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A risk assessment method to quantitatively investigate the methane explosion in underground coal mine

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ABSTRACT

Methane explosion in underground coal mine is one of the most deadly hazards to the miners and the surrounding environment. An improved analytical hierarchy process (IAHP) was developed to investigate the influencing factors of methane explosion quantitatively. IAHP was validated by statistical data, showing its advantages in reducing bias. Both IAHP results and statistical data indicated that electrical spark, blasting and friction spark were the leading ignition sources. Blasting operation, digging process, explosive charge and gas detect procedure showed the highest influencing weights to methane explosion. A case/example was provided to determine the safety level of an underground coal mine. Implementations were provided to avoid methane explosion in underground coal mines, such as avoiding high methane concentration (10–15 vol.%), taking care of rocks with more than 30% quartz and larger than 70 μm particle size, and using high melting point tool/equipment, and limiting coal pick speed within 1.5 m/s.

1. Introduction

Methane has been considered as one of the most deadly hazards for underground coal mining due to its explosion risk to both the miners and environment (Mahdevari et al., 2014; Saleh and Cummings, 2011). A statistic study indicated that 18 out of 26 extra-large coal mine accidents during 1949–2009 in China were caused or partly caused by gas explosions (Wang et al., 2014a; Wu et al., 2011). Flammable limit of methane is 5.0–15.0 vol.% in the air with a minimal ignition temperature of 540 °C (Eckhoff, 2005). One of the principles in avoiding methane explosion in underground coal mines is to maintain its concentration out of this range. Sometimes it is very difficult to achieve this. For example, at a typical gassy coal mine, ventilation air may contain 0.1–1% methane, whereas gas drained from the seam before mining can contain 60% to more than 95% methane depending on the presence of other gasses in the coal seams (Karacan et al., 2011).

Risk assessment is critical to avoid methane explosion as it can identify and eliminate the existing hazards in coal mines, which can provide guidance to help risk managers to develop/revise coal mine regulations. Risk assessment is well-accepted tool within the Australian minerals industry, with a significant history of applying the related techniques over recent years (Evans et al., 2007). Assessment of possible risks and determination of proper risk management methods for mining applications become a requirement to decrease the costs caused by those hazards, which ultimately satisfies the legal requirements to improve the working environment (Sari, 2002). The significances of risk

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assessment have been proven by a major safety improvement in the Australian mining industry during the past 15 years (Joy, 2004).

However, risk assessment of methane explosion is complicated. This is because the explosion would be triggered by many sources under a broad explosion range and very low minimum ignition energy. Open flame is an obvious ignition source, such as smoking, welding, smoldering coal fire and dynamite fire (Garcia-Torrent et al., 2012). Besides the open flame, sparks produced during mining process is an inconspicuous aspect, which has posed a serious threat to the safety of underground coal mines and caused many catastrophic explosions (Wang et al., 2014b). Between 2000 and 2005, the number of frictional ignitions reported in underground coal mines in the United States was between 34 and 60 per year (Krog and Schatzel, 2009). Eliminating those ignition sources are one of the two basic principles to avoid methane explosion (Brune et al., 2007).

The human factor is also an important aspect for the risk assessment of underground coal mine methane explosion. Thirteen major accidents during 2000 and 2009 in China are because of human errors (Wu et al., 2011). During the past few decades, mining processes were greatly improved, which are due to the improvement of both mining technologies and risk assessment methods. Although technologies improvement is helpful, an increasing percentage of human factors were shown in the explosion accidents. For example, a statistical study showed that although the accidents between 2001 and 2010 in China were reduced by 31.13% compared with data from 1980 to 2000, the proportion of accidents caused by mismanagement rose by 32.38% (Chen et al., 2013). Those accidents have aroused the needs of appropriate risk assessment methods.

Among those risk assessment methods, fault tree analysis (FTA) and analytical hierarchy process (AHP) are two excellent approaches for the risk assessment of coal mines. Zhang and Lowndes (2010) used a coupled FTA and artificial neural network model to improve the prediction of the potential risk of coal and gas outburst events during the underground mining of thick and deep coal seams. Lang and Zhou (2010) used AHP to analyze the influential factors that led to the spontaneous combustion of coal seams. However, FTA and AHP have their shortcomings in the practical applications. For example, FTA provides a limited quantitative analysis if the occurrence probabilities of those basic events are unknown and also the assessment outcomes of AHP are much dependent on personal judgments.

Under the fact of the limitations of FTA and traditional AHP, an improved analytical hierarchy process (IAHP) was then developed and applied for the risk assessment of methane explosion in an underground coal mine. A case/example was provided to determine the safety level of an underground coal mine and computer code was also developed to benefit the relevant practical applications. This study provides a technical guide to coal mine risk management and other relevant risk assessment.

2. Mathematical model of IAHP

2.1. *Principle theory*

Fig. 1 shows the calculation procedure of IAHP, which generally consists of two parts. The first part is based on the fault tree, which is to obtain the influencing weights of various factors on the underground coal mine methane explosion. Similarly, the objective of the second part is to obtain the influencing weights again, but which is based on traditional analytical hierarchy process. The two influencing weights for different factors are then combined by their weighting coefficients, which are dependent on the calculation processes of those two parts.

IAHP shows two advantages when comparing with traditional AHP: (i) the AHP model constructed by fault tree tends to provide a more comprehensive description of the whole calculation process, comparing to the traditional AHP model solely built from the scratch; and (ii) IAHP can reduce the biases

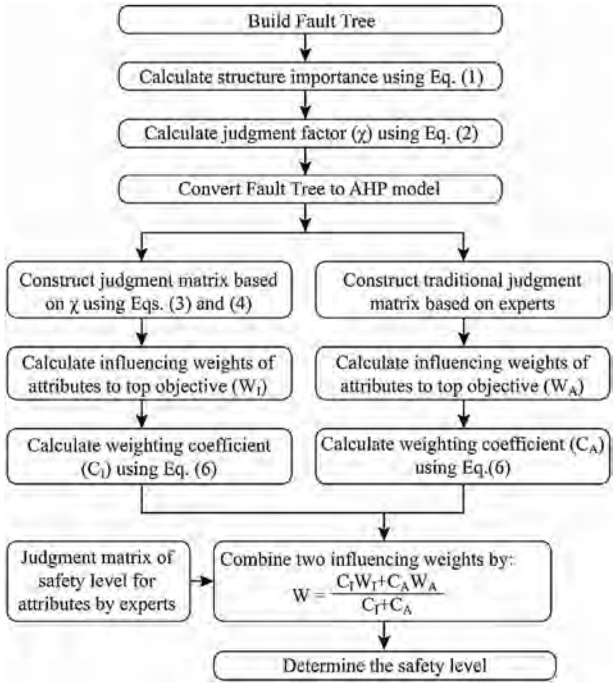

Fig. 1 – The calculation procedure of IAHP.

caused by the experts during the judgment processes after combining the results from the traditional AHP model with the analyzed outcomes based on fault tree.

2.2. *Fault tree analysis*

FTA is based on the fault tree built by deductive analysis method from the top event to the bottom basic events, as shown in Fig. 2. The importance of each basic event to the top event can be reflected by the special structure, which is called structure importance. To calculate the structure importance, it should be assumed that the occurrence probabilities of these basic events are the same. This assumption was taken which is because it is difficult to have an accurate estimation of the failure rate of an individual event or the probability of occurrence of undesired events due to a lack of sufficient data. It has been largely validated and taken to obtain minimal cut sets and minimal path sets during the quantitative analysis of fault tree (Markowski and Kotynia, 2011; Volkanovski et al., 2009; Yang et al., 2013). The structure importance can be obtained by

$$I = \frac{1}{n}\sum_{k=1}^{m}\frac{1}{R_k} \tag{1}$$

where I is the structure importance of basic event; n is the number of minimal cut (or path) sets of the fault tree; m is the number of minimal cut (or path) sets containing the target basic event; and R_k is the number of basic events in the analyzed minimal cut (or path) sets.

