Causation Analysis and Resilience Governance of Production Safety Accidents:A Case Study of 83 Gas Production Explosion Accidents

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Abstract. Safety production is related to the well-being of people, social prosperity and stability. It is a comprehensive reflection of the government's supervision capacity. This paper summarises the causal factors of gas explosion safety production accidents based on 83 reports. The causal factors are categorised into five levels: personnel, equipment, environment, business management, and government supervision. Through data statistics, the key and important causal factors of gas safety production accidents are identified and analysed. The paper also examines the differences between the key causal factors of three types of gas safety production accidents. The SPSS software was used to analyze the strength of association between the factors at each level. The results revealed the risk transmission path of safety production between the government's ineffective supervision, the enterprise's insufficient safety awareness, and the employee's improper operation. The research findings propose a new approach to enhance the comprehensive management capacity of the safety production system from the perspective of resilience governance. This promotes the development of the traditional risk governance model from passive and negative to multi-angle virtuous development, such as sustained adaptation, proactive error correction, systematic learning and multi-dimensional cooperation.

Keywords: Safety production; Accident causation; Resilience governance

1 Introduction

As urbanization continues, cities face a variety of complex risks, including production safety accidents and emergencies. Despite a sustained positive trend in China's production safety in recent years, there are still two major gas explosion accidents causing significant casualties that have attracted widespread attention. One in 2021 at the Yanhu community market in Zhangwan District, Shiyan City, Hubei Province, and the other in 2023 at the Fuyang barbecue in Yinchuan, Ningxia. These incidents underscore the importance of ongoing efforts to improve production safety in China. It is important to note that production safety is a shared responsibility between business management and the government supervision. Serious safety production accidents can result in widespread injuries that businesses may not be able to handle alone. Therefore, it is important for the government to take responsibility for ensuring production safety, as this is crucial for maintaining public security in the city.

The governance of urban public safety aims to enhance the investigation and remediation of risks and hazards in production safety, and prevent various types of accidents from occurring.

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However, it is impossible to predict and avoid all risks due to the limited cognition of the human mind. Therefore, when accidents are inevitable, reducing their impact on the urban system in a prepared and strategic way becomes an important trend in urban public safety governance [1]. Additionally, continuously improving the resilience of the urban system is crucial. Urban resilience governance refers to a governance model established by public governance subjects based on cooperative governance and organizational learning mechanisms to enhance their own adaptive capacity and that of their cities to cope with the impacts of compound disasters[2]. Organizational learning is the core mechanism to ensure the long-term promotion of resilience governance. Identifying the causes of accidents is crucial for effective organizational learning, experience accumulation, and prevention of similar accidents[3][4]. This is particularly important in the field of production safety, where scientific analysis of the causes of accidents is necessary for targeted prevention, control, and management of related safety risks and hazards.

This paper analyzes the causes of 83 gas production safety accidents and the common governance problems exposed in the accidents through investigation reports. The paper proposes the idea of resilience governance of safety production from the perspective of resilience governance to prevent accidents, reduce their impact, and promote the orderly development of urban production safety governance.

2 Literature review

2.1 Research into the causes of production safety accidents

Accident causation theory is a theory about the causes of accidents, mechanisms, division of responsibility, and how to take preventive measures to prevent accidents from occurring[5].The theory of accident causation has evolved from a 'simple paradigm' of single-factor cognition to a 'complex paradigm' of multi-factor and systemic overall safety cognition. This shift has been driven by the development of social production and the depth of theoretical research[6].The accident causation model has evolved from a linear chain model to an interrelated net-like systematic causation model. Initially, during the industrial era, the model focused on unsafe actions of human beings and unsafe states of objects. However, it has now shifted to a comprehensive focus on human factors, physical factors, factors within the organization, and factors external to the organization[7], and the concept of system safety has gradually evolved.A number of studies and researchers have reviewed major oil and gas pipeline accidents, summarised the root causes and lessons learned, and proposed risk prevention and control countermeasures[8][9].The literature [10] analysed the evolution path of building fire accidents from individual and organisational levels, based on the '2-4' model of accident causation. The results showed that inadequate production safety management systems, such as the lack of a production safety responsibility system, hazard detection and management, and safety training, are the root cause of building fires. The direct causes of building fires are primarily violations of operational rules, irregularities in supervision and management responsibility, non-standardized production design, and insufficient safety knowledge and awareness[11]. It is important to note that subjective evaluations should be excluded unless clearly marked as such.

