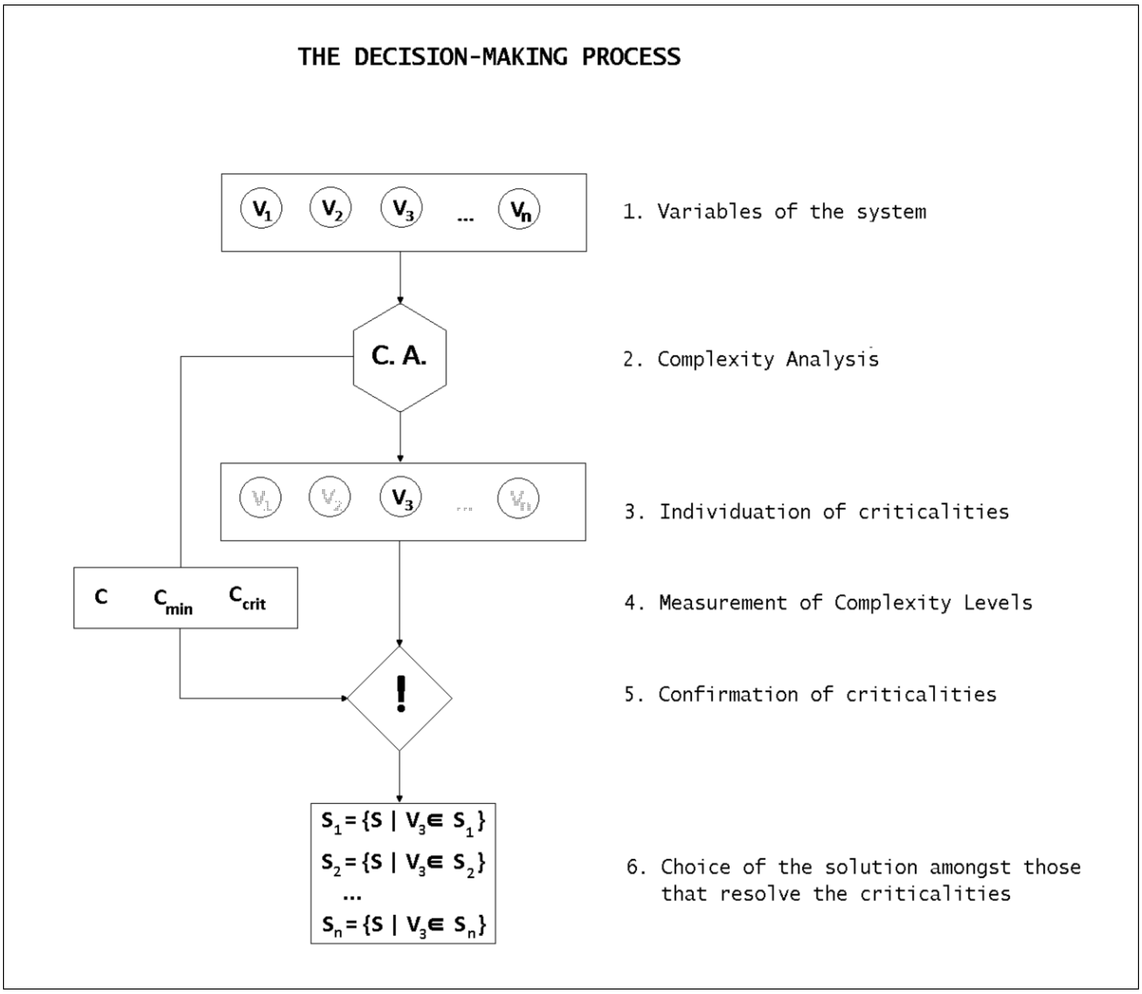


Figure 11 – Typical decision-making process that involves the C.A. results. The decision can be made considering also complexity and criticality as numerical values amongst the other factors

6. Conclusions

The experimental study dealt with in this paper has been developed to analyze the results of a vibration monitoring in an underground gypsum quarry exploited by explosive. In some cases, the measured ppv exceeded the limits suggested by the DIN 4150-3 Norm, and Complexity Analysis has been employed to check and verify the main reasons of that.