The reason of using structure importance is because it can reflect the importance and influence of basic events to top event well (Luo et al., 2013). Furthermore, it is often very difficult to estimate precise failure probabilities of individual components or failure events (Suresk et al., 1996). The usual way is to carry out the failure collection and analysis based on statistic data (Dhillon, 1999). However, the typical accidents data are included, but not for some specific events. To solve

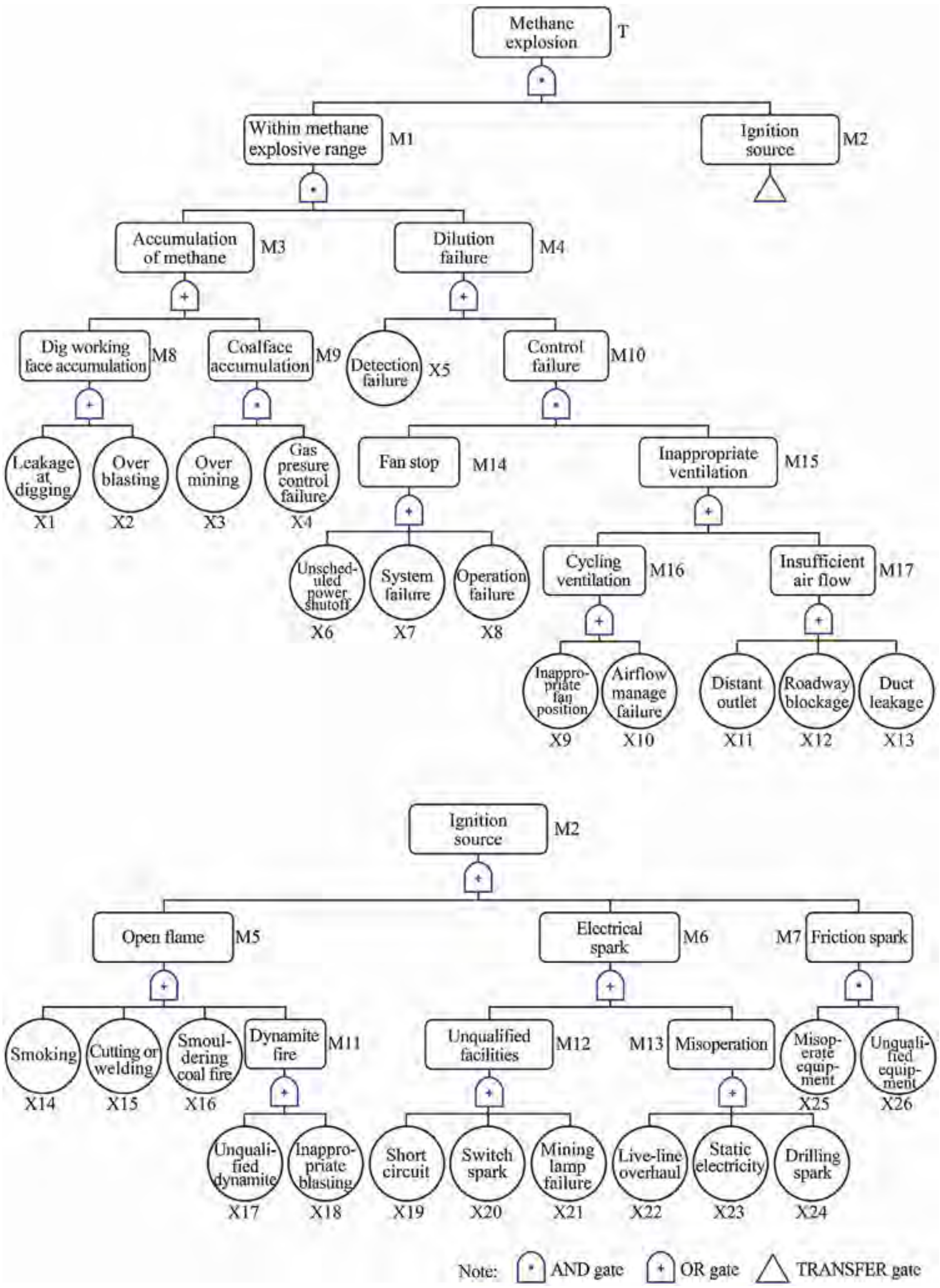

Fig. 2 – Fault tree regarding methane explosion in underground coal mine.

the problem, one alternative way is based on expert elicitation and fuzzy set theory (Dong and Yu, 2005). The obtained occurrence probabilities are also subjective based on experts' judgment. The structure importance from the fault tree can then be well used to reflect the importance and influence of those basic events to the top event without including more bias judgment.

Those structure importance obtained by Eq. (1) are fractions, which will be used for the construction of AHP model. To benefit the construction of AHP model, those fractions are converted to integers by,

$$\chi(i) = I_i \cdot M \tag{2}$$

where χ is the judgment factor of different basic events; M is the least common denominator of all the structure importance.

2.3. Analytic hierarchy process

Three levels can be found in a traditional AHP model, including top objective level, middle factor level, and bottom alternative level. This structure is similar to that of the fault tree. For example, the top objective level in traditional AHP model shows the same function as the top event in fault tree, while those alternatives at the bottom level of AHP model act the same like those basic events in the fault tree. The middle factors are the connections between the top and bottom levels.

Based on the similar structures, it is then possible to convert the fault tree to traditional AHP model. This can be fulfilled through three steps. During the first step, it is easy to convert the top event in fault tree to the top objective in the traditional AHP model by adjusting the description. For example, shown in Fig. 3, the top event "methane explosion" can be converted to "avoid methane explosion in underground coal mine". Following the same way, the second step is converting

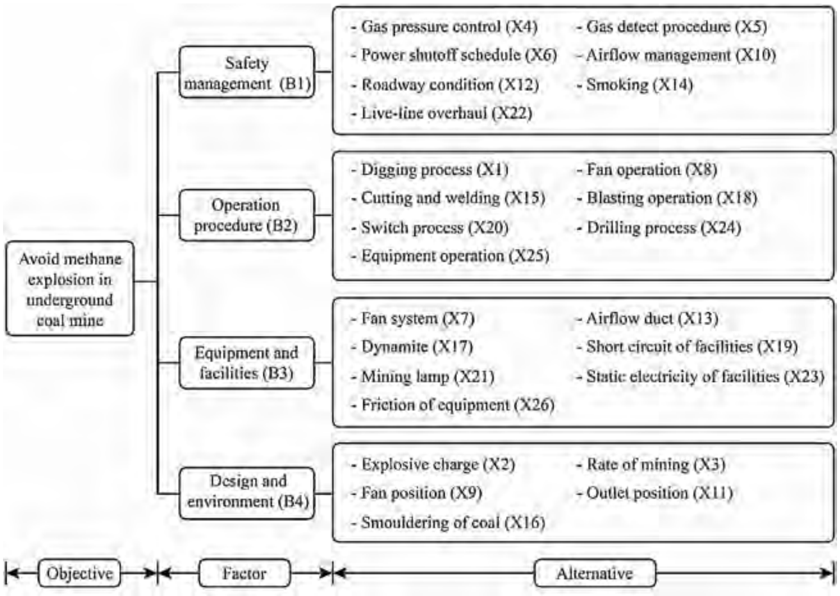

Fig. 3 – AHP model converted from fault tree.

those basic events in fault tree to the bottom alternatives at the bottom level of traditional AHP model. The third step is to group those bottom alternatives, constructing the middle factors in the AHP model.

The pair-wise comparison is then used to construct the judgment matrix for quantitative analysis. For the bottom alternatives, the pair-wise comparison can be made directly,

$$\begin{cases} a_{ij} = \dfrac{\chi(i)}{\chi(j)}, \text{if} \chi(i) \geq \chi(j) \\ a_{ji} = \dfrac{\chi(j)}{\chi(i)}, \text{if} \chi(i) < \chi(j) \end{cases} \tag{3}$$

where a_{ij} or a_{ji} is the element in the judgment matrix, which should be rounded to integers; and i and j denote to the row and column numbers, respectively.

For the middle factors in AHP model, they cannot be compared directly. Before that, the judgment factors of those bottom alternatives belong to them should be summed up first, and the judgment matrix is then built by the pair-wise comparison by the summed judgment factors of two middle factors.

$$\begin{cases} b_{ij} = \dfrac{\sum_{i=1}^{m}\chi(i)}{\sum_{j=1}^{n}\chi(j)}, \text{if} \sum_{i=1}^{m}\chi(i) \geq \sum_{j=1}^{n}\chi(j) \\ b_{ji} = \dfrac{\sum_{j=1}^{n}\chi(j)}{\sum_{i=1}^{m}\chi(i)}, \text{if} \sum_{i=1}^{m}\chi(i) < \sum_{j=1}^{n}\chi(j) \end{cases} \tag{4}$$

where b_{ij} or b_{ji} is also the element of the judgment matrix, which should also be rounded to integers; and m and n are the numbers of bottom alternatives under two middle factors, respectively.

