Modeling of Blast Induced Damage Distance for Underground Tunnels

Priti Maheshwari[1, *], Sunny Murmu[2], and Harsh Kumar Verma[3]

[1] Indian Institute of Technology Roorkee, Roorkee, India
priti_mahesh2001@yahoo.com
[2] Indian Institute of Technology (ISM) Dhanbad, Dhanbad India
sunny.murmu1@gmail.com
[3] CSIR- Central Institute of Mining and Fuel Research, Regional Centre, CBRI Campus, Roorkee, India
drharsh77@gmail.com

Abstract. One of the terminology which quantifies the amount of damage to the tunnel face, invert, crown and sidewall is damage distance. It is the minimum distance where blast provoked discontinuities are formed beyond the periphery of newly excavated face. This distance mostly contains the unnatural discontinuities developed due to blasting. In order to cater to the uncertainties and prediction of large numbers of outcomes for different combinations of controllable and uncontrollable parameters, probabilistic analysis has been carried out in this study. As input for probabilistic analysis, the controllable parameters taken into considerations are maximum charge per delay (*W*), perimeter charge factor (*P*), specific charge (*q*) and as uncontrollable parameters rock quality index (*Q*). Data has been compiled from the literature pertaining to three different underground tunnels. The relationship between damage distance and the input parameters have been determined by drawing scatter plots implementing simple regression. These input have then been used to develop a deterministic model for prediction of damage distance. Following this, the probabilistic analysis employing Monte-Carlo *(MC)* simulation has been carried out. The existing blast design has been found to have 100% probability of occurrence for damage distance greater than 1 m. The occurrence of 1 and 2 m damage distance has been found to be inevitable. In order to mitigate the intensity of damage distance, a proper blast design can be chosen by trial methods implementing probabilistic analysis.

Keywords: Damage distance, Monte-Carlo simulations, Underground tunnels, Blasting.

1 Introduction

Despite having ruinous characteristics and stern regulations for application, drill and blast method is widely acceptable for underground excavation, owing to the fact that it is not only inexpensive but readily available. It also can be implanted in any geo-mining condition with high advancement rate vis-à-vis the mechanical excavators. When blasting occurs, the blast holes join together in fractions of seconds thereby forming new free face.

Along with it follows the process of loosening of adjacent rock mass and tight joints. One cannot accurately decipher the damage blasting has incurred by just looking at the new free face developed. The major factors that contribute to the formation of damage zone are blast load and the in-situ stress redistribution [1]. The extent of damage to the rock mass is mainly dependent upon two major factors the controllable factors and the uncontrollable factors. The controllable factors are mostly the blast design implemented and the explosives used as per the blast design. The uncontrollable factors are the geotechnical and geological properties of rock mass. Due to the complexities associated with the blasting mechanism and rock mass properties it becomes very difficult to predict the amount of damage a particular blast will incur. One of the term which quantifies the amount of damage to the tunnel face, invert, crown and sidewall is damage distance. It is the minimum distance where blast provoked discontinuities are formed beyond the periphery of the newly excavated face. This distance mostly contains the unnatural discontinuities developed due to blasting.

Some of the studies dealing with determination of extent of damage due to blasting include Raina et al.[2], Ouchterlony et al. [3], Singh and Xavier [4], Warneke et al. [5], Ramulu et al. [6], Fu et al. [7], Verma et al. [8, 9] etc. Although these studies quantify the extent of damage, however, limited studies are available to cater to the uncertainties prediction of large numbers of outcomes for different combinations of controllable and uncontrollable parameters. In view of this, a probabilistic analysis has been presented in this work for this purpose. As input for probabilistic analysis, the controllable parameters taken into considerations are maximum charge per delay (W), perimeter charge factor (P), specific charge (q) and as uncontrollable parameters rock quality index (Q). Data has been compiled from the literature pertaining to three different underground tunnels. The tunnels comprises of different rock types ranging from fair to good quality (2.7-17.8) rating of rock mass as per Q-system of rock qualification. The relationship between damage distance and the input parameters have been determined by drawing scatter plots implementing simple regression. These input are then used to develop a deterministic model for prediction of damage distance. Following which probabilistic analysis employing Monte-Carlo *(MC)* simulation has been carried out.

