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Overbreak prediction of tunnels carved in rock mass through exponential smoothing: case study of tunnel in Brazil

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Fábio José Generoso[1,5]
https://orcid.org/0000-0003-4526-6462
André Cezar Zingano[2,6]
https://orcid.org/0000-0002-3740-9104
Irce Fernandes Gomes Guimarães[3,7]
https://orcid.org/0000-0002-6530-9434
Rogério Aguirre Dias[4,8]
https://orcid.org/0000-0002-5406-3141

[1]Instituto Federal do Norte de Minas Gerais – IFNMG,
Departamento de Infraestrutura,
Pirapora - Minas Gerais - Brasil.

[2]Universidade Federal do Rio Grande do Sul – UFRGS,
Departamento de Engenharia de Minas,
Porto Alegre – Rio Grande do Sul - Brasil.

[3]Universidade Federal de Ouro Preto – UFOP,
Escola de Minas, Departamento de Engenharia de Produção, Ouro Preto – Minas Gerais - Brasil.

[4]Toniolo, Busnello S.A,
Departamento de Engenharia,
Porto Alegre - Rio Grande do Sul - Brasil.

E-mails: [5]fabio.generoso@ifnmg.edu.br, [6]andrezin@ufrgs.br, [7]profirce@yahoo.com.br, [8]rogerio.aguirre@tbsa.com.br

Abstract

Among several works, constructions in rock masses are the most complex in engineering, due to many uncertainties of the environment. Tunnel construction is a case in point. A common problem found in tunnel excavations with the use of explosives is the occurrence of overbreak beyond the boundary line of the tunnel. Many researchers worldwide have proposed forecasting techniques based on the use of regression models or machine learning, however, these require many samples and variables, such as the explosive rate and rock mass. Predicting overbreak before blasting is essential in project management, as it can modify parameters of the blasting plan, design, schedule and employee safety. Therefore, this study sought to employ an exponential smoothing model, which could predict the percentage (%) of overbreak in a tunnel section, based solely on the previous overbreak values. This time series methodology has never been used before in tunnel excavations, although it is used in the financial market. The technique was tested in one Brazilian tunnel. The model proved to be very efficient in predicting overbreak in tunnel construction, since it can be adjusted at each advance. The model can be adjusted as a function of α: where α is close to zero, the model prioritizes past events, while for α close to 1, it prioritizes recent events. The best fit occurred with $\alpha = 0.9$; $0<\alpha<1$.

Keywords: tunnel; overbreak; exponential smoothing; time series.

1. Introduction

Studies have shown that as early as prehistory, Man was already using caves as shelter and also as a place for source of food. There are also occurrences of aqueduct constructions in Jerusalem as well as many others built during the Roman Empire. However, with population growth and overcrowding in large centers, alternative spaces have been sought, of which underground space is one. Tunnels have been a good solution, since they interfere little with the landscape and do not significantly "harm" the environment. Currently, the use of tunnels is being applied in more ways, such as road, rail and mining. For example, they are being used as channels to capture flood water in large urban centers. Worldwide, one of the most significant tunnel constructions is the English Channel, a submerged tunnel connecting England with France, extending for a length of 50 kilometers.

For Geraldi (2011), rock tunneling or dismounting is achieved using mechanized techniques or explosives, which alongside additional services, seek to excavate, cut and fragment soil and/or rock mass, in order to meet civil and environmental requirements. Among these construction techniques are explosive excavation and mechanical excavation - TBM (Tunnel Boring Machine) and NATM (New Austrian Tunnelling Method). Each one has its features, depending on the cost and on the interference in the adjacent mass. Another important variable regarding tunnel constructions is the recognition and the classification of rock mass for the site on which the construction will be carried out. One of the most important stages, and also, the most subject to uncertainty is drilling, and consequently, the rock mass' geomechanical classification. Inherent to tunneling in rock mass, in particular those that use explosives, is the "damage" caused in the mass and overbreak and underbreak should be highlighted. Figure 1 demonstrates these undesirable effects.