2.4. *Reducing bias by IAHP*

Based on Eqs. (3) and (4), influencing the weight of each bottom alternative to the top objective can be calculated. As mentioned above, calculation procedure of IAHP consists of two parts. Based on those two parts, the influencing weights of bottom alternative can be obtained by AHP model constructed by both fault tree and traditional methods. The influencing weights in IAHP, represented by W, can be obtained by combining these two,

$$W = \frac{C_I W_I + C_A W_A}{C_I + C_A} \tag{5}$$

where W_I and W_A are the influencing weights by fault tree and traditional AHP model, respectively; and C_I and C_A are the weighting coefficients for these two set of influencing weights.

The calculation of W_A is exactly the same with traditional AHP, following several procedures (Saaty, 2008) such as defining the problem and determining the kind of knowledge sought, structuring the decision hierarchy from the top objective to bottom alternatives, constructing a set of pairwise comparison matrix based on experts' opinion, and obtaining the W_A from the comparison matrix. The obtaining of W_I is similar to those traditional AHP. The only difference is the third step, namely constructing a set of pairwise comparison matrix, which is based on the structure importance obtained from fault tree analysis, but not experts. The detailed procedures can refer to Fig. 1.

Weighting coefficients of C_I and C_A are dependent on both the scale factor and consistency ratio factor,

$$C = F_s + F_{CR} \tag{6}$$

where F_s is the scale factor, which is determined by the numerical scale used during the construction of judgment matrix; and F_{CR} is the consistency factor, which is calculated based on the consistency ratio of the judgment matrix.

The numerical scale is used during the third step of AHP, namely constructing a set of pairwise comparison matrix. In the comparison matrix, two alternatives/factors are compared with quantitative description. The maximal value to describe

Table 1 – Usage of numerical scale of 9 for quantitative comparison.

Option	Numerical value
Equal	1
Marginally strong	3
Strong	5
Very strong	7
Extremely strong	9
Intermediate values to reflect fuzzy inputs	2, 4, 6, 8
Reflecting dominance of second alternative compared with the first	Reciprocals

the comparison is called numerical scale. Table 1 shows the usage of the numerical scale of 9 (Bhushan and Rai, 2004).

F_s is calculated based on the numerical scale. The numerical scale of 1–9 is found to be the most reliable one for judgment matrix (Saaty, 1977). However, many other scales have been utilized. For those numerical scales, their scale factors have been obtained previously in our study (Shi et al., 2009), shown in Table 2. Those missed values can be obtained by interpolation.

The F_{CR} is obtained by consistency ratio of a judgment matrix, which is expressed by,

$$F_{CR} = 1 - \frac{CR - CR_{min}}{CR_{max} - CR_{min}} = 1 - 10CR \tag{7}$$

where CR_{max} and CR_{min} are the maximum and minimum of consistency ratios, namely 0.1 and 0, respectively; and CR is the consistency ratio, which can be given by,

$$CR = \frac{\sum_{j=1} \alpha_j CI_j}{\sum_{j=1} \alpha_j RI_j} \tag{8}$$

where a_j is the influencing weight of middle factors; RI is the random consistency index; CI is the consistency index, which can be obtained by,

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{9}$$

where n is the size (or order) of the judgment matrix; and λ_{max} is the maximum eigenvalue of the matrix.

3. Results and discussion

3.1. *Build a fault tree*

A fault tree was built to address the factors resulting in methane explosion in the underground coal mine. The top event is methane explosion, which is followed by a logic analysis which deduces the reasons for the top event using logic gates (AND, OR). Structure importance of these basic events to the top event is reflected by their appearances in minimal cut sets or minimal path sets.

Methane explosion happens when two conditions are achieved, including the presence of methane and ignition source. Two middle events followed by the top event are within methane explosive range (M1) and ignition source (M2). A high methane concentration happens when both accumulation of methane (M3) and dilution failure (M4) exist. Methane is released from seams under ambient pressure at dig working face (M8) or coal face (M9). The amount of methane generated depends on the productivity of the coal mine, the gassiness of the coal seam and any underlying and overlying formations, operational variables and geological conditions (Karacan et al., 2011). These aspects can be reflected by several basic events, such as leakage at digging, over blasting, over mining and gas pressure control failure.

Besides the methane accumulation, dilution failure is another aspect for high methane concentration. The dilution failure is much due to detection failure in the first place and the subsequent control failure (M10) if the detection is successful. The above middle events (M8–M10) can be deduced further by middle event or basic event.

Three ignition sources would possibly ignite the methane–air mixture in underground coal mines, including open flame (M5), electrical spark (M6) and friction spark (M7). The open flame contains the fire due to smoking, cutting/welding, the heat caused by coal smoldering process, or the obvious one such as dynamite fire. Except the coal smoldering, the other three ignition sources are much related to the coal mine management. For example, blasting procedure against the regulation would contribute to the incendive ignition energy for methane mixture. The produce of electrical spark is closely tied up with facility and operation during the mining process. For example, the mining lamp could fail with two leading causes, such as leaking acid of battery (60%) and physical damage (25%) (Lewis and Gagg, 2010). The friction spark is then relevant to the usage of equipment, such as facility-to-rock or facility-to-facility friction.

Details of fault tree regarding methane explosion can be deduced into 26 basic events, seen in Fig. 2. Structure importance of these 26 basic events can be obtained by both minimal cut sets or minimal path sets. A minimal cut set represents a unique combination of component failures that would result in the top event, whilst a minimal path set, which can be transferred from fault tree by replacing the gates in an opposite way, is a combination of basic events could ensure the non-occurrence of the top event.

The number of minimal cut sets for this fault tree is 576. It is very difficult to gain the structure importance of all 26 basic events under such a large number of minimal cut sets. In an easier way, this fault tree can be converted to success tree in which the number of minimal path sets would be largely reduced to benefit the calculation. During this conversion, each basic event in a success tree should be assigned with an apostrophe, representing an opposite event. The minimal paths of the fault tree can be obtained:

$$P_1 = (X'_1, X'_2, X'_3) \tag{10a}$$

Table 2 – Scale factor (F_s) of numerical scale.

Scale	3	5	7	9	11	13	15	17	18	26
F_s	0.4610	0.7597	0.9286	1.000	0.8506	0.7468	0.6948	0.6234	0.5844	0.4091
Scale	30	34	36	44	52	60	68	75	85	90
F_s	0.3831	0.3182	0.2922	0.2078	0.1688	0.1429	0.0909	0.0779	0.0325	0

Table 3 – Structure importance and judgment factor of basic events.

Basic event	X'_1	X'_2	X'_3	X'_4	X'_5	X'_6	X'_7	X'_8	X'_9	X'_{10}	X'_{11}	X'_{12}	X'_{13}
Structure importance	1/9	1/9	1/18	1/18	5/72	1/24	1/24	1/24	1/36	1/36	1/36	1/36	1/36
Judgment factor	8	8	4	4	5	3	3	3	2	2	2	2	2
Basic event	X'_{14}	X'_{15}	X'_{16}	X'_{17}	X'_{18}	X'_{19}	X'_{20}	X'_{21}	X'_{22}	X'_{23}	X'_{24}	X'_{25}	X'_{26}
Structure importance	1/36	1/36	1/36	1/36	1/36	1/36	1/36	1/36	1/36	1/36	1/36	1/72	1/72
Judgment factor	2	2	2	2	2	2	2	2	2	2	2	1	1

$$P_2 = (X'_1, X'_2, X'_4) \tag{10b}$$

$$P_3 = (X'_5, X'_6, X'_7, X'_8) \tag{10c}$$

$$P_4 = (X'_5, X'_9, X'_{10}, X'_{11}, X'_{12}, X'_{13}) \tag{10d}$$

$$P_5 = (X'_{14}, X'_{15}, X'_{16}, X'_{17}, X'_{18}, X'_{19}, X'_{20}, X'_{21}, X'_{22}, X'_{23}, X'_{24}, X'_{25}) \tag{10e}$$

$$P_6 = (X'_{14}, X'_{15}, X'_{16}, X'_{17}, X'_{18}, X'_{19}, X'_{20}, X'_{21}, X'_{22}, X'_{23}, X'_{24}, X'_{26}) \tag{10f}$$

Based on Eqs. (1) and (2), the structure importance and judgment factors of these 26 basic events can be obtained, as shown in Table 3.

