A new methodology to estimate the powder factor of explosives considering the different lithologies of volcanic lands: a case study from the island of Tenerife, Spain

E. de Miguel-García[a,b*], J.F. Gómez-González[b]

[a] Department of Agrarian, Nautical, Civil and Maritime Engineering, University of La Laguna, 38071 La Laguna, Tenerife, Spain.

[b] Department of Industrial Engineering, University of La Laguna, 38071 La Laguna, Tenerife, Spain.

*Corresponding author:

Address: Department of Agrarian, Nautical, Civil and Maritime Engineering, University of La Laguna, 38071 La Laguna, Tenerife, Spain.

Phone: +34 922318240

E-mail: emiguelg@ull.edu.es

Abstract

Many populations live on small islands where there are no naturally occurring rivers and lakes. Therefore, they need to look for underground water sources that involves the use of complex, expensive civil engineering operations which normally use explosives. An adequate prediction of the amount of explosive and performance of blasts is essential for a proper drilling plan. In the present work, a new methodology is proposed to estimate the consumption of explosives with respect to each type of rock drilled, based on a regression model that relates the geomechanical characteristics of the rocks with the progress made with each blast. The model is obtained using real data from the drilling of 85.70 m in a water tunnel with a cross section of 4 m^2 on a volcanic island. The blast used gelatin-based explosives based on nitroglycol, placed according to the drilling and blasting pattern for tunnels (structure to capture groundwater). The extracted rocks were mechanically characterized (density, porosity and point load strength index) and correlated with the powder factor. A methodology based on a regression model was constructed with this information that allows predictions of the powder factor, number of blasts and the amount of explosive needed as a function of the geomechanical properties of the tested rocks. The blasting progress had a non-linear relationship with the geomechanical parameters of the different lithotypes. The data show that advance is strongly non-linearly correlated with the porosity and the point load strength index of the rock. The regression model will be useful in the design of tunnel construction projects, as it can provide a better estimation of duration and costs of civil works than those used at present.

Keywords: tunnel, blast, powder factor, advance, lithology.

1. Introduction

Approximately 22.4 % of fresh water is groundwater (Barberis, 1991) and this is the main water resource in semi-arid areas. It is necessary to sink wells and build horizontal tunnels in places to access fresh water where it accumulates underground. The origin of water tunnels goes back to the 8th century BC in the Middle East and then spread to the rest of the world (Cyprus, Sicily, Morocco, Spain, Mexico, Peru, etc.) (Nasiri and Mafakheri, 2015).

A common technique used in the particular case of the Canary Islands for the construction of wells and small tunnels involves the use of explosives (Lopez Jimeno et al., 2017). Therefore, the blast design is of great importance to determine the amount of explosive and its distribution according to the tunnel cross-section of the opening of the tunnel and the pull or advance required in each blast. Different authors have developed the design of parallel hole-cuts (Holmberg, 1982; Langefors and Kihlstrom, 1973; Persson et al., 1993). The existing documentation describes different types of drilling patterns based on the spacing between boreholes as well as the charge per borehole, taking into account the characteristics of the lithology. The powder factor and the advancement rate are theoretically obtained when the blast is designed, using the above parameters. Furthermore, the powder factor is defined as the quantity of explosive used per unit of rock blasted (kg/m^3). In the blast design, the geomechanical characteristics of the rocks to be blasted are taken into account, as well as the geometric design of the drilling pattern. The value of the constant 'c' of the rock in the formula described by Langefors and Kihlstrom takes the type of lithology into account (Langefors and Kihlstrom, 1973).

A study in two tunnels in Korea led to the development of a computerised design for tunnel blasting (Lee et al., 2005), which proposed a change in the method of obtaining the value of the constant 'c'. The above study, based on 23 blasts, analysed the relationship between the values of 'c' and the value of RMR (Rock Mass Rating) (Bieniawski, 1973) and a modification was proposed to the Langefors formula, considering an advance of more than 85% and an ideal charge concentration, $c = 5.73 \times 10^{-3} \times RMR + 0.057$. Therefore, in drilling where there is a wide variation in the geomechanical characteristics of the lithology to be drilled, the determination of the amount of explosive a priori to obtain the best powder factor is difficult to perform. From the economic point of view, bearing in mind that these civil engineering works usually have a high economic cost, a better estimate of the quantity of explosive to be used considering each lithology will give a better prediction of the cost of driving.

The aim of the present work is to find the correlation between the powder factor and the geological/geotechnical characteristics of different crossed volcanic lithologies in the building of a water tunnel. This research also aims to study how the characteristics of the rock (density, porosity and point load strength index) influence both the powder factor and the advance achieved according to the drilling and blasting pattern.

2. Material and methods

In order to develop the study, a water tunnel was driven on the volcanic island of Tenerife (coordinates 28.268611, -16.605556), located in the Canary Islands, in the North East Atlantic Ocean off the coast of Africa. The tunnel which is straight and was originally 4,000 m long was extended by 85.75 m for the present research work. A gelatin-based explosive for civil and mining purposes was used for charging the drilled holes. The drilling and blasting techniques used are those described by Langefors and Kihlstrom (Langefors and Kihlstrom, 1973).

The charge used, number of drilled holes, advance and a representative sample of rock were recorded from each blast. Geological and geotechnical tests were then performed in a licensed laboratory.

2.1 Description of water tunnels in Tenerife

The island of Tenerife is a volcanic island, where freshwater resources for water supply predominately come from groundwater (see video in supplementary material). Nowadays, groundwater accounts for more than half of the freshwater resources available to meet the current demands of irrigation, housing, tourism, industry, services and other usages.

The use of groundwater on the island of Tenerife from conventional tunnels dates back to at least 1910. There are currently 1,124 tunnels generally longer than 3 km, which produce an annual total water volume of 51.6 hm^3 (Hydrological Plan of Tenerife 2014, (Consejo Insular de Aguas Tenerife, 2018)). The water tunnels in Tenerife are built by tunnel driving in a straight line with dimensions of about 2.00 m high by 2.00 m wide and a gradient of 2%. Drilled tunnels cross a wide variety of volcanic rocks: basalt, phonolithic and ignimbrite trachyte, etc. At present, the drilling and blasting pattern is typically based on the dimensions of the cross-section to be opened (Lopez Jimeno et al., 2017) rather than on the geological and geotechnical characteristics of a highly heterogeneous volcanic rock found on the island of Tenerife.

2.2 Methodology for characterizing rocks

2.2.1 Sampling and data collection

In order to mechanically characterize the different rocks crossed during perforation, relatively undisturbed rock samples with suitable dimensions (larger than 40 cm) were collected after each blast. In addition, the following data were recorded for every blast: number of drilled holes, total charge/blast and advance made. The real specific drilling for 14, 16 or 17 blast-holes were 4.20 m/m^3 (4.34 m/m^3 theoretical), 4.80 m/m^3 (5.00 m/m^3 theoretical), and 5.10 m/m^3 (5.70 m/m^3 theoretical), respectively. A fixed reference point was taken to determine the advance. The advance in the tunnel was 85.70 m in total, of which 65.07 m were blasted and a rock sample was collected after each blast (68 rock samples). The remaining 20.63 m were excavated by an overshot mucker and pneumatic breakers as they did not need explosives. A database was then created with the information of each blast and the corresponding sample was classified.

2.2.2 Rock characterisation study

A set of laboratory tests were performed according to standard to identify rock type and determine the properties of the rock matrix, (Serrano, 2004). The parameters used to define the rock were density, porosity and point strength index.

