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Multi-attribute Analysis of Consequence Severity in Risk Assessment for Natural Gas Pipelines

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Abstract: In order to be quantitative to assess the natural gas pipeline system, the paper presents a decision model for consequence severity of the accident based on Multi-attribute Analysis Method (MAAM). The MAAM can help carry out decision analyses more scientifically to produce multi-dimensional risk measurements. The attribute tree is established depending on a decision object and simplified in a decision meeting and then utility functions related to important attributes of the decision tree are built. An optimum solution is achieved by determining weights of attributes in the Analytic Hierarchy Process and calculating utility values. Finally examples as practical tests are given, in which the MAAM was applied to a particular natural gas accident to determine its consequence severity. The result shows that the MAAM can effectively help the decision-maker make a rational decision about the consequence severity in case of a gas accident.

Key words: Urban gas pipelines, risk assessment, consequence severity, multi-attribute decision, utility theory

INTRODUCTION

Compared with road transportation, pipelines are a most practical and economical means to transport dangerous and flammable substances (e.g., natural gas). In most countries, the more that pipeline systems are expanded and natural gas consumption increases, the more their economies become dependent on the stable, continuous and safe operation of these facilities (Dey, 2002).

As shown in the historic data (Sklavounos and Rigas, 2006), the accident of natural gas transported through pipelines happened less frequently than that through the road, but the two means of transportation may result in consequences of different degrees. In order to reduce accidents of pipelines, some measures must be taken.

At present, only human or financial losses are considered in risk analysis and assessment methods (Jo and Ahn, 2005). In another word, possible influences of accidents on other aspects, such as on social stability, the normal operation of a natural gas pipeline company and the safeties of pipelines have not been sufficiently considered.

In primary risk assessment, preferences of a manager responsible for pipelines are rarely incorporated in value judgments (Jo and Ahn, 2002; Zhao *et al*., 2007). Actually, the manager has incorporated his/her preferences into the planning, prevention, supervision and maintenance of the pipeline safety. Cagno *et al*. (2000) thinks that many techniques of pipeline safety management have a very low efficiency. This often causes inefficiency in prioritizing those pipeline segments that must receive investment and supplementary maintenance. Papadakis (2000) emphasizes that, in view of the primary assessment techniques, the probability method of risk ranking (which combines probabilities of an event with its resulting consequences) fully reflects the priority level concept (Brito and de Almeida, 2009).

Thus, in order to help the decision-maker solve the problem, a multi-attribute decision model is provided in this paper. The model can assess the risk of the pipeline and judge the risk ranking from various aspects. The influences of the accident for pipelines, such as human, environments and economy are considered in this method.

ANALYSIS OF INFLUENCE FACTORS FOR THE CONSEQUENCE SEVERITY

According to the development of the risk assessment principles, the pipeline operation risk depends on two

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aspects, i.e., the accident probability and the consequence severity. The consequence severity refers to the range and extent to which an accident that occurs on a pipeline brings about, the damage consequence including damages to persons, damages to facilities and environment in the vicinity of the accident, influences on social stabilization and reputation of gas enterprises, damages to terminal users (in particular the production of industrial and commercial enterprises), economic losses of gas enterprises (Yang, 2008). Specific conditions of cities in our country must be considered when the consequence severity is calculated and the final assessment may be made under a comprehensive analysis of multiple factors. In practical production, the accident consequence of a natural gas pipeline is represented as follows (Wang *et al*., 2004): (1) Personal casualties, involving the floating population on the ground surface of the natural gas pipelines and the population residing in the buildings in the vicinity of the natural gas pipeline, (2) Property damage, involving the buildings (constructions) and other facilities in the vicinity of the natural gas pipeline, (3) Possibility of chain reaction generated from the explosion accident near a chemical factory or a gas station, (4) Influence on the production of the downstream industry and commerce user, particularly damages to the continuous production of the industry user, (5) Influence on the livelihood of downstream residential users, (6) Social panic and unrest resulting from the burning and explosive accidents in the political, military sensitive areas, (7) Diffusing of the remaining gas in the pipeline and other investment caused by emergency rescue and (8) Reduced sales due to the interruption of production.

As can be known from analyses, factors affecting the assessment of consequence severity include: basic pipeline attribute; the number of population, the number and type of buildings, surface traffic flow in the area of pipeline net; importance degree and properties of units in the vicinity of the pipeline; personnel evacuation conditions during accident and difficulty or easiness in pipe repair; influence of stopping gas supply and communication conditions between the adjacent or intersecting trench and dwelling houses.

