Revista de Medio Ambiente Minero y Minería 4(1): 18-26. Junio 2019. ISSN 2519-5352

Assessment of blasts environmental sustainability in open pit mining – Case study in small and large Brazilian mines

Vidal Félix Navarro Torres[a], Sergio Médici de Eston[b], Wilson Siguemasa Iramina[c], Leandro Geraldo Canaan Silveira[d], João Henrique R odrigues Costa[e]

[a]Vale Institute of Technology, Belo Horizonte, Minas Gerais, Brazil, vidal.torres@itv.org
[b]São Paulo University, smeston@usp.br
[c]São Paulo University, wilson.iramina@poli.usp.br
[d] Vale Institute of Technology, Belo Horizonte, Minas Gerais, Brazil, leandro.silveira@itv.org
[e]Vale Institute of Technology, Belo Horizonte, Minas Gerais, Brazil, joao.costa@pq.itv.org

Abstract

Assessment of blasts environmental sustainability in open pit mining deals with the development and application of an innovative mathematical model for environmental sustainability evaluation based on characteristics and quality standards of several parameters of the main four environmental components (atmosphere, lithosphere, hydrosphere and biosphere). Due to the great complexity of environmental parameters in open pit mining, the developed mathematical model was validated for only ground vibration and airblast in small and large Brazilian open pit mines. In both cases, the research focuses are human discomfort and structural damage.

Keywords: Environmental Sustainability, blasts, mathematical model, open pit mining.

Evaluación de la sostenibilidad ambiental de explotaciones en minería a cielo abierto - Estudio de caso en minas brasileñas grandes y pequeñas

La evaluación de la sostenibilidad ambiental de explotaciones en la minería a cielo abierto se ocupa del desarrollo y la aplicación de un modelo matemático innovador para la evaluación de la sostenibilidad ambiental basada en las características y estándares de calidad de varios parámetros de los cuatro componentes ambientales principales (atmósfera, litosfera, hidrosfera y biosfera). Debido a la gran complejidad de los parámetros ambientales en la minería a cielo abierto, el modelo matemático desarrollado fue validado solo para la vibración del suelo y el chorro de aire en minas a cielo abierto brasileñas grandes y pequeñas. En ambos casos, los focos de investigación son la incomodidad humana y el daño estructural.

Palabras clave: sostenibilidad ambiental, explosiones, modelo matemático, minería a cielo abierto.

1. Introduction

Sustainable development is defined as the one that meets the needs of current generations without comprising the ability of future ages to achieve their own necessities (WCED, 1987). Furthermore, sustainability can be comprehended as every piece of action in order to follow the sustainable development and it is known fact that this concept must include at least three pillars, environmental, social and economic (Navarro Torres, V. F.; Gama, C. D., 2005). When the issue comes to mining activities, especially in open pit mining, the attention is focused on environmental impact related to the ore exploitation and increasing concern with sustainability in this sector has been noticed.

The exploitation of ore resources in open pit mines as well as in quarries frequently involves rock blasting operations. Nevertheless, according to Dinis da Gama (1998), only 5 to 15% of the energy released by blasts is used effectively to fragment rock. It means that the largest part is transferred to the surrounding environment in form of side effects, likely to cause significant structural damage and human discomfort, which consist the most common cause of concerns and protests by affected people in the neighbourhood of these works.

A thoroughly literature review has shown some scientific work has been performed aiming quantify sustainability, highlighting those ones from Yale Center for Environmental Law and Policy and the Center for International Earth Science Information Network, Columbia University between 1999 and 2005, which has monitored 21 sustainability indices, including present and past levels of pollution, for instance (ESI, 2005). However, there are not any papers related to quantification of environmental sustainability in open pit mining.

Recent researches on this topic correspond to those applied in underground mines (Dinis da Gama C., Navarro Torres V.F. et al, 2012, Navarro Torres.V.F. et al., 2009). Hence, a mathematical model to quantify sustainability in open pit mining is extremely significant.