3.2. *Construct AHP model based on fault tree*

AHP model can be constructed based on these 26 basic events from fault tree by adjusting them neutrally. It is known that these 26 basic events can be classified into four groups (factors at the middle level of AHP model), including safety management (B1), operation procedure (B2), equipment and facilities (B3), and design and environment (B4). For example, alternatives such as digging process and blasting operation can be classified into operation procedure, while the fan system and airflow duct are under the factor of equipment and facilities. Hence, these four factors can construct the middle level in AHP model. The converted basic events are the alternatives at the bottom level. All these factors and alternatives serve as the objective of avoiding methane explosion in underground coal mines.

The AHP model converted from fault tree can be seen in Fig. 3. This figure has been rotated 90 °C anticlockwise for a better display. It can be seen that it contains three levels, including the objective at the top level, four factors at the middle level and 26 alternatives at the bottom level.

Judgment matrix for these four factors at the middle level can be constructed based on Eq. (4) and Fig. 3. It is known that the factor of safety management (B1) contains seven alternatives with a summation of judgment factor of 20. Similarly, the judgment factors of B2, B3 and B4 are 20, 14 and 18, respectively. During the construction, a pair-wise comparison of judgment factors among these four factors is taken using Eq. (4). Taking a_{12} in the judgment matrix for example, it is obtained that a_{12} is 1, and a_{21} is the multiplicative inverse of a_{12}, which is 1 as well. The rest parts of the judgment matrix can be gained following the same rule. The related judgment matrixes can be seen in Appendix C.

The judgment matrix at the bottom level can be obtained by the same way. Taking the seven alternatives below B1 for example, the judgment matrix can be calculated by pair-wise comparison of judgment factors among these seven alternatives. For instance, a_{14}, can be obtained by comparing the judgment factor of X4 and X10, which is 2. The related judgment matrix for alternatives belonging to each factor can be seen in Appendix C.

The judgment matrixes of the other three factors can be obtained one by one, and the details can be seen in Appendix C. The influencing weights of these 26 alternatives to the top objective can be then obtained, as shown in Fig. 5.

3.3. *Construct traditional AHP model*

For traditional AHP, the evaluation process is the same with that in Section 3.2, except that the judgment matrices are constructed by personal judgment, i.e. experts in the area. The obtaining of experts' judgment was following the usual three steps in traditional AHP method (Saaty, 2008). Three experienced experts were invited from coal industry. Before the process, factors and alternatives at middle and bottom levels of the AHP model were introduced, respectively. During the first step, three experts carried out pairwise comparisons among those 26 alternatives at a bottom level within four groups and then those four factors at the middle level of AHP model. During the second step, consistency of the obtained judgment matrices was analysed, following Eqs. (8) and (9). If the matrix did not achieve the consistency requirement, the expert was asked to repeat the first step until the requirement was fulfilled. The combination of three experts' judgment was taken place during the third step.

Appendix C shows the judgment matrices of four factors at the middle level. It was constructed by averaging the results of three experts. For the third step during the construction of those judgment matrices, Several possibilities are considered for averaging. First, these three experts have the same judgment about a comparison, considering one is more important or equal than another. For example, if the three experts give the scales of 2, 3 and 4 for the comparison of D1 and D2, a scale of 3 for this comparison is then obtained by simply averaging these three scales. It means D1 is moderately preferred to the D2.

For the second possibility, judgment of one expert is different from the other two. Under this circumstance, the averaging process is then taken by the majority. For example, three experts give scales of 1/3, 2 and 4 for the comparison between D1 and D2, which means the first expert considered the D2 is moderately preferred comparing to D1. The scale for this comparison (D1/D2) is 3 by averaging the two experts holding the same opinion that D1 is more preferred than D2.

The judgment matrix at the bottom level can be constructed by pair-wise comparison of those alternatives following the same way. The details can be seen in Appendix C. It should be noticed that, during the construction of all the judgment matrices, consistency check (using Eq. (9)) was carried out to ensure they are consistent. If the consistency check was unsuccessful, the experts were then requested again to adjust their matrices to avoid any error during the pair-wise comparison, until the consistency check was successful. Based on the judgment matrices from the three experts, influencing weights of these 26 alternatives can be obtained, as shown in Fig. 5.

3.4. *Sensitivity analysis*

For the sensitivity analysis of AHP model, three methods are usually used (Leonelli, 2012), namely one-at-a-time, probabilistic simulations, and mathematical modelling algorithms. Considering one-at-a-time algorithm can analyse only one element at a time and mathematical modelling algorithm just allows a chart for up to three elements, the probabilistic simulation was then utilized to conduct the sensitivity analysis in this study.

Monte-Carlo method was used during the probabilistic simulation, while in every iteration the weights of four factors at the middle level of AHP model were replaced by random numbers following Gama distribution and then the rankings of these factors were calculated and registered. Before the calculation, those random numbers were converted to AHP scale:

$$a_{ij} = \begin{cases} \frac{1}{2-R}, ifR \leq 1 \\ R, ifR > 1 \end{cases} \quad (11)$$

Fig. 4 shows the outcomes of sensitivity analysis based on this method for middle level of AHP models obtained by fault tree and experts, respectively. In this figure, the Y axis shows the four factors and X axis represents their rankings. The upper and lower caps show their best and worse rankings, while the horizontal lines inside the box are their average rankings, and the upper and lower sides of the box show the 25% and 75% of the ranking results.

It can be known from Fig. 4 that regarding the sensitivity analysis result for AHP model obtained by fault tree, the average, best and worse rankings for these four factors are the same except the 25% and 75% rankings. For the model constructed by experts, the average rankings are consistent with

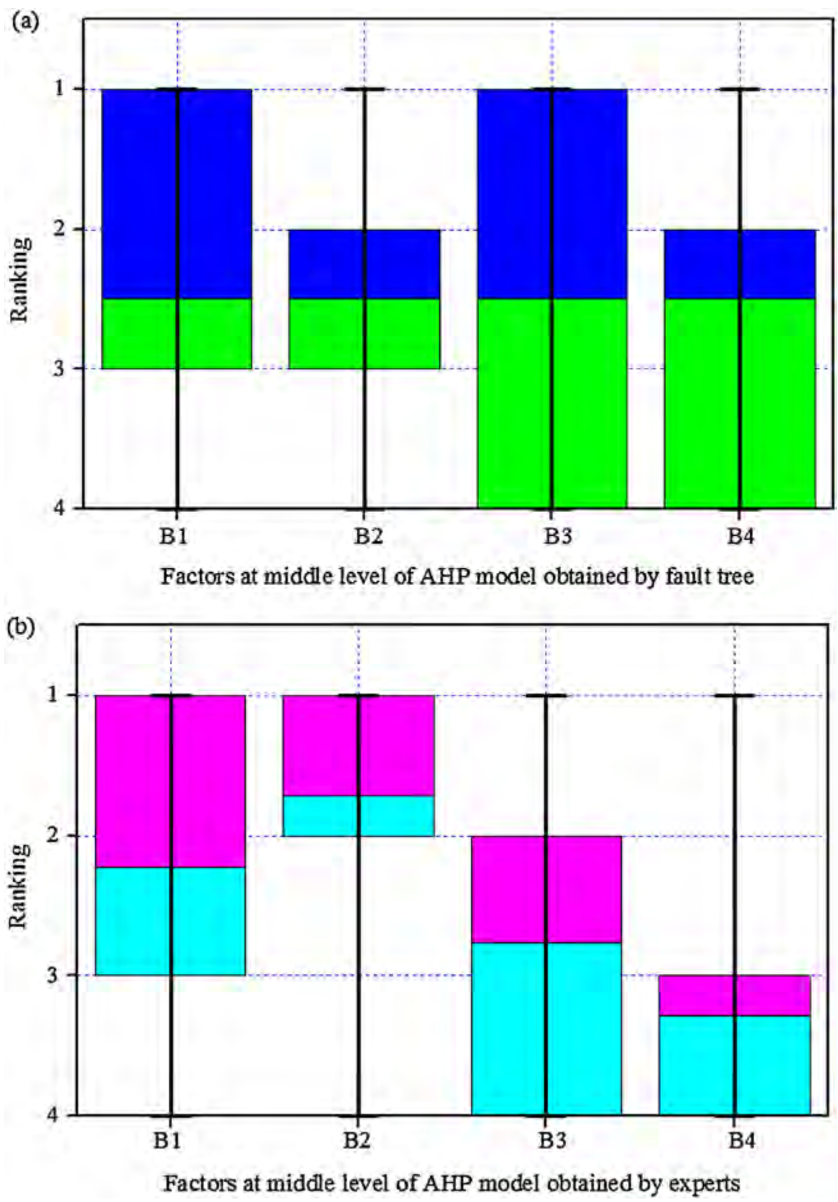

Fig. 4 – Sensitivity analysis of the middle level of AHP models obtained by fault tree (a) and experts (b). The upper and lower caps show their best and worse rankings, while the horizontal lines inside the box are their average rankings, and the upper and lower sides of the box show the 25% and 75% of the ranking results.

their influencing weights. For example, a factor with a higher influencing weight represents a bigger average ranking during the sensitivity analysis.

