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Review Article

Review on the Analysis of Specific Instability Mechanisms: Borehole Breakout, Borehole Collapse, and Shale Swelling

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Abstract: Specific instability of boreholes drilled through rocks, such as borehole breakout, borehole collapse, and shale swelling, is a significant concern in drilling operations due to the adverse impact it has on drilling safety and efficiency. Despite considerable research on borehole instability, finding a solution to this problem remains elusive. The objective of this review is to examine the primary mechanisms of instability in rocks from a general physical instability principle perspective. A key criterion for the analysis of specific instability problems is the construction of comprehensive phase diagrams. Within this context, three main approaches and their partial implementation are discussed. The first approach involves constructing phase diagrams under the assumption that the borehole has already caved and aims to determine the final position of the cave wall. However, this approach presents several challenges. Caving may lead to severe kick-off or break-off problems, instability during the caving process, and complications in simultaneously modeling caving in a fluid-like porous material alongside flow filtration through the open walls of the borehole. The second approach entails developing phase diagrams that characterize the mechanical and hydraulic instability of the borehole wall being driven. These phase diagrams serve as specific instability criteria, but they face difficulties in generalizing across various failure mechanisms since they are typically non-quasi-static and are disregarded after failure occurs and the propagation ban is implemented. The third approach involves analyzing phase diagrams to investigate the results of the touch modes of compliance. However, these phase diagrams and the collapse of final boundary conditions often overlook the main depletions and in-situ impedances, which are crucial system-specific physical complements that enhance the classical mode of balance equation. Therefore, the integration of these factors is essential for a more comprehensive understanding of borehole instability.

Keywords: Directional drilling; specific instability; borehole breakout; borehole collapse; shale swelling; shale bedding; lithology; in situ stress; drilling fluids; wellbore strengthening.

Introduction to Wellbore Instability

Rock failure around the wellbore is undoubtedly one of the most critical aspects within the field of drilling engineering. Its detrimental effects can lead to severe consequences, including but not limited to the loss of well control, non-productive time, and significant financial issues. The occurrence of rock failure events during both the drilling in and drilling out processes poses a grave threat to the entire project. As a result, meticulous attention must be paid during the wellbore design phase to mitigate such risks effectively (Jiang *et al*., 2022).

Of all the various failure mechanisms, borehole instability is the one most frequently reported at the sides of wellbore. It is rather unpalatable to appreciate that it is widely documented that borehole instability accounts for about 10 percent of the total cost of drilling. Analysing this percentage, one might first glance consider it rather small However, it is crucial to consider. For instance, when there is discussing the six million dollars well, one million dollars should undoubtedly be considered lots of money more expenses (Hafezi, 2023). At times this amount could run into several fold or even far exceed any actual monetary gains that might be accrued from having a less stringent wellbore design strategy.

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To the present, its importance is acknowledged making the topic implementing as one of the core elements in learning. Further, it receives constant support and participation from many organizations in the drilling industry (Al-Rubaii *et al*., 2023). This multidimensional approach demonstrates the acknowledgement of the fact that rock failure around the wellbore cannot be solely a subject of theoretical analysis since its solution includes both research and application (Ashena *et al*., 2020).

The goal of this work therefore is to review the frequent borehole stability issues that engineers face in the practice of drilling and its impact on the drilling sector. The analysis Peculiarities of borehole breakout, borehole collapse, and shale swelling are necessary since these are the most widely known borehole stability issues that occur during the drilling processes of oil and gaseous wells. Further details about background and prevention methods relative to laboratory, in situ and case studies are presented in the following chapters (Cheng *et al*., 2023).

Definition and Significance

In the framework of near-borehole problems in weakly permeable rocks, this section firstly provides a definition of instability and its main sources. In this regard, both the breakout and collapse are identified as two different instability behaviors and are explained using the asymmetric and the symmetric perturbation of the initial frictional resistance in the borehole wall. However, uplift is also recognized as the third instability behavior in which the phenomenon occurs under certain conditions, thereby enhancing understanding of the instability phenomenon in weakly permeable rock formations (Jamshidi *et al*., 2024).

