

# Research on Common Technical Risks and Prevention Strategies in Geothermal Well Drilling Engineering

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**Abstract:** As a clean, renewable, and stable baseload energy source, geothermal energy has become increasingly prominent in the context of global energy structure transformation and the “dual carbon” (carbon peak and carbon neutrality) goals. As the core conduit connecting underground geothermal reservoirs with surface utilization systems, the quality and safety of geothermal well drilling engineering directly determine the success or failure of the entire geothermal project. However, geothermal well drilling is characterized by complex geological conditions, great drilling depths, and high-temperature and high-pressure environments, which expose it to a variety of unique technical risks. This paper aims to systematically identify common technical risks throughout the full life cycle of geothermal well drilling engineering—including preliminary investigation, drilling operations, completion and cementing, and post-drilling testing—analyze their underlying causes in depth, and propose targeted, scientific, and effective prevention and control strategies. It is expected that this study will provide theoretical reference and practical guidance for improving the safety, economic efficiency, and success rate of geothermal well engineering in China.

**Keywords:** Geothermal well; drilling engineering; technical risk; risk identification; prevention and control strategies; drilling fluid; wellbore stability

## Introduction

With the intensification of global climate change and the urgent demand for sustainable development, the development and utilization of clean energy have become an international consensus. As a high-quality renewable energy source, geothermal energy originates from the Earth’s internal heat and is characterized by abundant reserves, wide distribution, recyclability, and independence from weather conditions. It can provide stable 24-hour output and is therefore an ideal baseload

energy source. In recent years, China has successively introduced policies to promote geothermal resource exploration and development, triggering a new wave of geothermal utilization projects. Geothermal wells are the key infrastructure for geothermal energy development. However, geothermal well drilling is far more than a simple “hole-drilling” activity; rather, it is a high-technology, high-risk, and capital-intensive systems engineering project that integrates multiple disciplines. Compared with conventional oil and gas wells, geothermal wells are generally deeper, involve



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higher bottom-hole temperatures, and are associated with more complex geological structures, making them more prone to technical challenges and risk events during implementation. Downhole accidents can not only cause significant economic losses and construction delays, but may also lead to safety incidents, environmental pollution, and even complete project failure. Therefore, systematically identifying potential technical risks and formulating effective prevention and control measures are of great significance for ensuring project implementation, reducing costs, and improving overall efficiency. This paper conducts an in-depth discussion on these issues, with the aim of providing a comprehensive and practical reference for geothermal well drilling engineering.

## 1. Technical Characteristics and Risk Source Analysis of Geothermal Well Drilling Engineering

To effectively prevent and control risks in geothermal well drilling engineering, it is necessary to develop a thorough understanding of its distinctive technical characteristics. The most prominent feature of geothermal wells is the high-temperature and high-pressure environment. As drilling depth increases, the temperature inside the wellbore rises sharply, posing severe challenges to the performance of drilling fluids, drilling tools, logging and monitoring instruments, and cement slurries. Abnormally high formation pressures may also induce well kicks or even blowouts. Meanwhile, geothermal resource-rich areas are usually characterized by highly complex and variable geological conditions, with drastic lithological changes and the widespread presence of unfavorable geological bodies, which significantly complicate well trajectory control and wellbore stability maintenance. In addition, in order to obtain sufficient geothermal fluids, geothermal wells typically require deep production casing setting depths. The resulting long open-hole sections expose large areas of the wellbore for extended periods, thereby substantially increasing the risk of wellbore instability<sup>[1]</sup>. Moreover, geothermal wells are designed for long-term service and must withstand repeated thermal stress cycles and chemical corrosion from geothermal fluids. Consequently, extremely stringent requirements are imposed on wellbore integrity. Any minor defects in casing materials or cementing quality may ultimately lead to wellbore failure.

## 2. Identification of Common Technical Risks in Geothermal Well Drilling Engineering

### 2.1 Risks in the Preliminary Investigation Stage

First, the risk of distorted geological models: Geological models established during the preliminary stage—primarily based on geophysical exploration methods (such as seismic, gravity, and magnetic surveys) and a limited number of shallow exploratory boreholes—often fail to accurately reflect the true conditions of deep formations. In particular, there is significant uncertainty in predicting small-scale faults, karst cavities, and abnormal pressure zones. This “geological uncertainty” constitutes the fundamental source of all subsequent engineering risks.

