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Application of Fuzzy Inference Systems for Open Stope Design in Narrow Orebody Conditions

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Abstract

Existing empirical stability graphs are inadequate for narrow-vein stope stability prediction. This study explores the use of Fuzzy Inference Systems (FISs) as an alternative to conventional empirical methods for evaluating stope overbreak in narrow-vein mining. A FIS is a rule-based computational model that converts inputs into outputs using fuzzy logic, linguistic rules, and membership functions, making it well suited for handling epistemic uncertainty associated with narrow-vein mining problems. Stope performance data from an Australian mine was used to establish the FIS. The input parameters included stope walls, hydraulic radius, rock mass domain and stability number. The FIS predictions were in close agreement with the observed stope dilution. Overall, the FIS model demonstrated good performance, with accuracy, sensitivity and specificity values of 87%, 67% and 91%, respectively. These findings suggest that FIS can serve as a valuable tool for assessing stope overbreak in narrow-vein environments and can complement existing empirical methods to help reduce dilution and improve stope design outcomes.

Keywords

Stope overbreak, Dilution, Narrow vein, Open stope mining, Fuzzy Inference Systems (FIS).

1 Introduction

Narrow-vein mining methods are used to extract thin tabular orebodies and controlling dilution in such mining environments remains a significant engineering challenge. Dilution is defined as the contamination of ore by non-ore material during the mining process and is associated with both direct and indirect costs (Stewart et al., 2007). Narrow vein mining involves extracting steeply dipping deposits with widths typically under 2–3 m. Traditionally characterized by high operating costs and low capital requirements, the industry has increasingly shifted toward mechanized methods such as long-hole stoping. While more productive and cost-efficient, this approach often leads to higher dilution. Even small increases in dilution can result in significant additional costs, especially as vein width decreases (Zhang et al., 2025). Factors influencing dilution in narrow-vein mining include blasting design, in-situ stress redistribution, stress relaxation, geological setting and inherent rock mass properties (Stewart et al., 2007; Wu et al., 2018; Adoko et al., 2020; Zuo et al., 2024).

To design narrow vein open stopes that minimize dilution, several methods have been in use. One of them is the so-called narrow-vein graph method by Stewart et al. (2007)as a way to overcome existing empirical stability graphs (Mathews et al., 1981; Mawdesley et al., 2001). However, the method has not been fully validated. Other design approaches include numerical modelling and AI-based design (Korigov et al., 2022; Szmigiel et al., 2025). While the AI-based tools yield very high accuracy, they, however, provide limited physical interpretation of the underlying dilution problem. To overcome this limitation, a fuzzy inference system (FIS) was proposed in this study. FIS has the capability to handle imprecise information that is often encountered in unplanned dilution problems (Bazarbay & Adoko, 2021).

2 Methods

2.1 Stope performance data

The data employed in this study was collected from the Barkers mine located approximately 25 km west-northwest of Coolgardie, Perth Australia. The mine is currently closed. The geological conditions at the Barkers mine are characterized by narrow, steeply dipping vein deposits with an average width of approximately 0.3 m (ranging from 0.2 to 0.4 m). The rock mass is generally of fair to good quality, based on scanline mapping, and exhibits relatively consistent geotechnical conditions across the studied stopes. The structural setting of the orebody is divided into several hangingwall and footwall domains that reflect variations in jointing, foliation, and faulting. In the hangingwall, the northern domain (HWN) is characterized by three joint sets, including two sub-vertical sets dipping to the southeast and southwest, and one sub-horizontal set. Adjacent to this area, the Hangingwall Fault zone (HWF) contains several faults that cut and displace the orebody, creating significant structural disturbance. South of the fault zone, the Hangingwall Central domain (HWC) is dominated by sub-vertical jointing similar to the surrounding zones. Further south, the Hangingwall South domain (HWS) also contains three joint sets comparable to HWN, although the orientation of the sub-horizontal set differs. In the footwall, Footwall Zone 1 (FZ1) is marked by strong foliation similar to that observed in the hangingwall (Stewart et al., 2007). These structural domains influence stope dilution differently. A sample of the dataset illustrating a few selected parameters is provided in Table 1 while the correlation matrix is given in Fig.1. HR stands for the hydraulic radius, N is the stability number. They are defined according to Mathews et al. (1981). As can be seen, dilution appears to depend primarily on the geotechnical domain and has almost zero correlation with the stability number N. This provide evidence that the stability graph method may be inadequate for predicting dilution in narrow-vein stopes.