2. Characterization of environmental impact in open pit mining

Open pit mining operations handle large volumes of ore and waste. As a result, during this process, there are risks of environmental impact on: atmosphere, underground and surficial water, rock mass and soil, biodiversity as well as the human being. Rock excavation modifies natural slopes, consequently altering its natural state of tensions. In its turn, use of explosives may cause ground vibration and air blast in the surrounding areas to blasts. Recent studies carried out in a city nearby an open pit mine, in Brazil, has shown that gases pollutants and respirable suspended particles generated by diesel oil emissions affects the respiratory system of people (Braga et al., 2007). Another environmental impact is the leaching that occurs when the water gets in touch with exploitation fronts or even with waste dumps and hence lead pollutants to rivers, lakes and aquifers.

Particle velocity vibration and frequency are the most used parameters in order to assess the side effects of rock blasts. According to Kahndelwal, M; Shing T.N (2006), frequency plays a key role in vibration analysis, because the response of the buildings nearby the seismic wave's propagation zones depends on ground vibration frequency.

Particularly, ground vibration might cause damage in buildings, whereby the safe peak rticle velocity for residential structures according to USBM is function of frequency (Table 1).

Table 1. Safe peak particle velocity for residential structures by USBM (Farhad F et al, 2014)

Type of structure	**Frequency (<40 Hz)**	**Frequency (>40 Hz)**
Modern homes-drywall interiors	19 mm/s	50 mm/s
Older homes-plaster on wood lath for interior walls	13 mm/s	50 mm/s

Human vibration sensibility depends on peak particle velocity level, vibration frequency, event duration and frequency of event. For values approximately below 2 Hz, the body acts as a unit mass. For sitting position, the first resonance is occurs between 4 and 6 Hz. On the other hand, for the standing one, resonance peaks occurs about 6 and 12 Hz. The USBM has suggested a human vibration sensibility basis of particle velocity (Table 2).

Table 2. Human ground vibration sensibility by USBM (Farhad F et al, 2014)

Effect on human	**Ground vibration level (mm/s)**
Imperceptible	0.025-0.076
Barely imperceptible	0.076-0.254
Distinctly perceptible	0.254-0.762
Strongly perceptible	0.762-2.540
Disturbing	2.540-7.620
Very disturbing	7.620-25.400

Eston (1998) carried out 133 measurements of primary and secondary blasts during 6 years, using engineering seismographs, in small Brazilian mines aiming at a behaviour analysis of ranges of particle velocity vibration and the frequencies as illustrated in Table 3 and Fig.2. Note that the majority of the vibration records are inferior to 5 mm/s and the frequency is less than 50 Hz.

Table 3. Percent per range of particle velocity vibration sum of small Brazilian mines

Range of particle velocity vibration sum (mm/s)	**Total (%)**
0-2,5	30
2,5-5	37
5-7,5	24
7,5-10	6
10-12,5	3

(Eston,1998).

In most cases of rock blasts in medium and large-scale open pit mining, the occurrence of frequencies are observed as shown in Table 4.

Table 4. Common frequencies in open pit mining (Farhad F et al, 2014)

Frequency type	Occurrence of 55 recorded frequencies for perpendicular components			
	1-4	**4-14**	**14-40**	**>40**
Transverse	13	5	0	0
Vertical	4	9	3	0
Longitudinal	10	11	0	0
Total	27	25	3	0

3. Mathematical modelling of sustainability in open pit mines

The environmental sustainability in open pit mining is based on main environmental components and it can be expressed by the Environmental sustainability index (ESI_O), as follows:

$$ESI_O = \frac{1}{N}(SI_a + SI_g + SI_w + SI_b + \cdots + SI_N) \quad (1)$$

Where: N is the number of possible environmental components, SI_a is the atmosphere sustainability index, SI_g is the geotechnical sustainability index, SI_w is the water sustainability index (surface and underground), SI_b is the biological sustainability index, related to animals and plants and SI_N is any other possible component.

