POSSIBILITIES FOR DEFINING THE COMPLEXITY OF BLASTING CONDITIONS FOR THE PURPOSE OF BLAST-INDUCED ROCK MOVEMENT PREDICTION

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ABSTRACT

This study aims to provide a comprehensive understanding of blast-induced rock movement for mining operations using the Blast movement monitoring (BMM) technology measurements. A reasonable way of quantifying the intricate dependencies between blast design parameters and the resulting displacement of fragmented rock is by applying well-established statistical methods. Focusing on both horizontal and vertical movement vectors, the study examines a set of easily accessible parameters such as Spacing, Burden, Bench height, Subdrilling length, Stemming length and Charge mass for each drillhole neighbouring each installed BMM’s location. Through correlation analysis and regression modelling, the relationships among these parameters and rock movement are established for Top and Bottom flitch levels. The study reveals how the influence of blast design parameters can vary across different components of movement. Horizontal movement towards the newly formed free face is predominantly affected by parameters tied to the drilling pattern. Similarly, vertical movement is influenced by these parameters, with distinct dependencies identified in different row zones within the blast panel. The study presents a robust multiple regression model for predicting bottom flitch horizontal movement, demonstrating the model's validity and presenting the relative significance of the applied predictors. By advocating an active experimental approach and iterative adjustments to blast design, this research aims to improve the understanding of how blast-induced rock movement can be monitored at an early stage of the life of mine. Additionally, this offers a pragmatic insight for applying an active experimental approach for obtaining a stratified sample during the trail-and-error process for the sake of optimizing blasting practices in open-pit mining operations. By using easily accessible predictors like blast design parameters and charging rules, this study aims to establish a middle ground between blast movement and other problems related to blasting.

Introduction

Blasting in the field of mining is integral to upholding product quality and operational viability. It primarily aims to achieve optimal fragmentation, accompanied by minimal commodity losses, dilution, and ore misclassification. Blast movement as a result demands acknowledgement and ideally control. Despite different endeavours to predict blast movement in open-pit mining, it remains in a domain of considerable uncertainty. Technical advancements in employing electronic detonators to enhance firing precision have been made, though many mining operations still opt for more economical alternatives like NONEL systems. Furthermore, the lack of a good understanding of the geological features of the blasted rockmass can further lead to uncertainty in the results following the proposed blast design and firing sequence. Consequently, blasting activities are left with no alternative other than dealing with the uncertainties deriving from the limited geological information. In scenarios where data is sparse, the most viable route for maintaining the desired effects of blasting involves drawing insights from past experiences, iterative experimentation, rigorous monitoring of different outcomes and patterns detection. This study seeks to provide a better understanding of how blast design parameters influence blast movement, thereby enabling adjustments to achieve the desired movement magnitude under specific conditions. Such insights hold relevance for operations constrained by scarce data when dealing with new geotechnical domains, as well as for mining sites at an earlier stage of their life of mine. In both cases each mining operation is heavily reliant on the outcomes of different trial-and-error blast design parameters and their resultant outcomes.

Blasting has been actively researched worldwide over the last 70 years, however, only recently has blast movement started to be a problem regarded with the importance it deserves. Early works on tracking blast movement employ the use of sandbags, pipes, mill balls, as well analysing video footage of blast movement for the purpose of kinematic analyses (Komir, 1972, https://blastmovement.com/). Only recently have empirical observations based on monitoring have provided a reliable source of obtaining blast movement data in three dimensions by the application of Blast movement monitors (BMMs) (Thornton, 2009, https://blastmovement.com/). Hence, this has provided new ways of studying how blast movement occurs in different conditions and parts of the blast panel. Indeed, these works have provided a way of upgrading the deterministic approach of kinematic models and have introduced the component of uncertainty for the occurring blast movement along the blast model. Additionally, interpolation modelling was proposed to quantify and interpret the blast movement distribution for the blast panel (Taylor, Firth, 2003). However, the in-depth use of robust mathematical or statistical tools has only recently been adopted for studying and predicting blast movement. Indeed, such models exhibit promising results, as they provide improved ore grade reconciliation, as well as possibilities for quantifying ore grade uncertainty in the muckpile's shape (Hmoud & Kumral, 2022; Vasylchuk & Deutsch, 2019). Therefore, this article aims to contribute to the large class of stochastic models by refining the ways of studying blast-induced rock movement for a better understanding of how flitch movement is affected by blast design parameters.

