Wellbore instability mechanism of hard brittle rock under unloading condition in the ultra-deep wells

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Abstract. Limestone, igneous rock and dolomite are widely distributed in ultra-deep wells in Tarim Basin. Hard brittle rocks show different mechanical properties under high stress conditions in ultra-deep wells. Traditional wellbore stability theory states that the greater the rock strength the more stable the wellbore. The actual drilling in Tarim oilfield (more than 7000 m true vertical depth) shows that in the same section of hard dolomite and mudstone formation, there are more dolomite enlargement and block falling during drilling, while the caliper of mudstone formation is regular. The unloading mechanical experiment of hard brittle rock shows that the deformation and failure characteristics of rock during unloading are different from those during loading. In the process of unloading confining pressure, the axial stress and confining pressure decrease linearly with the increase of strain, and the unloading modulus increases with the increase of the decreasing rate of confining pressure. The smaller the unloading rate of confining pressure, the more obvious the axial plastic flow becomes. The failure of unloading rock occurs mainly due to its brittleness. By comparing the failure degree under different stress paths, the unloading confining pressure before peak is greater than that after peak, and the unloading confining pressure after peak is greater than that of the loading test. Most of the unloading cracks are tensile cracks, but there are shear cracks in the sample, and tensile flakes on the surface of the sample after unloading confining pressure. Within the experimental range (unloading rate), there may be an unloading rate that causes the most severe damage to the rock sample, that is, with the increase of the rate of penetration (ROP), the degree of rock damage caused by stress unloading does not increase monotonously, and there may be a certain ROP that causes the greatest damage to the wellbore. Large unloading will aggravate the damage evolution and failure of tight brittle rock. For the safe drilling of such rock formation, the drilling rate and drilling fluid density should be optimized based on complete understanding of the geo-mechanical environment to minimize the damage and instability of surrounding rock caused by drilling unloading.

1. Introduction
The Ordovician and Cambrian formations in Tarim Basin are developing with sets of marine sedimentary series with carbonate rocks. From top to bottom, they are Ordovician Yingshan, Penglaiba, Cambrian Xiaqulitage, Awatage, Shayilik, Wusongger, Shoerbulake, and Yuertus formations. The upper Cambrian Qiulitage and lower Ordovician Penglaiba groups have high degree of crystallization and high compressive strength of dolomite. At the same time, affected by volcanic, hydrothermal, and other geological factors, siliceous and cherts are distributed in this section, which is difficult to predict. Quartz is occasionally found in the fracture fillings with strong vertical and horizontal heterogeneity of rocks.
The diameter of AX well in mudstone formation of S1K section is normal (average 9.86 in, median 9.9 in, maximum 11.81 in). The diameter of the first section of pure dolomite formation is expanded seriously, the maximum diameter is 33%, the average diameter is 10.15 in, the median value is 9.90 in, and the maximum value is 12.63 in.

Zhang Chengliang et al. [1] performed loading and unloading tests under different confining pressures, studied the mechanical properties under different loading and unloading paths, and obtained the deformation characteristics, damage evolution process, and strength characteristics of rock samples under loading and unloading. Chen Danxi et al. [2] studied the influence of stress path of unloading confining pressure on the strength and deformation characteristics of rock, and concluded that the stress path has no obvious influence on the strength, but has obvious influence on the deformation characteristics of rock. With the further study of unloading rock mechanics, the influence of unloading stress path on rock failure process is gradually found. Ha Qifu et al. [3] brought forward the concept of unloading nonlinear rock mechanics and pointed out the difference between unloading nonlinear rock mechanics and loading rock mechanics. He mentioned that loading rock mechanics method could not reflect the actual mechanical state of slope rock excavation unloading. Li Jianlin et al. [4] analyzed the engineering characteristics of unloading rock mass in terms of structural conditions, anisotropy, unloading, rheology, and deformation, and discussed the different mechanical conditions and mechanical properties of unloading rock mass. Consequently, he pointed out that unloading nonlinear rock mass mechanical theory and method should be selected to analyze unloading rock mass mechanical problems according to the mechanical conditions of unloading rock mass. The above research suggests that the unloading failure of rock is clearly different from the loading failure of rock. Therefore, it is impossible to study the mechanical properties and deformation characteristics of rock mass under known load by loading failure.
In the study of unloading mechanical properties and deformation and failure characteristics, Li Tianbin et al. [5] studied the deformation and failure characteristics of basalt under different stress paths and other confining pressure unloading conditions. The research showed that in the unloading stress state, there is an expansion of strong crack along the unloading direction, and with the increase of confining pressure during failure, the failure mode of the sample gradually transits from tensile failure to tensile shear failure. Huang Runqiu et al. [6] studied the deformation, parameters, and fracture characteristics of rock under unloading condition by unloading test of granite in its excavation area under conventional triaxial test, and considered that the failure of rock under unloading condition was caused by strong unloading rebound deformation and tensile expansion. Li Hongzhe et al. [7] performed the triaxial unloading test and multi-stage failure test of Jinping marble under unloading confining pressure and studied the unloading deformation and strength characteristics of rock under high stress conditions. They observed that unloading confining pressure is easier to cause rock failure than axial compression, and the lateral deformation of rock is accelerated after unloading, showing significant expansion. The above literature hints that the rock, after unloading, shows obvious dilatancy and rebound deformation.