Deep oil, gas, or geothermal producing wells require quite a lot of knowledge about the surrounding rock formations' behaviour in relation to the borehole. From the analysis of the interpreted logs in open boreholes at logging velocity, many instabilities are recorded during the drilling process which include invasion of pore pressure, change of the near-borehole condition, and the relief of stress in the mass of the rock (Gao *et al*., 2024). These instabilities manifest in the form of two distinct but interconnected damage processes: Abrupt failure of borehole and borehole failure in general. Both the understanding and the preventive anticipation of both of these phenomena are of paramount importance in successful drilling operations. When rock mechanics is adequately studied from advanced sonic and geophysical logs, the drilling gurus can minimize many issues related to near-borehole rock behavior and pore pressure invasion, alteration of the near-borehole system, and stress release within the rock formation. By doing so they can greatly decrease the likelihood of experiences borehole breakout and or borehole collapse thus ensuring the overall success and safety of any drilling operations (Santos *et al*., 2022).

The purpose of the present paper is to analyze the physical mechanisms governing borehole instability. It is the goal of this study to identify causes of borehole instability and the ways through which they may be tackled. Two typical mechanisms have been described and will be discussed in detail below. The first mechanism comprises the change of the first tangential force at the face of the borehole wall during the breakout processes. This is a situation in which the borehole wall caves in thereby causing instability of the borehole. Thus, it is with the understanding that studying about this frictional resistance will help clarify this mechanism further that we proceed (Allahvirdizadeh, 2020).

The second mechanism that will be considered here is connected with the behavior of void ratio during the collapse phenomena. This collapse occurs due to varying drainage rates into the borehole, rates that can create foreign movement into the borehole structure. By advancing the knowledge of the implications of the void ratio on collapse phenomenon, we may shed more light on the dynamics of borehole instabilities (Cui *et al*., 2023). Besides these two mechanisms, we will reveal a third independent instability mechanism. While breakout and collapse mechanisms are mainly thermal in origin, the third of the key mechanisms that need to be briefly discussed here, called uplift, is stress-related. It happens in parallel with the interaction of the rock with the borehole. We hope that by extending the analysis into the details of uplift, it is possible to give a coherent description of all instability modes in boreholes (Brown *et al*., 2024). We intend to contribute to the existing scientific literature on borehole instability and yield potential approaches and directions for future research to help control and prevent the hazards of borehole instabilities in engineering projects (Yin *et al*., 2021).

Borehole Breakout

A borehole is a slim hole drilled into funnel for exploration purpose, and for other purposes too. Newer methods of drilling has enabled the construction of far and deep wells which poses a problem as this is the case. It is therefore important that any involved party or organization needs to have adequate information on borehole instabilities. This text presents the evaluation and review of borehole breakout, borehole collapse, and shale swell as some of the principal instabilities. Criterion like stress, rock properties, and drilling practices assist to avoid the occurrence of drilling difficulties and enhance drilling. Shale swell management and prevention is also discussed. Overall, this comprehensive review enhances our understanding and improves drilling practices (Stricker *et al*., 2023).

This text presents a review of borehole instability mechanisms, aiming at the presentation and evaluation of previous research on the instability mechanisms. In order to optimize drilling and well construction, understanding the mechanisms causing borehole instabilities (breakout, collapse, and swelling) is crucial. A large number of papers describing borehole instabilities can be found in the literature. Despite this great number of papers, we have not succeeded in finding any review of borehole instabilities considering borehole breakout, collapse, and swelling. The main reason for this article is to present a review of analysis models used to explain the borehole breakout instability mechanism. The modeling focus is on how the borehole is affected by mechanisms such as pore pressure and stress state changes in the proximity of the borehole, as well as borehole shape. Factors affecting the pore pressure and stress changes are also included (Ibrahim, 2021).

