Use of fuzzy set theory for minimizing overbreak in underground blasting operations – A case study of Alborz Tunnel, Iran

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\textbf{Abstract}

In order to increase the safety of working environment and decrease the unwanted costs related to overbreak in tunnel excavation projects, it is necessary to minimize overbreak percentage. Thus, based on regression analysis and fuzzy inference system, this paper tries to develop predictive models to estimate overbreak caused by blasting at the Alborz Tunnel. To develop the models, 202 datasets were utilized, out of which 182 were used for constructing the models. To validate and compare the obtained results, determination coefficient ($R^2$) and root mean square error (RMSE) indexes were chosen. For the fuzzy model, $R^2$ and RMSE are equal to 0.96 and 0.55 respectively, whereas for regression model, they are 0.41 and 1.75 respectively, proving that the fuzzy predictor performs, significantly, better than the statistical method. Using the developed fuzzy model, the percentage of overbreak was minimized in the Alborz Tunnel.

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\textbf{1. Introduction}

Despite the intrinsic destructive characteristic, drilling and blasting method is the most satisfactory tool for excavation of rocks. This excavation method needs lower capital investment and is characterized by high progress rate for underground excavation works \cite{1}. More than 85\% of the energy produced in the blast is not used in the process of fragmentation and displacement of the rock. This energy causes the structural strength of the surrounding rock mass to be weakened. This is demonstrated by overbreak, leaving the fractured mass in a potential state of collapse \cite{2}. Therefore, overbreak is defined as the ratio of the difference between the theoretical and real areas of the cross sections from the perimeter of the tunnel cross section, excluding the floor \cite{3}. Controlling the overbreak in underground excavations is of great importance due to both economic and safety reasons.

Many studies have been performed in order to identify the causes of overbreak in underground excavations. Chakraborty et al. investigated the effect of rock mass quality and joint orientation on tunnel blasting performance with regard to pull, fragmentation and overbreak \cite{4}. Germain and Hadjigeorgiou, studied the influence of stope geometry and blasting patterns on overbreak \cite{5}. The effects of rock mass quality on overbreak were investigated by Innaurato et al. \cite{3}. The work of Singh and Xavier showed that proper planning and high accuracy in drilling have a significant role in decreasing the overbreak percentage \cite{6}. Kim et al. used numerical methods to simulate the blasting at tunnel contour holes in joint rock mass \cite{7}. Using regression analysis, Dey and Murthy established a relationship between the overbreak percentage and rock mass as well as charge and blast design parameters \cite{8}. Lu et al. showed that the in situ stress of surrounding rock mass is one of the main factors controlling the crack propagation in contour blasting, which has a significant effect on overbreak \cite{9}.

In order to reduce the overbreak in underground excavations, various parameters such as physico-mechanical properties of rock mass, properties of explosives and geometrical features of blasting patterns should be considered. The conventional methods used for assessing overbreak do not always take into account all parameters that affect the results. Since the excavated area out of the designed periphery of tunnel must be filled with concrete, a prediction of overbreak percentage before performing the blasting patterns can be very helpful in order to minimize the use of costly concrete as well as maximizing the safety of working environment.

Fuzzy model can deal with the complexity of the geological problems flexibly. The implementation of this technique in mining engineering has significantly increased in recent decades. Some of the researchers who have worked on this issue are: Chen et al. for road tunnel ventilation system; Sonmez et al. in Geological Strength Index (GSI); Aydin for classification of rock masses;
Nefesioglu et al. in determination of weighted joint density (WJD); Iphar and Goktan for Diggability Index Rating Method in surface mine for selection of equipment; Tzamos and Sofianos in extending the Q system's prediction for support system in tunnels; Azimi et al. for prediction of blastability of rock masses; Monjezi and Rezaei; Monjezi et al. for predicting burden from rock geomechanical properties and fragmentation due to blasting; Rezaei et al. for prediction of fly rock in surface mining; Mohamed in prediction of ground and air vibration; and Daftaribesheli et al. in assessment of rock slope stability, etc. [10–21].

In this paper, fuzzy set theory was employed to predict and minimize overbreak in the Alborz Tunnel of Iran. The results of fuzzy model were compared with those of multivariable regression analysis on the basis of practical data.

2. Case study

Alborz Tunnel is the largest tunnel to be excavated along the Tehran–Shomal Freeway which runs through Alborz Mountain Range, connecting capital city of Tehran to coastal regions of the Caspian Sea in the north (Fig. 1). The rocks that have been blasted during this study are Tuff and Anhydrite belonging to the Karaj Formation. The Tuffs are in three colors namely black, gray and green. The black Tuffs are fine grained whereas the green and gray Tuffs are coarse grained. The uniaxial compressive strength of the Tuffs ranges from 48 to 158 MPa whereas this parameter for the Anhydrite part ranges from 37 to 68 MPa. RMR and joint orientation parameters are shown in Table 1. The geomechanical and geological description of the Alborz region of Iran is thoroughly discussed by Yassaghi et al. [22]. The explosive used in the blasting operations is Emulsion cartridges with diameter of 35 mm. Compacted clay is used as stemming material, the blasting area operations is Emulsion cartridges with diameter of 35 mm.

