

Research Article

Study on the Law of Rock Anelastic Recovery and the Characteristics of In Situ Stress Field of 2000 m Deep Stratum in Metal Mines of Coastal Area

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In situ stress field in deep strata is dominated by self-weight stress and tectonic stress, which is the dynamic source of a series of mining dynamic disasters such as rock burst, mine earthquake, and collapse. To develop deep resources and build deep engineering construction, the distribution characteristics of the in situ stress field must first be ascertained, so as to provide a basic basis for the engineering surrounding rock support design and disaster risk prevention and control. In this paper, taking the Sanshandao Gold Mine in the coastal area as the engineering background, in the early stage of the construction of the 2000 m deep shaft, the anelastic strain recovery method was used to measure the deep in situ stress field. The laws and characteristics of hysteretic elastic recovery of rock at different depths are obtained through experiments, and the effects of temperature, time, and other factors on strain recovery are revealed. The in situ stress test results are basically consistent with the traditional test methods. This method has low operational complexity and better application effect in deep formations. The research has accumulated test experience and basis for carrying out in situ stress measurement in the range of 2000 m and even deeper.

1. Introduction

In situ stress is the fundamental force causing deformation and failure of mining and other underground projects, and its level and direction have a great impact on the stability of roadway surrounding rock. In situ stress measurement is a necessary prerequisite for determining the mechanical properties of engineering rock mass, analyzing the stability of surrounding rock, and realizing the scientific excavation design of underground engineering [1–5]. In the deep mining of 2000 m, the geological conditions of resource occurrence are complex, the in situ stress increases, the ground temperature increases, and the degree of rock fracture and water pressure increase, which makes it more difficult to carry out in situ stress tests [6–9]. Under the action of high ground stress, the deeply buried rock mass

shows different mechanical properties from the shallow rock mass. The rock shows stronger rheological properties and greater anelastic recovery deformation. Therefore, this feature of rock can be used to carry out the experiment of deep stress measurement by using the anelastic recovery method [10, 11].

It is used in combination with the drilling caving method and the hydraulic fracturing method to obtain more abundant in situ stress data [12]. Especially in the early stage of deep engineering construction, when the stress relief method and hydraulic fracturing method cannot be used, the ASR method can still obtain relatively reliable data and has wider applicability. Voight first proposed the anelastic strain recovery method (ASR method), which considers that the rock has creep (anelasticity), and the anelastic strain of the rock recovery is proportional to the stress state before the

isotropic rock strain recovery [13]. Blanton developed the theory of calculating the magnitude of horizontal principal stress, vertical stress, and Poisson's ratio using recovered anelastic strain, which is based on the belief that rock is linear viscoelastic, homogeneous, and isotropic [14]. Lin Weiren applied the anelastic strain recovery method to test the deep core, and the measurement results were in good agreement with the measurement results obtained by other methods [15]. After the 5.12 Wenchuan earthquake, this method was applied to the measurement of in situ stress in scientific boreholes for the first time in mainland China. The research results have a certain reference value for understanding the dynamic mechanism of the Wenchuan earthquake [16].

In order to study the engineering problems of the wellbore, roadway, large deformation of surrounding rock, and rockburst in Sanshandao Gold Mine in the depth range below -2000 m, the ASR method was used to carry out the measurement of the deep in situ stress field.

2. Principle of ASR Method (Constitutive Equation)

2.1. Arrangement of Strain Gauge. The anelastic strain recovery measurement of the measuring core shall ensure that the strain recovery value is not less than six independent directions. Two methods of strain rosette or strain gauge can

be used, and the strain rosette method is used in this experiment. The core is taken out from the drilled hole, with the top of the specimen facing upwards, and the surface is ground after cleaning the core. The strain flowers were pasted on the surface of the core along the baselines at -45° , 0° , 45° , and 90° , respectively, as shown in Figure 1.

The direction of the long axis of the variable plate is called the axial direction. The experimental strain gauge has a total of 9 axes from a1 to a9. The relationship between the 9 axes and the coordinate axes is as follows: the axis a1 is parallel to the x -axis and perpendicular to the y and z axes; the axis a2 is parallel to the y axis and is parallel to the x and z axes. The axis is vertical; the axis a3 is parallel to the z -axis and perpendicular to the x and y axes; the axis a4 is oblique to the x and y axes by 45° ; the axis a5 is oblique to the x and y axes by 45° and is perpendicular to the z -axis; the x and z axes are obliquely intersected by 45° ; the axes a8 and a9 are obliquely intersected with the y and z axes by 45° , as shown in Figure 2.

