Qualitative and quantitative analysis of hangingwall caving in longwall mining method using a fuzzy system

Kazem Oraee
Tarbiat modarres university, Tehran, Iran
kazemoraee@yahoo.com

Mehrshad Rostami*
Islamic Azad University, sciences and researches unit, Tehran, Iran
mehrshad17@gmail.com

ABSTRACT
Caving process is an important part in extraction sequences in caving methods such as longwall. Therefore qualitative and quantitative analysis of the caving can be useful to observe the conditions of the hangingwall and to predict the behavior of hangingwall during the face advance, planning the extraction operation and at last make true decisions in each condition. In this study, the parameters affecting on caving has been classified in four groups. These groups are: mechanical, geometrical, operational and geological parameters. Using fuzzy logic, the quality of caving according to these parameters and the factors resulting by them such as stability time, bulk factor, average particle size of the caved strata in the gob area and overhanging length has been analyzed. The results of analysis show that caving quality increases with increasing in bulk factor and decreasing in stability time, average particle size of the caved strata in gob area and over hanging length. The model was used for Tabas ParvardeV coal mine, located in Parvarde district, Yazd province in Iran. The results show medium to low quality for the siltstone and the sandstone layers in the immediate roof. The results also show a good convergence between the theoretical analysis and the mine observations.

Keywords: Longwall mining, hangingwall caving, stability time, bulk factor, strata, gob area, over hanging, Tabas Parvarde coal mine.

INTRODUCTION
Caving process is one of the most important extraction sequences in longwall mining method. prediction of composite layer behavior in hangingwall, before, during and after each stage of coal seam extraction and caving, plays an important role in production planning and depends on good recognition of hangingwall, parameters affecting on caving and composite layer behavior. Therefore presenting a model with ability of or. These approaches can be categorized into some groups such as analytical, geological, observational, and empirical methods, etc, for better recognition of roof strata conditions. Of these approaches, the empirical methods, typified by the rock mass classification systems and originally developed for tunnels (Wickham et al., 1972; Bieniawski, 1974), have been successfully modified for use in hard rock mines (Laubscher, 1977; Kendorski et al., 1983).

Classification systems for application to underground coal mines have been suggested by Ghose and Raju (1981) and others (Bieniawski et al., 1980; Seegmiller, 1983; Unal, 1983; Thill, 1984; Karmis and Kane, 1984). Ghose and Dutta used fuzzy logic and fuzzy sets theory to present a classification model for caving roofs in longwall coal mines in India for the first time (1987).

In this study, fuzzy sets theory is used to model the caving process. Fuzzy method is chosen because of its ability to explaining the characteristics and conditions of roof strata and predicting the hangingwall caving behavior is to be seen very important.

Because of the complicated conditions and too many effective parameters, the model must be able to gather all the effects of parameters and explain them together correctly and then present results with lowest error.

Many approaches are currently available for prediction of roof behavi
explain gradual changing in roof layer behavior and conditions and also aggregating too many different parameters together with lowest error. Fuzzy sets can also explain a qualitative phenomenon and change it to a numerical model very well and create a useful classification.

In this paper caving process is analyzed by evaluating the parameters affecting on it. Fuzzy sets theory is used to model the caving process and presenting a classification of hangingwall caving for longwall.

METHODS AND RESULTS

Caving of the roof strata

In longwall mining with caving, as the coal seam is removed and the face advances, the immediate roof sags away from the stronger higher strata. Even though the amount of sag is small, it relieves the immediate roof of all load of overburden. As advance of face continues, the roof span increases until caving occurs, creating a shelf over the emplaced supports. The caved material expands to fill the void and upper roof forms a span between it and the line where the immediate roof separated from it near the face of the coal [1].

A roof weakened by excessive fracturing, will produce a greater volume of gob when it caves, so that a shelf thickness of not less than three times the seam thickness will usually suffice. On the other hand, a strong roof under light cover where there has been little fracturing from the front abutment pressure will fall en masse and will require a thicker shelf or create the volume of gob needed.

Hangingwall is consisting some composite layers. When face advances, the first (lowest) composite layer starts to bend and then sags and some shear fractures will be generated in it and in the second composite layer. These cracks and fractures form into the first and second composite layer in a non-systematic manner but in a curvilinear shape with the upper part bending towards the goaf [1]. Thereafter as the winning operation proceeds, the first composite layer starts to cave and the second composite layer starts to sag. This process will continue in a vertical direction until it appears in the surface as subsidence.