3. Regression analysis

Multivariate regression analysis is a statistical method for determining the relationship between dependent variables with two or more independent variables [26]. A multiple linear regression model can be shown as follows [27]:

\[ Y = \beta_0 X_0 + \beta_1 X_1 + \ldots + \beta_n X_n + \epsilon \]  

(1)

where \( Y \) is the dependent variable; \( X_0, X_1, X_2, \ldots, X_n \) the independent variables; \( \beta_0, \beta_1, \beta_2, \ldots, \beta_n \) the regression coefficients; and \( \epsilon \) the error term.

Many researchers have applied multiple regression method in mining fields [27,28]. In this paper overbreak percentage is considered to be a function of seven parameters namely powder factor, specific drilling, ratio number of contour holes to the total number of holes, ratio amount of charge in contour holes to the burden in contour, ratio length of holes to the stemming L5, joint orientation favorability J0 (%), Rock mass rating RMR (%).

The variable “joint orientation favorability” was obtained from the sum of percent of favorable and very favorable joints for each section from the definition of favorability of joint orientation in tunneling based on Wickham et al. which was reported in modified form by Bieniawsky [24,25].

![Location of the Alborz Tunnel](image)
4. Fuzzy set theory

A fuzzy set is a class of objects with a cline of grades of membership. Membership (characteristic) function which assigns to each object a grade of membership ranging from zero and one is used to characterize the fuzzy set. In contrast to the classical set theory, fuzzy set theory employs the membership functions to process imprecise information. The classical set (called crisp set) takes only two values: one, when an element belongs to the set; and zero, when it does not but in fuzzy set theory, an element belongs to a fuzzy set with its membership degree ranging from zero to one [29]. Mathematically, the fuzzy set $A$ can be described as follows [29]:

$$A = \{X, \mu_A(X)/X \in U\}$$  \hspace{1cm} (3)

where $U$ is the universe of discourse defined for a specific problem; and $\mu_A(x)$ the membership degree of the variable $X$, which is defined as follows [29]:

$$\mu_A(X) \rightarrow [0, 1]$$  \hspace{1cm} (4)

The process of using membership functions to generate membership values for a fuzzy variable, or the process of converting a crisp input value to a fuzzy value is defined as fuzzification. Depending on the nature of the problem to be solved the shape of the membership functions can be either linear (trapezoidal or triangular) or non-linear [29]. This theory is also used for developing rule-based models which combine numerical data with expert knowledge [14]. With regard to the inference mechanism to compute the output of the model, rule-based models are classified into four main sets: fuzzy relational models, linguistic models, neural network based models and Takagi–Sugeno–Kang (TSK) fuzzy models. Several fuzzy inference systems have been used in various applications of these models. The most commonly used are as follows: Mamdani algorithm; TSK fuzzy algorithm; Tsukamoto algorithm; and Singleton algorithm [30].

The final goal of fuzzy sets is to imitate human approximate reasoning [29]. Fig. 4 shows a schematic illustration of a crisp set and fuzzy set with their membership functions [11].

The Mamdani algorithm is perhaps the most appealing fuzzy method to apply in engineering geological problems. The general “if-then” rule structure of the Mamdani algorithm can be described as follows: if $X_1$ is $A_{i1}$ and Then $Y$ is $B_i$ (for $i = 1, 2, \ldots, k$); where $k$ is the number of rules; $X_1$ is the input variable (antecedent variable); and $Y$ is the output variable (consequent variable) [11].

In spite of existence of many methods of composition of fuzzy relations in the literature, (e.g. min–max, max–max, min–min, max–mean, etc.), max–min and max–product methods are the two most commonly employed techniques [31]. Eq. (5) describes the Mamdani method [30]:

$$\mu_c k(z) = \max [\min(\mu A_k(\text{input}(x)), \mu B_k(\text{input}(y)))] \hspace{1cm} k = 1, 2, \ldots, k$$  \hspace{1cm} (5)
where $\mu_{c_k}$, $\mu_{A_k}$ and $\mu_{B_k}$ are the membership functions of the output “$z$” for rule “$k$”, input “$x$” and input “$y$”, respectively.

Since the rules are disjunctive, the aggregation operation max leads to an aggregated membership function consisted of the outer envelope of the individual truncated membership forms from each rule. An appropriate defuzzification technique should be considered to the aggregated membership function if there is a need for a crisp value for the aggregated output. The process of extraction of a representative crisp value from a fuzzy set is called defuzzification. There are several defuzzification methods: centroid of area (COA), center of gravity, mean of maximum, smallest of maximum, etc. the COA method is the most commonly used method [30]. Fig. 5 shows a two-rule Mamdani Fuzzy Inference System (FIS) which concludes the overall output “$z$” when subjected to two crisp inputs “$x$” and “$y$” [32].