Laboratory tests were performed in a licensed laboratory (Laboratories and Quality of Construction of the Ministry of Public Works and Transport, Vice-Ministry of Infrastructure and Transport of the Government of the Canary Islands, Spain). The first step was the visual description of the samples (American Society for Testing and Materials, 2001). The second step was to prepare the samples and to perform tests following the specifications in the current regulations of the Spanish Association for Standardization-UNE: UNE EN 1936: 2007 Natural stone test methods - Determination of real density and apparent density, and of total and open porosity; UNE 103301: 1994 Determination of a soil density. Method of balance with water bath and UNE 22950-5: 1996 Mechanical properties of rocks. Strength determination tests. Part 5: point load test.

Samples (n=68) were identified with nine different lithotypes with different mechanical characteristics (Fig. 1). The identified lithotypes were: (a) aphanitic massive basalt, (b) altered and highly altered aphanitic massive basalt, (c) vacuolar aphanitic basalt (vacuole <0.05 mm), (d) vacuolar aphanitic basalt (vacuole <0.3 mm), (e) phonolite, (f) red colour ignimbrite (vacuolar basaltic fragments), (g) highly altered red colour ignimbrite (vacuolar basaltic fragments), (h) agglomerate basaltic materials, (i) massive and vacuolar plagioclase basalt (Füster et al., 1969). In order to characterize the nine lithotypes found, the following averaged parameters were calculated:

point load strength index I_s (MPa), apparent density (g/cm^3), open porosity P (%) and hydrostatic balance density D (g/cm^3).

2.2.3 Blast design in the tunnel

The results of a blast depend directly on the drilling and blasting design (see Fig. 2) and on the properties of the rock. The blasts carried out for this study followed the design by Langefors and Kihlstrom (Langefors and Kihlstrom, 1973), commonly applied to these hydraulic works in tunnels on the island of Tenerife. The mean average advance is limited in this design by the diameter of the empty blasthole and the deviation of the loaded boreholes. If the deviation is below 2%, the actual pull is estimated to be 95% of the design pull (Lopez Jimeno et al., 2017).

The charge calculation for tunnel driving, when the cross section is small, is defined by the 'cut', 'cut spreader hole' and the 'lifters' for a cut of four squares with parallel holes (Fig. 2a). The linear charge concentration q (kg/m) is defined as:

$$q = 55\, D1 \left(\frac{B}{D2}\right)^{1.5} \left(B - \frac{D2}{2}\right)\left(\frac{c}{0.4}\right)\left(\frac{1}{PRP_{ANFO}}\right) \qquad (1)$$

$$B = 0.9 \left(\frac{q1\, PRP_{ANFO}}{c' f \left(\frac{S}{B}\right)}\right)^{1/2} \qquad (2)$$

where D1 is the diameter of the blast-hole (m), D2 is the expansion bore diameter (m), B is the dimension of the burden (m), 'c' is rock constant, PRP_{ANFO} is the relative weight strength of the explosive with respect to ANFO type explosive, f is the fixation factor of the Langefors formula, S/B is the relationship between spacing and burden and ´c´, which is the corrected constant of the rock, this constant has an empirical value that represents the amount of explosive to break 1 m^3 of rock.(Tatiya, 2005).

The drill plan and charging and firing pattern, which was used in the studied tunnel here, had a cut, cut spreader holes, stoping holes, lifters, contour holes as shown in Fig. 2a for seventeen blast-holes. The geometric characteristics of the tunnel are a height of 2.00 m, a side wall height of 1.80 m, a rise of the arch of 0.20 m and a width of 2.00 m, giving a total section of 3.94 m^2.

The characteristics of the selected drilling and charging pattern are: diameter of empty borehole 0.15 m, drilling diameter 0.033 m, contour drill angle 4º, angular deviation 0.01 m/m, splicing error 0.02 m, PRP_{ANFO} 1.09 and length of the drill 1.20 m.

2.2.4 Choosing the explosive

The impedance of a material Z is defined as the product of its density ρ by the propagation velocity of the wave V_p ($Z= \rho V_p$) (Zukas and Walters, 1998). For the practical design of a blast, it should be considered that the impedance of the explosive should be higher than that of the rock in order to ensure breakage (International Society of Explosives Engineers, 1998).

The impedances of commercial explosives only reach densities of approximately 1.5 g/cm^3 and detonation velocities of around 5,000 m/s, and in some cases even higher. However, most rocks have densities of around 2.3 g/cm^3 and P-wave velocities greater than 3.5 m/s, but it is good practice to try to find the best possible similarity with the use of explosives.

Mechanical properties of rocks are defined by their resistance and deformability. The strength properties of the rock, is the effort that a rock supports for certain deformations, that can be measured in the laboratory by geomechanical tests. Therefore, to determine the strength of the samples, it is necessary to obtain rock samples with dimensions indicated according to UNE 22950-5: 1996 Mechanical properties of rocks (resistance to point load).

Each hole was loaded with cartridges of RIODIN^{TM} (MAXAM Europe, S.A. Madrid, Spain), a commercial product with the characteristics shown in Table 1.

2.3 Methodology to predict the advance in the drilling of a tunnel

To date, the Swedish design has been the main model used, (Langefors and Kihlstrom, 1973) to determine the amount of explosive needed to excavate a tunnel according to the number of holes, the diameter of the uncharged or relief holes and length of drill, assuming a constant of the rock ‘c’, a value of 0.4 was assumed for “c” (Lopez Jimeno et al., 2017). In this model, the real advance is estimated as 95% of the drill length without taking account the geomechanical properties of the rock. However, in real situations as in the case study here, blast technicians chose the quantity of explosives, based on experience, depending on the type of rock found. For this reason, no correlation was found between the amount of explosive and the advance depending on the type of rock (see the Pearson correlation coefficient, Table 3). This makes it difficult to estimate the advance, and the amount of explosive needed to drill the whole tunnel which is previously defined in the plan of the civil engineering work. Therefore, considering this working procedure is in a real tunnel driving, a non-linear model that relates the advance with the geomechanical characteristics of the rocks is proposed here. This will make it possible to predict the advance of each blast and the number of blasts required in a particular tunnel if there is information on crossed lithotypes. This information could be obtained for example from a survey or previous studies in nearby areas.

Therefore, a new methodology based on a non-linear regression model has been developed to estimate the number of blasts required and the amount of explosive needed to drill a certain distance in a water type tunnel once the type of rocks and the thickness of each layer of rock have been defined. The proposed methodology is summarized in a block diagram in Fig. 3.

The non-linear relationship between the advance and the point load strength index or the porosity can be established with a logarithmic equation (eq. 3) (Fig. 4). Combining both expressions in a linear way, each one with a weight according to its Pearson correlation coefficient, gives a non-linear relationship that predicts the maximum advance according to the characteristics of the rocks, once a sufficient amount of explosive has been placed to reach the said maximum (eq. 4).

$$Ad_1(Is) = -a_1 ln(Is) + b_1$$

$$Ad_2(P) = a_2 ln(P) + b_2 \qquad (3)$$

$$Ad(Is, P) = \frac{\rho_{Is}}{\rho_{Is}+\rho_P} Ad_1(Is) + \frac{\rho_P}{\rho_{Is}+\rho_P} Ad_2(P)$$

Therefore, the advance function is defined as

$$Ad(Is, P) = a + bln\left(\frac{P^c}{Is}\right) \qquad (4)$$

$$a = \frac{\rho_{Is} b_1 + \rho_P b_2}{\rho_{Is}+\rho_P},\ b = \frac{1}{\rho_{Is}+\rho_P},\ c = \frac{\rho_P a_2}{\rho_{Is} a_1}$$

where ρ_{Is} and ρ_P are the Pearson correlation coefficients of the point load strength index and the porosity, respectively.