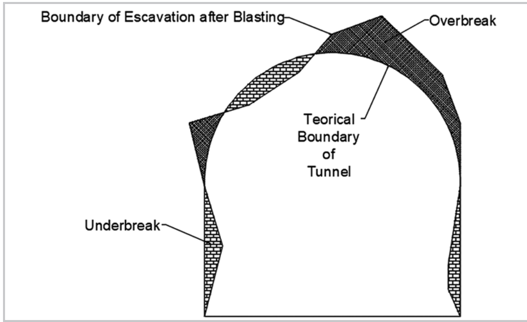

Figure 1 - Real and theoretical section of a tunnel.

One of the main challenges in tunnel engineering is to minimize this damage, but due to the great uncertainties and variability existing in natural rock mass, simulation and statistical prediction tools are required in order to predict, within a certain variability, or better, a certain confidence interval, the percentage (%) of overbreak and underbreak. Ibarra *et al.* (1996) state that in addition to the geological factors, the operational procedures also contribute to the occurrence of underbreak and overbreak. It is difficult to get and control many variables that govern these phenomena. Thus, researchers have been broadly looking for accurate prediction tools with less need for input data and computational resources.

2. Review

2.1 Geomechanical classification of rock mass

One of the most important tools in Rock Mechanics is geomechanical classification. There are innumerable classifications in technical literature worldwide, and each one with its own pertinent characteristics. These classification systems were developed by their authors based on several real observations of constructions, so it is extremely important to adopt the correct parameters relating to each specific system of classification. Nevertheless, there is a wealth of experience in this area. Among the most prevalent classifications are RMR – Rock Mass Rating (Bieniawski, 1989), RMi – Rock Mass Index (Palmstrom, 1996) and System *Q* (Barton *et al.*, 1974).

2.2 Geomechanical classification system - *Q* system

The *Q* system for rock mass classification is one of the most popular for projects for tunnel support. This was developed in 1974 by Barton, Lien and Lunde, in the Norwegian Geotechnical Institute, and was based on 212 real cases of tunnel construction in Scandinavia (Bieniawski, 1989). Barton *et al.*, (1974) proposed the classification based on Equation (1):

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \qquad (1)$$

where *RQD* is the rock quality designation index (Deere, 1963); J_n is the joint family number; J_r is the joint roughness number; J_a is the joint alteration number; J_w is the joint water reduction factor and SRF is the Stress reduction factor.

As it is noticed, such factors are achieved through tables developed by the authors, where each observation in loco results in a map of characteristics which will be rated by values obtained (Barton *et al.*, 1974), as they were surveyed in the field observation along the tunnel.

When applying these tabulated values to Equation 1, a numerical, quantitative value is achieved. With this *Q* value, the rock mass can be classified. See Table 1.

Table 1- Rock mass classes according to the *Q* parameter.

Geomechanical pattern of the mass	Q Values	Numerical Classification
Exceptionally poor	< 0.01	IX
Extremely poor	0.01 – 0.1	VIII
Too poor	0.1 – 1.0	VII
Poor	1.0 – 4.0	VI
Regular	4.0 – 10.0	V
Good	10.0 – 40.0	IV
Very good	40.0 – 100.0	III
Extremely good	100.0 – 400.0	II
Exceptionally good	400.0 – 1000.0	I

2.3 Reasons for overbreak

According to Jang & Topal (2013), overbreak is an area of the tunnel which has been excavated to excess, beyond the design boundary. It may occur in any type of method of underground excavation, and is an unavoidable consequence with the drill and blast technique.

For Nieble (2017), the damaging effect is part of the rock blasting and may bring neighborhood problems, as well as instability. It may also cause blocks and cracks, affecting the number of discontinuities and reducing the mass quality.

