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Operation Risks of Oil and Gas Pipeline Networks

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Abstract **Original Research Article**

Oil and gas pipeline networks serve as the core infrastructure for energy transportation, undertaking the long-distance and large-scale transmission of fossil energy resources. Due to the long service cycle, complex laying environment, continuous fluid scouring and aging of equipment, pipeline networks face diverse and dynamic operation risks throughout their service life, which seriously threaten energy supply safety and social public security. This paper systematically analyzes the main operational risk factors of oil and gas pipeline networks, including natural environmental erosion, human-induced damage, equipment aging failure, operational parameter fluctuation and system management loopholes. Combined with quantitative risk assessment methods and spatial analysis technology, it summarizes the occurrence mechanism and evolution law of typical pipeline accidents such as leakage, explosion and blockage. The study finds that external corrosion and third-party construction damage are the primary causes of pipeline network operation failures, while the lack of dynamic real-time monitoring and early warning mechanisms further amplifies accident risks. On this basis, this paper puts forward targeted risk prevention and control measures covering real-time monitoring, regular detection, standardized operation and emergency disposal, aiming to reduce the failure probability of pipeline networks, improve operational stability, and provide technical reference for the safe and efficient operation of oil and gas pipeline systems.

Keywords: oil and gas pipeline network; operation risk; risk assessment; pipeline failure; safety monitoring.

1. Introduction

With the rapid development of the global energy industry, oil and gas pipeline networks have formed a large-scale, cross-regional and interconnected operational system, becoming the most economical and efficient carrier of oil and gas transportation. Compared with railway, highway and marine transportation, pipeline transportation has the advantages of low cost, large volume and high continuity, and bears more than 80% of global oil and gas long-distance transportation tasks. However, oil and gas pipeline networks are mostly buried in complex geological environments such as mountains, rivers and urban built-up areas, operating in harsh natural conditions for a long time. Meanwhile, with the extension of service time, pipeline bodies, auxiliary equipment and supporting monitoring systems will inevitably age and degrade, leading to frequent potential safety hazards.

In recent years, pipeline leakage, explosion and fire accidents caused by operational risks have occurred frequently all over the world, causing huge economic losses, environmental pollution and casualty accidents. Different from single pipeline operation, the modern pipeline network presents the characteristics of networked connection and

collaborative operation. A single node failure may trigger cascading failures of the whole network, resulting in large-scale energy supply interruption. Therefore, systematic identification, quantitative analysis and effective control of oil and gas pipeline network operation risks are of great practical significance to ensure national energy security, reduce operational accidents and promote the sustainable development of the energy industry. This paper sorts out the key operational risk points of pipeline networks, analyzes the risk formation mechanism, and proposes feasible risk management and control strategies based on the current operation status of pipeline networks.

2. Main Operational Risk Types and Formation Mechanisms

2.1 Natural Environmental Risks

Natural environmental factors are the most persistent and widespread risk source of pipeline network operation, mainly including geological disasters, meteorological changes and soil corrosion. In mountainous and hilly areas, geological activities such as landslides, debris flows and ground settlement will cause extrusion, bending and even fracture of buried pipelines, destroying the structural integrity of pipeline networks. Extreme weather such as heavy rain, typhoon and extreme temperature will accelerate pipeline aging: low temperature will cause pipeline material brittleness and increase cracking risk, while high temperature will accelerate the aging of anti-corrosion coatings and sealing components.

Soil corrosion is a long-term hidden risk for buried pipelines. Different soil pH values, salinity and microbial activities will cause electrochemical corrosion and microbial corrosion on pipeline steel bodies. Long-term corrosion will form pitting defects and wall thinning on the pipeline surface, which will gradually expand under the action of internal oil and gas pressure, eventually leading to pipeline leakage. Relevant statistical data show that environmental corrosion-induced pipeline failures account for more than 35% of all pipeline operation accidents, becoming one of the core natural risks restricting pipeline network safe operation.

2.2 Human-Induced Operational Risks

Human-induced risks are the leading cause of sudden pipeline network accidents, mainly divided into third-party damage and operational misoperation. With the acceleration of urbanization and infrastructure construction, urban road reconstruction, municipal engineering construction and agricultural mechanical operation frequently cause accidental damage to buried pipelines. Most construction units lack professional pipeline identification capabilities and safety awareness, and blind construction easily causes pipeline scratching, extrusion and rupture, triggering oil and gas leakage accidents.

Internal operational misoperation is also an important hidden danger. In the daily operation and maintenance process, problems such as non-standard parameter adjustment, incomplete equipment inspection and improper maintenance operation will lead to abnormal operation of the pipeline network system. For example, excessive adjustment of pipeline internal pressure will exceed the design bearing limit of the pipeline, and untimely replacement of aging valves and pressure gauges will lead to failure of pressure regulation and monitoring functions, inducing operational failures. In addition, imperfect daily management system and insufficient professional ability of operation and maintenance personnel will further increase the probability of human-induced risks.