3.5. *Determine the key factors*

Weighting coefficients (e.g., C_I and C_A) are used to combine the influencing weights from two approaches, namely fault tree and traditional AHP. They contain two parts: the scale factor (F_s) and consistency ratio factor (F_{CR}), as shown in Eq. (6).

F_s is determined by the usage of the judgment scale. For those AHP models constructed by fault tree, the maximal judgment scale is used at the middle level, which is 20 for both safety management (B1) and operation procedure (B2). For traditional AHP, a 1–9 scale is used for the construction of AHP model by experts. According to Table 2, F_s for these two methods are 0.5406 and 1.0, respectively.

Based on Eqs. (7) and (8), F_{CR} of the AHP model by the fault tree and traditional method are 0.9805 and 0.7843, respectively.

Weighting coefficient for AHP model based on the fault tree can be given by:

$$C_I = F_s + F_{CR} = 1.5211 \quad (12a)$$

And weighting coefficient for the traditional AHP model can be obtained:

$$C_A = F_s + F_{CR} = 1.7843 \quad (12b)$$

Based on Eqs. (5), (9) and (12b), the final influencing weights of these 26 alternatives to the top objective can be obtained, show in Fig. 5. In this figure, the X-axis shows the 26 alternatives and Y axis is the influencing weights of these alternatives to the top objective. The horizontal lines inside those diamonds show the combined influencing weights of the two approaches, and the extension lines with a big head and small head represent the influencing weights obtained from fault tree and traditional AHP, respectively.

It is observed from Fig. 5 that four alternatives have the highest influencing weights, namely blasting operation (X18), digging process (X1), explosive charge (X2) and gas detect procedure (X5). It means these four aspects have a high influence on the methane explosion in underground coal mines. Zheng et al. (2009) received a similar result based on a statistical analysis of coal mine accidents that flame of blasting was the first key ignition source for the explosion of coal dust.

It is also known from Fig. 5 that several alternatives provide different results from the two approaches. For example, influencing weights of blasting operation (X18) are 0.0236 and 0.1528, respectively, for the fault tree and traditional AHP. And weights of explosive charge (X2) decreases from 0.111 to 0.0253 when fault tree is comparing with traditional AHP. All these adjustments are beneficial to reducing the bias during the assessment, which can be seen in the following section.

Based on Fig. 5, it is observed that some alternatives show the similar influencing weights from these three methods. These alternatives include gas pressure control (X4), gas detect procedure (X5), roadway condition (X12), smoldering of coal (X16), dynamite (X17), short circuit of facilities (X19), live-line overhaul (X22), and friction of equipment (X26). Among these 8 alternatives, there are four and three alternatives which can be classified into safety management (B1) and equipment and facilities (B3), respectively. It is known that alternatives in the aspects of safety management and equipment and facilities can be well recognized, with much less bias judgment.

An example of determining the safety level of an underground coal mine can be seen in Appendix A.

4. Validation and implementations

4.1. *Validation*

A statistical study regarding coal mine methane burning accidents between 2000 and 2012 in China was carried out by Xu et al. (2014). In this study, a total of 144 methane burning accidents were analyzed in the aspect of ignition source and location. These accidents have resulted in 440 deaths and 451 injuries. The detailed statistical result can be seen in Fig. 6.

It is observed that IAHP outputs are quite consistent with the statistical results. Fig. 6(a) shows that electrical spark and blasting result in 36% and 28% of the accidents during the period, respectively. As indicated in Fig. 2, alternatives from X14 to X26 are related to ignition sources. And the weighting percentage of electrical spark can be obtained by the summa-

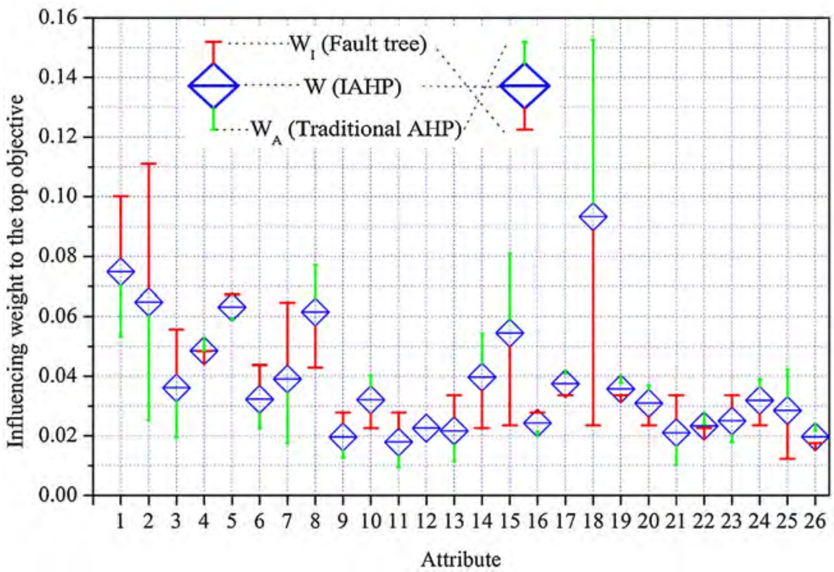

Fig. 5 – A combination of influencing weights of alternatives from two approaches.

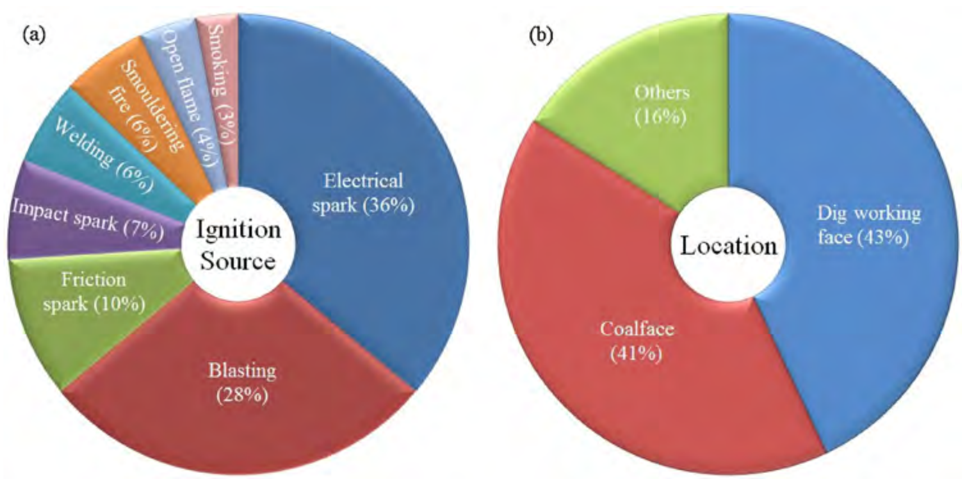

Fig. 6 – A statistical analysis of coal mine methane burning accidents between 2000 and 2012 in China in the aspect of: (a) ignition source; and (b) location (Xu et al., 2014).

tion of influencing weights from those alternatives related to electrical spark and all the ignition sources. It is known from Fig. 2 that five alternatives are relevant to producing electrical spark, namely X19–X24, while X17 and X18 are related to blasting. The weighting percentages of electrical spark and blasting can be then obtained as 36.1% and 28.1%, respectively. The results agree reasonably well with the statistical results of these two aspects, namely 36% and 28%. In addition, the weighting percentage of friction spark is 10.4%, which is also consistent with the statistical result of 10%. The detailed comparisons between statistical results and IAHP outputs can be seen in Table 4.

IAHP shows its advantage in reducing bias judgment. It is known from Table 4 that traditional AHP output shows a quite different result for blasting that its weighting percentage is higher than those of electrical spark. After combining the results from the fault tree, it is observed that the weighting percentages of electrical spark and blasting, namely 36.1% and 28.1%, are quite consistent with the statistical result. It is also observed that IAHP shows the advantage to reducing the biased judgment for all other aspects/alternatives in Table 4. All these adjustments are helpful to approach the judgments to the statistical results.

