Deep borehole in situ stress measurements by hydraulic fracturing method in Xuefengshan area

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Abstract. The in situ stress state is a key parameter for shale gas exploration and geodynamics. To obtain the ultra-depth stress state of the Xuefengshan area, the hydraulic fracturing in situ stress method was employed in this study to determine the stress state at a depth range of 170–2021 m. The test results, which are the first reported for borehole depth greater than 2000 m in China, show that the magnitude of the in situ stress increases with the depth of the borehole. At a depth of 2021 m, the measured maximum and minimum horizontal principal stresses were 66.31 MPa and 43.33 MPa, respectively. The linear fitting relationships between the maximum and minimum horizontal principal stresses with the depth of the test borehole were $S_H = 0.033999D + 5.9996$ and $S_h = 0.020729D + 4.8058$, respectively. In the borehole depth range of 170–800 m, the relationships of the three principal stresses were $S_H > S_h > S_v$, which is favorable for reverse faulting. At borehole depths of 1000–2021 m, the relationships changed to $S_H > S_v > S_h$, which implies that the deep stress regime of this area is strike-slip faulting.

1. Introduction

The in situ stress state is an important reference for underground engineering construction, resource exploration and development, nuclear waste disposal site safety evaluation, and other related research fields. In addition, tectonic activities and the resulting geological disasters are closely related to this stress state. Therefore, it is of great significance to obtain the in situ stress state values of key structural and engineering areas for stability evaluation of active faults, seismic geological research, and engineering geological problem analysis [1-7].

In March 2019, we used the hydrofracturing method to conduct in situ stress measurement in the pilot borehole of the Xuefengshan Scientific Drilling Project and obtained valid data of 16 test intervals in the depth range of 170–2021 m. These test data and related research results offer important reference information and guidance for basic geodynamic research near survey areas, exploration and development of deep resources, and the construction of underground major projects.

In this study, the in situ stress measurement process and data analysis method are discussed, and the maximum and minimum horizontal principal stresses of 16 test intervals and their variation characteristics with the borehole depth are given.

2. In situ stress measurement of deep borehole hydrofracturing in Xuefengshan

2.1 Test overview

The Xuefengshan deep borehole is located in Mayang Miao Autonomous County, Huaihua City, Hunan Province (27.775°N, 109.802°E). From top to bottom, the exposed strata are of Quaternary,
Cretaceous, Cambrian, Sinian, and Nanhua ages. The borehole is a four-spud drilling structure, in which a Ф98 mm drill bit was used to drill the fourth spud in the section to a final depth of 2403.91 m from an initial depth of 90.65 m. All in situ stress measurements were obtained in this section. The static water level is zero. According to the technical specifications of hydraulic fracturing [8-9], a high-pressure sealing test was first conducted on the drill pipe to be used for measurement; the drill pipe and downhole measurement equipment were connected; and the measurement was conducted from shallow to deep levels according to the pre-selected depth of the measurement section. In the depth range of 170–2050 m, more than 20 test sections were tested. During the testing process, some of the test sections showed obvious and primary fracture reopening, poor repeatability of several previous and subsequent cycles, and changes in the reopening pressure or shutting pressure from high to low. To avoid the influence of the measurement results, the data of these sections were not involved in the calculation and analysis of the ground stress results of the borehole. After eliminating these data, valid measurement data of 16 sections were obtained. Fig. 1 shows pressure versus time curves of the test section recorded by the downhole pressure sensor as well as the standard specifications of the 16 test sections. Except for those of 1375.00 m and 1482.00 m, the recording curves all showed obvious fracturing pressure, good the repeatability of each reopening cycle, and clear the pressure parameter points. These data provide an important research basis and guarantee the reliability of the test results.
Figure 1. Underground pressure recording curves (depth range: 170–2021 m).
2.2 Data processing and in situ stress measurement results

In theory, the data recorded by the ground pressure sensor plus the hydrostatic column pressure corresponding to the depth of the measurement section should be completely consistent with the data recorded by the downhole pressure sensor. However, friction in the system causes difference between the two data types [10]. Taking the 1267 m section as an example, the ground pressure sensor data plus the hydrostatic column pressure and the downhole pressure sensor data were superimposed together, as shown in Fig. 2. The ground pressure was about 2 MPa higher than the downhole pressure corresponding to the fracture and reopening pressures. However, after the pump was disengaged, the fluid velocity in the system tended to be zero, and the corresponding friction resistance was significantly reduced, which brought the ground and underground pressures close to identical. Therefore, when measuring deep borehole in situ stress, a large pipeline length and a high flow rate of the pumped fluid during fracturing or reopening cause greater system friction. This in turn makes the interpreted values of the fracturing and reopening pressures larger than the actual values. However, because the shutting pressure is not affected by this phenomenon, the maximum horizontal principal stress will be reduced if calculated according to the recorded data of the ground pressure sensor. Therefore, the pressure sensor, automatic data acquisition system, and storage unit should be set up in the test section during the in situ stress measurement of deep borehole hydraulic fracturing, with the recorded data of the underground pressure sensor used for data calculation.