5. Use of fuzzy model to predict overbreak percentage in Alborz Tunnel blasting

In this study a fuzzy model based on the Mamdani algorithm is introduced for prediction of overbreak percentage in Alborz Tunnel. In order to estimate overbreak percentage, Rock Mass Rating, joint orientation favorability, ratio number of contour holes to the total number of holes, ratio depth of hole to the stemming, ratio amount of charge in contour to the burden, specific drilling and powder factor are used as input parameters. Fig. 6 shows input and output variables of the model in MATLAB environment. The most common types of membership functions, triangular and trapezoidal are used in this paper [30]. Figs. 7–14 present the membership functions of input and output parameters. In these membership functions $C_1$ stands for class 1 and $C_2$ for class 2
Fig. 10. Membership function of ratio of depth of hole to the stemming.

Fig. 11. Membership function of ratio of amount of charge in contour to the burden.

Fig. 12. Membership function of specific drilling.

Fig. 13. Membership function of powder factor.

Fig. 14. Membership function of overbreak percentage.

defuzzification is performed by centroid of area method to obtain crisp output values.

Accurate estimation of overbreak percentage can be provided by use of proper input data. For example in case of imposed input parameters as $RMR = 50$, $JO = 50$, selection of $NC = 0.225$, $LS = 7.5$, $CB = 67.5$ kg/m, $S_d = 2.4$ m/m$^3$ and $P_f = 1.7$ kg/m$^3$ would give the predicted overbreak percentage of 1.5 (see Fig. 15). Since the fuzzy model has the ability of interpolating input parameters, it is feasible to predict overbreak percentage in any situation. The developed fuzzy model was used to predict overbreak percentage in the Alborz Tunnel blasting operations and the results were compared with measured percentage of overbreak. Considering the coefficient of determination between measured and predicted overbreak (0.96), it is concluded that fuzzy inference system is a reliable approach to use in the Alborz Tunnel. Fig. 16 shows the results of predicted percentage overbreak for fuzzy model.

6. Evaluation of model performance

A fuzzy model along with the statistical model has been developed using database from the Alborz Tunnel with 20 validation datasets which are not used in model development. To validate and compare the acquired results from fuzzy and statistical methods, correlation coefficient ($R^2)$ and Root Mean Square Error (RMSE) can be used [18].

$R^2$ can be calculated by the following Eq. (6) [30]:

$$R^2 = 100 \left[ \frac{\sum (A_{ipred} - \bar{A}_{pred})(A_{imeas} - \bar{A}_{imeas})}{\left( \sum (A_{ipred} - \bar{A}_{pred})^2 \sum (A_{imeas} - \bar{A}_{imeas})^2 \right)^{0.5}} \right]^2$$

where $A_{imeas}$ is the $i$th measured element; $A_{ipred}$ the $i$th predicted element; $A_{pred}$ the average of predicted sets; $A_{imeas}$ the average of measured sets; $n$ the number of datasets and $i = 1, 2, 3, \ldots, n$.

RMSE can be calculated by the following Eq. (7) [18]:

$$RMSE(A) = \left[ \frac{1}{n} \sum (A_{imeas} - A_{ipred})^2 \right]^{0.5}$$

where $A_{imeas}$ is the $i$th measured element; $A_{ipred}$ the $i$th predicted element; $n$ the number of datasets and $i = 1, 2, 3, \ldots, n$.

The result of simulation of the overbreak percentage with regression model based on data testing and Eq. (1) is shown in Fig. 3. Here the square determination coefficient ($R^2$) and RMSE are 0.41 and 1.75 respectively. The result of simulation with fuzzy model is shown in Fig. 16. Its determination coefficient ($R^2$) and RMSE are 0.96 and 0.55 respectively, indicating that the fuzzy model has lower levels of errors than statistical model. The models performance indices are summarized in Table 2. The linearity assumption in statistical model as well as experts’ experiences and corrective rules lead to higher precision in the simulation results of fuzzy model. Therefore employing the fuzzy inference
system can be a good tool to deal with the uncertainties that encounter the results of underground blasting operations, specially minimizing the overbreak percentage that can cause both economic and safety problems in vast scales.

7. Conclusions

Tunnels are excavated for different purposes, such as transportation and mining but whatever the purpose are, there are some very important issues, such as safety of the work environment and costs of construction that should be strictly dealt with while constructing the structure. In cases of using drilling and blasting method to excavate the tunnel, the importance of safety of the work environment and costs of construction is significant. In this regard, minimizing the amount of overbreak percentage is of great importance to assure the safety of work environment and reduce the costs of construction.

Having sufficient application flexibility and the ability to cope with complex and ill-defined systems, the fuzzy inference system seems to be a suitable measure to minimize unwanted results in underground blasting operations. In this research a fuzzy model was developed to minimize overbreak percentage in blasting operations of the Alborz Tunnel and the results of the model were compared with the results of multivariable regression analysis.

It was concluded that the fuzzy model performs much better than the statistical model. $R^2$ and RMSE for the fuzzy model were equal to 0.96 and 0.55 respectively, and for the regression model were 0.41 and 1.75, respectively. It is probably because of the linearity assumption in regression method that causes the lower performance. Application of the developed fuzzy model in blasting operation of the Alborz Tunnel caused a great decrease of overbreak percentage and increase in the blasting operations efficiency, providing a safer working environment and reducing the haulage costs and time.

Table 2

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References


