Study on the hydration of hard and brittle mudstone and its influence on the wellbore stability

Chunlai Chang*, Jielei Cui, Wen Li, Yubo Sun, Fu Tao, Huijun Zhang

1 Mud Service Company BHDC, CNPC, Tianjin 300270, China
2 No.5 Drilling Engineering Company BHDC, CNPC, Hejian Hebei 062450, China
*Corresponding email: changchunl@petrochina.com.cn (Chunlai Chang)

Abstract. The instability of hard and brittle mudstone wellbore in the Xujiahe Formation in the Western Sichuan Depression is widespread, which has led to accidents such as sticking and collapse. In this paper, the Xujiahe Formation in the Western Sichuan Depression is taken as the research object, and the method of indoor experiment and theoretical simulation is used to study the instability phenomenon of the wellbore. The following points of knowledge have been obtained: The clay minerals in the mudstones of the Xujiahe Formation in the Western Sichuan Depression are mainly illite and chlorite (content>90%), with a small amount of illite/montmorillonite mixed layer, and the pore throat radius is between 14.56nm-24.47nm, belonging to the mesoporous type; After the mudstone hydrates, its compressive strength, cohesion, elastic modulus, and tensile strength will continue to decrease with the increase of water, while the Poisson’s ratio will continue to rise; The relationship between the dry core and the wet core can be used to correct the acoustic velocity of the collapsed mudstone section; the nature of the wellbore instability is that the liquid pressure in the wellbore is less than the formation pressure, and the formation pressure exceeds the rock strength, which leads to instability. We use the borehole expansion rate to realize the evaluation of wellbore stability. The research results have guiding significance for the evaluation of the stability of the hard and brittle mudstone wellbore of the Xujiahe Formation in the Western Sichuan Depression, and provide technical support for the next step of drilling safety.

1. Introduction
The Western Sichuan Sag is located in the western part of the Sichuan Basin and is a large foreland basin formed by the thrusting of the Longmen Mountain. The clay minerals of the Upper Triassic Xujiahe Formation are dominated by illite, supplemented by the of illite/montmorillonite mixed layer[1]. The mudstone stratigraphy, microcracks and micropores are developed and belong to the typical hard and brittle mudstone. The instability of the wellbore is widespread, such as in Well CQ181, JL5, HL3, CJ566. When the hard and brittle mudstone is in contact with the aqueous solution, the two will exchange material and hydration[2]. The hydration will increase the circumferential stress and radial stress difference of the borehole lining formation, reduce the mechanical strength of the rock, and destroy the formation resistance to shearing. The shear force weakens the tensile fracture force of the formation, resulting in instability of the borehole wall, and the instability of the borehole wall will lead to accidents such as collapse, diameter reduction, and sticking[3].

For hard and brittle mudstone, especially the wellbore instability caused by the development of a large number of micro-cracks, the evaluation methods of wellbore stability have not been studied in depth. Holtz (1965) discovered the swelling phenomenon of mudstone for the first time; Low (1958)
proposed the hydration swelling force of shale based on this. In addition to studying its principle and formation mechanism, Deng Hu and Zhao Feng (2008) also proposed to use physical model analysis of the hydration process. Meng Yingfeng et al. (2010) used scanning electron microscopy and XRD technology to develop the hard and brittle mudstone surrounding structure, Shi Bingzhong (2012) used CT technology to study the development of hard and brittle mudstone cracks. Wang Yi et al. (2011) used mud chemistry method to carry out the evaluation of wellbore instability and found that the hydration of hard and brittle mudstone has been gradually deepened from the macro to the micro[4].

Starting with the basic characteristics of hard and brittle mudstone, we clarify the influence of hydration on the rock mechanical strength and sound velocity, establish wellbore stability evaluation standards, and realize the evaluation of the stability of hard and brittle mudstone wellbore, which has guiding significance to ensure the safety of drilling and avoid underground accidents.

2. Methods and materials

Experimental materials: triaxial tester (Jiangsu Suzhou Tuoce Instrument Equipment Co., Ltd.), XRD ray diffractometer (Shanghai Institute of Ceramics, Chinese Academy of Sciences), strain gauge (Beijing Bofei Electronic Technology Co., Ltd.), incubator (Suzhou Weir Laboratory Supplies Co., Ltd.), sonic detector (Beijing Mingda TEDA Technology Co., Ltd.), sodium chloride, potassium chloride[5].