Measuring blast-induced rock movement and its variability

Due to the three-dimensional nature of blast movement, the already-established horizontal (M_H) and vertical components (M_V) of the 3D movement vector (M_{3D}) were utilized in this study. However, in order to identify how movement is affected by the assumed blast design parameters, the horizontal vector is divided into its two components: $M_{H\text{-}ff}$ – the vector of horizontal movement towards the newly formed free face (perpendicular to the isochrone line) and $M_{H\text{-}dev}$ – the vector of horizontal movement deviating from the direction of $M_{H\text{-}ff}$. Naturally, both components of the horizontal movement vector can be obtained by applying trigonometric dependencies:

$$M_{H-ff} = M_H . \cos \alpha_H, \text{ (1.1)} \qquad M_{H-dev} = M_H . \sin \alpha_H, \text{ (1.2)},$$

where M_H is the scalar value of the horizontal movement vector, m;
$M_{H\text{-}ff}$ – scalar value of the horizontal movement vector component, perpendicular to the newly formed free face (perpendicular to the isochrone line), m;
$M_{H\text{-}dev}$ – scalar value of the horizontal movement vector component, deviating from the overall movement direction towards the newly formed free face, m;
α_H – deviation angle of horizontal movement (compared to the perpendicular of the isochrone), °.

Use of locally estimated values of charging rules for studying blast-induced rock movement

The Burden is the most crucial and significant parameter of every blast design, as the choice of its value ultimately impacts the blast's overall performance. This is why determining the Burden's value is the first step in creating suitable blast confinement during the blasting of consecutive rows. It is widely observed that the explosive is not able to break the rock if the burden is too large, hence the movement of the material is minimal. In contrast, the throw of the material is significant when the burden is too small. From a practical standpoint, a blast design variables (subdrilling, stemming, charging length, spacing and delays) can be manipulated in a relatively straightforward manner. However, the choice of an optimal set of parameters is not an easy task. The reason behind this is that they are constrained by different blast outcome parameters, such as parameters of the rock fragmentation's distribution, flyrock, airblast, backbreak, as well as blast vibration levels. Although blast design parameters have previously been used for establishing predictive models for the magnitude of the horizontal vector component of blast movement (Yu et al., 2019, Yu et al., 2020), very few papers address how movement occurs on two or more flitch levels (Hmoud & Kumral, 2021; Hmoud & Kumral, 2022). Additionally, using the conventional blast design parameters for controlling the magnitude of movement can provide the basis for a holistic approach, which could serve as a complement to the prediction and otpimization of all forementioned outcomes of rock blasting.

As the prediction accuracy of blast movement is highly dependent on the utilized input data, this requires accurate and precise measurements that ensure minimal noise in the obtained dataset. However, the noise component in blasting can be substantial, which further implies that the choice of predictor variables must rely on highly informative parameters. Supposedly, blast-induced rock movement is dependent on charging rules of the closest drillholes for each installed BMM, however, a certain level of autocorrelation cannot be disregarded as charging rules in neighbouring drillholes from sequential or previous rows can also influence the direction and magnitude of movement. Charging rules of drillholes from front rows can influence blast movement depending on the degree of fragmentation and the position of the material in front of the BMM. Additionally, delays between rows can also affect the levels of fragmentation and rock movement. Furthermore, the charging rules of the previous row can also influence the volume of gas products which can further lead to a higher or lower magnitude of movement. Therefore, this case study assumes that the five closest drillholes have the greatest influence on the movement of the installed monitor as shown on Fig. 1. Hence the aim of this paper is to estimate which zone is the most informative one and provide an argument for disregarding others.

