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Safety Analysis of High Pressure Water Jet Slotting Equipment Based on Fuzzy Fault Tree

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Abstract. Safety is the foundation of all production activities. In order to further enhance the safety of high pressure water jet technology in the production process, the fuzzy analysis method and the fault tree method are used to analyze the risk factors in this paper. the risk factors existing in the personnel, equipment and environment of water jet in coal mine mining environment are analyzed. Secondly, the probability and importance of various events in the process of equipment application are analyzed by using fuzzy accident tree. The results show that: the most common risk factors in the use of high pressure water jet equipment are equipment grounding and circuit connection problems, followed by the standard operation education management of operators.

Keywords. High-pressure water jet technology equipment; Risk analysis; Fuzzy analysis; Fault tree.

1. Introduction

High pressure water jet is a high-tech technology emerging in the world. Its principle is to pressure water to hundreds of atmospheres through a high pressure water generator, and then form a high-speed fine 'water jet' through a jet device with a small aperture. The speed of this 'water jet' is generally more than twice the Mach number, with huge impact energy, can complete different kinds of tasks. Compared with other similar technologies, high pressure water jet has the advantages of high energy gathering, non-destructive cutting and no spark, and its application is very extensive[1–3]. Such as high pressure water jet cutting, high pressure water jet rock breaking, high pressure water jet shot peening and so on.

The connection diagram of the high pressure water jet equipment listed below is shown in figure 1 and the application of the water jet equipment in the coal mine is shown in figure 2. The principle of the equipment is to use the high pressure fine jet and the rotating nozzle to rotate the coal body around the borehole in the drilled

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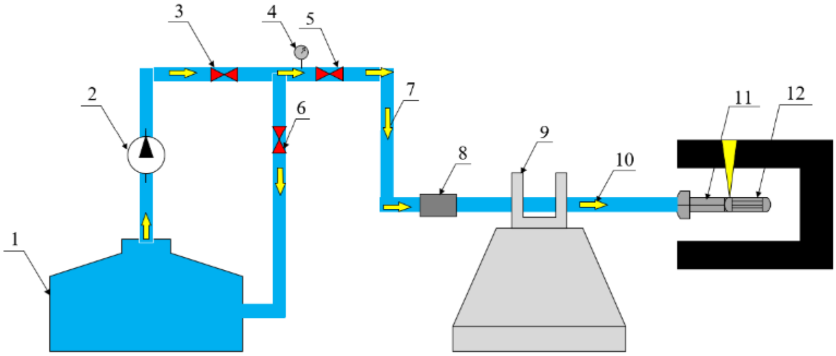
borehole. Cutting, while the drill pipe moves along the axial direction of the borehole to form a radial continuous reaming of the full length of the borehole, thereby expanding the borehole diameter. The pressure devices such as high pressure containers and their moving parts of high pressure water jet equipment applied in coal mining may cause harm to the operators. Therefore, some phenomena in the use of high pressure water jet equipment can be determined, the causes of casualties caused by high-pressure water jet equipment can be obtained. Through the analysis of personnel casualties by fuzzy fault tree, it can be concluded that the causes of potential factors that are most likely to lead to accidents when casualties occur in the use of high pressure water jet equipment[4].



1- Water tank; 2- emulsion pump; 3-stop valve 1; 4-damping pressure gauge; 5- stop valve 2 (pressure relief valve); 6- stop valve 3; 7- high pressure water pipe; 8-high pressure sealed water conveyer; 9- Drilling rig; 10- High pressure drill pipe; 11- automatic switching slit cutter; 12-bit

