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Research on the Evolution Mechanism and Risk Prevention and Control of Leakage Accidents in Depleted Oil and Gas Reservoir-Type Underground Gas Storages

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Abstract: With the acceleration of the global low-carbon energy transition, the demand for natural gas continues to grow. As core infrastructure for ensuring a stable natural gas supply, the safety issues of underground gas storages (UGS) are becoming increasingly prominent. In China, depleted oil and gas reservoir-type UGS account for 76%, making them the main type in this field. However, frequent leakage accidents pose a serious threat to the safe operation of UGS. This study takes depleted oil and gas reservoir-type UGS as the research object to systematically investigate the evolution mechanism and risk prevention and control of leakage accidents. Firstly, through statistical analysis of accident cases and expert interviews, the main influencing factors of leakage accidents were identified, including three categories: geological body leakage, injection-production well leakage, and surface facility leakage. Secondly, using the Grounded Theory method, the core categories in the driving stage of leakage accident evolution were extracted, and a conceptual model of driving factors for leakage accident evolution based on the four elements of "Human, Machine, Environment, and Management (H-M-E-M)" was constructed. Thirdly, through system dynamics modeling and numerical simulation, the dynamic evolution law of leakage accidents from initial evolution to secondary disasters was revealed. Finally, from the three dimensions of source prevention, process control, and emergency response, precise whole-process prevention and control measures were proposed targeting the four categories of factors: human, equipment, environment, and management. The research indicates that injection-production well leakage is the main form of UGS leakage, accounting for 57%, followed by geological body leakage (28%). The evolution of leakage accidents is influenced by the coupling effect of the four elements: Human, Machine, Environment, and Management. The constructed evolution mechanism model can effectively reflect the structural characteristics of the leakage accident system. The research results provide a theoretical basis and technical support for the precise identification and efficient prevention and control of leakage risks in depleted oil and gas reservoir-type underground gas storages.

Keywords: Depleted oil and gas reservoir, Underground gas storage, Leakage accident, Evolution mechanism, Risk prevention and control, Human-machine-environment-management, Grounded theory, System dynamics.

1. Introduction

1.1. Research Background and Significance

Against the backdrop of the global low-carbon energy transition, natural gas, as a clean and efficient transitional energy source, has seen a steady increase in demand. As a major energy-consuming country, China is actively promoting the adjustment of its energy structure, leading to the rapid development of the natural gas industry. However, the imbalance between supply and demand in terms of time and space imposes higher requirements on the construction of storage and peak-shaving systems. Underground gas storages (UGS), with advantages such as large capacity, high safety, and good economy, have become core infrastructure for ensuring a stable natural gas supply. With the rapid growth of natural gas consumption, the safety issues of UGS facilities are becoming increasingly prominent. Therefore, researching the evolution mechanism and risk prevention and control of leakage accidents in underground gas storages holds significant theoretical and practical importance.

According to the China Natural Gas Development Report (2025), there are 796 underground gas storages in operation globally. In China, depleted oil and gas reservoir-type storages account for 76%, with their working gas volume representing over 70% of the national total. Current domestic and international research primarily focuses on accident causes, consequence assessment, and risk control, while in-depth studies on the evolution mechanism of leakage accidents remain insufficient. Furthermore, risk prevention and control measures often lack systematic, whole-process management. This project aims to elucidate the evolution mechanism and disaster-causing laws of leakage accidents in depleted oil and gas reservoir-type UGS, enhance the level of precise risk identification and efficient prevention and control, and provide theoretical support and technical guarantees for the safe operation of gas storages [1].

1.2. Domestic and International Research Status

Numerous typical safety accidents have occurred in foreign gas storages, such as injection-production well leaks, surface subsidence, and storage collapse. Through statistical analysis of accidents, Luo Jinheng et al. pointed out that leakage is the primary failure mode for depleted reservoir-type UGS. Zhang Zhe et al. found that wellbore integrity failure and trap seal failure are the main failure forms. Wang Zhechao et al. analyzed the root causes of typical accidents and provided suggestions for China's UGS construction. Evans reviewed the research progress of risk assessment methods. Tang Chenfei indicated that casing damage is a key cause of natural gas leakage. Research shows that leakage risks are mainly concentrated in three areas: underground cavities, injection-production wells, and surface facilities [2, 4].

1.3. Research on the Evolution Mechanism of Leakage Accidents

The concept of evolution has been widely applied in various disciplinary fields and has promoted the development of interdisciplinary subjects such as evolutionary economics and evolutionary game theory. The evolution of a leakage accident in a depleted reservoir-type UGS is a dynamic, complex, and uncertain process. Under the coupled action of multiple factors like geological conditions, operating parameters, and environmental factors, the energy accumulated during leakage can undergo sudden qualitative changes, potentially triggering major accidents like fires and explosions, leading to severe consequences.

2. Influencing Factors of Leakage Accident Evolution and Their Mechanisms

2.1. Methods for Identifying Influencing Factors

(1) Accident Case Analysis Method

Focusing on typical leakage accident cases, this method uncovers accident evolution patterns and root causes through statistical analysis of accident characteristics and patterns, providing empirical support for identifying influencing factors. Statistics include accident location, time, specific point, evolution process, etc., using charts and graphs to visually present data characteristics.