Table 1. Dataset sample.

Wall Surface	Geotechnical Domain	HR (m)	N	Overbreak (m)	Dilution Category
HW	HWN	5.87	15.78	0.5	Minor Sloughing
FW	FZ1	5.87	22.87	1.1	Moderate Sloughing
HW	HWN	3.43	14.20	0.9	Minor Sloughing
FW	FZ1	3.43	17.28	1	Moderate Sloughing
HW	HWN	2.20	14.20	0.5	Minor Sloughing
FW	FZ1	2.20	14.23	0.35	Minor Sloughing
FW	FZ1	4.58	17.28	0.6	Moderate Sloughing
HW	HWS	3.79	19.31	0.4	Blast Damage Only
FW	FZ1	3.79	22.87	0.1	Minor Sloughing

2.2 Basics of Fuzzy inference system (FIS)

FIS is a form of approximate reasoning, which uses the concept of fuzzy set theory that was introduced by Zadeh (1965). A fuzzy set is a set without a crisp, clearly defined boundary and can contain elements having partial degree of membershipwith valuesranging from 0 to 1. It is a convenient tool to represent gradual and partial membership to a set. A FIS defines relationships between system input and output variables using linguistic labels (i.e., fuzzy sets) defined by membership functions, logical operations and IF-THEN rules known as fuzzy inference process. This process maps a given input to an output using fuzzy logic provides the basis from which decisions can be made or patterns discerned. In the inference process of the fuzzy rule, the fuzzy proposition needs

to be represented by an implication function. The implementation of a FIS includes four steps: fuzzification, rule evaluation, aggregation and defuzzification. Two ways of constructing a FIS are possible: expert knowledge-based approach and data-driven methods.

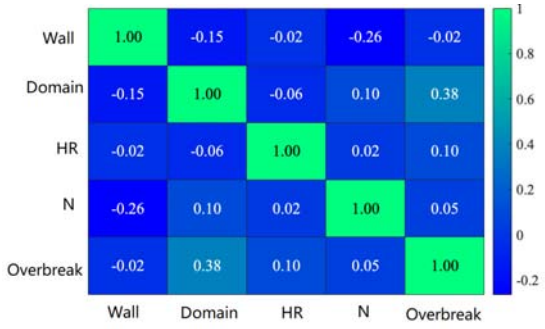


Fig. 1 Correlation matrix for selected parameters in the dataset.

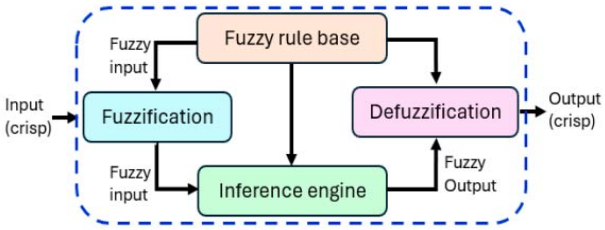


Fig. 2 Fuzzy Inference system illustration (Adoko et al., 2011).

3 Results

3.1 Establishing the FIS for open stope design

In this study, the expert knowledge-based approach was implemented using the Matlab software platform. A set of rules capable of representing the complex relationship between the unplanned dilution and its influencing factors was derived based on previously gained knowledge. The variable spaces were divided into 2-4 groups using Gaussian membership functions. They are defined according to Table 2. Moreover, for the output membership (dilution), the overbreak (e.g.0.25; 0.75; 1.25) was used to define the range of the membership space. These thresholds correspond to blast damage only, minor sloughing, moderate sloughing and severe sloughing, respectively. Examples of the membership functions associated with the parameters are shown in Fig. 3. In total, 21 rules were implemented for the FIS model. These rules capture the complex and nonlinear behaviour governing dilution. A sample of the rules is provided in Table 3. In addition, Fig. 4 provides the surface plot of the FIS output. It provides a three-dimensional representation of the FIS output.

