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Research Progress on the Stability of Coalbed Methane Wells: From Theoretical Models to Numerical Simulation

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Abstract

As coalbed methane exploration and development advance into deeper and more geologically complex areas, borehole stability has become one of the core technical bottlenecks restricting the safe and efficient development of coalbed methane. This paper systematically reviews recent research progress in the field of coalbed methane wellbore stability, with a focus on two main directions: mechanical analysis models and numerical simulation methods. First, it elaborates in detail on five types of mechanical models based on approximate strength theory, fracture damage mechanics, weak plane structures, discontinuous media, and fracture mechanics, analyzing the theoretical foundations, applicable conditions, and their applications and limitations in evaluating coal seam wellbore stability. Second, it provides an overview of early international numerical simulation studies represented by software such as FLAC and STAB-ViewTM, and then comprehensively summarizes the latest applications of multi-physics field numerical simulation techniques—including discrete element method, finite element method, RFPA, and COMSOL—in research on coalbed methane wellbore stability, revealing the influence mechanisms of factors such as in-situ stress, joint systems, drilling fluid parameters, and multi-field coupling effects on borehole stability. Finally, in light of the current engineering requirements for deep coalbed methane horizontal well development, it points out deficiencies in existing research regarding the adaptability of theoretical models, multi-field coupling mechanisms, and intelligent prediction methods, and provides an outlook on future research directions, aiming to offer theoretical support and methodological reference for the optimized design and risk control of coalbed methane drilling engineering.

Keywords

Coalbed Methane; Wellbore Stability; Mechanical Models; Numerical Simulation; Multi-Field Coupling; Horizontal Wells.

1. Introduction

As a clean energy source, coalbed methane is of significant importance for optimizing the energy structure and ensuring energy security through large-scale development. However, coal seams are characterized by low strength, well-developed cleats, pronounced anisotropy in mechanical properties, and low formation pressure, which result in a much higher risk of wellbore instability during drilling compared to conventional reservoirs. Wellbore instability can not only lead to drilling accidents such as stuck or buried drill pipes, increasing non-productive time and costs, but also affect subsequent completion and recovery rates. Therefore, it is crucial to conduct in-depth research on coalbed methane wellbore stability and to establish evaluation methods and control technologies suitable for the characteristics of coal seams. This paper, based on a review of relevant domestic and international literature, systematically summarizes the progress in mechanical theory and numerical simulation studies on coalbed methane wellbore stability, evaluates the contributions and limitations of existing results, and discusses future research trends, aiming to provide a reference for academic research and engineering practice in this field.

2. Research Progress on Mechanical Analysis Models for Coal Mine Wall Stability

Mechanical models are the theoretical foundation for analyzing the stability of well walls, with their core lying in reasonably describing the failure criteria of coal and rock and the stress state around the well. In view of the particularity of coal and rock, researchers have developed various analytical models from different perspectives.

2.1. Approximate Strength Failure Theory Method

This method considers coal rock as a continuous and homogeneous material and uses classical strength criteria (such as Mohr-Coulomb, Hoek-Brown, and Drucker-Prager criteria) to evaluate whether the wellbore wall has failed. These criteria provide the critical conditions for wellbore collapse or fracture by comparing rock strength parameters (cohesion, internal friction angle, etc.) with the stress state around the wellbore. The study by Thotsaphon et al. (2001) indicates that a reduction in bottomhole pressure during production can alter the effective stress distribution around the well, potentially inducing shear failure in the coal seam[1]. This type of method is simple in form and relatively easy to obtain parameters, making it widely used in preliminary engineering design. However, it fails to fully consider discontinuous structures such as widely developed cleats and fractures in coal and rock, as well as the anisotropy of coal and rock strength. Therefore, there are certain limitations in prediction accuracy, especially in coal seams with well-developed fractures, where significant deviations may occur.

