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Risk analysis of urban gas pipeline network based on improved bow-tie model

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Abstract. Gas pipeline network is a major hazard source in urban areas. In the event of an accident, there could be grave consequences. In order to understand more clearly the causes and consequences of gas pipeline network accidents, and to develop prevention and mitigation measures, the author puts forward the application of improved bow-tie model to analyze risks of urban gas pipeline network. The improved bow-tie model analyzes accident causes from four aspects: human, materials, environment and management; it also analyzes the consequences from four aspects: casualty, property loss, environment and society. Then it quantifies the causes and consequences. Risk identification, risk analysis, risk assessment, risk control, and risk management will be clearly shown in the model figures. Then it can suggest prevention and mitigation measures accordingly to help reduce accident rate of gas pipeline network. The results show that the whole process of an accident can be visually investigated using the bow-tie model. It can also provide reasons for and predict consequences of an unfortunate event. It is of great significance in order to analyze leakage failure of gas pipeline network.

1. Introduction

With the widespread use of natural gas, more and more gas pipelines are laid in urban areas. In China, the construction of gas pipeline network reached its peak in recent years. Due to a variety of reasons, gas pipeline network accidents frequently occurred. These accidents have aroused great concern in society. Urban gas pipeline, oil pipeline, communication, drainage, heat [1] and other networks are laid crossing each other. Some of the pipeline networks are in serious aging but still overloaded. This can greatly increase the probability of an accident. The accident rate of gas pipeline follows the rule of "bathtub curve", which is manifested in the fact that accidents prone to happen in the early and late stages [2] of the life cycle of gas pipelines. Most of China's urban gas pipeline networks are in their early and late stages [3]. And gas pipeline network is a major hazard source in urban areas. In the event of an accident, there could be grave consequences. These accidents could bring great loss to lives, property, and society.

It is of great significance in order to conduct a necessary risk analysis and studies of urban gas pipeline network. The bow-tie model introduced in this paper represents risk identification, risk analysis, risk assessment, and risk control as in one chart. This is a highly visible, straightforward structured approach. It is easy to understand and master, and easy to use and operate, so it is ideal for conducting a risk analysis of urban gas pipeline network. Moreover, the bow-tie model conducts a risk analysis of urban gas pipeline by combining fault tree analysis (FTA), event tree analysis (ETA) [4], pipeline failure probability, and its consequences together. Reasons for pipeline failure are located by analyzing fault trees. Then risks can be prevented after they are identified and prevention and control measures are adopted. Possible consequences of an accident can be predicted by analyzing event trees. Then mitigation measures can be adopted to minimize losses to guarantee the safety of people's lives and property. The improved bow-tie model introduced in this paper analyzes accident causes from four aspects: human, materials, environment and management; it also analyzes the consequences from four aspects: casualty, property loss, environment and society. Then it quantifies the causes and consequences to conduct a risk analysis of urban gas pipeline network.

2. Introduction to the bow-tie model and its improvement

2.1. Development of bow-tie model

The bow-tie model appeared in the 1970s. Later David Gill developed it and named it Bow –tie Diagram [5]. It was proposed in university course notes as a systematic model and was constantly reviewed. At the end of the last century, the bow-tie model was successfully applied to analyze accidents by explosion [6]. At the beginning of this century, NASA used the bow-tie model in risk management, promoting its development in the field. The Bow-tie model is widely used in risk analysis and management of oil, natural gas and other industries because of its practical and highly visualized features.