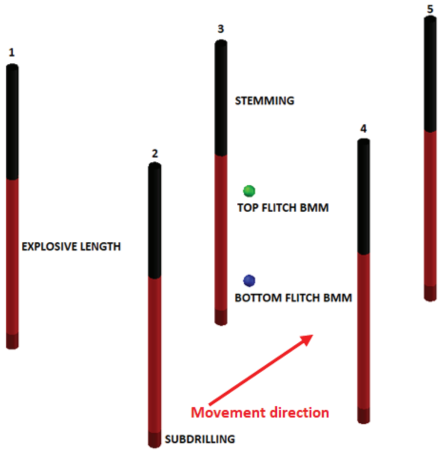

Fig. 1. Zone of influence assumed to affect BMM movement in echelon blasting

Each drillhole zone was studied in terms of the variability of the locally estimated blast design parameters and charging rules around each monitor location, as shown in Fig. 1. The reason why local parameters were established was to provide a more robust way for taking into account the varying features in different parts of each blast panel. Additionally, this also served the purpose of avoiding the use of repeating values in the dataset, regarding variables describing the blast design parameters. A total of six cases were considered for establishing a quantifiable estimation of the most relevant zone and its respective blasting conditions (Fig. 2).

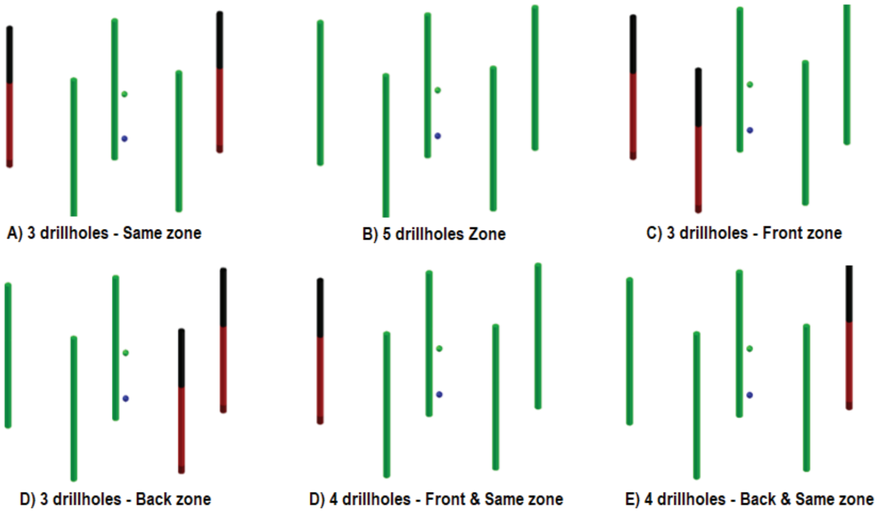

Fig. 2. Assumed zones for the investigation of blast design parameters on blast movement

Averaged blast design parameters (stemming length and subdrilling length) were established locally, based on each studied BMM's location. The height of the bench was also averaged for each zone. Additionally, the Euclidean distance between two neighbouring drillholes in a same row was used to represent the Local Spacing. In a similar manner, the Local Burden was assumed to be the perpendicular line from each drillhole to the Local Spacing line. Zones, which contain more than one Local Burden or Local Spacing assume their averaged values.

Applied sampling strategy

The following case study is based on the practical results from a open-pit gold mining operation with relatively short benches (with a height of 5m) and a relatively low powder factor (0,3 – 0,55 kg/m³). Rock conditions include soft to medium-hard rock formations (clasts and clays, breccias and siltstone with high content of quartz). Furthermore, blast movement in the studied conditions is achieved with regular intervals of delays between consecutive rows by applying an echelon firing pattern with 17 ms inter-row delays and 42 ms delays between rows. This provides a near-parallel movement direction for each consecutive row, which is crucial for minimizing ore grade dilution, losses and misclassification. However, it should be pointed out that the firing sequence is oriented in a direction where the Burden of the blast the way it is shot is parallel to the Spacing of the blast as it is drilled. Hence, the Spacing parameter (as drilled) corresponds with the actual Burden value of the shot.