Three separated zones can be observed in the hangingwall shown in figure1 named 'caving zone', 'weighting zone' and 'stable super incumbent roof zone'. These three zones are separated with two curves. The caving zone is located under the lower 3 curve and does not cause any weighting on the supports. The caving process and generation of the shear fractures start in the weighting zone located between two curves. The face support mainly withstands the load by the weighting zone caused as follows:

1-the load caused by the deflection of strata, only if the immediate roof strata layer is thick and very stable;
2-the combination of load offered by the detached roof rockmass of the lower composite layers and load offered by deflection of the upper composite layers;
3-the load totally offered by the detached roof rockmass if strata layers are very weak and unstable. Third zone in the hanging wall called stable zone, has got no influences on in the weightings at the supports. The formation of the curve depends on the strength of the strata, number of layers, fracture planes, water condition, and geological disturbances.

Caving indexes

The caving that occurs as soon as possible, with minimum overhanging and sufficient bulking factor is high quality caving. Two groups of indexes are presented in this paper to explain the caving quality. First group consists of overhanging and stability time of the roof layer after the face advances, and the second group consists of the particle size of the fractured roof rocks and the bulking factor. The quality of caving decreases when overhanging increases due to long stability time of the roof layers. Also the quality of caving increases when the bulking factor decreases due to larger particle sizes of the fractured roof rockmass. So overhanging and bulking factor are selected as representative of each mentioned groups to study and observe the influences of the different factors on caving quality.

Overhanging

Overhanging is a non-desirable phenomenon in roof strata caving. If overhanging take place in a large distance and time, non-desirable weightings over the supports will occur. Overhanging length depends on mechanical characteristics, type, strength, depth, and the thickness of the roof layers.

Bulking factor

The initial bulking factor is usually larger than one since the volume of broken roof rocks is larger than that of the original intact strata. It varies with the shape of the fragments, their size and size distribution, and the configuration of the caved rock fragments.

Bulking factor decreases with increasing size, size range and regularity of shape of the fragments. The bulking factor of the stronger and harder rocks will be smaller because they will result in larger fragments; conversely, the weaker and softer rocks will result in smaller fragments and consequently a larger bulking factor.
Sufficient bulking factor results high quality caving due to sufficient filling the void area after the coal wining. Bulking factor depends on the strength and thickness of the immediate roof, mining height and sagging of the lowest uncaved layer in contact with the gob area.

**Parameters affecting on caving**

For groups of parameters affecting on the caving quality are geometrical, geological, mechanical and operational parameters. Each group is consisting one or more parameters.

**Geometrical parameters**

Geometry of the coal seam and the roof strata are so important in hangingwall caving. Depth, thickness and stratigraphic sequences of the roof strata and their effects on the caving have been evaluated and observed in this study.

**Thickness of the roof strata**

This parameter has two effects on caving. First on the overhanging of the roof layers and second on the particle size of the fractured and falling roof rocks consequently in bulking factor. In the case of thin immediate and main roof layers during the mining process, these layers sag and fall in a short time, so overhanging does not take place or is too low. On the other hand, in this case the particle size of the caved roof rock is small and bulking factor is high enough to fill the void area due to wining the coal seam. Increasing in the thickness of the layers would result decrease in number of shear cracks, increase in overhanging length and stability time and decrease in the bulking factor.

When the roof is massive like the case of massive sand stone, sandy shale with high strength, etc, the roof layer overhangs a large area for a larger period and also it breaks in large blocks and does not fill the void area. In this case the roof does not cave easily and needs induced caving by blasting or hydro-fracturing.

**Depth**

In deep cases the abutment pressure is very high and so overhanging is too low. Abutment pressure will decrease with decrease in depth so that the particle size of the caved roof rock will increase.

**Operational parameters**

Size of the face (working area) and especially the mining height are the important operational parameters that have been considered in this study. Since the width of the working area increases, the abutment pressures will increase, so the shear cracks will appear sooner and sagging and caving will occur sooner. One of the important parameters in this group is the mining height. Caving and its height are directly in relation with the mining height. Caving is limited in its vertical extent because of the decrease in density of the roof material on fragmentation when bulking controlled caving occurs. Hence, the caving height can be determined from the following relation [2]:

\[ H_c = \frac{h - S_2}{b - 1}, \quad S_2 \leq S_{\text{max}} \]  

Where \( H_c \) is the height of the caved roof, \( h \) is the mining height, \( S_2 \) is the sagging of the lowest un-caved strata, \( S_{\text{max}} \) is the maximum allowable sagging and \( b \) is the bulking factor of the caved roof. If the strata break and fall without any sagging, that is, \( S_2 = S_{\text{max}} = 0 \); then the caving height is:

\[ H_c = \frac{h}{b - 1} \]

As can be observed from these equations the bulking factor decreases when mining height increases. Caving height and mining height are in a direct relation.