2.2. Constitutive Equations. K. Matsuki proposed an ASR measurement method to determine three-dimensional in situ stress [17]. For isotropic viscoelastic materials, the local stress and pore water pressure are gradually released at $t = 0$, and the normal anelastic strain recovers in time from 0 to t , which is represented as follows:

$$\begin{aligned} \varepsilon_a(t) = & \left(\frac{1}{3}\right) \left[(3l^2 - 1)\sigma_x + (3m^2 - 1)\sigma_y + (3n^2 - 1)\sigma_z + 6lmt\tau_{xy} + 6mnt\tau_{yz} + 6nl\tau_{zx} \right] \text{Jas}(t) \\ & + (\sigma_m - p_0) \text{Jav}(t) + \alpha_T \Delta T(t). \end{aligned} \quad (1)$$

where l , m , and n are direction cosines of the strain axis, corresponding to the x , y , and z axes; σ_x , σ_y , σ_z , τ_{xy} , τ_{yz} , and τ_{zx} are stress components; σ_m is the average normal stress; p_0 is the pore water pressure; α_T is the linear thermal expansion coefficient; $\Delta T(t)$ is the temperature change during measurement; and $\text{Jas}(t)$ and $\text{Jav}(t)$ are the ASR compliance in shear mode and volume mode, respectively.

The above equations provide the computational basis for the ASR measurement method. The anelastic strain depends on the in situ stress tensor component, pore water pressure, temperature changes in the core during the experiment, and anelastic strain recovery compliance in shear and bulk modes. Therefore, if the material constant ($\text{Jas}(t)$, $\text{Jav}(t)$, α_T) and pore water pressure are known, and the temperature is constant during the test, the three-dimensional in situ stress tensor can be obtained by measuring the anelastic strain in no less than six independent directions.

For an isotropic viscoelastic material, the three principal directions of the in situ stress are consistent with the three principal directions of the anelastic strain. Therefore, it is only necessary to determine the direction of the principal strain to obtain the direction of the principal stress.

The principal stress deviator is given by the following:

$$s_i = \sigma_i - \sigma_m \quad (i = 1, 2, 3). \quad (2)$$

In the formula, s_i is the principal stress deviation (s_1, s_2, s_3); σ_i is the three principal stresses ($\sigma_1, \sigma_2, \sigma_3$); and σ_m is the average principal stress, $\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$.

The principal strain deflection is given by the following:

$$e_i = \varepsilon_i - e_m \quad (i = 1, 2, 3). \quad (3)$$

In the formula, e_i is the principal strain deflection (e_1, e_2, e_3); ε_i is the three principal strains ($\varepsilon_1, \varepsilon_2, \varepsilon_3$); and e_m is the average principal strain, $e_m = (\varepsilon_1 + \varepsilon_2 + \varepsilon_3)/3$.

Through theoretical tests, it can be proved that the ratio of the deviated components of the principal stress is given by the ratio of the deviated components of the anelastic strain [18, 19]. If the rock material is isotropic, the ratio of the direction of the in situ principal stress to the principal stress deviator can be determined without knowing the anelastic strain recovery flexibility of the two modes.

2.3. Calculation of Principal Strain. The core coordinate system is set as o -xyz, and the z -axis is the same as the radial

direction of the core. Then, the relationship between the strain value measured by the rosette attached to the core surface and the strain tensor can be written as the following formula:

$$A\varepsilon = b. \quad (4)$$

In the formula, $\varepsilon = [\varepsilon_x, \varepsilon_y, \varepsilon_z, \varepsilon_{xy}, \varepsilon_{yz}, \varepsilon_{zx}]^T$ represents the strain tensor of the rock, $b = [b_1, b_2, b_3, b_4, b_5, b_6, b_7, b_8, b_9]^T$ is the strain value measured by the strain gauge pasted on the core surface, and $b_1, b_2, b_3, b_4, b_5, b_6, b_7, b_8, b_9$ corresponds to the axial strain acquisition values of a1–a9 in this measurement. A is the coefficient matrix, and the expansion formula (5) of A is as follows:

