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ORIGINAL PAPER

Stability Assessment of Underground Mined-Out Areas in a Gold Mine Based on Complex System Theory

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Abstract For deep mining of a gold mine in the Altay city, Xinjinag autonomy region, China, it is necessary to evaluate the stability of mined-out areas of upper levels and then to treat those mined-out areas. Based on the features of underground mining, in this paper, a complex system model of stability assessment of underground mined-out area has been set up, which is constituted by 3 sub-systems of geological factors, mining engineering factors and management factors, and this system could be studied and analyzed by using the fuzzy analytic hierarchy process method and the catastrophe theory modeling method. By using those two methods and utilizing measured data of the gold mine, some useful conclusions of stability assessment of mined-out areas have been given out, which would be helpful for the mined-out areas treatment and also for the safely deep mining of the mine.

Keywords Underground mined-out areas · Complex system · Fuzzy AHP · Catastrophe theory model · Stability assessment

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1 Introduction

The existence of underground mined-out areas is potential safety hazard, which may restrict the development of a mine. With the increase of mining depth, ground pressure also increases, which may cause the collapse of mined-out areas. Therefore, the identification and treatment of mined-out areas are crucial to the safe exploitation of underground mines (Miao et al. 2009).

A gold mine, which belongs to the Altai city, Xinjiang autonomy region, China, locates at the northeast of the Haba River County. There are No. 1 and No. 2 mining districts in the mine, of which No. 1 is the main production district at the moment. The 12# vein (Zheng et al. 2010) is the main mining orebody, with features of a total thickness of 30 m, a grade of 2 g/t, a discontinuous strike length of 400 m, a dipping angle of 79°–82° and dip direction of SW220°, is schematically presented in Fig. 1. The upper part vein, i.e., over +610 m level, was mined-out by an open-pit, and the lower part, starting from +570 m level, is being mined underground by using short-hole shrinkage stoping method.

