

Integrated geomechanical framework for wellbore stability management in horizontal drilling

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Abstract. Wellbore instability is a major challenge in horizontal drilling, especially in anisotropic and unconventional formations. Factors such as stress concentrations, pore pressure anomalies, and reactive shales contribute to borehole collapse, stuck pipe, and reduced drilling efficiency. Advanced approaches-integrating Mechanical Earth Models (MEMs), real-time monitoring, and optimized mud weight-are essential for predicting and preventing instability. This paper also considers the impact of well trajectory, drilling fluid selection, and delayed integration of geomechanics into well planning. A case study from the V. Filanovsky field (North Caspian Sea) demonstrates the use of 3D geomechanical modeling for casing design, sidetrack planning, and drilling fluid optimization. Implementation of casing-while-drilling (CWD) significantly reduced open-hole exposure and improved borehole integrity. These strategies support safer, more efficient well construction under complex geological conditions. The integration of data-driven modeling and engineering decisions enhances well longevity, reduces non-productive time, and contributes to more resilient and sustainable drilling operations.

Keywords: wellbore instability; stress concentration; geomechanical modeling; safe mud-weight window; horizontal drilling; casing while drilling.

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1. Introduction. Horizontal drilling has become a primary method for accessing unconventional hydrocarbon reservoirs. It provides significant advantages in terms of reservoir contact, productivity, and economic efficiency, particularly in low-permeability formations such as tight gas, shale, and coalbed methane [1,2]. However, as well trajectories increase in length and complexity, issues related to borehole integrity and stability have also significantly intensified.

One of the most critical challenges in horizontal drilling is wellbore instability, which can lead to severe operational problems such as stuck pipe, excessive torque and drag, loss of circulation, and borehole collapse. Compared to vertical wells, horizontal wells present a higher risk of instability due to greater exposure to weak formations, longer open-hole sections, and complex in-situ stress interactions. This is especially relevant when drilling through laminated shale formations or highly anisotropic zones, where bedding planes or natural fractures may intersect the well path at unfavorable angles [3].

International research highlights that borehole failure is strongly influenced by the orientation of the wellbore relative to the principal stress directions, the presence of anisotropic rock fabric, and the selection of drilling fluid properties [4]. Studies have demonstrated the importance of geomechanical modeling [5–7] and real-time wellbore stability analysis to reduce these risks [8]. For instance, the use of Mechanical Earth Models (MEMs) and anisotropic failure criteria has become a standard practice in planning horizontal wells in formations such as the Barnett, Eagle Ford, and Marcellus shales [9].

In addition, pore pressure anomalies, thermal effects, and chemical interactions between drilling mud and rock formations have been identified as destabilizing factors in horizontal wells [10]. In HPHT (high-pressure, high-temperature) environments, temperature gradients can significantly alter stress distribution and rock strength, potentially leading to unexpected collapse or fracturing [10].

To address these challenges, a growing body of international literature supports the integration of advanced monitoring tools (e.g., LWD, borehole imaging), inhibitive mud systems, and real-time MEM updating techniques [6,11]. Moreover, ongoing research continues to explore the role of machine learning and artificial intelligence in predicting instability events and optimizing mud weight in real time [12].

Recent advancements in horizontal drilling-such as underbalanced drilling (UBD), slim hole completions, lateral sidetracks, and multilateral wells-have improved reservoir contact and field development efficiency. However, these techniques introduce new mechanical and operational risks. For instance, slim hole completions may reduce annular space, limit mud circulation and affecting hole cleaning, while lateral sidetracks and multilateral junctions introduce complex stress interactions that can destabilize the borehole. These innovations necessitate more advanced geomechanical planning and real-time stability assessment tools to address the compounded risks introduced by non-traditional well architectures.

This paper builds upon that foundation by examining key mechanisms of instability, evaluating geomechanical modeling strategies, and highlighting best practices from global case studies. The goal is to support safer and more efficient horizontal well construction in complex and anisotropic formations.