$$A = \begin{bmatrix} l_1^2 & m_1^2 & n_1^2 & 2l_1m_1 & 2m_1n_1 & 2n_1l_1 \\ l_2^2 & m_2^2 & n_2^2 & 2l_2m_2 & 2m_2n_2 & 2n_2l_2 \\ l_3^2 & m_3^2 & n_3^2 & 2l_3m_3 & 2m_3n_3 & 2n_3l_3 \\ l_4^2 & m_4^2 & n_4^2 & 2l_4m_4 & 2m_4n_4 & 2n_4l_4 \\ l_5^2 & m_5^2 & n_5^2 & 2l_5m_5 & 2m_5n_5 & 2n_5l_5 \\ l_6^2 & m_6^2 & n_6^2 & 2l_6m_6 & 2m_6n_6 & 2n_6l_6 \\ l_7^2 & m_7^2 & n_7^2 & 2l_7m_7 & 2m_7n_7 & 2n_7l_7 \\ l_8^2 & m_8^2 & n_8^2 & 2l_8m_8 & 2m_8n_8 & 2n_8l_8 \\ l_9^2 & m_9^2 & n_9^2 & 2l_9m_9 & 2m_9n_9 & 2n_9l_9 \end{bmatrix}. \quad (5)$$

l_i, m_i, n_i is the cosine of the axis a1–a9 relative to the coordinate system $o-xyz$. From the pasting method of the strain gauge, we can see that the cosine of each strain axis is shown in Table 1.

Substituting the data in the table into the expansion of A, the coefficient matrix A can be obtained as the following formula:

$$A = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0.5 & 0.5 & 0 & 1 & 0 & 0 \\ 0.5 & 0.5 & 0 & -1 & 0 & 0 \\ 0.5 & 0 & 0.5 & 0 & 0 & -1 \\ 0.5 & 0 & 0.5 & 0 & 0 & 1 \\ 0 & 0.5 & 0.5 & 0 & -1 & 0 \\ 0 & 0.5 & 0.5 & 0 & 1 & 0 \end{bmatrix}. \quad (6)$$

The number of unknowns in the strain component (1) is $n=6$, and the number of independent equations is $m=9$. The most accurate solution can be obtained by using the least-squares method to solve the above overdetermined equations. The least-squares method is used to solve the following equation (7), and the solution process is as follows:

$$A^T A \varepsilon = A^T b. \quad (7)$$

The solved equation is as follows:

$$\varepsilon = (A^T A)^{-1} A^T b. \quad (8)$$

The strain component ε can be solved from this, and it can be represented by three principal strains, and the magnitude of the principal strain can be obtained by solving the following equation:

$$\begin{bmatrix} \varepsilon_x - \lambda & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_y - \lambda & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_z - \lambda \end{bmatrix} \begin{Bmatrix} l \\ m \\ n \end{Bmatrix} = 0. \quad (9)$$

To solve the above system of linear homogeneous equations, the determinant coefficient can be 0 to solve. The specific solution process is as follows:

$$\begin{vmatrix} \varepsilon_x - \lambda & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_y - \lambda & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_z - \lambda \end{vmatrix} = 0. \quad (10)$$

The determinant is expanded to a cubic equation in one variable:

$$\varepsilon^3 - (\varepsilon_1 + \varepsilon_2 + \varepsilon_3)\varepsilon^2 + (\varepsilon_2\varepsilon_3 + \varepsilon_3\varepsilon_1 + \varepsilon_1\varepsilon_2)\varepsilon - \varepsilon_1\varepsilon_2\varepsilon_3 = 0, \quad (11)$$

where $\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = \varepsilon_x + \varepsilon_y + \varepsilon_z$, $\varepsilon_2\varepsilon_3 + \varepsilon_3\varepsilon_1 + \varepsilon_1\varepsilon_2 = \varepsilon_y\varepsilon_z + \varepsilon_z\varepsilon_x + \varepsilon_x\varepsilon_y - \varepsilon_{yz}^2 - \varepsilon_{zx}^2 - \varepsilon_{xy}^2$, $\varepsilon_1\varepsilon_2\varepsilon_3 = \varepsilon_x\varepsilon_y\varepsilon_z - \varepsilon_x\varepsilon_{yz}^2 - \varepsilon_y\varepsilon_{zx}^2 - \varepsilon_z\varepsilon_{xy}^2 + 2\varepsilon_{yz}\varepsilon_{zx}\varepsilon_{xy}$.

The result of solving the above one-dimensional cubic equation is the three principal strain values.