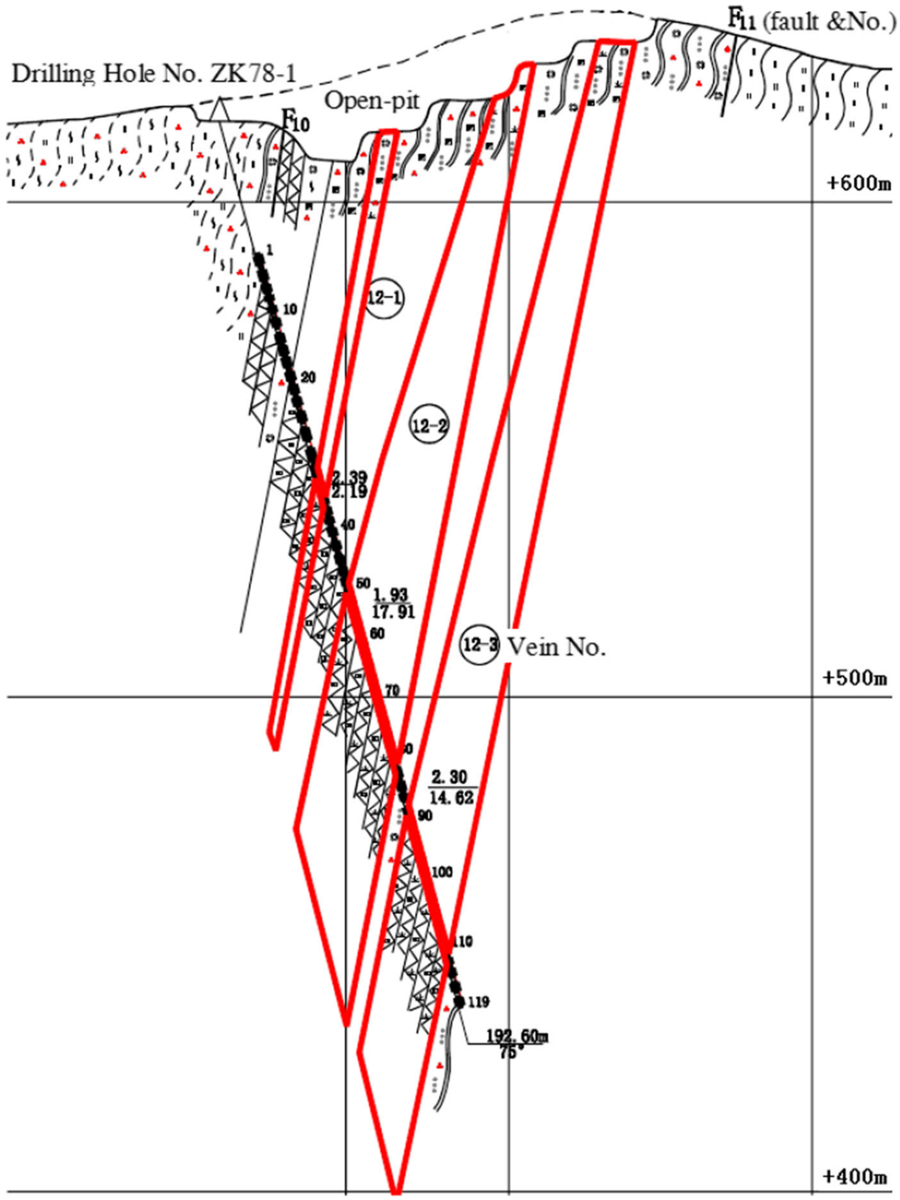

Fig. 1 Section view of 12# vein in No. 1 mining district

After about 10 years' mining production, there are a number of mined-out areas left at +570, +530, +490 and +450 m levels without being treated, as shown in the Fig. 2. In Fig. 2, there were several stopes which were not totally mined-out because of internal waste or large-scale fault. And according to the mine plan, mining operation will be arranged at +410 m level in the next 2 years. Hence, the stability of those mined-out areas has to be carefully studied before starting mining operation at the +410 m level.

2 Complex System Model for Stability Assessment of Underground Mined-Out Areas

During underground metal mining practice, stability assessment of the underground mined-out areas is a significant issue (Li and Chen 2008). The assessment methods can be sorted into 2 groups. One group is called the formulation method, i.e., based on a large number of statistical data about various factors influencing on rock mass stability, some main factors

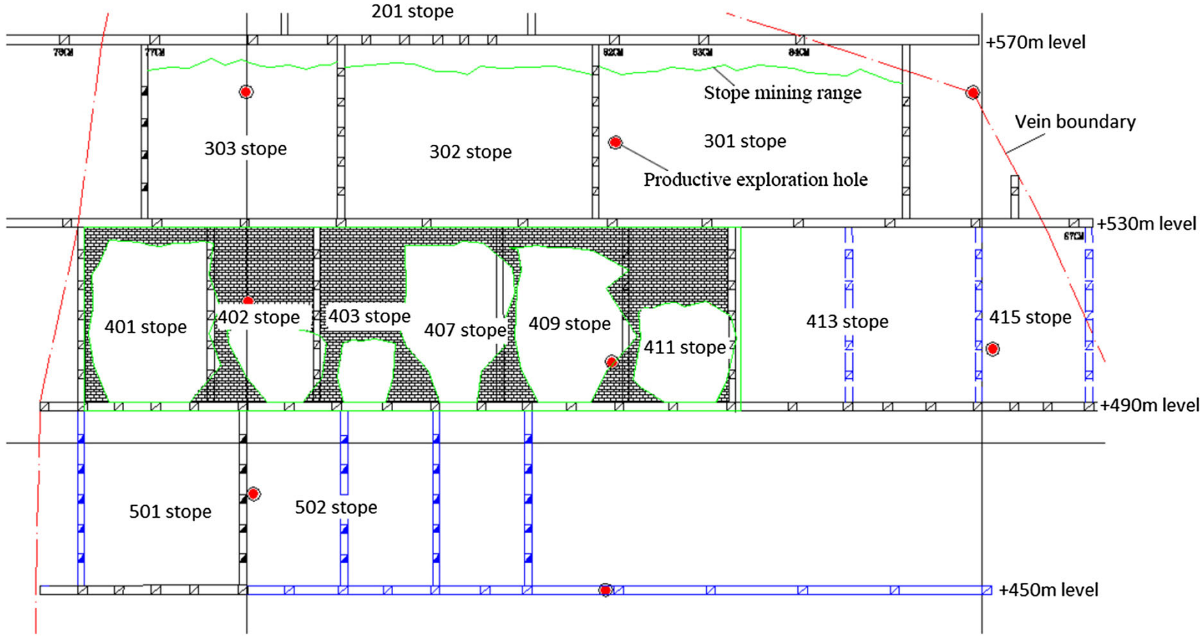

Fig. 2 Longitudinal view of mined-out areas of 12–3# vein in No. 1 mining district

are used to make up assessment formulas, such as stability prediction formula or stability coefficient formula. For instance, the Mathews method as shown in Fig. 3, however in which the stability number N is rather difficult to calculate for actual using. In contrast, the other one is called factor evaluating method, i.e., according to value range or membership degree of factors in stability rank, a corresponding relationship

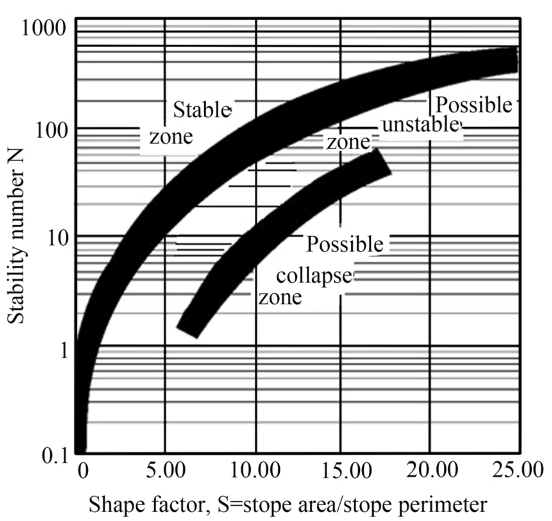

Fig. 3 The Mathews method for evaluating the stope stability

between the factors and the stability rank is set up by using some methods, such as fuzzy distinguishing method (Wu et al. 2010), grey clustering method and artificial neural network method (Hopfield 1986; Singh et al. 2001). The reliability of stability assessment method mainly depends on factor selection, factor weighting arrangement and the rationality of corresponding relationship between the factors and the stability rank.