Experimental method: In-situ stress, inclination angle, azimuth angle, drilling fluid performance and other factors all affect the stability of the borehole wall. The essence is that the density of the drilling fluid in the wellbore is lower than the formation pressure, and the pressure on the formation exceeds its own rock strength. The borehole expansion rate can be used to evaluate the stability of the borehole wall. The calculation formula of borehole expansion rate is:

$$
\Delta r = \frac{\sqrt{\frac{B^2 - 4AD}{4A^2}} - \frac{B}{2A} - \frac{r_w}{n}}{n}
$$  \hspace{1cm} (1)

$$
A = \left[ \cot \left( 45. \text{deg} - \frac{\varphi}{2} \right) \cdot \text{deg} \right] n (0.00981 \rho H) - \left[ 2\cot \left( 45. \text{deg} - \frac{\varphi}{2} \right) \cdot \text{deg} \right] + \sigma_{h1} - \\
\cot \left( 45. \text{deg} - \frac{\varphi}{2} \right) \cdot \text{deg} \right]^2 \sigma_{h2} \hspace{1cm} (2)
$$

$$
B = \left[ 1 + \cot \left( 45. \text{deg} - \frac{\varphi}{2} \right) \cdot \text{deg} \right] \left( \frac{\sigma_{h1} + \sigma_{h2}}{2} \right) - \frac{L}{n} - \left( \frac{\sigma_{h1} + \sigma_{h2}}{2} \right) \left( \sigma_{h1} + \sigma_{h2} \right) \hspace{1cm} (3)
$$

$$
D = \frac{3}{2} \left[ 1 + \cot \left( 45. \text{deg} - \frac{\varphi}{2} \right) \cdot \text{deg} \right] \left( \sigma_{h1} - \sigma_{h2} \right) r_w^4 \hspace{1cm} (4)
$$

Where: $\Delta r$ is the theoretically calculated borehole expansion rate; $\sigma_{h1}$ is the maximum horizontal principal stress, MPa; $\sigma_{h2}$ is the minimum horizontal principal stress, MPa; $P_w$ is bottom hole liquid column pressure, MPa; $\rho$ is the formation water density, g/cm$^3$; $n$ is the effective stress coefficient; $r_w$ is the borehole diameter, m; $C$ is the cohesion, MPa; $\Phi$ is the internal friction angle, °; $H$ is the well depth, m.

3. Results and analysis

3.1. Analysis of the basic characteristics of hard and brittle mudstone

The type and content of clay minerals have important research significance for the stability of the borehole wall. Mudstone, which is dominated by soft minerals such as montmorillonite and illite/montmorillonite mixed layer, has strong anion exchange capacity (montmorillonite cation exchange capacity 80-150CEC), large specific surface area (montmorillonite surface area 800m2/g), and strong hydration expansion ability. The wellbore is prone to collapse, shrinkage, etc. Mudstone
composed of mainly hard and brittle minerals such as illite and kaolin, has weak anion exchange capacity (illite cation exchange capacity is 3-15CEC), the specific surface area is small (illite surface area is 30m²/g), slip instability is easy to occur, and the formation stability is poor.

Through the XRD ray diffraction analysis of the mudstone of the Xujiahe Formation in the Western Sichuan Depression, it is concluded that the main types of clay minerals are illite and chlorite, accounting for 70.1% to 86.2%. Clay minerals are mainly hard and brittle minerals, which are prone to slippage. The hard and brittle mudstones of the Xujiahe Formation in the Western Sichuan Sag are very well developed with micro-cracks, which are related to the development of brittle minerals such as quartz, dolomite, and calcite. The pore radius ranges from 14.56nm to 24.47nm, belonging to the type of mesopores. The development of micro-cracks provides channels for aqueous solution transportation.

Table 1. Analysis of the relative content of clay minerals in the Xujiahe Formation in the Western Sichuan Depression.

| No. | Total content (%) | Illite (%) | Chlorite (%) | ilite/montmorillonite (%) | Mixed layer ratio (%) |
|-----|------------------|------------|--------------|--------------------------|-----------------------|
| 1   | 56.5             | 70.1       | 20.2         | 8.7                      | 10                    |
| 2   | 67.2             | 80.5       | 13.4         | 6.1                      | 10                    |
| 3   | 53.6             | 86.2       | 9.8          | 4.0                      | 5                     |
| 4   | 65.4             | 75.8       | 20.2         | 4.0                      | 5                     |

3.2. The influence of mudstone hydration rock mechanical properties

During the drilling process, the type and mass concentration of ions in the mudstone are exchanged with the ions in the aqueous solution. For clay minerals, they are prone to swelling when exposed to water, thereby hydrating. After the hard and brittle mudstone is hydrated, the performance parameters of the mudstone also change. Huang Rongzun pointed out that cohesion and internal friction angle are inversely proportional to water content, while Poisson's ratio is directly proportional to water content.