It can be seen that the solution process of the above equations is actually to find the eigenvalues and eigenvectors of the matrix. The eigenvalues of the matrix are the principal strains, and the eigenvectors are the direction cosines of the principal strains. Therefore, knowing the geographic direction of the principal strain will know the geographic direction of the principal stress [20, 21].

2.4. Calculation of Principal Stress. The magnitude of the principal stress σ_i ($i=1, 2, 3$) calculated by the anelastic strain recovery method can be obtained from the following:

$$\sigma_i = \frac{e_i(t)}{Jas(t)} + \frac{\{e_m(t) - \alpha_T \Delta T(t)\}}{Jav(t)} + p_0. \quad (12)$$

In the experiment, the constant temperature water tank ensures that the temperature change is 0, so as long as $Jas(t)$, $Jav(t)$, and the in situ principal stress can be obtained according to the deviatoric strain and pore water pressure. Then, the vertical stress can be expressed by the following formula:

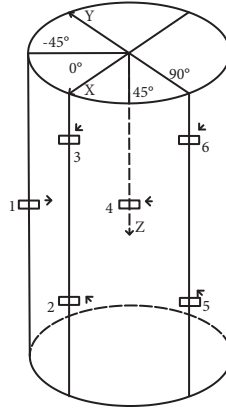


FIGURE 1: Schematic diagram of the arrangement of strain gauges on the core surface.

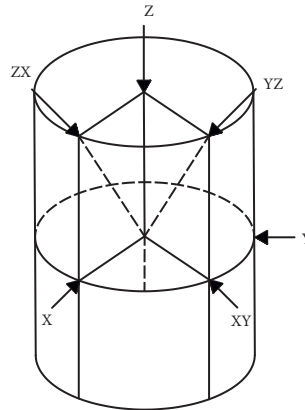


FIGURE 2: Corresponding axial positions of the strain gauges.

$$\sigma_v = \frac{\{([l_p^2 e_1(t) + m_p^2 e_2(t) + n_p^2 e_3(t)] / (Jas(t)/Jav(t))) + e_m(t)\}}{Jav(t)} + p_0, \quad (13)$$

where l_p, m_p, n_p is the cosine of the direction between the vertical stress and the three principal strain axes.

$Jas(t), Jav(t)$ is the anelastic strain recovery flexibility under the two modes, which can generally be obtained from experiments. Some literature approximates the ratio of the two [22, 23]. At the same time, the vertical principal stress is equal to the gravity of the overburden:

$$\sigma_v = \rho gh. \quad (14)$$

Therefore, it can be obtained from the previous article, and (12)–(14) can be combined to complete the stress solution, thereby obtaining the values of the maximum principal stress, the intermediate principal stress, and the minimum principal stress.

3. Field Experiment of ASR Method

3.1. Engineering Background. The Sanshandao Gold Mine is located in Laizhou City, Shandong Province. From the perspective of regional structural conditions, it is located on the east side of the Yimu fault zone. The geology of the

mining area is controlled by the regional EW tectonic system and the NNE trending Neocathaysian tectonic system. In order to meet the development and utilization of deep mineral resources in the Sanshandao Gold Mine, a shaft with a diameter of 10 m and a depth of -2000 m is proposed to be built in the Xiling mining area as an auxiliary shaft in the mining area. During the preliminary engineering survey, the drilling depth of the exploration hole is -2017 m. The lithology of the deep strata is mainly granite. Figure 3 shows the core exposure of the deep part of the formation.

After years of mining, the research experience in the Sanshandao Gold Mine shows that the deep formation is in a state of high stress and strong compression, and the rock has high hardness and high energy content. In construction disturbances, it is easy to produce strong rock dynamic disasters, which brings challenges to excavation support. Under the influence of high stress, the wall of the deep shaft and the structural material of the chamber will be deformed and damaged. As the depth increases, the in situ stress increases linearly. When reaching a certain depth, the entire deep formation rock mass is in a state of strong compressive

TABLE 1: Cosine values of each strain axis.

Strain axial	Direction cosine		
	l_i	m_i	n_i
a_1	1	0	0
a_2	0	1	0
a_3	0	0	1
a_4	0.7071	0.7071	0
a_5	0.7071	-0.7071	0
a_6	-0.7071	0	0.7071
a_7	0.7071	0	0.7071
a_8	0	0.7071	-0.7071
a_9	0	0.7071	0.7071



FIGURE 3: Core exposure of some strata (-1815.56~-1820.16 m, -1897.46~-1902.06 m).

stress due to the constraint of the surrounding rock. Once the external conditions change, the stress inside the rock mass will crush the rock, and the energy will be released rapidly, causing damage to the deep well engineering [24-26].