To determinate the most likely number of blasts and the amount of explosive, the following steps need to be followed (Fig. 3):

1- Determine the wanted length to drill into the tunnel and the drill length.

2- Determine point load strength index and porosity according to lithotype.

3- Introduce the expected order and thickness of the lithological layers. On the contrary, if this information is not known, perform a high enough number of simulations, randomly varying the order and thickness of layers, to have a likely solution.

4- Run the simulation. The advance is calculated with equation 4 in each lithotype layer. The advance in the zone between two different lithotypes is calculated according to the proportion in which they are found in the blast.

2.4 Statistical analysis

Once the rocks had been classified according to their lithotype, each lithotype was characterized by its averaged parameters (arithmetic mean and the standard deviation). The Anderson-Darling test and the one-sample Kolmogorov-Smirnov test showed that the averaged data of the lithotype set had a normal distribution. Any case, it has been taken into account that the dataset is small (Bland and Altman, 2009; Kitchen, 2009) and both, the Spearman's rank-order correlation coefficients and the Pearson correlation coefficients were calculated. Results showed that variables D, Is and P have a similar correlation with Av with both tests. Therefore, the Pearson correlation coefficient was used in this work. Data analysis, correlations and plots were performed using the application of Excel spreadsheets (Microsoft® Office) and the MATLAB® (Mathworks Inc., Natick, MS, USA).

3. Results and discussion

3.1 Characterization of the lithotypes

The lithotypes with their geomechanical features (point load strength index Is (MPa), open porosity P (%) and hydrostatic balance density D (g/cm^3)) are shown in Table 2 where the values correspond to the mean values and standard deviation values. In addition, the mean explosive charge used, the mean advance and the mean powder factor for each lithotype are shown.

The Pearson product-moment correlation coefficient (LeBlanc, 2004) was calculated (Table 3) to determine the linear correlation between the point load strength index, the open porosity and the density with the advance. These results show that advance is moderately positively correlated with the porosity and moderately negatively correlated with the point load strength index, both cases have a statistically significant linear relationship ($p<0.05$). The correlation between advance and density is negative although its $p=0.0575>0.05$ (meaning that the Pearson correlation coefficient is not significantly different to zero).

3.2 Relationship between lithotypes and blasting process

The relationship between advance and powder factor (relationship between the charge (kg) and the unit volume (m^3)) with the geotechnical characteristics of the different lithotypes are shown in Fig. 4. The Pearson correlation coefficients between the density (g/cm^3), the point load strength index Is (Mpa) as well as the porosity P (%) versus the advance D (m) were calculated (Table 3). This statistical analysis (f-test) shows that the correlation between advance and density is weak with a $p = 0.0575$ ($p>0.05$ no correlation). However, the point load strength index and the porosity are negatively and positively correlated with the advance, respectively, with a $p<0.05$. In other words, there is an inverse and direct relationship between the point load strength index and the porosity with the advance, respectively. On the other hand, the statistical analysis shows a low correlation between the quantity of explosives and the advance (significance F is 72.5% versus the critical value of 5%). Therefore, the interpretation that can be drawn is that the advance mainly depends on the properties of the rock and not so much on a slight variation of explosive charge used. It should be mentioned that, under real working conditions in the tunnel (4,000 m from the entrance), the operators placed more than enough explosive to guarantee the desired pull according to the blast design and their own experience with each type of rock but without a previous geotechnical study. Therefore, if the geotechnical characteristics of the rocks were known, it would be possible to adapt the quantities of explosive per blast in order to improve the powder factor. This could explain why there is a low correlation between the amount of explosives and the advance. Thus, the results show that the advance only depends on the geotechnical properties of the rock, and mainly on the porosity and the point load strength index. However, the relationship between the point load strength index and advance is a decreasing non-linear one while the relationship between porosity and advance is an increasing non-linear relationship (Fig. 4a).

Fig. 4b shows the relationships between the powder factor and geotechnical variables of the tested lithotypes. Data show that powder factor is higher with rocks of high density, high point load strength index, and low open porosity. However, to establish a single relationship between geomechanical variables and powder factor is not so straightforward. For instance, phonolite (e) has a high Is, high D and low P but its powder factor is similar to the highly altered red colour ignimbrite (g) that has a lower Is, a lower D and a higher P.

On the other hand, the mechanical state of the rock affected the advance that could be made with each blast. Such as is the case of the aphanitic massive basalt altered with a higher open porosity and less point load strength index than other rocks with no alteration (Table 2), where a greater advance was made, always within the margin established by the drill length, even though the mean average amount of explosive was slightly lower. Fig. 5 shows that rocks of the same lithotype that have a greater porosity and a lower point load strength index will be able to be blasted with greater pulls than unaltered rocks with the same explosive charge. This happened in precisely three cases of rocks (aphanitic massive basalt, vacuolar aphanitic basalt and red colour ignimbrite) that were found in the tunnel.

The results obtained show that neither the advance nor the powder factor have a linear relationship with a simple unique geomechanical property (Fig. 4). However, in order to determine the importance that each geomechanical parameter has for the prediction of the advance of a blast, the Pearson correlation coefficients between advance and the set of geomechanical parameters were studied (Table 3). It is mainly the point load strength index and porosity of the rock that have a significant weight with a negative and positive nonlinear correlation, respectively, on the advance. It is also noteworthy that the mechanical state of the rock can cause the advance to change significantly (Fig. 5). In general, an increase in porosity and a decrease in the point load strength index in a given lithotype could mean that the advance is greater than in the case of the rock not being altered.

3.3 Prediction of the advance in the drilling of a tunnel

The methodology defined in methods (Fig. 3) allows an estimation of the advance for each blast which subsequently makes it possible to have an improved estimation of the number of blasts and the total quantity of explosive needed to continue a water tunnel.

In the case study described here, the parameters for the non-linear relationship (eq. 4) between the measured advance and geomechanical properties (point load strength index (I_s) and porosity (P)) of the found lithotypes are summarized in the Table 3 and 4.

The traditional formula (Langefors and Kihlstrom, 1973) applied to the design of small tunnels estimates an advance of 95% of the theoretical pull. Therefore, according to this formula in the case study here, where 45.07 m were drilled, the estimated number of blasts would be 40 using a drill length of 1.2 m. On the other hand, the required amount of explosive given by the formula depends on the drilling and blasting design applied. In the case described here, the operators used three drilling and blasting designs for the tunnel with 14, 16 or 17 blast-holes depending on the type of rock. Therefore, the estimated amount of explosive would be between 333.00 kg (powder factor; 1.85 kg/m^3) and 289.28 kg (powder factor; 1.60 kg/m^3) calculated on the basis of the drilling and blasting design of 17 and 14 blast-holes, respectively, using a constant ‘c’ of 0.4. However, in the case study here, the tunnel technicians used configurations of drilling and blasting design with 14, 16 or 17 blast-holes with different amounts of charge according to their own experience, where the type and the state of the rock were considered. Their main objective was to drill the maximum pull with the minimum amount of explosive to reduce costs and increase the economic benefits. For this reason, experimentally, 48 blasts and 297.25 kg of explosive with a powder factor 1.65 kg/m^3 were needed using a drill length of 1.2 m to drill 45.07 m. As one can see, the amount of explosive used in the actual blast is within the range given by the formula for the drilling pattern used, although the number of blasts was greater and the mean average amount of explosive per blast was 6.2 kg.