2.2. Bow-tie model principle

The bow-tie model is a practical, easy-to-use risk analysis and evaluation method [7]. It combines FTA with ETA, accident prevention measures and control mitigation measures for the first time. It analyzes causes and consequences of an accident using quality features of FTA and ETA [8]. It identifies risk factors at all stages. Therefore it can inform accident development and results of risk analysis [9]. FTA takes an accident as top event and finds the direct and indirect reasons leading to the top event. Then it analyzes all the reasons qualitatively. It provides the basis for the analysis of accident causes. ETA begins with the top event that can lead to an accident, taking into account of the successes and failures of events in terms of time development. ETA can analyze a variety of accident models and their consequences that may occur in complex systems. In a bow-tie diagram, the accident is situated in the center with FTA to its left and ETA to its right. From right to left, FTA finds out accident causes layer by layer, identifies risk factors, and develops prevention control measures. Regarding the central accident as top event, ETA infers the consequences of an accident according to different conditions. As a result, mitigation measures are developed. Bow-tie model shows the whole process of an accident as well as the links between its parts [10]. A bow-tie model is shown in figure 1.

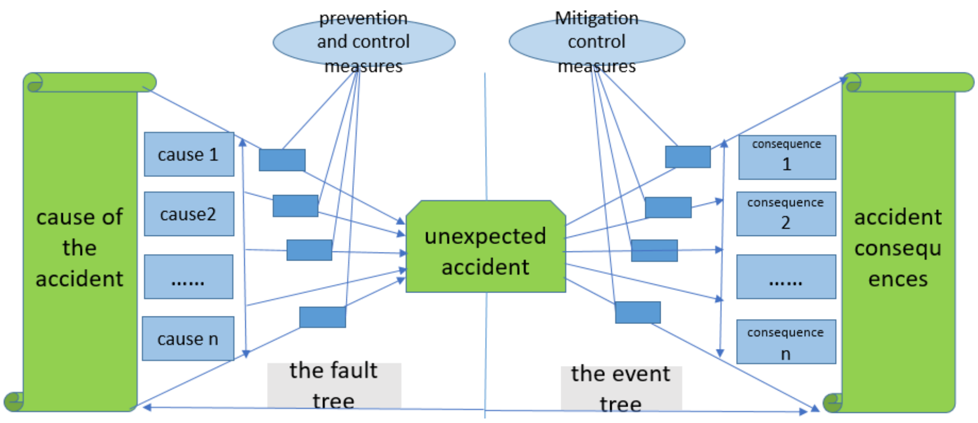

Figure 1. Bow-tie model diagram.

2.3. Improved bow-tie model

People usually choose the traditional one when applying the bow-tie model. However, it lists accident causes and consequences indiscriminately, making it difficult to identify then shoot problems. Therefore, the author proposes the improved bow-tie model. The improved bow-tie model analyzes accident causes from four aspects: human, materials, environment, and management. Then it develops prevention control measures accordingly to comprehensively identify higher risk factors with focuses on prevention and control. It also analyzes accident consequences from four aspects: casualties, property losses, environmental and social consequences. Then effective emergency rescue could be carried out to reduce the damage index using mitigation measures put forward by the model. The traditional bow-tie model only qualitatively analyzes events and their consequences. When conducting a risk analysis of urban gas pipeline network, the author made a statistical analysis on the causes and consequences and determined their quantities. Quantification can visibly show the causes more likely leading to gas pipeline network accidents and their more damaging consequences. When producing statistics on accident consequences, the type of an accident is determined by the aspect which has sustained the most damages. There are four aspects to consider, which are the previous listed casualty, property loss, environment and society. For example, a gas pipeline network failure is the most disastrous regarding casualties. When preparing statistics, the accident is categorized as one of accidents with casualties. The improved bow-tie model is shown in figure 2.