![Figure 1. The influence of rock mechanical properties of mudstone hydration (a, Elastic Modulus; b, Poisson's ratio).](image)

3.3. The influence of mudstone hydration on cracks

After the hydration of the mudstone in the Western Sichuan Depression, the micro-cracks gradually expanded and gradually changed from the mesopores to the macropores, destroying the rock. Through indoor experiments, the whole process of crack evolution can be clearly observed, from the original crack-microcrack generation-microcrack expansion-bifurcation-multiple bifurcation merging-rebifurcation-remerging-macroporous crack-destroying the rock. For hard and brittle mudstone, due to
the development of brittle minerals such as quartz and calcite, and the development of calcite along with the development of joints, the fractures formed by these joints facilitate the migration of water-based drilling fluid, increase the hydration area, enhance hydration, and cause micro-cracks which could cause further development, expansion, formation of large cracks, resulting in instability of the wellbore.

3.4. The influence of mudstone hydration on the speed of sound

In the evaluation of borehole stability, GR, AC, DEN and other curves are commonly used. For sonic logging, mudstone swells in contact with water, which will cause the sonic data to fail to truly reflect the formation information. The current sonic correction method is not perfect. Drilling fluid can well protect the formation. The use of oil-based drilling fluid to obtain correct sonic data is currently a generally accepted correction method, but this method has a big cost problem. By analyzing the sonic time difference data of dry and wet cores, it can be found that after mudstone encounters water, the sonic time difference will increase, resulting in a low speed. By analyzing the relationship between dry core and wet core, the sonic time difference can be corrected. We perform linear fitting and use wet core data as X data to obtain the true acoustic wave velocity.

![Figure 2. The influence of mudstone hydration on the sonic jet lag.](image)

3.5. Evaluation of mudstone wellbore stability

The reason for the instability of the borehole wall is that the pressure of the drilling fluid in the wellbore is lower than the pressure in the formation. When the pressure difference between the two exceeds the strength of the rock, brittle deformation develops. The stress state can be characterized by radial stress, circumferential stress, vertical stress, and shear stress. There is no unified method for the evaluation of borehole stability. The borehole expansion rate can be used to evaluate the stability of the borehole. We select Well X in the Lianhuashan structure in the Western Sichuan Depression as an example well and calculate its wellbore expansion rate. It is found that more than 70% of the intervals have borehole collapse. Combined with the formation collapse density curve, when the shale content increases, the collapse density increases, and the borehole expands. The calculated results of the model are consistent with the measured data.

4. Conclusion

(1) The clay minerals of Xujiahe Formation in Central Sichuan Sag are mainly illite and chlorite, which belong to hard and brittle clay minerals. Microcracks are generally developed and the hydration
is strong. The hydration will change the circumferential stress and diameter of the wellbore. The increase of the directional stress difference reduces the mechanical strength of the rock, destroys the stratum resisting shear force, weakens the stratum's tensile fracture force, and thus leads to instability of the wellbore. After the hard and brittle mudstone undergoes hydration, its compressive strength, cohesive force, elastic modulus, and tensile strength decrease continuously with the increase of water, while Poisson's ratio keeps rising.

(2) Hydration will cause the wall of the mudstone well to collapse, resulting in the acoustic time difference, which cannot accurately reflect the formation information. The sonic correction can be achieved by using the dry and wet rock facies fitting relationship. When the mudstone encounters water, it will self-absorb and expand, destroying the original formation stress structure. At the same time, the hard and brittle mudstone generally develops micro-fractures, which become important migration channels for hydration, aggravating the damage of the wellbore stability.

Acknowledgments
This work was not supported by any funds. The authors would like to show sincere thanks to those techniques who have contributed to this research.

References
[1] Zhang, F., Zhang, S., Jiang, X., Lu, R., Chen, M. (2008) Borehole stability in naturally fractured reservoirs during production tests. Petroleum Science. 5: 247–250.
[2] Ping, Q., Shen, R., Li, F., Wang, Z. (2011) Time delay effect due to pore pressure changes and existence of cleats on borehole stability in coal seam. International Journal of Coal Geology. 85: 212–218.
[3] Gaede, O., Karrech, A., Regenauer-Lieb, K. (2013) Anisotropic damage mechanics as a novel approach to improve pre-and post-failure borehole stability analysis. Geophysical Journal International. 193: 1095–1109.
[4] Liu, T., Liu, H., Meng, Y., Han, X., Cui, S., Yu, A. (2020) Multi-coupling stress field and evaluation of borehole stability in deep brittle shale. Arabian Journal of Geosciences. 13: 1–9.
[5] Hashemi, S.S., Taheri, A., Melkoumian, N. (2014) Shear failure analysis of a shallow depth unsupported borehole drilled through poorly cemented granular rock. Engineering Geology. 183: 39–52.