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Risk analysis of emergency response to community gas pipeline leaks using AcciMap and the STAMP model

Jiahao Liu

College of Safety and Ocean Engineering, China University of Petroleum (Beijing), China. Key Laboratory of Oil and Gas Safety and Emergency Technology, Ministry of Emergency Management, China. E-mail: 1505751124 @qq.com

Jinqiu Hu*

College of Safety and Ocean Engineering, China University of Petroleum (Beijing), China. Key Laboratory of Oil and Gas Safety and Emergency Technology, Ministry of Emergency Management, China. E-mail: hujq @cup.edu.cn

Shaohua Dong

College of Safety and Ocean Engineering, China University of Petroleum (Beijing), China. E-mail: shdong @cup.edu.cn

Jiancheng Shi

College of Safety and Ocean Engineering, China University of Petroleum (Beijing), China. Key Laboratory of Oil and Gas Safety and Emergency Technology, Ministry of Emergency Management, China. E-mail: 316402969 @qq.com

Sanfeng Yang

College of Safety and Ocean Engineering, China University of Petroleum (Beijing), China. Key Laboratory of Oil and Gas Safety and Emergency Technology, Ministry of Emergency Management, China. E-mail: 962234370 @qq.com

In communities, the frequency of gas pipeline leakage incidents is maintained at a high level due to the complex human and architectural environment of urban communities, as well as the widespread use of the pipelines. When a leak occurs in a gas pipeline, the gas company and the relevant departments need to carry out emergency response. As the response process involves personnel, emergency resources, repair equipment and coordination of social organizations, these uncertainties lead to the existence of risks in the emergency response process. In terms of risk analysis, the AcciMap and STAMP models are currently the most representative methods of systematic analysis. The feasibility of both models in a wide range of industries has been demonstrated in the research literature. However, despite their advantages, their research on risk analysis during emergency response has been limited so far. The aim of this study is to use the AcciMap and STAMP models to identify risk factors during emergency response to the leakage of community gas pipeline, and to compare the variability of the two models for gas pipe leak emergency response. STAMP was used to obtain the failure factors, unsafe control, safety constraints and psychological causative factors, and AcciMap was used to obtain six levels of risk factors. The comparison of the results revealed that the two models have complementary factors, with AcciMap capturing more soft factors in terms of government legislation, social culture, and management, while STAMP more precisely analysed the risk factors that directly lead to system failure.

Keywords: Community gas pipelines, emergency response, leakage, risk analysis, AcciMap, STAMP.

1. Introduction

City gas pipelines are responsible for transporting gas and are one of the important facilities in cities and towns. As urbanization accelerates and the government popularizes the use of gas, the risk of leaking from city gas pipelines is gradually increasing. Xing et al. (2020). Urban communities are the main target of city gas supply, and due to their complex human and architectural environment, leak in community gas pipelines are relatively easy to derive into accidents. According to accident statistics, communities account for more than 50% of gas pipeline accidents in Beijing, with more than 300 accidents occurring last year alone, seriously affecting the safety of people and property.

Emergency response to leakage of pipelines is an important tool to prevent accidents from occurring, and the emergency response process involves the interaction of multiple social levels, people, and objects, constituting a complex system. There are many hidden risks in the emergency response process for leakage of community gas pipeline, and there have been cases where risks in the emergency response process have led to leakage of pipeline becoming accidents resulting in injuries and fatalities. For example, a major gas explosion in Shiyan, Hubei due to gas pipeline corrosion leak disposal is not timely, resulting in the leakage of natural gas gathered in the confined space, met with the restaurant merchants exhaust fumes pipe discharge sparks explosion, resulting in 16 deaths, 138 people were injured, resulting in direct economic losses of 53.95 million yuan. However, there is a lack of analysis of the risks. Therefore, it is important to study the emergency disposal process and its risks, reduce the mistakes of emergency disposal, and prevent the occurrence of gas pipeline accidents to ensure the smooth emergency disposal of leakage of pipeline.

The Accident Mapping (AcciMap) and the Systems Theoretic Accident Model and Processes (STAMP) are the most representative system analysis method. Svedung and Rasmussen (2002). Leveson (2004). Compared with traditional risk analysis methods such as Fault Tree Analysis, they can analyse risk factors systematically and the analysis results are more comprehensive. These two methods have been well applied in a wide range of fields. Qiao et al. used the STAMP model to analyse major accidents in coal mines and obtained a more comprehensive picture of the causes of accident risk in addition to equipment defects and personnel irregularities. Qiao et al. (2021). Xing et al. proposed an accident model for urban pipelines based on the STAMP model and found that a more in-depth accident conclusion could be drawn. Xing et al. (2020). Zhao et al. used AcciMap to analyse the risk-causing factors of construction elevators from a superficial to a deeper level, and thus obtained the specific control contents of construction elevator construction. Zhao et al. (2022).