Figure 1. Diagram of connection of water jet technology equipment

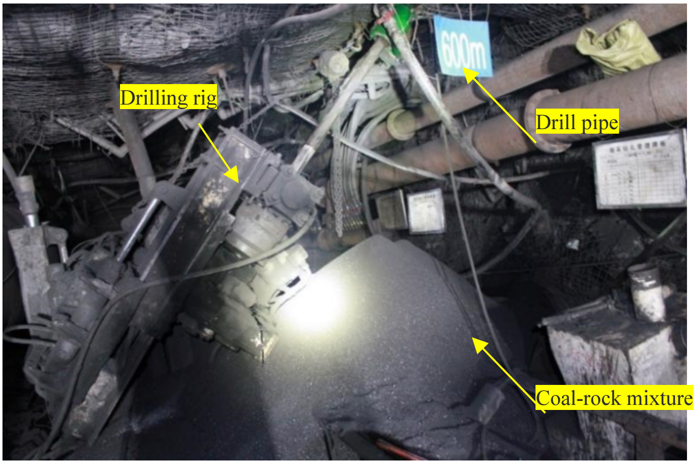


Figure 2. Application of water jet equipment in coal mine

2. Analysis of risk factors

According to the hazard identification method[5–9], the operation risk factors of high pressure water jet equipment include three aspects : unsafe operation behavior, unsafe state of water jet equipment and problems in protective facilities. According to relevant research[10–13], casualties are mainly caused by human factors, which are the unsafe state of high-pressure water jet equipment and the lack of safety protection equipment.

2.1 Unsafe Status of the device

High pressure water jet equipment[14] has higher pressure vessels and high pressure water conveying pipelines, so there is high pressure vessel damage, pipeline rupture, unstable links and other risks of high pressure water leakage. At the same time, high pressure pressure pump and drill are electrical equipment, and there are risks of leakage of electricity in equipment, facilities, circuits and other parts, and various faults may occur during the operation of mechanical parts. Such as accidental start, accidental stop, moving parts are thrown out, equipment substandard caused by a series of failures.

2.2 Unsafe behavior of personnel

The high pressure water jet equipment produces higher pressure water with strong kinetic energy when it is ejected through the nozzle orifice. When it comes into contact with the human body, It will hurt people. Meanwhile, the addition of abrasives strengthens its power. When the operator makes mistakes in judgment, illegal operation, improper operation, fatigue operation, and cleaning up the material, it is very likely to contact with the dangerous parts, and then the danger occurs[15].

2.3 Protection Device Problems

High pressure water jet device has high pressure vessel, rotating mechanism, electrical device and other parts illegal operation during inspection operation, and rotating parts without protection or lack of protection due to maintenance, electrical devices exposed, contact with water and then conductive, operators do not wear protective devices, or no protective operation will greatly reduce the safety factor of operation, resulting in dangerous accidents.

2.4 Working environment status

The impact characteristics of high pressure water jet equipment in coal mine mining and the characteristics of cutting broken coal and rock will increase the free surface of coal seam gas emission, increase the permeability of coal seam, and a large amount of gas will be analyzed, resulting in a large number of flammable and explosive gases in the working environment. At this time, if there is a fire source or equipment to generate an electric spark, it is very likely to cause a combustion explosion accident[5].

3. Fault Tree Analysis

Fault tree analysis[16–18] refers to an analysis method commonly used in safety system engineering. Through deductive reasoning, the trigger events that lead to accidents are gradually found from a possible accident, direct and indirect causes, and the logical relationship between them is expressed in the form of logical tree diagram. In the past, the fault tree mainly focused on the analysis of high-risk operating environment and equipment, and mainly carried out qualitative analysis. The introduction of fuzzy algorithm can quantitatively analyze low-risk equipment such as high pressure water jet equipment.

3.1 Building a fault tree

According to the results of risk factor analysis[19,20], the fault tree is established as shown in Figure 3. Taking the casualty accident as the top event *T*1, the intermediate events *M*1, *M*2 and *M*3 are electric shock, explosion and mechanical injury respectively. The intermediate events *M*4 ~ *M*10 are leakage, fire source, combustible gas, equipment failure, body contact with dangerous parts and protection failure respectively. The intermediate events *M*11 ~ *M*13 are electrical spark, gas diffusion obstruction and equipment error action respectively. The basic events *X*1 ~ *X*26 are shown in Table 1.