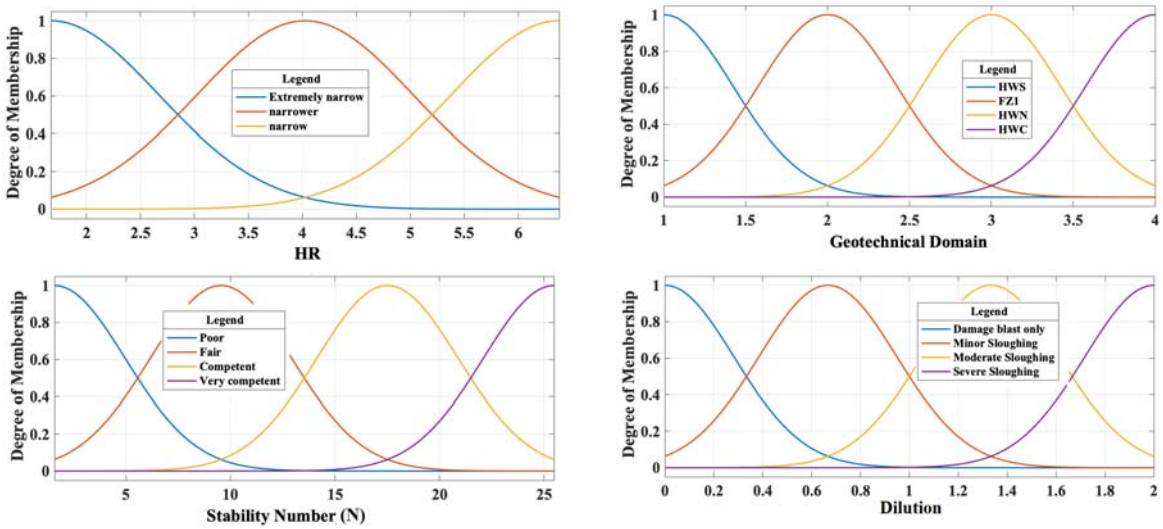


Fig. 3 Membership functions of selected parameters.

Table 2 Variable definition.

Variable	Type	Membership Function Labels
Surface	Input	Footwall; Hangingwall
Geotechnical Domain	Input	HWS; FZ1; HWN; HWC
HR (Hydraulic Radius)	Input	Extremely narrow, narrower; narrow
N (Stability Number)	Input	Poor; Fair; Competent; Very competent
Dilution	Output	Damage blast only; Minor Sloughing; Moderate Sloughing; Severe Sloughing

Table 3. Rule sample.

Rule	Representation
1	If (Surface is Hangingwall) and (Geotech domain is HWS) and (HR is extremely narrow) and (N is Competent) then (Dilution is Minor Sloughing)
2	If (Surface is Footwalll) and (Geotech domain is FZ1) and (Hydraulic Radius is Extremely narrow) and (Stability Number is Competent) then (Dillution is damage blast only).
3	If (Surface is Hangingwall) and (Geotech domain is HWN) and (HR is narrow) and (N is Fair) then (Dilution is moderate sloughing)