Stability assessment of underground mined-out areas is related with many factors of geological conditions, mining engineering conditions and management conditions. Generally speaking, if a system has the following features then it can be regarded as a complex system: (1) indivisible feature, i.e., under limited information and knowledge, essentially the whole behavior of a complex system cannot be determined by analyzing sub-behaviors of some parts of the system; (2) undetermined feature, i.e., under limited information and knowledge, essentially the whole behavior of a complex system could not be totally determined beforehand (Wang 2006). Therefore, the stability assessment of underground mined-out areas can be regarded as a complex system.

For a complex system, system state variables, which should submit to the dynamic changing style, are usually non-linear function variables. In underground

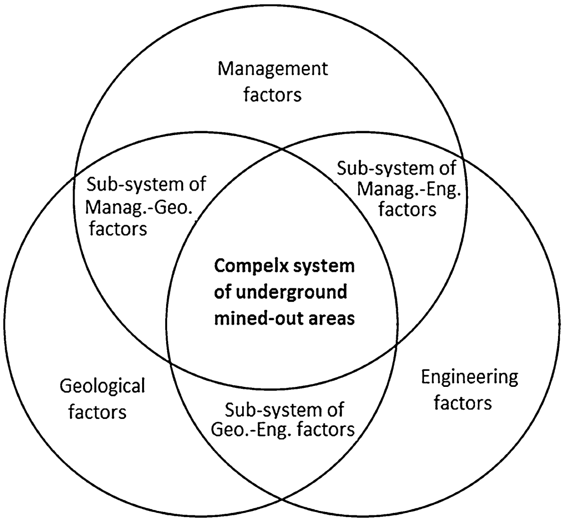

Fig. 4 The complex system of underground mined-out areas

mined-out areas, country rocks may have some displacement or even damage, which are caused by mining excavation. The rock properties and the uncertainties of excavation discharge and country rock displacement would lead to a very complicated change of those state variables. For the complex system of underground mined-out areas, outside observed data are a set of special solutions during the system movement. The evolution and the development of those observed data present the locus of the system developing. Hence the features of the complex system could be studied by using observable state variables (Zhou et al. 2007; Van Loon 2002).

There are a number of complex properties of the stability assessment of underground mined-out areas, such as dynamic openness, subject pluralism, sensibility of initial conditions, dynamic evolution and so on. A number of factors related with geological conditions, mining engineering conditions and management conditions makes up the complex system of underground mined-out areas, as shown in Fig. 4.

3 Fuzzy AHP of Stability Assessment of Underground Mined-Out Areas

3.1 Fuzzy AHP Model

The complex system of underground mined-out areas can be modeled and analyzed by using analytic hierarchy process (AHP) method, and some researchers have published their research works, for instance,