**Geological parameter**

Some parameters such as presence of fracture planes like shear cracks, joints, etc, and water content form the group of geological parameters. Presence of geological factors influences on the strength of the roof layers. Water content of the roof rockmass reduces the strength of the roof layers and also presence of the fractures reduces the strength of roof layer rockmass, so under the weightings these layers will cave easier than the others. In this study the influence of these parameters are combined with the mechanical parameter (strength of the roof strata).

**Mechanical parameters**

Strength of the roof layers is the key parameter in the caving. High strength layers do not cave easily and they cause large length of overhanging and they cave in large blocks, so the bulking factor in these cases are small.

The caving of the roof ceases when the gap from the floor to the roof is filled with broken, loose material. The bulking factor of the broken material determines the height of the caving zone. When this material is subjected to stress, two main parameters control its compaction process: these are the initial bulking factor and the strength of rock fragments. Initial compaction of such bulked material will be larger at the initial loading stage. The material will be stiffer and the modulus will increase when the load is increased. This is due to more densely compacted material; in other words, reduction in void volume present inside the rock fragments by further failure. It is not possible to compress the material back into its original intact volume; however, it may be accepted that the compaction of such material to its original volume is possible at infinite pressure. Satisfying this condition and taking the characteristics of caved rocks into account, the following equation suggested for backfill materials by Salamon [3] may be used to describe the stress–strain behavior of goaf material:

\[ \sigma = \frac{E_0\epsilon}{1 - \frac{\epsilon}{\epsilon_m}} \]  

Where \( E_0 \) is the initial modulus of the material when the material is at infinite pressure, \( \epsilon_m \) is the maximum strain that the material can achieve, and \( \epsilon \) is the current strain.
Fuzzy set theory

The fuzzy set theory was first introduced in 1965 by Lofty Zadeh as a mathematical way to represent linguistic vagueness [4]. It can be considered as a generalization of classical set theory. In a classical set, an element belongs to or does not belong to a set. That is, the membership of an element is crisp (0, 1), and an “A” crisp set of real objects are described by a unique membership function such as \( x_A \) in Fig. 2a. Contrary, a fuzzy set is a generalization of an ordinary set which assigns the degree of membership for each element to range over the unit interval between 0 and 1 (Fig. 2b). That is, the transition from “belong to a set” to “not belong to a set” is gradual, and this smooth transition is characterized by the membership function that gives fuzzy sets flexibility in modeling commonly used linguistic expressions such as “the strength of the roof layer is high” or “caving quality is low”.

In addition, fuzzy set theory can be used for developing rule based models which combine physical insights, expert knowledge and numerical data in a transparent way that closely resembles the real world. Fuzzy set theory provides a systematic calculus to deal with linguistic information, and it performs numerical computation by using linguistic labels stipulated by membership functions [5]. Moreover, fuzzy “if–then” rules form the key component of a FIS that can effectively model human expertise in a specific application.

![Figure 2- (a) Crisp set and (b) fuzzy set](image)

**Fuzzy if–then rules**

To inference in a rule based fuzzy model, the fuzzy proposition need to be represented by an implication function. The implication function is called fuzzy “if–then” rule. A fuzzy if–then rule, also known as the fuzzy rule, assumes the form “if \( x \) is \( A \) then \( y \) is \( B \)’’ where \( A \) and \( B \) are linguistic values defined by fuzzy sets on universes of discourse \( X \) and \( Y \), respectively. Often “\( x \) is \( A \)” is called the antecedent or premise, while “\( y \) is \( B \)” is called the consequence or conclusion. Examples of fuzzy if–then rules are widespread in daily linguistic expressions such as “If strength is high, then overhanging is large” [5].

Most rule-based systems involve more than one rule. The process of obtaining the overall consequent (conclusion) from the individual consequents contributed by each rule in the rule base is known as aggregation of rules. In determining an aggregation strategy two simple extreme cases exist, namely; conjunctive system of rules and disjunctive system of rules [6].

