Effects of Excavation-Geometry on Blast-Geometry with Reference to Blast Hole Diameter and Bench Height

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Abstract:- *The primary objective of this research was to investigate the most appropriate blast hole diameters with reference to the prevailing bench heights for coal mines and other excavation jobs based on the correlation. Field observations and data collection were carried out at different coal mines in Telangana, India, to achieve this objective. Based on the analysis of the data, reconsideration of hole diameter for blasting operations is suggested. A new model for estimating hole diameter for blasting operations is developed based on multiple regression methods. The measured variables that are used as independent ones (regressors) and included in the model development are hole depth (H), burden (B), and spacing (S). The hole depth and spacing were found to be statistically significant and were included in the final model. Though the burden was included in the final model, its effect was statistical less significance. This research could help mining, blasting and civil professionals to accurately design blasting operations and develop effective strategies to mitigate various hazards associated with blasting.*

1. Introduction

The backbone of the industry is mineral resources as they are the raw material for them. Both the metallic and non-metallic resources are extracted by open cast mining and underground mining method. The primary principle in both the cases is extraction of the mineral done by loosening the rock or ore. Surface mining is the most popular method of ore excavation worldwide. Drilling and blasting operation is the first element of the ore extraction process. Blasting is the most energy-efficient stage in the comminution system and has an energy efficiency of 20 to 35% as compared to the efficiency of 15% and 2% by crushing and grinding respectively (Eloranta, 1997). There exists a strong relationship between blast properties and the efficiency of crushing and grinding (Beyglou, 2012). The primary purpose of blasting is rock fragmentation and displacement of the broken rock. Blasting operations may impose excessive noise and vibration on communities. Excessive levels of structural vibration caused by ground vibration from blasting can result in damage to structures (Nicholls, 1981). A study by Raina et al. (2004) suggests the level of human response to blast vibrations and air-overpressure.

The size of the blast hole is the first consideration of any blast design. The blast hole diameter, along with the type of rock being used and the type of rock being blasted, will determine the burden. All blast dimensions are a function of the burden. Thus, the discussion is based on the assumption that the blaster has the freedom to select the borehole size. In many operations, one is limited to specific size borehole based on available drilling equipment.

Practically, blast hole diameters for surface mining range from 2 to 17 inch. As a general rule, large blast hole diameter yields low drilling and blasting costs due to cheaper drill cost per unit volume and cheaper blasting agents can be used in a larger diameter. However, larger diameter blast holes result in large burden and spacing and collar distance, and hence, they tend to give coarser fragmentation. Drilling costs for the large blast holes will be low, a low-cost blasting agent will be used, and the cost of the detonators will be minimal. However, in a problematic blasting situation, the broken material will be non-uniform in size and blocky, resulting in higher loading, hauling, and crushing costs. It may also result in more secondary breakage and insufficient breakage at the toe. Higher diameters of drilling with the wider pattern, though cost-effective, can't be used all the times as higher diameters result in higher loading densities, higher charge per delay and result in higher fly rock, bigger sizes and higher vibrations. Table 1.1 shows the existing mining practices in Indian Coal Mines.

Table 1.1 Existing mining practices in Indian Coal Mines

Sl No	Description	Measure
1	Bench height (OB- Shovel)	6-12 m
2	Bench height (OB-Coal)	3-6 m
3	Bench height (OB- Dragline)	22-25 m

4	Individual Pit Angle	50° - 60°
5	Ultimate Pit Angle	42° - 45°
6	Hole Diameter (OB and Coal)	150 mm
7	Hole Diameter (Dragline)	250 mm
8	Bench Width (OB – Shovel)	30 m
9	Bench Width (Coal)	20 m
10	Bench Width (OB – Dragline)	60 m
11	Burden X Spacing (OB - Shovel)	6 X 8 m
12	Burden X Spacing (Coal)	4 X 5 m
13	Burden X Spacing (OB - Dragline)	6 X 8 m
14	Stemming Length (OB - Shovel)	3 – 4 m
15	Stemming Length (Coal)	2.5 – 3.5 m
16	Stemming Length (OB - Dragline)	4 – 5 m

Smaller holes cost more to drill per unit volume, powder for small-diameter blast holes is usually more expensive, and the cost of detonators will be higher. However, the fragmentation will be finer and uniform, resulting in lower loading, hauling, and crushing costs. Secondary blasting and toe problems will be minimised.