It can be seen from the above analysis that the rock failure mechanism and rock strength under unloading condition still need to be improved. It is very important to study the influence of unloading confining pressure on rock failure under different initial geostress states.

2. Rock mechanical test under different stress paths
The samples used in this experiment are dolomite cores, mainly composed of feldspar and calcite, 25.4 mm wide, 50 mm thick, and converted into rock samples as per the ISRM standards. The rock strength was calculated using the MTS-815 servo strength tester.

Firstly, the specimen was tested by loading and the compressive strength of rock was determined. Then the loading test was performed based on the pre-peak unloading confining pressure. The displacement control loading method was used in the experiment, and different loading rates were adopted for different stress levels. When the stress level was lower, the loading rate was larger. The loading rate decreased with increasing stress levels, and the loading rate was controlled from 0.05 mm/min to 0.5 mm/min.

2.1. Conventional triaxial loading test
The confining pressure of the sample 1 was 40MPa, as shown in Figure 1, and the sample strength was 144 MPa, as depicted in Figure 3. The specimen showed brittle failure. The axial stress of the specimen decreased rapidly after reaching the peak strength, and the residual strength was 86 MPa. According to the results of conventional triaxial test, the unloading test adopted three methods based on the true situations.

2.2. Unloading confining pressure before peak 1
The stress path was adopted in the test. First, the confining pressure of 40 MPa was applied, followed by a gradual decrease in the confining pressure to 0 MPa after the axial pressure increased to 115 MPa (80% strength under the confining pressure). After a period of stability, the confining pressure was renewed to 20 MPa until it was damaged. The test scheme is suitable when the drilling fluid density is not enough to support the wellbore during the drilling process under high stress conditions.

As shown in Figure 2, when the confining pressure was reduced, the axial stress followed. At the beginning, the decrease was small, and it fluctuated. When confining pressure was lowered to a certain extent, a stress drop occurred, and the axial stress decreased by about 90 MPa in a few seconds. The fluctuation in the axial stress decreased with higher confining pressure. After confining pressure reduced to zero, the axial strain rate remained steady at 0.05 mm/min, and after a period of stability, the rate of 0.3 MPa/s was be used to increase the confining pressure to 20 MPa, the axial stress increased with confining stress and the growth rate decreased gradually when the axial stress was reaching a new peak strength. The residual strength was about 70.6 MPa.
Figure 2. Stress-strain curve of conventional unloading triaxial loading test

Figure 3. Stress-strain curve of confining pressure before peak 1

Figure 4. Stress-strain curve of unloading confining pressure before peak 2

Figure 5. Step by step unloading confining pressure before peak 3
2.3. Unloading confining pressure before peak 2
The stress path of the test is as follows. Firstly, the confining pressure was applied to 40 MPa, then the confining pressure was gradually reduced to zero when the axial stress increased to 100.8MPa (70% of the strength under the confining pressure), until the specimen was destroyed. The test scheme corresponds to the situation wherein the density of drilling fluid is low, and the pressure of drilling fluid column is not enough to support the wellbore in the medium under in-situ stress situations. As shown in Figure 3, when the axial stress reached 100.8 MPa, the confining pressure decreased at the rate of 0.1 MPa/s, and the sudden decrease of axial stress was obvious at the initial stage, at about 17 MPa. After that, the axial stress fluctuated and decreased with the increase of axial strain, and the unloading modulus at this stage was $3.89 \times 10^4$ MPa. When the confining pressure was reduced to zero, the axial loading rate was still 0.05 mm/min. At this stage, the axial stress slowly rose to a new peak strength, after which the specimen was destroyed to the residual strength, which is about 9.1 MPa.

