

A Study on Innovation in QHSE Regulatory Models for Petroleum Engineering Service Companies Empowered by Digital and Intelligent Technologies

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Abstract

Through a comparative analysis of domestic and international QHSE regulatory practices, considering the realities of the technical services industry in petroleum engineering, this paper proposes a path for establishing a new QHSE regulatory mechanism in the context of digital and intelligent technologies. The study confirms that digital and intelligent technologies serve as the core engine driving the paradigm shift in QHSE regulation from a “system-constrained” model to a “data-driven” one. By establishing an intelligent closed-loop system of “perception-early warning-collaboration-optimization,” it is possible to effectively resolve the structural challenges of traditional regulation, namely “incomplete oversight, inaccurate judgment, ineffective control, lack of connectivity, and difficulty in achieving a closed-loop.” This study aims to establish a new digital and intelligent QHSE regulatory ecosystem that is comprehensive in coverage, agile in response, and efficient in operation. Through an implementation strategy involving platform integration, overseas expansion, standardized training, and grassroots demonstrations, it seeks to provide QHSE management safeguards for the high-quality development of petroleum enterprises and the expansion of their overseas operations.

Keywords

Petroleum Engineering Technical Services; QHSE Regulation; Digital and Intelligent Transformation; Data-driven; Intelligent Closed-loop Management.

1. Introduction

Petroleum engineering technical services encompass multiple specialized fields, including geophysical exploration, drilling, and oil and gas testing. Given the complex operational environments and cumulative potential risks, traditional QHSE regulatory mechanisms have revealed issues such as regulatory gaps, low efficiency, insufficient coordination in risk management, and slow emergency response [1]. Establishing a digital and intelligent regulatory capability system featuring rapid detection, real-time monitoring, proactive early warning, coordinated response, and systematic assessment—to achieve effective “four-all” management (covering all personnel, all process, all aspects, and all the clock)—has become an urgent priority for the industry.

Digital transformation and intelligent development represent strategic choices for petroleum enterprises in implementing the new development philosophy, driving the evolution of QHSE management from a “regulation-constrained” model to a “self-managed” one [2]. This transformation must be achieved through the deep integration of next-generation digital technologies—such as the Industrial Internet and artificial intelligence—with traditional engineering technologies. It requires reshaping the underlying logic and operational paradigms of QHSE management to bring about a fundamental shift in risk prevention and control from

“post-incident response” to “pre-incident early warning,” and in management efficiency from “human-driven” to “system-autonomous.”

2. Current Status of QHSE Regulatory Models in Leading Domestic and International Enterprises

Driven by digital and intelligent technologies, the digital and intelligent transformation of QHSE regulation has become a focal point of research and practice both domestically and internationally. Related research has gradually expanded to cover technology applications, model innovation, and the exploration of theoretical methods, with domestic and international enterprises having achieved practical results at various stages.

In the global energy sector, the intelligent transformation of QHSE management has entered a phase of deep application. Leading companies such as Shell, Schlumberger, and Baker Hughes have leveraged technologies like the Internet of Things, artificial intelligence, and digital twins to establish an intelligent closed-loop management system based on “sensing-analysis-decision-execution,” achieving a shift from passive compliance to proactive foresight and from experience-driven to data-driven approaches. The domestic petrochemical industry is undergoing a transformation from “passive compliance” to a deep integration of “systematic prevention and control” and “digital transformation.” Major energy enterprises such as CNOOC and SINOPEC are actively exploring pathways to integrate next-generation information technology with work safety management, forming distinctive digital practice models.

Although domestic and international research on digital and intelligent QHSE regulation has achieved certain results, significant shortcomings remain. First, the in-depth application of digital and intelligent technologies is insufficient; technologies such as big data and artificial intelligence often remain at a superficial level, and their potential has not been fully tapped. Second, it is difficult to implement innovative regulatory models; coordination among internal departments is poor, and there are barriers to integrating digital and intelligent regulation with traditional regulatory models. Third, the lack of unified technical standards and operational guidelines constrains the promotion and application of digital and intelligent regulation.

3. Issues with Domestic QHSE Regulatory Models in Engineering and Technology Operations

Domestic engineering and technology have achieved certain research results in the field of QHSE regulation within digital and intelligent scenarios, but there are still some shortcomings.