![Figure 2](image_url)

**Figure 2.** Comparisons of ground and underground pressure at the 1267 m test interval.

The peak value of the first cycle was taken as the fracturing pressure (P_f) of each survey section, and the reopening pressure (P_r) and shutting pressure (P_s) were calculated by data analysis of the third reopening cycle. For the reopening pressure, linear fitting was conducted from the beginning of the pressure increase. The pressure value corresponding to the position at which the pressure increase curve obviously deviated from the linear part was taken as the P_r of the measurement section. For the shutting pressure, the single tangent, dt/dp, dp/dt and Muskat methods were used to calculate the P_s [8-9]. Then, and the mean values of the four methods were taken to calculate the maximum and minimum horizontal principal stresses. The calculation results of the pressure parameters of each measurement section are shown in Table 1, the first column of which gives the depth value at the center of the test section. Because the value of shutting pressure calculated by computer in the 170.00 m measurement section was abnormal, a manually measured value was adopted. No obvious fracturing pressure was noted in the measurement section at 1374.00 m and 1482.00 m, which might be attributed to the existence of primary fractures in the experimental location. Thus, the maximum (S_H) and minimum (S_h) horizontal principal stresses as well as the hydraulic fracturing tensile strength of the rocks were
obtained according to the relevant calculation formulas of hydraulic fracturing in situ stress measurement theory [8-12], as shown in Table 2.

The distribution of principal stresses with borehole depth is shown in Fig. 3. The magnitudes of maximum and minimum horizontal principal stresses increased with borehole depth. At borehole depths 170–800 m, the relationships of the three-dimensional principal stresses were $S_H > S_V > S_h$, which is favorable for reverse faulting. At the depth range of 1000–2021 m, the relationships changed to $S_H > S_V > S_h$, which implies that the deep stress regime of this area is strike-slip faulting. By linear fitting the measured data, the respective relationships between the maximum and minimum horizontal principal stresses with borehole depth were $S_H = 0.033999D + 5.9996$ ($R^2 = 0.93$) and $S_h = 0.020729D + 4.8058$ ($R^2 = 0.96$), where $D$ represents the depth of the borehole in meters; and $S_H$ and $S_h$ are the maximum and minimum horizontal principal stresses, respectively, in units of megapascals.

| Depth of measurement center (m) | $P_b$ (MPa) | $P_r$ (MPa) | dp/dt | dt/dp | $P_s$ (MPa) | $P_s$ (MPa) | $P_s$ (MPa) | $P_s$ (MPa) | $P_s$ (MPa) | $P_s$ (MPa) |
|-------------------------------|-------------|-------------|------|-------|-------------|-------------|-------------|-------------|-------------|-------------|
| 170.00                        | 28.97       | 14.32       | —    | —     | 10.00       | —           | —           | —           | —           | —           |
| 278.00                        | 23.64       | 10.67       | 7.76 | 7.76  | 7.64        | 7.56        | 7.68        | 0.10        | —           | —           |
| 368.00                        | 20.09       | 14.54       | 11.79| 11.81 | 11.10       | 11.30       | 11.50       | 0.35        | —           | —           |
| 458.00                        | 19.91       | 13.60       | 12.04| 11.85 | 12.02       | 11.93       | 11.96       | 0.09        | —           | —           |
| 512.00                        | 25.48       | 17.58       | 14.59| 14.41 | 14.52       | 14.35       | 14.47       | 0.11        | —           | —           |
| 655.00                        | 28.38       | 22.71       | 21.77| 20.56 | 21.70       | 21.93       | 21.49       | 0.63        | —           | —           |
| 763.00                        | 25.58       | 20.71       | 19.81| 19.32 | 19.73       | 19.66       | 19.63       | 0.21        | —           | —           |
| 1032.00                       | 32.79       | 27.34       | 25.42| 25.62 | 25.45       | 25.57       | 25.52       | 0.10        | —           | —           |
| 1140.00                       | 35.77       | 31.50       | 29.88| 29.96 | 30.04       | 29.99       | 29.97       | 0.07        | —           | —           |
| 1175.00                       | 34.66       | 27.42       | 28.87| 28.86 | 28.89       | 28.82       | 28.86       | 0.03        | —           | —           |
| 1267.00                       | 41.63       | 34.10       | 31.85| 32.67 | 32.71       | 32.85       | 32.52       | 0.45        | —           | —           |
| 1374.00                       | —           | 34.52       | 35.82| 37.65 | 37.77       | 37.71       | 37.24       | 0.95        | —           | —           |
| 1482.00                       | —           | 40.42       | 39.03| 40.23 | 41.02       | 41.14       | 40.35       | 0.97        | —           | —           |
| 1751.00                       | 42.85       | 37.61       | 38.48| 37.92 | 37.93       | 37.81       | 38.03       | 0.30        | —           | —           |
| 1760.00                       | 45.35       | 38.97       | 39.60| 40.41 | 40.72       | 40.40       | 40.28       | 0.48        | —           | —           |
| 2021.00                       | 47.44       | 43.47       | 42.79| 43.42 | 43.73       | 43.37       | 43.33       | 0.39        | —           | —           |