2 Data Acquisition

Three set of blast data pertaining to three underground tunneling projects having different rock types has been taken [8]. Brief information has been presented in Table 1 where range of values of maximum charge per delay (W), perimeter charge factor (P), specific charge (q), rock quality index (Q) and damage distance (DD) has been reported along with details of the project sites.

Table 1. Details of blast data [8].

Project site and rock type	No. of observations	Range of parameters				
		W (kg)	P (kg/m^3)	Q	q (kg/m^3)	DD (m)
Singoli-Bhatwari Hydro Power Project, Rudraprayag, Quartz Biotite Schist	20	21.2-43.2	0.9-2.2	2.7-10.7	1.6-2.6	2.85-3.85
Tapovan Vishnugaad Hydro Power Project,Tapovan, Quartzite	12	14.3-42.1	0.7-1.9	6.8-17.8	1.6-3.3	2.7-3.85
Tapovan Vishnugaad Hydro Power Project,Tapovan, Augen Gneiss	24	18-41	0.9-2.3	3.6-4.33	1.4-2.9	2.96-3.88

3 Development of Empirical Relationship: Deterministic Analysis

It has been noticed that when simple regression between each of the individual input parameters and damage distance did not help in developing any significant relationship between these. Therefore, new variables in the form of combination of one or two input parameters have been defined which resulted into meaningful correlations. These variables have been defined as: $\omega = P^{0.05}\sqrt{W+q}, \phi = \frac{W}{Q^{0.05}}$ *and* $Z = \omega\phi$. An attempt has then been made to establish a correlation between damage distance and these parameters and a linear relationship between damage distance and parameters, ω and ϕ has been observed as tabulated in Table 2.

Table 2. Predictive models.

Parameters	Predictive models	R^2
DD vs. ω	$DD = 0.4121\omega + 1.0072$	0.83
DD vs. ϕ	$DD = 0.0448\phi + 2.1263$	0.83

Further, in order to develop a more significant relationship for the prediction of damage distance incorporating the controllable and uncontrollable blast factors, multiple regression has been employed. The resulting model has been given below:

$$DD = \left[k\left(\frac{\omega}{Q^{0.05}}\right)\left(P^{0.05}\sqrt{W+q}\right)\right] + \lambda \tag{1}$$

where, k and λ are regression constants and have been found as 0.0052 and 2.5191 respectively with R^2 as 0.82. The above empirical equation has been used for the prediction of damage distance for a different data set. In order to study the goodness of fit, two parameters namely root mean square error (RMSE) and variance accounted for (VAF) have been obtained and these have been worked out to be 0.0185 and 82% respectively. Low values of RMSE and higher values of VAF signify goodness of fit. These values therefore, indicate that the developed model predicts the damage distance fairly accurately, thus validating the developed empirical relationship.

4 Probabilistic Analysis

For probabilistic analysis, Monte-Carlo simulation technique has been adopted for which a deterministic model is essential. Developed empirical relationship (Eq. 1) has been used for this purpose. The input parameters include maximum charge per delay (W), perimeter charge factor (P), specific charge (q), rock quality index (Q). In order to carry out a probabilistic analysis, first appropriate probability distribution functions for these input parameters have been determined. For this purpose, first an appropriate distribution function has been assumed looking at the variation in the data set. Parameters of assumed distribution function have been determined which is followed by conduct of goodness of fit test. Chi-square test has been employed to check for goodness of fit.

4.1 Determination of Suitable Distribution Function

Maximum Charge per Delay (W). Raw data pertaining to maximum charge per delay indicated that it follows triangular function with parameters as minimum, most likely and the maximum values of sample data. These parameters have been found to be 14.3 kg, 26.8 kg and 44.3 kg respectively. Chi square (χ^2) value has been computed as 16.32 which has been found to be less that tabulated value of χ^2 indicating the suitability of assumed distribution function with a significance level of 0.005. Accordingly, probability density function of W has been determined as shown in Fig. 1.