The new methodology proposed here to predict the advance based on a non-linear regression model (eq. 4) where the point load strength index and the porosity of the rock are variable, proposes that 303.1 kg of explosive (powder factor; 1.68 kg/m^3) distributed in 49 blasts are needed to advance 45.07 m. In addition, the amount of explosive required was calculated based on the information provided by the technicians on the amount of explosive charge they normally use depending on the type and state of the rock (Table 2). These values are close to the real ones in the case study. Therefore, this methodology allows a better estimation of the real advance/blast in the drilling and the required quantity of explosives which, in turn, will give a better estimation of the cost of a tunnel driving and the duration of the civil engineering work. This methodology allows the engineer to be more precise when they design a project. Therefore, taking into account that the direct cost resulting from the consumption of explosive in the advance of a tunnel can be estimated from the powder factor where a lower powder factor means a lower consumption of explosive. The methodology developed here allows this powder factor to be estimated, as well as the number of blasts required. In addition, it should be mentioned that a higher number of blasts causes delays in work plans, which also implies monetary losses which should be predicted when the budget of the civil work is prepared. In the case study here, the traditional formula (Langefors and Kihlstrom, 1973) estimates that 333 kg are needed to drill the 45.07m whereas the methodology proposed here estimates that 303.1 kg are needed to advance the same distance. Therefore, the budget for this civil engineering work, using the method proposed here, would have included 29.9 kg less explosive and the expected expenses for explosives could have been reduced by 9%.

In the case of new projects, the engineer could apply the methodology proposed here. In such cases, before drilling a tunnel, an optional survey study could be carried out which would provide data about the distribution and type of rock. Therefore, a computer simulated tunnel, with a cross section of 2.00 m high by 2.00 m wide could be built to predict advances/powder factors and the number of blasts needed to build the final tunnel. Fig. 6 shows examples of tunnels with different distributions of lithotypes. In this case, in order to apply the methodology proposed here, it would be necessary to geomechanically characterize the lithologies that the tunnel goes through beforehand, assuming the costs of tests and exploration that this work entails. However, these costs should be justified by a better estimation of the powder factor, as well as in planning the work. In addition, if other tunnels need to be drilled, in nearby areas, or in areas with the same lithologies, simulations could be used, with the data obtained, without having to re-explore and test the rocks again. It is only necessary to run the proposed simulation (Fig. 3). If a survey study is not undertaken to study the types of rocks and thickness of the layers, the number of blasts can be estimated based on the proposed methodology. In these cases, it is assumed that there are a high number of possible tunnels, constructed with random rock layer distributions with the geomechanical characteristics shown in Table 5, and with a layer thickness that is chosen randomly (e.g. between 3 and 10 m). This allows the preparation of a forecast of the required number of blasts and the amount of explosive (Fig. 6), according to the usual drill plan and charging and firing patterns (characteristics of rock and number of boreholes). Once these results from a high number of tunnels are obtained, the quantity of explosives and the expected number of blasts that will be needed can be estimated (Fig. 7) with greater precision. If it is supposed that a driving project of a tunnel of 120 m with a drilling length of 1.2 m in a tunnel with a lithotype profile similar to the Güimar tunnel (Fig. 7a) with layers between 3 and 10 m, the proposed methodology gives the likely number of blasts as 128 with 795 kg of explosive (Fig. 7c). If the same simulations are done with a tunnel where every lithotype has the same probability of being there (Fig. 7b), the number of blasts is 128 and 129 with 790 and 800 kg of explosives, respectively (Fig. 7d). These values are different to those expected in the traditional methods where an efficiency of 0.95 with a drilling length of 1.2 m is assumed and where between 105 and 106 blasts would be necessary. This means that by using the traditional model, the expected number of blasts and kilograms of explosive increases by 22 %. A case where there are two proposed tunnels with a different composition is shown in Fig. 7g and h. In the former, there are four times more aphanitic massive basalt and red colour ignimbrite than the other lithotypes (Fig. 7e) and in the latter, there are four times more phonolite and agglomerate basaltic material (Fig. 7f). As can be seen, the amount of explosives and the number of blasts that are most likely to be needed are different depending on the type of rock expected to be found along the tunnel (compare Fig. 7 c, d, g and h).

The methodology described here can be used to define a driving engineering project for a water tunnel with greater precision taking into account the particularities of the rocks. In previous works, the technical design of the blast is based on a mathematical formula that depends on the geometry of the space to be drilled and on a constant 'c'. The Computerized Design Program for Tunnel Blasting proposed a change in how to obtain this value in two tunnels in Korea (Lee et al., 2005). In this study Lee et al. analysed, after 23 blasts test, the relationship between the values of ‘c’ and the RMR (Bieniawski, 1973). Lee et al. proposed a modification of ‘c’ in the Langefors formula, which predicts a smaller theoretical advance of 85% or more of the perforation with an ideal amount of charge. However, experimentally, it has been seen that using the drilling and blasting pattern based on the Langefors formula, the advance is different depending on the type of rock and its geomechanical properties. The method proposed here is based on the obtained experimental results, where the advance depends on the geomechanical properties of the rocks. The proposed methodology may serve as a tool to improve the civil engineering project for a tunnel, both technically and economically.

4. Conclusion

In this research, a new methodology has been proposed to predict the advance, powder factor and the number of blasts in the tunnel driving; it specifically refers to a case study in a volcanic territory. The geomechanical influence of different lithotypes of volcanic rocks on the island of Tenerife, found in the drilling of 65.07 m of underground water tunnels with the use of explosives is studied here. The dimensions of the tunnel were 2.00 m high by 2.00 m wide. The drilling was completed by gelatinous explosive, with an average load of 6.2 kg, distributed according to the drilling and blasting pattern for tunnels.

The characteristic values of point load strength index (MPa), hydrostatic density (gr/cm^3) and porosity (%) of each sample were correlated with the values of the explosive charge (kg) and the advance (m) obtained in each blasting. The results show that neither the advance nor the powder factor have a linear relationship with a single unique geo-mechanical property, instead, there are non-linear relationships with the set of geomechanical parameters of the rocks.

This research work describes a new methodology based on a non-linear relationship between the advance and point load strength index or porosity (eq. 4) that predicts the maximum advance according to the characteristics of the rocks.

A horizontal mechanical survey with core recovery could provide the geological and the geomechanical information to build a simulated tunnel to predict the powder factor and the number of blasts needed to drill a tunnel. The geological and the geomechanical information of the tunnel and the method proposed here based on the experimental results could provide a better estimation of the execution time of the works in a tunnel project. Finally, all this predicted information is of much value and could be translated directly into economic evaluations improving decision making in a project of this type.

The study has certain limitations. Firstly, the lack of a larger number of samples, whose number was limited by the magnitude of the civil engineering work. Secondly, the difficulty in taking measurements due to the extreme working conditions (4,000 linear m from its entrance, a low level of light, etc.). In addition, there were extreme environmental conditions, with high humidity levels and temperatures, which are markedly different to the laboratory conditions where the geomechanical tests were done. Therefore, all the above have caused certain low degree of adjustment of the regression model between the geomechanical properties and the advance. Therefore, it is necessary to collect more information from future civil engineering works in tunnels, with the goal of building a larger database to improve the model.