All the sustainability indices of open pit mining will be calculated by a single equation, as follows:

$$SI_{a,g,w,b,N} = \frac{1}{n}\left\{n - \frac{\sum_{i=1}^{l_1} a_{1(i)}}{l_1 P_1} - \frac{\sum_{i=1}^{l_2} a_{2(i)}}{l_2 P_2} - \cdots - \frac{\sum_{i=1}^{l_n} a_{n(i)}}{l_n P_n}\right\} \quad (2)$$

Where: n is the number of pollutants, l_1, l_2,....,l_n are the numbers of evaluation/measurement locations, a_1, a_2,....a_n are the environmental parameters on evaluation and P_1, P_2,.....P_n are the admissibility standards.

A careful analysis of the environmental parameters in open pit mining has allowed a characterization of three groups, regarding their environmental effects and admissibility standards.

Based on these three groups of environmental parameters, considering Y as a minimum acceptable standard, X as a maximum permissible standard and x_i as the local condition of environmental parameters on assessment, it was developed mathematical expressions to calculate the sustainability index (SI) according to three criteria, taking into account a scale of 0 to one 1.

a) When $x_i \leq X$;
b) When $x_i \geq Y$ and;
c) When $Y \leq x_i \leq X$

The specifics cases of ground vibration and airblast correspond to first criterion (Fig. 3), which means $x_i \leq X$ and their general equation is as follows:

$$SI_1 = 1 - \left|\frac{x_i}{X}\right| \quad (3)$$

Conditions:

a) If $x_i = X$ or $x_i > X$, so $SI_1 = 0$;
b) If $x_i = 0$, so $SI_1 = 1$

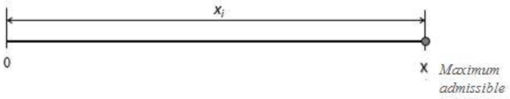

Fig. 1. First criterion of sustainability.

Moreover, it can be adopted levels of sustainability as presented in Table 4.

Table 4. Levels of sustainability.

Level of sustainability	Colour	ESI_O
High	🟩	$0.60 < ESI_O \leq 1.00$
Medium	🟨	$0.20 < ESI_O < 0.60$
Low	🟥	$0.00 < ESI_O \leq 0.20$

4. Case studies – model validation for ground vibration and airblast.

4.1. Small mine

4.1.1. Description of the area

The Juruaçu open pit mine is located in Perus, state of São Paulo, Brazil, 30 km distance from the homonym capital. Its mining activity consists of sand and rock exploitation and then further processing to civil construction. It is carried out detonations of explosives charges to fragment granitic rock, which is transported by conveyor belts to successive stages of grinding, until reach the specified size. The annual average production rounds 1.8 Mt and the waste withdrawal is 180.000 m^3.

The mine is located in crystalline terrains of the São Roque Group, in the geomorphological province of Atlantic plateau, subdivision ridge of São Roque Zone (IPT, 1981). This group is mainly compounded of clastic sediments, predominantly clayey nature, metamorphosed into phyllites. Besides, it can be observed outcrops of conglomeratic metasediments, amphibolites, limestone and abundantly intrusive granites (Coutinho, 1972). The Atlantic plateau mainly consists of crystalline rocks, Precambrian and Cambro-Ordovician, cut by covers of sedimentary basins of São Paulo and Taubaté and by intrusive basic rocks and alkaline Mesozoic-Tertiary (IPT, 1981). The ridge of São Roque comprises an extensive mountainous area of diverse lithology ranging from low-grade metamorphic to migmatic and gneissic rocks with granitic intrusions.

Moreover, rounded top hills with restricted ridges and slopes with straight profiles, sometimes abrupt, characterize the relief of Juruaçu area. Drainage is high density with restricted interior alluvial plains, closed valleys with dendritic pattern (IPT, 1981).