(2) Grounded Theory Research Method

Grounded Theory refines research questions from real-world scenarios. Through systematic sorting and in-depth analysis of original data, it constructs an objective and scientific conceptual system. The application process includes data collection and organization, extraction of valuable information, and theoretical layered construction. This study uses Grounded Theory to extract key factors driving the evolution stage of leakage accidents and constructs a conceptual model, laying a theoretical foundation for subsequent research.

2.2. Influencing Factors of Leakage Accident Evolution

Combining the actual operating conditions of depleted reservoir-type UGS with expert interviews, a statistical analysis was conducted on 60 underground gas storage leakage accident cases (the earliest dating back to 1940), revealing the accident distribution: 17 geological body leaks (28%), 34 injection-production well leaks (57%), and 9 surface facility leaks (15%). The probability of leakage in geological bodies and injection-production wells is higher due to the complex underground environment and difficulty in detection and maintenance, whereas risks in surface facilities can be effectively reduced through regular inspections [3].

To further enhance the comprehensiveness of influencing factor identification, interviews were conducted with 5 senior safety management experts (from storages like Xiangguosi, Hutubi, Suqiao, each with over 10 years of experience) based on the case analysis. The interview information was systematically organized to supplement and identify influencing factors in the initial evolution stage. Ultimately, the influencing factors were summarized, including: geological body leakage (reservoir fractures, boundary faults, cap rock failure, etc.), injection-production well leakage (casing damage, cement sheath absence, anti-corrosion coating failure, etc.), and surface facility leakage (seal failure, valve leakage, external force damage, etc.) [5].

3. Numerical Simulation and Model Construction

3.1. Data Collection

Research data originated from personnel interviews and documentary materials. Interviewees included 24 individuals from UGS site management departments, operating companies, research institutions, and petroleum universities. Documentary materials encompassed institutional norms, operational documents, research reports, and 45 related literature pieces. A total of 90 interview statements and 110 original text statements were collected, with 80% used for coding analysis and 20% for subsequent theoretical saturation testing.

3.2. Numerical Coding

Through axial and selective coding, the core categories of driving factors in leakage accident evolution were determined: human factors (behavioral and personal factors), equipment factors (usage and maintenance), environmental factors (natural and social), and management factors (institutional and other).

3.3. Numerical Modeling

Based on the coding results, a conceptual model of influencing factors for the driving stage of leakage accident evolution in depleted reservoir-type UGS was constructed. The model indicates that whether a leakage accident evolves into secondary disasters like fires or explosions depends on the interaction of the four elements: Human, Machine, Environment, and Management (H-M-E-M).

3.4. Model Testing

Consistency and applicability tests were conducted on the constructed system dynamics model, including parameter meaning and value verification, and appearance inspection. The model was built from five subsystems: initial evolution, human-driven, equipment-driven, environment-driven, and management-driven. Parameters were scientifically defined based on the actual system, effectively reflecting the structural characteristics of the leakage accident evolution system.

4. Risk Prevention and Control Measures for Leakage Accidents

Based on the evolution mechanism of leakage accidents and the coupling characteristics of the H-M-E-M four elements, precise whole-process prevention and control measures are proposed from the three dimensions of source prevention, process control, and emergency response.

4.1. Prevention and Control Measures for Human Factors

Build a trinity prevention and control system encompassing awareness cultivation, skill enhancement, and behavioral norms: conduct regular safety training and warning education; establish skill assessment systems for key positions, prohibiting unqualified personnel from working; improve on-site operation behavior control, set up safety supervision posts, and prevent human errors [6].

4.2. Prevention and Control Measures for Equipment Factors

Establish a full lifecycle equipment management system: formulate usage specifications for key equipment and monitor operational status in real-time; establish a graded maintenance mechanism, focusing on the inspection and maintenance of leak-prone parts like casings, cement sheaths, and anti-corrosion coatings; introduce advanced technologies like non-destructive testing and downhole imaging to enhance hazard identification capabilities [6].

4.3. Prevention and Control Measures for Environmental Factors

Construct a multi-dimensional environmental risk response system: routinely monitor geological and meteorological conditions, establish disaster warning systems; designate safety protection zones, strengthen community liaison, and establish joint prevention and control mechanisms for external risks; optimize protective designs based on regional environmental characteristics to enhance the storage's environmental resilience.

4.4. Prevention and Control Measures for Management Factors

Build a refined safety management system: improve safety management systems and clarify job responsibilities; establish safety management assessment and incentive mechanisms; build an information management platform for closed-loop online risk management; establish cross-departmental coordination mechanisms for resource sharing and enhanced overall prevention and control capabilities.

4.5. Emergency Response Measures

Construct a rapid and efficient emergency response system: develop graded and classified emergency plans, conduct regular drills; improve the configuration of emergency supplies, ensuring immediate availability; establish emergency linkage mechanisms with fire, medical, environmental protection, and other departments, achieving rapid response and efficient disposal to minimize accident losses.

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