These results were obtained in a type of tunnel with specific dimensions and lithology; this opens up new future lines of work, for example to corroborate their extrapolation to larger tunnels or their application to outdoor blasting. In addition, future works will be aimed at studying the possibility of improving the method presented here with artificial intelligence.

Conflict of interest statement

None declared.

Acknowledgements

The authors would like to thank the owners of the La Paloma water tunnel, the University of La Laguna (Spain) and the Service of Laboratories and Quality of Construction of the Ministry of Public Works and Transport, Vice-Ministry of Infrastructure and Transport of the Government of the Canary Islands, Spain for their collaboration in this research work.

REFERENCES

American Society for Testing and Materials, 2001. Annual Book of ASTM Standards [WWW Document]. URL https://www.astm.org/BOOKSTORE/BOS/index.html

Barberis, J., 1991. The Development of International Law of Transboundary Groundwater. Nat.

Resour. J. 31, 167–186.

Bieniawski, Z.T., 1973. Engineering Classification of Jointed Rock Masses. Civ. Eng. South Africa 15, 343–353. https://doi.org/http://dx.doi.org/10.1016/0148-9062(74)92075-0

Bland, J.M., Altman, D.G., 2009. Analysis of continuous data from small samples. BMJ 338, a3166. https://doi.org/10.1136/bmj.a3166

Consejo Insular de Aguas Tenerife, 2018. Plan Hidrológico de Tenerife [WWW Document]. URL www.planhidrologicodetenerife.org

Füster, J.M., Páez, A., Sagredo, J., 1969. Significance of basic and ultramafic rock inclusions in the basalts of Canary Islands. Bull. Volcanol. 33, 665–693. https://doi.org/10.1007/BF02596745

Holmberg, R., 1982. Charge calculations for tunneling., in: W.A. Hustrulid (Ed.), Underground Mining Methods Handbook, SME. pp. 1580–1589.

International Society of Explosives Engineers, 1998. The Blasters' Handbook. ISEE, Cleveland, USA.

Kitchen, C.M.R., 2009. Nonparametric vs Parametric Tests of Location in Biomedical Research. Am. J. Ophthalmol. 147, 571–572. https://doi.org/10.1016/J.AJO.2008.06.031

Langefors, U., Kihlstrom, B., 1973. The modern technique of rock blasting, 2nd ed. Wiley & Sons, New York, USA.

LeBlanc, D.C., 2004. Statistics: concepts and applications for science. Jones and Bartlett, Sudbury, MA.

Lee, C.I., Jong, Y.H., Jeon, S., Choi, Y.K., Kim, H.S., 2005. The Computerized Design Program for Tunnel Blasting. International Society of Explosives Engineers, pp. 1–10.

Lopez Jimeno, C., Lopez Jimeno, E., Ayala Carcedo, F.J., Visser de Ramiro, Y., 2017. Drilling and blasting of rocks. Taylor & Francis, London, UK.

Nasiri, F., Mafakheri, M.S., 2015. Qanat water supply systems: a revisit of sustainability perspectives. Environ. Syst. Res. 4, 1–5. https://doi.org/10.1186/s40068-015-0039-9

Persson, P.-A., Holmberg, R., Lee, J., 1993. Rock and Explosives Engeneering. CRC Press, New

York, USA.

Serrano, A., 2004. Mecánica de las rocas I: Descripción de las rocas. C. E. T. S. Ingenieros de Caminos, Canales y Puertos., Madrid, Spain.

Tatiya, R., 2005. Civil excavations and tunnelling : a practical guide. Thomas Telford, London, UK.

Zukas, J.A., Walters, W.P., 1998. Explosive Effects and Applications. Springer New York. https://doi.org/10.1007/978-1-4612-0589-0

TABLES

Table 1. Characteristics of the RIODIN ™ (MAXAM Europe, S.A. Madrid, Spain)**.**

COMPONENT	**%**	**Diameter cartridge**	26 mm approx.
Nitroglycol:	26-34	**Cartridge length**	200 mm approx.
Nitrocellulose:	0.5-2	**Weight**	152 gr. approx.
Nitrate Ammonic:	52-70	**Manufacturer**	MAXAM Europe

PARAMETER	**VALUE**	**TESTING METHOD**
Decomposition temperature:	≥ 165 ºC	UNE 31 017
Explosion temperature:	≥ 190 º C	UNE 31 017
Sensitivity to impact:	≥3J	UNE 31 016 (UNE-EN 13631-4)
Sensitivity to rubbing:	247 N	UNE 31 018 (Pr EN 13631-3)
Density:	1.45-1.50 g/cm^3	ITEUN EXP-516
Water Resistance:	OK	ITEUN EXP-515
Solubility in water (ammonium nitrate):	192 g/100 ml water to 20 ºC	

Table 2. Characteristic parameters for each lithotype obtained and the blasting information. Mean values (standard deviation).

	Characterization of lithotypes				Blasting information		
	Lithotype (number of samples)	**Point load strength index Is (MPa)**	**Open porosity (%)**	**Hydrostatic balance density (g/cm^3)**	**Explosive (kg)**	**Advance (m)**	**Powder factor (kg/m^3)**
a	Aphanitic massive basalt (5)	3.17 (1.08)	6.70 (4.45)	2.56 (0.20)	5.84 (0.90)	0.91 (0.13)	1.63 (0.31)
b	Altered and highly altered aphanitic massive basalt (5)	0.36 (0.23)	27.39 (11.47)	1.88 (0.31)	5.67 (0.84)	0.97 (0.14)	1.48 (0.22)
c	Vacuolar aphanitic basalt, vacuole <0.05 mm (9)	1.35 (0.92)	24.20 (6.26)	2.12 (0.16)	6.32 (1.27)	0.97 (0.09)	1.66 (0.43)
d	Vacuolar aphanitic basalt, vacuole <0.3 mm (6)	3.57 (2.03)	18.91 (8.71)	2.19 (0.11)	6.69 (0.629)	0.98 (0.12)	1.73 (0.27)
e	Phonolite (4)	5.84 (1.18)	3.78 (1.99)	2.59 (0.11)	6.33 (0.52)	0.86 (0.07)	1.84 (0.24)
f	Red colour ignimbrite (9)	1.03 (0.59)	28.65 (4.97)	1.90 (0.12)	6.39 (0.42)	0.94 (0.14)	1.74 (0.30)
g	Highly altered red colour ignimbrite (4)	0.29 (0.22)	35.05 (4.34)	1.84 (0.08)	6.50 (0.24)	0.99 (0.03)	1.65 (0.07)
h	Agglomerate basaltic materials (8)	0.41 (0.28)	37.70 (10.07)	1.70 (0.26)	5.81 (0.49)	0.96 (0.14)	1.54 (0.24)
i	Massive and vacuolar plagioclase basalt (7)	4.49 (1.18)	6.66 (1.71)	2.58 (0.06)	5.79 (0.52)	0,98 (0.12)	1.50 (0.23)

Table 3. Pearson correlation coefficients corresponding to the advance and the density, point load strength index and the porosity calculated with the mean values of the lithotypes from Table 2. P-values for testing the null hypothesis of no correlation against the alternative that there is a non-zero correlation (p-value=0.05).