2. Mechanisms and modeling approaches for wellbore instability. Wellbore instability is primarily caused by a range of geological, mechanical, and operational factors that interact along the borehole trajectory. One of the dominant contributors is the concentration of mechanical stresses around the wellbore wall due to the redistribution of the in-situ stress field during drilling. When the tangential or hoop stress exceeds the compressive or tensile strength of the surrounding rock, failure may occur in the form of shear collapse or tensile fracturing. This risk is amplified in formations exhibiting anisotropy in their mechanical properties. Transversely isotropic rocks, such as laminated shales, demonstrate directional variation in strength and deformability based on bedding orientation. Ignoring such anisotropy in geomechanical models can result in incorrect predictions of failure zones and ineffective well trajectory design. Another critical factor is the presence of abnormal pore pressures. Both overpressured and underpressured intervals affect the effective stress acting on the wellbore and may lead to loss of circulation or structural collapse if not properly accounted for. Furthermore, the interaction between drilling fluids and formation minerals, especially clays, can significantly weaken the rock matrix. Incompatible fluids may trigger hydration and swelling, which further destabilize the wellbore. To address these issues, comprehensive geomechanical modeling strategies are employed. The development of a Mechanical Earth Model (MEM) integrates well log data, core testing, seismic surveys, and drilling history to characterize key elastic and strength parameters. In this context, advanced modeling approaches for multiphase flow systems-such as those that account for phase transitions-demonstrate the value of integrating thermodynamic behavior into stability prediction models [13]. This model provides the basis for stress analysis and stability forecasting. Failure criteria such as Mohr-Coulomb, Drucker-Prager, and Mogi-Coulomb are applied to evaluate the likelihood of shear and tensile failures, considering various borehole inclinations and azimuths. An essential output of the MEM is the determination of a safe mud weight window, which defines the pressure range necessary to maintain wellbore integrity without inducing collapse or fracturing. In addition, temperature variations and chemical reactions between the mud and formation are factored into stability analysis, especially in high-pressure, high-temperature (HPHT) environments. Thermal modeling and mud compatibility testing are therefore integrated into the geomechanical workflow to provide more accurate predictions and safer drilling operations.

The chart (Fig. 1) illustrates the relationship between drilling mud weight and the associated wellbore stability risks. The red zone on the left represents the collapse risk region, where the mud weight is insufficient to counteract the in-situ stresses, potentially leading to shear failure or borehole collapse. On the right, the orange zone indicates the fracture risk region, where excessive mud weight can induce tensile failure or hydraulic fracturing of the formation. The green zone

between these two extremes represents the safe mud weight window - the optimal range where the borehole is most stable, minimizing both collapse and fracturing risks. Determining and maintaining mud pressure within this window is critical for avoiding non-productive time and ensuring safe drilling operations.