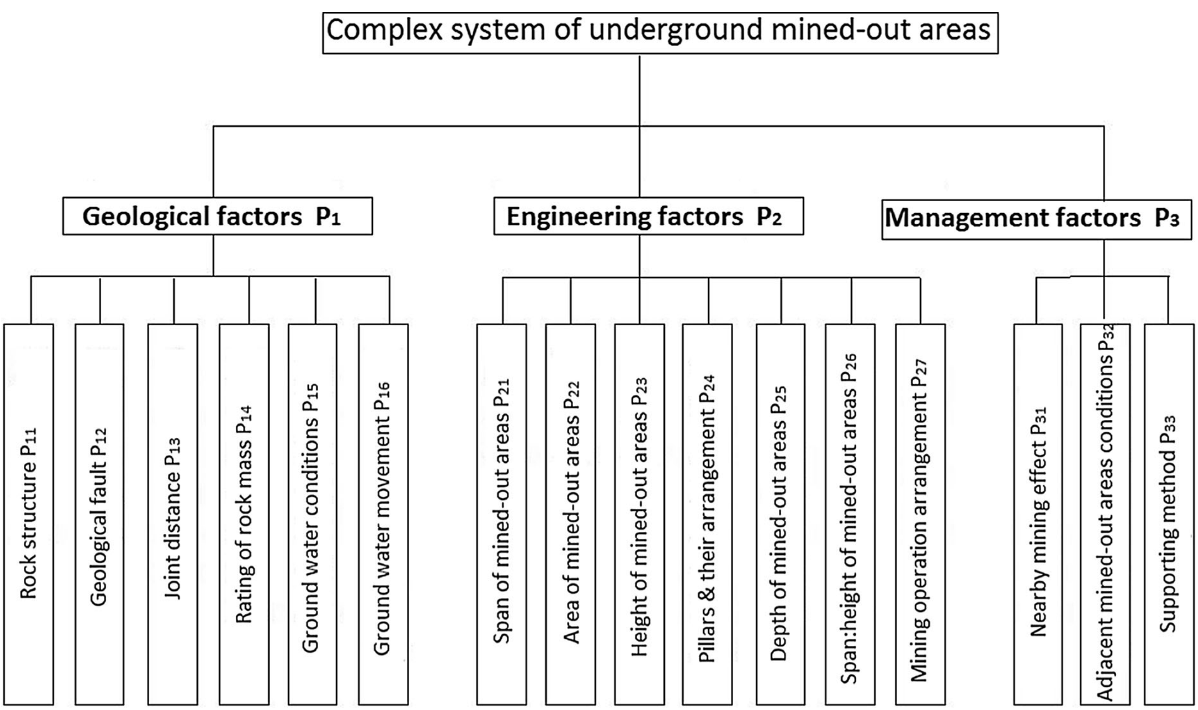

Fig. 5 Stability assessment model of underground mined-out areas based on complex system

Table 1 Rating standard of factors in the fuzzy AHP model

Factors		Rating standard			
		1 class	2 class	3 class	4 class
Geological factor P_1	P_{11}	Integral, block	Layer structure	Fractured	Fragmented
	P_{12}	No fault or fold	Little effect	Large effect	Faults in country rocks
	P_{13} (cm)	>100	50–1001	30–50	<30
	P_{14} (%)	>60	50–60	40–50	<40
	P_{15}	No ground water	Little effect	General effect	Large effect
	P_{16}	No seepage	Little seepage	General seepage	Heavy seepage
Engineering factor P_2	P_{21} (m)	<40	40–80	80–120	>120
	P_{22} (m^2)	<800	800–1200	1200–2700	>2700
	P_{23} (m)	<8	8–20	20–30	>30
	P_{24}	Regular pillars	Irregular pillars	No pillars or pillars damaged	No pillars or pillars collapsed
	P_{25} (m)	<100	100–200	200–400	>400
	P_{26}	<1	1–2	2–3	>3
	P_{27}	Reasonable	Even reasonable	General	Not reasonable
Management factor P_3	P_{31}	No effect	Little effect	General effect	Large effect
	P_{32}	No	A few	Numbers	Big numbers
	P_{33}	reasonable	Even reasonable	General	Not reasonable

Table 2 Stability classes of underground mined-out areas

Rating class	Stability state and treatment suggestions of mined-out areas
I class	Stable, not necessary to monitor or to treat mined-out areas
II class	General stable, need to monitor or to treat mined-out areas for mining safety
III class	Need immediately to monitor or to treat mined-out areas, and to make an emergency measure
IV class	Need immediately to treat mined-out areas, and to withdraw miners and equipment around the mined-out areas

Table 3 Value of membership degree of qualitative factor

Class	1 rating	2 rating	3 rating	4 rating
I class	0.45	0.30	0.15	0.05
II class	0.35	0.45	0.15	0.15
III class	0.15	0.15	0.45	0.35
IV class	0.05	0.10	0.25	0.45

uncertainty AHP (Deng and Jia 2012), grey AHP (Cheng et al. 2011a), rough sets theory and AHP (Cheng et al. 2011b). In this paper, a fuzzy AHP model is set up as shown in Fig. 5.

The rating standard of those factors shown in the Fig. 5 is listed in Table 1. For setting up the 4 classes of rating standard, they were considered with the RMR (Rock Mass Rating) of CSIR (Council for Scientific and Industrial Research), the possible maximum area of stope back and also the judgements of the mine engineers.

For stability assessment of underground mined-out areas, stability classes should be set up, as listed in Table 2.

For those quantitative factors listed in Table 1, their membership degree related with the rating standard class can be obtained from the membership function. There are many different types of membership functions, such as normal type and fall-half type. Based on features of the factors, a lower semi-trapezoid membership function is used as follows:

$$u_{\mathrm{I}}(x) = \begin{cases} 1 & (x \le a_1) \\ \dfrac{a_2 - x}{a_2 - a_1} & (a_1 < x \le a_2) \\ 0 & (x > a_2) \end{cases} \tag{1}$$

Table 4 Combination weights of factors

Factor P_{ij}	Factor P			Combination weight
	Geological $P_1 = 0.1062$	Engineering $P_2 = 0.6333$	Management $P_3 = 0.2650$	
P_{11}	0.1447	0	0	0.0154
P_{12}	0.0798	0	0	0.0085
P_{13} (cm)	0.2576	0	0	0.0274
P_{14} (%)	0.4394	0	0	0.0467
P_{15}	0.0544	0	0	0.0058
P_{16}	0.0240	0	0	0.0025
P_{21} (m)	0	0.3711	0	0.2350
P_{22} (m^2)	0	0.1577	0	0.0999
P_{23} (m)	0	0.2541	0	0.1609
P_{24}	0	0.0345	0	0.0218
P_{25} (m)	0	0.1017	0	0.0644
P_{26}	0	0.0586	0	0.0371
P_{27}	0	0.0222	0	0.0141
P_{31}	0	0	0.2157	0.0572
P_{32}	0	0	0.7231	0.1916
P_{33}	0	0	0.0612	0.0162