Fuzzy inference system

The FIS is a popular computing framework based on the concepts of fuzzy set theory, fuzzy if–then rules, and fuzzy reasoning. FISs have been successfully applied in fields such as automatic control, data classification, decision analyses, expert systems, and computer vision. Because of its multidisciplinary nature, FISs are associated with a number of names such as fuzzy rule based systems, fuzzy expert systems, fuzzy modeling, fuzzy associative memory, fuzzy logic controllers and simply fuzzy models.

The basic structure of a FIS consists of three conceptual components: a rule base, which contains the selection of rules; a database, which defines the membership functions used in the fuzzy rules; and a reasoning mechanism, which performs the inference procedure upon the rules and given facts to derive a reasonable output or conclusion. Basic FIS can take either fuzzy inputs or crisp inputs, but the outputs it produces are almost always fuzzy sets. In cases where a crisp value is needed, defuzzification method should be carried out. A FIS with a crisp output is shown in Figure 3, where the dashed line indicates a basic FIS with fuzzy input and the defuzzification block serving for transforming an output fuzzy set into a crisp single value.

There are several FISs that have been employed in various applications. The most commonly used include:

- Mamdani fuzzy model;
- Takagi–Sugeno–Kang fuzzy (TSK) model;
- Tsukamoto fuzzy model;
- Singleton fuzzy model.

The differences between these FISs lie in the consequents of their fuzzy rules, and thus their aggregation and defuzzification procedures differ accordingly. In this paper, the Mamdani fuzzy model is widely used since this model is easier to interpret and analyze when compared with the others.

The Mamdani fuzzy model

The Mamdani FIS (figure 4) was first proposed as an attempt to control a steam engine and boiler combination by a set of linguistic control rules obtained from experienced human operators [7].

Defuzzification methods

Defuzzification refers to the way a crisp value is extracted from a fuzzy set as a representative value.

Although there are a number of defuzzification methods in the literature such as centroid of area (COA) or center of gravity, mean of maximum, smallest of maximum, etc. The most widely adopted defuzzification method is COA method which is used in this study.

Fuzzy system can properly combine these parameters with different characteristics and different influences on immediate roof caving. This fuzzy approach proved to be a very effective way to cope with the non-linearity and the dynamic behavior of the plant.
According to qualitative analysis of hangingwall caving and the influence of each parameter on caving quality, a fuzzy model was made with four output parameters. Caving quality (CQ) is presented as the output of the model.

This model can be used as a classification for the manner of the immediate roof caving in longwall faces.

### Input parameters

Four input parameters have been chosen as input parameters of the model. These parameters are strength, depth, thickness of each layer in the immediate roof, and the mining height. To create the model the MATLAB software, version 7.3.0 was used. This software is able to create mamdani and TSK fuzzy systems graphically.

#### Thickness of the roof layer

This parameter is separated into five fuzzy sets as can be seen in the figure. Table 1 shows the ranges of each set and class.

<table>
<thead>
<tr>
<th>Thickness(m)</th>
<th>0-0.5</th>
<th>0.5-1</th>
<th>1-2</th>
<th>2-4</th>
<th>4+</th>
</tr>
</thead>
<tbody>
<tr>
<td>class</td>
<td>Very thin</td>
<td>thin</td>
<td>med</td>
<td>thick</td>
<td>Very thick</td>
</tr>
</tbody>
</table>

Table 1 - Thickness of the roof layer

#### Depth of the roof layer

This parameter is classified into three fuzzy sets as can be seen in figure 6 and table 2.

<table>
<thead>
<tr>
<th>Depth(m)</th>
<th>0-70</th>
<th>70-250</th>
<th>250-650</th>
</tr>
</thead>
<tbody>
<tr>
<td>class</td>
<td>low</td>
<td>med</td>
<td>high</td>
</tr>
</tbody>
</table>

Table 2 - Depth of the roof layer

---

**Figure 3 - Block diagram for FIS [5]**

**Figure 4 - The Mamdani FIS [5]**

**Figure 5 - Thickness of the roof layer fuzzy sets**

**Figure 6 - Input fuzzy sets for depth of the layer in hangingwall**
Mining height

Mining height as the third parameter in the model is classified into three fuzzy sets. These sets and their ranges are shown in figure 7 and also table 3.

<table>
<thead>
<tr>
<th>MH(m)</th>
<th>0-0.75</th>
<th>0.75-2</th>
<th>2-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>class</td>
<td>low</td>
<td>med</td>
<td>high</td>
</tr>
</tbody>
</table>

Table 3 - Mining Height (MH)

Figure 7 - Input fuzzy sets for mining height

Strength of the roof layer

Strength of the roof layer is forth and last internal parameter of the model that is classified into five fuzzy sets presented in figure 8 and table 4.