2.3 Equipment Aging and System Failure Risks

Oil and gas pipeline network system includes pipeline body, valves, compressors, pressure regulating equipment, monitoring sensors and other auxiliary facilities. Long-term continuous operation will lead to fatigue aging and performance degradation of various equipment. The pipeline body will produce fatigue cracks under the long-term alternating action of internal fluid pressure and external geological stress. Valves and sealing devices are prone to aging and leakage after long-term use, resulting in pipeline pressure loss and medium leakage.

Intelligent monitoring equipment failure is a new

type of operational risk in modern pipeline networks. With the popularization of intelligent monitoring systems, sensors, data transmission equipment and remote monitoring terminals undertake the task of real-time perception of pipeline operation status. Equipment failure, signal delay and data distortion will lead to inability to accurately perceive abnormal pipeline conditions, resulting in missed judgment and delayed disposal of potential risks, and small hidden dangers will evolve into major safety accidents.

2.4 Network Cascading Operation Risks

Modern oil and gas pipeline networks have formed a complex interconnected network structure, and the operational state of each pipeline node is closely coupled. Different from single pipeline operation, the networked pipeline system has obvious cascading failure characteristics. When a single pipeline segment fails and leaks, the internal pressure of the local network will drop sharply, which will affect the transportation efficiency and pressure stability of the connected pipeline segments. If the system cannot adjust the operation parameters in time and isolate the fault section, the fault will spread along the network, causing large-scale abnormal operation of the pipeline network, and even leading to regional energy supply paralysis in severe cases.

3. Current Problems in Pipeline Network Risk Management

At present, the risk management of oil and gas pipeline networks mostly adopts post-disposal and regular inspection modes, and there are obvious deficiencies in dynamic early warning and precise prevention and control. First, the risk monitoring means are relatively single. Most pipeline networks rely on regular manual detection and fixed-point sensor monitoring, which cannot realize full-coverage and real-time perception of long-distance pipeline operation status, and it is difficult to identify micro hidden dangers in time.

Second, the risk assessment mechanism is imperfect. Traditional risk assessment mostly adopts qualitative analysis, lacking quantitative calculation of risk probability and accident consequence. It cannot accurately distinguish high-risk sections and key risk factors of the pipeline network, resulting in targeted risk prevention and control measures cannot be formulated.

Third, the emergency disposal capability is insufficient. The pipeline network emergency response system has problems such as imperfect emergency plans, insufficient reserve of emergency equipment and unskilled disposal process. When sudden leakage and explosion accidents occur, the response speed is slow and the disposal efficiency is low, which aggravates the accident loss and impact range.

4. Operational Risk Prevention and Control Countermeasures

4.1 Build Intelligent Dynamic Monitoring System

Integrate Internet of Things, digital twin and sensor monitoring technology to build a full-coverage real-time monitoring system for pipeline networks. Arrange high-precision pressure, temperature, vibration and leakage monitoring sensors along the pipeline to realize real-time collection of pipeline operation data. Build a digital twin model of the pipeline network to simulate the operation state of the pipeline system dynamically, realize real-time early warning of abnormal pressure, leakage and structural defects, and change the traditional passive post-disposal mode into active pre-warning prevention.

4.2 Implement Quantitative Risk Assessment and Hierarchical Management

Adopt Bayesian network, gray relational analysis and other quantitative risk assessment methods to calculate the failure probability and accident risk level of each pipeline section. Classify the pipeline network into high, medium and low risk levels according to the risk assessment results, implement hierarchical and classified management, increase the detection frequency and maintenance intensity of

high-risk sections, and allocate management resources precisely to improve the efficiency of risk control.

4.3 Strengthen Daily Operation Standardization Management

Improve the daily operation and maintenance management system of pipeline networks, standardize the operation procedures of parameter adjustment, equipment inspection and maintenance. Strengthen the professional training of operation and maintenance personnel, improve their risk identification ability and standardized operation level. Establish a third-party construction early warning and protection mechanism, strengthen the publicity and inspection of pipeline protection in construction areas, and reduce human-induced pipeline damage accidents.

4.4 Optimize Emergency Disposal Mechanism

Improve the pipeline network emergency response plan, refine the disposal process of leakage, explosion and other sudden accidents, and clarify the responsibilities of each department. Equip special emergency disposal equipment and materials, and carry out regular emergency drills to improve the rapid response and on-site disposal capability of the emergency team. Establish a multi-department collaborative emergency linkage mechanism to realize rapid disposal and accident control after pipeline network accidents.

5. Conclusion

The operation risks of oil and gas pipeline networks are diverse, dynamic and cascading, involving natural environment, human operation, equipment performance and network system operation. At present, the pipeline network risk management mode is relatively backward, with deficiencies in real-time monitoring, quantitative assessment and emergency disposal. To ensure the safe operation of pipeline networks, it is necessary to rely on intelligent technology to build a dynamic monitoring and early warning system, implement quantitative hierarchical risk management, standardize daily operation and maintenance management, and optimize emergency disposal mechanisms. Through full-cycle and multi-dimensional risk prevention and control, the operational failure rate of oil and gas pipeline networks can be effectively reduced, and the safety and stability of energy transportation can be guaranteed.

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