Although AcciMap and STAMP models have been well used in a wide range of fields, their application in emergency disposal risk analysis is limited. In order to identify the risk factors in the emergency disposal process of community gas pipeline leakage to reduce the process errors and prevent accidents, the risk analysis is performed. Due to uncertainty about the effectiveness of STAMP and AcciMap models in the application of emergency disposal risk analysis, two models were used to conduct risk analysis of community gas pipeline leakage risk disposal, respectively. Meanwhile, the effectiveness and difference of their application in this regard were analysed by comparing the analysis results of the two models.

The remainder of the paper is organized as follows: Section 2 provides a brief discussion of STAMP and AcciMap and details the methodology. Section 3 is a case study to illustrate the application of the methods to emergency response to community gas pipeline leaks. Section 4 provides a discussion of this work.

2. Methodology

Systems accident models are the mainstream paradigm of accident models. Traditional methods, such as fault tree, event tree, and bow-tie, treat the accident evolvement as a linear process. An accident is usually modeled as an event chain, and the interactions of multiple stakeholders in a complex social-technical system are difficult to be captured. While systems accident models regard the system as a whole rather than considering a single or some components in the system in isolation. The analysis results of the systems accident models are comprehensive. Zhang et al. (2022).For two models, a summary of comparison according to the systems theory criteria (i.e., system structure, system components, and system component relationships) and application criteria (i.e., reliability, usability, and graphical representation) is provided in Table 1. Rad, Lefsrud, and Hendry. (2023).

Table 1. Comparison of the AcciMap and STAMP methods.

Criteria sub-category	AcciMap	STAMP
System structure	Hierarchical	Hierarchical
System components	Human, organizational, and technical factors Considers intra-organizational factor	Human, organizational, and technical factors Considers intra-organizational factor
System components relationships	Between and within system levels	Between and within system levels
Reliability	Medium	Medium
Usability	Medium	Medium
Graphical representation	High	Low

2.1.STAMP

In 2004, Leveson et al. first proposed the STAMP model for system security analysis, which starts from the system theory and considers security control as the main factor to ensure the security of the whole system. Leveson (2004). The three main components of STAMP model are security constraints, hierarchical security control structure, process model. In STAMP, the source of system risk is not the misoperation of personnel or the failure of components, but the ineffective safety constraints, which will lead to the source of system risk causation. Altabbakh et al. (2014).

The hierarchical security control structure is a necessary step of the STAMP model (see Fig.1). In this case, the higher hierarchy is responsible for the performance of the next level by enforcing security constraints on the lower hierarchy. The lower level needs to provide feedback on the successful implementation or failure of these security constraints. Thus, lack of constraints, inadequate operation of security controls, and restricted feedback are the main causes of system risk, and in addition, the occurrence of problems such as sabotage external to the system may also lead to problems in system security. The process model is a feedback-based high-level subsystem decision-making process that corrects the internal state of the system and maintains the dynamic equilibrium of the system. Han et al. (2022).

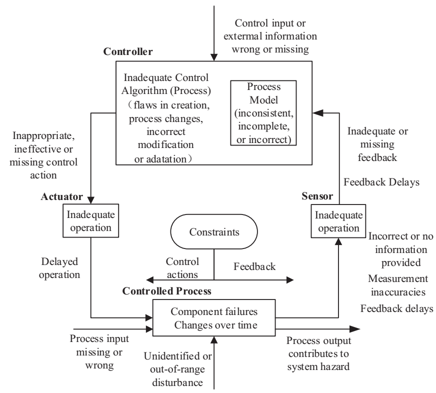

Fig. 1. Hierarchical security control structure. Altabbakh et al. (2014).

2.2.AcciMap

The AcciMap model is derived from Rasmussen's risk management framework, which addresses all system levels of operational and security management. The AcciMap model assumes that risk throughout the system is controlled through laws, rules, and directives, and that each system level is involved in risk management. In order for the system to operate safely, decisions made at higher levels are passed on to lower levels and reflected in actions and decisions at lower levels. In addition, information at lower levels involving the state of the system needs to be fed upward to inform higher level decisions and actions. Salmon et al. (2012).

