Overbreak in Underground Excavations - Some Key Insights*

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ABSTRACT: Drilling and blasting has been a preferred method of rock excavation world-wide. Blasting inevitably causes damage to the peripheral rock mass, which culminates in the form of overbreak and damaged zone. Damage or overbreak not only endangers the safety of structure and cost escalation but also delayed completion. Too large damage zone endangers the safety of the front line workers due to reduction of stand-up time especially for poor rock mass. Functionality and post-construction performance of structures get affected due to large extent of damage zone, if not taken care in time. Field investigations were carried out at five different Himalayan tunnels to formulate an empirical equation for predicting blast-induced overbreak for wide range of rock mass qualitywherein Q values ranged between 0.03 and 17.8. The proposed equation involves parameters like specific charge, perimeter charge factor, maximum charge per delay, rock mass quality (Q), advancement and confinement factors. These parameters are readily available at the site without any difficulty. Nearly 113 experimental blasts were monitored and data so collected were used to formulate an index termed as scale effect (Si), which is the ratio of tunnel cross-sectional area and block size of rock mass. It is revealed that when Si becomes greater than 4, the range of overbreak lies between 8 and 25%. The paper presents details of the field investigations, rock mass characterisation and optimised blast design to achieve the safe and productive blasting operation for critical excavation in Tehri Pumped Storage Plan Project. A detailed discussion and analysis of impact of the blasting operation through geotechnical instrumentation data is also given in details in this paper.

1. Introduction

Drilling and blasting method (DBM) is globally used for rock excavation due to low investment, cheap explosive energy, easy acceptability among the stakeholders, possibility of dealing with different shapes and sizes of openings and reasonably faster rate of advancement in a suitable geotechnical mining condition. This makes DBM a preferred method of rock excavation (Innaurato et al., 1998; Verma et al., 2018).

DBM inevitably damage surrounding rock mass due to formation of network of fine cracks leading to safety and stability problems. Rock mass damage zone surrounding an underground opening consists of overbreak zone (failed zone), damaged zone and a disturbed zone. The three zones of damage are shown in Fig 1. The overbreak zone represents the zone beyond the minimum excavation line of the designed periphery from where rock blocks/slabs detach from the rock mass. It is a measure of difference in excavation between 'as designed profile' and 'as excavated profile'. Overbreak varies from 5 to 30% which incurs significant cost and increases cycle time of the tunnelling operation. Overbreak assessment in tunnels assumes greater importance to minimize cycle time operation and optimisation. Usually host of geotechnical parameters, blast design and operational parameters and explosive properties influence it. Overbreak may also occur due to the effect of the ground conditions and the nature of excavation being adopted(Ibarra et al., 1996). The factors influencing the smoothness and softness of the perimeter can be classified into four categories viz. drilling accuracy, perimeter hole spacing and loading (charging), treatment of first row in-holes and geology (Macknown, 1984). Zone immediately beyond the overbreak zone is damaged zone. The damaged zone is a zone of influence around tunnel beyond the overbreak zone. The irreversible changes in the rock mass properties take place in this zone due to the presence of fine networks of micro-cracks and fractures induced by the blasting and excavation process. This zone is characterized by deterioration in mechanical and physical properties and increase in transmissivityproperties. The disturbed zone is a zone in the rock mass immediately beyond the damaged zone where changes in the rock mass properties are insignificant and reversible. This zone is dominated by changes in stresses and hydraulic permeability.

Overbreak as well as damaged zone has significant impact on the project cost, construction period, safety and performance of the underground structures. In the case of the civic tunnels, damaged zone can adversely affect the stability of the structure and hence they need to be accounted for while designing support system for openings.

In light of the above observations, field investigations were carried out at the sites of five hydroelectric projects to assess various aspects of overbreak resulting in blasting. Using data obtained from the field, an empirical equation has been developed to estimate the overbreak (%) during construction of civic tunnels.