Second, the risk of misjudgment of reservoir parameters: Deviations in the evaluation of key geothermal reservoir parameters, including temperature, permeability, porosity, and fluid properties, may result in a series of erroneous decisions regarding well location deployment, wellbore structure design, and production capacity forecasting.

### 2.2 Risks during the Drilling Operation Stage

#### 2.2.1 Risk of Wellbore Instability

This is one of the most common technical risks encountered in geothermal well drilling. It mainly manifests in the following forms:

(1) Wellbore collapse: In formations such as mudstone, shale, coal seams, and fault-fractured zones, if the drilling fluid column pressure is insufficient to balance the formation collapse pressure, or if chemical interactions such as hydration and dispersion occur between the drilling fluid and the formation, the wellbore rock may spall and fall off. In severe cases, this can lead to pipe sticking or even stuck and buried drilling tools.

(2) Wellbore shrinkage: In formations with strong plasticity—such as salt rock and gypsum—or in weak formations under high in-situ stress, creep deformation toward the wellbore may occur, resulting in a reduction in wellbore diameter. This can prevent drilling tools or casing strings from being smoothly run into the hole.

#### 2.2.2 Risks of Lost Circulation and Well Kick/Blowout

(1) Lost circulation: When drilling into fractured formations, karst cavities, or highly permeable strata, large volumes of drilling fluid may be lost into the

formation. This not only results in significant drilling fluid loss and increased costs, but may also induce wellbore instability in overlying formations due to the reduction of hydrostatic pressure, and even trigger blowouts. In geothermal wells, the invasion of cold drilling fluid into the geothermal reservoir may additionally cause reservoir damage and reduce production capacity.

(2) Well kick/blowout: When encountering high-pressure formations (such as abnormally high-pressure aquifers or gas-bearing layers), if the drilling fluid density is insufficient to balance the formation pressure, formation fluids may flow into the wellbore, resulting in a well kick. If not controlled in a timely manner, the continuous pressure release may escalate into a catastrophic blowout, posing serious threats to personnel safety, equipment integrity, and the surrounding environment.

### 2.2.3 Risk of Stuck Pipe

Stuck pipe refers to a condition in which the drill string loses mobility in the wellbore and cannot be run in or pulled out normally. Common types include:

First, differential pressure sticking: In permeable formations, the drill string may be pressed tightly against the wellbore wall, where a large pressure differential causes the drill string to be firmly stuck to the formation.

Second, cuttings-induced sticking: Due to factors such as lost circulation, insufficient pump pressure, or excessive tripping speed, drill cuttings may accumulate at the bottom of the hole or around the drill string, burying it and causing sticking<sup>[2]</sup>.

Third, keyseat sticking: In well sections with large changes in inclination and azimuth, rotation of the drill string may wear a “keyseat” into the wellbore. During tripping out, the tool joints can become lodged in the keyseat.

### 2.2.4 Risk of Drill String Failure

Under harsh operating conditions involving deep wells, high temperatures, and high torque, drilling tools such as drill pipes and drill collars are prone to failure modes including fatigue fracture, washout, and thread back-off. Such failures often lead to complex downhole fishing operations.

### 2.2.5 Risks in Directional Drilling

For cluster wells or wells requiring obstacle avoidance,

the application of directional drilling technology increases the difficulty of trajectory control. Problems such as insufficient build-up rate, deviation from the designed trajectory, and excessive dogleg severity (wellbore curvature) may occur, adversely affecting subsequent casing running and overall completion quality.

### 2.3 Risks in the Completion and Cementing Stage

First, the risk of poor cementing quality: Cementing is a critical operation for ensuring the long-term integrity of the wellbore. The main risks include:

(1) Poor cement bond: Failure of the cement slurry to effectively isolate formations may result in channeling, allowing fluid communication between formations with different pressure regimes, or leading to contamination of geothermal reservoirs by shallow groundwater.

(2) Micro-gaps and micro-annuli in the cement sheath: After cement placement, factors such as slurry weight loss, formation fluid invasion, or subsequent thermal cycling may create micro-scale gaps between the cement sheath and the casing or formation, compromising zonal isolation.

(3) Effects of high temperature on cement slurry performance: High temperatures accelerate cement hydration reactions and shorten thickening time, which may cause premature setting of the cement slurry before it reaches the intended position, resulting in a “flash set” or incomplete cement placement accident.

Second, the risk of casing damage: During casing running, irregular wellbores or excessive dogleg severity may cause running difficulties. During the waiting-on-cement period, gas migration may form a high-pressure gas column outside the casing, exerting compressive forces on the casing. Over long-term service, thermal stress and corrosive effects may further lead to casing deformation or rupture.