The AcciMap model focuses on the following Six levels of activity: Government, Regulators, Company, Management, Operators, Environment and Equipment. The AcciMap safety risk management framework is shown in Figure. 2. Considering that the regulatory function in China is mainly undertaken by relevant government departments and the adaptability of each level in the gas field. Therefore, it is combined and improved into five levels: Government and related departments, Gas company, Emergency response team and resource management, Emergency responders, Environment and Equipment.

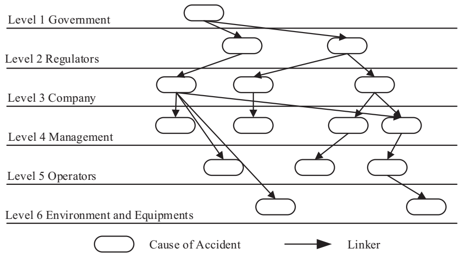

Fig. 2. AcciMap safety risk management framework. Zhao et al. (2022).

3. Risk Analysis

In the process of emergency response and disposal of leakage of community gas pipeline. First of all, the pipeline leaks and personnel find the leak and alert the gas company's emergency alarm room, which needs to be recorded and immediately reported to the company's operation and dispatch centre after receiving the alarm information, which carries out different levels of emergency response according to the emergency situation and should immediately contact the local company for on-site control of the leak site. Then, the company will coordinate its internal emergency response team, emergency resources, emergency experts and external social resources to prepare for the emergency disposal work. The local company will conduct temporary control and exploration at the site and provide timely feedback to the operation and dispatch center so that the dispatch center and company leaders can make further decisions and plans. The gas company, the local company and the social forces work together to carry out the emergency disposal of community gas pipeline leaks, exchanging and cooperating with each other during the period, and ending the emergency after the disposal has reached the end of the emergency criteria.

3.1.*STAMP*

The hierarchical security control structure for the leakage of community gas pipeline emergency response is shown in Fig. 3. Physical layer analysis, basic layer analysis, and operational layer analysis of the emergency disposal process based on the risks that may be brought to the emergency disposal process of leakage of community gas pipeline.

3.1.1.*Physical layer analysis*

For the physical layer of the emergency disposal process, it mainly includes the site control equipment of the local company's emergency disposal team, the gas concentration detection of the control group and the pipeline repair equipment of the technical group. The emergency disposal team needs to first carry out emergency control work on site, including pipeline positioning, gas concentration detection, alert zone delineation and other work, involving equipment including pipeline diagrams and files, combustible gas detectors, alert lines and so on. Control needs to control the emergency site to prevent the gas concentration from being too high derived into an accident, involving equipment including combustible gas detectors, ventilation apparatus and other equipment. The technical team is responsible for pipeline positioning, leak finding and leak repair, etc. The equipment involved includes earthwork tools, pipe detectors, perforating machines and other equipment. The results are shown in Table 2.

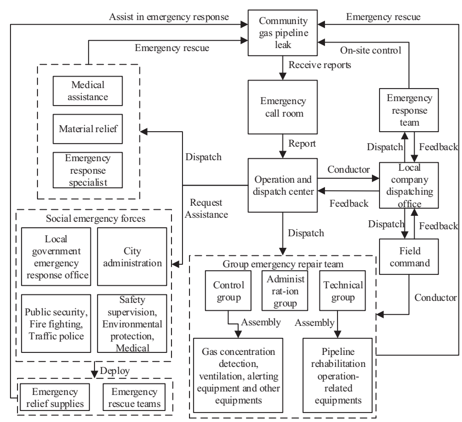

Fig. 3. The hierarchical security control structure for the leakage of community gas pipeline emergency response.

3.1.2.*Basic layer analysis*

For the basic layer of the emergency disposal process, it mainly includes the emergency response duty room, the site command and emergency disposal team of the local company, the emergency disposal site control group, the technical and administrative group and the social rescue force. The site command needs to make decisions on the overall work of the site, supervise the site work and feedback the site situation. The administrative group is responsible for press releases, proper handling of gas supply affecting users, etc. The results are shown in Table 3.

3.1.3. *Operational layer analysis*

For the operation layer in the process of emergency disposal, it mainly includes the operation and dispatch centre of the company and the dispatch office of the local company. The company's operation and dispatching centre is mainly responsible for the command of work conditions and resource dispatching, and the staff support for on-site command and decision making. The local companies are mainly responsible for information feedback, on-site emergency control and assistance to complete the emergency disposal work. The results are shown in Table 4.

