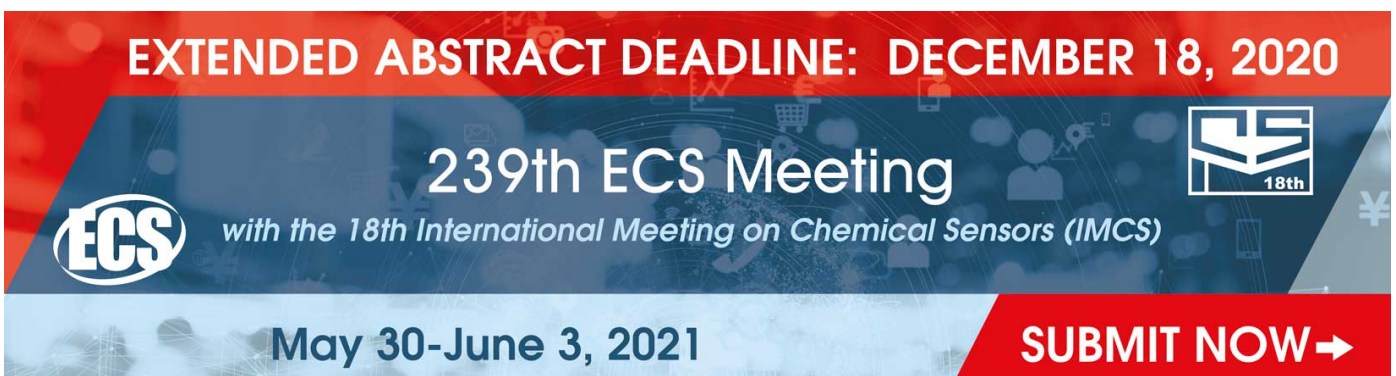


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In-situ stress measurement technology and field application based on micro-optical imaging measurement method

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Abstract. In-situ stress is natural stress existing in rock masses. As an important basic parameter, accurate in-situ stress is highly beneficial to the theoretical research and engineering application of rock mechanics. In-situ tests in boreholes are the most direct and effective way to obtain in-situ stress. However, the high temperature and high water pressure testing environment in boreholes limits the application scope of measurement sensors. In this study, a micro-optical imaging measurement method is proposed. On the basis of this method, an aperture measurement device is developed, and a complete set of in-situ stress measurement technology is formed. Laboratory and field application tests are carried out. The results of the temperature and pressure test in a laboratory show that the in-situ stress test technology improves service temperature and pressure and offers an extensive application range. The field test on a shallow borehole in an iron mine roadway and a deep borehole in a shale gas exploration well reveals the deformation of the test boreholes in the process of stress relief. This result proves the feasibility of the in-situ stress measurement technology. On the basis of the theory of elasticity, in-situ stress is calculated with reference to the in-situ diameter deformation of the boreholes and the mechanical parameters of the rock core. A number of in-situ stress tests are carried out under different borehole depths, and the testing times are recorded. Results show that the application of wireline coring drilling technology speeds up the test process. Hence, it can boost the operability of the in-situ stress test. In sum, the in-situ stress measurement technology based on the micro-optical imaging measurement method is feasible and operable and may thus improve the application depth of the in-situ stress measurement method based on the stress relief method.

1. Introduction

In the field of geological engineering, in-situ stress is the basic data used to design oil and gas exploration programs and predict stratum fracture pressure. Obtaining accurate in-situ stress data is of great significance to oil and gas field exploration and development.

In-situ stress testing methods come in different forms. The stress relief method for borehole diameter deformation, in particular, is a mature and widely used in-situ stress test method. The method is used to calculate in-situ stress by measuring the deformation of the borehole diameter. It is known to have high accuracy and reliability. However, the common stress relief testing equipment is only suitable for the in-situ stress testing of shallow boreholes. Common measurement technologies cannot easily adapt



to the temperature and water pressure of deep boreholes. Therefore, the research and application of measurement technologies under high temperature and high pressure conditions are important in the development of in-situ stress tests.