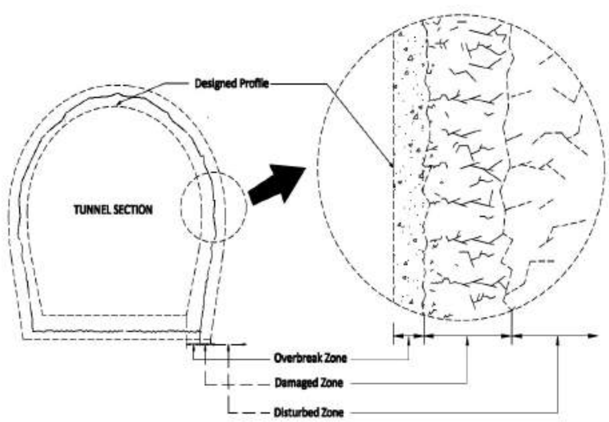

Fig. 1: Blast induced rock mass damage zone around an underground opening

2. FIELF INVESTIGATIONS

Field experiments were carried out to look into the insight of these influencing parameters at five tunnel construction sites. These sites are integral parts of three major hydroelectric projects located in Himalaya. They include Access Tunnels (AA10R and AA7) from Pump Storage Plant (PSP) of THDC India Limited at Tehri, Head Race Tunnel (HRT) of Singoli-Bhatwari Hydroelectric Power Project (SBHEP) at Rudraprayag, HRT and Bypass Tunnel (BPT) of TapovanVisnhnugaad Hydroelectric Power Project (TVHEP) at Tapovan. The data was obtained from 113 blasts undertaken at such construction sites. Detailed site description is presented in a research paper Verma et al., (2018). Rock mass characterisation, blast vibration monitoring, overbreak assessment and estimation of damaged zone were carried out for each blast. Figure 2 shows photograph of head race tunnel of Singoli-Bhatwari Hydro project site at Rudraprayag.

All experimental blasts were closely monitored and all drilling related data,especially perimeter holes and holes in the penultimate row and their corresponding depths were collected. Charge loading parameters such as explosive consumption in a hole, total charge, initiation sequence, maximum charge per delay were recorded meticulously. All the blasts were conducted out using 40 mm cartridge emulsion explosives and non-electric initiation system. Pull obtained in each round was obtained after surveying of tunnel profile and advancement. Factors on advancement and confinement were calculated for each blast to represent different features of underground excavation. The data parameters, which were collected, are described below.

- Specific charge (q) (kg/m^3): It is defined to be the ratio of total quantity of explosive and volume of broken rock.
- Maximum charge per delay (W) (kg): It is the maximum quantity of explosive fired in a delay series or within 8 ms.
- Perimeter charge factor (q_p) (kg/m^3): Similar to specific charge, it is the quantity of explosive used in perimeter holes and the volume of rock corresponding to burden of the contour holes.
- Advancement factor (A_f): It is ratio of pull (l) and hole depth (d) in a blast round.
- Confinement factor (C_f): It is ratio of hole depth (d) and cross-sectional area of tunnel (a).

Rock mass quality index, Q [Barton et al. 1974) is used for rock mass characterisation. This system of rock mass characterization has been recommended specifically for tunnels and caverns with an arched roof. It is observed that *Q*-system is a preferred method of rock mass classification for civil construction such as tunnels and caverns for various purposes like support design and engineering classification of rock mass. In *Q*-system, Stress Reduction factor (*SRF*) is one of the parameters which accounts for active stresses during construction of an underground opening and that is why *Q*-system has been selected for rock mass characterisation in the present study.

In all the experimental sites, *Q* ranges from 0.03 to 17.8 indicating that the suggested method could be applicable to a wide range of rock mass under non-squeezing ground condition.