For this shaft engineering area, the current in situ stress test depth is about -1000 m, and the main method used is the division method that can be applied in well extension engineering. The stress status of deeper formations is still unclear, and it is urgent to carry out in situ stress tests at a depth of -2000 m for various engineering risks that may occur in well construction projects [27, 28]. Since there is no well-extension project such as roadway at this depth, the stress relief method cannot be tested, so the hydraulic fracturing method and ASR method are mainly used for testing. This paper mainly introduces the sampling test work of the ASR method in the range of -1180 m ~ -1960 m; the magnitude of the in situ stress can be obtained, and the determination of the initial direction of the core is generally obtained by the paleomagnetic method, which requires special indoor conditions and instruments to be completed. Limited by the field test conditions, the in situ stress in the deep formation is mainly measured by the ASR method, and the in situ stress field direction is obtained by the hydraulic fracturing method, which will not be introduced in this paper.

3.2. Experimental Device. ASR measurement equipment mainly includes deformation monitoring system, constant temperature system, information acquisition, and

processing system. By measuring the anelastic microstrain recovery of the in situ oriented core in the deep formation, and using the acoustic monitoring system to monitor the core acoustic emission (energy) and wave velocity field evolution, the three principal stresses of the stratum where the core is located can be calculated, which provides a basis for studying the creep mechanism of rock unloading under high in situ stress.

Deformation monitoring system is used to measure the multidirectional deformation of rock samples. The Donghua test DH3816N static stress-strain test and analysis system combined with the supporting software DHDAS dynamic signal acquisition and analysis system was used to monitor the strain of the core specimen.

Constant temperature water bath system is used to provide a constant temperature test environment for rock samples. The constant temperature system is an important factor to ensure the accurate results of ASR in situ stress measurement. In this experiment, the TYC-DZ type anelastic strain recovery method three-dimensional in situ stress test system-high-precision water bath incubator is used. The temperature change range of the constant temperature water bath is within $\pm 0.1^\circ$. The instrument is shown in Figure 4.

3.3. Experimental Process. The core used in this anelastic strain recovery method in situ stress test was taken from the auxiliary shaft exploration borehole in the Xiling mining area of the Sanshandao Gold Mine. On-site sampling needs to be taken back to the laboratory immediately after the XY-



FIGURE 4: High-precision water bath constant temperature system.

8 drilling rig salvages the core, and the core sample is measured immediately after the core sample is lifted from the borehole. The selection of core samples generally needs to meet the following conditions: ① the core texture is uniform and there is no original crack; ② the length of the core sample is 15–20 cm, the surface is complete, and the strain gauge can be attached; ③ the deeper the core is collected, the more accurate the calculation is. Because more stress is released and the strain recovery is larger, it is easier to calculate the in situ stress state; ④ try to stay away from the fault zone in the formation.

After past the gauge, as shown in Figure 5(a), the strain gauge is connected to the DHDAS dynamic signal strain acquisition instrument (using terminal blocks) to check whether the channel is balanced. After the inspection is correct, the core is wrapped (guaranteed to be sealed) and placed in a constant temperature water tank for testing; at the same time, the temperature of the water tank must be consistent with the in situ temperature environment of the rock sample during the test. At the same time, a core of the same lithology is used as a compensation sample to connect to the compensation channel of the strain acquisition instrument to exclude the influence of system displacement and thermal expansion of the rock. During the test, the long-term stability of the core and the equipment and the constant temperature should be ensured for about 7 days. The ASR experimental acquisition system is shown in Figure 5(b).

4. Data Analysis and Discussion

4.1. Calculation and Analysis of Measured Data. The core sample is granite with a diameter of $\phi 60$ and a length of 150~200 mm. The measurement duration for each core sample is 6–7 days. In total, anelastic strain recovery tests of five samples in the depth range of –1180 m to –2008 m were completed. The anelastic strain recovery curves are shown in Figures 6–9; in order to facilitate comparison, –1180 m rock samples are tested at room temperature, other rock samples are placed in the water bath incubator, and the data with small error and good continuity in 9 directions are selected for analysis. It can be seen from the recovery curve that the anelastic strain of each strain gauge is a tensile change,

indicating that the rock sample is under compression in the in situ state. With the increase of measurement time, the strain recovery occurred in all 9 strain axes of the test core, and gradually became flat and became stable on the 5th to 7th day.