In this study, an in-situ stress measurement method based on borehole cross-sectional shape analysis is proposed, and a device for measuring borehole cross-sectional shape based on a micro-optical imaging measurement is developed. Through a temperature and pressure test in the laboratory, this work finds that the proposed measurement technology can improve the upper limits of the operating temperature and pressure of the deformation measurement device. According to field test conditions, the auxiliary equipment for the in-situ stress test based on a wireline coring drilling tool is designed. A complete in-situ stress testing technology is thus formed. Through the field test, the in-situ stress testing technology is successfully applied to a number of boreholes with different depths, and in-situ stress test data are obtained. The test efficiency is determined by recording the testing time and auxiliary working time for the boreholes of different depths.

2. In-situ stress measurement technology

The main innovations of the proposed in-situ stress measurement technology are as follows: (1) the borehole deformation measurement device adopts the unique micro-optical measurement technology to adapt to the test conditions of deep boreholes and (2) a set of auxiliary test equipment based on wireline coring technology is designed to greatly reduce the total test time.

2.1. Measurement principle

The stress relief method involves releasing rock stress around boreholes. The sensor used for this method records rock deformation. In-situ stress is then calculated according to the quantitative relationship between rock deformation and in-situ stress. For an in-situ stress test on deep holes, the in-situ stress and hydrostatic pressure on borehole deformation should be considered.

Assuming that the test borehole is a circular hole, the shape of the circular hole is deformed by two-dimensional stress (σ_1 , σ_2) and hydrostatic pressure (p_1). Suppose that point P on the borehole wall is deformed to $P'(x, y)$, as shown in Figure 1.

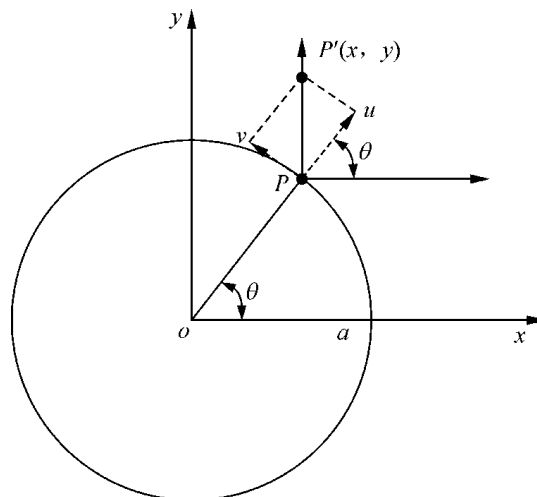


Figure 1. Displacement of any point on the hole.

According to the basic theory of elastic mechanics, the radial displacement (u) and the tangential displacement (v) of point P on the borehole wall can be expressed as

$$\begin{cases} u = u|_{\sigma=\sigma_1} + u|_{\sigma=\sigma_2} + u|_{\sigma=p_1} = \frac{a}{E} [(\sigma_1 + \sigma_2) + 2(\sigma_1 - \sigma_2) \cos(2\theta)] + \frac{1+\mu}{E} ap_1 \\ v = v|_{\sigma=\sigma_1} + v|_{\sigma=\sigma_2} + v|_{\sigma=p_1} = -\frac{2a}{E} (\sigma_1 - \sigma_2) \sin(2\theta) \end{cases} \quad (1)$$

where E the elastic modulus of the rock,
 μ the Poisson's ratio of the rock,
 a the radius of the test borehole.

Through equation transformation, we obtain $P'(x, y)$:

$$\begin{cases} x = a[1 + \frac{(3\sigma_1 - \sigma_2)}{E} + \frac{1+\mu}{E} p_1] \cos \theta \\ y = a[1 + \frac{(3\sigma_2 - \sigma_1)}{E} + \frac{1+\mu}{E} p_1] \sin \theta \end{cases} \quad (2)$$

Let

$$\begin{cases} A_1 = a[1 + \frac{(3\sigma_1 - \sigma_2)}{E} + \frac{1+\mu}{E} p_1] \\ B_1 = a[1 + \frac{(3\sigma_2 - \sigma_1)}{E} + \frac{1+\mu}{E} p_1] \end{cases} \quad (3)$$

Substituting Equation (3) into Equation (2) yields the following equation:

$$\begin{cases} x = [A_1] \cos \theta \\ y = [B_1] \sin \theta \end{cases} \Rightarrow \frac{x^2}{A_1^2} + \frac{y^2}{B_1^2} = 1 \quad (4)$$

Equation (4) is the standard ellipse equation. It proves that the geometric shape of the circular hole after deformation is ellipse under the action of two-dimensional plane stress and hydrostatic pressure. Therefore, if the in-situ stress measurement device can obtain the shape characteristics of the borehole cross section and the parameters of the rock mechanics at the measuring point in a rock mechanics test, then in-situ stress can be calculated.