Previous research has systematically investigated the causes, mechanisms, and factors contributing to various types of accidents using accident causation theory. This provides a foundation for analyzing the mechanisms of production safety accidents[12]. However, most current research tends to focus on the technical level, rather than the governance level of accident prevention and effective system governance initiatives. This approach fails to prevent similar accidents from occurring both within and outside the system. Therefore, further in-depth research is required to address this gap.

2.2 Research related to resilience governance

Resilience is a term derived from the Latin word 'resilio', which means 'to bounce back'. The term 'resilience' is commonly used to describe the ability to recover from adversity. It has been translated as 'Elasticity' and 'Resilience' in various disciplines.In the mid-19th century, the concept of resilience was introduced to the field of mechanics as a form of 'Engineering Resilience'. This refers to an object's ability to return to its original state after being impacted by external forces. In 1973, ecologist Holling introduced the concept of 'Resilience' into ecology. The concept of 'Ecological Resilience' was later developed based on 'Engineering Resilience', which highlights a system's ability to absorb and adapt to external impacts [13].After the 1990s, resilience research has deepened and expanded, and the concept of resilience has gradually attracted the attention of researchers in various fields, including disaster science, psychology, public management, and urban planning. The multidisciplinary concept of 'evolutionary resilience' emphasises the sustained adaptive capacity, learning capacity, transformation capacity, and ability to change of social-ecological systems when subjected to external pressures[14].

In recent years, the idea of resilience has been widely applied to urban governance research and practice. The results of a study's systematic review of the literature for 2019 and 2020 confirm that urban resilience is a growing phenomenon with associated benefits for the well-being of citizens[15].Fallon proposes the development of a resilience governance framework for hydrological systems and suggests a shift in focus from the institutional structure to within the governance system[16].Haldane proposes elements of a framework for strengthening health system resilience by reviewing the responses of 28 countries during COVID-19[17]. Based on the evaluation indexes of domestic and international scholars, it was proposed that resilient cities should possess the following characteristics: social synergy, environmental resilience, technological intelligence, engineering redundancy, organizational self-organization, and institutional learning.

In general, previous studies on resilience have provided us with a good research perspective and theoretical basis for understanding and dealing with urban safety issues. To prevent and resolve security risks and improve urban safety, it is important to understand that production safety accidents cannot be attributed to a single person or factor[18]. Recurring accidents of the same kind are often caused by systemic deficiencies in the organization, society, culture, and other factors. Therefore, it is crucial to address these underlying issues to prevent future incidents[19]. From this perspective, the systemic characteristics of resilience governance, which emphasise the organisation's capacity for continuous adaptation, reflection and learning, fit well with the complex and uncertain risks and occasional occurrence of serious accidents that China's current stage of occupational safety governance faces. Therefore, it is necessary to start from the perspective of resilience governance, combined with the analysis of accident causation, to enhance the resilience of the safety production system and governance effectiveness in a targeted manner.

3 Research framework and data

3.1 Research framework

Drawing on the systematic safety ideas in previous accident causation studies[7][8][9][10], this paper categorizes the causes of gas production safety accidents into five levels: Personnel, Facility, Environment, Business Management and Government Supervision, as showed in Figure 1.

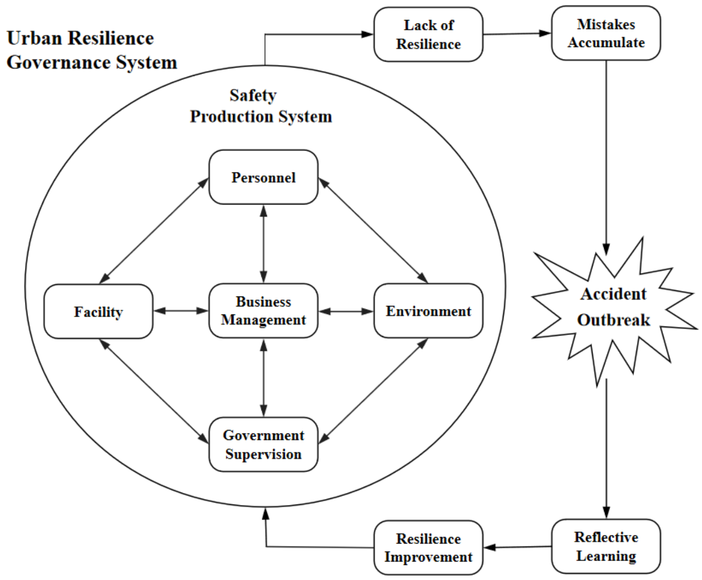

Fig. 1. Resilience governance framework for safety production.