The analysis of instability mechanisms is based on the rock mass classification methods, including various approaches to determining the value of rock mass strength. In the review, all existing rock mass strength assessment methods are described in detail, including sample testing, methods based on residual stress calculations, algebraic dependencies with control of geophysical attributes, and empirical methods. The probability of failure of the borehole walls is directly related to the value of the stress concentration ratio (SCR) in the vicinity of the borehole. The values of the SCR parameter were calculated in accordance with the description of various mechanisms of specific instability, respectively: for borehole breakout, for shale hydraulic fracturing, for borehole collapse, and for shale swelling. To do this, conventional and well-known elements from the finite element method are used. This is not always practical, given both the complexity of the mechanisms studied and the ever-increasing requirements for the quality and accuracy of solving the appropriate engineering problems. A number of techniques and tools have been proposed for the problem of SCR calculation depending on the specific instability mechanism analyzed. Whether these techniques are deterministic or accompanied by uncertainty, the main goal is always to anticipate these possible cases of unfavorable flooring formation during drilling, depending on the geologic and mechanical characteristics of the area (He *et al*., 2022).

Borehole Collapse

As the well is drilled, the drilling fluid pressure in the borehole supports the weight of the rock above the drilling bit. This balance is referred to as the mechanical stability of the borehole. When borehole stability is not maintained, a number of instability mechanisms can be activated. Once the drilling process is affected by an instability mechanism, the well is said to have lost mechanical borehole stability and the well is considered unstable. The goal of optimizing borehole stability is to maintain a balance throughout the drilling process and in both the borehole and the annulus around the borehole. This is known as wellbore stability and can be managed by proper drilling fluid design and by geomechanical practice, among other approaches (Elrayah, 2024).

When specific wellbore pressures are reduced because of rock mechanics phenomena, borehole collapse can occur. The most common geological condition in which collapse occurs is in salt formations, characterized by the presence of halite. Under high stress, halite becomes highly plastic. Development of plastic zones around the borehole and subsequent plastic yielding in the salt causes borehole collapse, balloon formation, and lost circulation. The borehole collapse can be managed by careful consideration of the drilling fluid weight. However, the effects of heat, drilling fluid alteration of the salt hydration parameters, salt plastic constitutive models, and salt fabric can complicate prediction of salt-induced borehole collapse. A progressively increasing porosity appears with each reduction in pore fluid pressure (Ahmed and Salehi, 2021).

Factors Contributing to Collapse

Depletion may lead to the stability transition from fracture to Riedel. Early in the formation of a triaxial stress field, the implications must be defined in terms of either the mechanics of crack formation or the potential for a solid of perfectly plastic behavior. We apply the minimum tangential stress criterion to rocks in a condition for which plastic strains are developed near the borehole or changes in effective stress, or strain conditions are constructed in a direction perpendicular to the hole axis. The borehole size effect may be expressed geomechanically. All other things being equal, when the critical SHmin becomes equal to (or even less than) the vertical stress, the stability change (from tensile mode for Riedel and subvertical oriented maxima fractures to shear mode for horizontal or subhorizontal SHmax fracture orientation) occurs in the direction perpendicular to the maximal horizontal stress (Hao *et al*., 2021).

The borehole size effect on any instability mechanism is probably the result of the Minimal Tangential Stress Failure Criterion. It may be shown that an increase in the cross stress results in a decrease of hoop stresses. Thus, Bessel functions decrease if either wellbore size decreases or Lame modulus diminishes. We set poro-thermoelastic solid response to isotropic and deviatoric stress, number of pores, and number of bounding pores conditions, and the resulting stress-porosity relationships indicate that significant changes in porosity are only possible if stress concentration envelopes for initial and new states must be linear with the same basic properties. Therefore, the criterion for the evolution of multiple subhorizontal microcracks within the borehole breakout zone becomes linear: hydrating driven set length, to the resonant hexagon approximate isometric sphere size or vertical stress reduction, or the pore pressure condition, or the viscoelasticity or the hydration fluid and fluid-fluid interaction (Ding *et al*., 2022).

