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Perspective

Accurate stress measurement using hydraulic fracturing in deep low-permeability reservoirs: Challenges and research directions

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Abstract:
Although there is increasing recognition of the significance of deep in-situ stress measurement for the safe and efficient exploitation of geo-energy in deep low-permeability reservoirs, accurate measurement of deep stresses using the hydraulic fracturing technique still requires substantial enhancement. In this work, the major challenges in the precise hydraulic fracturing stress measurement in deep low-permeability reservoirs are pointed out, including high rock temperature, high pore pressure, fracturing mechanism, rock tensile strength, and drilling conditions. Under such circumstances, several future research directions are proposed accordingly. These involve the thermal-pore-elastic effect, downhole sensors and flow meters, appropriate indoor tensile strength test methods, new stress calculation methods, hybrid test techniques, and refined coupled numerical models. The future research recommendations will provide several fresh perspectives for geo-energy development in deep low-permeability reservoirs in subsequent stages.

1. Introduction

With the continuous reduction of shallow energy and the high requirements for energy conservation and environmental protection in China, the development of geo-energy (oil, gas, geotherm, etc.) in deep low-permeability reservoirs is a major demand for realizing China's energy succession strategy. It is also a key focus of current and future energy exploration, development, and utilization. The burial depth of energy in low-permeability reservoirs in China is usually 1,500-4,000 m, and some tight sandstone, shale, and dry-hot rock reservoirs are buried at depths exceeding 5,000 m or even nearly 10,000 m (Su et al., 2020). The occurrence environment of deep reservoirs generally exhibits the typical characteristics of low permeability, high temperature, high confining pressure, and high pore pressure. The hydraulic fracturing (HF) technique is currently the main means of increasing reservoir permeability and improving productivity. The development of energy in deep low-permeability reservoirs requires an accurate understanding of the in-situ stress state because the stress field strongly affects the initiation and propagation path of hydraulic fractures, thereby affecting the fracturing effect. Moreover, in-situ stress is the main driving force for oil and gas migration and accumulation and is also the fundamental factor causing a series of engineering problems such as well leakage and wellbore instability during drilling. Thus, accurately determining the deep stress state is a prerequisite for improving resource

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recovery efficiency.

The HF method suggested by the International Society for Rock Mechanics (Haimson and Cornet, 2003) is currently the most commonly used method for deep stress measurements worldwide. Although this method is excellent in many aspects, the classical HF theoretical framework is incomplete and has some remarkable limitations (Lakirouhani et al., 2016). The measurement theory and calculation approach of the classical HF method is based on the plane strain theory of elasticity, which can meet the accuracy requirements for predicting rock stress in low-temperature and low-pressure environments in shallow strata (generally less than 1,000 m). However, there are significant limitations in evaluating stress in deep low-permeability rock masses, and the accuracy of stress measurement results is greatly questioned. One key reason is that huge temperature and pore pressure differences exist between deep and shallow wells, which cannot be ignored in stress calculations. In deep and ultra-deep formations, the rock temperature, wellbore pressure, and pore pressure significantly increase, and the changes in these factors can produce a notable influence on the stress measurements. This may lead to measurement results that do not match reality. As a result, the existing HF measurement theory and calculation approaches are seriously challenged.

Although there is increasing recognition of the importance of precise measurement of deep in-situ stress for safe and efficient development of geo-energy in deep low-permeability reservoirs, some potential research areas and challenges of the HF method still need further investigation. Addressing these issues can not only provide a scientific basis for energy extraction design, reservoir transformation, and wellbore maintenance in deep low-permeability reservoirs but also facilitate the exploration of cutting-edge scientific problems related to in-situ stress in the deep crust.