Its application made it possible to detect reliably how, in order to limit vibrations, it’s possible to reduce the charge per delay employed in the quarry. The C.A. results detected as a main criticality the number of holes per row of the V-shaped open cut that were initiated with zero delay. The solution to reduce ground vibrations, then, was found not by merely reducing the CPD by the charging parameters, but by micro-delaying the open cut and reducing its number of rows being fired contemporarily, without changing the charging scheme of the holes [15]. In this way, at the same time the CPD was reduced and the confining conditions of the blast were changed. The identification of the critical parameters CPD and number of holes per delay, their connection, the critical value of CPD and how to reduce it has been suggested thanks to the C.A. application. Figure 11 resumes a typical decision-making process based on the results of C.A.

It can be inferred that C.A. can lead to:

- a comprehension of where criticalities are in the work system
- an individuation of where to operate in order to reduce criticalities
- a choice of the better method to increase robustness and avoid unexpected results
- a way to manage the reliability of the work system

The effectiveness of C.A. as a tool also in explosive works needs further investigations; the example here presented, anyhow, confirms its capability to detect structural correlations that are confirmed by empirical laws experimentally found.

Acknowledgments

The authors are kindly grateful to the company “Estrazione Gesso s.n.c.” and to eng. Sandro Gennaro for the precious help given during the field studies in Murisengo. A special acknowledgment goes to dr. Jacek Marczyk and Ontonix s.r.l., for the authorization to use his Complexity Analysis software for the purpose of the research.

References

[1] MANCINI, R., CARDU, M., PIOVANO V. How the underground quarry design evolves from feasibility study to operation: an analysis of two Italian cases. In *Proceedings of the Symposium on Industrial Minerals and Building Stones.* Istanbul, Turkey. 2003, pp. 767-774.

[2] AFENI T.B., OSASAN K.S. Assessment of noise and ground vibration induced during blasting operations in an open pit mine — A case study on Ewekoro limestone quarry, Nigeria. *Mining Science and Technology (China)*, Volume 19, Issue 4, 2009, pp. 420-424.

[3] DAI K., CHEN S. Strong ground movement induced by mining activities and its effect on power transmission structures. *Mining Science and Technology (China)*, Volume 19, Issue 5, 2009, pp. 563-568.

[4] DIN 4150-3 Structural Vibration - Effects of vibration on structures. *Deutsches Institut für Normung E.V.*, 1999

[5] MARCZYK J. Measuring and Tracking Complexity. In *Proceedings of the 6th International Conference on Complex Systems*, New England Complex Systems Institute, 2006 Boston, MA, USA

[6] MARCZYK J. *Complexity Management in Engineering*, Ontonix s.r.l., Como, 2008

[7] OTTINO J.M. Engineering complex systems. *Nature*, Volume 427, Issue 29, 2004, p. 399.

[8] DELLINO G., KLEIJNEN J.P.C., MELONI C. *Robust Optimization In Simulation: Taguchi And Response Surface Methodology* (Discussion Paper), Tilburg University, 2008, ISSN 0924-7815, 41 pp..

[9] SECCATORE J., DE TOMI G., DOMPIERI M., REZENDE A. Blasting Fragmentation Management Using Complexity Analysis. In *Proceedings of the 6th Congress of open pit and underground mining.* Brasilian Institute of Mining, 2010, Belo Horizonte, MG, Brasil

[10] BIENIAWSKI Z.T. Engineering classification of jointed rock masses. *Trans. South African Institute of Civil Engineering*, 1973, 15, pp. 335–344

[11] FAVREAU R F, LILLY D. Optimizing blasts through characterization and on-site computer modeling during blast preparation. In *Proceedings of Annual Meeting Society of Mining Engineers AIME*. Minnesota, 1986.

[12] KUSHWAHA A.,BANERJEE G. Exploitation of developed coal mine pillars by shortwall mining—a case example. *International Journal of Rock Mechanics and Mining Sciences,* Volume 42, Issue 1, 2005, Pages 127-136.

[13] CHE Z., YANG H. Application of open-pit and underground mining technology for residual coal of end slopes. *Mining Science and Technology (China),* Volume 20, Issue 2, 2010, pp. 266-270.

[14] SADOVSKIJ M.A. Evaluation of seismically dangerous zones in blasting. *Seismic Institute of the Academy of Sciences*, 1941, URSS. , in RATTI G. "On the effects of blast-induced vibrations", *Bulletin of Subalpina Mining Association*, 1966 III, n°3-4.

[15] BIRCH, W. J.; PEGDEN, M. Improved prediction of ground vibrations from blasting at quarries. *Mining Technology,* Volume 109, Number 2, 2000 , pp. 102-106.