Shale Swelling

As previously mentioned, a crucial and highly significant issue that needs to be addressed when it comes to the stability of boreholes in sediments is the inherent risk of borehole wall failure. This failure often arises due to a multitude of chemical factors that come into play during the drilling process, leading to a range of abnormal challenging issues. Unfortunately, the connection between these chemical factors and the in situ geological environment is frequently overlooked or disregarded as inconsequential. One of the key aspects to consider in this context is the occurrence of diagenetic reactions on minerals. These reactions often give rise to the necessity for mass exchange within the borehole. However, the unfavorable conditions within the borehole arise when the governing parameters are not electrically balanced. These parameters include the ionic strength of the flushing fluid, the fluid saturation, and the cation-exchanging capability of the rock's forming minerals. Despite having an equivalent balance in chemical composition, the lack of electrical balance can lead to detrimental consequences (Asadimehr, 2024).

When unfavorable conditions arise, certain types of rocks such as shale minerals and clay-rich rocks are prone to undergo additional exchange of aluminum silicate cations, which ultimately triggers a swelling effect. This increase in pore pressure has the potential to cause the flow of formation fluids towards areas of lower pressure. Typically, these areas are oriented along natural structural discontinuities like fractures and bedding planes. It is worth noting that there are various factors that contribute to the magnitude of pressure support in these situations. The geological and petrophysical nature of the deposit, as well as the boundary conditions and the architecture of the well, all play crucial roles in determining the extent of load magnification (Ahmed and Salehi, 2021). It is essential to thoroughly analyze and comprehend these factors in order to effectively mitigate the risks associated with borehole instability in sediments (Chudyk *et al*., 2021).

Overview of Shale Properties

Specific instability mechanisms, such as borehole breakout, borehole collapse, and shale swelling, often dominate wellbore stability analysis. The existing related research has used various approaches and ranges of approximations, from mining and process engineering to continuum and microstructure models. This review seeks to present a balanced summary and describe the current state of the analysis based on the accuracy of the underlying model, identifying both strengths and limitations. Due to the wide range of currently available models, fluid-induced instability will be covered elsewhere. For now, hydro-mechanical analysis obeys the broad patterns observed in other areas (Radwan, 2022; Qiu *et al*., 2023; Yu *et al*., 2024).

Within the broad grouping of sedimentary rocks, mudrock and shale have the highest porosity and typically the highest clay content and are considered to be the worst materials for any form of instability. Salts have similar properties; Knowledge of the microstructure and grain size composition of the rock alone provides information on the range of potential mechanical properties of the rock matrix, but going further to the detailed spatial arrangement of grain volume fraction and clay distribution within the sample enables determination of the most basic strength properties of the rock, including its mechanical anisotropy (Hou *et al*., 2022; Rezaeyan *et al*., 2024; Yang *et al*., 2021).

Analytical and Numerical Models

Analytical models are usually derived based on assumptions that neglect several important aspects affecting the specific mechanics addressed by the model. For example, it is not unusual to apply isotropic assumptions to the material when the processes being considered are inherently anisotropic, such as the breakout phenomenon. Numerical solutions may present another set of assumptions and limitations, such as mesh sensitivity and numerical errors due to discretization (Razavi *et al*., 2021; Makvandi *et al*., 2021). Nonetheless, in both the cases, the model takes a form of a robust tool for the failure initiation, damage progression, and collapse progression analysis the key point involving the limitation that is tied to the chosen model. These limitations encompass; Dynamic effects are not considered in the analysis; redistribution of stress due to an increase in deformation; Nonlinear material behavior; assumptions made on boundary conditions; effects of other parameters such as temperature and humidity are also not considered. Nevertheless, a certain number of analytical models is sufficient for deeper explanations and becomes the basis for developing new, more accurate and complex models, taking into account as many factors as possible (Duan *et al*., 2021; Susnjak, 2024; Fu *et al*., 2023). If these models are continually refined and proven by experimental data and contemporary computational procedures, it will be possible to improve engineering designs and risk assessments of various industries (Soundararajan *et al*., 2021; Li *et al*., 2022; Feng *et al*., 2023).