(1) There are blind spots in on-site monitoring, and data collection relies on manual efforts. Traditional regulatory methods fall short in covering key safety information such as the status of the work site, equipment operating parameters, and Well bore Dynamics. Monitoring methods are limited, and data acquisition is incomplete and untimely. Most data rely on manual recording and reporting, which is not only inefficient but also carries risks of data omissions, false reports, and subjective tampering, making it difficult to achieve real-time, accurate, and comprehensive monitoring of hazard sources.

(2) Risk assessment relies heavily on individual experience, with a lack of intelligent early warning systems. In predicting major engineering risks—such as well surges, well leaks, and stuck pipes—as well as safety risks during operations, current practices largely depend on the personal experience and subjective judgments of management and supervisory personnel. There is a lack of real-time, precise data support, early warning systems, accurate decision-making tools, and advanced risk control mechanisms. This results in delayed risk identification, insufficient scientific basis for decision-making, and weak preventive capabilities.

(3) Regulatory effectiveness diminishes at each level, and accountability is not fully enforced. On-site supervision exhibits a “top-down” phenomenon where intensity weakens progressively, resulting in violations and accident hazards that “recur despite repeated inspections.” The scope, quality, and timeliness of supervision struggle to effectively extend to grassroots operational sites. The detection and correction of violations primarily rely on a limited number of full-time supervisors, failing to establish a comprehensive, multi-dimensional supervision network that is “all-staff, full-process, all-encompassing, and round-the-clock.” Consequently, primary responsibility is not being fully implemented.

(4) Information systems are isolated from one another, and there is a lack of mechanisms for coordinated collaboration. Data standards vary across specialized systems—such as production operations, engineering and technology, equipment management, and safety management—and these systems operate independently. Data silos result in delayed information transmission and difficulties in data sharing, preventing effective coordination in critical areas such as process safety, work permits, equipment status, and emergency command. There is a lack of a multi-disciplinary collaborative supervision mechanism supported by a unified platform.

(5) The closed-loop management of hidden hazards is ineffective, and technical support for tracking rectification efforts is lacking. For identified hazards, the rectification process often becomes merely a formality due to the absence of robust IT-based tracking and supervision tools and a closed-loop management mechanism. This results in slow progress and inconsistent quality of rectification, with similar issues recurring repeatedly, leading to a vicious cycle of “identification—rectification—recurrence.” Overall governance efficiency is low, and systemic problems remain unresolved.

4. A Study on QHSE Regulatory Models for Petroleum Engineering Service Companies Empowered by Digital and Intelligent Technologies

The deep integration of digital and intelligent technologies with QHSE regulation in petroleum engineering centers on three key dimensions: data collection and integration, data analysis and risk early warning, and the establishment of big data sharing platforms. By addressing the operational characteristics and risk types of core disciplines such as drilling, down hole operations, geophysical exploration, and logging, this approach establishes a specialized, end-to-end digital and intelligent regulatory technology system.

4.1. Research on Data Collection and Integration Technologies in Digital and Intelligent Scenarios

Data collection and integration form the foundation of digital and intelligent QHSE supervision. It is necessary to establish a collection system characterized by “comprehensive sensing, precise collection, and real-time transmission” [3] tailored to the operational scenarios and core risks of different disciplines. This system should cover six core dimensions: equipment status, process parameters, energy consumption indicators, occupational health, environmental impact, and personnel management. Each discipline should develop a differentiated technical architecture based on its specific characteristics.

4.1.1. Drilling Operations

Drilling operations require end-to-end monitoring of down hole conditions, equipment performance, and personnel behavior. Core equipment includes three major categories: drilling rig systems, well control systems, and auxiliary systems. A “distributed data collection + centralized management” model is adopted, with multi-dimensional sensors and RFID systems deployed on critical equipment such as top drives and mud pumps to monitor equipment status in real time; process parameters such as load and pressure are collected at critical points like

the hook and riser; energy consumption is monitored via smart meters and fuel systems; hazardous gas sensors and smart wristbands are deployed to safeguard personnel occupational health; environmental management is conducted through VOC monitoring and drone inspections; and on-site intelligent management of personnel and operational scenarios is achieved through UWB positioning, smart access control, and video surveillance.