2.2. Fracture Damage Mechanics Method

This method approaches from the microscopic level, treating coal rock as a material containing initial defects (microcracks and micropores), and uses damage mechanics and fracture mechanics theories to study the initiation, propagation, and coalescence of defects under stress, as well as their impact on macroscopic mechanical properties. Tang Liqiang et al. (2007) combined the stress distribution around the wellbore with a coal rock failure criterion that considers damage evolution, establishing a calculation model for collapse pressure and fracture pressure, thus achieving quantitative prediction of the safe drilling fluid density window. The fracture damage mechanics method can reveal the progressive failure process of wellbore instability, providing a theoretical tool for understanding the mechanisms of damage accumulation and instability in coal rock under the influence of drilling fluid intrusion, pressure fluctuations, and other factors. However, this method requires high accuracy in determining the microscopic structural parameters of coal rock (such as initial damage distribution and fracture toughness) and involves considerable model complexity.

2.3. Weak Point Structural Method

This method explicitly considers the weak structural planes present in coal rock (such as cleat planes, bedding planes, and joint planes) and transforms the wellbore stability problem into the slip stability problem of weak planes under shear and normal stresses. Liu Xiangjun et al. (2002) systematically analyzed the impact of weak plane orientations (dip, strike) and frictional properties on the stability of vertical and inclined wellbores by establishing a simplified geomechanical model that includes weak planes. The study shows that when the wellbore trajectory intersects a weak plane at an unfavorable angle, wellbore stability is significantly reduced, and the stability of the weak plane often dominates the overall risk of failure. This method captures the key feature of the discontinuity in coal rock structures, making it closer to engineering practice, but its analytical results heavily depend on accurately characterizing the spatial distribution and mechanical properties of weak planes, which is often difficult to obtain precisely before actual drilling.

2.4. Non-continuum Analysis Method

Given the characteristic of coal rock being cut into discrete blocks by a dense joint network, discontinuous media analysis methods (such as the discrete element method and block limit equilibrium method) have been introduced into studies on wellbore stability. Chen Mian et al. (2013), based on the idea of discrete elements, regarded coal rock as composed of numerous separable and slidable blocks, established a calculation model for wellbore collapse pressure, proposed the concept of a 'wellbore stability coefficient,' and pointed out that only when this coefficient is positive can increasing the drilling fluid pressure effectively stabilize the wellbore. Zhang et al. (2015) further considered the randomness of block shapes and sizes, and based on limit equilibrium theory, classified movable blocks around the wellbore and assessed their stability. This model can intuitively simulate the process of wellbore instability caused by block sliding [2]. This type of method can effectively reproduce the sliding and collapse mechanism of the coal mass along the cleavage planes, making it a powerful tool for analyzing the stability of strongly discontinuous coal and rock mine walls.

2.5. Fracture Mechanics

This method focuses on the extension behavior of pre-existing macroscopic fractures (or cleats) in coal rock under the stress field around the well. Using linear elastic or elastoplastic fracture mechanics, the stress intensity factor at the fracture tip is calculated, and fracture toughness is used as the criterion to predict whether the fracture will undergo unstable propagation, ultimately leading to extensive wellbore failure. Early studies by S.E. Laubach et al. (1998) indicated that significant stress concentration exists at the tips of coal rock fractures, which is a potential source of instability [3]. Ai C. et al. (2014) further established a fracture propagation model that considers fluid-solid coupling and time effects, and quantitatively analyzed the impact of fracture length, inclination, and drilling fluid exposure time on wellbore stability [4]. Fracture mechanics reveals the mechanism of 'fracture-driven' wellbore instability and is suitable for analyzing conditions caused by drilling fluid pressure fluctuations or fracture propagation induced by production pumping.

3. Progress in Numerical Simulation Research on Coalbed Methane Wellbore Stability

Numerical simulation technology can take into account complex geological conditions, wellbore geometry, and construction parameters, intuitively displaying the stress, deformation, and failure process of the wellbore. It has become an important tool for studying the stability of coalbed methane wellbores. Its development history shows a trend from the early use of general-purpose software abroad to targeted simulation research in China that considers the characteristics of coal and rock.