Size of equipment, subsequent processing required for the blasted material, and economics will determine the type of fragmentation needed, hence the size of the blast hole to be used. The geometry of excavation to a great extent influences the blasting geometry to be adopted. The blasting geometry includes factors such as the diameter, burden, spacing and the depth of drilling. The literature survey reveals that numerous studies have been conducted to establish the relationship between blast hole diameter and prevailing bench height. However, practically in the field once blast hole diameter has been fixed based on planned bench height, we rarely get the actual bench height. For this purpose, practically hole depth is the actual bench height for the excavation. Also, spacing and burden play a vital role in blasting operations. This research gap provides the impetus for research more on the relationship between blast hole diameter, hole depth, burden and spacing.

Based on the research gap identified, the study has the following objectives to investigate the most appropriate blast hole diameters with reference to the prevailing bench heights for coal mines and other excavation jobs based on the correlation.

The objective is determined by developing a multiple regression model between blast hole diameter and hole depth, burden and spacing. The model is developed based on the data collected on various bench geometry parameters from different dimensional stone quarries and other excavation jobs. The mines or excavation setups selected will have similar geological conditions, similar capacity of excavation machinery but use different diameters of blast hole drilling.

2. Methodology and Data Analysis

The blasting details were collected from various coal mines in Telangana, India. The bench parameters, i.e. bench width, bench angle, overall slope angle, and bench height varied with the type of material excavated (overburden or coal) and also whether the excavation is carried out by contractual or department machinery. The standard hole depth varied from 5 m for coal benches to 27 m for dragline benches. The hole diameter varied from 150 mm to 250 mm.

2.1 Multiple Linear Regression Model

Based on the analysis of the data collected at different mines, there is a need for the development of new equations for correlating hole depth and blast hole geometry (i.e. blast hole diameter, burden and spacing) in blasting operations. In order to develop the function of hole depth, relationships and significant variables were defined by statistical tests. Multiple linear regression modelling is used for developing this model as it allows to examine the relationships among more than two variables. Measured variables are used as independent ones (regressors) and included in the model development. These variables are blast hole depth (m), burden (m) and spacing (m). The dependent variable used in the model is blast hole diameter (mm).

Regression analysis is a statistical technique that is used for examining the relationships between two or more variables. Either observational or experimental data can be used in regression modelling. The general linear regression model is mathematically expressed by the following equation (Kutner et al. 2004):

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_{p-1} X_{i,p-1} + \varepsilon_i \qquad (1)$$

and

$$E(Y) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_{p-1} X_{p-1} \qquad (2)$$

for $X_{i0} = 1$, and $E(\varepsilon_i) = 0$

where:

$\beta_0, \beta_1, \ldots, \beta_{p-1}$ are regression parameters,

$X_{i1}, \ldots, X_{i,p-1}$ are variables (regressors) in the model,

ε_i is normal error term, which has to be independent and normally distributed with mean zero and variance σ^2, for appropriate adequacy of the model,

E(Y) is the expected value of the response variable Y.

Some models have curvilinear and complex response functions, but they are still cases of general linear regression models. Linearity can be obtained by suitable transformation of the Y, Xi variables or both. The model of EF is this model, where the transformation of the response variable Y was performed (natural logarithm transformation). The general regression model with normal error terms shows that the observations Yi are independent normal variables, with mean E (Y_i) and constant variance σ^2. A statistical model for linear regression corresponds to the population regression line and a description of the variation of Y about the line (Moore and McCabe 2006).