	Pearson correlation coefficient ρ	**p-value**
Advance, D	-0.6511	0.0575
Advance, Is	-0.76	0.0163
Advance, P	0.71	0.0326
Advance, kg explosive	-0.15	0.6962

Table 4. Correlation equations between density (g/cm^3), point load strength index Is (MPa) as well as porosity (%) versus advance (m).

Geotechnical parameters	**Advance (m)**	**R^2**	**Standard error**
Point load strength index, Is (MPa)	Ad1= -0.029 ln(Is) + 0.9419	0.65	0.02
Open porosity, P (%)	Ad2= 0.0406 ln(P) + 0.8186	0.67	0.02
Point load strength index, Is (MPa) and Open porosity, P (%)	Ad= 0.5170 Ad1 + 0.4830 Ad2 =0.88235+0.01499*ln($P^{1.30789}$/Is)	0.72	0.02

Table 5. Number of blasts and kilograms of explosive to build the water tunnel, experimental data versus the two models.

	Lithotype in the water tunnel	**# of blasts**	**Explosive (kg)**	**Advance (m)**
a	Aphanitic massive basalt	5	29.2	4.55
b	Altered and highly altered aphanitic massive basalt	5	28.35	4.85
c	Vacuolar aphanitic basalt, vacuole <0.05 mm	9	56.90	8.70
d	Vacuolar aphanitic basalt, vacuole <0.3 mm	5	33.15	4.67
e	Phonolite	4	25.30	3.45
f	Red colour ignimbrite	9	51.90	7.25
g	Highly altered red colour ignimbrite	4	26.00	3.95
h	Agglomerate basaltic materials	8	46.45	7.65
	Total (experimental data)	**48**	**297.25**	45.07
	Predictions			
Swedish model (using 6.2 kg of explosive on average per blast, and drilling length 1.2 m with efficiency 0.95) (Langefors and Kihlstrom, 1973; Lopez Jimeno et al., 2017)		**40**	**248**	45.07
Proposed mathematical model		**49**	**303.10**	45.07

FIGURE CAPTIONS

Fig. 1. Lithotypes. The identified lithotypes were: (a) aphanitic massive basalt, (b) altered and highly altered aphanitic massive basalt, (c) vacuolar aphanitic basalt (vacuole <0.05 mm), (d) vacuolar aphanitic basalt (vacuole <0.3 mm), (e) phonolite, (f) red colour ignimbrite (vacuolar basaltic fragments), (g) highly altered red colour ignimbrite (vacuolar basaltic fragments), (h) agglomerate basaltic materials, (i) massive and vacuolar plagioclase basalt (Füster et al., 1969).

Fig. 2. Geometric drill pattern. a) Blast pattern with 17 boreholes used in the tunnel of the present work based on the blasting manual, Geological and Mining Institute of Spain. b) Front of a tunnel after a blast.

Fig. 3. Block diagram of the method. The proposed methodology is shown to estimate the powder factor according to the different lithologies of the volcanic lands.

Fig. 4. Relationship between lithotype and blasting process. a) and b) show the relation between advance (m) and powder factor (kg/m^3) versus point load strength index Is (MPa), hydrostatic balance density D (g/cm^3) and open porosity P (%), respectively. Black lines are the fit. The lithotypes are: (a) aphanitic massive basalt, (b) altered and highly altered aphanitic massive basalt, (c) vacuolar aphanitic basalt (vacuole <0.05 mm), (d) vacuolar aphanitic basalt (vacuole <0.3 mm), (e) phonolite, (f) red colour ignimbrite (vacuolar basaltic fragments), (g) highly altered red colour ignimbrite (vacuolar basaltic fragments) and (h) agglomerate basaltic materials.

Fig. 5. Point load strength index Is (MPa) and open porosity (%) versus advance (m). The lithotypes are: (a) aphanitic massive basalt, (b) altered and highly altered aphanitic massive basalt,

(c) vacuolar aphanitic basalt, vacuole <0.05 mm, (d) vacuolar aphanitic basalt, vacuole <0.3 mm, (f) red colour ignimbrite and (g) highly altered red colour ignimbrite.

Fig. 6. Application of the mathematical model in computer simulated **tunnels.** The mathematical model is applied to predict the number of blasts and the amount of charge needed in four tunnels to drill 100 m. The lithotypes are: (a) aphanitic massive basalt, (b) altered and highly altered aphanitic massive basalt, (c) vacuolar aphanitic basalt, vacuole <0.05 mm, (d) vacuolar aphanitic basalt, vacuole <0.3 mm, (e), phonolite, (f) red colour ignimbrite, (g) highly altered red colour ignimbrite and (h) agglomerate basaltic materials.

Fig. 7. Relationship between lithotype, number of blasts and amount charge of explosive calculated with the proposed mathematical model. a), b), e) and f) are the histograms with the lithotypes used in the simulated tunnels. a) has a distribution similar to the lithotypes found in the Güimar tunnel, b) corresponds to a uniform distribution, e) and f) are proposed non-uniform distributions . c), d), g) and h) give the probability of the number of blasts and the kilograms of explosive needed for the simulated tunnels of 120 m, corresponding to the a), b), e) and f), respectively. The lithotypes are: (a) aphanitic massive basalt, (b) altered and highly altered aphanitic massive basalt, (c) vacuolar aphanitic basalt, vacuole <0.05 mm, (d) vacuolar aphanitic basalt, vacuole <0.3 mm, (e), phonolite, (f) red colour ignimbrite, (g) highly altered red colour ignimbrite and (h) agglomerate basaltic materials.