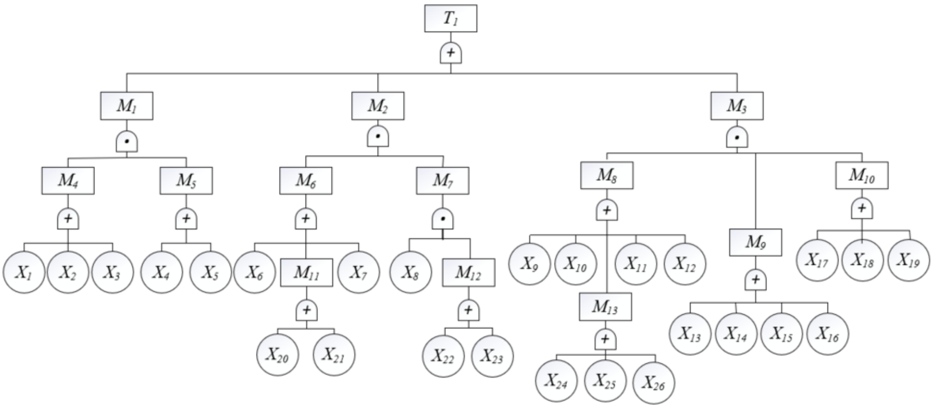


Figure 3. Human casualty accident tree

Table 1. Meaning of basic event symbols

Symbol	Meaning	Symbol	Meaning
*X*1	The protective equipment is not qualified	*X*14	Operation is not performed as required
*X*2	The device is improperly grounded	*X*15	Inspection and handling
*X*3	Unprotected measure	*X*16	Fatigue operation
*X*4	Equipment leakage	*X*17	Unprotected
*X*5	Circuit damage leakage	*X*18	Damage of protective facilities
*X*6	Bring into the fire	*X*19	No protection was used
*X*7	Electrostatic spark	*X*20	Failure of explosion-proof device

$X8$	Mass desorption release of gas	$X21$	Non-explosion-proof device
$X9$	High pressure pipeline rupture	$X22$	Ventilation failure
$X10$	Pressure vessel rupture	$X23$	No ventilation
$X11$	Seal component failure	$X24$	Accidental startup
$X12$	The high-pressure pipe is loose	$X25$	Touch switch by mistake
$X13$	Accidental contact	$X26$	Emergency brake failure

Through the analysis of the fault tree structure, there are 98 minimum cut sets and 18 minimum path sets[21]. The minimum path set is shown in Table 2:

Table 2. Minimal set

Serial number	Minimal set	Serial number	Minimal set
1	$X1,X2,X3,X6,X7,X9,X10,X11,X12,X20,X21,X24,X25,X26$	10	$X4,X5,X6,X7,X9,X10,X11,X12,X20,X21,X24,X25,X26$
2	$X1,X2,X3,X6,X7,X13,X14,X15,X16,X20,X21$	11	$X4,X5,X6,X7,X13,X14,X15,X16,X20,X21$
3	$X1,X2,X3,X6,X7,X17,X18,X19,X20,X21$	12	$X3,X4,X5,X14,X15,X16$
4	$X1,X2,X3,X8,X9,X10,X11,X12,X24,X25,X26$	13	$X4,X5,X8,X9,X10,X11,X12,X24,X25,X26$
5	$X1,X2,X3,X8,X13,X14,X15,X16$	14	$X4,X5,X8,X13,X14,X15,X16$
6	$X1,X2,X3,X8,X17,X18,X19$	15	$X4,X5,X8,X17,X18,X19$
7	$X1,X2,X3,X9,X10,X11,X12,X22,X23,X24,X25,X26$	16	$X4,X5,X9,X10,X11,X12,X22,X23,X24,X25,X26$
8	$X1,X2,X3,X13,X14,X15,X16,X22,X23$	17	$X4,X5,X13,X14,X15,X16,X22,X23$
9	$X1,X2,X3,X17,X18,X19,X22,X23$	18	$X4,X5,X17,X18,X19,X22,X23$

3.2 Fuzzy quantitative analysis

It is difficult to determine the probability of each basic event, so the fuzzy evaluation basic data of expert scoring are selected[22–24], and the weights of the three experts are 0.350, 0.335 and 0.315 respectively. Five possibility criteria for expert evaluation are as follows: Very high(VH), high(H), medium(M), low(L), very low(VL), represented by fuzzy trapezoid number, corresponding to:

VH(0.7,0.8,0.9,0.9);H(0.6,0.7,0.7,0.8);M(0.4,0.5,0.5,0.7);ML(0.2,0.3,0.3); L(0.1,0.1,0.2,0.3)

After grading the expert scores, compare the graded trapezoidal fuzzy numbers to determine the similarity degree of fuzzy numbers evaluated by different experts. Let *Gi* (*i*=1,2,…,n) and *Gj* (*j*=1,2...,n) is the trapezoidal fuzzy number of two different experts on the same event, expressed as *Gi*(a1,a2,a3,a4) and *Gj*(b1,b2,b3,b4).