4.1.2. Monitoring of ground vibration and airblast.

It was carried out the monitoring of 4 blasts in distinct days and it was installed 20 engineering seismographs at several points surrounding to the detonation of explosive charges area in order to record particle velocity vibration (mm/s) and airblast (dBL). The equipment was from GEOSONICS®, fifteen SSU 3000EZ + model with the following serial numbers: SN 8894, SN8895, SN 8896, SN8897, SN 8947, SN8849, SN 8950, SN 8951, SN 8952, SN 8953, SN 8954, 8955 SN, SN 8956, SN 8957 and five SSU 3000LC model with serial numbers SN3700, SN 3702, SN3706, SN 3707, SN 3708. Furthermore, they were set for a trigger of 0.18 to 0.5 mm / s and temporal window of 5 s. The main blast parameters can be seen in Table 5.

Table 5. Blast parameters in Juruaçu mine

Blast identification	No. of Blast holes	Blast hole diameter (in)	Burden (m)	Spacing (m)	Delay (ms)	MCPD (Kg)
1-16/10/2012	168	3.5	2.8	2.6	5/42/75	90
2-07/11/2012	147	3.5	2.8	2.5	42/75	102
3-16/11/2012	125	3.5	2.6	2.5	42/75	98
4-28/11/2012	157	3.5	2.8	2.5	25/42/75	98

4.1.3. Recorded database and propagation law of vibration

All 71-recorded data of airblast in the measurement points were plotted in function of its distance from the respective source and presented in Fig. 5. It is noticeable that the major airblast values occurs on short distances and lessen when the space between the measure and the blast becomes larger, for a R squared of 0.57.

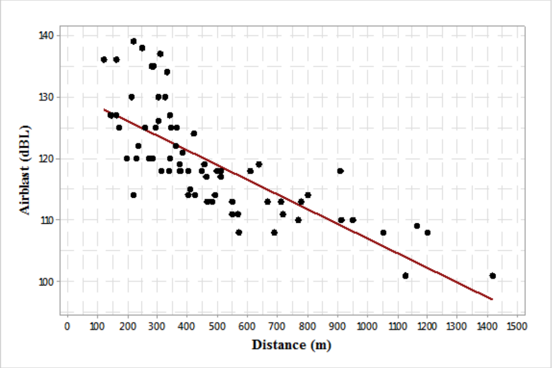

Fig. 2. Airblast versus distance for Juruaçu mine data.

Several authors (Dinis da Gama, 1998; Holmberg, 2000) recognized that the most utilized equation in science in order to describe the behaviour of seismic waves in the ground, generated by blast is the following:

$$v = aQ^bD^C \quad (4)$$

Where: v is the particle velocity vibration sum (mm/s), Q is the maximun explosive charge per delay (Kg), D is the distance between the blast and measurement points and a, b, c are the constants of locations and particularities of the blast.

From this equation it can be obtained a chart of iso-velocities of vibration (an accurate map of vibration generated by kriging interpolation between known points), once that recorded data of vibration would be available to attain this relation and thus recalculate the vibration velocity. In this way, as depicted in Fig. 6, it was used the statistic software LABFit® to plot all data of particle vibration velocity recorded, together with maximum explosive charge per delay and the distance.

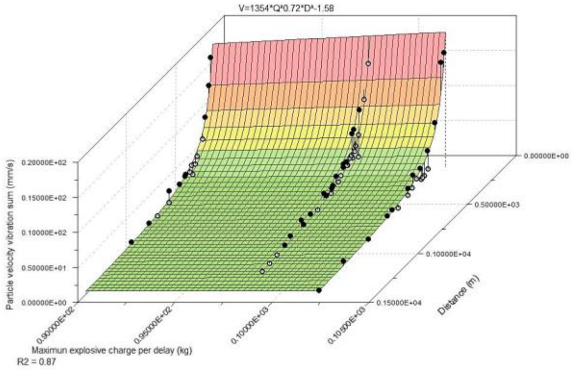

Fig. 3. Particle velocity vibration versus maximum explosive charge per delay and distance for Juruaçu mine data.