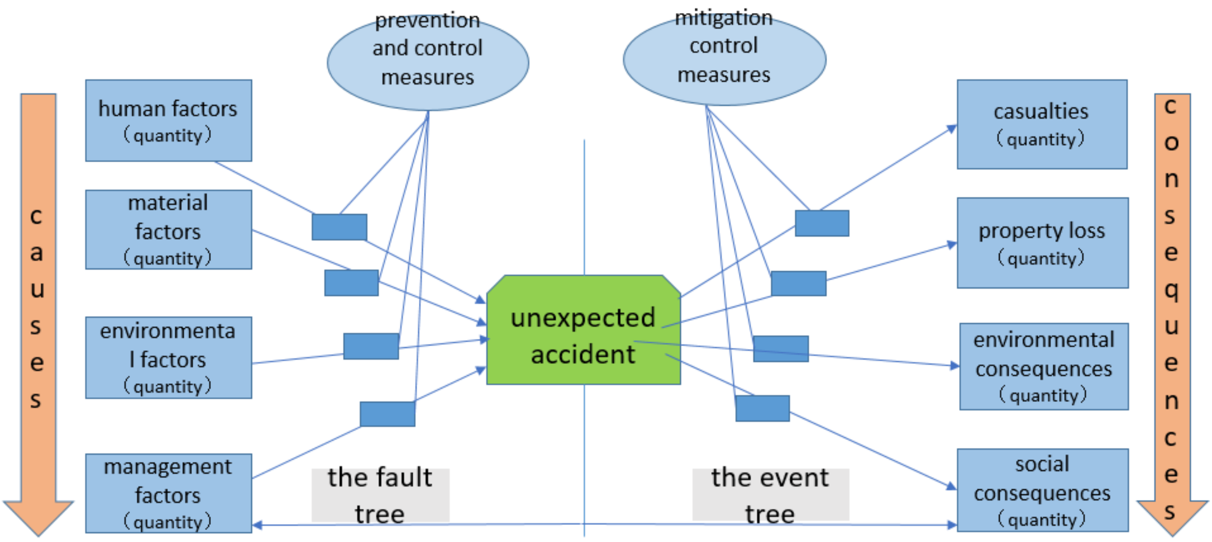

Figure 2. Improved bow-tie model diagram.

3. Analysis of urban gas pipeline failure

3.1. Fault tree analysis of gas pipeline failure

At present, in many cities and towns of China, a large amount of aged gas pipeline networks are still running. And a large number of new pipeline networks continue to be built. This has led to many gas pipeline network failures. They have brought grave losses to people's lives, property loss, environment, and society. Therefore, it is necessary for the author to conduct an analysis of urban gas pipeline network failure.

In order to conduct a fault tree analysis of urban gas pipeline network failure, the author has built a fault tree as shown in figure 3.