<table>
<thead>
<tr>
<th>Strength (MPa)</th>
<th>0-15</th>
<th>15-30</th>
<th>30-70</th>
<th>70-120</th>
<th>&gt;120</th>
</tr>
</thead>
<tbody>
<tr>
<td>class</td>
<td>very poor</td>
<td>poor</td>
<td>med</td>
<td>high</td>
<td>very high</td>
</tr>
</tbody>
</table>

Table 4 - Strength of the roof layer

Output of the model

The rule base of the model consists of 220 IF-Then rules and the output of the model is called CQ (caving quality) that explains the quality of caving according to caving indexes (bulk factor and overhanging), in five fuzzy set from the very low to very high caving quality as can be seen in the figure 9 and table 5. Schema of the model with 4 input parameters, the FIS of the system and the CQ as output of the model is shown in figure 10.

Figure 9 - Output of the model

<table>
<thead>
<tr>
<th>CQ</th>
<th>0-20</th>
<th>20-40</th>
<th>40-60</th>
<th>60-80</th>
<th>80-100</th>
</tr>
</thead>
<tbody>
<tr>
<td>class</td>
<td>very low</td>
<td>low</td>
<td>medium</td>
<td>high</td>
<td>very high</td>
</tr>
</tbody>
</table>

Table 5 - Classification of the caving quality (CQ)

The table shows that the mining height in this case is medium. The model results show a poor CQ for silt and sandstone because of its thickness, and high strength. Medium thickness, medium strength, and also medium depth of the sandy silt layer results a moderate CQ by the model. In siltstone with joints, poor strength due to presence of joints helps the layer to cave easily. Therefore high CQ is expectable in this case, but because of its high thickness, model result shows moderate CQ of 52.1. Aggregating the results for three immediate roof layers shows medium to low caving quality due to the thickness and strength of the silt and sandstone.

Observations of the face confirms the results of the model, the caving quality (CQ) in this case is low because of the large
over hanging occur due to high thickness of the sandstone layer in hangingwall.

CONCLUSIONS
A detailed study of behavior of strata around the coal mining panel was presented in this paper. After identifying the behavior of the roof layers during the caving (bending, sagging, and caving) three zones have been identified in the hanging wall called; caving zone, weighting zone, and stable superincumbent zone. Then two groups of indexes have been introduced to describe the caving quality.

Then four groups of parameters affecting the caving evaluated and after that a classification has been presented to classify and qualitative analysis of hanging wall introducing a parameter called 'caving quality', using fuzzy sets theory. The fuzzy system modeled the caving process around the hangingwall with four input parameters called depth of the roof layer, thickness of the roof layer, mining height, and the strength of the roof layer. At last the system was used to model the caving behavior of the ParvardeV coal mine hangingwall in Tabas district, Yazd province, Iran. The results of the model show that the caving quality in this mine is medium to low.

REFERENCES
Jang RJS, Sun CT, Mizutani E. 1997; Neuro -fuzzy and soft computing. Upper Saddle River: Prentice-Hall; 614pp


Peng SS; Chiang HS; 1984; Longwall mining. New York: Wiley: p. 708


Stefanko ,R ;1983 ; Coal Mining Technology, theory and practice; Published by Society of Mining Engineering of The American Institute of Mining and Metallurgical and Petroleum engineering Inc; pp 127-159.

Zadeh LA.; 1965; Fuzzy sets. Inform Control;8: pp338–53.

<table>
<thead>
<tr>
<th>Bed</th>
<th>Thickness(m)</th>
<th>Strength(MPa)</th>
<th>Depth(m)</th>
<th>Mining Height(m)</th>
<th>CQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>1.2</td>
<td>19</td>
<td>94</td>
<td>0.9 to 1.2</td>
<td>-</td>
</tr>
<tr>
<td>Siltstone with joints</td>
<td>2.42</td>
<td>23.5</td>
<td>94.4</td>
<td>-</td>
<td>52.1 (moderate)</td>
</tr>
<tr>
<td>Sandy silt</td>
<td>1.4</td>
<td>34.7</td>
<td>93.87</td>
<td>-</td>
<td>57.9 (moderate)</td>
</tr>
<tr>
<td>Silt and sandstone</td>
<td>2.05</td>
<td>86.4</td>
<td>91.82</td>
<td>-</td>
<td>38.8 (moderate)</td>
</tr>
</tbody>
</table>

Table 6 –results of the model for the Tabas Parvarde IV coal mine