The statistical data processing has allowed obtaining the propagation law of vibration, for a correlation of 0.87, as expressed:

$$v = 1354.Q^{0,72}.D^{-1,58} \qquad (5)$$

The constants value is quite similar to those descripted by various authors and organized by Navarro Torres VF & Bernardo P (2004), thus ensuring more trust on this parameters and hence constituting a powerful tool to recalculate the vibration velocity and then calculate the sustainability indices.

4.1.4. Environmental sustainability index

There are not any Brazilian official standards of human comfort whereby it was applied the standard CETESB D7.013 (2015) from the state of São Paulo, Brazil, (mine location), maximum limit of 4.2 m/s. Using (2), the particular equation to calculate the geotechnical sustainability index in any point due to ground vibration is:

$$SI_{gv} = 1 - 0,238\,v \qquad (6)$$

Where: v is the particle vibration velocity sum (mm/s).

By its turn, it was also applied (2) to calculate the atmospheric sustainability index due to airblast, regarding CETESB D7.013, maximum value of 128 dBL, as follows:

$$SI_{ap} = 1 - 0,0078\,p \qquad (7)$$

Where: p is the airblast (dBL).

From any point and its respective SI_{gv} and SI_{ap}, it can be generated a contour map of environmental sustainability, using the software Surfer®, as depicted in Fig. 7. Note that, in areas closer to the community, the mine operates with an Environmental sustainability index of round 0.5, which we considerate a medium level of sustainability. The worst values, less or equal to 0.2, occurs inside and around the pit, which is explicated by the highest levels of vibration and airblast due to the short distance between measurement points and source.

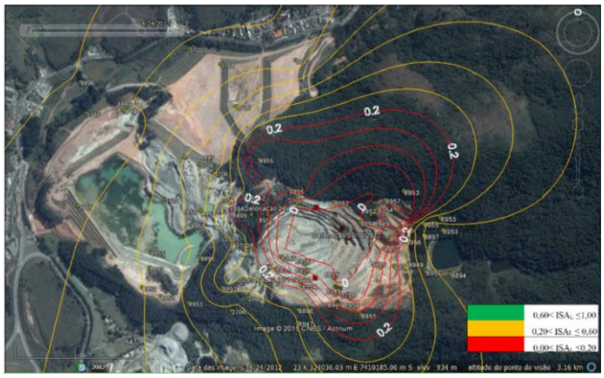

Fig. 4. Contour map of sustainability at Juruaçu mine.

Moreover, this mine sustainability can be evaluated as a whole by the calculus of Environmental sustainability index (ESI_O) using (1) and (2), as presented in Table 6.

Table 6. Levels of sustainability for Juruaçu mine.

SI	Value	Classification
SI_{gv} $(due\ to\ ground\ vibration)\ glo$	0,35	Medium
SI_{ap} $(due\ to\ airblast)\ global$	0,08	Low
$ESI_O\ global$	0,22	Low

4.2. Large scale mine

4.2.1. Description

Fazendão is an open pit mine located in Mariana, state of Minas Gerais, Brazil, 140 km of distance from its capital, Belo Horizonte. It is property of VALE.S.A., within the “Quadrilátero Ferrífero”, an area of intense iron mining activity, which consists its work. The Quadrilátero Ferrífero is considered as one of the most important mineral provinces in the world, comprising important deposits of iron, as well as gold and manganese. The large iron ore reserves are found in metamorphic Precambrian rocks of Paleoproterozoic Cauê Formation, offering great economic interest due to its grade and extent.

4.2.2. Monitoring of ground vibration an airblast

As the main objective of this study was to validate the model, it was used the data base relative to the monitoring carried out by Sequência Engenharia Projetos e Meio Ambiente Ltda (2014; 2015). In order to record ground vibration and airblast it was used 6 Instantel Inc. seismographs model: MiniMate DS-077 Série II, MiniMate Plus, MiniMate Pro4 e MicroMate, with the following serial numbers: 4499, 5935, BE 17764, BE17765, MP 12698 and UM 6308. They were located in two points, called “Igreja” and “Casa” in the community surrounding to the mine so as to register the parameters related to its respective monitored blasts, as depicted in Fig. 9 and 10. Furthermore, they were set for a trigger of 0.51 mm/s and temporal window of 5 s. Blast parameters or even blast design were not informed.