APPLICATION OF THE MULTI-ATTRIBUTE UTILITY THEORY IN CONSEQUENCE SEVERITY

Multi-attribute utility theory: The Multi-attribute Utility Theory (MAUT) is a structured, logical and systematic decision analysis theory (Rahaman, 2003; Li, 2002) and is mainly used to evaluate influences of various factors (attributes) that may play on the decision result to make a comprehensive consideration and select a largest utility solution.

The MAUT method used to solve problems includes the steps as following:

Step 1: Determining all of attributes to be considered, $X = \{x_1, x_2, ..., x_n\}$

Step 2: Establishing the expression U(X) of attribute utility functions

Step 3: Determining alternative solutions $A = \{A_1, A_2, ..., A_m\}$

Step 4: Calculating the utility $U_i(X)$, $(i = 1, 2, ..., m)$of each solution

Step 5: Determining the optimum solution

The utility $U(A_i)$ of the i-th solution may be calculated by the following expression:

$$U(A_i) = \sum_{j=1}^{n} w_j v_j(d_{ij}) \quad (1)$$

where, w_j is the weight of the j-th attribute and $w_j = 0$,

$$\sum_{j=1}^{n} w_j = 1$$

where, $v_j(d_{ij})$ is the utility value of the j-th attribute of the i-th solution and $0 = v_j(d_{ij}) = 1$, $j = 1, 2, \ldots, n$.

After the overall utilities of all solutions are calculated, the overall utilities are arranged in sequence and the solution having a largest utility is the optimum solution.

Establishment of an attribute tree: An initial attribute tree is made by using a brainstorming method. All of factors related to the decision must be considered regardless of the importance of involved factors, so as to ensure that important factors related to the gas accident consequence would not be omitted. The initial attribute tree needs to be simplified by omitting factors with small importance degree and with little influence on decision consequence, so as to form a concise attribute tree. According to the characteristics of the gas accident, an attribute tree including eight factors in making decision is established, as shown in Fig. 1.

Attribute value and utility function: After the attribute tree is established, the utility evaluation is made for each attribute in the tree. Generally, one attribute utility function is established for each attribute, the value of which is ranged between 0 and 1. The utility of the best result or the minimum adverse result of each factor is generally allocated (for example, minimum expense, minimum leakage amount) as 1 and the utility of the worst result is allocated as 0 (Xu *et al*., 2008). In the description,

Table 1: Expression of utility function of each attribute

Attribute name	Utility expression parameter	Range
Population around the pipeline	-0.62+0.62exp(0.00096x)	0<x<1000
Building properties and scale (0~100)	x/100	0<x<100
Traffic situation	-0.54+0.54exp(0.00065x)	0<x<160
Stopping gas damages	-0.78+0.78exp(0.00041x)	0<x<2000
Repair-investment /10/3 Yuan	1	0<x<120
	1.096-0.096exp [(x-120)0.03.5]	120<x<200
Site control (0~100)	x/100	0<x<100
Leakage control (0~100)	x/100	0<x<100
Deflagrated dangerous/m	-0.24+0.24exp(0.0328x)	0<x<50

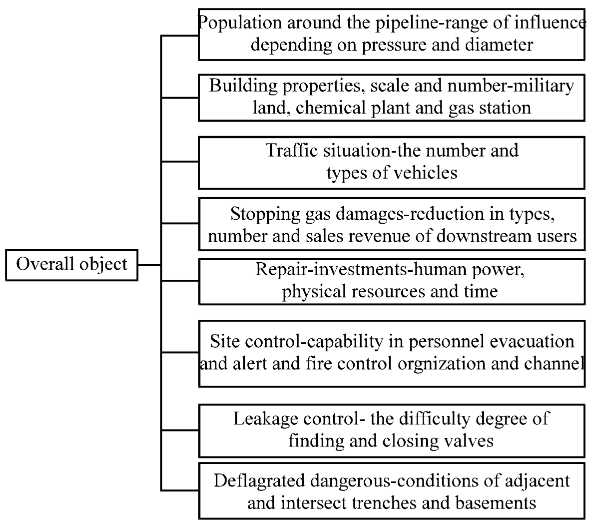

Fig. 1: Attribute tree of evaluation of gas accident consequence decision

the utility function is represented in index form (Xu *et al*., 2008; Brito and de Almeida, 2009), i.e., $u = \lambda - \frac{r}{\theta} e^{-\theta x}$. For decision-makers with different risk consciousness, the degree of acceptance toward accident consequence is different. Thus, the curve smoothness of the utility function is substantially different. There are risk loving type, risk aversion type and risk neutralism type.