Table 5 Stability assessment results of 12 mined-out areas at the gold mine

No.	Mined-out areas	Membership degree of mined-out areas				Stability class
		I	II	III	IV	
1	301	0.1542	0.3333	0.2452	0.2680	II
2	302	0.2316	0.3234	0.1877	0.2618	II
3	303	0.2866	0.2320	0.3677	0.1182	III
4	401	0.3101	0.2007	0.3293	0.1642	III
5	402	0.0770	0.3569	0.3652	0.2052	III
6	403	0.0770	0.4466	0.1662	0.3147	I
7	405	0.0770	0.4466	0.1662	0.3147	II
8	407	0.1096	0.3938	0.3530	0.1429	II
9	409	0.2062	0.3023	0.3530	0.1429	III
10	411	0.2272	0.2576	0.3530	0.1731	III
11	413	0.3722	0.1441	0.3530	0.1416	I
12	501	0.0841	0.4046	0.1610	0.3530	II

$$u_{\mathrm{II}}(x) = \begin{cases} 0 & (x < a_1, x > a_3) \\ -\dfrac{a_1 - x}{a_2 - a_1} & (a_1 < x \le a_2) \\ \dfrac{a_3 - x}{a_3 - a_2} & (a_2 < x \le a_3) \end{cases} \tag{2}$$

$$u_{\mathrm{III}}(x) = \begin{cases} 1 & (x < a_2, x > a_4) \\ -\dfrac{a_2 - x}{a_3 - a_2} & (a_2 < x \le a_3) \\ \dfrac{a_4 - x}{a_4 - a_3} & (a_3 < x \le a_4) \end{cases} \tag{3}$$

$$u_{\mathrm{IV}}(x) = \begin{cases} 0 & (x < a_3) \\ -\dfrac{a_3 - x}{a_4 - a_3} & (a_3 \le x < a_4) \\ 1 & (x \ge a_4) \end{cases} \tag{4}$$

where, a_1, a_2, a_3 and a_4 are the rating standards of factors, while x is a measured datum.

For those qualitative factors listed in Table 1, their membership degree related with the rating standard class could be obtained from a value table. For

Table 6 Several often used catastrophe theory models

Catastrophe theory model	Dimension of controlling variables	Potential function*
The cusp catastrophe	2	$V(x) = \frac{1}{4}x^4 + \frac{1}{2}ax^2 + bx$
The Swallowtail catastrophe	3	$V(x) = \frac{1}{5}x^5 + \frac{1}{4}ax^3 + \frac{1}{2}bx^2 + cx$
The butterfly catastrophe	4	$V(x) = \frac{1}{6}x^6 + \frac{1}{4}ax^4 + \frac{1}{3}bx^3 + \frac{1}{2}cx^2 + dx$

* In the potential functions in Table 6, x is state variable, and a, b, c and d are controlling variables