Temperature changes have a significant effect on rock hysteretic recovery. At the beginning of the experiment, core samples at a depth of –1180 m were tested at room temperature. As shown in Figure 6, with the passage of time, the overall trend of the hysteretic recovery strain curve is upward. Except the a1 strain curve, which reaches 900 microstrains, the maximum values of other strain curves are in the range of 300–550 microstrains. However, with the periodic increase and decrease of temperature between day and night, the strain curve will also change periodically, and a temperature difference between day and night can cause 150 microstrain errors. Therefore, the ASR method needs to be guaranteed under constant temperature conditions.

The four core samples in Figures 7–10 were tested under constant temperature conditions. The strain curve is relatively smooth. The temperature adjustment of the incubator has a slight but negligible effect on the curve. During the testing process of the –2008 m core sample, the a5, a7, and a8 strain gauges fell off and only the strain recovery in 6 directions was recorded, which could meet the calculation requirements.

Table 2 shows the final anelastic strain recovery measurements for the 4 specimens. The value of each strain component is in the range of 300 to 1500 microstrains, which can meet the requirements of the measurement.

After obtaining the anelastic strain values through actual measurement, firstly 6 strain values are obtained by solving the aforementioned equations (8) and (11) and then the eigenvalues and eigenvectors of the strain matrix are found, which are the directional cosines corresponding to the 3 principal strains and principal strains.

The principal stress values are solved by (12)–(14). Among them, the ratio of shear mode anelastic recovery flexibility to volume mode anelastic recovery flexibility is set as 2, and the average density of the overlying rock layer is 2.7 g/cm^3 . Then, the vertical principal stress can be calculated by (14), and finally, the maximum principal stress value

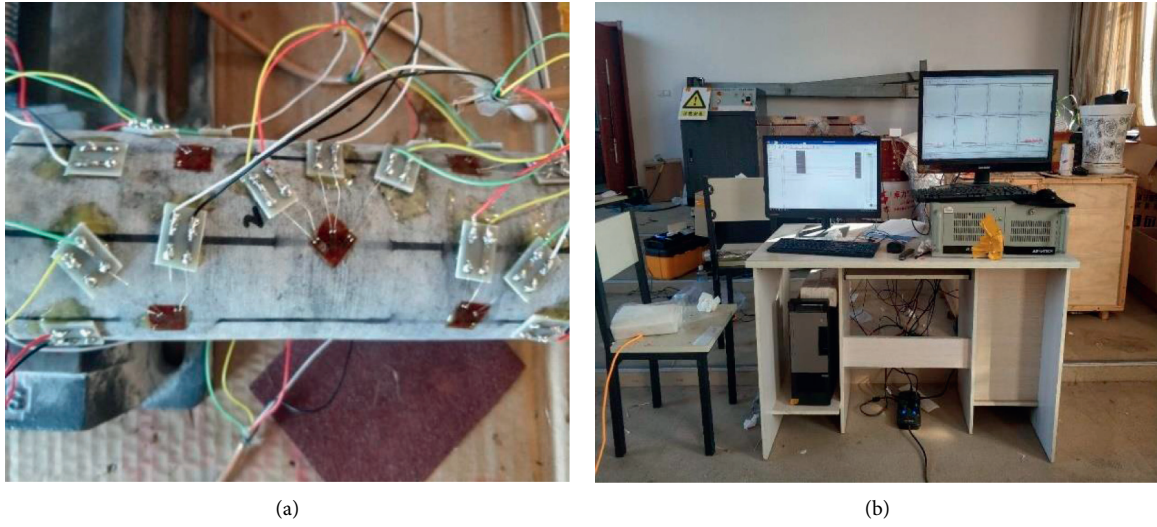


FIGURE 5: (a) Layout of core strain gauges in an actual test; (b) signal acquisition of ASR in situ stress measurement experiment.