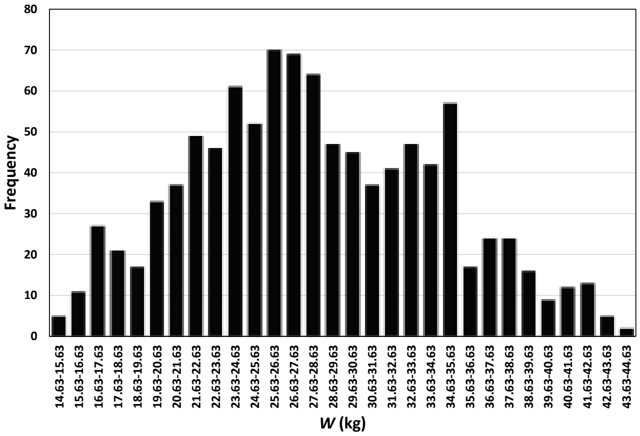

Fig. 1. Probability density function for maximum charge per delay (*W*).

Rock Quality Index (*Q*). Rock quality index has been found to follow lognormal distribution with mean 5.78 and standard deviation of 3.09. Figure 2 shows the probability density function for *Q*.

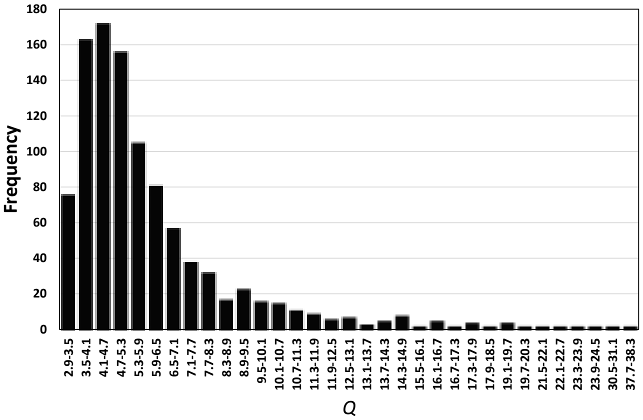

Fig. 2. Probability density function for rock quality index (*Q*).

Perimeter Charge Factor (*P*). Perimeter charge factor is the ratio of amount of explosive in perimeter holes to the volume of broken rock and this has been found to follow a triangular distribution function with parameters as minimum (0.6), most likely (1.1) and the maximum (2.49) values of sample data. Figure 3 depicts the probability density function for P. In this case as well, Chi-square test has been conducted and found to be satisfactory.

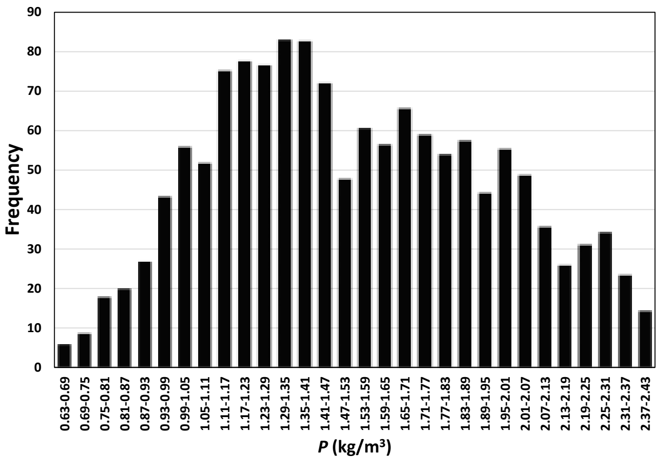

Fig. 3. Probability density function for perimeter charge factor (*P*).

Specific Charge (*q*). Specific charge has been taken as discrete function with mean of 2.08 and standard deviation of 0.36 and its probability density function has been shown in Fig. 4.