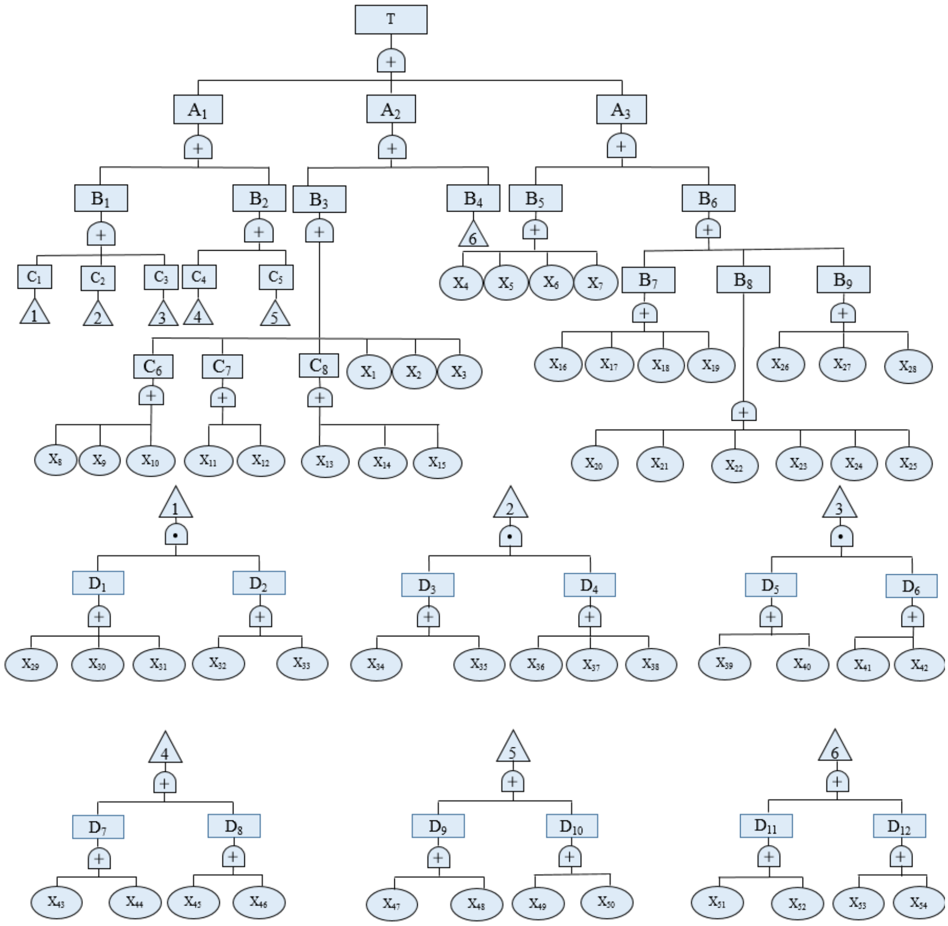

Figure 3. Leakage accident tree of gas pipe network.

Risk factors are identified by fault tree analysis of urban gas pipeline network failure. The events represented by specific symbols are shown in table 1.

Table 1. Urban gas pipeline network leakage accident tree symbol representative event.

serial number	basic event	serial number	basic event	serial number	basic event
T	pipeline leakage	X_1	natural disasters	X_{34}	acidic medium
A1	pipeline perforation	X_2	unintentional damage	X_{35}	water in pipe network
A2	pipeline rupture	X_3	deliberate destruction	X_{36}	poor quality of internal corrosion coating
A_3	related accessories leaked	X_4	internal overpressure	X_{37}	corrosion inhibitor failure
B_1	pipeline corrosion	X_5	film or pressure tube vibration damage	X_{38}	aging and damage of inner coating
B_2	pipeline defect	X_6	film aging	X_{39}	corrosive gases

					in the atmosphere
B_3	third party damage	X_7	gasket damage	X_{40}	high humidity and temperature
B_4	mechanical failure	X_8	pipeline network is not clear	X_{41}	coating repair, replacement is not timely
B_5	voltage regulator leakage	X_9	illegal construction	X_{42}	coating aging
B_6	valve leakage	X_{10}	construction error	X_{43}	uneven grain size
B_7	stem defect	X_{11}	not found in time	X_{44}	improper selection
B_8	screw defect	X_{12}	not timely treatment	X_{45}	uneven deformation
B_9	valve defect	X_{13}	uneven bottom	X_{46}	serious welding defects
C_1	buried corrosion	X_{14}	failure to take necessary protective measures	X_{47}	welding defect
C_2	internal corrosion	X_{15}	not according to actual traffic intensity design	X_{48}	welding material defect
C_3	atmospheric corrosion	X_{16}	stem deformation by external force	X_{49}	mandatory installation
C_4	pipeline quality defect	X_{17}	stem severely corroded	X_{50}	large fault between pipe segments
C_5	improper construction	X_{18}	stem wear	X_{51}	security system design is not reasonable
C_6	construction failure	X_{19}	filler filling is not standard	X_{52}	system design safety factor is small
C_7	illegal tying	X_{20}	nuts loosening	X_{53}	soil settlement
C_8	traffic damage	X_{21}	bolt pretightening force is not uniform	X_{54}	installation stress
D_1	soil corrosion environment	X_{22}	Insufficient bolt pretightening force		
D_2	external corrosion failure	X_{23}	incorrect gasket mounting		
D_3	internal corrosion environment	X_{24}	gasket aging		
D_4	internal	X_{25}	insufficient gasket		

	corrosion failure		
D_5	corrosive atmosphere	X_{26}	improper valve body
D_6	failure of protective measures	X_{27}	severe corrosion of valve body
D_7	material defect	X_{28}	valve manufacturing defects
D_8	poor rolling process	X_{29}	chemical corrosion environment
D_9	pipeline welding	X_{30}	electrochemical corrosion environment
D_{10}	pipeline installation	X_{31}	microbial corrosion environment
D_{11}	low pressure bearing capacity	X_{32}	cathodic protection failure
D_{12}	pipe network under high stress	X_{33}	coating failure

By analyzing the fault tree of urban gas pipeline network failure layer by layer, the basic event could be found. First, it needs to find key control points and key prevention stages of the accident. Then, it is possible to qualitatively analyze the probability of the accident. Finally, appropriate prevention and control measures could be developed based on the analysis results.