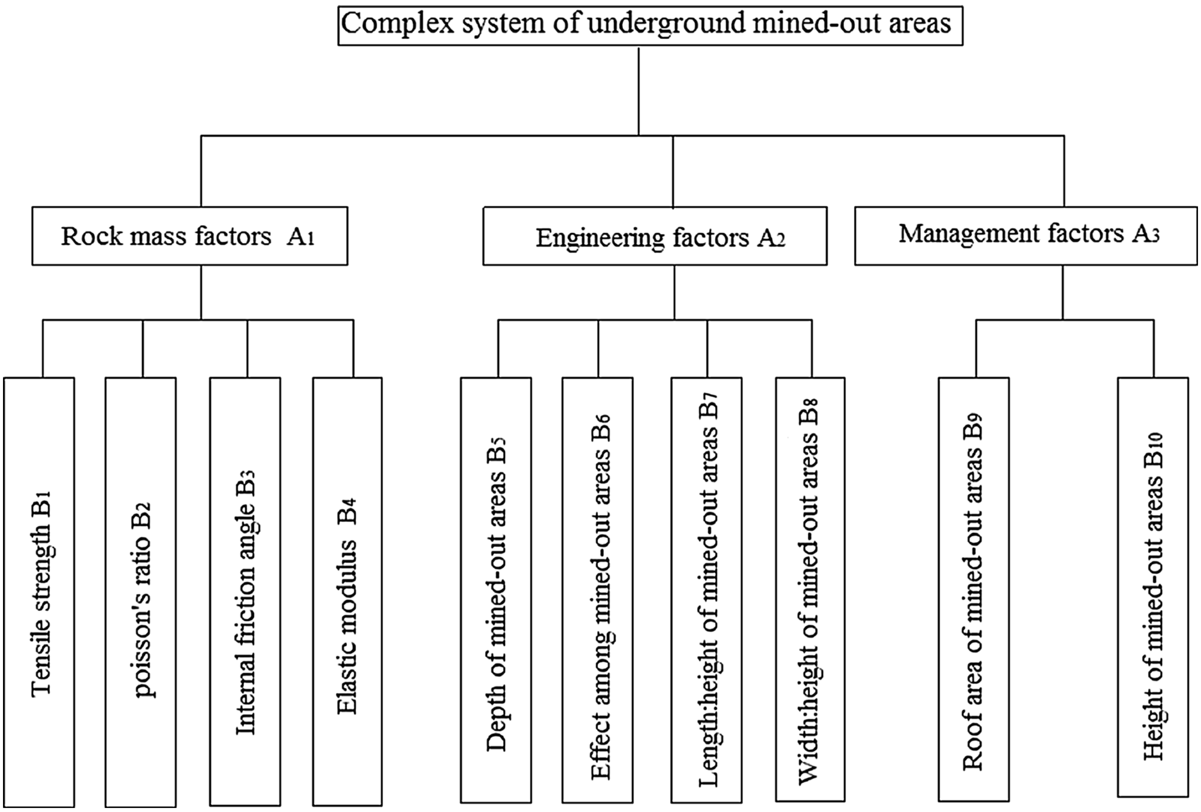

Fig. 6 Stability assessment model of underground mined-out areas based on catastrophe theory

Table 7 Suggested range of standardizing factors

Degree of unstable risk	Small	General	High	Very high
Value range				
The smaller the better	$[0, x_1)$	$[x_1, x_2)$	$[x_2, x_3)$	$[x_3, +\infty)$
The bigger the better	$[x_3, +\infty)$	$[x_2, x_3)$	$[x_1, x_2)$	$[0, x_1)$
Range of standardizing factor	$(a_2, a_1]$	$(a_3, a_2]$	$(a_4, a_3]$	$[a_5, a_4]$
Suggested range of standardizing factor	(0.75, 1]	(0.5, 0.75]	(0.25, 0.5]	[0, 0.25]

example, the factor P_{33}, i.e., supporting method of mined-out areas, can be described by 4 ratings of reasonable, even reasonable, general and not reasonable, and its membership degree is listed in Table 3, where values are obtained from a fuzzy statistics way.

3.2 Stability Assessment Results of Fuzzy AHP

Based on the method of fuzzy AHP model, the combination weights of factors in stability assessment of mined-out areas of the gold mine are listed in Table 4.

The typical 12 mined-out areas of the gold mine that are shown in the Fig. 2 are analyzed. The 4 membership degrees of those mined-out areas are listed in Table 5. To find out the biggest one from the 4 membership degrees of the mined-out areas, the stability class of each mined-out area is given out, as listed in Table 5 as well.

4 Catastrophe Theory Method of Stability Assessment of Underground Mined-Out Areas

4.1 Catastrophe Theory Model

Catastrophe theory is used to describe or to predict a qualitative change process of continuity interruption of a thing, by utilizing topology of dynamic system to set up mathematical models of discontinuity change of natural phenomenon or social activity (Gilmore 1981; Ling 1997). The study object of catastrophe theory model is potential function of a system, and this function is determined by the relative contact and the interaction of all parts of the system. Several often used catastrophe theory models are listed in Table 6.

As the dimension of controlling variables in catastrophe theory models is 2–4, therefore, for using catastrophe theory models to evaluate the stability of underground mined-out areas, the assessment model is shown in Fig. 6 (Ma and Huang 2010). From Fig. 6, it could be seen that the A_1 (Rock mass factors) and A_2 (Engineering factors) are simulated by using the butterfly catastrophe model with 4 variables, A_3 (Management factors) is simulated by using the cusp catastrophe model with 2 variables, and the whole system is simulated by using the swallowtail catastrophe model with 3 variables.

Setting the most unstable state of underground mined-out areas be 0, and the most stable state be 1, then for aggregate analysis, a standardizing processing of factors Bi, i.e., the controlling variables, is needed. The suggested range of standardizing factors is listed in Table 7.

Based on the Table 7, the standardizing processing is as following:

1. The factor value that is the smaller the better:

$$u_t = \begin{cases} \text{Small}: a_1 - \dfrac{x}{x_1}(a_1 - a_2) \quad (x \in [0, x_1)) \\ \text{General}: a_2 - \dfrac{x - x_1}{x_2 - x_1}(a_2 - a_3) \quad (x \in [x_1, x_2)) \\ \text{High}: a_3 - \dfrac{x - x_2}{x_3 - x_2}(a_3 - a_4) \quad (x \in [x_2, x_3)) \\ \text{Very high}: a_4 - \dfrac{x - x_3}{(\sqrt{2} - 1)x_3}(a_4 - a_5) \quad \left(x \in \left[x_3, \sqrt{2}x_3\right)\right) \\ 0\left(x \in \left[\sqrt{2}x_3, +\infty\right)\right) \end{cases} \tag{5}$$

Table 9 Rating of stability coefficient (SC) of mined-out areas

Rating	IV	III	II	I
Unstable risk	Very high	High	General	Small
SC value	0–0.25	0.25–0.5	0.5–0.75	0.75–1