2.4. Unloading confining pressure before peak 3
The stress path of the test is as follows. Firstly, the confining pressure was applied to 40 MPa, and when the axial stress increased to 115 MPa (80% of the strength under the confining pressure), the confining pressure was reduced to 15 MPa, maintained for a period, then reduced to 10 MPa, and maintained for a period, and the confining pressure was reduced to 0 MPa until the sample was broken. The test corresponded to the adjustment of drilling fluid density in the drilling process, and the stress of rock around the wellbore was gradually released. As shown in Figure 4, when the confining pressure was reduced to 15 MPa, the axial stress decreased; however, no damage occurred. When the confining pressure was stabilized, the axial stress increased, but the loading modulus decreased. When the confining pressure was reduced to 10 MPa again, the specimen was not destroyed, and the axial stress still rebounded after it reduced to a certain value, and the loading modulus further decreased. When the confining pressure was finally reduced to zero, the axial stress dropped abruptly by about 20 MPa.

2.5. Unloading deformation and failure characteristics
(1) The axial pressure of sample 2 fluctuated and decreased, indicating that it has an axial plastic flow, while sample 3 had no such stage, indicating that the smaller the unloading rate of confining pressure, the more obvious was the axial plastic flow.
(2) For conventional triaxial loading test, the samples generally had shear failure and many cracks. After failure, the residual strength of rock was high due to mutual friction. Under the unloading condition, from the sudden drop of stress and the unloading modulus of axial stress, the brittleness of the sample was obvious. Therefore, the damage degree of unloaded rock was more serious.
(3) Since the axial stress of sample 2 during unloading was greater than that of sample 3, the elastic potential energy accumulated in sample 2 was also greater than that of sample 3. Therefore, the damage degree of sample 2 was greater than that of sample 3. Sample 2 had a tensile crack, while the crack of sample 3 did not. Sample 4 had tensile cracks and shear cracks at the same time. Since sample 4 had entered the plastic deformation stage, oblique shear cracks formed inside it. When the confining pressure was removed, strength fell off on the surface of the sample caused by tensile cracks, resulting in the formation of tetragonal pyramids at both ends of the sample.

3. Strength characteristics under different unloading paths
Based on the analysis of the above test results, the following conclusions can be drawn.
(1) When the confining pressure is removed, the axial stress decreases linearly with the increase of strain, and its unloading modulus is directly related to the unloading mode of confining pressure, and its reduction rate increases with the increase of confining pressure reduction rate.
(2) Comparing the axial unloading modulus of sample 2, 3, and 4, it was observed that the unloading modulus of sample 4 was the largest, which indicates that the rock damage degree under this stress path was the most severe. It also indicates that the drilling fluid density must be raised to an appropriate level after the formation is opened in the drilling process.
(3) If there is an obvious stress drop during the test, it indicates that the specimen is damaged, and the degree of damage is related to the value of the stress drop.

4. Conclusion

(1) In the process of unloading confining pressure, the axial stress and confining pressure decrease linearly with the increase of strain, and the unloading modulus increases with the increase of the decreasing rate of confining pressure.
(2) The smaller the unloading rate of confining pressure, the more obvious is the axial plastic flow.
(4) The failure of unloading rock is mainly due to brittleness. By comparing the failure degree under different stress paths, the unloading confining pressure before peak is greater than that after peak, and the unloading confining pressure after peak is greater than that of loading test.
(5) Most of the unloading cracks are tensile cracks, but there are shear cracks in the sample after unloading confining pressure, and there are tensile flakes on the surface of the sample after unloading confining pressure.

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