2. Major challenges

2.1 High rock temperature

The geothermal gradient is generally approximately 3 °C /100 m, and the geothermal gradient in locally abnormal areas can reach 10 °C/100 m. The rock temperature of a kilometer-deep hole exceeds 40 °C, and the temperature of a few kilometers deep hole can reach over 200 °C. For example, the rock temperature in the test section with a depth of 4700 m in the Qinghai deep exploration area reached 219.2 °C, and the bottom temperature of the Songke No. 2 well with a depth of 6,400 m in the Cretaceous Continental Scientific Drilling in the Songliao Basin of China was 238.83-265.11 °C (Qu et al., 2017). The high-temperature environment will have a significant impact on the mechanical properties and constitutive relationships of rock masses, the deformation of borehole walls, the formation and propagation of hydraulic fractures, and the distribution of stress fields. The fracture criteria and mode of the borehole wall will also change, leading to inaccurate stress calculation results (Lakirouhani et al., 2016). When conducting HF tests in high-temperature deep holes, the circulation of colder drilling and fracturing fluids (usually normal-temperature water) can significantly reduce the temperature of the surrounding rock during the necessary drilling and testing processes, and even lower the rock temperature by more than 100 °C (Wu et al., 2017). This huge temperature drop can cause significant stress changes. In addition, the effective stress theory holds that the breakdown pressure of the surrounding rock of the borehole wall is a function of the in-situ stress and the strength of the surrounding rock, and the rock temperature possesses a direct influence on the breakdown pressure (Gan et al., 2015). Therefore, the influence of rock temperature changes on the stress calculation cannot be ignored.

2.2 High pore pressure

In many deep formations, pore pressure is not hydrostatic pressure, but overpressure (Sampath et al., 2018). For example, the predicted formation pressure of the Songke No. 2 well indicates that the pore pressure in the Huoshiling Formation is as high as 67.18 MPa (Qu et al., 2017). Similarly, high pore pressure was also observed in other oil and gas fields (Zoback et al., 2007). The impact on rock mass fracture is not the original pore pressure within the rock mass, but the actual pressure within the pores or fissures when the rock fractures. The change in pore pressure will lead to a change in breakdown pressure, which has a significant impact on the evaluation of in-situ stress. To accurately predict stress, it is first necessary to determine the pore pressure of the formation (Zhang and Zhang, 2017). A series of indoor experiments have been conducted to simulate rock fracturing with initial pore pressure and revealed that when fracturing fluid was allowed to enter the surrounding rock, the measured breakdown pressure and reopening pressure were lower than those predicted by traditional methods (Lee and Haimson, 1989; Schmitt and Haimson, 2017). Hence, the change in pore pressure is also an important factor that cannot be ignored in the measurement of stresses.

However, the existing HF methods have not solved the problem of the influence of changes in rock temperature and pore pressure on the calculation results of stress. Moreover, rock temperature has a significant impact on the diffusion of pore pressure, and the thermal effect on pore pressure is directly proportional to the temperature difference. Apparently, there is a clear coupling effect between the rock temperature and pore pressure, but their relationship with in-situ stress has not been well elucidated and quantitatively characterized.

2.3 Fracturing mechanism

During the deep HF, various factors such as the properties of low-permeability rock masses, the high-temperature and high-pressure occurrence environment, the fracture fluid properties and flow characteristics, and the interaction between rock mass and fluid lead to a more complex mechanism of wellbore rock fracture. Moreover, the process of HF depends on many parameters, and the interdependence between each parameter makes fracture mechanism and prediction research very difficult. At present, the research on fracture propagation mostly relies on laboratory experiments and numerical simulation, but a reliable and effective mathematical and mechanical model has not yet been established to study the mechanical response and fracture spatial propagation during HF in deep low-permeability reservoirs. Although considerable efforts have been made in previous studies, the abnormal changes in breakdown pressure observed in indoor and field experiments under different conditions still cannot be well explained (Sampath et al., 2018). Furthermore, the modeling of the criteria for determining the initiation and propagation of hydraulic fractures is not accurate, and a fracture criterion for the surrounding rock of the borehole wall that conforms to the actual deep geological structure characteristics and occurrence environment has not yet been established. The issue of HF is not only about predicting fracture initiation but more importantly, determining the critical mechanical conditions for fracture initiation and propagation. However, most existing models have not taken into account the comprehensive effects of rock temperature, pore pressure, and breakdown pressure, which cannot well explain the critical mechanical conditions for fracture initiation and propagation.