### 2.4 Risks in the Post-Drilling Testing and Stimulation Stage

(1) Reservoir damage risk: The invasion of drilling fluids or cement slurry filtrate into the reservoir may block pore throats or react chemically with reservoir minerals to form precipitates, severely impairing reservoir permeability and resulting in production performance far below expectations.

(2) Sand production risk: For unconsolidated sandstone geothermal reservoirs, if effective sand

control measures are not implemented, formation sand may be produced along with geothermal fluids during production or reinjection. This can cause abrasion of surface equipment and may even lead to wellbore collapse.

(3) Induced seismicity risk: Large-scale extraction or reinjection of geothermal fluids may alter the local crustal stress field and induce microseismic activity. Although most induced earthquakes are imperceptible, their potential social and environmental impacts should not be underestimated.

### 3. Integrated Prevention and Control Strategies for Technical Risks in Geothermal Well Drilling Engineering

#### 3.1 Strengthening Detailed Preliminary Investigation and Risk Pre-assessment

First, high-precision geophysical exploration: Advanced techniques such as three-dimensional seismic surveys, magnetotellurics (MT), and microseismic monitoring should be employed to accurately delineate geological structures, fault systems, and the spatial distribution of geothermal reservoirs in the target area, thereby reducing geological uncertainty.

Second, establishment of an integrated geology–engineering model: Multisource data—including geological, geophysical, and geochemical information—should be integrated, and professional software (e.g., Petrel, Techlog) should be used to construct high-fidelity three-dimensional geomechanical models. These models enable prediction and visualization of pressure regimes and mechanically weak zones that may be encountered during drilling<sup>[3]</sup>.

Third, conducting risk pre-assessment: Prior to drilling design, multidisciplinary expert teams should be organized to systematically identify potential risk points using methods such as HAZOP (Hazard and Operability Analysis). The probability of occurrence and severity of consequences should be evaluated, and the wellbore structure and construction plan should be optimized accordingly.

#### 3.2 Optimization of Drilling Engineering Design

(1) Scientific design of wellbore structure: In accordance with the “top-down” pressure control principle, the setting depths and sizes of casing strings at different intervals should be rationally determined to ensure an adequate safety window—that is, the

difference between formation fracture pressure and pore pressure—to accommodate variations in drilling fluid density.

(2) Precise design of drilling fluid systems: This is the core measure for preventing wellbore instability and lost circulation.

First, for wellbore stability: Drilling fluids with strong inhibition properties—such as KCl–polymer drilling fluids and oil-based or synthetic-based drilling fluids—should be selected to effectively suppress shale hydration and swelling. Plugging materials (e.g., ultrafine calcium carbonate and asphalt-based materials) can be added to seal microfractures and enhance the pressure-bearing capacity of the wellbore.

Second, for high-temperature environments: High-temperature-resistant additives (such as sulfonated agents, modified starches, and synthetic polymers) should be used to ensure stable rheological properties and fluid-loss control performance of drilling fluids under elevated temperatures.

Third, for reservoir protection: Shielding and temporary plugging techniques should be adopted to form a dense, low-permeability mud cake in the near-wellbore zone, preventing deep invasion of drilling fluid filtrate.

(3) Application of managed pressure drilling (MPD) technology: By precisely controlling surface backpressure through a closed-loop pressure control system, real-time and fine regulation of the wellbore pressure profile can be achieved. This approach effectively addresses formations with narrow density windows, prevents lost circulation and well kicks, and represents a key technology for drilling deep and geologically complex geothermal wells.

#### 3.3 Improving the Level of Refined Management during the Drilling Operation Stage

(1) Real-time monitoring and while-drilling analysis: Measurement While Drilling (MWD) and Logging While Drilling (LWD) technologies should be employed to obtain real-time geological and engineering parameters—such as inclination, azimuth, gamma ray, and resistivity. By integrating these data with surface mud logging information, timely judgment of downhole conditions and early risk warning can be achieved.

(2) Strict implementation of operational procedures: Reasonable drilling parameters (weight on bit, rotary

speed, and pump rate) should be strictly controlled to avoid excessive surge and swab pressures. Tripping speeds should be carefully managed to prevent large pressure fluctuations. In addition, solid control should be strengthened to maintain stable drilling fluid properties.