For a 2-year-long period a passive experiment was conducted, during which various movement outcomes were gathered for three blasting patterns (Burden x Spacing): 3 x 3 m, 3 x 3.45 m and 3.2 x 3.7 m. Furthermore, two blasting agents were utilized: ANFO and packaged water gel explosive. In addition, a number of blasts were performed with unmined material in front of the free face (i. e. chocked blasts). Due to the unbalanced representation of different compound blasting conditions in the gathered dataset, only ANFO observations were used for this analysis. This can be justified by the significantly smaller number of observations of shots, which use packaged water gel as an explosive. Additionally, a stratified sampling strategy was applied in order to achieve a more balanced dataset, in which observations for the three different types of drilling patterns are better represented, compared to the initial dataset. Hence, a total of 37 paired observations (Top and Bottom flitch) were randomly selected from all 6 strata (3 drilling pattern types and blasting with our without a buffered free face) from 16 shots. This approach aims to imitate the situation for the mining operation as in cases of the early stages of blasting in a new geotechnical domain. Hence, the stratified dataset from the 16 shots aims to emulate the trial-and-error process of different blast design parameters, given that an active experimental approach is adopted. This way, a preliminary assessment can be made on which blast design parameters affect blast-induce rock movement more significantly and which can vary without significantly affecting movement.

Results

Pearson's correlation coefficient was calculated for the variables' pairs to measure the dependency level between the assumed parameters of interest and blast design parameters. The choice of Pearson's correlation was for the purpose of investigating the presence of a linear relationship, as the basic practical intuition behind blast design parameters is that they affect blast movement in a linear fashion.

The correlation levels between the $M_{H\text{-}ff}$ scalar values and blast design parameters are shown in Table 2a and Table 2b.

Table 2a

Corrleations with $M_{H\text{-}ff}$ (TOP FLITCH)						
Row zone	**A**	**B**	**C**	**D**	**E**	**F**
Spacing (as drilled)	**-0.776****	**-0.733****	**-0.552****	**-0.707****	**-0.697****	**-0.780****
Burden (as drilled)	-0.170	-0.195	-0.201	-0.195	-0.189	-0.185
Bench height	-0.121	-0.065	-0.147	0.014	-0.113	-0.050
Subdrilling	**0.535****	**0.545****	**0.546****	**0.549****	**0.542****	**0.542****
Stemming	**-0.536****	**-0.541****	**-0.536****	**-0.536****	**-0.536****	**-0.536****
Charge mass	**0.520****	**0.547****	**0.491****	**0.521****	**0.525****	**0.545****

Note: * $p < 0.05$ ** $p < 0.01$

Table 2b

Corrleations with $M_{H\text{-}ff}$ (BOTTOM FLITCH)						
Row zone	**A**	**B**	**C**	**D**	**E**	**F**
Spacing (as drilled)	**-0.782****	**-0.791****	**-0.680****	**-0.723****	**-0.771****	**-0.791****
Burden (as drilled)	**-0.377***	**-0.387***	**-0.325***	**-0.429****	**-0.355***	**-0.410****
Bench height	-0.250	-0.180	-0.143	-0.183	-0.192	-0.206
Subdrilling	**0.713****	**0.724****	**0.716****	**0.721****	**0.721****	**0.721****
Stemming	**-0.655****	**-0.655****	**-0.655****	**-0.655****	**-0.655****	**-0.655****
Charge mass	**0.602****	**0.657****	**0.650****	**0.534****	**0.639****	**0.605****