2.4 Rock tensile strength

In HF tests, the stress components mainly include the maximum horizontal principal stress, minimum horizontal principal stress, vertical stress, and their directions. The vertical stress magnitude is usually considered the easiest component to determine in the stress tensor, calculated by integrating the rock density within the test depth range (Rajabi et al., 2016). The HF method can directly measure the minimum horizontal principal stress on the plane perpendicular to the borehole axis, but whether the measurement result is affected by temperature and pore pressure changes has not been discussed, and new research is needed. The maximum horizontal principal stress is indirectly estimated based on elastic theory and the Kirsch solution, which requires accurate determination of the reopening pressure or the rock tensile strength that is suitable for the in-situ HF test according to the pressure-time curve (Chang et al., 2014). However, the accurate determination of the rock tensile strength and the breakdown pressure of the borehole wall in the HF test section has always been a key scientific issue affecting the calculation of the maximum horizontal principal stress.

Regarding the estimation of the maximum horizontal principal stress by using the reopening pressure, the reliability of this method has been questioned from multiple aspects (Yamashita et al., 2010). To solve this problem, linear elastic models, porous medium elastic theory models, linear elastic fracture mechanics models, and point stress concentration models have been proposed. However, the theoretical assumptions of these models are different, and the breakdown pressure and tensile strength during HF are important mechanical parameters. Moreover, the reopening pressure is significantly influenced by factors such as high temperature and high pressure in the formation, rock properties, borehole size, and pressurization rate (Haimson and Cornet, 2003; Sampath et al., 2018; AlTammar et al., 2019). These factors lead to the poor prediction accuracy of the maximum horizontal principal stress, and its reliability is highly controversial. There is currently no unified standard for determining it in the world. In addition, the compliance of the HF test system has a significant impact on the tensile strength of the rock mass in the test interval in the deep borehole (the compliance of the system increases with depth), resulting in significant errors in the reopening pressure yielded from the pressure-time curve. This further affects the accuracy of the maximum horizontal principal stress calculated based on classical formulas, and the calculated values are often smaller. Consequently, the accurate determination of tensile strength remains a key challenge affecting the estimation of the maximum horizontal principal stress.

2.5 Drilling conditions

Deep high-temperature, high-pressure, and low-permeability reservoirs will bring many difficulties and challenges to drilling, requiring high performance of guiding and measuring tools, especially in terms of high-temperature and high-pressure resistance. Due to the deep drilling, rock properties or drilling difficulties may result in unexpected oblique boreholes. There is still no clear answer to the extent to which inclined boreholes can be used for the HF stress measurement. The plane strain assumption used in the basic Hubbert and Willis equations is invalid for inclined boreholes when assuming that the principal stress acts in both vertical and horizontal directions (Haimson et al., 1993). In addition, the complex geological environment of deep reservoirs makes it easier to cause problems such as borehole wall collapse and drilling jamming during deep drilling compared to shallow drilling, which affects in-situ stress measurement and even leads to measurement failure. Hence, in deep low-permeability reservoirs, the safe and accurate operations of the drilling, guiding, and measuring tools are crucial.

3. Future research directions

In response to the above challenges, the prominent problems faced by deep HF stress measurements urgently need to be solved theoretically, experimentally, and on-site. Some potential research directions in this field in the future are suggested as follows:

1) There is an urgent need to study the thermal-pore-elastic effect of deep low-permeability rocks and to clarify the strain characteristics, structural changes, and fracture initiation and propagation paths of rocks under the coupling action of temperature and pore pressure by combining advanced laboratory experiments, field tests, and other methods, thereby further comprehensively revealing the fracturing mechanism of deep low-permeability rocks. At the same time, it is necessary to focus on analyzing the mechanical conditions for fracture initiation and propagation, and quantitatively obtaining the mathematical relationship between fluid pressure, pore pressure, temperature, and far-field stress during fracture initiation and propagation. These efforts are helpful to establish a judgment criterion for fracture initiation and propagation in the borehole wall surrounding rock considering the coupling effect of temperature and pore pressure. On this

basis, it is expected to construct a new HF stress calculation model suitable for deep low-permeability reservoirs.

