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Impact of drilling fluids on friction coefficient of brittle gas shale

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ABSTRACT

The stability of the horizontal long section of a wellbore is the main restriction of efficient development of shale gas. The use of oil-based drilling fluids in the initial stage of Longmaxi shale gas exploration in the Southern Sichuan Basin, China still causes wellbore collapses for reasons not well understood. Based on the geological characteristics and engineering conditions of brittle shale, a significant factor influencing shale wellbore stability-friction coefficient is proposed. Due to the developed facture networks of brittle shale in this region, frictional sliding along the fracture surface is the main source of movement within the Longmaxi Formation. Here, we determined the effects of drilling fluids on the Longmaxi Formation shale in Southern Sichuan Basin. Natural fractures slide due to compression shear slip, and the friction coefficient of the fracture surfaces is a controllable factor of shear and slip in natural fractures in shales. The typical experimental apparatus of rock friction sliding was modified to accommodate for drilling fluids and typical in-situ temperatures. Results show that the friction coefficient decreases, induced by infiltration of drilling fluids filtrate, and the friction coefficient is more sensitive to oil-based drilling fluid filtrate than water-based. The high-pH oil-based drilling fluid filtrate shortens the length of time taken by static friction stage, and smooths the time vs friction coefficient curve, which creates an easier situation for frictional sliding. High viscosity and good wettability lead to the strong lubricity of oil-based drilling fluid. The surface properties of the shale samples changed after the high alkalinity fluid immersion, such as fracture surface planarization, and floc-like particle generation, causing an obvious reduction of friction coefficient between fracture surfaces. As a result of rock strength decreasing after immersion into drilling fluids filtrate, asperities on fracture surface were prone to shear failure in the process of frictional sliding, and their failure products migrated with the fracture surface movement. This not only decreased the roughness shale surface but also acted as a friction reduction agent between the sliding surfaces. This study provides theoretical guidance for drilling fluid selection and optimization during brittle shale well drilling.

1. Introduction

With global hydrocarbon exploitation and development moving towards more challenging natural gas reservoirs, and shale gas becoming a focus of the petroleum industry, safe and efficient drilling of these reservoirs is needed to ensure the wellbore stability of penetrated shale formations.[1,2] Drilling of shale has long been a challenge due its potential for wellbore instability. Over 90% of the formations drilled through worldwide are shale formations, and about 75% of drilling operations' problems are related to shale formations.[3] In particular, the stability of the horizontal long section of a wellbore is the key factor of restricting the efficient development of shale gas.[4]

Gas shale is typically characterized as brittle, with a high content of brittle minerals (quartz, feldspar, etc.) that are prone to develop micro fractures. Well-developed natural fractures are beneficial for the efficient development of shale reservoirs; however, they also lead to drilling fluids loss. The existence of a small fracture in the wellbore can greatly decrease the wellbore pressure containment, which refers to the maximum pressure a wellbore can withstand before the wellbore starts to leak its fluid into the formation.[5,6] Fracture plugging with loss control material is the most common method to control lost circulation.[7] However, due to the long soaking time of drilling fluids and the wellbore pressure surging during shale drilling operations, plugging failure often occurs and drilling fluid filtrate loss along the fracture surfaces thus repeats. This in turn may cause strong interactions between the drilling fluid and shale, along with severe wellbore instability potential.[8]

Most studies on wellbore stability mechanisms of shale had mainly have focused on mechanics, physical chemistry and multi field coupling.[9–15] Nevertheless, wellbore instability has yet to be effectively answered.[16,17] Other studies have presented new insights on why wellbore instability can still occur in shale gas wells induced by oil-

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based drilling fluids, and revealed that friction properties of fracture surfaces play a significant role in wellbore stability of shale formations.[18–20] Due to the developed natural facture networks of shale, frictional sliding along the fracture surface is the mode of main movement of the rock.[21] The frictional force between natural fractures and/or shale beddings decreases, induced by good lubrication of oil-based drilling fluids filtrate, and very little force can move and collapse them rock mass from the wellbore.

Generally, an alkaline environment is required to improve the stability of a drilling fluids system, while the drilling fluids themselves have a high pH value, typically ranging from 9.0 to 11.5. Considering the long interaction time between the shale and high pH drilling fluids, friction within shale appears to be more complex. To our best knowledge, few papers have been published on the experimental method of frictional properties of hard brittle shale under the influence of drilling fluids. In this paper, the Longmaxi Formation shale in Southern Sichuan Basin of China was used as an example to determine the effects drilling fluids have on the frictional properties of shale using laboratory experiments. Also, a friction coefficient, a significant factor influencing shale wellbore stability, is proposed.