The obtained correlation coefficients show that zones *A*, *B*, *D*, *E* and *F* tend to be more informative for the movement of the Top flitch of the bench, while zones *A*, *B*, *C*, *E* and *F* are the most informative ones for Bottom flitch movement. The least influential zone for Top flitch movement is the Front rows zone (C), while for movement on the Bottom flitch level, it is the Back rows zone (D). Hence these subtle differences are due to the fact that upper flitch movement is affected more by the volume of gas products pushing the rockmass forward, while the lower flitch movement is affected by the confinement of the rockmass from previously blasted rows. The highest influence on horizontal movement towards the free face in both cases can be attributed to the Spacing (as drilled) for obvious reasons. In addition, the Subdrilling and Stemming lengths also affect $M_{H\text{-}ff}$ in a meaningful way. Their respective lengths can affect the amount of explosive for the respective drillholes, hence the higher correlation coefficients for the relation of blast movement to the Charge mass. Therefore, the main conclusion which can be drawn from this analysis is that the movement perpendicular to the isochrones of the firing pattern on both flitch levels is affected primarily by the distance to the newly formed free face, represented by the Spacing (as drilled) in the echelon firing pattern. Interestingly, correlation levels are higher for the movement occurring on the Bottom flitch level, which can be explained by the confining volume of rockmass from the upper flitch, which leaves no space for the rock to move, but forward. A fact worth mentioning is that there is a significant level of correlation between Top and Bottom flitch movement for $M_{H\text{-}ff}$ ($r = 0.765$). Once more, this is due to the dependence of the movement vector on the blast design and the charging rules which are the same for both monitors. Hence, the vectors used to describe the horizontal forward movement on both flitches should be regarded as dependent.

The secondary vector component for the horizontal movement Is the deviation from the perpendicular to the isochrone or newly formed free face ($M_{H\text{-}dev}$).

Table 3a

Correlations with $M_{H\text{-}dev}$ (TOP FLITCH)						
Row zone	**A**	**B**	**C**	**D**	**E**	**F**
Spacing (as drilled)	0.169	0.102	0.027	0.093	0.100	0.139
Burden (as drilled)	-0.036	-0.002	0.041	-0.014	0.004	-0.026
Bench height	0.047	0.039	0.069	-0.020	0.067	0.005
Subdrilling	-0.191	-0.181	-0.188	-0.187	-0.185	-0.185
Stemming	0.014	0.024	0.014	0.014	0.014	0.014
Charge mass	-0.072	-0.038	-0.053	-0.119	-0.060	-0.093

Table 3b

Correlations with $M_{H\text{-}dev}$ (BOTTOM FLITCH)						
Row zone	**A**	**B**	**C**	**D**	**E**	**F**
Spacing (as drilled)	0.147	0.071	0.030	0.020	0.091	0.090
Burden (as drilled)	-0.019	0.024	0.046	0.042	0.015	0.011
Bench height	0.027	0.030	0.034	-0.017	0.021	-0.002
Subdrilling	-0.300	-0.276	-0.283	-0.279	-0.285	-0.285
Stemming	-0.198	-0.198	-0.198	-0.198	-0.198	-0.198
Charge mass	-0.012	-0.008	0.004	-0.018	-0.007	-0.019

As can be observed by the two correlation tables, the $M_{H\text{-}dev}$ parameter does not correlate at a practically significant level with none of the blast design parameters. This movement vector depends primarily on the deviation of the delays for each drillhole compared to its nominal value. Due to the use of a NONEL initiation system, this parameter cannot be efficiently controlled for the current mining operation, as it is primarily the result of the nature of the non-electric technology. Hence these deviations can be assumed as the “random noise” component in the system. However, once more both flitch vector variables ($M_{H\text{-}dev}$) should be considered as dependent (r = 0.638).

A relatively lower level of correlation is observed for the scalar value of the vertical component vector of blast movement for both flitch levels (r = 0.589). This can be attributed to the described effect of buffering vertical movement for the Bottom flitch by the rockmass from the Top flitch. More information on how M_V is affected by blast design parameters can be seen in Table 4.