4.1.2. Down hole Operations Specialization

Down hole operations take place in complex environments and face multiple risks, including high pressure, high temperatures, and toxic or hazardous media. The core operations encompass four major scenarios: fracturing and acidizing, well testing and workover, coiled tubing, and pressure-retaining operations. Key equipment includes fracturing trucks, workover rigs, coiled tubing units, and pressure-retaining systems. Fracturing and acidizing operations utilize a "distributed sensing + edge computing" architecture, deploying multi-parameter sensors to monitor equipment status and collect process parameters such as pressure and flow rate in real time; Well testing and workover operations adopt a "multi-source sensing + centralized monitoring" model to enable predictive maintenance of equipment and monitoring of formation parameters; coiled tubing and pressure-retaining operations focus on core risks such as string failure and pressure runaway, establishing a comprehensive system for collecting process parameters throughout the entire process. Energy consumption, environmental, and personnel monitoring equipment are deployed simultaneously, and combined with high-precision positioning and intelligent video analysis to ensure on-site safety management.

4.1.3. Geophysical Exploration

Geophysical exploration operations are characterized by vast operational areas, a wide variety of equipment, and complex environments. Seismic exploration serves as the core operational scenario, with key equipment including source systems, acquisition systems, and processing and interpretation systems. By adopting a "distributed data acquisition + satellite communication" model, sensors are deployed on source trucks and acquisition stations to monitor equipment status, acquisition parameters, and energy consumption data in real time. Satellite positioning and Ad Hoc Network Technology enable remote monitoring of field personnel and equipment. Concurrently, environmental impact monitoring is conducted to address regulatory blind spots in wide-area operations, achieving synergy between efficient operations and risk management.

4.1.4. Logging Operations

Logging operations face multiple risks, including high temperatures, high pressures, toxic gases, and radioactive materials. Core operations encompass four major scenarios: cable logging, logging-while-drilling (LWD), production logging, and perforation operations. Core equipment includes logging systems, LWD tools, and perforation equipment. Cable logging employs a "Down hole sensing + surface monitoring" architecture, deploying tension, depth, and radiation sensors to enable end-to-end risk monitoring; Log-in-place operations employ a "log-in-place measurement + real-time transmission" solution, transmitting formation data via drilling fluid pulses while simultaneously monitoring mud gas risks; production logging focuses on the challenges of multiphase flow measurement, collecting fluid production profile data and deploying hazardous gas monitoring equipment; perforation operations address explosives and well control risks by establishing a "full-process monitoring + intelligent early warning" system to achieve explosives lifecycle management and control of blasting impacts.

4.2. Research on Data Analysis and Risk Early Warning Technologies

Based on multi-source data collected throughout the entire process, and by integrating technologies such as big data and artificial intelligence, an intelligent analysis and early warning system has been established to address core risks across various disciplines, thereby achieving

the transition from “data collection” to “risk prediction” [4]. The system covers four key early warning dimensions: equipment failure, process risks, environmental and health risks, and operational behavior risks, with each discipline developing its own differentiated early warning model.

For the drilling discipline, addressing complex deep-well operating conditions, a comprehensive early warning system integrating big data and AI is established. This system predicts remaining equipment service life using operational data, optimizes mechanical drilling speed through deep learning, integrates liquid level monitoring data to enable early spill detection, and utilizes video analysis to identify safety violations. Additionally, a risk knowledge graph and expert system are constructed to provide comprehensive early warnings for down hole anomalies and equipment failures.

The logging discipline has established a multi-parameter correlation analysis model. It conducts equipment health assessments and corrosion early warnings based on vibration spectra and temperature trends; employs machine learning to build a fluid loss monitoring system; integrates data from the driller’s navigation system to enable intelligent well control management; uses time-series analysis to predict mud loss risks; and combines remote expert consultation to achieve visual early warnings for drilling risks.

The cementing discipline focuses on the core objective of well bore integrity. It employs vibration and temperature monitoring to provide early warnings for cement truck malfunctions and uses statistical process control to monitor cement slurry performance parameters, ensuring construction quality. The discipline has established models for predicting dust concentration and assessing cement slurry loss risks, while simultaneously building an energy consumption benchmark model to achieve synergy between quality control and environmental risk prevention.

The Down hole Operations specialization focuses on high-risk scenarios such as fracturing and well testing. It conducts equipment health assessments and early fault diagnosis based on vibration analysis; employs machine learning to predict pressure anomalies and fracturing fluid loss; develops toxic gas dispersion models and noise impact assessment algorithms; and utilizes intelligent video analysis and personnel tracking to enable automatic identification of safety violations and dynamic risk assessment.