(1) Similarity function[22] *Sij*:

$$S_{ij}(G_i,G_j)=1-\frac{1}{4}\sum_{n=1}^{4}|a_n-b_n| \tag{1}$$

The size of *Sij* represents the similarity between *Gi* and *Gj*.

(2) Calculate the average similarity degree of the I-th expert

$$AA(E_i)=\frac{1}{n-1}\sum_{(i\neq j,i=1)}^{n}S_{ij}(G_i,G_j) \tag{2}$$

(3) Calculate the relative similarity of each expert

$$RA_i=\frac{AA(E_i)}{\sum_{i=1}^{n}(E_i)} \tag{3}$$

(4) Estimate the similarity coefficient of each expert

$$C(E_i)=\alpha P(E_i)+(1-\alpha)RA_i \tag{4}$$

Where, α is relaxation factor, $0 \leq\alpha\leq 1$, α=0.5; $P(Ei)$ is the weight value of each expert.

(5) Calculate the aggregate fuzzy number of basic events

$$\overline{R}=\sum_{i=1}^{n}C(E_i)\times G_i \tag{5}$$

In the formula Gi score the corresponding fuzzy trapezoid number for the expert.

(6) The heart area method formula is used for de-fuzzification[22]

$$R=\frac{1}{3}\frac{(a_4+a_3)^2-a_4a_3-(a_1+a_2)^2+a_1a_2)}{a_4+a_3-a_1-a_2} \tag{6}$$

(7) Calculate the trapezoidal fuzzy number of the basic event and process the expert judgment result R and the fuzzy probability of the basic event probability and the actual probability conversion relation[22].

$$P(R)=\begin{cases}\frac{1}{10^k} & R\neq 0\\ 0 & R=0\end{cases},(k=(\frac{1-R}{R})^{\frac{1}{3}}\times 2.301) \tag{7}$$

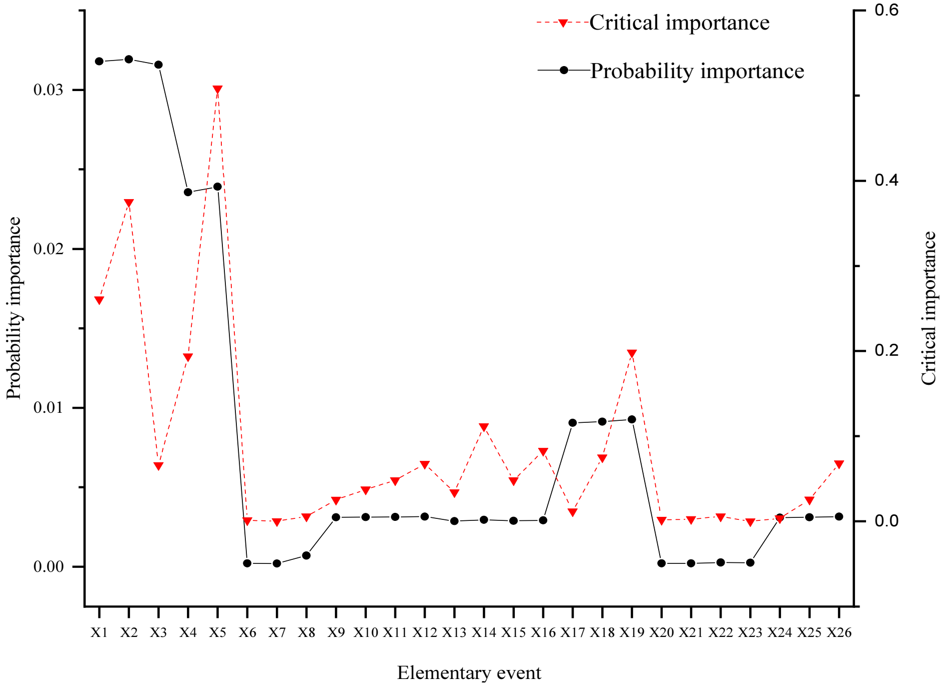
The actual probability, critical importance and probability importance calculated by transforming the relationship are shown in Table 3.