Table 4a

Corrleations with *Mv* (TOP FLITCH)						
Row zone	**A**	**B**	**C**	**D**	**E**	**F**
Spacing (as drilled)	-0.406**	-0.363*	-0.271	-0.327*	-0.355*	-0.387*
Spacing (as drilled)	-0.266	-0.277	-0.290	-0.246	-0.283	-0.261
Bench height	-0.252	-0.163	-0.209	-0.140	-0.220	-0.187
Subdrilling	0.529**	0.529**	0.532**	0.525**	0.530**	0.529**
Stemming	-0.532**	-0.541**	-0.532**	-0.532**	-0.532**	-0.532**
Charge mass	0.434**	0.448**	0.449**	0.442**	0.454**	0.452**

Table 4b

Correlations with *Mv* (BOTTOM FLITCH)						
Row zone	**A**	**B**	**C**	**D**	**E**	**F**
Spacing (as drilled)	-0.516**	-0.413**	-0.218	-0.421**	-0.381*	-0.494**
Burden (as drilled)	-0.311	-0.349*	-0.353*	-0.348*	-0.337*	-0.335*
Bench height	-0.310	-0.188	-0.272	-0.186	-0.286	-0.227
Subdrilling	0.453**	0.460**	0.465**	0.464**	0.458**	0.458**
Stemming	-0.429**	-0.448**	-0.429**	-0.429**	-0.429**	-0.429**
Charge mass	0.297	0.284	0.317*	0.365*	0.318*	0.333*

In terms of Top flitch vertical movement, the only correlations worth acknowledging are the ones with Subdrilling, Stemming and partially the Spacing (as drilled). Similar to the horizontal movement towards the newly formed free face, the Top flitch vertical vector is less affected by the Front rows zone, but rather it is affected by its closest drillholes. In a similar fashion, the Bottom flitch vertical vector is also not affected significantly from the Front rows zone. Contrary to horizontal movement, vertical movement is more distinct for the upper flitch, compared to the lower flitch, based on their correlation coefficient with the studied parameters. To conclude, the most influential zones in this case for the Top flitch movement are *A*, *B*, *E* and *F*, while for the bottom flitch they include *A*, *B*, *D* and *F*. To summarize all results and their corresponding conclusions drawn from the correlation analysis, Table 5 represents the most informative zones for each movement component and feature regarding blast movement.

Table 5

Blast movement vector component	**Most informative zones**	
	Top flitch	**Bottom flitch**
$M_{H\text{-}ff}$	*A*, *B*, *D*, *E*, *F*	*A*, *B*, *E*, *F*
$M_{H\text{-}dev}$	None of the proposed parameters are informative	
M_V	*A*, *B*, *E*, *F*	*A*, *B*, *D*, *F*

Zones *A*, *B* and *F* are present in all cases for Top and Bottom flitch movements both for $M_{H\text{-}ff}$ and M_V. Hence, a certain level of spatial autocorrelation between movement in neighbouring zones is evident. However, it should be pointed out that zone *A* provides the most practical and versatile set of parameters, which can be used for the modelling of blast movement. Zones which span over more rows are not able to cover BMM locations close to the free face, as there may be no rows to calculate an average value. In addition, this could lead to a "smoothing" effect to some extent. Hence, zone *A* is able to quantify the complexity of blasting conditions as closest to the free face as possible. Therefore, as the most flexible strategy, it was used for building a multiple regression model with the following regression formula for the movement of the Bottom flitch $M_{H\text{-}ff}$ vector:

$$M_{H-ff}^{BOT} = -1.329\ Avg.Burden + 2.312\ Avg.Subdrilling - 1.578\ Avg.Stemming + 8.340 \quad (2)$$

All coefficients are statistically significant with p-values lower than 0.05. Nonetheless, their estimates can be improved given that more observations are accumulated for the dataset. The metrics depicting the accuracy of the model are presented in Table 6.