2.2. Measurement device

2.2.1. Borehole deformation measurement device

The cross-sectional shape of a test borehole is known to change under the combined action of in-situ stress and hydrostatic pressure. To obtain the shape characteristics of test boreholes, this study develops a borehole deformation measurement device that is based on the micro-optical imaging technique. The structure of the aperture deformation measurement device is shown in Figure 2.

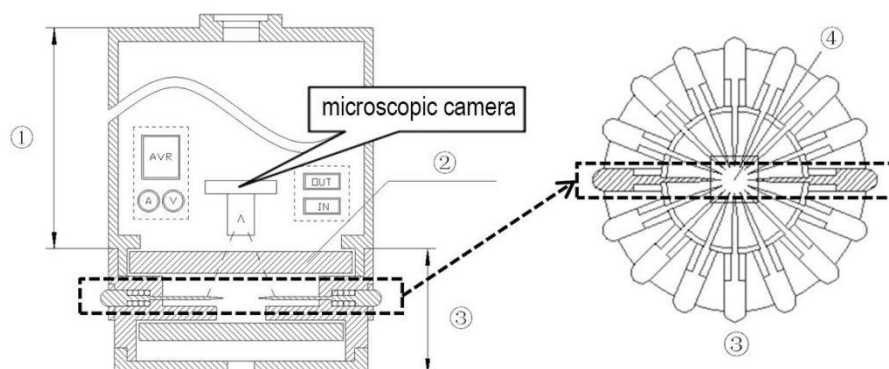


Figure 2. Structure overview

In Figure 2, ① is the micro-optical deformation recording component, ② is the optical glass, ③ is the borehole wall deformation sensor arranged symmetrically, and ④ is the measurement area. When the borehole is deformed, ③ transfers the wall displacement of the borehole to the center of the

measurement device, and ① records the displacement through the optical glass. The borehole deformation measurement device adopts the technology of separating the deformation recording element and the deformation sensor. The separation technology effectively avoids the influence of temperature and pressure on the sensor.

The CCD component of the micro-optical camera is manufactured to have a rectangular field of view and different pixels on the horizontal and vertical sides. As the measurement area is a square with a side length of 3.5 mm, the physical resolution of the image should be based on the shortest side. For example, if we use a standard component with a resolution of 768×576 , then the resulting image should have a physical resolution of 0.006 mm per pixel (i.e., 3.5 mm divided by 576)^[1].

2.2.2. Auxiliary equipment for in-situ stress test

A set of auxiliary equipment is developed to complement the borehole deformation measurement device for measuring the test borehole deformation at the bottom of the borehole. The auxiliary equipment is designed on the basis a wireline coring tool and can thus quickly complete the operations of “cleaning the bottom of the borehole,” “drilling the test borehole,” and “recovering the stress relief and measurement device.” The schematic of the operations is shown in Figure 3.