3.1. Overview of Early Numerical Simulation Research Abroad

Since the 21st century, foreign scholars, represented by the United States, have conducted a large amount of pioneering work on the stability of coalbed methane wellbores using various commercial numerical simulation software, laying the foundation for subsequent research. Cameron and others used the Fast Lagrangian Analysis of Continua (FLAC) for simulation analysis and concluded that small-diameter wellbores are more advantageous than conventional wellbores in both enhancing production capacity and improving wellbore stability [5]. Whittles D N and others used the FLAC-2D finite element software to establish a series of plane strain models for predicting wellbore stability [6]. GENTZIS, based on FLAC software, specifically analyzed the differences in wellbore stability of coal seam horizontal wells under two different conditions: underbalanced drilling and overbalanced drilling [7]. Gentzis T. used STAB-View TM 2D and 3D software to comprehensively analyze wellbore stability throughout the drilling and production process (including stress changes caused by production); the range of the wellbore yield zone was calculated using STAB-View TM 2D software, and the impact of horizontal well trajectories (including inclination and azimuth angles) on wellbore stability was systematically analyzed using STAB-View TM 3D software. The safe drilling fluid density window for different trajectory parameters was quantitatively provided [8]. In addition, E. Karatela used discrete element software to study the effects of the ratio of in-situ stresses (the ratio of maximum to minimum horizontal principal stresses) and the orientation of natural fractures on wellbore stability. He systematically analyzed the controlling effects of different fracture angles on wellbore stability under various stress ratio conditions and proposed a method for evaluating wellbore stability based on discrete element results [9]. These early studies focused on using existing general tools to solve practical engineering problems, emphasizing the key role of macro engineering factors such as wellbore size, drilling methods, wellbore trajectory, and the stress environment of the formation.

3.2. Discrete Element Numerical Simulation

The discrete element method is naturally suited for simulating the discontinuous characteristics and block movements of coal rock, making it a powerful tool for studying the stability of coal mine walls. Beyond the early work of E. Karatela, domestic researchers have carried out extensive in-depth studies using software such as PFC and UDEC. Simulations by Zhai Xiaopeng et al. (2011) revealed that ground stress release and joint seepage are key factors causing wall collapse, and provided an empirical range for the minimum density of collapse-preventing drilling fluids. The study by Zhao et al. (2012) highlighted the controlling influence of the spatial distribution of the joint system (spacing ratio between face joints and end joints) on the collapse location, pointing out that merely increasing mud density is not always effective and should be combined with the use of plugging materials[10]. In recent years, research has become more refined. Sun Zhengcai et al. (2020) explored the coupling effects of geostress heterogeneity and joint angles, finding that when the anisotropy of geostress is strong, the joint angle has a significant impact on the deformation patterns and stability of the wellbore. Discrete element modeling has obvious advantages in revealing the mesoscopic mechanisms of coal and rock collapse, but it requires high computational effort and precise calibration of input parameters (such as contact stiffness between blocks and friction coefficients).

3.3. Finite Element Numerical Simulation

The finite element method (FEM) is proficient in handling stress-strain analysis and multi-physics coupling problems in continuous or quasi-continuous media. Chen Yiting (2012) used finite element analysis to study the softening effect of adsorbed gas on the mechanical properties of coal and rock, confirming that increased gas content can deteriorate wellbore stability. Liu Xiaoqiang et al. (2016), focusing on the special structure of multi-branch radial coalbed methane wells, used the ABAQUS software system to study the effects of factors such as geostress difference, wellbore diameter, and azimuth, providing a basis for optimizing the design and construction of radial wells. FEM has broad applications in analyzing complex issues such as wellbore trajectory optimization, casing stress, and thermal–fluid–solid coupling. With the continuous advancement of constitutive models, finite element models that can account for coal and rock plasticity, damage, and anisotropy are under development.

3.4. RFPA Numerical Simulation

RFPA (Realistic Failure Process Analysis) is a numerical method based on finite element principles that can simulate the material failure process. It is particularly suitable for studying the initiation, propagation, and penetration of cracks. Zhihao He (2013) used RFPA to study the effects of wellbore trajectory, joint density, and orientation on wellbore stability under seepage-stress coupling. The simulation results intuitively showed that the damage zone around the wellbore is more developed when drilling along the direction of the maximum principal stress. Qianwei Wang (2018) further applied RFPA to analyze the stability of coal-rock gas radial wells, quantifying the variations in fracture pressure and collapse pressure under different wellbore orientations. The RFPA method performs excellently in simulating progressive failure and brittle fracture of coal-rock, helping to understand the dynamic evolution process of wellbore instability.