Table 8 Factor value range of the catastrophe theory model

Factor	Unstable risk of underground mined-out areas			
	Small (0.75, 1]	General (0.5, 0.75]	High (0.25, 0.5]	Very high [0, 0.25]
B_1	[2, +∞)	[1.5, 2)	[1, 1.5)	[0, 1)
B_2	[0, 0.15)	[0.15, 0.3)	[0.3, 0.45)	[0.45, 1]
B_3	[60, +∞)	[40, 60)	[20, 40)	[0, 20)
B_4	[40, +∞)	[30, 40)	[20, 30)	[0, 20)
B_5	[0, 100)	[100, 150)	[150, 200)	[200, +∞)
B_6	[0, 0.25)	[0.25, 0.5)	[0.5, 0.75)	[0.75, 1]
B_7	[0, 0.5)	[0.5, 1)	[1, 1.5)	[1.5, +∞)
B_8	[0, 0.5)	[0.5, 1)	[1, 1.5)	[1.5, +∞)
B_9	[0, 600)	[600, 700)	[700, 800)	[800, +∞)
B_{10}	[0, 8)	[8, 20)	[20, 30)	[30, +∞)

2. The factor value that is the bigger the better:

$$u_t = \begin{cases} \text{Very high}: a_5 + \dfrac{x}{x_1}(a_4 - a_5) & (x \in [0, x_1)) \\ \text{High}: a_4 + \dfrac{x - x_1}{x_2 - x_1}(a_3 - a_4) & (x \in [x_1, x_2)) \\ \text{General}: a_3 + \dfrac{x - x_2}{x_3 - x_2}(a_2 - a_3) & (x \in [x_2, x_3)) \\ \text{Small}: a_4 + \dfrac{x - x_3}{(\sqrt{2} - 1)x_3}(a_1 - a_2) & \left(x \in \left[x_3, \sqrt{2}x_3\right)\right) \\ 1\left(x \in \left[\sqrt{2}x_3, +\infty\right)\right) \end{cases} \tag{6}$$

where, a_1, a_2, a_3, a_4, a_5, x_1, x_2 and x_3 are shown in the Table 7, and x is the standardizing factor value.

There are 10 factors shown in the Fig. 6, and in consideration of the actual data of the gold mine, the value ranges of those factors can be listed in Table 8.

A stability coefficient (SC) of each mined-out area is calculated by using the catastrophe theory model, and the SC values are divided into 4 ratings, as shown in Table 9.

4.2 Assessment Results of Catastrophe Theory Model

The original or measured data of catastrophe theory model factors of the gold mine are listed in Table 10, and the normalization data are listed in Table 11.

Table 10 Original or measured data of factors of the gold mine

No.	Mined-out areas	B1 (MPa)	B2	B3 (°)	B4 (GPa)	B5 (m)	B6	B7	B8	B9 (m^2)	B10 (m)
1	301	1.24	0.38	38.1	29.7	155	0.6	2.00	1.301	611	33.0
2	302	1.24	0.38	38.1	29.7	155	0.7	1.69	1.243	860	32.0
3	303	1.24	0.38	38.1	29.7	155	0.6	1.28	1.343	860	32.0
4	401	1.62	0.31	40.2	28.7	195	0.7	1.11	0.968	1090	35.0
5	402	2.27	0.19	42.2	34.1	194	0.8	2.18	2.000	1008	26.6
6	403	1.62	0.31	40.2	28.7	190	0.9	1.61	1.646	1000	36.0
7	405	1.62	0.31	40.2	28.7	186	0.9	1.61	1.646	624	36.0
8	407	1.62	0.31	40.2	28.7	182	0.8	1.61	1.646	770	36.0
9	409	2.27	0.19	42.2	34.1	180	0.7	1.11	1.010	970	36.0
10	411	1.62	0.31	40.2	28.7	178	0.7	1.58	1.646	1070	36.0
11	413	2.27	0.19	42.2	34.1	178	0.6	1.05	2.000	861	38.0
12	501	2.27	0.19	42.2	34.1	237	0.6	2.18	2.000	768	39.0

Table 11 Normalization data of factors of the gold mine

No.	Mined-out areas	x_{B_1}	x_{B_2}	x_{B_3}	x_{B_4}	x_{B_5}	x_{B_6}	x_{B_7}	x_{B_8}	x_{B_9}	$x_{B_{10}}$
1	301	0.608	0.859	0.851	0.868	0.689	0.737	0.470	0.810	0.850	0.575
2	302	0.608	0.859	0.851	0.868	0.689	0.669	0.645	0.823	0.452	0.594
3	303	0.608	0.859	0.851	0.868	0.689	0.737	0.775	0.800	0.452	0.594
4	401	0.748	0.802	0.840	0.859	0.524	0.669	0.817	0.876	0.177	0.531
5	402	0.912	0.682	0.829	0.904	0.529	0.594	0.000	0.547	0.305	0.695
6	403	0.748	0.802	0.840	0.859	0.548	0.506	0.673	0.718	0.315	0.506
7	405	0.748	0.802	0.840	0.859	0.566	0.506	0.673	0.718	0.831	0.506
8	407	0.748	0.802	0.840	0.859	0.583	0.594	0.673	0.718	0.570	0.506
9	409	0.912	0.682	0.829	0.904	0.592	0.669	0.817	0.869	0.349	0.506
10	411	0.748	0.802	0.840	0.859	0.600	0.669	0.683	0.718	0.215	0.506
11	413	0.912	0.682	0.829	0.904	0.600	0.737	0.830	0.547	0.452	0.447
12	501	0.912	0.682	0.829	0.904	0.372	0.737	0.000	0.547	0.574	0.410