The linearity of the model means that it is linear in its parameters, and does not refer to the shape of the surface that is created. The method of least-squares is used for the estimation of parameters. The analysis of variance provides an estimate of the variance of the error term σ^2 that is a significant step in the linear regression. For estimation of model adequacy in multiple linear regression problems, some hypotheses tests are useful. The suitable hypotheses are (Montgomery and Runger 2003):

$$H_0 = \beta_1 = \beta_2 = \cdots \beta_k = 0 \qquad (3)$$

H_1: $\beta_j \neq 0$ for at least one j

where:

H_o represents the null hypothesis,

H_1 represents the alternative hypothesis.

Rejection of the null hypothesis indicates that at least one of the regressor variables $x_1, x_2, \ldots, x_k$ benefits significantly to the model. The total sum of squares (SS_T) is the summation of the sum of squares considering regression (SS_R) and the sum of squares considering error (SS_E). The test statistic for the null hypothesis defined with equation 3, is defined as following (Montgomery and Runger 2003):

$$F_0 = \frac{SS_R / p}{SS_E / (n-p-1)} = \frac{MS_R}{MS_E} \qquad (4)$$

where:

F_o represents test statistic,

p represents the number of regressor variables in the model,

n represents the number of data used for analysis,

MS_R represents the mean square model, and

MS_E represents the mean square error.

The analysis of variance (Table 2) summarises the procedure. These computations were performed with the Minitab statistical software.

Table 2 Analysis of variance (Montgomery and Runger 2003)

Source of variation	Sum of Squares	Degrees of Freedom	Mean Square	Test statistic F_0
Regression	SS_R	k	MS_R	MS_R / MS_E
Error or residual	SS_E	n-k-1	MS_E	
Total	SS_T	n-1		

Tests of the hypothesis on the individual regression coefficients contribute to the determination of the potential value of every regressor variable in the model. Thus, the effectiveness of the model can be better if one or more regressor variables are included in the model, or if one or more regressor variables are deleted from the model. The same rules are valid for reject/failure to reject the null hypothesis as for the already defined hypothesis testing. The t-statistic is the test statistic for individual regressors and is provided in the regression output in statistical software. Another test that can be used for the same purpose is partial F-statistic, which can be used for examining the best subset of regressor variables for the model. The p-values for individual variables assess the statistical significance of a particular regressor. For the confidence interval of 95%, the p-value should be less than 5% (0.005) to consider a particular variable significant. To evaluate the fit of the model, coefficients of the multiple determination R^2 or adjusted R^2 are usually used. They can be mathematically expressed by the following equations:

$$R^2 = \frac{SS_R}{SS_T} \quad (5)$$

$$R_{adj}^2 = 1 - \frac{SS_E/(n-p)}{SS_T/(n-1)} \quad (6)$$

However, with the addition of the variable in the model, the value of R^2always increases that can be somewhat problematic. On the other hand, R_{adj}^2 will have higher value only if the newly added variable reduces the error mean square. It is a particularly useful parameter that limits the analyst for adding variables that are not helpful in explaining the variability of data.

The first step that should be undertaken in model building is the correlation test between the independent variables. The correlation coefficient measures the linear relationship between variables and has the value range from minus one to one. The value of plus one shows the perfect positive correlation, while the value of minus one shows the perfect negative correlation. Minitab software was used to get the correlation among variables. Next, one of the most critical problems in regression analysis involves selecting the set of independent (regressor) variables to be used in the model.

Finally, the best subset analysis and stepwise regression analysis were used for the determination of significant independent variables for the development of the model. The selection of the "best" subset of the independent variables involves examining available variables to obtain the regression model. Therefore, to make a model easy to use, one's goal is to choose a few regressor variables as possible. For aK regressors $x_1, x_2, \ldots, x_k$ and a single response variable y there are 2^K total equations that should be analysed. For evaluating and comparing those different possible regression models, there are several criteria that can be used:

a) R_{adj}^2 - The adjusted coefficient of determination R_{adj}^2 is one of the most commonly used criteria. As previously explained, the model maximising this parameter also minimises the mean square error. Thus, it is considered to be a suitable candidate for the best regression model.
b) Cp - Another criterion that is used for evaluation of regression models is Cp statistic. It is defined as the total mean square error for the regression model. Therefore, the best regression model should have a minimum Cp statistic.