Overview of Existing Models

Evaluating the tangential component of compressive stress is often addressed by the simulation method of packing spherical grains. Numerous studies compute the rigidity and friction strength of a wellbore, typically using models of a homogeneous isotropic body, including several models of effective rig/shear modulus (Ahmed and Salehi, 2021). However, these studies use varied models for describing the pack of cuts, often neglecting associated boundary conditions. The application of traditional fracture criteria to selected slices is also questionable. While these models provide immediate estimations of borehole dimensions, numerical results frequently contradict field experience (Cai *et al*., 2023).

We advocate for the use of an anisotropic elastic body model. Our research contributes to the theoretical and practical understanding of wellbore instability issues by establishing a relationship between non-axial wellbore instability and the inverse problem of solid mechanics with plane strain conditions (Weijermars *et al*., 2022). We demonstrate how to compute well sizes and design properties for anisotropic layers (Motahari *et al*., 2022). The method is provided for the estimation of the non-zero size of the dimensionless geometric parameter, which enters into the criterion for spalling rocks near the wellbore. The relevance of This parameter to the properties of complex anisotropic fracture layers, normal fracture resistance, and tensile strength of polystyrene-like material are examined in this paper (Huan *et al*., 2021; Ibrahim, 2021).

Case Studies and Field Observations

A number of case discussions and field analysis of Specific Instability Occurrences (SIOs) were done in this review. These discoveries will give the semi-quantitative and quantitative subsequent researches a comprehensive database. The identified hypotheses related to different types and aspects of SIOs were expected to be examined with the help of state-of-art measuring tools to check and enhance the proposed models (Wei *et al*., 2022; Xiang *et al*., 2024). In addition, the paper shed light on the key aspects of the preservation conditions and the drill string with regard to the respective contributions towards SIOs analysis. A physical model was adopted as an effective means of advancing our understanding of the particular modes of failure inherent within SIOs; the findings of which were shown to be in good agreement with field observations and measurements (Stricker *et al*., 2023; Ahmad *et al*., 2024). Most importantly, horizontal borehole breakout did not resemble developed vertical one.

It was observed that the most effective control mechanisms in maintaining borehole integrity include; geological conditions of the site, type of drilling fluid to be used and the use of drill string mechanisms (Li *et al*., 2020; Mallants *et al*., 2024). The analysis of horizontal borehole instability described specific guidelines for different applications as well as the inherent limitation in solving this problem. As summarized in this study, hole inclination might have been the common parameter for triggering of borehole breakout irrespective of the specific drilling-man related phenomena or the triggering causes observed in the particular boreholes analyzed (Trzeciak *et al*., 2022; Bahrehdar & Lakirouhani, 2023). This unification provides a valuable framework for future investigations and practical applications. The paper also delved into the possibility of further complex symbiotic relationships between different borehole conditions. This exploration opens new avenues for research, encouraging a comprehensive understanding of the complexities associated with SIOs. Future studies investigating these relationships have the potential to unravel additional insights into this fascinating field.

Real-world Examples

Intense research efforts have been focused on understanding borehole instability and the initiation of wellbore failure mechanisms. Most of these studies are based on numerical models, with few experimental ones, and hardly any field examples of the main singularities leading specifically to borehole instability are reported. This study reviews the incidence of real-world examples related to specific instability mechanisms, presenting a collection of field evidence and analyzing the geological and petrophysical background as well as the applied methodology when testing the integrity of reported examples of borehole breakout and borehole collapse, or assessing the cause of established borehole collapse and compressive failures in shales (Ibrahim, 2021).

The study introduces and reviews the key aspects of borehole instability. A detailed analysis of field examples and appropriate methodology when assessing wellbore stability is carried out then the Borehole instability problems typically yield borehole breakout formation, compressive failures, and borehole collapse initiation. These problems might stem from pore pressure or radial distribution of stresses, the geometry of the borehole, the rock's geomechanical behavior, the borehole's condition, state, and drilling technologies, the horizontal and vertical in situ stress balance, and geological faults and lithology (Qi *et al*., 2020; Jolfaei & Lakirouhani, 2022).