Table 12 Calculated x_A & SC values of mined-out areas

No.	Mined-out areas	x_{A_1}	x_{A_2}	x_{A_3}	SC
1	301	0.796	0.677	0.712	0.677
2	302	0.796	0.707	0.523	0.523
3	303	0.796	0.750	0.523	0.523
4	401	0.812	0.722	0.354	0.354
5	402	0.832	0.417	0.500	0.417
6	403	0.812	0.611	0.410	0.410
7	405	0.812	0.616	0.668	0.616
8	407	0.812	0.642	0.538	0.538
9	409	0.832	0.737	0.427	0.427
10	411	0.812	0.668	0.360	0.360
11	413	0.832	0.678	0.449	0.449
12	501	0.832	0.414	0.492	0.414

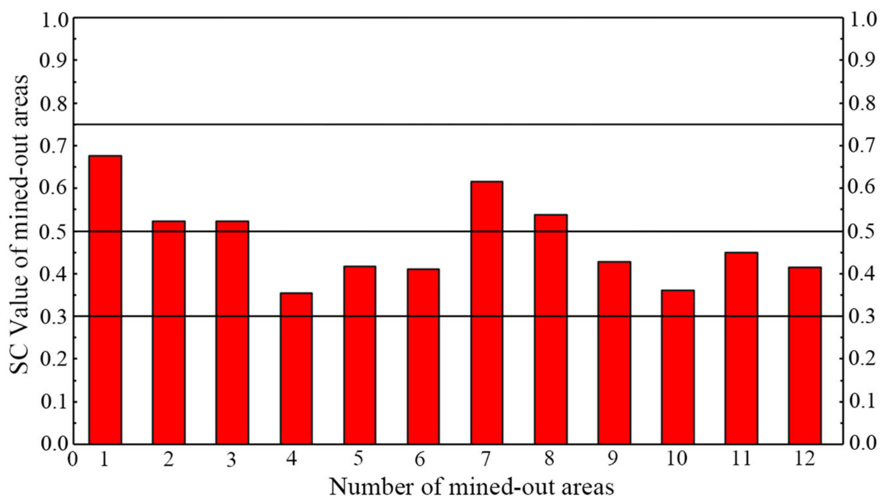

Fig. 7 Stability coefficient (SC) value of the 12 mined-out areas

According to the complementary principle, the second layer indexes (x_A) of the catastrophe theory model can be calculated. And among the 3 values of x_A to select the smallest one, then the SC is given out, as listed in Table 12.

Based on the SC values listed in Table 12, a SC histogram of 12 mined-out areas of the gold mine is shown in Fig. 7.

According to Table 9, the SC values for 301, 302, 303, 405 and 407 mined-out areas ranged from 0.5 to 0.75, i.e., the unstable risks of these 5 mined-out areas are in general rating, and some monitoring steps and treatment plans need to be taken. The SC values for 401, 402, 403, 409, 411, 413 and 501 mined-out areas are ranged from 0.25 to 0.50, i.e., the unstable risks of these 7 mined-out areas are in high rating, and thus some monitoring and treatment methods should be taken immediately.

5 Conclusions

1. Stability assessment of underground mined-out areas is a complex system. In this paper, a complex system model is developed, which is made up by 3 sub-systems of geological factors, engineering factors and management factors.
2. Based on the proposed complex system, the stabilities of 12 typical mined-out areas of the

Table 13 Evaluating result comparison of the two methods and suggested treatment method of mined-out areas in the gold mine

No.	Stope No.	Fuzzy AHP model	Catastrophe model	Suggested treatment method
1	301	II	General	Monitored and sealed
2	302	II	General	Monitored and sealed
3	303	III	General	Backfilled with tailings
4	401	III	High	Backfilled with tailings
5	402	III orII	High	Backfilled with tailings
6	403	II	High	Backfilled with tailings
7	405	II	General	Monitored and sealed
8	407	II	General	Monitored and sealed
9	409	III	High	Backfilled with tailings
10	411	III	High	Backfilled with tailings
11	413	I or III	High	Backfilled with tailings
12	501	II	High	Backfilled with tailings

gold mine in the Altai city are evaluated by using the fuzzy AHP model and the catastrophe theory model. The obtained results show that 9 mined-out areas out of 12 have the same stability rating assessed by these two models, only 3 mined-out areas (i.e., 303, 403 and 501 mined-out areas) have a small difference of stability rating. Hence, for the purpose of making treatment plan for the mined-out areas and arranging mining operations at deep levels in the gold mine, the obtained stability assessment results for the mined-out areas are dependable and helpful. (3) According to the stability assessment results of the mined-out areas in the gold mine, those mined-out areas should be monitored by using some remote controlling equipment. The mined-out areas are suggested to be treated on time by backfilling with mill tailings or waste rocks. Evaluating result comparison of the two methods (i.e., the Fuzzy AHP model and the Catastrophe model) as well as the suggested method for dealing with the mined-out areas in the gold mine are demonstrated in Table 13.

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