2. Shear slip of natural fractures in Longmaxi brittle gas shale

Rupture is the only failure mechanism for integrate rock. If weak joints exist in the rock, such as pre-existing faults, natural fractures and bedding planes, frictional sliding along the weak joints is thought to be the main failure mechanism.[22]

The Longmaxi Formation is the leading target play of shale gas development in the Southern Sichuan Basin, China, with a large amount of natural gas produced from this organic-rich, over-mature shale.[23,24] Because of the developed fractures and micro-fracture networks of the Longmaxi Formation shale, frictional sliding along the fracture surface can easily occur, induced by the change of stress state of near wellbore rock. The Longmaxi shale gas reservoir in the Southern Sichuan Basin has abnormally high pressure, with its formation pressure coefficient ranging from 1.35 to 1.55. In this circumstance, most of the natural fractures are open.[25] The in-situ stress gradient test results of the Longmaxi shale gas reservoir show that the maximum horizontal principal stress, minimum horizontal principal stress and the vertical stress are 2.67, 2.46 and 1.99 MPa/100 m, respectively. As the surrounding rock stress is higher than the formation pressure, the normal stress on the fracture surface is in a compression state and compression shear may occur (Fig. 1).

Under the assumption that natural fractures are initially open, compression shear alone on the fracture surfaces can be expressed as follows[26]:

$$\tau_{eff} = (1 - C_v)\frac{\sigma_1 - \sigma_3}{2}\sin 2\psi - \mu[(1 - C_n)(\sigma_1 \sin^2\psi + \sigma_3\cos^2\psi) - \beta p] - C \quad (1)$$

where τ_{eff} is the effective shear driving force, σ_1 and σ_3 are the maximum and minimum principle stresses, respectively, μ is the frictional coefficient, ψ is the angle between the fracture and the direction of σ_1, β is the connected area against the total area, p is pressure in the fracture, and C is the cohesion on the fracture surfaces, where C_n and C_v are respectively the compression transmitting factor and shearing transmitting factor, which are strongly dependent on the morphological properties of the fracture, such as roughness and the correlation between the surfaces in contact, and the elastic moduli of the rock.[27,28]

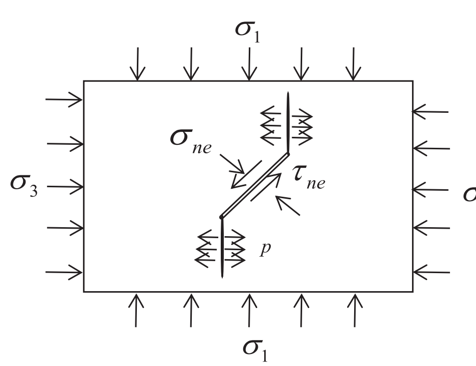

Fig. 1. Sketch of compression shear slip of natural fractures in brittle shale.[26]

Apparently, when τ_{eff} is positive, shear slip will occur. When τ_{eff} is negative, the fracture will not slip. The frictional coefficient is a controllable factor of shear and slip in shale natural fractures. In addition, the frictional coefficient is also strongly related to the properties of drilling fluids, and the interaction between shale rock and the drilling fluids. In next section, a typical experiment apparatus of rock friction sliding was designed and improved to perform friction behaviors test under in-situ temperature and consisting of drilling fluids. Combining wettability testing, micro-scanning and triaxial mechanical testing, we investigated the effects of drilling fluids on friction properties of hard brittle shale.

3. Experimental samples and methods

3.1. shale samples

Samples were taken from the Longmaxi Formation in the Southern Sichuan Basin, China. Mineral composition of the samples were tested with X′ Pert Pro XRD made by Holland Panalytical company and test results are listed in Table 1. The shale has a rather high clay mineral content and other brittle minerals. Geochemical test results show that the TOC (Total Organic Carbon) of this shale ranges from 1.9% to 7.3%, with an average of 4.0%, which belongs to organic-rich shale. Shale samples were cored on the direction parallel to the bedding plane with a diameter of 25.4 mm, and their end surfaces were cut smoothly. Each sample was then cut into two different shapes (Fig. 2): one was sliced on the direction normal to the bedding with a thickness of 5.0 mm, and the other was semi-cylindrical sample sliced along the axis. The frictional surfaces were polished with an 80 mesh metallographic sandpaper to a relatively smooth surface make sure that the initial roughness of fracture surface remained consistent.

3.2. Drilling fluids

Two typical drilling fluid systems used in the related experiments were from a shale gas well in in the Southern Sichuan Basin. Their basic properties are shown in Table 2. The filtrate was centrifuged from the drilling fluids with a TG16-WS high-speed centrifuge. To investigate the impact of alkali fluids on the friction properties of the samples, a pH of 11.5 alkali solution was prepared using deionized water, NaOH and 3% KCl.

3.3. Experimental method

To analyze the impact of fluid-rock interaction on the friction properties, immersion tests were carried out before friction coefficient testing. The samples were dried at 60 °C for two days, and then weighed and scanned. These samples were hung in heat-resistant plastic bottles with a 300-ml drill-in fluids filtrate, and were immersed beneath a liquid level of 2 cm. These plastic bottles were then sealed and placed in a thermostatic water bath at 70 °C for seven days. The samples were taken out from the bottles after 7d-immersion and were dried at 60 °C for two days, and finally the sample surfaces were scanned.

The methods for friction property testing are shown in Table 3. The sample was considered to be in a “dry condition” when the weight did not further decrease after being dried in the over at 60 °C for an extended period of time. The goal was to have the sample fully dried before introducing drilling fluids to reduce the impact of unknown