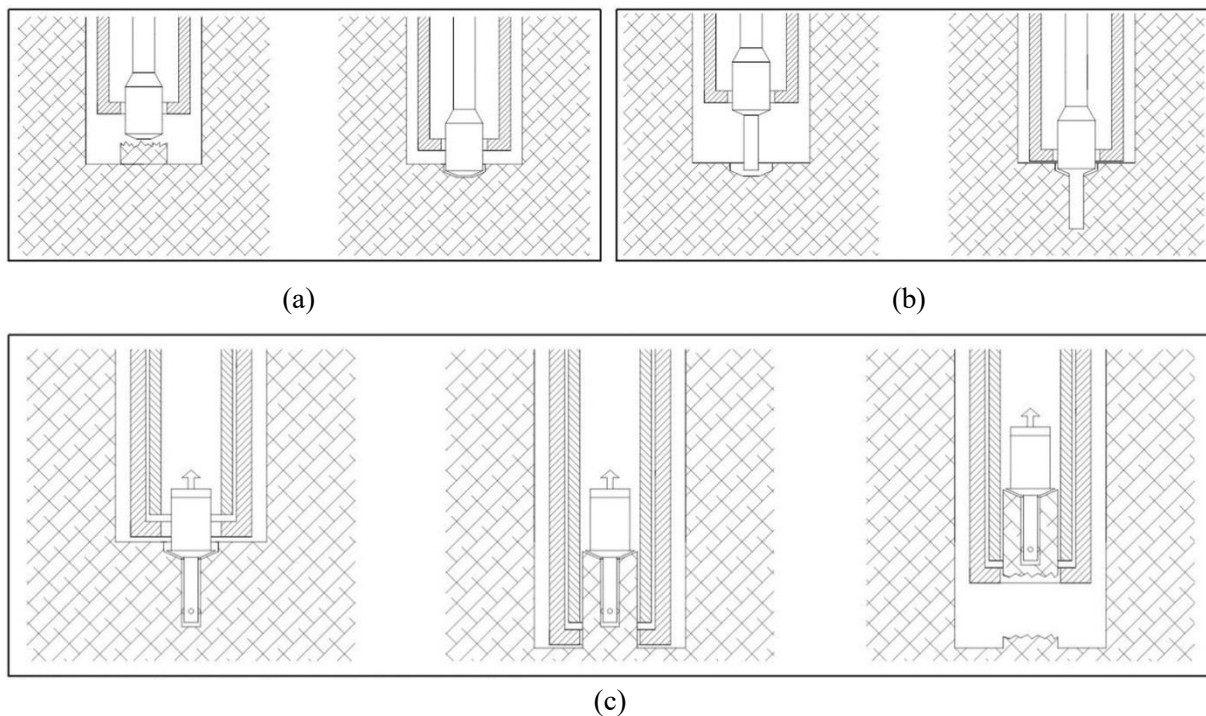


Figure 3. Schematic of operation

In Figure 3, (a) shows the auxiliary equipment cleaning the bottom of the borehole and drilling to form a conical borehole, (b) shows the auxiliary equipment drilling further at the bottom of the borehole to form a test borehole, (c) shows the auxiliary equipment drilling further at the bottom of the borehole to relieve the in-situ stress of the core and recycling the borehole deformation measurement device. Through these simple operations, the in-situ stress test in the deep borehole can be completed quickly.

3. Laboratory tests

Geothermal gradient is known to exist in deep rocks, and high water pressure is inevitable in deep boreholes. Therefore, a high temperature and high water pressure testing environment may exist in boreholes and thereby limit the application scope of measurement sensors. According to the temperature and water pressure conditions that may exist in deep boreholes, this study measured the

normal working time of the measurement device under the designed temperature and water pressure in a laboratory test.

3.1. Calibration test

After ensuring the quality of the procured components, fine machining, and system assembly, we tested the system's precision to verify whether it met the design goals. For the calibrator, we used the GWB-200JA device provided by the University of Science and Technology Beijing; the minimum scale of the device was 0.0002 mm.

We conducted the calibration test following the procedure below:

- (1) The borehole wall deformation sensors are numbered in a clockwise order.
 - (2) The calibrator and borehole wall deformation sensor move synchronously, and the displacement and image are recorded simultaneously.
 - (3) The precision calibration of each sensor is realized according to the sequence of the test numbers.
- The deformation process of the borehole wall deformation sensor in the calibration test is shown in Figure 4 by using micro-optical images.