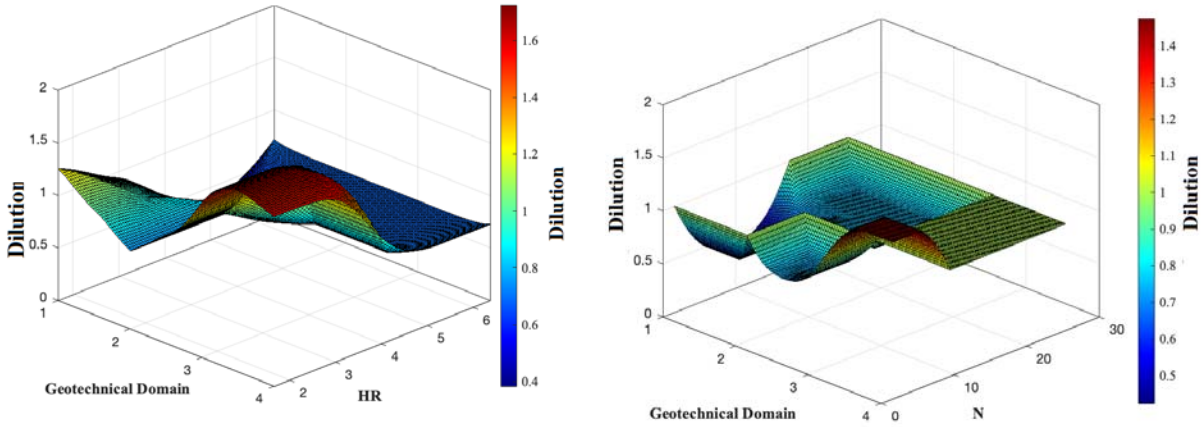


Fig. 4 Sample of the surface graphs.

3.2 Validation

The classification performance of the FIS model is evaluated using classification indices namely accuracy, sensitivity (true positive rate), and specificity (false positive rate) as they representindicators of the classification quality. These parameters are determined according to Eq. 1:

$$\text{Accuracy} = \frac{T_p + T_n}{T_p + T_n + F_p + F_n};\quad \text{Sensitivity} = \frac{T_p}{T_p + F_n};\quad \text{Specificity} = \frac{T_n}{T_n + F_p} \qquad (1)$$

where: F_p, T_p,F_n, and T_n stand for: false positive, true positive, false negative, and true negative, respectively. The confusion matrix is shown in Table 4 while a sample of the evaluation dataset is provided in Table 5.

Overall, the performance of the model was good with the obtained average accuracy, sensitivity and specificity values of 87%, 67% and 91%, respectively. In the calculation of these indices, F_p, T_p,F_n, andT_n values were taken from Table 2 (confusion matrix) and Eq.1 was applied accordingly. These results indicate that the FIS successfully captured the relationships between the unplanned dilution and its influencing factors. In table 4 “Cat” refers to the dilution levels.

Table 4. Confusion table.

		FIS predicted dilution			
		Cat 1	Cat 2	Cat 3	Cat 4
Actual dilution	Cat 1	30	12	5	0
	Cat 2	2	35	4	1
	Cat 3	0	1	20	2
	Cat 4	0	1	1	1

Table 5. Sample of the output results.

Wall surface	Rock domain	HR (m)	N	Overbreak (m)	Actual dilution	FIS output	Predicted dilution
HW	HWN	5.87	15.78	0.50	Minor Sloughing	0.30	Minor Sloughing
FW	FZ1	5.87	22.87	1.10	Moderate Sloughing	0.28	**Minor Sloughing**
HW	HWN	3.43	14.20	0.90	Minor Sloughing	0.70	Minor Sloughing
FW	FZ1	3.43	17.28	1.00	Moderate Sloughing	1.20	Moderate Sloughing
HW	HWN	2.20	14.20	0.50	Minor Sloughing	0.60	Minor Sloughing
FW	FZ1	2.20	14.23	0.35	Minor Sloughing	0.35	Minor Sloughing
FW	FZ1	4.58	17.28	0.60	Moderate Sloughing	0.90	Moderate Sloughing
HW	HWS	3.79	19.31	0.40	Blast Damage Only	0.27	**Minor Sloughing**
FW	FZ1	3.79	22.87	0.10	Minor Sloughing	0.30	Minor Sloughing
HW	HWS	2.79	19.31	0.40	Blast Damage Only	0.10	Blast Damage Only
FW	FZ1	2.79	20.08	0.50	Moderate Sloughing	1.21	Moderate Sloughing
HW	HWS	3.95	19.31	0.20	Blast Damage Only	0.10	Blast Damage Only
FW	FZ1	3.95	17.28	0.75	Moderate Sloughing	1.15	Moderate Sloughing
HW	HWS	4.60	19.31	0.30	Blast Damage Only	0.15	Blast Damage Only
FW	FZ1	4.60	2.54	0.80	Moderate Sloughing	1.80	**Severe Sloughing**
HW	HWS	2.28	1.93	0.20	Blast Damage Only	0.10	Blast Damage Only
FW	FZ1	4.89	17.28	1.25	Moderate Sloughing	1.09	Moderate Sloughing
HW	HWS	1.99	13.13	0.00	Blast Damage Only	0.08	**Minor Sloughing**
FW	FZ1	1.99	20.08	0.00	Minor Sloughing	0.40	Minor Sloughing
HW	HWN	4.12	12.46	0.20	Blast Damage Only	0.10	Blast Damage Only
FW	FZ1	4.12	20.08	0.30	Minor Sloughing	0.60	Minor Sloughing
HW	HWS	3.98	13.13	0.30	Blast Damage Only	0.22	Blast Damage Only
FW	FZ1	3.98	20.08	0.00	Blast Damage Only	0.48	**Minor Sloughing**