The Geophysical Exploration and Logging discipline addresses special risks associated with wide-area field operations, high-temperature and high-pressure environments, and radioactive materials. It establishes equipment health monitoring and fault early-warning models, utilizes machine learning to perform real-time quality inspection of collected data, and monitors occupational health risks such as noise and toxic gases. Concurrently, it conducts ecological impact assessments and explosive risk management, and combines remote transmission technology to achieve precise risk control and intelligent early warning throughout the entire process.

4.3. Big Data Sharing and Application Platform

The establishment of an integrated big data sharing and application platform serves as the core vehicle for achieving data-driven and intelligent QHSE supervision. Through this platform, data integration, system coordination, and decision support are realized. The core components include two major modules: the QHSE Smart Supervision System and the Digital Twin Platform for operational sites. This breaks down data silos and enables cross-departmental, end-to-end collaborative supervision.

4.3.1. Smart QHSE Supervision System Enabling Cross-Departmental Collaboration and Full Staff Participation

By establishing a unified data standards system and creating a “data lake” to enable comprehensive data sharing and in-depth data mining [5], the platform system integrates functions such as engineering data, equipment data, remote monitoring, intelligent violation detection, online approval, automatic task assignment, crew navigation, milestone control, and critical operation management. Through the mining and analysis of massive amounts of regulatory data, it enables risk early warning, trend forecasting, and optimized decision-making, thereby providing decision support for digital and intelligent QHSE supervision.

The QHSE Smart Supervision System comprises business modules such as safety management, environmental protection and energy conservation, quality management, health management, and comprehensive management, and includes both management and field interfaces. The management interface serves senior, middle, and executive management, while the field interface serves front line personnel. By enhancing capabilities for sensing, monitoring, early warning, response, and assessment of safety and environmental risks at the worksite, the system comprehensively improves the effectiveness of risk control during operations and the level of data integration and application.

4.3.2. Digital Twin Platform for Work Sites

Through multi-source data fusion, 3D modeling, and real-time simulation technologies, the system constructs 3D models with centimeter-level precision to recreate the actual environment of the entire work site. By integrating various IoT sensors, it simultaneously collects operational data such as temperature, pressure, flow rate, and smart sensing data [6]. By linking the 3D scene with business system data and presenting them interactively, the platform enables real-time mapping and visual monitoring of physical entities and quality data, providing comprehensive and transparent decision support for QHSE management.

(1) Creation of 3D Digital Twin Models for Key Operational Scenarios

Using advanced modeling techniques, we construct 1:1 3D digital twin models for key operational scenarios. During the construction process, we accurately replicate the equipment layout, process flows, and personnel activity zones of the operational site. Through IoT technology, real-time data collected by on-site sensors is mapped to the digital twin model, ensuring that the virtual model remains synchronized with the actual operational scenario in real time [7]. This allows managers to gain a real-time, intuitive understanding of actual conditions at the operational site through the digital twin model, enabling them to fully grasp on-site dynamics even when not physically present.

(2) Risk Simulation and Emergency Plan Drills

Utilize the constructed digital twin model to conduct risk simulations and emergency plan drills. During the simulation process, various potential risk scenarios are artificially created to observe changes in the operational environment within the digital twin model, as well as the propagation and scope of risks. Through simulation, potential losses and consequences under different risk scenarios are assessed in advance, providing a basis for formulating scientifically sound and reasonable emergency response plans. At the same time, existing emergency response plans are tested to verify their feasibility and effectiveness. Based on the results of these simulations, the plans are optimized and refined to enhance response capabilities when actual risks occur and minimize losses.

4.4. Research on Management Mechanism Reform

The effective operation of the new digital and intelligent QHSE regulatory mechanism requires not only technical support but also supporting management mechanisms. It necessitates a systematic upgrade and refinement of the existing management system to clarify standards,

define responsibilities, and optimize processes. This will facilitate the transition of digital and intelligent technologies from “technical implementation” to “management effectiveness,” ultimately achieving the “Four Comprehensives” regulatory objectives.

4.4.1. Establishing Technical Standards and a Data Governance System

Based on the characteristics of petroleum engineering operations, systematic and standardized technical requirements should be established across all aspects, including hardware configuration, data standards, safety management, and quality control. Standardized norms for sensor deployment, data collection, transmission and sharing, as well as analysis and application, should be unified to ensure the standardized application of digital and intelligent regulatory technologies. A comprehensive data governance system should be established to define management requirements for data collection, storage, usage, and security, thereby ensuring data authenticity, integrity, and security, and providing a foundation for data-driven regulatory decision-making.