The reduction of bias judgment is because of the combination of FTA and AHP. The structure importance obtained by fault tree can reflect the importance of basic events to the top event, which is a good way to adjust the biased judgment during AHP. It should also be noticed that we did not use the key importance of basic events as it is difficult to obtain the occurrence probability of these basic events. This is also addressed by Mentes and Helvacioglu (2011) that it is difficult to have an exact estimation of the failure rates of the occurrence of undesired events due to the lack of sufficient data.

IAHP output is also quite consistent with the statistical result in the term of location. Fig. 6(b) (Xu et al., 2014) shows that 43% of the accidents happen at dig working face, while 41% accidents at the coalface. The others locations include coal bunker, roadway, old coal mining area, etc. It is observed from Fig. 2 that alternatives of X1 and X2 are directly relevant to dig working face and X3 and X4 to the coalface. The summation of dig working face and coalface related alternatives are 0.1397 and 0.0846, respectively. It is also consistent with the statistical result that dig working face and coal face takes up 43% and 41% of all the 144 accidents. However, a detailed comparison of percentage between the IAHP output and the statistical result in the term of location seems to be very difficult as it is hard to identify the relevant indirect alternatives for these two locations. For example, roadway blockage (X12) would happen at both dig working face and coalface.

Although IAHP showing it advantage in reducing bias and its output obeys well with the statistical result, some alternatives are overestimated. For example, shown in Table 4, IAHP reduces the weighting percentage of welding (X15) from 14.0% to 11.7%, but the weighting percentage of 11.7% is still a way to go when comparing to the statistical result of 6%. The same phenomenon is applied to smoking (X14) as well. This is probably because of the different definition of some attributions from the statistical study, such as an open flame.

Table 4 – A comparison of weighting percentage for ignition source between IAHP outputs and statistical results.

Ignition source	Alternative	Statistical result (Xu et al., 2014)	Traditional AHP output	IAHP output
Electrical spark	X19–X24	36%	28.6%	36.1%
Blasting	X17, X18	28%	33.4%	28.1%
Friction spark	X25, X26	10%	11.1%	10.4%
Impact spark[a]	–	7%	–	–
Welding	X15	6%	14.0%	11.7%
Smoldering	X16	6%	3.7%	5.2%
Open flame[b]	–	4%	–	–
Smoking	X14	3%	9.4%	8.5%

[a] The impact spark is assumed to be included in friction spark in this study.
[b] Open flame is divided into smoking, cutting/welding, smouldering coal fire and dynamite fire in this study, shown in Fig. 2.

4.2. Implementations

According to previous experimental studies, electrical spark shows a high probability of igniting methane mixture after its presence as the required energy for igniting methane is low. A 40 J electrical spark is reliably enough to ignite methane–air mixture during a board range of methane concentration of 5–13 vol.% (Bai et al., 2011). During the higher side of this range, namely 10–15 vol.%, the mixture is the most dangerous range for underground coal mines as the minimum ignition energy can be reduce sharply, as low as 3–4 mJ (Phuoc and White, 1999). However, most of the mining processes cannot be done without electricity supply. It is one of leading ignition sources for the methane burning/explosion in underground coal mined, which represents about 36% of the accidents according to the results from above analysis. Explosion protection is then significant for all the electrical disconnects with the possible exposure to methane (Dubaniewicz, 2009).

Blasting itself could bring in huge damages for underground coal mines, not to mention its effects on igniting the methane. Specific standards/manuals have been developed to guide blasting in underground coal mines. Blast damage index is one of the methods to evaluate its damage to underground coal mines, based on inputs such as density and tensile strength of rock mass (Dhillon, 2010). Several measures could be useful to ensure a safe blasting in underground coal mines, such as eliminating black power, replacing with safer explosives, following safety requirements, improving blasting techniques and increasing the awareness of hazards (Verakis, 1992). It is also important to consider a range of hazards caused by human errors, such as from mine manager, mine safety personnel, worker's representatives, electrical and mechanical engineers (Cioca and Moraru, 2012).

During the operation of equipment, a high proportional of friction sparks can be produced, such as rock/equipment on rock friction. A much higher temperature of 1100–1550 °C than the ignition temperature of methane (540 °C) was found during a rock-on-rock experiment (Ward et al., 1995). But not all rock can provide enough ignition energy for methane mixture. It is known that only rocks with a high melting point were likely to cause ignitions by the mechanism involving a hot spot, such as those containing appreciable quantities of quartz (Rae, 1963). It can be further specified that rocks which have a more than 30% quartz content and a usually larger than 70 μm particle size showed a high risk of igniting methane (Powell et al., 1975; Trueman, 1985). It is indicated that ignition of methane is more like caused by the transient hot spot produced on the pick after multiple impacts on the rock, but not the burning metal sparks (Eckhoff, 2005; Ward et al., 1995). Steel sparks from single impacts were also unlikely to ignite natural gas/air, but burning particles of titanium, zirconium, magnesium and aluminum can (Eckhoff, 2005).

Equipment is also a critical aspect in preventing the methane ignition/explosion. For example, as the harder aluminum alloy is generally more incendive than softer alloy, it should avoid those harder aluminum alloy equipment and several percents of silicon could worsen the situation (Phillips, 1996). Another way is to examine those equipments regularly, which is because the risk of frictional ignition rises rapidly for worn equipment/tools as they need a higher cutting force or energy (Phillips, 1997). It is also known that new and undamaged cutter picks are extremely difficult, if not impossible, to cause a frictional ignition (Phillips, 1996). High melting point tools are also better as they require a relatively higher energy to form an incendive metal smear on rocks (Blickensderfer, 1975).

Good equipment operations are useful in reducing the probability of methane explosion. The distance and speed of friction during operations are the main influencing factors (Wang et al., 2014b). For example, hot picks are found to be more incendive than cool ones when the coal pick speeds are lower than about 2.83 m/s (Trueman, 1985). It is suggested to reduce the pick speed to 1.5 m/s (preferably 1 m/s) as the cutting speed largely affect the risk of methane ignition (Phillips, 1996). But for those machine tools into rocks, the cutting rate was found to have no direct influence on the probability of methane ignition, and the leading factor is the cutting depth (Trueman, 1985). Some frictional ignition prevention technologies are also mature to reduce the production risk of friction sparks, such as carbide-capped picks and water sprays (Cain, 2003).

The above contents have provided many suggestions to prevent methane explosion, but removing methane from the coal mine is still a key issue to prevent the related explosions. The removal of methane can be prior to, during, and after coal production based on various in-seam and surface-to-mine borehole designs (Karacan et al., 2011). Good ventilation condition is always beneficial to exhaust the methane to the air. Those technologies of mitigating and utilizing methane in coal mines are promising measures not only benefit the reduction of methane but also better usages of methane (Karacan et al., 2011; Su et al., 2005).

5. Conclusions

Methane explosion is one of the fatal incidents in underground coal mines, causing many problems for both human beings and the surrounding environment. An improved analytic hierarchy process (IAHP) was used to investigate the causes for methane explosion, including 26 alternatives divided in the aspect of safety management, operation procedure, equipment and facilities, and design and environment. From the comparisons, it is obtained that IAHP results obey reasonably well the statistical data of accidents in coal mines, showing its advantage in reducing bias of personal judgment comparing to traditional AHP. Both the IAHP and statistical results show that three ignition sources take most part of the sources for methane ignition/explosion, namely electrical spark (36%), blasting (28%) and friction spark (10%). In the aspect of the whole coal mine, four factors were found having the highest influencing weight to methane explosion in underground coal mines, namely blasting operation (influencing weight of 0.093), digging process (0.0749), explosive charge (0.0648) and gas detect procedure (0.0631). Based on IAHP results, an example/case was also provided to obtain the safety level of an underground coal mine, shown in Appendix A.

Several implementations were provided to avoid methane explosion in underground coal mines. It should be especially aware of the upper level of explosion range (i.e. 10–15 vol.% methane) as the minimum ignition energy can be as low as 3–4 mJ. Explosion protection is recommended for all electrical disconnects and equipment. The blasting procedure and charge should follow the relevant guides to avoid over blasting. During mining process, especially at digging working face, the operation should be aware of rock with more than 30% quartz and larger than 70 μm particle size as it is likely to cause ignition by the mechanism involving a hot spot. All the equipment should use high melting point tool as it requires a higher energy to form an incendive metal smear on the rock. It is suggested that coal pick speed should be limited to 1.5 m/s (preferably 1 m/s) to reduce the risk of igniting methane.