Overbreak is the volume of rock outside the minimum excavation line removed during excavation operations (IS: 19401, 1996). Conventionally, overbreak is expressed in percent of theoretical rock volume produced in each round of blast. In the present study, it has been measured using a total station survey equipment after each round of blast covering wide range of *Q* values. Table-1 shows the general information and various rock-strength parameters. Figure 3 shows experimental investigations of rock core samples in the laboratory.

Fig. 2: Photograph showing Head Race Tunnel of Singoli-Bhatwari Project, Rudraprayag

Fig. 3: Laboratory investigation of rock core samples obtained from the experimental sites

Table-1: Geotechnical Properties of Rock in Experimental Tunnels (L&T-SBHEP, 2007; PSP, 2007; NTPC, 2006; NTPC, 2010)

Sl. No	Experimental Tunnel Site	Predominant Rock Type	σ_t MPa	Vp m/s	E MPa	Data Set	V_{cr} mm/s	Range of Q
1	HRT SBHEP	Quartz Biotite Schist	6.71	3267	12600	27	1739.8	0.8 - 1.1
2	HRT TVHEP	Augen Gneiss	8.7	5400	27900	30	1683.8	0.03 - 1.68
3	BPT TVHEP	Quartzite	12.4	6200	55500	20	1754.5	2.7 - 11.1
4	AA7 PSP	Phyllitic Quartzite Thinly Bedded (PQT)	4.3	5400	10500	24	221.65	3.6 - 4.3
5	AA10R PSP	Phyllitic Quartzite Massive (PQM)	7.2	6000	12700	12	340.15	6.8 - 17.8

Notations: *σ_t: Tensile strength, V_p: P-wave velocity, E: Young Modulus; V_{cr}: Critical peak particle velocity; SBHEP: Singoli-Bhatwari Hydroelectric Project; TVHEP: TapovanVishnugaad Hydroelectric Project, Tapovan; PSP: Pump Storage Plant, Tehri*

3. ANALYSIS

The data were analysed to identify the influence of different parameters in the prediction of overbreak (%) induced by blasting. The average and maximum overbreak were correlated with the maximum charge per delay, *W*. The variation of overbreak in respect of maximum charge per delay is shown in Fig.4. It is evident from this figure that the maximum overbreak increases with the increase in maximum charge per delay in more than 20% cases in 25-30 kg range. Whereas, average overbreak increases approximately 13% cases beyond 30 kg of maximum charge per delay. The difference of average and maximum overbreak increases with the increase in maximum charge per delay indicating the predominance of higher maximum charge per in overbreak scenario around underground openings.

The variations of average overbreak with specific charge, *q*, is shown in Fig. 5. The commonly used specific charge lies in the range of 1.2 to 2.0 kg/m^3 which corresponds overbreak in the order of 10 - 12%. There is increase in overbreak with the increase in specific charge beyond 2.0 kg/m^3. The specific charge greater than 2.5 kg/m^3 may result in overbreak as high as 20% and more. Earlier studies showed that a tunnelof cross-sectional area less than 20 m^2 requires specific charge greater than 2.0 kg/m^3 due to higher confinement [Olofsson, 1990; Chakraborty et al., 1998). As the size of opening increases, the specific charge reduces. In openings having large cross-sectional area, higher specific charge indicates availability of surplus explosive energy. The surplus unutilized explosive energy is converted into blast vibration causing higher overbreak.

Blast induced damage to the surrounding rock mass, either in the form of overbreak or damaged zone or both, depends significantly upon the quality of rock mass. Figure 6 shows the variation of overbreak with the rock mass quality, *Q*. It may be noted from Fig.6 that the average overbreak is highest for the lower class of rock mass which, then decreases with the increase in rock mass quality. In case of good rock mass, the average overbreak value reduces approximately by 6%.