$P_b$: fracturing pressure; $P_r$: reopening pressure; $P_s$: shutting pressure

Table 1. Pressure parameters of in situ stress measurement results of deep borehole hydrofracturing in Xuefengshan (according to downhole pressure records).

| Depth of measurement | Fracturing parameters (MPa) | Principal stress value (MPa) |
|----------------------|----------------------------|-----------------------------|

Table 2. In situ stress measurement results of the Xuefengshan deep borehole (according to downhole pressure record).
| center (m) | \( P_0 \) | \( P_b \) | \( P_r \) | \( P_s \) | \( T \) | \( S_H \) | \( S_h \) | \( S_V \) |
|-----------|------|------|------|------|------|------|------|------|
| 170.00    | 1.70 | 28.97| 14.32| 10.00| 14.65| 13.98| 10.00| 4.51 |
| 278.00    | 2.78 | 23.64| 10.67| 7.68 | 12.97| 9.60 | 7.68 | 7.37 |
| 368.00    | 3.68 | 20.09| 14.54| 11.50| 5.55 | 16.28| 11.50| 9.75 |
| 458.00    | 4.58 | 19.91| 13.60| 11.96| 6.31 | 17.70| 11.96| 12.14|
| 512.00    | 5.12 | 25.48| 17.58| 14.47| 7.90 | 20.71| 14.47| 13.57|
| 655.00    | 6.55 | 28.38| 22.71| 21.49| 5.67 | 35.21| 21.49| 17.36|
| 763.00    | 7.63 | 25.58| 20.71| 19.63| 4.87 | 30.55| 19.63| 20.22|
| 1032.00   | 10.32| 32.79| 27.34| 25.52| 5.45 | 38.89| 25.52| 27.35|
| 1140.00   | 11.40| 35.77| 31.50| 29.97| 4.27 | 47.01| 29.97| 30.21|
| 1175.00   | 11.75| 34.66| 27.42| 28.86| 7.24 | 47.41| 28.86| 31.14|
| 1267.00   | 12.67| 41.63| 34.10| 32.52| 7.53 | 50.79| 32.52| 33.58|
| 1374.00   | 13.74| —    | 34.52| 37.24| —    | 63.46| 37.24| 36.41|
| 1482.00   | 14.82| —    | 40.42| 40.35| —    | 65.82| 40.35| 39.27|
| 1751.00   | 17.51| 42.85| 37.61| 38.03| 5.24 | 58.99| 38.03| 46.40|
| 1760.00   | 17.60| 45.35| 38.97| 40.28| 6.38 | 64.27| 40.28| 46.64|
| 2021.00   | 20.21| 47.44| 43.47| 43.33| 3.97 | 66.31| 43.33| 53.56|

\( P_b \): the fracturing pressure; \( P_r \): reopening pressure; \( P_s \): shutting pressure; \( P_0 \): pore pressure; \( T \): tensile strength of rock; \( S_H \): maximum horizontal principal stress; \( S_h \): minimum horizontal principal stress; \( S_V \): vertical stress (density of rock = 2.70 g/cm\(^3\))

**Figure 3.** Distribution of in situ stress along the borehole depth in the Xuefengshan deep borehole.
3. Conclusions
Using the deep-borehole hydraulic fracturing in situ stress measurement system, valuable deep in situ stress measurement data has been obtained in the borehole depth range of 170–2021 m in the Xuefengshan area, which is of great significance for basic geoscience research and deep resource exploration and development of this area. Moreover, this achievement also marks the staged progress of deep hydraulic fracturing in situ stress measurement technology in China. The main results of this research are summarized in the following points.
(1) The measurement results show that the magnitude of the in situ stress increases with the borehole depth. At a depth of 2021 m, the measured maximum and minimum horizontal principal stresses were 66.31 MPa and 43.33 MPa, respectively. The linear fitting relationships between the maximum and minimum horizontal principal stresses with the borehole depth were \( S_H = 0.033999D + 5.9996 \) and \( S_h = 0.020729D + 4.8058 \), respectively.
(2) At borehole depths of 170–800 m, the relationships of the three principal stresses were \( S_H > S_v > S_h \), which is favorable for reverse faulting. Those at depths of 1000–2021 m were \( S_H > S_V > S_h \), which implies that the deep stress regime of this area is strike-slip faulting.
(3) A comparison of the data recorded by the downhole pressure sensor and by ground pressure sensor demonstrated the necessity of installing a downhole pressure sensor during the deep borehole measurement process. Such a step will reduce the reading error of the reopening pressure caused by the friction resistance, which in turn will decrease the calculation error of the maximum horizontal principal stress.

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