Singh & Xavier (2005) also observe that the accomplishment and the blasting plan, the characteristics of the explosives, in addition to the geological factors, contribute to the occurrence of these damages. For Dias (2011), Figure 2 shows overbreak generated by geological structures and by the drilling operation, respectively.

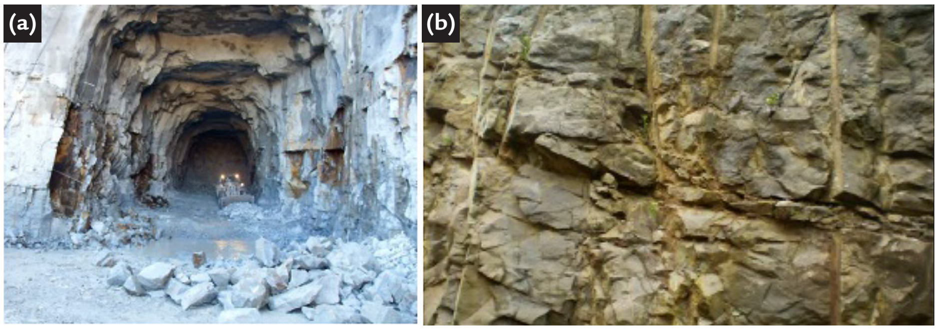

Figure 2 - (a) Overbreak generated by geological structures (discontinuities). (b) Sample of overbreak generated by deviations from controlled holes.

2.4 Theoretical review and characteristics of the site

The tunnel used for this study is located in gneiss rocks. Its geomechanical classes and geometry of the sections are shown in Table 2.

Table 2 - Geometric and geomechanical characteristics of the tunnel and rock mass, respectively.

	Average design cross-section area (m^2)	Class Q Barton *et al.* (1974)
Tunnel	133.25	III
		IV

The rock mass geomechanical classification ranges between classes III and IV according to the Q classification of (Barton *et al.*, 1974) and can be defined as a very friable material (classes III and IV).

2.5 Simple exponential smoothing – (SES)

Simple exponential smoothing models (SES), similarly to the moving average models, are based on previous data to understand the behavior of the series. However, in the first, different weights are assigned to each term of the series, unlike the moving average which standardizes the weight to all the terms for the prediction (Xavier, 2016).

Pellegrini & Fogliatto (2001) state that the simple exponential smoothing model can be expressed by Equation (2).

$$\hat{Z}_{t+1} = \alpha z_t + (1- \alpha)\hat{z}_t \qquad (2)$$

where z_t is the current level; α is the smoothing or weight constant, where $(0 < \alpha < 1)$; $\hat{z}_t$ is the last estimated value, and $\hat{z}_{t+1}$ is the next estimated value.

The prediction starts with a random α, which can be optimized by computational calculations or manually. The model's performance can be analyzed by comparing it through the mean square errors (MSE), whereupon α minimizes the (MSE) (Pellegrini & Fogliatto, 2001).

2.6 The state of the art

In the last years, several authors have sought to discover models to predict overbreak occurrences in underground tunneling. Most models in literature use linear and non-linear regressions and machine learning algorithms.

Among these authors, we can mention some such as: one of the pioneers, Ibarra *et al.* (1996) who, in their multiple linear regression model, require as input variables, the explosive rate at the edge of the tunnel and the Geomechanical Classification System - Q system (Barton *et al.*, 1974). Other authors have proposed a Wavelet Neural Network model, where the variables are; discontinuous orientation, trace length and spacing. According to Mottahedi *et al.* (2018), its model is based on fuzzy, Support Vector Machine (SVM), Artificial Neural Network (ANN), Multiple, linear and non-linear regressions, where the input variables are: specific charge, specific drilling, ratio of amount of charge in contour holes to the burden in contour, tunnel cross section area and RMR

A summary of the most recent studies on predicting overbreak in underground tunneling can be seen in Mottahedi *et al.* (2018). Several of these models, especially those that use artificial intelligence, require a huge amount of data for modeling, which is not unusual. On the other hand, the model applied in this study, (SES), requires only the measurements of overbreak from the previous sections, and a simple computational resource, with just an electronic spreadsheet, which makes the operation *in loco* easy.