Personnel mainly refers to safety inspection and maintenance staff who are responsible for carrying out their superiors' tasks and dealing with potential accidents. Facility causation refers to production equipment, emergency equipment, and other related machinery. Environmental causation refers to the physical environment of the site. Business management causation refers to the safety production responsibilities of the enterprise, including safety management and on-site safety management. Government supervision causation refers to the development and implementation of safety system norms, supervision, law enforcement, approval, and other matters within the scope of production safety responsibilities. Safety accidents are caused by the non-linear and dynamic interactions among five levels: personnel, equipment, environment, business management, and government supervision. The occurrence of safety accidents and their destructive impacts indicate the lack of resilience of the production safety system in terms of risk perception, facility redundancy, environmental adaptation, organizational synergy, and institutional learning. In the event of an accident, it is crucial to conduct a scientific analysis of its causes, identify the key factors, clarify their correlation, and summarize the lessons learned. This will enable us to promptly and effectively improve the production safety system, prevent similar accidents from occurring, and minimize their impact on people's lives and livelihoods, thereby enhancing public safety in the city.

3.2 Data sources

This paper presents a study based on 83 national gas production safety accident investigation reports from 2010-2021. The reports were obtained from publicly released accident investigation reports on the website of the Ministry of Emergency Management of the People's Republic of China, the websites of the people's governments at all levels, and the websites of the emergency management departments of the regions through public searching. The reports were used as the textual database for this study.

3.3 Data encoding

Accident reports were manually coded to extract relevant causative factors. Twenty accident investigation reports were randomly selected. The sections on direct causes, indirect causes, and responsibility determination were extracted and reviewed repeatedly while referring to relevant research literature. This process resulted in the identification and refinement of 38 causal factors of gas production accidents. The findings were used to construct a systematic analysis framework for gas safety accident causation, as shown in Table 1 below.

Table 1. Framework for analyzing the system of causation of gas production safety accidents.

Causal level	Causal factor
Personnel (P)	P1 Low security awareness and improper disposal P2 Unauthorized operation, work,or direction P3 Unlicensed and unqualified to work P4 Inadequate security P5 Failure of safety managers P6 Insufficient security knowledge and skills
Business management (B)	B1 Failure to implement the main responsibility for production safety B2 Inadequate safety management systems and mechanisms (inadequate management of employees) B3 Ineffective inspection of production safety B4 Lack of safety management on the construction site (failure to identify underground pipeline information) B5 Failure of relevant personnel to attend (failure of safety supervisors to attend; failure to notify relevant pipeline personnel to attend for guidance) B6 Inadequate safety supervision (no on-site sidewalking by supervisors) B7 Inadequate identification of safety hazards (inadequate pipeline management; inadequate inspections) B8 Inadequate safety education and training B9 Insufficient operational staff and equipment B10 Inadequate technical safety briefings B11 Ineffective emergency response (inadequate emergency response plan, or not activated) B12 Illegal operation, failure to obtain required licenses B13 Inadequate inter-firm coordination and communication B14 Illegal subcontracting

	B15 Incompatible security conditions at the site B16 Illegal construction and failure to follow design plans B17 Failure to review and approve as required； B18 Failure to report as required B19 Emergency drills are not in place
Government supervision (G)	G1 Ineffective supervision of production safety (territorial supervision, supervision of construction works, supervision of gas industry safety, supervision of special equipment safety, daily supervision of gas use safety) G2 Uncertainty of supervisory responsibilities and inadequate performance of duties by relevant personnel G3 Ineffective dissemination of safety knowledge G4 Ineffective investigation, rectification and supervision of hidden safety hazards G5 Ineffective investigation and handling of violations G6 Inadequate law enforcement inspections G7 Weak implementation of work deployment G8 Inadequate emergency management (inadequate rescue plans, failure to organize emergency drills)
Facility (F)	F1 Machinery and equipment breakdowns F2 Broken anti-corrosion layer F3 Corrosion and aging of components
Environment (E)	E1 Wet environment E2 Bad weather

4 Research Findings

4.1 Statistical analysis of accident causation

According to the systematic analysis framework of accident causation proposed in this paper, 83 accident investigation reports were textually analyzed, and 38 causative factors were statistically ranked in terms of frequency of occurrence and frequency. The higher the frequency of causal factors, the more likely they are to cause accidents. Causal factors with a frequency of occurrence $F \geq 50\%$ were classified as critical causal factors; causal factors with $25\% \leq F < 50\%$ were classified as important causal factors; causal factors with $10\% \leq F < 25\%$ were classified as minor causal factors; and causal factors with $F < 10\%$ were classified as general causal factors. The statistical results of the frequency and frequency of occurrence of each gas accident causal factor are shown in Figure 2.