Table 2. The results of physical layer analysis.

Failure Factors	Insecure Control	Security Requirements and Constraints
Equipment for Emergency Response Team	(i) Equipment failure, can not effectively complete the site control work (ii) The lack of pipeline drawing file information in the local company	(i) Regular maintenance and inspection of equipment (ii) Gas companies to improve the relevant information preparation procedures
Equipment for Control Group	(i) Equipment failure, can not effectively complete the field control work (ii) Some equipment without explosion-proof function	(i) Regular maintenance and inspection of equipment (ii) May produce ignition source equipment using explosion-proof equipment
Equipment for Technical Group	(i) Equipment failure, can not effectively complete the pipeline repair work (ii) Some equipment without explosion-proof function	(i) Regular maintenance and inspection of equipment (ii) may produce ignition source equipment using explosion-proof equipment

Table 3. The results of Basic layer analysis.

Failure Factors	Insecure Control	Security Requirements and Constraints	Psychological Causes	Decision-making environment
Emergency call room	(i) The receiving officer does not receive the alarm information in time, resulting in a lack of timely emergency response (ii) Not reported to the company's operation and dispatch centre in a timely manner, resulting in a delayed emergency response	(i) Regular emergency training to improve emergency skills (ii) Develop standard specifications for emergency response processes	(i) An avoidance mentality regarding the potential liability that may result from the activation of emergency procedures (ii) There is a fluke information about the alarming information of the alarming personnel	Production Metrics driven
Emergency Response Team	(i) Failure to execute the orders of the territorial company in a timely manner (ii) Unskilled in emergency procedures and lagging behind in action (iii) Unskilled use of equipment	(i) Regular emergency training to improve emergency skills (ii) Regular skills training and assessment of personnel	(i) A sense of luck about the size of the spill (ii) Not realizing the importance of emergency response	Emergency Skills assessment is not in place

Table 3 (Continued). The results of Basic layer analysis.

Failure Factors	Insecure Control	Security Requirements and Constraints	Psychological Causes	Decision-making environment
On-site Command	(i) Failure to execute the orders of the territorial company to participate in the field command in a timely manner (ii) Failure to make decisions on site (iii) No timely feedback on site conditions	(i) Participate in emergency drills and familiarize themselves with emergency procedures (ii) Conduct training related to emergency decision-making	(i) An avoidance mentality regarding the potential liability resulting from emergency response (ii) The existence of a fluke mentality about the incident emergency	Production Metrics driven
Control Group	(i) Not being prepared to make emergency response in the first place when receiving instruct-ions (ii) Unskilled in the emergency disposal process and unable to complete it quickly according to the emergency plan (iii) Unskilled in the use of equipment, unable to effectively control the situation on site	(i) Regular emergency drills to improve emergency skills (ii) Skills assessment and training, personnel licensed to work	(i) A fluke mentality about the incident emergency (ii) Slack personnel, negative response to emergency	Emergency Skills Assessment is not in place
Technical Group	(i) Not being prepared for emergency response in the first place when instructed to do so (ii) Insufficient experience in emergency response to develop a timely pipeline rehabilitation program (iii) Insufficient skills or unskilled use of equipment to complete the pipeline rehabilitation work in accordance with regulations	(i) Conducting regular emergency drills to improve emergency response skills (ii) Develop pipeline rehabilitation programs and training and assessment	(i) The existence of a fluke mentality about the incident emergency (ii) lower psychological quality of personal operational panic did not meet the operational requirements	Emergency Skills Assessment is not in place
Administrat-ion Group	(i) Failure to go to the scene in time to make emergency actions that may cause confusion in public opinion. (ii) Insufficient experience and misunderstanding of the scene disposal situation	(i) Regular emergency drills to improve emergency skills (ii) Strengthen industry emergency knowledge learning	Failure to recognize the potential for subsequent derivative accidents resulting from pipeline leaks	Emergency Skills Assessment is not in place
Social rescue force	Inexperienced, unable to respond quickly and in an orderly manner when instructed	Local government departments to develop special emergency plans for gas leaks and regular training drills	Insufficient awareness of the nature and potential dangers of gas pipeline leakage incidents	Safety Responsibility drive

Table 4. The results of Operational layer analysis.