2) The development of downhole sensors and flow meters should be strengthened to fundamentally eliminate the influence of the compliance of the test system. In addition, another practical strategy is to use indoor testing methods to determine the tensile strength of rocks, which can effectively improve or avoid a series of effects of the compliance of the test system on the measurements. The development of appropriate indoor tensile strength test methods is crucial for the reliability and applicability of the HF test data interpretation. It is recommended to choose rock tensile strength test methods with similar rock sample shapes and loading conditions based on different experimental and engineering purposes, such as hollow cylinder fracturing tests. Moreover, the influence of various factors (such as pressurized rate, confining pressure, and size effect) on breakdown pressure or rock tensile strength needs to be further studied to establish a standard method for extrapolating laboratory data to field conditions. On the other hand, it is also essential to explore new methods that can directly measure the maximum horizontal principal stress.
3) For inclined boreholes, a true three-dimensional analysis is needed to develop accurate stress calculation methods that consider the actual inclination of the borehole. In addition, deep stress measurement requires high-performance testing equipment, such as new types of drill bits, packers, and guiding tools that are resistant to high temperature, high pressure, and corrosion. Also, the research on advanced drilling techniques in deep high-temperature and high-pressure formations needs to be increased to improve the high reliability and stability of the HF test system. Related techniques include cutting-edge rock-breaking techniques, refined and automated pressure control drilling techniques, precision steering drilling techniques, and measurement while drilling techniques.
4) In addition to innovative improvements to traditional HF interpretation methods, new stress measurement methods represented by hybrid measurement techniques can also be developed for deep reservoirs, which use at least two direct and/or indirect methods to determine stress on-site. This is the forefront direction of the future development in deep stress measurement. Hybrid test techniques based on their respective attributes can compare the results obtained by one technique with those obtained by another technique, especially by considering the consistency and reliability of information to provide a confidence level for stress measurement. The stress data determined by each method can be analyzed and checked separately to determine whether the simplified assumptions related to each method are satisfied. In addition, different stress indicators obtained through hybrid test techniques can be combined (especially when the amount of test data for each technique is limited) to impose stricter constraints on the stress state in a specific area, thereby obtaining more reliable stress assessments.
5) Under deep high-temperature and high-pressure conditions, the anisotropic in-situ stress field exists in low-permeability rocks. The compressibility of injection systems and the viscous flow of fluids in plane strain hydraulic fractures can reduce the accuracy of stress measurements, but these problems have not been well quantified. Thus, a refined coupled numerical model that considers the compressibility of injection systems, viscous flow of fluids, and near-borehole stress field effects needs to be developed to estimate the level of error associated with HF stress measurements under non-ideal conditions. Moreover, the coupled numerical model can be applied to calibrate stress measurement results under field conditions, ensuring sufficient accuracy of stress measurements.

4. Conclusions

To enhance the exploitation of geo-energy in deep low-permeability reservoirs, it is urgent to investigate precise in-situ stress measurements using the HF technique in the reservoirs. Given the severe challenges faced by this field in terms of high rock temperature, high pore pressure, fracturing mechanism, precise determination of rock tensile strength, and drilling conditions, several future research directions that must aim to surpass previous efforts are proposed. These include the thermal-pore-elastic effect and fracturing mechanism, the development of downhole sensors and flow meters, the appropriate indoor tensile strength test methods and a standard method for extrapolating laboratory data to field conditions, the accurate stress calculation methods that consider the actual borehole inclination, the advanced drilling techniques, the hybrid test techniques, and the refined coupled numerical models. These forward-looking research trends contribute to the profound improvement of the HF stress measurement technique, providing new solutions for the precise determination of the deep rock stress, and ultimately serving the safe and efficient development of geo-energy in deep low-permeability reservoirs and other earth science issues related to in-situ stresses.

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Conflict of interest

The authors declare no conflicts of interest.

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