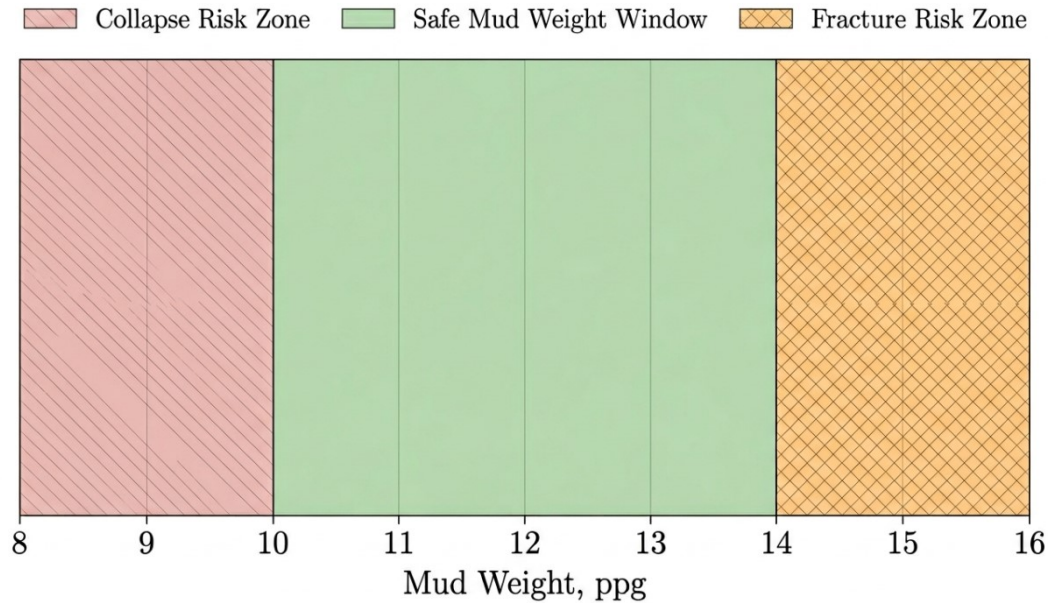


Figure 1. Safe mud-weight window and associated wellbore-stability risk zones

One of the most frequently cited operational risks is the delayed integration of geomechanical analysis into the well planning process. When MEMs are developed late or not fully calibrated, options for adjusting casing depth, mud program, or trajectory may be limited or costly. Early incorporation of MEMs-ideally during field development planning-enables proactive mitigation of risks and allows for safer, more efficient design decisions.

3. Trajectory optimization, fluid strategy and real-time adaptation. The design of the well trajectory plays a pivotal role in ensuring mechanical wellbore stability, particularly in horizontal and extended-reach drilling operations. One of the most effective strategies for minimizing the risk of borehole collapse or failure is to align the well path with the direction of the minimum horizontal stress. This alignment reduces hoop stress around the borehole wall, thereby minimizing the risk of shear or tensile failure. Deviating from this principle, especially in anisotropic or fractured formations, can introduce complex stress interactions that significantly degrade well integrity.

Another key consideration in trajectory planning is the avoidance of unfavorable intersections with geological features such as bedding planes, faults, or fracture networks. Crossing these features at oblique angles can trigger delamination or slippage along weak planes, leading to instability and borehole enlargement. Therefore, trajectory planners must assess bedding orientation and structural geometry when designing well paths. Additionally, tortuosity-the degree of curvature and deviation in the wellbore-should be minimized. High tortuosity not only increases mechanical drag and tool wear but also concentrates stress in localized zones, which can result in borehole deformation or tool sticking. An example of a planned trajectory with overlaid geomechanical risk zones is shown in Fig. 2.

Modern geomechanical and reservoir modeling software such as Petrel, Landmark, and JewelSuite provides robust 3D visualization capabilities that allow engineers to overlay stress field data with lithological and geomechanical property distributions. These tools enable more informed decision-making in path selection, casing setting depths, and the prediction of potential instability zones before drilling begins.

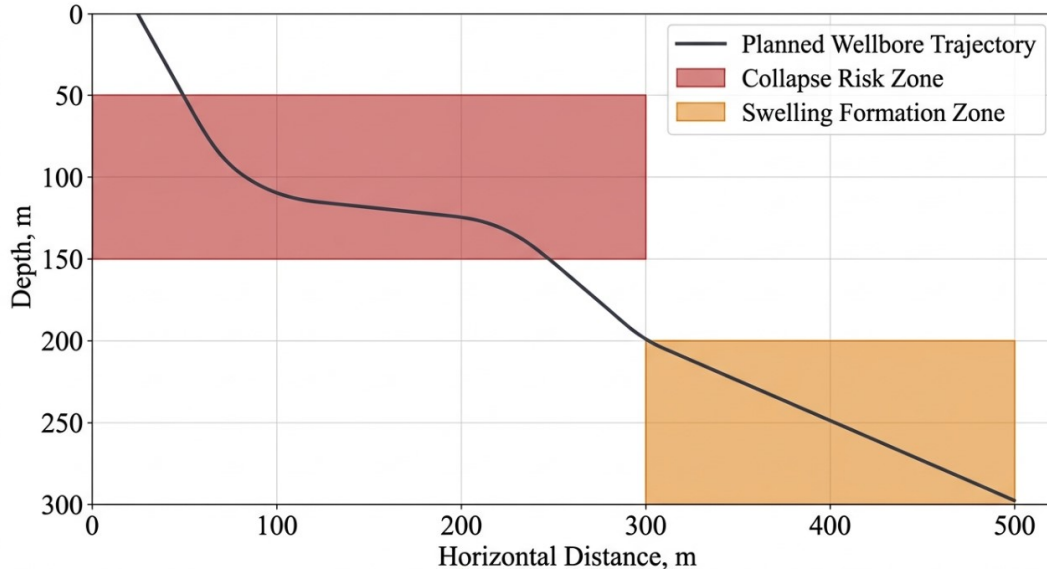


Figure 2. Planned well trajectory with collapse-risk and swelling-formation zones