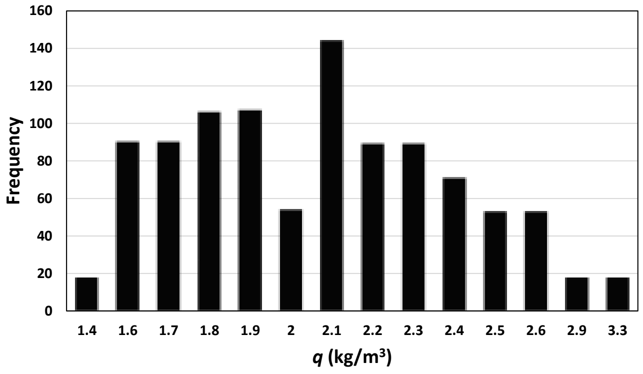

Fig. 4. Probability density function for specific charge (*q*).

4.2 Generation of Random Variables

The input parameters, maximum charge per delay and perimeter charge factor have been found to honor triangular probability distribution. Their random variables have been generated using inverse transform method. For the generation of random variables for rock quality index, first variables following normal distribution were generated from central limit theorem. These have subsequently been converted into lognormally distributed random variables. All the random variables have been generated in accordance with the number of iterations required for Monte-Carlo (MC) simulation. This has been taken as 1000 owing to the fact that there was no change in the results even when this number was increased.

4.3 Monte-Carlo Simulations

After the generation of random variables for all the input parameters, these have been fed to the deterministic model (Eq. 1) for the simulations. This resulted into 1000 number of realizations of damage distance. The probability density function of damage distance has been obtained and has bene presented in Fig. 5.

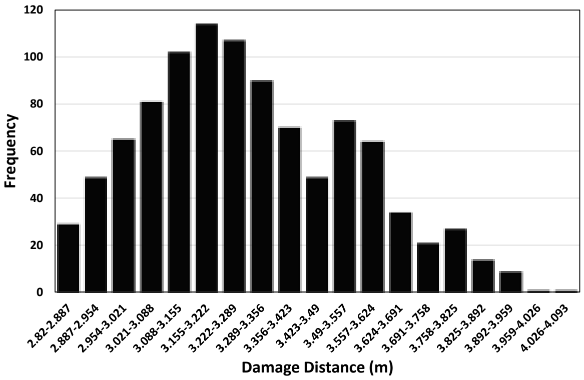

Fig. 5. Probability density function for damage distance (*DD*).

5 Results and Discussion

On completion of *MC* simulations implementing 1000 iterations, 1000 number pf realizations for damage distance have been obtained. The probability distribution function corresponding to these values has been determined and it has been observed that it follows a Weibull distribution having two governing parameters, i.e., scale parameter and the shape parameter. These have been obtained as 0.62 and 2.35 respectively. As data for damage distance was available from the three sites (Table 1), Chi-square test has been performed to check the goodness of fit for Weibull distribution. Computed value of Chi-square has been found to be 25.19 which is lower than the standard value of Chi-square with a significance level of 0.005. This establishes the goodness of fit with respect to Weibull distribution to damage distance.

Employing this information, the probability distribution function for damage distance has been determined from all the three set of data namely, experimentally observed data set, predicted data set from developed empirical model and simulated data set from probabilistic analysis. All the three distribution functions have been plotted in Fig. 6. It has been observed that simulated results are in close agreement with measured results depicting the effectiveness of probabilistic analysis.

The probability for occurrence of different outcome has been analyzed. The existing blast design that has been used for the tunneling purpose in this study, has a probability of occurrence of 100% for damage distance greater than 1 m. The probability of damage distance occurring greater than 2 m, 3 m, and 4 m are 100%, 90% and 0% respectively. The occurrence of 1 and 2 m damage distance has been found to be inevitable. This zone is called the inelastic zone where attenuation of blast energy occurs. In order to mitigate the intensity of damage distance a proper blast design can be chosen by trial methods implementing probabilistic analysis. For different blast designs different scenarios of damage distance can be predicted and the best among them should be chosen and employed for sound blast for underground excavation.