Fig. 1

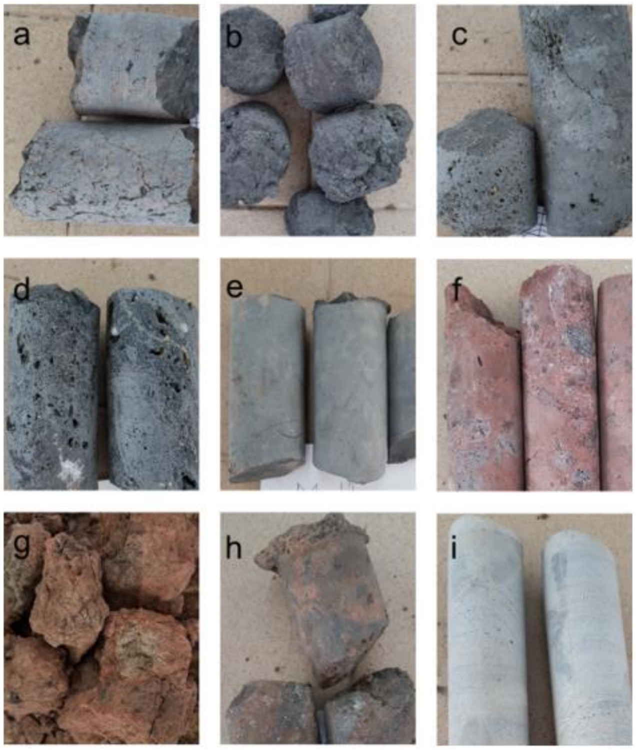


Fig. 2

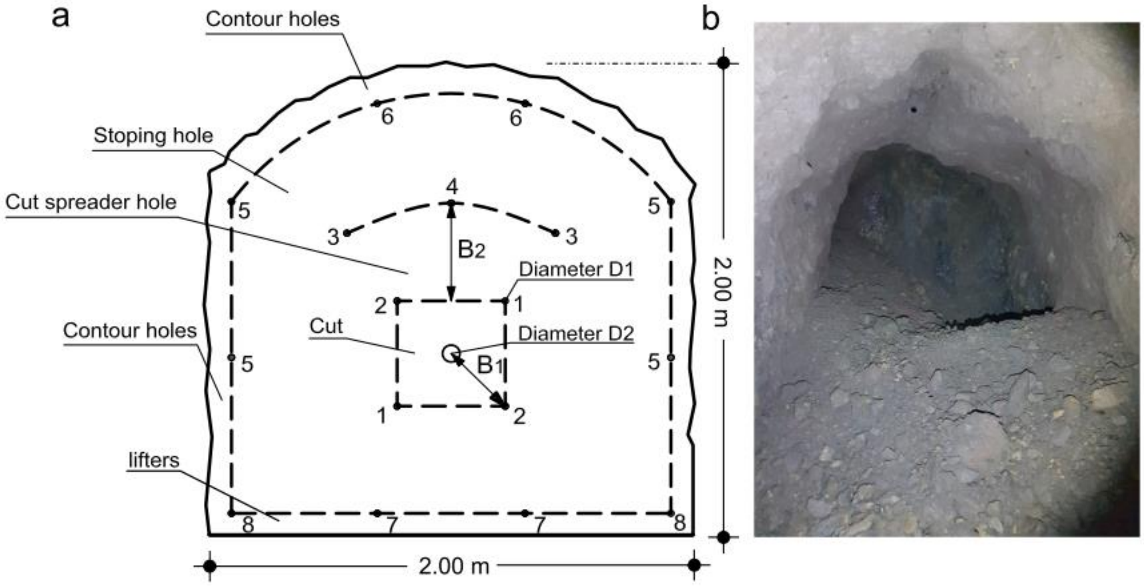
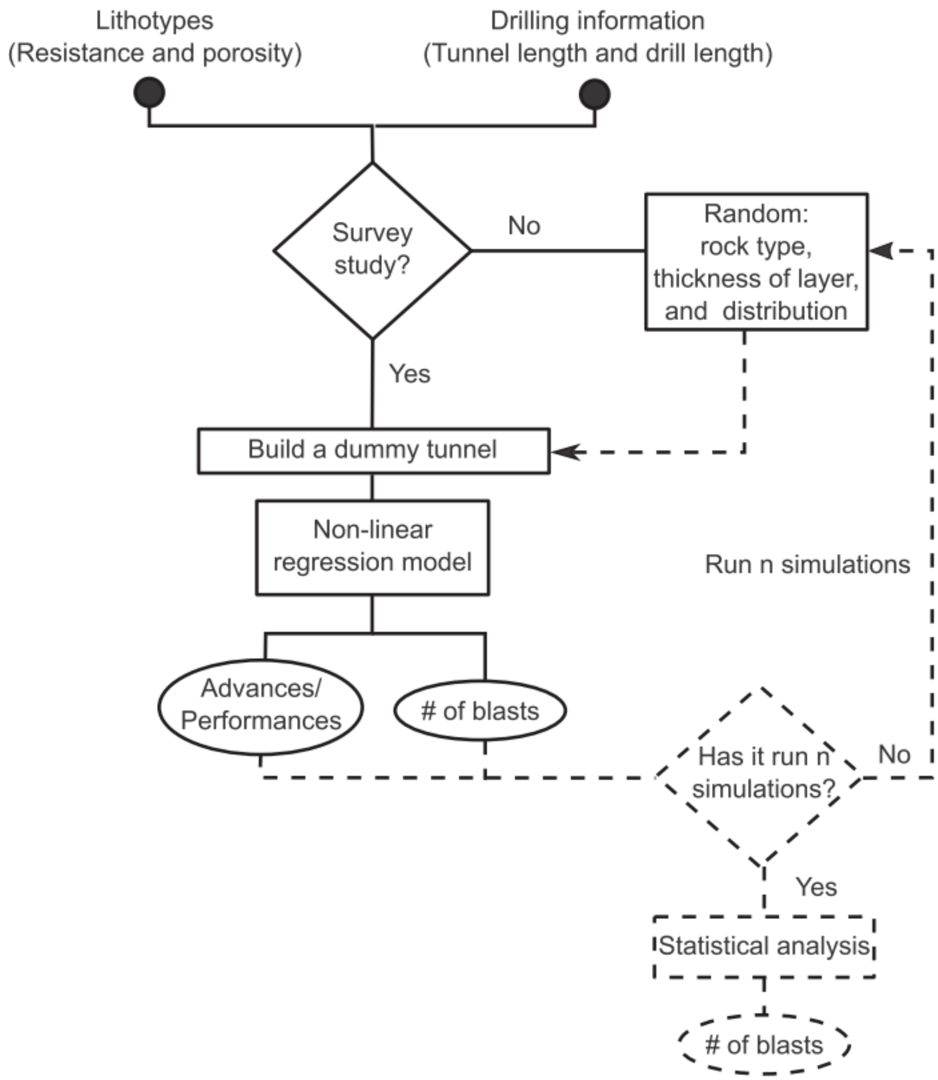
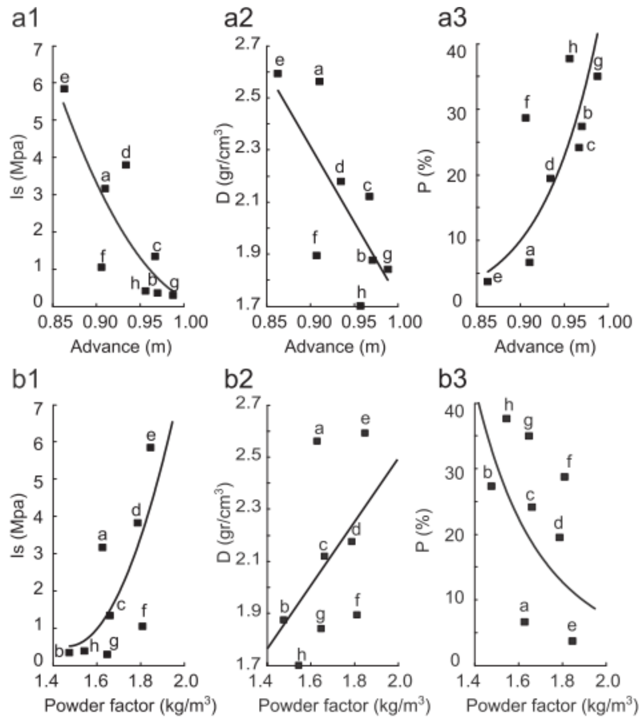

a
b
Contour holes
Stoping hole
Cut spreader hole
Contour holes
lifters
Cut
Diameter D1
Diameter D2
B2
B1
2.00 m
2.00 m
1
2
3
4
5
6
7
8

Fig. 3



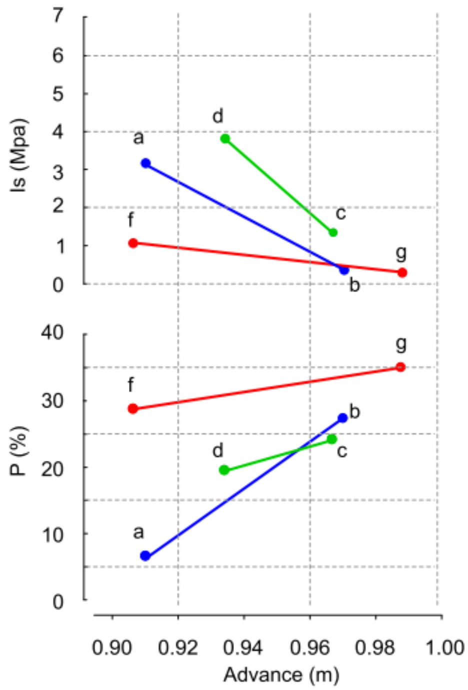
Lithotypes
(Resistance and porosity)
Drilling information
(Tunnel length and drill length)
Survey study?
No
Random:
rock type,
thickness of layer,
and distribution
Yes
Build a dummy tunnel
Non-linear regression model
Run n simulations
Advances/ Performances
# of blasts
Has it run n simulations?
No
Yes
Statistical analysis
# of blasts