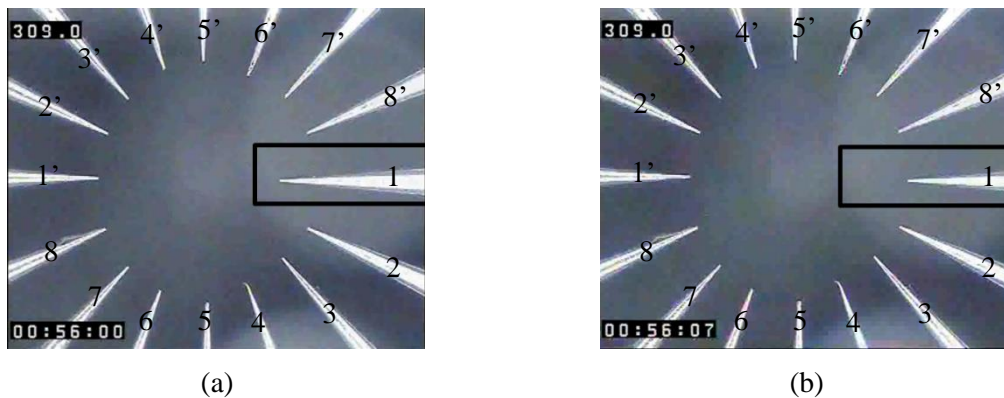


Figure 4. Micro-optical images in calibration testing.

In Figure 4, (a) is the image before the calibrator moves, and (b) is the image after the calibrator moves. Therefore, the sensor's displacement in the micro-optical images is expressed by the number of pixels. The ratio of the sensor's displacement in the images to the actual movement displacement measured by the calibrator is the accuracy of the measurement device; it can be expressed as follows:

$$\eta = \frac{\Delta d}{\Delta p} \quad (5)$$

where η The accuracy of the measurement device,

Δp The actual movement displacement measured by the calibrator,

Δd The motion displacement of the borehole wall deformation sensor in the micro-optical image.

The calibration results are shown in Table 1.

Table 1. Calibration results.

Test number	1	2	3	4	5	6	7	8	Average
$\eta(\mu\text{m}/\text{PIX})$	3.27	3.27	3.29	3.37	3.39	3.39	3.26	3.25	3.31

According to the results of the calibration test, the accuracy of the measurement device was about 3.31 $\mu\text{m}/\text{pixel}$. Therefore, when the sensor has a 1 pixel displacement in the image, the actual displacement is 3.31 μm .

3.2. Operating temperature and pressure test

The gravity of the drilling fluid is between 1.0 and 1.6, and the geothermal gradient is about 1 $^{\circ}\text{C}$ –3 $^{\circ}\text{C}$. According to the design requirements for pressure and temperature in the simulation test environment,

we designed the withstand voltage test of the measurement system. On the basis of the operating temperature and pressure test, the working condition of the measurement equipment under high temperature and high pressure conditions was studied. The test process is as follows:

(1) The micro-optical deformation recording component and borehole wall deformation sensor are taken as the key components of the minimum system for the test.

(2) The minimum system is placed in the hydraulic cylinder of the MTS rock mechanics test system, and the displacement of the hydraulic cylinder of the piston is recorded when the confining pressure of 1 MPa is loaded each time.

The principle of the confining pressure loading test and the MTS rock mechanics test system for the confining pressure loading experiment are shown in Figure 5.

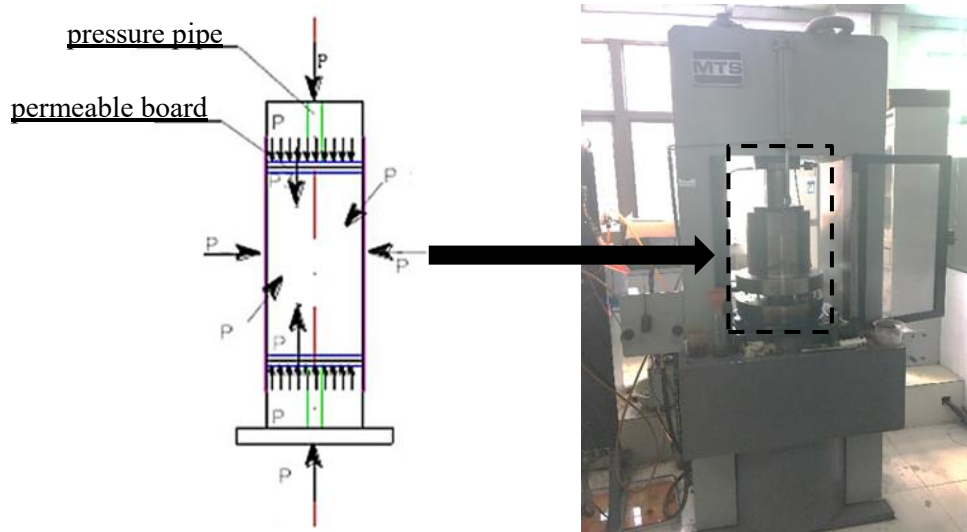


Figure 5. Testing principle and MTS system.