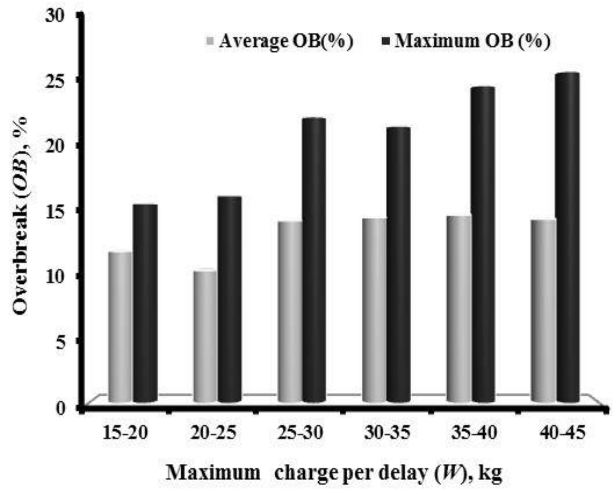

Fig. 4: Variation of observed overbreak with maximum charge per delay, *W*

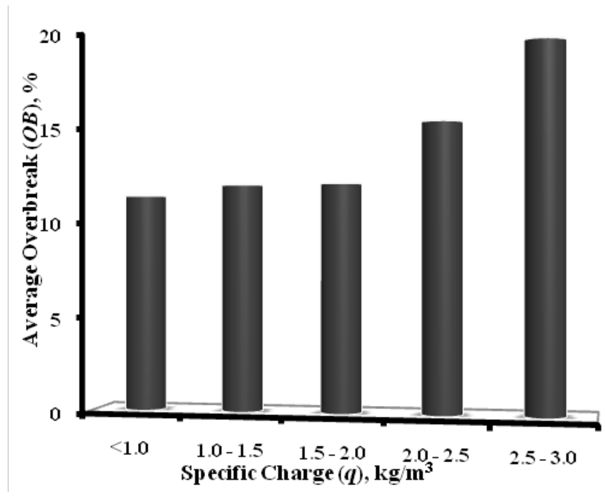

Fig. 5: Variation of average overbreak with specific charge, *q*

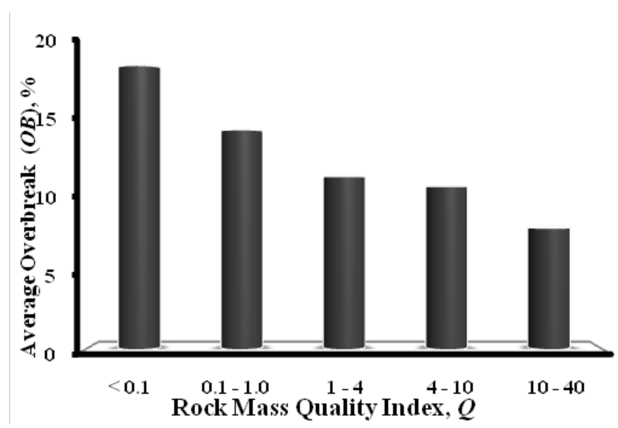

Fig. 6: Variation of average overbreak with rock mass quality index, *Q*

Figure 7 shows the variation of average overbreak with the ratio of perimeter charge factor and advancement factor (q_p/A_f). The term q_p/A_f measures the optimal utilisation of explosive energy and progressive enlargement of the tunnel. It is established that charging in perimeter holes have significant impact on resultant overbreak around an underground opening. Ibarra, (1996) observed that perimeter powder factor (charge factor) is directly proportional to the overbreak and underbreak. Analysis of observed data from the experimental blasts shows that the ratio of q_p/A_f is even better correlated with overbreak in underground construction (Fig.7).