3.2. Event tree analysis of gas pipeline failure

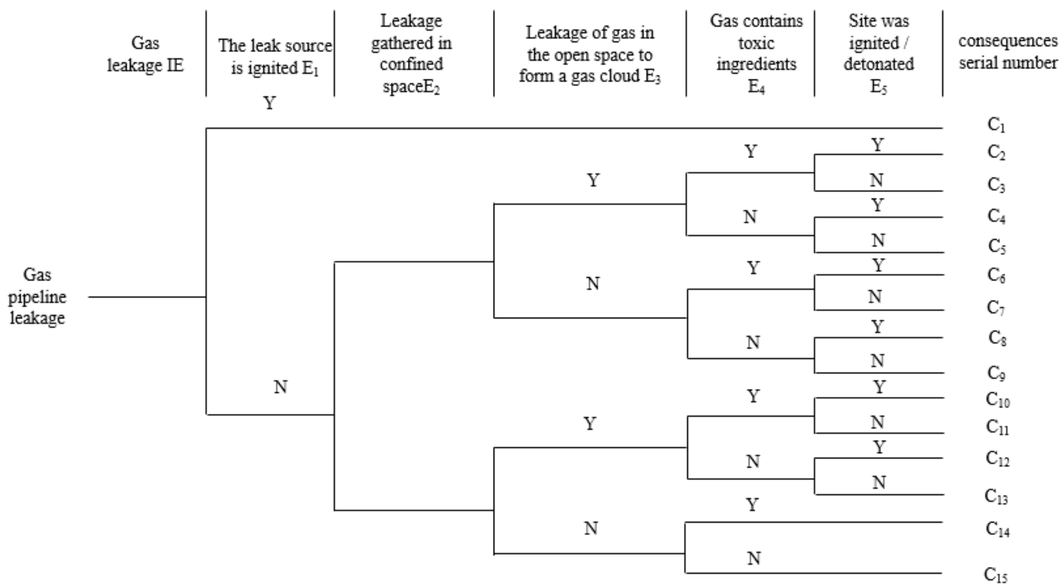

Figure 4. Gas pipeline leakage consequence event tree.

In different environment and under different conditions, the accident consequences will be different as well. By analyzing the event tree of urban gas pipeline network failure, accident consequences under different environmental conditions are found. Gas pipeline leakage consequence event tree is shown in Figure 4.

Events in the event tree of gas pipeline network failure are represented by symbols shown in table 2.

Table 2. Urban gas pipeline network leakage incident tree event.

event sequence	consequence event	event sequence	consequence event
C_1	jet fire, fire	C_9	Explosion hazard, suffocation
C_2	confined space explosion, steam cloud explosion, poisoning	C_{10}	steam clouds explode, fire
C_3	poisoning, suffocation, explosion hazard	C_{11}	poisoning, explosion hazard
C_4	confined space explosion, steam cloud explosion	C_{12}	steam clouds explode, fire
C_5	suffocation, explosion hazard	C_{13}	gas loss, explosion hazard
C_6	confined space explosion, fire, poisoning	C_{14}	poisoning, gas loss
C_7	Poisoning, explosion hazard, suffocation	C_{15}	gas loss, diffusion
C_8	confined space explosion, fire		

By analyzing the event tree, it is found that a pipeline network failure can cause grave consequences such as fire, vapor cloud explosion, suffocation, and poisoning in different environmental conditions. Especially in densely populated urban areas, these consequences could bring immeasurable losses to people and environment, creating uproar in society.