Fig. 4



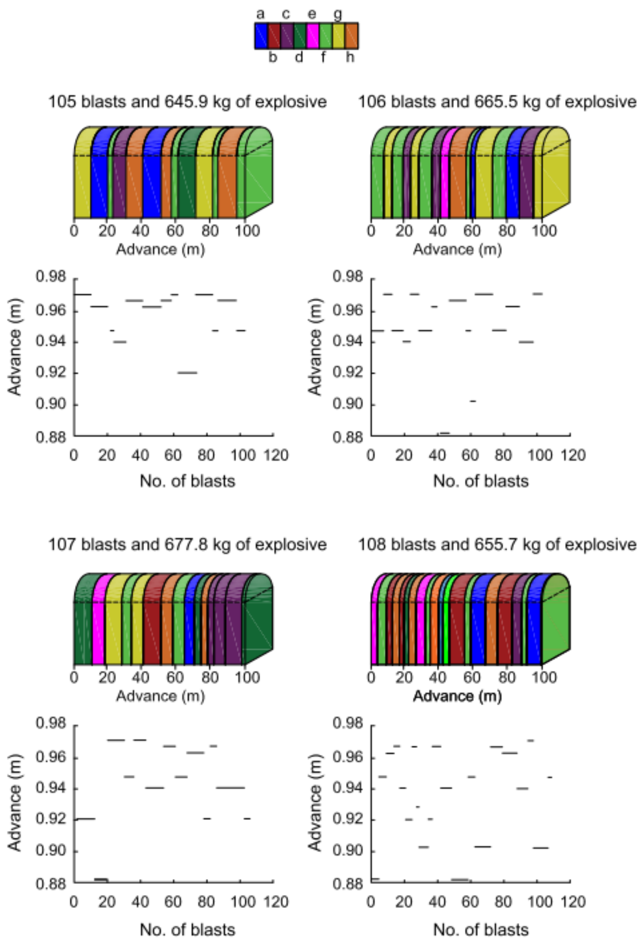
a1
a2
a3
Is (Mpa)
D (gr/cm^3)
P (%)
Advance (m)
Advance (m)
Advance (m)
b1
b2
b3
Is (Mpa)
D (gr/cm^3)
P (%)
Powder factor (kg/m^3)
Powder factor (kg/m^3)
Powder factor (kg/m^3)

Fig. 5



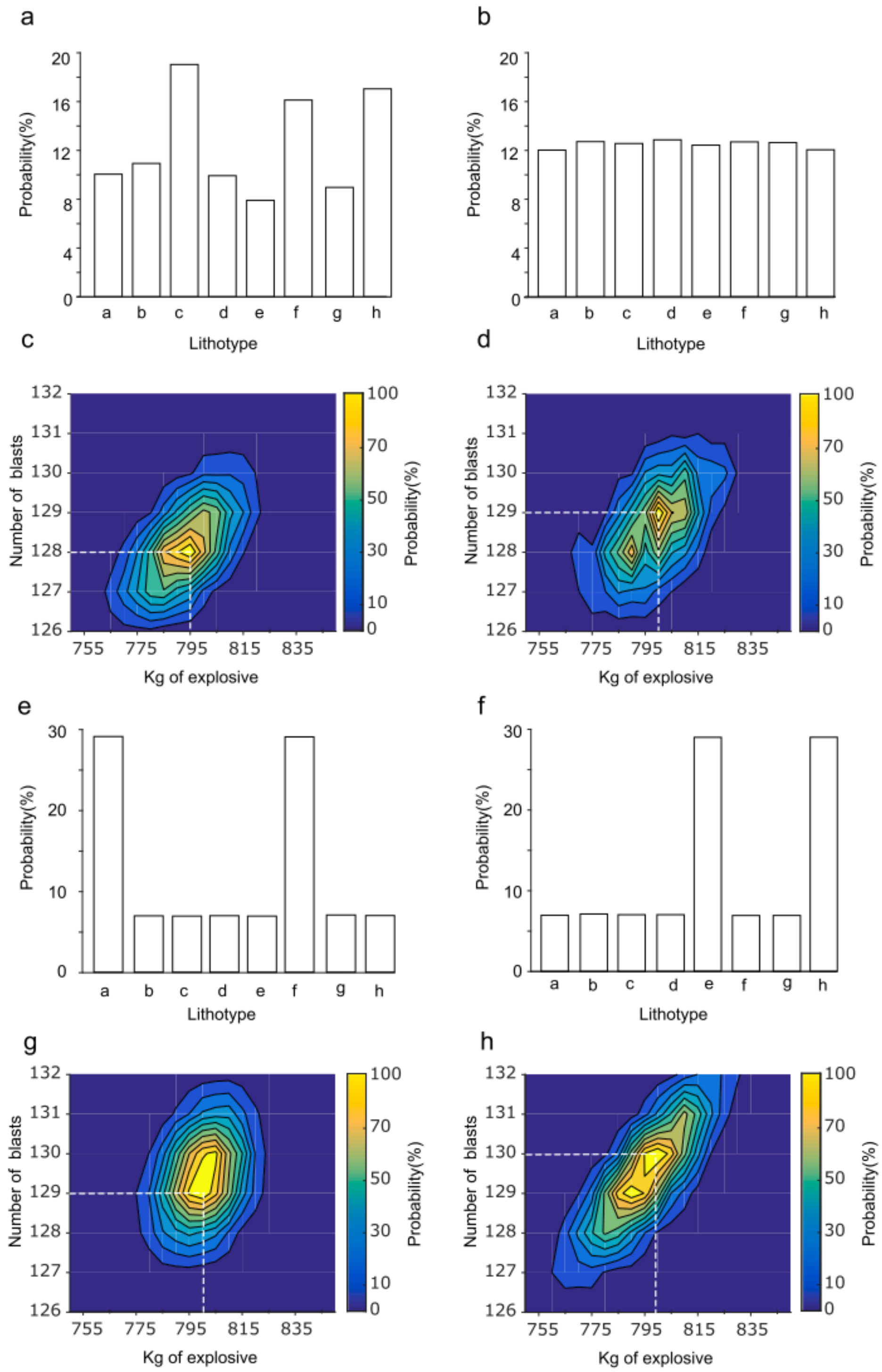
Is (Mpa)
P (%)
Advance (m)
a
b
c
d
f
g
0
1
2
3
4
5
6
7
10
20
30
40
0.90
0.92
0.94
0.96
0.98
1.00

Fig. 6



a c e g
b d f h
105 blasts and 645.9 kg of explosive
106 blasts and 665.5 kg of explosive
107 blasts and 677.8 kg of explosive
108 blasts and 655.7 kg of explosive
Advance (m)
No. of blasts

Fig. 7



a
b
c
d
e
f
g
h
Probability(%)
Lithotype
Number of blasts
Kg of explosive