Table 6

R^2	R^2 *(adjusted)*	R^2 *(prediction)*
0.7182	0.6948	0.6577

The standardized effects of the predictor variables is shown on Fig. 3. Hence, the most important parameter is the blast's Burden, followed by the charging rules.

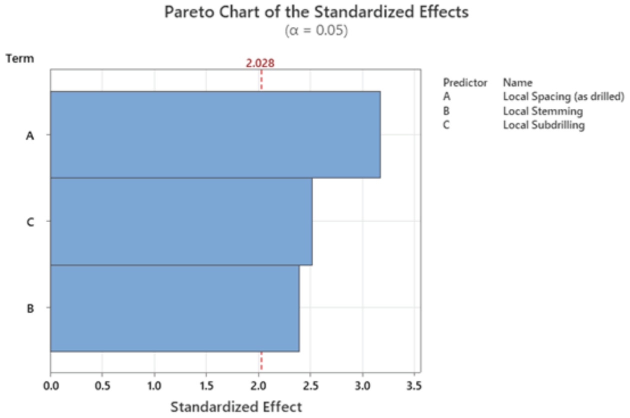

Fig. 3. Standardized effects for predictor variables

Last but not least, the model can be considered valid, as there is no evidence that the residuals are not normally distributed, and are heteroskedastic and autocorrelated (Fig. 4).

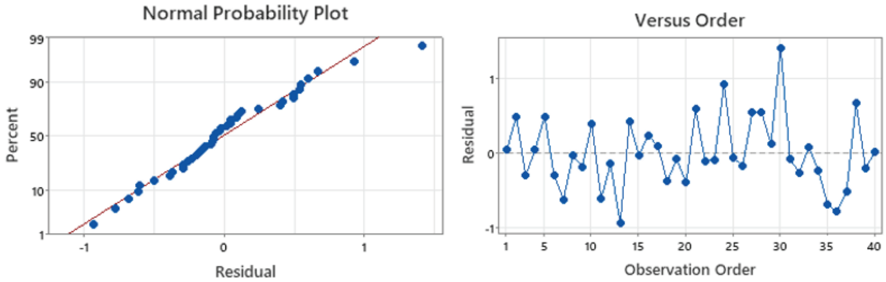

Fig. 4. Regression model validity. Normal distribution resemblance of residuals (left) and random variance in the model's residuals (right)

The unexplained variance can attribute to a mean absolute error of 0.38 m, which should be investigated in the future, as there is indeed a missing factor which should be addressed in future studies.

Conclusions

In conclusion, the performed analyses show that each 3D movement vector component is affected in a different manner by the blast design parameters. The Same row zone (zone *A*) parameters provide a practical and accurate level of understanding of how blast movement in a certain location of the blast panel is affected by its neighbouring drillholes. Furthermore, the correlation and regression analysis provided insight for better understanding how blast design parameters affect the horizontal component of blast movement, directed towards the newly formed free face. It is evident that horizontal blast movement towards the free face for the upper flitch is mostly dependent on the Same 3 rows zone or All 5 rows zone. In contrast, the bottom flitch is more dependent on front-row movement, as well as all row zones. Furthermore, it is important to say that the process of gathering a stratified sample for establishing key dependencies, as well as a basis for a regression model, can be accelerated from 2 years to only a few months. Hence, a better systematic approach would be the adoption of an active experimental approach, while iteratively adapting the blast pattern design with a trial-and-error process. This way the established correlations from this paper can be estimated at a very early stage of the life of mine and hence, can be further improved as long blasting is performed in the same geotechnical domain. Moreover, the regression model can be used not only for predictive modelling, but also for optimizing the blast design and charging rules in terms of blast movement with respect to additional optimization criteria and constraints related to rock fragmentation, airblast, flyrock, vibrations, etc. Additionally, to improve the accuracy of the regression model and for the reduction of the “noise” component, measurements must be performed more accurately and precisely in terms of Stemming and Subdrilling lengths.

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