The hydraulic oil flow is known to be proportional to the piston's displacement. When the piston's displacement of the hydraulic cylinder is proportional to the confining pressure, the hydraulic oil does not enter the minimum system. The piston's displacement and confining pressure during loading are shown in Figure 6.

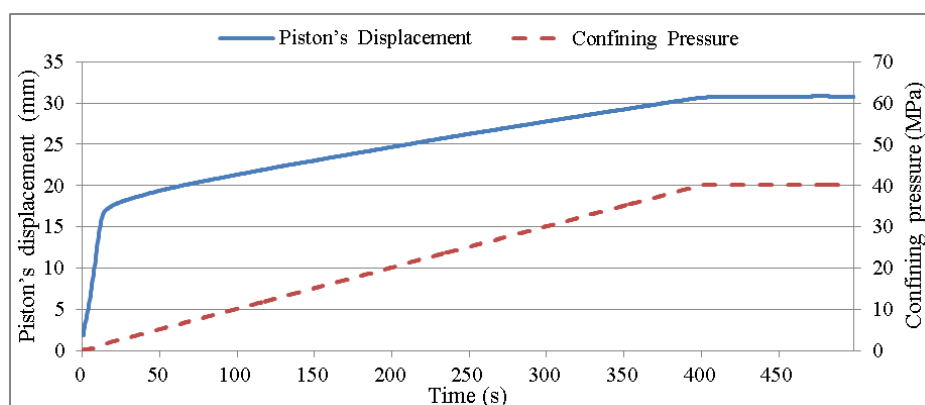


Figure 6. Relationship between piston's displacement and confining pressure.

In this test, the minimum system was operated normally. The results proved that the separation technology effectively avoided the influence of temperature and pressure on the sensor.

4. Field tests

The field application of a shallow borehole in an iron mine roadway and a deep borehole in a shale gas exploration well reveals the deformation of the test borehole in the process of stress relief. This result

proves the feasibility of the in-situ stress measurement technology. In the field tests, different types of auxiliary equipment are used to test the in-situ stress several times, the test data are obtained, and the testing time and auxiliary working time are recorded. By analyzing the test data and test time, we obtain the in-situ stress data and determine the test efficiency.

4.1. Field test of shallow borehole

The new in-situ stress testing technology is used to measure the deformation of a borehole at an iron mine roadway by employing the stress relief method. Given the limitation of the roadway's height, single barrel core drilling equipment is used to complete the in-situ stress test.

When the drilling depth completely exceeds the length of the borehole deformation measurement device, the in-situ stress of the rock is regarded as completely relieved. Through the recovery of the core barrel, the borehole deformation measurement device is also recovered. The annular core and borehole deformation measurement device are shown in Figure 7.



Figure 7. Annular core and borehole deformation measurement device.

By using digital image processing technology, we analyze the micro-optical images of the whole stress relief process and determine the displacement of each sensor in the images. The micro-optical images before and after stress relief are shown in Figure 8.

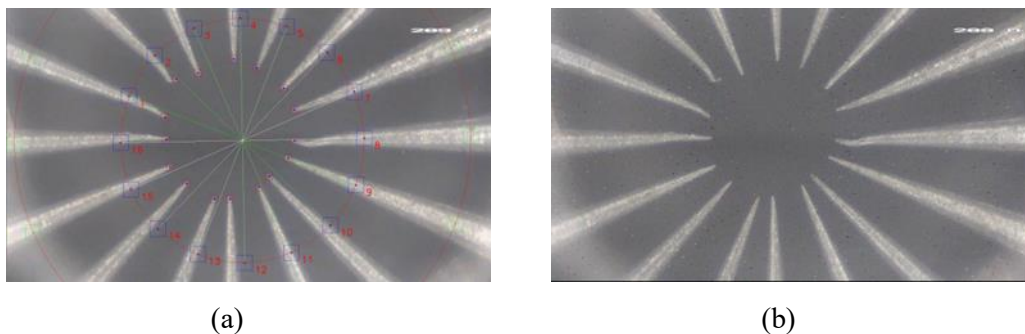


Figure 8. Micro-optical images before and after stress relief.