4. Application of improved bow-tie model in risk analysis of urban gas pipeline network failure

4.1. Building of improved bow-tie model of gas pipeline network failure

In order to better understand urban gas pipeline network failure, it needs to build an improved bow-tie model to comprehensively analyze it.

- Identify the top event

A wide variety of pipeline networks are laid out in densely populated urban areas. Aged pipeline network, occupied infrastructure, and others all could cause pipeline failure. As a result, the gas pipeline network failure is identified as the top event (or an unexpected event).

- Identify the initiating events

By analyzing the fault tree of gas pipeline failure, the event causes are identified. According to the improved bow-tie model, the initiating events are divided into four categories: human, materials, environment and management. This paper suggests analyzing the event causes from four aspects: 1) human-made mistakes when operating; 2) flaws in pipeline network; 3) disasters in environment; 4) lack of regular checkup by the management.

- Develop prevention and control measures

In view of each type of accidents that have been identified, appropriate prevention and control measures need to be developed to prevent accidents and reduce the accident rate.

- Identify the outcome risk

A pipeline network failure can cause grave consequences such as fire, explosion, suffocation, and poisoning. According to the improved bow-tie model, the accident consequences are to be analyzed

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and identified from four aspects: casualties, property losses, environmental and social consequences.

- Develop mitigation and control measures

According to the probable consequences of the accident, corresponding mitigation measures need to be developed in order to minimize losses caused by the accident and to mitigate damages done to people, property, environment, and society.

- In light of steps performed above and the statistics of 223 incidents of gas pipeline network failure of city X in the period of two years, the author has built an improved bow-tie diagram of gas pipeline network failure as shown in figure 5.

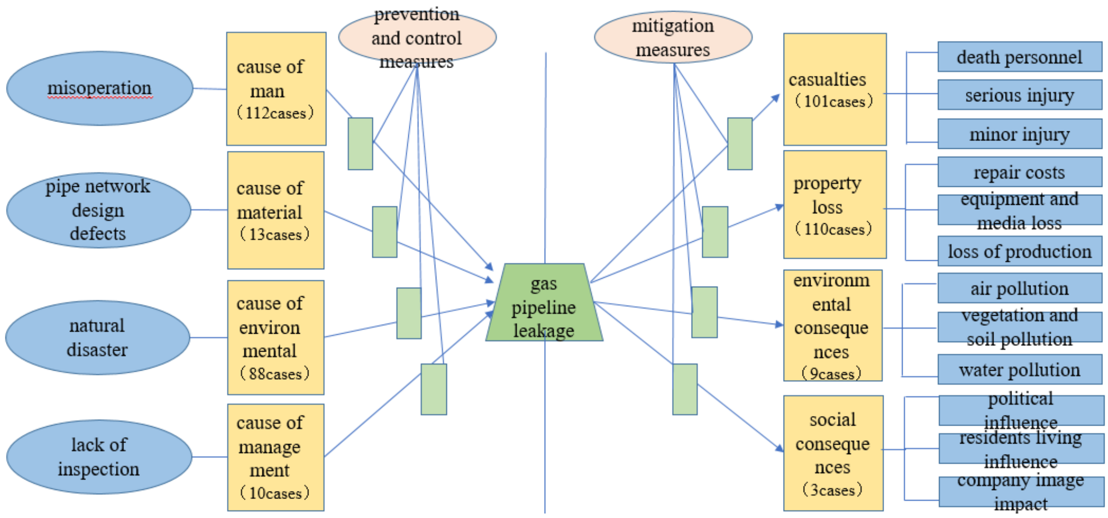

Figure 5. Improved bow-tie model for leakage accident of gas pipeline network.

4.2. Risk Analysis Based on Improved Bow-tie Diagram

- Human-made mistakes when operating

By conducting a risk analysis of urban gas pipeline network failure based on improved bow-tie model, it is found that if people make mistakes leading to accidents, it is usually because of lack of safety knowledge, awareness, skills, and incompetence on the part of personnel. They can manifest in forms of improper and even illegal operations and constructions. Among them, inappropriate operation is the most common. Under certain conditions, these risk factors made by human could lead to gas pipeline failure, fire, explosion, and other major disasters, resulting in grave consequences.