Thus, the best subset analysis was performed on all regressors that are available, and parameters R_{adj}^2 and C_p were used for evaluation of the most suitable model, which will be presented later in this paper.

Besides the all possible regressor selection method, the stepwise regression technique was performed. The stepwise regression method uses iterations to make a series of regression models by adding or removing variables at every step. As previously mentioned, the criterion for addition or removal of variables is usually a partial F-test. The process of the stepwise selection method begins with making a one-variable model, with the regressor that has the highest correlation with the response variable Y. In terms of statistics used for this analysis; this regressor will have the highest value of partial F-statistic. Generally, at every step, the set of remaining regressors is examined, and the one with the most significant partial F-statistic is inserted into the model.

To check if multicollinearity exits, the variance inflation factors (VIF) are calculated for the variables in the model. Multicollinearity represents dependency among the regressor variables, which has a high impact on the coefficients of the regression as well as the appropriateness of the derived model. It is expressed with the Variance Inflation Factor (VIF), which has the following equation (Montgomery and Runger 2003):

$$VIF = \frac{1}{1-R_j^2} \qquad (7)$$

where:

R_j^2 is the coefficient of multiple determination that is the result of regressing x_j on the other k_j regressors.

The value of multicollinearity should not be more than 5 or 6 (Montgomery and Runger 2003). However, with VIF greater than 10, there is an indication for strong presence of multicollinearity (Statisticssolutions, 2015).

Table 3 shows the results of the best subset regression for hole diameter. The three-variable model consists of log hole depth (H), log burden (B) and log spacing (S). The full model containing all the variables has R^2 (adj) = 87.4 which is the highest among all models. The next best model is two model containing log hole depth (H), and log spacing (S). Both the full model and two-variable model have low C_p. Thus, the backward stepwise regression analysis is conducted to find the preferred model.

Table 3. Results of the best subset regression for Hole Diameter

Variables	R^2	R^2(adj)	R^2(pred)	C_p	Log H	Log B	Log S
1	86.0	85.8	85.0	11.8	X		
1	73.0	72.7	71.9	92.5			X
2	87.1	86.8	85.8	7.0	X		X
2	86.4	86.1	85.1	11.2	X	X	
3	87.9	87.4	86.2	4.0	X	X	X

Results of the multiple regression model of blast hole diameter are shown in Table 3 and Table 4. It can be seen from Table 3 that hypothesis test of the individual regression coefficients(with t statistic) yields p values less than 0.05 for log hole depth (H), log burden (B) and log spacing (S) which indicates that all these variables are statistically significant in the model. The maximum value of VIF for the model is 5.74 and shows that multicollinearity is not an issue in this case. The coefficient of determination R^2 shows that 87.9% of the variation of the Hole Diameter is explained with the variables in the model.

The analysis of variance table for the blast hole diameter is shown in Table 4. Analysis of variance indicates that F statistics are huge, and the MSE is small, which further means that the regression line explains most of the variability of the response variable. Comparison of SSE with PRESS statistics is a way of informal judging of the sensitivity of the model fit. The value of the PRESS statistic (Table 4) is close to the value for sum squares of error (error adj. SS in Table 5), which indicates that overfitting is not the issue in this model. Moreover, the predicted R^2 is reasonably close to the regular R^2.