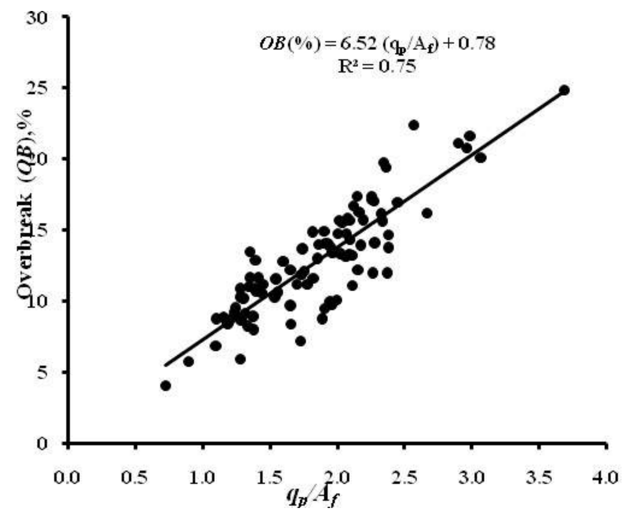

Fig. 7: Plot of observed overbreak (%) and q_p/A_f

The parameter q_p is a measure of the explosive quantity used for breaking rock mass in contour area.It has been widely used to study damage to the surrounding rock mass due to blasting in underground excavation (Maerz, et al., 1996, Ibarra et al., 1996, Dey and Murthy, 2012). Higher perimeter charge factor (q_p) gives rise to greater overbreak. utilized is calculated using Overbreak caused by perimeter charge factor can be reduced by optimum advancement in a blasting round. This is due to the availability of better free face and lesser burden on the contour holes. Greater advancement may reduce negative impacts of perimeter charge factor on overbreak in a round of blast. It does not mean long tunnel round will reduce overbreak. For example, say in a blast round having hole depth of 3.2 m, an advancement of 3.0 m will probability cause lesser overbreak as compared to a blast round with only 2.5 m pull in a same rock mass condition.

Another aspect of blast induced damage as revealed in Fig. 7 is that a better advancement in a blast round will optimally utilise the explosive energy and hence damage to the rock mass will be reduced. Higher advancement enhances the utilization of explosive energy in productive work, i.e. breaking and displacement of rock pieces. The unutilized explosive energy would otherwise be converted into seismic waves and the resultant effect will be higher vibration impacts in the surrounding rock mass. This has been observed by undertaking blast vibration measurement is the five experimental tunnel sites referred in this study. Better advancement also provides free face to contour holes. In tunnel blasting, better advancement ensures sequential initiation of holes and progressive initial cut which ensures less damage to the surrounding rock mass.

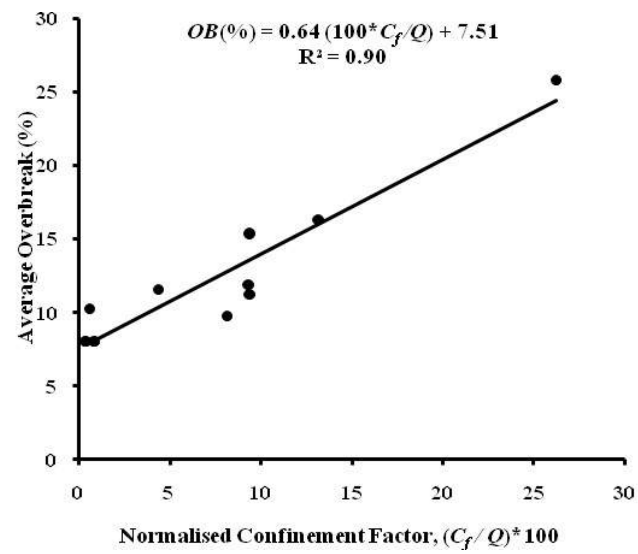

Fig.8: Plot of average overbreak versus normalised confinement factor *(C_f/Q)*

The focus was made on ten cases of confinement factor with different cross-sectional area and hole depth. In all the ten cases, confinement factor was normalised with rock mass quality index *Q*. The plot of average overbreak with normalized confinement factor is presented in Fig.8. It is clear that average overbreak increases with increase in confinement factor. Greater depth of hole beyond optimum value will increase overbreak substantially due to increase in confinement factor.