The curve of the utility function is determined by three undetermined parameters λ, r, θ in the expression. Three equations may be established jointly by certain feature points of the function, i.e., maximum utility point (u = 1), minimum utility point (u = 0) and middle value point (u = 0.5) and thus a sole utility function may be solved. The expression of the utility function with eight attributes herein is shown in Table 1.

DETERMINATION OF ATTRIBUTE WEIGHTS WITH THE HIERARCHY ANALYTIC METHOD

A judgment matrix is formed, in which every two factors of consequence severity are compared. Nine integers from 1 to 9 serve as the scale of importance of one factor compared with another factor (You and Zhu, 2009). The scale is defined as follows:

If a first factor has the same influence capacity as a second, the scale is 1, the influence capacity of the first factor is increasingly larger than that of the second factor, the scale is increased. The maximum scale is 9, indicating that the influence capacity of the first factor is greatly larger than that of the second factor. For example, if A is significantly more important than D, Tad is 8 and the rest may be deduced by the same way. After specialists repeatedly discuss the eight factors affecting the consequence severity, a right upper triangular matrices is obtained, in which every two factors are compared. Elements in the lower-left triangle are reciprocal of elements in the upper-right triangle, i.e., $T_{ij} = 1/T_{ji}$.

After the elements in the lower-left triangle are filled, the whole judgment matrix is obtained, shown in Table 2.

Table 2: A judgment matrix of every two factors be compared

T	A	B	C	D	E	F	G	H	W
A	1	1	6	8	7	5	3	4	0.3316
B	1	1	4	6	5	3	2	3	0.2508
C	1/6	1/4	1	3	2	2	1	1/5	0.0685
D	1/8	1/6	1/3	1	2	1	2/3	1	0.0535
E	1/7	1/5	1/2	1/2	1	4/3	4/5	1	0.0638
F	1/5	1/3	1/2	1	3/4	1	4/3	2	0.0720
G	1/3	1/2	1	3/2	5/4	3/4	1	2	0.0874
H	1/4	1/3	5	1	1	1/2	1/2	1	0.0724

According to program of block diagram, as shown in Fig. 2, a biggest characteristic root of matrix is solved, i.e., $\lambda_{max} = 8.049$, CI = 0.007, CR = 0.005. CI and CR are greatly less than 0.1. Thus, it is determined that the judgment matrix has a satisfied consistency and the eigenvector W is the weight of the above factors.

Decision model application: A gas leakage in a certain bustling area of Beijing is taken as an example in this description. A pavement was soaked in rainwater and collapsed to stave the underground gas pipeline, which caused the leakage of gas. Eight hours after the accident, the air was mingled with a strong odor of natural gas. Gas companies and government departments of the city immediately made a rush-repair to the broken-road. The accident caused an evacuation of about 600 dwellers near the spot, stopping gas supply for about 500 houses and making 5 roads jammed near the accident so that about 10 bus routes along these roads were bypassed. Finally four alternative solutions to handling the consequence are obtained on calculating the number of people and vehicles near the accident and by the statistics of the cost for stopping gas and repairment:

- Not taking any measures
- In the range of 500 m from where the accident takes

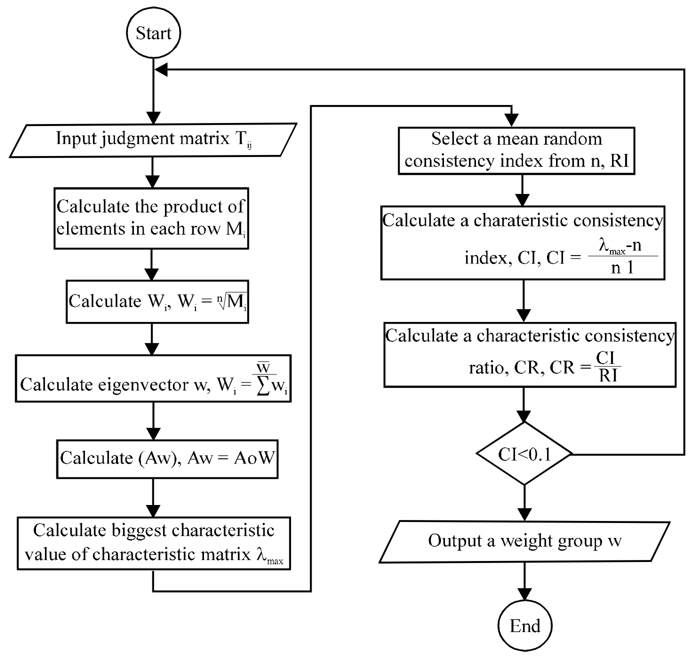

Fig. 2: Block diagram illustrating the calculation of judgment matrix to obtain weight vector