In Figure 8, (a) is the image before stress relief, and (b) is the image after stress relief. According to the result of Equation (4) and the pixel coordinate position of the sensors, the borehole shape is fitted with an ellipse shape, and the error data are eliminated via screening. The fitting result of the test borehole's cross-sectional shape is shown in Figure 9.

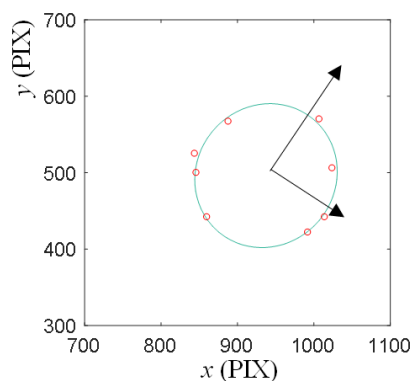


Figure 9. Fitting results of test borehole's cross-sectional shape

4.1.1. *Calculation of in-situ stress data.* The parameters of rock mechanics and the test borehole's deformation data are shown in Table 2.

Table 2. Parameters of rock mechanics and test borehole's deformation data

Test borehole's deformation data				Parameters of rock mechanics		
(1)	(2)	(3)	(4)			
α (°)	-9.5	13.0	80.5	125.5	E ($\times 10^3$ MPa)	41.1
D (μm)	81.82	74.38	35.11	39.95	μ	0.26

where α The deformation direction (°),
 D The diametric deformation (μm);
 E The elastic modulus of the rock ($\times 10^3$ MPa),
 μ The modulus of elasticity.

According to the test data and parameters in Table 2, the in-situ stress data can be solved by the elastic mechanics method. The results are shown in Table 3.

Table 3. In-situ stress data

Combination relationship	σ_H (MPa)	σ_h (MPa)	θ (°)
(1)(2)(3)	38.61	25.74	169.5
(1)(2)(4)	34.96	14.37	174.2
(2)(3)(4)	34.64	21.99	193.0
(1)(3)(4)	40.42	24.00	189.7
Average	37.16	21.53	181.6

The average values of the calculation results indicate that the maximum horizontal principal stress is 37.16 MPa, the minimum horizontal principal stress is 21.53 MPa, and the direction of the maximum horizontal principal stress is 181.6°.

4.1.2. *Calculation of in-situ stress test efficiency.* We assume that the time of stress relief is the testing time (T_1) and that the rest time is the auxiliary working time (T_2). The testing time and auxiliary working time are determined in the field. The test efficiency can be calculated with Equation (6) on the basis of the statistical results of the testing time.

$$T_e = \frac{T_1}{T_1 + T_2} \quad (6)$$

where T_e The test efficiency (min),
 T_1 The testing time (min),
 T_2 The auxiliary working time (min).

The testing times of six in-situ stress tests on two boreholes of different depths are recorded. The calculation results for the test efficiency are shown in Table 4.

Table 4. Testing time and test efficiency

No.	Borehole depth (m)	T_1 (min)	T_2 (min)	Total testing time (min)	Test efficiency (%)
ZK720-1	26	51	139	190	26.8%
ZK720-2	53.6	44	140	184	23.9%
ZK816-1	32.8	70	121	191	36.6%
ZK816-2	33.3	49	129	178	27.5%
ZK816-3	33.9	55	140	195	28.2%

ZK816-4	34.5	73	110	183	39.9%
Average		57	130	187	30.5%

As shown in Table 4, the testing times (T_1) of the six in-situ stress tests are similar, and the average value is about 57 min. The auxiliary working time (T_2) is generally more than 2 h, and it increases with the increase of borehole depth.

4.2. Field test of deep borehole

By using the stress relief method, we utilize the new in-situ stress testing technology to measure the deformation of a shale gas exploration borehole with a depth of 602–702 m. A set of auxiliary equipment based on a wireline coring tool is adopted to complement the borehole deformation measurement device for measuring the deformation of the test borehole at the bottom of the deep borehole.