Fig. 5. Blasts monitored by point “Igreja”.

Fig. 6. Blasts monitored by point “Casa”.

4.2.3. Recorded data base and statistical data treatment.

It was not possible to obtain the propagation law of vibration due to the great number of measurements in only two points, therefore it has become necessary a statistical data treatment, using in this case the software Minitab®, in order to obtain the most representative value of particle velocity vibration and airblast for the evaluation locals to apply in the model. Fig. 11 presents the histogram with fit, regarding the identified distribution, for particle velocity vibration at the point “Igreja”.

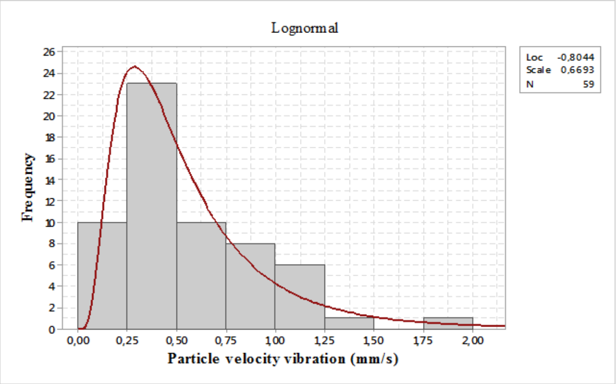

Fig. 7. Histogram with fit for particle velocity vibration sum at point “Igreja”.

Fig. 12 represents the histogram with fit, regarding the identified distribution, for airblast at the point “Igreja”. We have noticed that Weibull distributions have shown bigger p – value than the Normal distribution, however we have assumed the second one, supported by the Central limit theorem, which states that the majority of random phenomena could be approximate to normal distributions, when the randomness of a physical phenomenon is the accumulation of small additive random effects (SOONG, 2004).

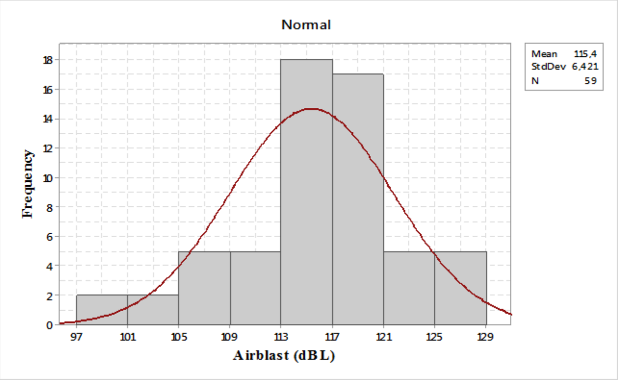

Fig. 8. Histogram with fit for airblast at point “Igreja”.

Once again, Fig. 13 and 14 represents the histogram with fit for particle vibration velocity and airblast, but this time for the point “Casa”. The interpretation was based on Central limit theorem. Table 7 summarizes the statistical analysis, showing the expectancy for the mean value for all data set.

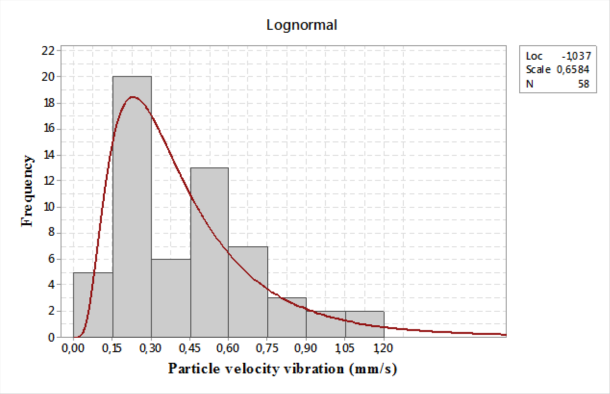

Fig. 9. Histogram with fit for particle velocity vibration sum at point “Casa”.