3. Method

In this study, the cross sections of one tunnel, set in Brazil is used. The rock mass in which the tunnel is inserted consists of sections in soil, rock and a combination of soil and rock. The sections excavated in soils were excluded from the study. Cross sections excavated in rock are predominately excavated in *Q* system© classes III and IV (Barton *et al*., 1974). The tunnel is 216.35 m long, where the areas of 36 cross sections were measured, and their respective overbreak, all sequential and equally spaced every 2.5m. The quantitative values of the *Q* classification, Barton *et al*. (1974), section by section, were not provided by the contractor of the construction. Likewise, the exact description of the construction cannot be published, since the contractor requested confidentiality. The company, in charge of carrying out the excavation, kindly provided only the qualitative classification of the rock mass, the section area of the tunnel project and the real area after blasting. Under this experimental condition, the challenge is to estimate the overbreak of the next cross section based only on the measurements of overbreak in the previous sections. For the tunnel under this study, the rock mass class and the percentage area of overbreak in relation to the design cross-sectional area were tabulated. It was a condition to make the modelling and the application more generalized. In this study, only the overbreak prediction will be considered.

4. Results and discussion

Models with α = 0.2, α = 0.5 and α = 0.9 were randomly chosen and verified in Equation (2). However, the best adjustment was for α = 0.9; where (MSE) was the smallest. See Table 3.

Table 3 - Synthesis of the (MSE) for the tunnel.

α chosen	α =0.2	α =0.5	α =0.9
MSE	413.87	263.98	199.42

Only the results of simulation for the most favorable situation, that is for α = 0.9, will be shown, since the calculation is similar. One option would be to use a software to obtain an optimized α that could provide a lower MSE.

Table 4 displays the measured values of the % overbreak for the tunnel, and the % overbreak predicted by the model, for each section, including the average value. It can be noted that the values of predicted overbreak and the real % overbreak of the first section are the same. The reason is that the model needs a previous value to predict the next one, so this assumption must be assumed. Figure 3 shows a flowchart where Equation (2) was applied in an initial section of Table 4.

Table 4 - Predicted and real % overbreak for each section and class of the mass from Tunnel.

Section	Rock Mass Class	Predicted % Overbreak	Real % Overbreak	Section	Rock Mass Class	Predicted % Overbreak	Real % Overbreak
1	III	15.17	15.17	19	IV	9.84	8.75
2	III	15.17	11.78	20	IV	8.86	8.00
3	III	12.11	5.63	21	IV	8.09	6.66
4	III	6.28	4.42	22	IV	6.81	7.68
5	III	4.60	3.09	23	IV	7.59	5.06
6	III	3.24	3.08	24	IV	5.31	4.86
7	III	3.10	5.68	25	IV	4.91	5.07
8	III	5.42	6.76	26	IV	5.06	7.46
9	III	6.62	6.72	27	IV	7.22	8.39
10	III	6.71	4.08	28	IV	8.27	8.34
11	III	4.34	4.00	29	IV	8.33	8.58
12	III	4.03	4.09	30	IV	8.56	9.44
13	III	4.09	6.78	31	IV	9.35	8.12
14	III	6.51	9.26	32	IV	8.24	6.45
15	III	8.98	7.97	33	IV	6.63	2.95
16	III	8.07	7.09	34	IV	3.31	4.82
17	III	7.19	5.14	35	IV	4.67	10.87
18	IV	5.34	10.34	36	IV	10.25	10.69
				Average		7.17	7.03