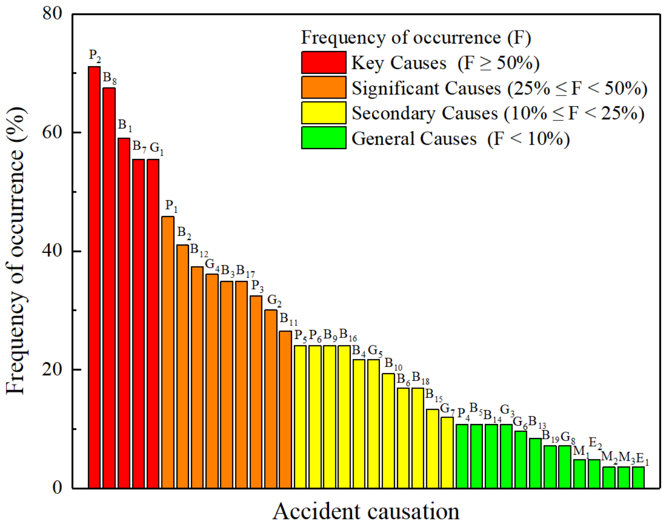

Fig. 2. Statistics on the causes of gas production and safety accidents.

4.2 Analysis of key causes of gas production safety accidents

In the statistics of all gas production accidents, the key causative factors with the highest frequency and greatest impact must be emphasized and prioritized. The first key cause of gas safety accidents is illegal operation and unauthorized work by on-site personnel (P2), which is also the direct cause of most gas accidents. Other key causes include lack of safety education and training (B8), failure to implement safety responsibilities (B1), inadequate investigation of hidden dangers (B7), and ineffective government supervision of production safety (G1). The failure to implement the main responsibility for production safety is also a significant cause of accidents. This is due to the lack of attention paid to production safety work, resulting in the existence of hidden dangers such as inadequate investigations. However, the government supervision function has not been effective in dealing with hidden safety hazards and violations of rules and regulations in a timely manner, which ultimately leads to production accidents.

The major, minor and general causes of gas production accidents, although occurring relatively infrequently, are still common causes of many some gas accidents. That is the variety of accident types and the random nature of their occurrence, among other things, make the statistics unimpressive. However, the existence of any of the causal factors has increased the safety risk of the production system to a certain extent, and has become an enabler of the outbreak of safety accidents, none of them should be neglected.

4.3 Classification analysis of gas safety production accident

There are three primary types of gas production accidents: natural gas pipeline leakage accidents, liquefied petroleum gas cylinder leakage accidents, and gas accidents. Considering that the key causative factors of each type of gas accidents may differ, the causative factors of each type of accidents were analyzed separately for comparison. Figure 3 shows the key causative factors for the three major types of gas production accidents, categorized as having a frequency of causative responses greater than or equal to 50%:

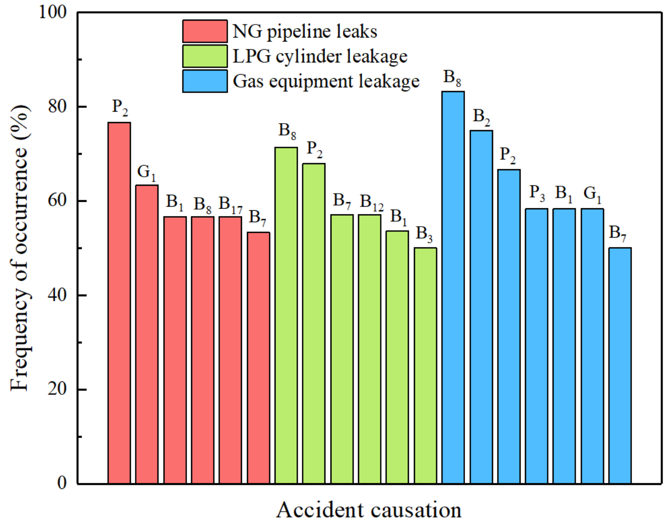

Fig. 3. Key causes of three kinds of gas production accidents.