Appendix A. An example to obtain safety level by using fuzzy AHP

Fuzzy AHP is used to determine the safety level of an underground coal mine based on the IAHP outputs, namely influencing weights of 26 alternatives to the top objective. In fuzzy AHP, the safety of an underground coal mine can be divided into five levels, including excellence, good, medium, bad and very bad. The marks for these five levels are shown in Table A1.

According to the influencing weights of these 26 alternatives shown in Fig. 4, influencing weights of the four factors (B1–B4) at the middle level can be obtained by summarizing the influencing weight of all the alternatives under them:

$$W_F = (0.2618,\ 0.3755,\ 0.2001,\ 0.1627) \tag{A1}$$

Fig. 4 shows the influencing weight of each alternative to the top objective. To obtain their influencing weights to each factor, all the weights belonged to each factor are normalized:

$$W_{B1} = (0.1854, 0.2409, 0.1236, 0.1228, 0.0865, 0.1517, 0.0891) \tag{A2}$$

$$W_{B2} = (0.1995, 0.1637, 0.1453, 0.2486, 0.0822, 0.0848, 0.0759) \tag{A3}$$

$$W_{B3} = (0.1956, 0.1086, 0.1874, 0.1789, 0.1052, 0.1251, 0.0991) \tag{A4}$$

$$W_{B4} = (0.3982, 0.2216, 0.1205, 0.1101, 0.1495) \tag{A5}$$

An underground coal mine was evaluated by five experts in this area. According to the existing conditions of this coal mine, all the alternatives at the bottom level were evaluated by these five experts one by one to determine which safety level they are in. Taking one alternative for example, if two experts considered a safety level of excellence and the other three considered a level of good, a judgment matrix can be obtained by the percentage located in each safety level:

$$R = (0.4, 0.6, 0, 0, 0) \tag{A6}$$

These five experts provided their judgment on the seven alternatives (X4–X6, X10, X12, X14 and X22) below the factor of safety management (B1), which is:

$$R_{B1} = \begin{pmatrix} 0.2 & 0.8 & 0 & 0 & 0 \\ 0.2 & 0.6 & 0.2 & 0 & 0 \\ 0.8 & 0.2 & 0 & 0 & 0 \\ 0.4 & 0.6 & 0 & 0 & 0 \\ 0.2 & 0.6 & 0.2 & 0 & 0 \\ 1.0 & 0 & 0 & 0 & 0 \\ 0.8 & 0.2 & 0 & 0 & 0 \end{pmatrix} \tag{A7}$$

The other three judgment matrices for operation procedure (B2), equipment and facilities (B3) and design and environment (B4) were obtained by the same way, shown in Appendix C. Fuzzy weight vector for the four factors at the middle level of AHP model can be given by:

$$B = W_i \cdot R_i = \begin{pmatrix} 0.4735 & 0.4610 & 0.0655 & 0 & 0 \\ 0.5178 & 0.3545 & 0.0878 & 0 & 0 \\ 0.7156 & 0.2646 & 0.0198 & 0 & 0 \\ 0.5798 & 0.3316 & 0.0886 & 0 & 0 \end{pmatrix} \tag{A8}$$

where i is the *ith* factor at the middle level of AHP model.

The safety level of this coal mine can be obtained by these judgment matrices provided by five experts and the influencing weights obtained through IAHP:

$$F = S \cdot (W \cdot B)^T = 88.60 \tag{A9}$$

where S is the vector of safety marks, and a vector (95, 85, 75, 65, 55) was utilized to determine the safety level in this study, obtained from Table A1.

From the above analysis, it is observed that the mark for this underground coal mine is 88.60. According to Table A1, the safety level of this coal mine is good. To benefit the whole calculation process of IAHP, a computer code based on MATLAB was developed and the details can be seen in Appendix C.

Table A1 – Safety level of underground coal mine.

Safety level	Excellence	Good	Medium	Bad	Very bad
Mark	≥90	90–80	80–70	70–60	<60

Appendix B. The MATLAB code of IAHP

```
function iahp
%IAHP is an improved analytic hierarchy process (IAHP) which adopts the merits of
%both fault tree analysis (FTA) and traditional analytic hierarchy process (AHP).
%
% The modelling inputs contain G, A1, A2, B1, B2, R, J. The details can be seen
% in the M file named iahpdata, shown in Appendix C.
%
% G is the matrix of alternatives at the bottom level of AHP model. For
% example, in this paper, the 26 alternatives can be classified into four
% groups, including (X4, X5, X6, X10, X12, X14, X22), (X1, X8, X15, X18,
% X20, X24, X25), (X7, X13, X17, X19, X21, X23, X26) and (X2, X3, X9, X11,
% X16). So the G can be written as a matrix of [4 5 6 10 12 14 22; 1 8 15
% 18 20 24 25; 7 13 17 19 21 23 26; 2 3 9 11 16 0 0]. Please be noticed if
% there is any absence, use the zero in the matrix.
%
% A1 and A2 are 2D matrix, which are the judgment matrix for objective at
% the top level constructed by fault tree and experts, respectively.
%
% B1 and B2 are MATLAB cell, which are the judgment matrix for each factor at
% the middle level by fault tree and experts, respectively. For example,
% B1{1} represents the judgment matrix of Safety Management (B1) constructed
% by fault tree, shown in Table 4. The details can be seen in Section 3.2
% and 3.3 of this paper.
%
% R is a MATLAB cell too, containing the judgment of several experts on the
% existing conditions of a system, shown in Appendix A. The format of R
% is similar to B1 and B2. For example, R{1} represents the judgment matrix
% of experts for factor named Safety Management (B1).

% J is the maximal judgment factor for the middle level of AHP model
% constructed by fault tree. The details can be seen in Eq. (4).

iahpdata;% The input, please see the MATLAB file in Appendix C.


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% BASIC
INFORMATION %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
NG=size(G,1); % Number of factors at the middle level
fori=1:NG
NA(i)=size(B1{i},1);% Number of alternatives under each factor
end
```

```
%%%%%%%%%%%%%%%%%%%%%%%%% JUDGMENT MATRIX
CALCULATION %%%%%%%%%%%%%%%%%%%%%%%%%
[W0, Lamda0, CI0, CR0]=ahp(A1);% Top level of AHP model by fault tree
if CR0>0.1
fprintf(2, 'Consistency Check of A1 is FAILED!\n\n');
end

[W0(2,:), Lamda0(2), CI0(2), CR0(2)]=ahp(A2);% Top level of AHP model by experts
if CR0(2)>0.1
fprintf(2, 'Consistency Check of A2 is FAILED!\n\n');
end

fori=1:NG% Middle level of AHP model by fault tree
    [W1{i}, Lamda1(i), CI1(i), CR1(i)]=ahp(B1{i});
if CR1(i)>0.1;
fprintf(2, 'Consistency Check of B1{%d} is FAILED!\n\n', i);
end
end

fori=1:NG% Middle level of AHP model by experts
    [W2{i}, Lamda2(i), CI2(i), CR2(i)]=ahp(B2{i});
if CR2(i)>0.1;
fprintf(2, 'Consistency Check of B1{%d} is FAILED!\n\n', i);
end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% WEIGHTS
CALCULATION %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
G1=G';
G1(G1==0)=[];% Order of weights

W1{NG+1}=[];% Weights of alternatives by fault tree
fori=1:NG
W1{NG+1}=[W1{NG+1},W1{i}*W0(1,i)];
end

W2{NG+1}=[];% Weights of alternatives by experts
fori=1:NG
W2{NG+1}=[W2{NG+1},W2{i}*W0(2,i)];
end

fori=1:size(G1,2)% Sequencing the weights
WI(i,1)=W1{NG+1}(find(G1==i));
WA(i,1)=W2{NG+1}(find(G1==i));
end
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% COMBINE
WEIGHTS %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Fs1=SF(J);% Scale factors of AHP model by fault tree
Fs2=SF(9);% Scale factors of AHP model by experts

RI=[0 0 0.58 0.90 1.12 1.24 1.32 1.41 1.45 1.49 1.51];% Table 2
fori=1:NG
RI1(1,i)=RI(1,size(B1{i},1));
RI2(1,i)=RI(1,size(B2{i},1));
end
FCR1=1-10*(W0(1,:)*CI1')/(W0(1,:)*RI1');% Consistency Ratio Factor
FCR2=1-10*(W0(2,:)*CI2')/(W0(2,:)*RI2');

CI=Fs1+FCR1;% Weighting coefficient of AHP model by fault tree
CA=Fs2+FCR2;% Weighting coefficient of AHP model by experts

W=(CI*WI+CA*WA)/(CI+CA);% Combination, seen in Eq. (5)


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% FUZZY
AHP %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
WF(1,1:NG)=0;
fori=1:NG
for j=1:NA(i)
      WF(1,i)=WF(1,i)+W(G(i,j));% Eq. (A1)
WB(i,j)=W(G(i,j));
end
   WB(i,:)=WB(i,:)/sum(WB(i,:));% Eqs. (A2) to (A5)
end

fori=1:NG
B(i,:)=WB(i,1:NA(i))*R{i};% Eq. (A8)
end

F=[95 85 75 65 55]*(WF*B)';% Final mark
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
OUTPUT %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fprintf('\n                    The Output of IAHP model              \n');
fprintf('
__________________________________________________________________\n');
fprintf('   Alternative          WI            WA             W     \n');
fori=1:sum(NA)
fprintf('      X%2d            %1.4f          %1.4f          %1.4f   \n', i, WI(i), WA(i), W(i));
end
fprintf('   ---------------------------------------------------------------\n');
fprintf('   CI of AHP model by fault tree: ');
fori=1:NG
fprintf('  %1.4f  ',CI1(i));
end
fprintf('\n',CI1(i));
fprintf('   CI of AHP model by experts: ');
fori=1:NG
fprintf('  %1.4f  ',CI2(i));
end
fprintf('\n',CI1(i));
fprintf('   ---------------------------------------------------------------\n');
fprintf('   ______________________Final mark = %2.2f____________________________\n',
F);
end


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% AHP
METHODOLOGY %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [w, lamda, ci, cr]=ahp(a)% AHP methodology
fori=1:size(a,2)
a1(i)=sum(a(:,i));% Summarize each column
      a2(:,i)=a(:,i)./a1(i);% Normalize each column
end
fori=1:size(a,1)
         w(i)=sum(a2(i,:)/size(a,2));% Average each row
end
lamda=max(eig(a));% Maximal root
ci=(lamda-size(a,1))/(size(a,1)-1);% Consistency Index
RI=[0 0 0.58 0.90 1.12 1.24 1.32 1.41 1.45 1.49 1.52 1.54 1.56 1.58 1.59];% Table 2
cr=ci/RI(size(a,1));% Consistency Ratio
end
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% SCALE
FACTOR %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [b]=SF(n)% Scale Factor
   a=[3 5 7 9 11 13 15 17 18 26 30 34 36 44 52 60 68 75 85 90;0.4610 0.7597 ...
      0.9286 1.000 0.8506 0.7468 0.6948 0.6234 0.5844 0.4091 0.3831 0.3182 ...
      0.2922 0.2078 0.1688 0.1429 0.0909 0.0779 0.0325 0]; % Scale factor in Table 1
if n>90
fprintf(2, '  The Scale is beyond the limit of 90, please try again!\n\n');
elseif isempty(find(a(1,:)==n))==0% The value is in the list
      b=a(2,find(a(1,:)==n));
else
for i=1:size(a,2)% Interpolation
if (n-a(1,i))*(n-a(1,i+1))<0
break;
end
end
      b=a(2,i)+(n-a(1,i))*(a(2,i+1)-a(2,i))/(a(1,i+1)-a(1,i));
end
end
```