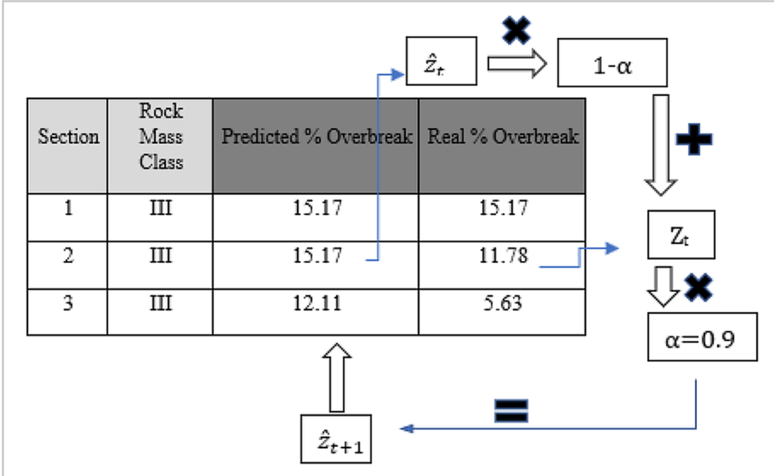

Figure 3 - Flowchart of applying of the model.

Figure 4 offers a broader picture between the predicted and real values of the % overbreak, along the 36 continuous sections of the tunnel. It is possible to compare the variability for each mass class zone Q; III and IV.

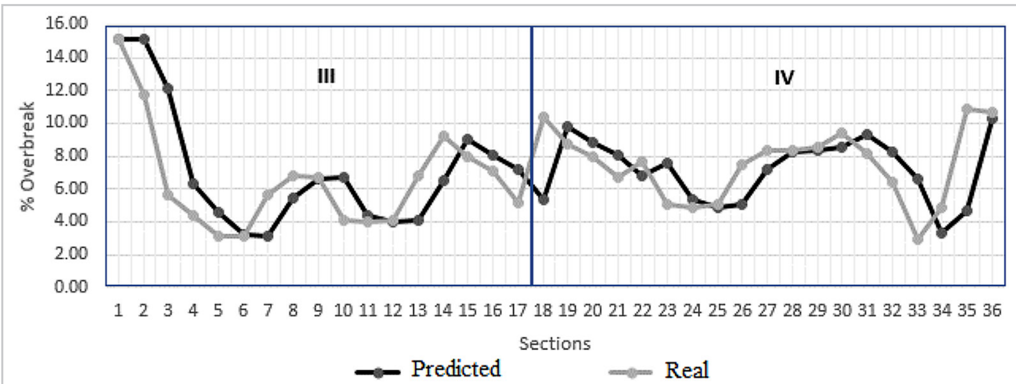

Figure 4 - Values of predicted and real % overbreak along the sections of the tunnel.

Note that although the tunneling sections are in the same classification zone of the rock mass class, there are still some outliers; for example, sections 2, 3, 18 and 35, among others in Figure 4. The reason for these can be explained by the failures in both the rock mass and the pre-existing blocks, where the failure plans, along with the tunneling line, lead free faces to the detachment of these blocks, resulting in pre-existing overbreak. Geological overbreak is one reason behind such occurrences; although there are operational factors, such as the amount of explosives and deviation of holes that can also cause overbreak.

5. Conclusions

This study has shown that the simple exponential smoothing model (SES) is well suited as a tool for predicting overbreak. Although several forecasting methods are already being used, as evidenced in the published literature, they are often complex models to both understand and apply in loco, and therefore require computational knowledge. The (SES), on the other hand, is a simple model which can be easily applied to the field routine, including the adjustment of the α, to minimize the MSE. It requires only overbreak measurements for each cross section, which can be obtained using a topographical instrument - such as a laser scanner -, and an electronic spreadsheet.

It is worth mentioning here that this article is part of a doctoral thesis in which two other tunnels were also studied with the massif classes II, III, IV and V of the Q system, (even more extensively than the tunnel in this study), proving that the (SES) model is a good fit for predicting overbreak in tunnel construction.

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