The study shows that there are some differences between the key causal analyses of the various types of accidents and the overall analyses in section 4.2. In the case of natural gas pipeline accidents, the prominent issue that distinguishes them from other accidents is the failure of relevant enterprises to review and approve them according to regulations (B17); in the case of LPG cylinder leakage accidents, special attention needs to be paid to the situation in which the relevant enterprises are operating illegally, failing to obtain the required licenses (B12), and failing to carry out effective safety production inspections (B3); and in the case of gas leakage type of accidents, it is necessary to pay attention to the relevant enterprises to improve their safety production management system (B2), clear production safety management responsibilities, while avoiding situations such as safety management personnel being on duty without licenses and without relevant qualifications (P3). To sum up, in the prevention and management of production safety accidents, in addition to addressing some common causes, we should also focus on the different causes of various types of accidents.

4.4 Correlation analysis of the causes of gas production safety accidents

To examine the correlation between various levels, such as business safety management and government supervision, in the causal system of gas production safety accidents, accident data was cross-tabulated. This analysis was conducted to determine the strength of the correlation between the causal factors at each level and to provide data support for further in-depth analysis of the causal logic of gas production safety accidents.

The accident data is organized into an accident causality association structure matrix, with each accident record as a row and accident causality as a column. Additionally, the accident level is quantified, with a weight of 1 for general accidents, 2 for larger accidents, and 3 for major accidents. Based on this, the quantitative value of a specific accident level is calculated by adding the corresponding weight of the accident level to 50% of the number of fatalities divided by the upper limit of fatalities at that level, and 50% of the economic loss divided by the upper limit of economic loss at that level. The statistical strength of the association between different levels of the causal system model was assessed using the Pearson's Chi-square (χ^2) test with SPSS 25 software, and with a larger Cramer's value indicating a stronger correlation.The results are presented in Table 2.

Table 2. Accident causation correlation test results (partial).

Related items	Pearson's chi-square value	Significance (bilateral)	Cramer's value
P2*B9	21.526	0.000	0.392
P3*B9	29.264	0.000	0.461
P6*B8	11.127	0.001	0.217
B1*G2	20.954	0.000	0.18
B1*G4	14.574	0.000	0.283
B1*G7	13.405	0.000	0.197
B11*G3	17.671	0.000	0.387
B11*G4	9.679	0.002	0.325
B11*G6	11.099	0.001	0.308
B11*G8	22.898	0.000	0.355
B12*G5	21.856	0.000	0.262
B12*G6	7.73	0.005	0.282
B12*G7	15.458	0.000	0.404
B16*G3	13.674	0.000	0.244
B16*G6	12.797	0.000	0.395
B16*G8	6.709	0.010	0.235
B17*G3	16.074	0.000	0.331
B17*G4	10.786	0.001	0.171
B17*G6	6.089	0.014	0.313
B17*G8	7.406	0.007	0.302

The χ^2 results indicate a significant correlation between the different levels of gas production safety accidents. This correlation can be observed in the following aspects:

① There is a significant correlation between the lack of implementation of the main responsibility of enterprises for work safety and the causal factors of ineffective government supervision of work safety, unclear supervisory responsibility, ineffective supervision and rectification of hidden safety hazards, and ineffective implementation of work deployment. The government serves as the highest administrator of production safety and is responsible for ensuring that enterprises establish a solid production safety defense. Effective safety supervision by government can break the chain of causation of accidents, preventing and reducing production safety accidents. If the government does not investigate and address issues related to illegal operations, construction, and non-compliance with regulations, it may result in uncontrolled and frequent production safety accidents, which could pose a serious threat to the long-term safety of the city.

② There is a strong correlation between on-site construction operators' illegal and unauthorized operation and insufficient staffing and safety equipment of the enterprise. Additionally, there is a significant correlation between insufficient safety knowledge and skills and the lack of education and training provided by the business. These findings indicate that the enterprise's main body does not implement the main responsibility for safety production, nor invest enough in the personnel and equipment required for safety production. Furthermore, insufficient safety education and training for employees can result in serious deficiencies in their safety knowledge and skills. Additionally, the tacit allowance of unlicensed operators by business operators significantly increases the risk of production safety and the likelihood of accidents.