4. SCALE EFFECT ANALYSIS

The overbreak in underground excavation is influenced by the block size of rock mass with respect to size of opening which is also termed as scale effect. An index named 'scale effect' representing the ratio of tunnel cross-sectional area (a) and block size has been formulated and analysed. Block size is a ratio of RQD and Joint number, J_n. Higher value of 'scale index' indicates the opening in highly fractured rock mass whereas, lower value indicates the opening in massive rock formation. Overbreak will be higher for higher values of 'scale index' and vice-versa. Figure-8 shows the effect of 'scale index' on resulting overbreak. It may be observed that as 'scale index' increases, the resulting overbreak increases. 'Scale index' lower than 3 resulted in overbreak less than 10% (Fig. 9) The range of overbreak was found to be greater than 25%for 'scale index' of 4 and above. Whereas, the range of overbreak lies between 4 and 12% for 'scale index' lower than 4 and it lies between 8 and 25% for 'scale index' greater than 4.

The scale effect analysis may be useful in deciding the allowable limit of overbreak while framing the contract guidelines. In many countries, special standards to regulate the overbreak and deviation from the designed profile are recommended. The Swiss Society of Engineer and Architects recommend overbreak profile to be lower than $0.07\sqrt{a}$ with maximum limit of 0.4 m [Innaurato et al., 1998)], where a detonates cross-sectional area of tunnel. The Construction Manual guidelines recommend 150 - 200 mm of overbreak in crown area and 100 - 150 mm in side-walls [Cunnigham&Geotzsche, 1990; Korea Highway Corporation, 2002; Mandal and Singh, 2005). Using this 'scale index' for a given rock mass, range of allowable overbreak can be suggested.

5. EMPIRICAL DETERMINATION OF OVERBREAK

It is evident from the above discussions that overbreak is directly proportional to specific charge (q), maximum charge per delay (W), perimeter charge factor (qp)and confinement factor whereas it is inversely proportional to rock mass quality index (Q) and advancement factor (A_f). The data monitored during field study were grouped together to obtain regression analysis and in Fig. 10. The predictor equation of overbreak (in %) based on the observations of 113 experimental blast is given in equation-1. It encompasses various influencing parameters of underground construction works. As peak particle velocity (PPV) of vibration is dependent significantly on maximum charge per delay rather than total charge used in the blasting round, the parameter 'W' becomes an appropriate for explosive energy.

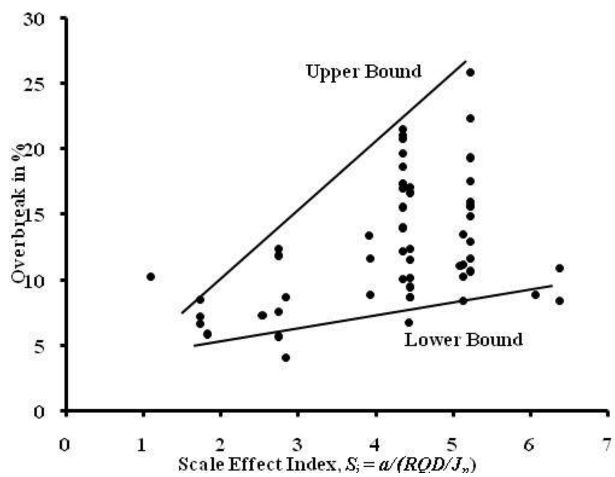

Fig. 9: Plot of 'scale effect index' versus overbreak (%)