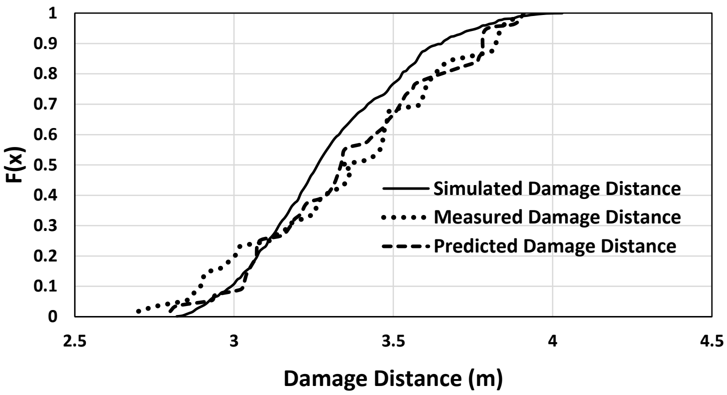

Fig. 6. Comparison of probability distribution function for damage distance (*DD*).

6 Concluding Remarks

Blast data from three different underground tunnel excavation sites have been acquired. The rock quality associated with this study has been found to range from fair to good quality of rock mass according to Q-system of classification. The random variables have been considered as maximum charge per delay, rock quality index, perimeter charge factor and specific charge. The influence of these parameters have been determined and an empirical model has been developed. This deterministic model has then been used for the probabilistic analysis employing Monte-Carlo simulation by feeding the realizations of various input parameters into the deterministic model. The random variables (following appropriate probability distribution function) corresponding to each set of input parameters have been generated and then fed to the developed deterministic model for damage distance. Realizations of damage distance have been obtained as a result of Monte-Carlo simulations. The probability distribution functions for the simulated, measured and predicted damage distance have then been compared followed by which the blast design implemented for tunneling purpose has been analyzed. It has been found that probability of occurrence of damage distance greater than 2 m, 3 m, and 4 m are 100%, 90% and 0% respectively. The occurrence of 1 and 2 m damage distance has been found to be inevitable. Such a probabilistic analysis helped in analyzing the blast design so that a better design could be proposed minimizing the damage distance.

References

1. Martino, J. B., Chandler, N. A.: Excavation-induced damage studies at the underground research laboratory. International Journal of Rock Mechanics and Mining Sciences 41, 1413-1426 (2004).
2. Raina, A.K., Chakraborty, A.K., Ramulu, M., Jethwa, J.L.: Rock mass damage from underground blasting, a literature review, and lab- and full scale tests to estimate crack depth by ultrasonic method. FRAGBLAST-International Journal of Blasting and Fragmentation 4, 103–125 (2000).
3. Ouchterlony, F., Olsson, M., Bergqvist, I.: Towards new Swedish recommendations for cautious perimeter blasting. FRAGBLAST: International Journal of Blasting and Fragmentation 6 (2), 235-261 (2002).
4. Singh, S.P., Xavier, P.: Cause, impact and control of overbreak in underground excavation. Tunnelling and Underground Space Technology 20, 63–71 (2005).
5. Warneke, J., Dwyer, J.G., Orr, T.: Use of a 3-D scanning laser to quantify drift geometry and overbreak due to blast damage in underground manned entries. In: Eberhardt, E., Stead, D., Morrison, T. (Eds.), Rock Mechanics: Meeting Society's Challenges and Demands, Taylor & Francis Group. London, Vancouver, Canada, pp. 93–100 (2007).
6. Ramulu, M., Chakraborty, A.K., Sitharam, T.G.: Damage assessment of basaltic rock mass due to repeated blasting. Tunneling and Underground Space Technology 24, 208–221 (2009).
7. Fu, H., Wong, L.N.Y., Zhao, Y., Shen, Z., Zhang, C., Li, Y.: Comparison of excavation damage zones resulting from blasting with NONEL detonators and blasting with electronic detonators. Rock Mechanics and Rock Engineering 47, 809–816 (2014).
8. Verma, H.K., Samadhiya, N.K., Singh, M., Prasad, V.V.R., Goel, R.K.: Investigations of rock mass damage induced by blasting in tunnelling. Journal of Rock Mechanics and Tunnelling Technology 22 (1), 49–61 (2015).
9. Verma, H.K., Samadhiya, N.K., Singh, M., Goel, R.K., Singh, P.K.: Blast induced rock mass damage around tunnels. Tunnelling and Underground Space Technology 71, 149-158 (2018).