- Prevention measures

To avoid human-made mistakes, appropriate prevention and measures need to be developed. Regular safety training and education can make employees take safety issues more seriously by exposing them to more safety lessons. Regular assessment of employees can help make sure that tasks are manned by capable people with certificates.

- Flaws in pipeline network

Accident causes regarding flaws in pipeline network are generally design flaws, technical defects, welding and construction defects, pipe, equipment, device, too accessory defects, and corrosion failure. They manifest in the pipes made of inferior materials and techniques, pipeline network aging, design and construction flaws, poor network design, and cracks in shoddy welding work. Among them, design flaw in pipeline network is the most serious.

- Prevention measures

Strict quality control is recommended to ensure the quality of the pipe network. Implementing strict guidelines and using quality materials in welding work can improve its overall quality. Then serious welding defects can be avoided. Clear design of pipeline network can prevent accidents from happening.

- Disasters in environment

Environmental causes leading to urban gas pipeline network failure include interference by other pipeline networks, human-made environment such as theft of devices and equipment, external environment such as lack of protection measures, and natural environment such as floods and earthquakes. Among them, natural disasters are the most serious.

- Prevention measures

Strengthening the supervision and protection of the network can prevent the theft of equipment and devices. Adequate protection should be given to the pipeline network. There should be emergency preparedness and contingency plan in place in case of an emergency to reduce accident loss and control damages to the pipeline network.

- Lack of regular checkup by the management

Defects in the management of pipeline network also can cause accidents in pipeline network. Command defects in the organization, safety training and education deficiencies, fire management defects, and lack of regular inspection and checkups can all lead to accidents. Among them, inadequate inspection is the most serious.

- Prevention measures

Effective organization and command system are needed. Employees are required to attend trainings on safety management to recognize responsibilities towards management and protection. Regular and effective inspections of pipeline network should be carried out to reduce the accident rate.

In case of an urban gas pipeline network failure, it will bring grave consequences to people’s lives and safety, society, and environment. It is very likely to cause deaths, serious and minor injuries, and environmental pollution, which will affect the normal life of residents and cause adverse social effects. In order to reduce the accident rate and loss, we should pay attention to promote public safety awareness and detect and address problems in time.

5. Conclusions

Urban gas pipeline network failure is a major safety concern. In the event of an accident, there could be grave damages and consequences. This paper uses the improved bow-tie model to conduct a risk analysis of urban gas pipeline network failure and draws the following conclusions:

- The bow-tie model perfectly combines quality features of both FTA and ETA. It clearly analyzes causes and consequences of an accident, then develops prevention and mitigation measures accordingly;
- The improved bow-tie model conducts a risk analysis of urban pipeline network failure by analyzing accident causes and consequences from four aspects respectively. The four aspects of accident causes are people, materials, environment, and, management; the four aspects of accident consequences are casualty, property loss, environment, and, society.
- The improved bow-tie model is ideal for risk analysis of urban gas pipeline network failure. It can analyze its cause risks and consequence risks. And it can develop prevention and mitigation measures accordingly to eliminate these causes and consequences. The whole process can be shown dynamically.
- Through the use of improved bow-tie model for urban gas pipeline network risk analysis, we can know that human causes are the most important factors in the causes of gas pipe network leakage, followed by environmental factors such as corrosion, we should focus on these two aspects of prevention and control to reduce the incidence of accidents better. Gas pipe network leakage, resulting in casualties, property loss is more serious, we should mainly from these two aspects to develop mitigation measures to reduce the impact of accidents.

The improved bow-tie model is easy-to-understand, clear, and practical, so that people can understand the causes and consequences of an accident simply by reading the figures it provides. It is of great significance to the analysis of gas pipeline network failure.

Acknowledgments

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