3.5. COMSOL Multiphysics Coupled Numerical Simulation

COMSOL Multiphysics, with its powerful multiphysics coupling simulation capabilities, is used to study wellbore stability issues involving interactions among various processes such as fluid, solid, thermal, and chemical effects. Tong Meng (2015) simulated the wellbore creep behavior of coalbed methane wells and analyzed the effects of coal rock rheological parameters, in-situ stress, and time factors on wellbore diameter reduction. Liang Yongchang (2017) established a more comprehensive thermo-hydro-mechanical coupling model to simulate the heat exchange between drilling fluid and formation during drilling, as well as the resulting dynamic response of the surrounding temperature field, stress field, and seepage field. Such studies reveal long-term aging effects and thermal effects that are easily overlooked in traditional mechanical analysis, providing important references for evaluating the stability of deep coalbed methane wells, geothermal wells, and similar cases.

4. Current Challenges and Future Research Directions

Although significant progress has been made in the study of coalbed methane wellbore stability, there are still many challenges in the face of increasingly complex development conditions (such as deep wells, high geostress, and high-angle horizontal wells):

1. Adaptability and accuracy of theoretical models: Most existing mechanical models are based on specific assumptions and still do not adequately describe the extreme heterogeneity, anisotropy, and strong discontinuity of coal rock. There is an urgent need to develop constitutive models and failure criteria that can comprehensively consider the matrix, fracture system, and the interactions between them.

2. Unclear mechanisms of multi-field coupling effects: Deep coalbed methane development involves the strong coupling of high geostress, high temperature, fluid seepage, adsorption/desorption, and other physicochemical processes. How these processes jointly affect coal rock mechanical properties and wellbore stability has not yet been fully elucidated.

3. Difficulty in data acquisition and model parameterization: Coal rock mechanical parameters are highly variable, and critical input data such as in-situ stress and detailed descriptions of fracture networks are difficult to obtain accurately, limiting the predictive reliability of models.

4. Weak research on deep horizontal wells: Wellbore stability in deep coalbed methane horizontal wells faces a more complex stress state and longer exposed wellbore sections. Most existing studies focus on shallow vertical wells or simplified conditions, lacking systematic mechanistic analysis and control methods.

Future research should focus on the following directions:

1. Develop multiscale coupling theory and intelligent constitutive models: Combine techniques such as micro-CT and digital core analysis to establish a cross-scale theoretical framework from

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microstructure to macroscopic response, and explore the use of machine learning methods to build data-driven intelligent constitutive models.

2. Deepen multiphysical-chemical coupled numerical simulation: Develop or apply more advanced numerical platforms to study in depth the mechanisms of wellbore instability under fully coupled thermo-flow-solid-chemical conditions, especially considering the effects of gas adsorption/desorption.

3. Promote in situ monitoring and real-time intelligent early warning technology: Develop real-time wellbore status monitoring methods based on measurement-while-drilling, microseismic, distributed optical fiber, and other technologies, and combine digital twins and artificial intelligence algorithms to achieve dynamic assessment and intelligent early warning of wellbore stability risks.

4. Strengthen the integration of engineering practice and theory: Conduct case studies on typical mining areas (such as deep coal seams in the Ordos Basin), and through repeated verification and integration of laboratory experiments, numerical simulations, and field data, establish a more region-specific system for wellbore stability evaluation and control.

5. Conclusion

The stability of coalbed methane well walls is a complex system issue controlled by multiple factors such as geology, mechanics, and drilling engineering. This paper systematically reviews the research progress in mechanical analysis models and numerical simulation techniques in this field. Studies indicate that research methods have continuously deepened, evolving from continuous medium approximation to discontinuous medium analysis, and from single mechanical field to multi-physics field coupled simulation, leading to an increasingly clear understanding of the mechanisms behind coal seam wall instability. Early foreign research focused on using general software to address macro engineering problems, whereas domestic research, building on this foundation, places more emphasis on exploring microscopic mechanisms by combining the unique structure of coal seams (such as cleats) and developing specialized methods (like RFPA). However, in the face of new challenges in deep coalbed methane resource development, existing theories still have shortcomings in terms of model universality, multi-field coupling mechanism description, and application in deep horizontal wells. In the future, interdisciplinary integration and the introduction of advanced technologies (such as artificial intelligence and in-situ monitoring) are needed to drive coalbed methane well wall stability research towards greater precision, intelligence, and real-time capability, ultimately providing solid theoretical and technical support for the safe, efficient, and green development of China's coalbed methane resources.

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