(3) Strengthening emergency response plans: Detailed and practical emergency plans should be formulated for major risks such as blowouts, lost circulation, and stuck pipe incidents. Sufficient emergency materials (e.g., lost circulation materials, pipe-freeing agents, and well control equipment) should be prepared, and regular emergency drills should be conducted to ensure effective response capability.

### 3.4 Innovation in Completion and Cementing Technologies

(1) Optimization of cementing design: Detailed cementing simulations should be conducted to optimize cement slurry formulations (e.g., adding silica flour to enhance high-temperature strength and stability, using retarders to extend thickening time), cementing procedures, and displacement schemes.

(2) Application of advanced cementing techniques:

First, stage cementing: Long cementing intervals are divided into several stages to reduce the cement slurry volume and hydrostatic pressure in a single operation, thereby lowering the risks of lost circulation and gas migration.

Second, reverse squeeze cementing: This technique is used to remediate sections with poor cementing quality by injecting cement slurry into the annulus and squeezing it into the target interval<sup>[4]</sup>.

Third, use of high-performance cement alternatives: Materials such as geopolymer cement can be adopted, as they exhibit superior high-temperature resistance, corrosion resistance, and lower shrinkage.

(3) Enhancing cementing quality evaluation: Advanced logging tools—such as Cement Bond Logging/Variable Density Logging (CBL/VDL) and Segmented Bond Tool (SBT)—should be utilized to comprehensively and objectively evaluate the bonding quality at both the first and second interfaces, providing a reliable basis for subsequent operations.

### 3.5 Emphasis on Post-Drilling Testing and Reservoir Protection

Well testing programs should be scientifically designed, and geothermal fluid production should

be induced through a stepwise pressure drawdown approach to avoid excessive pressure differentials that could cause reservoir sanding or damage. Effective reservoir stimulation should be implemented when necessary. For low-permeability geothermal reservoirs, acidizing or hydraulic fracturing may be considered to enhance productivity; however, their potential impacts on wellbore integrity and induced seismicity must be carefully evaluated. A long-term monitoring system should be established by installing temperature, pressure, and flow sensors at the wellhead and downhole. Continuous monitoring of production performance and wellbore integrity enables early detection of abnormalities and timely intervention.

### Conclusion

Geothermal well drilling engineering is characterized by significant challenges and high levels of risk. This paper systematically reviews the technical risks throughout the entire life cycle of geothermal well drilling engineering, encompassing geological uncertainty risks in the preliminary stage as well as specific risks arising during drilling, completion, and cementing operations. These risks fundamentally stem from the distinctive technical characteristics of geothermal wells, particularly high-temperature and high-pressure conditions. Effective risk prevention and control require a systematic and forward-looking integrated management strategy. This includes source control by reducing “unknowns” through high-precision investigations and integrated modeling; design-first principles that embed risk prevention and control measures into engineering design; technology-driven approaches that enhance risk response capabilities through advanced technologies; refined management to achieve dynamic, closed-loop risk control; and the establishment of a full life-cycle perspective to ensure long-term safe and efficient operation. Looking ahead, with the deep integration of emerging technologies such as artificial intelligence and petroleum engineering, risk identification in geothermal well engineering is expected to become more intelligent, prediction more accurate, and control more proactive. Continuous technological innovation and management optimization will help reduce engineering risks and provide strong support for the high-quality development of China’s geothermal energy industry.

## References

- [1] Meng Fanjian, Zhao Shuxing, An Guangwei. Research on Safety Production Management Technologies for Geothermal Well Construction [J]. *Smart China*, 2025, (08): 46–47.
- [2] Shi Leyan, Ma Jingjing. Research on Key Drilling Technology for Medium- and Deep-Geothermal Wells [J]. *Petrochemical Technology*, 2025, 32(12): 155–157.
- [3] Tao Yulong. Discussion on Risk Control in Geothermal Well Construction [J]. *Engineering Construction and Design*, 2022, (14): 278–280.
- [4] Chen Xueke, Zeng Dezhi. Research Progress on Wellbore Safety Risk Assessment of Geothermal Wells [C]//Youth Working Committee of the Chinese Petroleum Society, Chengdu University of Technology, National Key Laboratory of Oil and Gas Reservoir Geology and Development Engineering. Proceedings of the 6th Forum on Science and Technology Innovation in Complex Oil and Gas Engineering (2024). Southwest Petroleum University, National Key Laboratory of Oil and Gas Reservoir Geology and Development Engineering, 2024: 8–16.