Equally important is the management of drilling fluids, which serve as both a mechanical support and chemical buffer during drilling. The mud system must maintain a pressure regime within the safe operating window to counteract formation pressures without fracturing the surrounding rock. In reactive shale environments, oil-based or potassium-based muds are preferred due to their inhibitive properties that mitigate clay swelling and hydration. Maintaining a consistent mud weight helps prevent pressure surges and swab effects, which can destabilize the borehole. Techniques to suppress pressure pulsations in multiphase systems [14] may also be conceptually extended to manage transient pressure loads in drilling annuli and circulation systems. The addition of chemical inhibitors further stabilizes reactive formations and reduces the tendency for dispersion or caving. The rheological properties of the mud are also essential in transporting cuttings efficiently, especially in high-angle or horizontal sections where gravitational transport is limited. High viscosity and optimized flow characteristics ensure that cuttings do not accumulate and contribute to pack-offs or stuck pipe events. As drilling operations become more complex, the importance of real-time monitoring and adaptive control systems has grown significantly. Logging-while-drilling (LWD) technologies provide continuous feedback on borehole conditions, enabling early detection of enlargement, breakouts, or washouts. Borehole imaging tools offer high-resolution insights into the structure and integrity of the borehole wall, revealing features such as fractures, bedding planes, or instabilities in formation contact. Additionally, downhole pressure sensors monitor equivalent circulating density (ECD) and annular pressure variations, which are critical for detecting abnormal pressure regimes or surge/swab conditions. All of these real-time data streams are increasingly being fed into integrated drilling management systems, which update the Mechanical Earth Model (MEM) and enable dynamic adjustment of drilling parameters. This feedback loop enhances decision-making and supports a predictive, rather than reactive, approach to instability mitigation. The integration of real-time monitoring, optimized trajectory design, and adaptive fluid management forms the backbone of a modern, risk-informed drilling strategy.

Selecting the optimal stability strategy often requires trade-offs with other drilling and completion goals. For example, increasing mud weight may improve borehole support but also increase the risk of differential sticking or lost circulation. Similarly, trajectory optimization to avoid stress concentration zones may lengthen the well path or reduce reservoir exposure. Engineers must balance these factors-ROP, hole cleaning efficiency, cuttings transport, wellbore size, and stimulation potential-within an integrated design framework to ensure both structural integrity and operational feasibility.

4. Case studies and future perspectives. Practical implementation of geomechanical strategies in various drilling environments has demonstrated significant improvements in wellbore stability and overall operational efficiency. Numerous case studies across different geological basins illustrate how localized modeling and real-time decision-making contribute to mitigating instability-related risks (see Table 1).

Table 1

Case Study	Key Challenges	Geomechanical Strategy	Outcome
Bakken Formation, USA	Anisotropy, stuck pipe risk	Anisotropic MEM, optimized mud weight	Reduced stuck pipe incidents; improved prediction accuracy
South China Shale Gas Field	Structural complexity, shale instability	Trajectory aligned with Shmin, LWD tools, oil-based mud	Stabilized borehole; enhanced real-time decisions
North Sea HPHT Field	High pressure and temperature (HPHT)	Thermo-mechanical modeling, casing and mud design	Maintained integrity in HPHT conditions; improved safety and pressure containment
V. Filanovsky Field, North Caspian Sea	Complex tectonic stress, instability zones	3D geomechanical model, CWD implementation, optimized trajectory and mud system	Improved wellbore integrity; reduced open-hole exposure; optimized casing and fluid design

In the Bakken Formation (USA), operators confronted challenges typical of anisotropic shale formations, where conventional models often failed to predict borehole behavior accurately. To address this, advanced anisotropic geomechanical models were developed, which incorporated the orientation of bedding planes into the stress analysis. These models allowed for better prediction of failure envelopes and optimized trajectory design. By calibrating mud weights to local collapse and fracture gradients, operators significantly reduced the incidence of stuck pipe and improved drilling efficiency in horizontal sections.