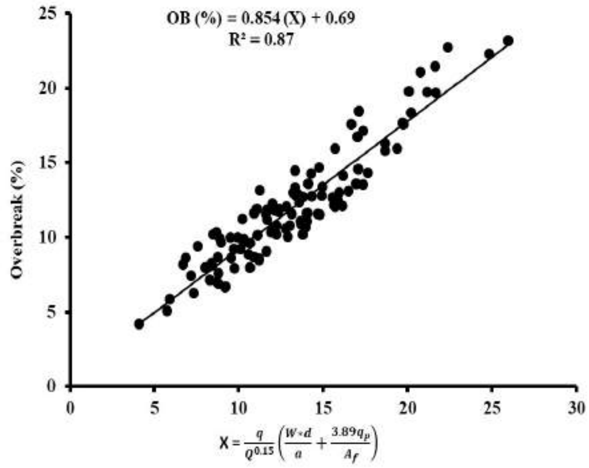

Fig. 10: Plot of factor X versus observed overbreak (%)

$$OB(\%) - 0.854 * \frac{q}{Q^{0.15}}\left(\frac{W*d}{a} + \frac{3.89q_p}{A_f}\right) \quad (1)$$

Where,

= perimeter charge factor, kg/m^3,

W =maximum charge per delay, kg,

q = specific charge, kg/m^3,

Q = rock mass quality index (Barton' Q-system)

d = hole depth, m,

l = pull, m, and

a = tunnel cross-sectional area, m^2.

Perimeter charge factor (q_p) represents energy concentration in contour holes irrespective of the outcome of blast design. Its effect can be minimised by better advancement rate. Effect of tunnel cross-sectional area is considered in the form of confinement factor. Larger cross-sectional area provides lesser confinement. For a given tunnel size, depth of hole can play a crucial role in defining overbreak zone. Effect of hole depth in respect of damage in the form of overbreak will be less in large size tunnel and more in smaller tunnel size. A poor blast design will result in more overbreak. In the proposed correlation, advancement factor has been considered to be a representative parameter for performance of the blast design. Greater advancement rate utilizes explosive energy in productive manner and therefore, the overbreak caused by the blast induced vibration is reduced.

Rock mass quality index, Q[Barton et al. 1974) is used for rock mass characterisation. Q is used in denominator of the proposed predictive model to indicate that a better rock mass quality would sustain higher level of blast vibration and therefore the overbreak induced by blasting will be lower. The proposed correlation is developed from a wide range of Q value which includes extremely poor rock mass to good rock mass condition and therefore equation-1 can be used for prediction of overbreak for these classes of rock mass. Smooth wall blasting is mostly used in underground for controlling of overbreak. In smooth wall blasting, closely-spaced holes are used. These holes are charged with lower charge factor. In smooth wall blasting, values of perimeter charge factor will be very less and hence the predicted overbreak will be reduced. Proposed predictive model can discriminate between conventional and smooth wall blasting techniques.

6. CONCLUSIONS

A comprehensive field investigation have been carried out at five tunnel construction sites to evolve empirical equations for estimation of overbreak (%) using readily available site parameters. Data of 113 blasting experiments in different rock mass from extremely poor to good have been taken into account.

Analysis of field data reveals that the overbreak in underground blasting operations is significantly influenced by the perimeter charge factor and maximum charge per delay. They are found to be significant in poor quality rock mass. Parametric analysis reveals that the deteriorating effects of blast design parameters are enhanced in poor quality of rock mass. 'Scale effect' analysis has been carried out by formulating an index which is the ratio of tunnel cross-sectional area and block size of rock mass. The analysis reveals that the range of overbreak (%) lies between 8 and 25% for openings in rock mass having Si greater than 4.

It has been observed that the overbreak (%)can be expressed in terms of rock mass quality index (Q), perimeter charge factor (q_p), specific charge (q), maximum charge per delay (W), advancement (A_f) and confinement factors (C_f). As the proposed model is based on readily available site parameters, it may be useful to the practicing engineers and geologists while optimising the support design.

Achieving advancement through optimized blast pattern is advantageous in reducing blast induced damage to the surrounding rock mass. Overbreak is found to be the result of complex interactionsof improper sequences of excavation, unscientific blasting practices and inadequate primary support. Presence of unfavourable joints, their directions, non-cohesive filling materials and adverse ground water conditions aggravate occurrence of immediate overbreak.

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