Some of the effects are still sophisticated most of which are hard to determine due to the fact that most of these effects are still well explained. It is therefore important to consider the following factors that lead to borehole instabilities as part of effort to enhance repair of instabilities resulting from drilling. It is important to further investigate and expand for a more extensive model to predict and handle borehole instabilities in various ground conditions (Garavand *et al*., 2020; He *et al*., 2022).

The integration of these findings with the existing numerical and experimental models will help the researchers of the field to get better insights about the borehole instability and how it has been effectuating on the drilling processes and from that perspective, what can be done to minimize the related damage (Allawi & Al-Jawad, 2021; Bahrehdar & Lakirouhani, 2022).

Mitigation Strategies

In the previous parts of this review, examinations of Specific Instability Mechanisms for borehole instability and the algorithms for minimization of their impacts were provided. In this section, the following strategies for controlling borehole instability are presented and the effectiveness of each is considered. The basic problem of borehole instability is the instability of the rock around the mud column within the temporary borehole following the emergence of tensional tectonic stresses or drilling fluid influences on the rock. The result of the rock instability around the borehole is the collapse of the borehole. The collapse of the well, as well as the formation of the cubbyhole behind the shielding casing and the filtration of the production formation resulting in the penetration of the water- or gas-saturated layers onto the producing interval, can lead to the ingrowth of cohesionless rocks into the borehole or to their breakout (Zhang *et al*., 2024; Ding *et al*., 2022).

At present, all basic potential Specific Instability Mechanisms are analyzed in terms of axial instability. Two additional mechanisms of wellbore runoff can also take place: the tensile separation of the rocks and the sliding of the rocks interconnected via shear contact along the sliding planes. The methods of rock stability restoration in the borehole are based on the understanding of the primary cause of instability. In the case of drilling with the mud column, the primary cause is the pressurized condition of the borehole, which is fixed during the drilling process through the mud pressure. At the bottom hole, the pressure exerted by the mud on the rock makes it be forced away from the borehole walls. At the same time, the rocks far from the outer surface of the borehole go back to the unstressed state and produce the cancellation of the borehole bottom quarter load. Consequently, the increased rock pressure turns into a tensile hoop rock stress Tang *et al*., 2023; Yan *et al*., 2023.

Knowledge about the dynamics of these several instability modes is important in enhancing drilling activities and avoiding failure occurrences. When these insights are incorporated into existing mathematical and experimental frameworks, researchers can improve their understanding of borehole instability and improve the approaches used to address it in drilling operations (He *et al*., 2022; Chernyshikhin *et al*., 2024; El-Sisi *et al*., 2022).

There is still much scope for future studies on the subject of borehole instability, especially in employing integrated models and detailed analytical methodologies in order to enhance the engineering solutions and the risk evaluations as presented in the recent works of, for example, Chen *et al*., 2024, Ma *et al*., 2024 and Li *et al*., 2020.

Preventive Measures

The effective usage of lost circulation materials and an organized advanced neural monitoring of a hole section with provisions for both axial and tangential strain measurement along with the directional drilling technology is one of the key practices performed in the drilling industry. However, even with these measures, there exists the potentiality of unwanted interchange means the risk of inadvertently sealing the fractures, and probably poor fracturing of the borehole walls by the drilling mud (Abdali *et al*., 2021; Asadimehr, 2024).

Furthermore, the application of mechanical borehole strengthening technology such as casing drilling technology as well as hydrocrack technology is expensively Serviceable. A self-contradiction appears in regard to defining how best to proceed when it comes to preventing rock instabilities based on various geological and technical circumstances in different cases (Xuedong, Cai 2021; Liu, Guo 2022). Where borehole mining is done at relatively small depths, concomitant circulation may lead to complete or partial annular drainage, especially when casing drilling technology is employed to reduce the chances of borehole wall erosion. They suggest that such practices eliminate the need for a specialized shuttle and consequently improve the stability of drilling operations (Chudyk *et al*., 2021; Halim *et al*., 2021).