Point	SI_{gv}		SI_{ap}
Igreja	0,93		0,10
Casa	0,94		0,10
SI_{gv} **global**	0,94	SI_{ap} **global**	0,10

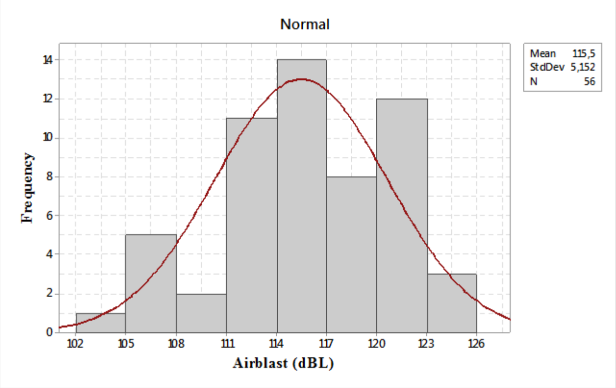

Fig. 10. Histogram with fit for airblast at point “Casa”.

Table 7. Summary of statistical analysis

4.2.4. Environmental sustainability index

1. Aiming calculate the geotechnical sustainability index due to ground vibration, (SI_{gv}) it was applied the standard CETESB D7.013 from the state of São Paulo, Brazil, maximum limit of 4.2 m/s for human comfort. Additionally, if we evaluate the structural damage, applying the American standard, USBM (RI 8507), for instance, which establish the maximum limit of 13 mm/s for dominating frequencies below 40 Hz in old buildings the particular equation from (2) results a SI_{gv}, as follows:

$$SI_{gv} = 0{,}5(2 - 0{,}238v - 0{,}08\, v) \tag{8}$$

Where: v is the particle vibration velocity sum (mm/s)

In its turn, it was also applied (2) to calculate the atmospheric sustainability index due to airblast, regarding CETESB D7.013, maximum value of 128 dBL, as follows:

$$SI_{ap} = 1 - 0{,}0078\, p \tag{9}$$

Where: p is the airblast (dBL).

Table 8 and 9 presents the results from (5) and (4) for the measurement points and the global value of Environmental sustainability index from (1) with its classification, respectively.

Table 8. Sustainability indices for measurement points in Fazendão mine.

Table 9. Levels of sustainability in Fazendão Mine.

SI	Value	Classification
SI_{gv} $(due\ to\ ground\ vibration) glo$	0,94	High
SI_{ap} $(due\ to\ airblast)\ global$	0,10	Low
$ESI_O\ global$	0,52	Medium

In order to provide a better view of how does the Sustainability indices vary, it was built a radar chart as depicted in Fig.15.

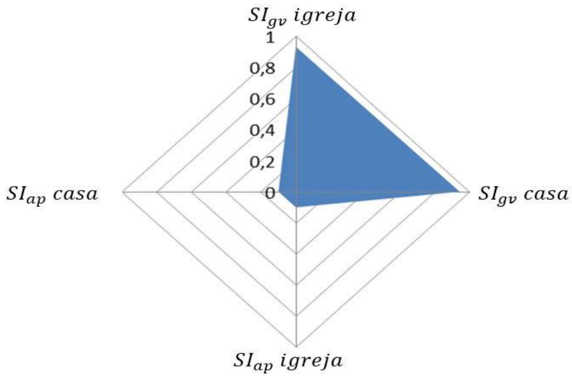

Fig. 11. Radar chart of sustainability in Fazendão mine.

5. Conclusions

The developed mathematical model quantifies environmental sustainability in open pit mining through the Environmental sustainability Index expressed in the scale 0 to 1, where values close to zero reflect the proximity to the permissible value. On the other hand, indices near to one can be interpreted as an absence of pollutant.

The model validation for two parameters (ground vibration and airblast), in small and large scale mines, shows its great potential in the assessment and management of environmental sustainability in open pit mines.

To ensure a properly assessment of sustainability in Fazendão Mine, it would be necessary a major number of measurements points. Nevertheless, once that our aim was to validate the model, the database was sufficient.