Table 3. experts score and calculate the results table

Event number	Expert 1	Expert 2	Expert 3	Actual probability	Critical importance	Probability importance
*X*1	VH	H	H	0.009041698	0.260748409	0.031798592
*X*2	H	H	H	0.012953661	0.375043839	0.03192462
*X*3	M	L	L	0.002305293	0.066032162	0.031583889
*X*4	H	M	M	0.009068135	0.193754087	0.023559665
*X*5	H	VH	H	0.02344526	0.508317603	0.023906518
*X*6	M	H	L	0.005947095	0.001142814	0.000211888

*X*7	M	L	VL	0.001484668	0.000284024	0.000210941
*X*8	H	M	M	0.009068135	0.005781679	0.000703027
*X*9	M	H	M	0.008995027	0.025387244	0.00311207
*X*10	H	H	M	0.013243462	0.037538804	0.003125468
*X*11	VH	H	M	0.016947395	0.048218657	0.003137245
*X*12	H	VH	H	0.023612646	0.067641219	0.003158661
*X*13	H	M	H	0.013104726	0.034106419	0.002869752
*X*14	VH	VH	VH	0.041585267	0.1114462	0.002955031
*X*15	H	H	H	0.018414797	0.048185701	0.002885277
*X*16	VH	H	VH	0.031265888	0.082898262	0.002923552
*X*17	L	VL	M	0.001414259	0.011617446	0.0090577
*X*18	H	M	M	0.009068135	0.075065652	0.009127661
*X*19	H	VH	H	0.023612646	0.19837621	0.009263629
*X*20	M	H	M	0.008995027	0.001733832	0.00021254
*X*21	H	H	M	0.013243462	0.002563727	0.000213455
*X*22	H	VH	H	0.023612646	0.005696667	0.000266019
*X*23	VL	L	VL	0.00035225	8.30046E-05	0.000259829
*X*24	L	L	L	0.0012616	0.003533124	0.003087972
*X*25	H	M	M	0.009068135	0.025595469	0.003112299
*X*26	VH	H	H	0.023751845	0.068049672	0.003159111

According to table 3, a comparison diagram of the probability importance and street importance of basic events is drawn, as shown in figure 4:



Figures 4. Probability importance and critical importance of basic events

From Figure 4, the maximum probability importance event of *X*2 equipment grounding failure is 3.19×10-2, and the maximum critical importance event of *X*5 circuit damage leakage is 3.19×10-2. In the critical importance, in addition to the problem of equipment circuit damage and leakage, there are also dangers caused by operators not operating as required and not wearing protection. Therefore, it is necessary to strengthen safety management and safety common sense education to improve the safety literacy of operators.

(8) The top event probability is calculated by the minimum path set[25]

$$P(T_1) = 1 - \prod_{i=1}^{n}(1 - q_i) \tag{8}$$

In the formula q is the actual probability of the basic event in the smallest set.

Through the calculation of the top event probability P (T1) by Equation (8), the incidence of personnel injury accidents is 0.1103 %, and the probability of occurrence is low. The basic events, critical importance, probability importance, and the maximum events are X14, X5, and X2, and the maximum values are 4.16×10-2, 3.19×10-2, and 3.19×10-2, respectively.

4 Conclusion

(1) By introducing the fuzzy fault tree method to analyze the mining operation of high pressure water jet equipment in coal mine, the hidden dangers of accidents can be found quickly and effectively, and the occurrence of casualties can be avoided. In this paper, the total probability of casualties is 0.1103 %. The probability of the basic event X14 not operating as required is 4.16×10-2. The probability of X5 circuit damage leakage is 3.19×10-2. The probability of X2 equipment grounding failure is 3.19×10-2. Considering the two importance rankings of the basic event X2 equipment grounding failure, special attention is needed.

(2) According to the importance of basic events, high pressure water jet technology needs to pay attention to the leakage of circuit equipment and the operation management education of operators in the process of coal mine mining application. At the same time, according to the probability importance and critical importance, it is concluded that the electric shock accident is the most direct and most likely cause of casualties, so it is necessary to pay attention to the personal protection and insulation protection of personnel. The final analysis results can also be used as the basis for the implementation of accident prevention.

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