3.3 Discussions

According to the previous study by Stewart et al. (2007), the empirical ELOS method achieved an overall performance of less than 40%, which is consistent with the findings of the present study. The results suggest that the stability number alone is not a reliable predictor of unplanned dilution in narrow-vein stopes. Instead, the geotechnical domain appears to exhibit a stronger correlation with stope overbreak. This observation highlights the importance of incorporating geological and geotechnical uncertainty into predictive models, which supports the application of FISs to this problem. In addition, the results showed that severe sloughing (Category 4) was poorly classified. This category exhibited substantially lower sensitivity (33.3%) and precision (25.0%), despite maintaining a high specificity (97.3%). The low sensitivity is likely attributable to the limited dataset, as only three samples belonged to this category. Furthermore, the FIS was developed using a knowledge-based approach, where the membership functions and rule base were established using engineering judgement and operational experience. While this approach produced encouraging results, future studies should investigate data-driven or hybrid approaches for FIS development. Machine learning optimization techniques could be used to automatically refine membership functions and fuzzy rules, potentially improving predictive accuracy and model generalization. Furthermore, combining moderate and severe sloughing categories may help reduce ambiguity between overlapping classes and improve classification performance in future implementations.

4 Conclusions

In this study, a FIS model for open stope design in narrow vein conditions was proposed. The study demonstrated the applicability of FISs for predicting stope overbreak in narrow-vein mining environments, where conventional empirical stability graphs often exhibit limitations. By incorporating key geotechnical and stope design parameters, including stope walls, hydraulic radius, rock mass domain, and stability number, the developed FIS model successfully captured the complex relationships governing stope performance. The predicted dilution values were found to be in close agreement with observed stope dilution data obtained from the Australian mine case study.

The performance evaluation indicated that the proposed FIS model achieved good predictive capability, with overall accuracy, sensitivity, and specificity values of 87%, 67%, and 91%,

respectively. These results suggest that fuzzy logic-based approaches can effectively manage the epistemic uncertainty associated with narrow-vein mining conditions and provide a practical complement to traditional empirical design methods. The high specificity further demonstrates the model's ability to reliably distinguish dilution levels, thereby supporting improved stope design and dilution control.

Despite the encouraging results, several limitations should be acknowledged. The study was based on data from a single mining operation, which may limit the generalizability of the developed model to other geological and mining conditions. In addition, some classification categories contained limited data samples, potentially affecting model sensitivity and increasing the likelihood of misclassification. The current rule base and membership functions were also developed using available operational knowledge and may require further refinement to improve predictive robustness. Hence, future research should focus on expanding the dataset using information from multiple mining sites and varying geological settings to improve model generalization. Further improvements to the fuzzy rule base and membership function optimization may also enhance classification performance. In addition, merging categories with overlapping characteristics, such as moderate and severe sloughing, could reduce ambiguity and improve model stability.

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