4.4.2. Improving Organizational Responsibilities and Operational Support Systems

Clarify the division of responsibilities among organizational units at all levels within the enterprise regarding digital and intelligent QHSE supervision. Establish a three-tier management system featuring central coordination by headquarters, leadership by specialized departments, and execution by grassroots units, clearly defining the boundaries of authority and responsibility for each department in tasks such as data collection, system operation and maintenance, risk management, and performance evaluation. Establish scientific workflows and allocate sufficient human, material, and financial resources to ensure the normal operation, maintenance, and optimization of digital and intelligent systems, thereby guaranteeing the effective implementation of the digital and intelligent supervision mechanism.

4.4.3. Establishing Management Processes and a Continuous Improvement System

Establish a standardized operational mechanism for digital and intelligent QHSE supervision, integrating the application of digital and intelligent technologies into the entire process of QHSE daily management, risk control, emergency response, and performance evaluation to achieve a deep integration of technology and management; Establish a scientific performance evaluation methodology, incorporating the effectiveness of digital and intelligent supervision applications, the efficiency of risk early warning and response, and the closure rate of hazard rectification into the evaluation system; build a mechanism for continuous optimization and improvement, dynamically adjusting the digital and intelligent technology system and management processes in response to technological advancements, operational requirements, and regulatory issues to ensure the adaptability and effectiveness of the supervision mechanism.

5. Conclusion and Recommendations

5.1. Conclusion

Through a comparative analysis of domestic and international QHSE regulatory practices, and in conjunction with the practical realities of engineering technology in the petroleum industry, this study proposes a theoretical framework and technical implementation pathways for QHSE regulation of petroleum engineering service enterprises in a digital and intelligent context. It clarifies a dual innovation approach of “technological integration + institutional support” and establishes a full-chain digital and intelligent regulatory system covering data collection, analysis and early warning, platform development, and management safeguards.

(1) Digital and intelligent technologies provide the core driving force for the transformation of QHSE regulatory models. Leveraging the real-time sensing capabilities of the Internet of Things, risk modeling through big data, intelligent early warning via artificial intelligence (AI), and scenario simulation through digital twins, QHSE regulation has evolved from “post-event

tracing” to “pre-event prevention,” from “manual inspections” to “intelligent monitoring,” and from “fragmented management.

(2) Process reengineering must be centered on “data integration” to reconstruct management logic. Research has found that optimizing QHSE processes in a digital and intelligent environment requires breaking down departmental barriers and data silos. Through a closed-loop design of “risk identification – standard embedding – real-time monitoring – automated response – review and iteration,” regulatory requirements are transformed into quantifiable data metrics, and cross-entity collaborative responses are achieved through digital platforms.

(3) The effectiveness of digital and intelligent supervision depends on the synergy among “technology, systems, and culture.” At the technological level, it is necessary to ensure the comprehensiveness of data collection and the reliability of algorithms; at the systemic level, it is necessary to clarify the division of data responsibilities and establish mechanisms for dynamically updating standards; and at the cultural level, it is necessary to encourage employees to shift from “passive compliance” to “active participation.” An imbalance among these three elements will result in digital and intelligent supervision becoming nothing more than a “technological gimmick.”

5.2. Recommendations

The future implementation and promotion of digital and intelligent QHSE regulatory mechanisms will focus on three core directions:

(1) Promote the deep integration of digital and intelligent regulatory mechanisms into oil companies’ integrated production and operations platforms; develop and integrate dedicated functional modules to enable real-time collection, dynamic analysis, and intelligent early warning of safety, health, environmental, and quality data; and build an integrated digital and intelligent management ecosystem;

(2) Launch pilot projects at the grassroots level to establish “Demonstration Teams for Digital and Intelligent QHSE Self-Management.” Strengthen the deployment of smart devices and decision-support tools on the front lines, explore data-driven models of grassroots self-management and incentive mechanisms, and develop replicable and scalable best practices;

(3) Improve standards and training systems by leading or participating in the development of technical standards, operational specifications, and implementation guidelines for QHSE management in digital and intelligent scenarios. Concurrently, develop supporting training courses and digital toolkits to build a competency development system covering different levels and positions, thereby promoting the large-scale application of digital and intelligent QHSE oversight in the petroleum engineering and technical services industry.

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