Failure Factors	Insecure Control	Security Requirements and Constraints	Psychological Causes	Decision-making environment
Operation and dispatch centre	(i) Misjudgement of the level of emergency events; (ii) Inadequate emergency supplies and personnel security (iii) unreasonable emergency decision-making; (iv) Delayed information flow	(i) Develop criteria for judging emergency response levels (ii) Strengthening the construction of emergency response teams and resources (iii) Improve the communication mechanism at all levels	(i) There is a mentality of avoidance of responsibility for mistakes arising from the emergency (ii) There is a fluke information about the emergency of the situation	Safety production responsibility drive
Local company dispatching office	(i) The local company's emergency personnel and materials are not in place (ii) No timely decision support and feedback information for on-site disposal	(i) Strengthen the construction of emergency response teams and resources (ii) Regular participation in emergency drills to improve the quality of emergency decision-making (iii) Improve communication mechanisms at all levels	(i) There is a mentality of avoidance of responsibility for the mistakes arising from the emergency (ii) There is a fluke information about the emergency of the situation	Safety production responsibility drive

3.2.*AcciMap*

The AcciMap model for emergency response to community gas pipeline leaks is shown in Fig.4 The model describes the risk causal factors involved and categorizes them into five levels. The first is the government and related departments level. The soundness of the government's safety management system affects the industry safety climate and production safety responsibilities of gas companies, which in turn affects the safety and responsibility awareness of emergency response teams and resource management personnel. Whether the government has developed a special emergency plan for gas leaks will directly affect the safe operation of government emergency personnel, which will be reflected in aspects such as traffic fluency. Whether government supervision and inspection are in place will directly affect the safety management system of the gas company, which is reflected at the company level in the review of personnel qualifications and the preparation of emergency plans. In addition, the government's review and filing of the gas company's emergency plans will further improve the quality of the gas company's emergency plan preparation and implementation.

Whether the gas company conducts an emergency disposal process risk analysis and emergency response, as well as the timeliness of its communication mechanisms will affect the safe operation of field commanders. This will be reflected in the response to emergencies such as inclement weather, stability of earth structures, and the identification of hidden hazards such as ignition sources and equipment. The importance that the gas company places on emergency response and the completeness of existing plans will affect the management aspects of the emergency response team and equipment, which in turn will affect the safe operation of emergency personnel. In addition, the importance that emergency team management places on safety inspections, specific construction plans, and safety technical briefing training will also directly affect the safe operation of emergency personnel and the condition of equipment.

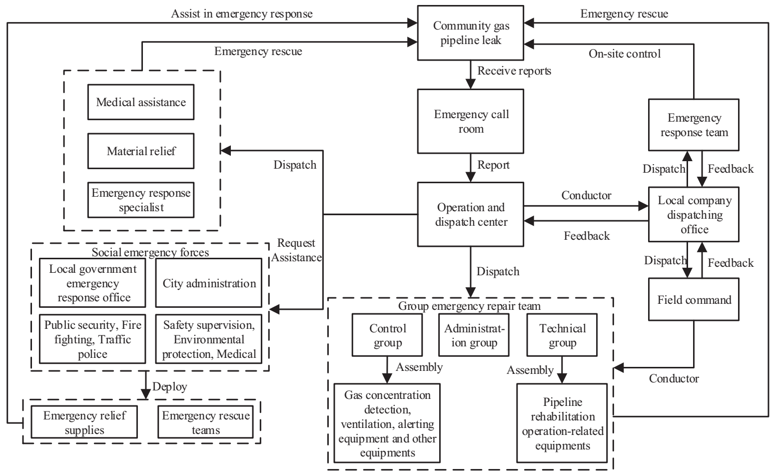

Fig. 4. The AcciMap model for the leakage of community gas pipeline emergency response.

4. Conclusion

In this paper, risk analysis is performed in order to identify the risk factors in the emergency disposal process of community gas pipeline leakage in order to reduce the mistakes in the process and prevent accidents. Due to the uncertainty of the effectiveness of STAMP and AcciMap models in the application of emergency disposal risk analysis, the risk analysis of community gas pipeline leakage risk disposal was carried out using two models respectively. The study shows that both models are comprehensive in terms of risk identification results. While each method has produced its own results, there was the element of being complementary to each other. The AcciMap model captures more of the soft factors of government legislation, social culture, and management and links them to other levels because it defines such levels as Government and Regulators. While STAMP defines concepts such as unsafe control, security constraints and hierarchical security controls, he is more precise and detailed in analysing risk factors that directly lead to system failure and their security constraints.

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