Table 3: Influence value of different strategies on different attributes

	Population around the pipeline			Building properties and scale (0~100)		
Strategy	Optimistic	Middle	Pessimistic	Optimistic	Middle	Pessimistic
1	500	600	700	10	15	30
2	300	320	500	7	12	20
3	230	260	280	5	10	12
4	100	160	180	2	8	10
	Traffic situation/vehicle			Losses by stopping gas/house		
Strategy	Optimistic	Middle	Optimistic	Middle	Optimistic	Middle
1	100	130	100	130	100	130
2	80	85	80	85	80	85
3	60	70	60	70	60	70
4	30	35	30	35	30	35
	Leakage control (0~100)			Deflagrated dangerous/m		
Strategy	Optimistic	Middle	Optimistic	Middle	Optimistic	Middle
1	0	0	0	0	0	0
2	100	90	100	90	100	90
3	70	60	70	60	70	60
4	70	60	70	60	70	60
	Repair investment/103 Yuan			Site control (0~100)		
Strategy	Optimistic	Middle	Pessimistic	Optimistic	Middle	Pessimistic
1	0	0	0	0	0	0
2	60	80	100	80	70	60
3	80	100	130	50	45	40
4	60	70	100	40	35	25

place, the traffic-control measures are to be taken, in which about 100 vehicles and 500 people will be involved, gas supply stopped for about 700 houses since the valves of the pipelines are directly closed and the rush-repair investment is about 100 thousand Yuan

- In the range of 300 m from where the accident takes place, the traffic-control measures are to be taken, in which about 80 vehicles and 280 people will be involved, gas supply stopped for about 1000 houses since the valves of the pipelines are directly closed and the rush-repair investment is about 130 thousand Yuan
- In the range of 100 m from where the accident takes place, the traffic-control measures are to be taken, in which about 50 vehicles and 180 people will be involved, gas supply stopped for about 1000 houses since the valves of the pipelines are directly closed and the rush-repair investment is about 150 thousand Yuan

Table 3 shows the influence values of different strategies on different attributes. Assumed that the risk attitude of the decision-maker is optimistic, corresponding values in Table 3 are applied to the utility function formula and the utility of corresponding attributes may be calculated. The importance degree of eight attributes is ranked, that is, Leakage control>Population around pipeline>Losses by stopping gas>Traffic situation>Site control>Deflagrated dangerous>Building properties and scale>Repair-investment. Respective weights of attributes are solved, so as to further calculate the overall utilities of the solutions. The overall utilities of the four solutions are 0.397, 0.370, 0.453 and 0.653, respectively. According to the largest overall utility rule, the optimum consequence handling solution should be the fourth solution.

CONCLUSION

Application of the multi-attribute analysis method to urban gas pipeline risk assessment is considered in this study. Based on the numerical and analytical analyses, it can be concluded that:

- The contribution of each attribute to the solution is represented by the way of utility, which may efficiently help the decision-maker select an optimum solution from the alternative solutions
- The specific solving method of the utility function of associated attributes in the multi-attribute utility analysis is provided in this description. The result shows that the multi-attribute utility analysis method can efficiently help the decision-maker make the optimum and reasonable decision in handling the gas accident consequence
- Since the analysis process of decision is relatively complex, the decision analyst must know and determine the analysis process, the analysis method and the analysis object. Unlike the case in the mid-stage and post-stage of the accident, there is no enough time in the early stage to establish an accident model. Thus, the decision-maker must make a decision within a short time in an urgent situation when much information is uncertain
- Therefore, to handle any potential consequence of the natural gas pipeline accident, the decision-maker should pre-simulate the accident scene, set the influence factors of the accident, consider the disadvantages and advantages and set the attribute weight factors, so as to make a quick decision response to any consequence of the natural gas pipeline accident

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