③ Ineffective business emergency response and poor emergency response plans are significantly related to the government's insufficient safety education and publicity, poor popularization of safety knowledge, and insufficient emergency management. This highlights the crucial role of the government as a model leader in the construction of emergency management functions. If the relevant government departments pay attention to the construction of emergency management, have a perfect emergency rescue plan, often organize emergency drills, then enterprises and the public will also learn from the relevant emergency knowledge, understand the relevant risks of accidents, so as to be able to detect and solve the safety hazards in a timely manner, or in the case of accidents, skilled, effective response to minimize the impact of the accident.

5 Conclusion

Given the complex changes in both internal and external environments in the field of production safety governance, and the continuous emergence of new risks, it is urgent to address the governance dilemma brought about by the passive and negative response in the traditional risk governance model. To promote the orderly development of production safety governance, it is necessary to adopt the concepts of continuous adaptation, proactive transformation, multifaceted cooperation, and systematic reflection and learning in the governance of resilience. A comprehensive understanding of production safety accidents and accurate identification of accident causes and hidden dangers are essential for effective accident prevention and management. This paper examines official gas accident investigation reports from 2011 to 2021 using systems thinking and accident causation theory. The study results indicate that gas production safety accidents are primarily caused by illegal, irregular, and unauthorized behaviors of operators, lack of safety education and training in enterprises, failure to implement the main responsibility for safety production in enterprises, lack of investigation of hidden dangers, and ineffective government supervision of safety production.

This study highlights several significant issues with the safety production system:

① Responsible parties involved in production safety, including staff who violate the law, enterprises that fail to fulfill their training responsibilities, and government departments that neglect their supervisory duties, all lack awareness of production safety, safety knowledge, and crisis management skills. The ideological basis for disaster prevention and mitigation is also weak. To enhance production safety, it is crucial to consistently strengthen risk management and control, as well as awareness of hidden trouble management initiatives. We must continue to promote the 'double prevention mechanism' of risk management and control, as well as hidden trouble investigation and management. Production and management units, as well as government regulators, recognize the ideological importance of production safety and maintain a constant commitment to ensuring safety. This responsibility is essential to effectively promote the implementation of safety measures at all levels.

② Production safety systems remain inadequate in both government departments and business organizations. These systems reduce uncertainty by constraining and limiting people's choices, increasing predictability of behavior. As society, economy, and technology continue to develop, the number, type, and scale of production and operation units expand, making production safety a critical concern. The core of enhancing the resilience of the production safety system is the ability to learn and adapt. The system must be able to adapt to the complex and changing environment. Learning from crises is a powerful tool to enhance system resilience, and every incident provides a 'window of opportunity' to observe system failures and learn from them. Better learning results can only be achieved through deep system change. The resilience gained from post-accident crisis learning should be continually refreshed and accumulated to become the system's enduring ability to combat external risks, thereby preventing and reducing major production safety accidents.

③ There is a significant disparity between the fundamental safety measures and the actual requirements. Enterprises lack adequate safety production equipment and emergency resources, and the government has limited supervision resources and personnel. Additionally, unreasonable urban planning has a negative impact on safety production development. To enhance safeguarding resilience, safe production should integrate engineering projects with non-engineering initiatives. To improve safety in production, it is recommended to enhance the redundancy of safety production facilities and equipment, and strengthen the essential safety of production equipment. Additionally, promoting the application of intelligent technology and equipment can help reduce dangerous operations by replacing people with machines. Secondly, we will use technical means such as big data and intelligence to break down information barriers between the government, enterprises, and society. This will enable real-time, accurate, and reliable sharing of safety information on risks, hidden dangers, and accidents, thereby enhancing the resilience of safety production governance. Finally, urban development should be planned rationally based on scientific predictions. This will improve the foresight of pre-planning and construction of production safety, and prevent the expanding impact of production safety risks due to short-sighted man-made design.

Originally, production safety belonged to the scope of the enterprise's own management, but production safety accidents, especially serious accidents, have seriously affected the personal and property safety of the surrounding population, so that production safety has become a "public affair", which goes beyond the internal affairs of the business organization. Therefore, to improve the resilience in safety production governance system, it is necessary not only for enterprises to fulfill their responsibilities and self-governance, and for the government to provide effective supervision, but also for industry associations, the public, the media, social organizations, and other diverse stakeholders to participate widely and effectively. This will not only help promote the rational allocation and sharing of resources but also overcome the lack of resources in government's independent supervision, enhancing the effectiveness of safety governance and forming a resilience governance system with a benign interaction.

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