Appendix C. The MATLAB code of IAHP Input (iahpdata)

```
clc;
clear;

G=[4 5 6 10 12 14 22;
  1 8 15 18 20 24 25;
  7 13 17 19 21 23 26;
  2 3 9 11 16 0 0];% Dividing all alternatives in four groups

A1=[1 1 1 1;
   1 1 1 1;
   1 1 1 1;
   1 1 1 1];% Top level of AHP model by fault tree

B1{1}=[1 1 1 2 2 2 2;
        1 1 2 3 3 3 3;
        1 1/2 1 2 2 2 2;
        1/2 1/3 1/2 1 1 1 1;
        1/2 1/3 1/2 1 1 1 1;
        1/2 1/3 1/2 1 1 1 1;
        1/2 1/3 1/2 1 1 1 1];%  B1 at the middle level of AHP model by fault tree

B1{2}=[1 3 4 4 4 4 8;
        1/3 1 2 2 2 2 3;
        1/4 1/2 1 1 1 1 2;
        1/4 1/2 1 1 1 1 2;
        1/4 1/2 1 1 1 1 2;
        1/4 1/2 1 1 1 1 2;
        1/8 1/3 1/2 1/2 1/2 1/2 1];% B2 at the middle level of AHP model by fault tree

B1{3}=[1 2 2 2 2 2 3;
        1/2 1 1 1 1 1 2;
        1/2 1 1 1 1 1 2;
        1/2 1 1 1 1 1 2;
        1/2 1 1 1 1 1 2;
        1/2 1 1 1 1 1 2;
        1/3 1/2 1/2 1/2 1/2 1/2 1];% B3 at the middle level of AHP model by fault tree

B1{4}=[1 2 4 4 4;
        1/2 1 2 2 2;
        1/4 1/2 1 1 1;
        1/4 1/2 1 1 1;
        1/4 1/2 1 1 1];% B4 at the middle level of AHP model by fault tree
```

```
A2=[1 1/2 2 3;
   2 1 3 5;
   1/2 1/3 1 2;
   1/3 1/5 1/2 1];% Top level of AHP model by experts

B2{1}=[1 1/2 2 2 2 1 2;
        2 1 2 2 2 1 2;
        1/2 1/2 1 1/2 1 1/3 1;
        1/2 1/2 2 1 2 1 2;
        1/2 1/2 1 1/2 1 1/3 1;
        1 1 3 1 3 1 2;
        1/2 1/2 1 1/2 1 1/2 1];% B1 at the middle level of AHP model by experts

B2{2}=[1 1/2 1/2 1/3 2 2 1;
        2 1 1 1/3 2 2 2;
        2 1 1 1/2 2 2 2;
        3 3 2 1 4 3 3;
        1/2 1/2 1/2 1/4 1 1 1;
        1/2 1/2 1/2 1/3 1 1 1;
        1 1/2 1/2 1/3 1 1 1];% B2 at the middle level of AHP model by experts

B2{3}=[1 2 1/3 1/3 2 1 1;
        1/2 1 1/3 1/4 2 1/2 1/2;
        3 3 1 2 2 2 2;
        3 4 1/2 1 4 2 2;
        1/2 1/2 1/2 1/4 1 1/2 1/2;
        1 2 1/2 1/2 2 1 1/2;
        1 2 1/2 1/2 2 2 1];% B3 at the middle level of AHP model by experts

B2{4}=[1 1 2 2 2;
        1 1 2 2 1/2;
        1/2 1/2 1 2 1/2;
        1/2 1/2 1/2 1 1/2;
        1/2 2 2 2 1];% B4 at the middle level of AHP model by experts

R{1}=[0.2 0.8 0 0 0;
       0.2 0.6 0.2 0 0;
       0.8 0.2 0 0 0;
       0.4 0.6 0 0 0;
       0.2 0.6 0.2 0 0;
       1.0 0 0 0 0;
       0.8 0.2 0 0 0];% Experts' judgment about alternatives under B1

R{2}=[0.2 0.4 0.2 0 0;
       0.4 0.4 0.2 0 0;
       0.8 0.2 0 0 0;
       0.6 0.4 0 0 0;
       0.8 0.2 0 0 0;
       0.6 0.4 0 0 0;
       0.4 0.4 0.2 0 0];% Experts' judgment about alternatives under B2
  R{3}=[0.8 0.2 0 0 0;
         1.0 0 0 0 0;
         0.6 0.4 0 0 0;
         0.8 0.2 0 0 0;
         1.0 0 0 0 0;
         0.4 0.6 0 0 0;
         0.4 0.4 0.2 0 0];% Experts' judgment about alternatives under B3

  R{4}=[0.6 0.4 0 0 0;
         0.4 0.2 0.4 0 0;
         0.8 0.2 0 0 0;
         0.6 0.4 0 0 0;
         0.6 0.4 0 0 0];% Experts' judgment about alternatives under B4

  J=20;% Maximal judgment factor of the factors in middle level

  fprintf('  The input is successful!\n\n');
```

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