In the South China Shale Gas Field, the complex stratigraphy and structural heterogeneity of the formations demanded a more dynamic drilling approach. Directional wells were strategically aligned parallel to the minimum horizontal stress to minimize hoop stress and enhance mechanical stability. The deployment of oil-based drilling fluids, known for their superior shale inhibition properties, helped to preserve borehole integrity. Additionally, microseismic monitoring and logging-while-drilling (LWD) tools were employed in real time to adjust operational parameters based on formation behavior. This adaptive strategy reduced borehole enlargement and improved rate of penetration (ROP) across laterals.

The North Sea High-Pressure High-Temperature (HPHT) Fields presented another layer of complexity, where elevated bottomhole pressures and temperatures altered the mechanical behavior of formations significantly. Here, thermo-mechanical models were used to simulate the effects of temperature changes on stress distribution and rock strength. Engineers tailored casing programs and mud weight schedules to accommodate thermal expansion and contraction, which proved

essential in avoiding formation breakdown and maintaining annular integrity. The use of synthetic-based muds further supported pressure containment in deep, high-temperature zones.

An illustrative case from the V. Filanovsky field in the North Caspian Sea demonstrated the practical benefits of comprehensive geomechanical integration. A full 3D geomechanical model was developed to address the region's complex tectonic and lithological conditions. This model was instrumental in identifying instability-prone intervals along the planned well trajectories and provided a basis for critical well design decisions. Key engineering outcomes included optimized casing design, targeted trajectory adjustments to avoid geohazards, and the implementation of casing-while-drilling (CWD) and cementing technologies in the intermediate section. These measures significantly reduced open-hole exposure time and enhanced wellbore integrity. Additionally, the model guided the selection and density adjustment of drilling fluids to maintain wellbore pressure within the safe operational window.

These field-based applications underscore the value of localized, data-intensive geomechanical workflows, especially when dealing with anisotropy, high-pressure regimes, and chemically reactive formations. However, as horizontal drilling continues to expand into even more technically challenging environments, further advancements are necessary.

Looking to the future, the integration of machine learning and artificial intelligence is expected to transform wellbore stability forecasting. Predictive models trained on historical well data can rapidly identify patterns of failure and recommend real-time adjustments to mud weight, trajectory, or drilling parameters. Moreover, real-time MEM updating systems-capable of ingesting LWD, seismic, and pressure data-will allow dynamic refinement of geomechanical models during drilling. Another promising frontier is the development of basin-scale geomechanical models, which incorporate regional tectonics, structural geology, and reservoir properties to guide large-scale field development planning.

By coupling these innovations with continued investment in high-resolution data acquisition and interdisciplinary collaboration, the oil and gas industry can reduce instability-related non-productive time (NPT), improve safety margins, and extend the productive life of horizontal wells-particularly in deep, unconventional, and structurally complex basins.

Beyond operational efficiency, effective wellbore stability management contributes to broader environmental and sustainability goals. Reducing open-hole exposure and instability minimizes waste from sidetracks and collapse recovery operations. Techniques like casing-while-drilling (CWD) reduce formation damage and non-productive time (NPT), while optimized mud systems lower environmental impact. As the industry advances, resilient wellbore design will become a cornerstone of environmentally responsible hydrocarbon production.

5. Conclusions. The main conclusions are as follows:

1. Wellbore stability in horizontal drilling requires a multidisciplinary and data-driven approach, combining geomechanics, drilling engineering, and real-time analytics to manage complex formation behaviors effectively.

2. Early integration of geomechanical modeling-including the development of Mechanical Earth Models (MEMs)-is critical for predicting stress distributions and identifying instability-prone zones before drilling begins.

3. Optimized trajectory design, aligned with in-situ stress orientations and informed by anisotropic properties, significantly reduces the risk of borehole collapse and mechanical failure.

4. Proper mud system selection and management-such as maintaining appropriate mud weight and using chemically compatible fluids-enhances borehole support and minimizes formation reactivity, particularly in shale zones.

5. Real-time monitoring and adaptive drilling technologies, including LWD tools, borehole imaging, and downhole pressure sensors, enable early detection of instability indicators and allow proactive adjustments during operations.

6. The combination of these techniques reduces non-productive time (NPT), enhances operational safety, and improves the overall success rate and cost-efficiency of horizontal well

construction.

7. State-of-the-art digital technologies and continuous feedback loops provide a robust foundation for confident decision-making in geomechanically challenging environments.

Conflict of interest.

The authors declare that they have no conflict of interest in relation to this research.

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