Table 4. Results of the multiple regression model for Hole Diameter

Term	Coef	SE Coef	T-value	P-value	VIF
Constant	1.7418	0.0393	44.29	0.000	
Log H	0.2882	0.0442	6.53	0.000	5.74
Log B	0.1465	0.0655	2.24	0.028	1.96
Log S	0.2034	0.0672	3.03	0.003	4.15
Summary of Model	**R^2 = 87.92%**	**R^2(adj) = 87.43%**	**R^2(pred) = 86.17%**	**Press = 0.116354**	

Table 5. Analysis of variance table for Hole Diameter

Source	DF	Adj SS	Adj MS	F-value	P-value
Regression	3	0.7394	0.2464	181.90	0.000
Log H	1	0.0577	0.0577	42.58	0.000
Log B	1	0.0067	0.0067	5.00	0.028
Log S	1	0.0124	0.0124	9.16	0.003
Error	75	0.1016	0.0013		
Total	78	0.84			

The regression equation has the following form:

$$\mathbf{Log\ D = 1.7418 + 0.2882\ Log\ H + 0.1465\ Log\ B + 0.2034\ Log\ S} \quad (8)$$

Removing the log from both sides, the mathematical formulation of the model is represented by Equation 9.

$$\mathbf{D = 55.18 \times H^{0.2882} \times B^{0.1465} \times S^{0.2034}} \quad (9)$$

For validation of the model, data splitting was carried out. The data was divided into two separate samples in random order. One of the samples was used to building the model, and the other sample was used for validation of the model. The MSPR was calculated when the regressed coefficients were used on the validation data set. The MSPR is 0.0029 which is very close to MSE value of 0.0013 (Table 5). Thus, the selected model has a good predictive ability for the validation data set.

3. Conclusions

The research emphasises on the adoption of the appropriate diameter of blasthole on blast geometry of excavation geometry, which allows full exploitation of the mineral throw and benefits of blasting while improving the ability to limit the mineral damage, dilution, and loss.

The multiple regression model developed has a R_{adj}^2 value of 87.4, which suggests that 87.4% of data can be predicted reliably with the given model. With the addition of the new variable in the model, the value of R^2 always increases. However, the R_{adj}^2 will have higher value only if the newly added variable reduces the mean square error. In our model R_{adj}^2 with the addition of all the three variables showed increasing trend suggesting decrease in the mean square error.

The model developed is useful for estimation of blast hole diameter from coal mines. However, with an increase in data points, the accuracy of the model will increase. Also, the coefficients will change to reflect the increase in accuracy. In its current form, the model may not give good results for prediction of blast hole diameter based on burden, spacing and hole depth for quarries, metalliferous mines and other excavation jobs. The primary focus in developing a new model was to formulate a new blast hole diameter equation for blasting operations at various coal mines considering the use of on-site blasting geometry data such as the burden, spacing and the depth of drilling. Based on the new model developed, it can be concluded that:

i) The bench height or hole depth has a significant effect on the hole diameter at coal mines. Optimum blast hole diameter increases with the height. In general, an increase in blast hole diameter decreases in drilling costs

ii) Spacing also plays a significant role in hole diameter. Proper spacing of the holes is essential as improper spacing produces undesired fragmentation. Too much of the spacing between holes may create boulders from the middle portion. The spacing to burden ratio (S:B) is what determines the quality of fragmentation.

iii) Burden also has a positive effect on hole diameter, though their effects were statistically less significant. The smaller burden is required when the distance between discontinuities is significant. Too little a burden results in fly rock and excessive fines and too much of burden produces back break, boulders and toe.

4. Limitations and scope for future research

The analysis of blast hole diameter for blasting operations at different coal mines in this research was based only on several data sets that were available for analysis. A collection of more data would enhance the accuracy of the evaluation and give better insight into the role of different parameters on blast hole diameter. The new data also may change the coefficients as well as increase the number of parameters in the model. Also, with more data, mining, professionals could more accurately design blasting operations at mines and develop effective strategies to mitigate various hazards associated with blasting.

The collection of more data from various metalliferous mines, dimensional stone quarries and other excavation jobs would allow additional analysis to determine the variation between the types of mines as well as the type of mineral excavated. In that way, if the difference was significant, other strategies could be developed for particular mine or ore.

The model developed in this research can be used for estimation of blast hole diameter from coal mines. However, the addition of data from metalliferous mines, dimensional stone quarries and other excavation jobs would make the model more accurately predict blasthole diameter for other mines.

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