When the drilling depth completely exceeds the length of the borehole deformation measurement device, the in-situ stress of the rock is regarded as completely relieved. We make use of the slip socket to innovatively retrieve the borehole deformation measurement device and core. This application expands the use and scope of the slip socket. The measurement device and core are shown in Figure 10.



Figure 10. Recycling of borehole deformation measurement device and core after the test

In Figure 10, the upper part of the core is the part subjected to stress relief, and the lower part of the core is the complete solid core. Through a rock mechanics experiment, we obtain the rock mechanical parameters of the complete solid core, including the elastic modulus (E), Poisson's ratio (μ), tensile strength (σ_t), and degree of anisotropy (R_E). Take the test data at 636 m as an example. The rock mechanical parameters at certain confining pressures are shown in Table 5.

Table 5. Rock mechanical parameters of complete solid core

Borehole depth (m)	E (GPa)	μ	σ_t (MPa)	R_E
636	23.69	0.23	5.07	1.874

4.2.1. Calculation of in-situ stress data. The image file in the borehole deformation measurement device is copied to a computer, and the deformation of the test borehole is obtained by analyzing the micro-optical image. The deformation analysis results are shown in Table 6.

Table 6. Test borehole deformation data

	(1)	(2)	(3)	(4)	(5)
Deformation direction ($^\circ$)	265.5	243	198	175.5	108
Diametric deformation (μm)	46.77	44.11	49.84	105.42	33.26

Equations (1)–(4) show that elliptical deformation occurs in the test borehole under the action of in-situ stress and water pressure. The in-situ stress can then be calculated according to the deformation of the test borehole in any three directions^[2]. The results of the in-situ stress calculation are shown in Table 7.

Table 7. Calculation results of in-situ stress

Combination relationship	σ_H (MPa)	σ_h (MPa)	Azimuth ($^\circ$)
(1)(2)(3)	16.67	15.07	202.1

(1)(2)(4)	25.82	17.91	189.7
(1)(4)(5)	26.94	16.79	152.1
Average	23.14	16.59	181.3

On the basis of the average value of the calculation results, we find that the maximum horizontal principal stress at 636 m is 23.14 MPa, the minimum horizontal principal stress is 16.59 MPa, and the direction of the maximum horizontal principal stress is 181.3°.

4.2.2. Calculation of in-situ stress test efficiency. The testing times of the five in-situ stress tests on the borehole at different depths were recorded. The test efficiency can be calculated according to Equation (6) and the statistical results of the testing time. The calculation results are shown in Table 8.

Table 8. Testing time and test efficiency

No.	Borehole depth (m)	T_1 (min)	T_2 (min)	Total test time (min)	Test efficiency (%)
ZK3-1	602	40	94	134	29.9%
ZK3-2	636	32	103	135	23.7%
ZK3-3	662	79	95	174	45.4%
ZK3-4	701	41	124	165	24.8%
Average		48	104	152	31.0%

Table 8 shows that the testing times (T_1) of the six in-situ stress tests are similar and that the average value is about 48 min. The auxiliary working time (T_2) is generally more than 1.5 h, and it increases with the increase of borehole depth.

Comparing Table 4 and Table 8 reveals that the testing time (T_1) and auxiliary working time (T_2) can be shortened by using the auxiliary equipment based on the wireline coring tool. This modification ensures that the in-situ stress test is completed quickly.

5. Conclusion

In this study, we proposed a new structural design for in-situ stress testing equipment and validated the effectiveness of the equipment via field tests. On the basis of the analysis of the in-situ stress test results, we derived the following conclusions:

- (1) The results of the laboratory and field tests show that the new in-situ stress testing technology is feasible and that the test data are reliable.
- (2) The new in-situ stress testing technology can be used to measure boreholes' diameter deformation and cross-sectional shape. Hence, it may serve as a new method for in-situ stress measurement in deep boreholes.
- (3) The testing times for several field tests show that the application of the auxiliary equipment based on a wireline coring tool accelerates the in-situ stress test process and improves the test efficiency. High test efficiency enables the measurement of the in-situ stress of deep rock mass through the stress relief method.

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