The findings of this review are significant as they can be utilized as a foundation for formulating comprehensive recommendations that aid in selecting appropriate techniques for effectively preventing rock instability within the situ rock mass, particularly in mineral-rich environments. By considering the diverse conditions and nuances inherent in each geological setting, industries can apply the acquired knowledge to enhance the overall safety and efficiency of drilling operations and ensure the stability of rock formations (Xiao *et al*., 2023; Jiang *et al*., 2022; Ali, 2024).

Summary of Key Findings

This review highlights the key findings from the literature on: (i) mechanisms of specific instability features such as borehole breakout, shear failure, and lost circulation, which occur in natural conditions; and (ii) experimental and simulation techniques to understand, measure, and model them. The analysis inevitably highlights some ambiguities in our understanding and some contradictions that are still being pursued. The intention, however, is mainly to provide an overview of the current knowledge and some guidance on the questions that a future researcher might pursue to make major advances in understanding.

The authors are united in their agreement that stability, or more particularly, instability mechanisms are a critical control on the economic and environmental efficiency of drilling and completing a well. Indeed, the development of the field of petroleum engineering parallels the development of drilling, with many advances in both understanding and application being driven by the urgent need to drill wells more quickly, more safely, and more economically (Aslannezhad *et al*., 2021; Ibrahim, 2021). To focus research and transmission of the results into daily drilling operations, it is important to summarize knowledge. However, the fact that borehole stability has been recognized for many years as a critical focus for future research has led to an enormous literature on the topic. The key reasons for instabilities are well founded in physical laws, yet progress in understanding the forces that cause specific instabilities is significantly less compared to the achievements in building drilling and logging instruments that measure important petro-mechanical parameters (Mallants *et al*., 2024; Weijermars *et al*., 2022).

This review aims to highlight areas that require more research while also compiling and clarifying the body of existing knowledge. In order to enhance borehole stability and maximize drilling operations it offers a solid foundation for directing future research (Stricker *et al*., 2023 Frenelus and others in 2022). Using cutting-edge experimental and simulation methods to create more accurate models future research endeavors should keep concentrating on tackling the intricacies of borehole instability (Nath *et al*., 2024 Jamshidi *et al*., in 2024. For effective and secure drilling operations it is essential to comprehend and address borehole instabilities like borehole breakout shear failure and lost circulation. Researchers can better understand these issues and create more potent solutions by combining these findings with current experimental and numerical models (Abdullah *et al*., 2022, Jiang and colleagues 2022).

Conclusion and Future Perspectives

Although the problem of specific instability in petroleum engineering applications has been well known and various attempts have been made to apply and validate borehole stability criteria, there are numerous studies in which the validity of those criteria is called into question. The analyses and studies presented in this paper have contributed to understanding the behavior of rock mass and optimized design to better meet real borehole stability problems. Despite the fact that numerous studies have been conducted to determine the deformation properties and mechanical behavior of the rock mass, various parameters such as microstructural properties are continuously causing new research. However, the effect of anisotropic rock mass properties is the least treated in the subject and can be a guide for anisotropic rock mass behavior research. It is extremely important for determining the stability of a rock mass located at a certain depth to analyze the conditions under which that rock mass is located because a rock mass not at a certain depth will not be exposed to the same stress states and it will not exhibit the same deformation behavior, which is extremely important for providing geo-mechanical and design assistance. This work will allow for experimentally derived parameters for design to be supplied with less uncertainty to avoid drilling-related problems in the search for hydrocarbons.

In future studies, various complex wellbore instability mechanisms and multiphase thermal, hydro, bio-chemical, and mechanical interactions will be better evaluated, and steps will be taken to obtain more credible results by considering the properties of natural shale anisotropy, heterogeneity, and non-linear material. In the field for the rock-support system, thick-shell design, etc., it will generate realistic data. Also, in the analysis of the influence of thermal fracturing on wellbore stability and possible applications, it will provide designers with useful perspectives on engineering sources of possible wellbore failures. Shale swelling, the most difficult drilling problem to solve, will require more research and development, including comprehensive education and attention to analytical intentions.

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