2. Acknowledgments

Authors would like to thank Vale Institute of Technology for support this research project. Thanks, are also due to the Vale- Fazendão Mine for providing the necessary data. In addition, authors would also like to express their deep-felt gratitude to USP – Universidade de São Paulo for the partnership and availability during the scientific work.

3. References

1. **2005 Environmental Sustainabilty Index (ESI)** (2005). New Haven, Conn.: Yale Center for Environmental Law & Policy. 2005.

2. Braga, A. L. F; Pereira, L. A. P; Procópio, M.; André, P.A Saldiva, P. H. **Associação entre poluição atmosférica e doenças respiratórias e cardiovasculares na cidade de Itabira, Minas Gerais, Brasil. Rio de Janeiro: Cad. Saúde Pública**, *Sup* 4:S570-S578,2007. 9 p.

3. Dinis da Gama, C. **"Ruídos e Vibrações Ligados à Utilização dos Explosivos e Equipamentos"**. *Comunicações do 1º Seminário de Auditorias Ambientais Internas. Divisão de Minas e Pedreiras do Instituto Geológico e Mineiro de Portugal.* 1998.

4. Dinis da Gama C, Navarro Torres VF and Verissimo AC. **Scienfific Final Report WP 6: Environmental Assessment of UCG and CO2 Storage**, European Project, 2012, 23p.

5. Coutinho, J.M.V. **Petrologia do pré-cambriano de São Paulo e arredores**. *Boletim IG- USO, v.3.* São Paulo. 1972, p 5-99.

6. Farhad F, Mohammad Ali EF and Hamid M. Simultaneous investigation of blast induced ground vibration and airblast effects on safety level of structures and human in surface blasting. **International Journal of Mining Science and Technology** 24 (2014) 663–669 p.

7. Holmberg, R. – Explosives and Blasting Technique. Proc. 1st **World Conference on Explosives & Blasting Techniques**. A. Balkema, Rotterdam. 2000

8. Eston, S. M. **Uma análise dos níveis de vibração associados a detonações**. São Paulo: Escola Politécnica da Universidade de São Paulo. Doctoral thesis. 1998. p 101-103.

9. Instituto de Pesquisas Tecnológicas do Estado de São Paulo – IPT. **Mapa Geomorfológico do Estado de São Paulo**. Escala 1: 1000.000. São Paulo. 2 V. Publication IPT Nº 1.183, 1981.

10.Kahndelwal, M.; Shing TN. Prediction of blast induced ground vibrations and frequency in opencast mine: a neural network approach**. JSound Vib**. 2006. 289 p.

11.Navarro Torres V.F; Bernardo P. *El "Blastware III" e "Mlinreg.bas" como herramientas para la prevención y control ambiental de vibraciones en voladuras.* **V Simposium Internacional de Tecnología de la Información Aplicada a la Minería** 14 – 17 de setembro, Lima-Perú. 2004. 20 p.

12.Navarro Torres, V. F.; Dinis Da Gama, C. **Engenharia ambiental subterrânea e aplicações.** Rio de Janeiro: CETEM/CYTED, 2005. 550 p.

13.Navarro Torres, V.F.; Dinis Da Gama, C. **Environmental sustainability index of geotechnical works**. Geotechnical National Congress. Lisboa, 2009, 10pp.

14.Soong, T.T. **Fundamentals of Probability and Statistics for Engineers**. State University of New York at Buffalo, Buffalo., New York. USA. 2004, p 199.

15.Sequência Engenharia Projetos E Meio Ambiente Ltda. **Relatório de monitoramento sismográfico. Mina de Fazendão**. 2014. 232 p.

16.Sequência Engenharia Projetos E Meio Ambiente Ltda. **Relatório de monitoramento sismográfico. Mina de Fazendão**. 2015. 208 p

17.WCED (World Commission on Environment and Development). **Our Common Future.** Oxford: Oxford University Press, 1987. 300 p.

Artículo recibido: 13.02.2019
Aceptado en: 08.03.2019