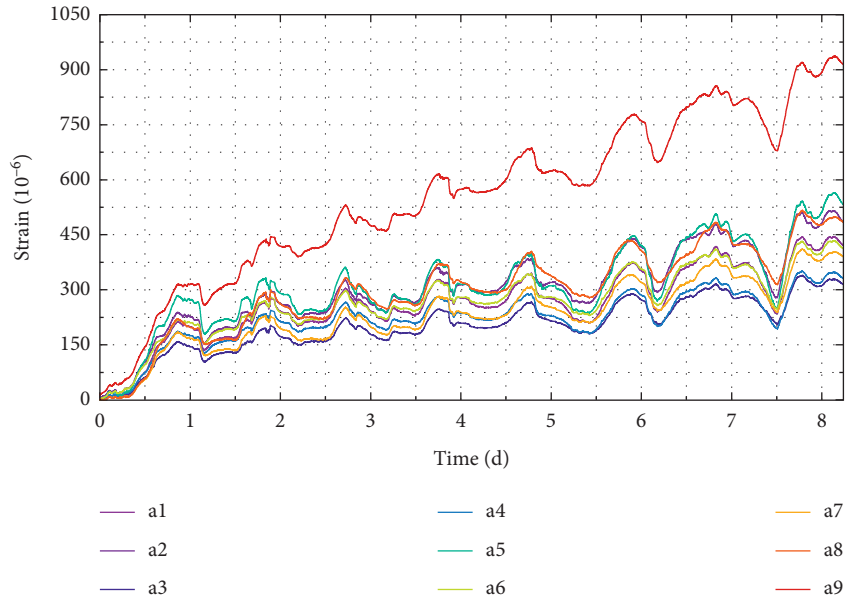


FIGURE 6: -1180 m core sample anelastic recovery strain curve.

and the minimum principal stress value of the corresponding depth are obtained, as shown in Table 3.

In order to verify the validity of the experimental results of the ASR method, as a reference object for comparison, this paper also gives the distribution law of the in situ stress test results obtained by the hydraulic fracturing method [29], as shown in equation (15). The maximum and minimum principal stress values corresponding to the experimental depth of the ASR method were calculated, respectively, as shown in Table 3.

$$\begin{aligned}
 \sigma_{\max} &= 0.030D + 10.142 \\
 \sigma_{\min} &= 0.019D + 7.986 \\
 \sigma_v &= 0.027D - 0.019.
 \end{aligned} \tag{15}$$

Among them, D is the absolute value of drilling depth, and the unit is m ; the unit of principal stress σ_{\max} , σ_{\min} , σ_v is MPa.

Compared with the test results obtained by the hydraulic fracturing method, the results obtained by the ASR method are basically the same, and the absolute value of the error is in the range of 0.4–10.4%. Time is the most important factor affecting the test results. The time for core strain recovery to be basically completed is generally 3–5 days. With the increase of depth, the recovery time increases slightly without much change. However, after the core is separated from the in situ formation at the bottom of the hole, the elastic strain will recover rapidly in a short time, and at the same time, the anelastic strain will also begin to recover. In the drilling exploration, the core is taken out by rope coring, which takes

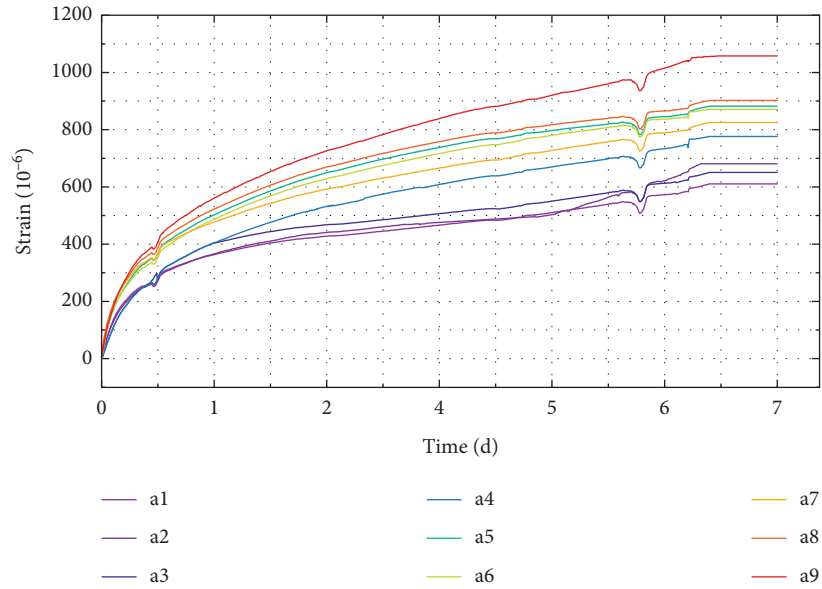


FIGURE 7: -1816 m core sample anelastic recovery strain curve.

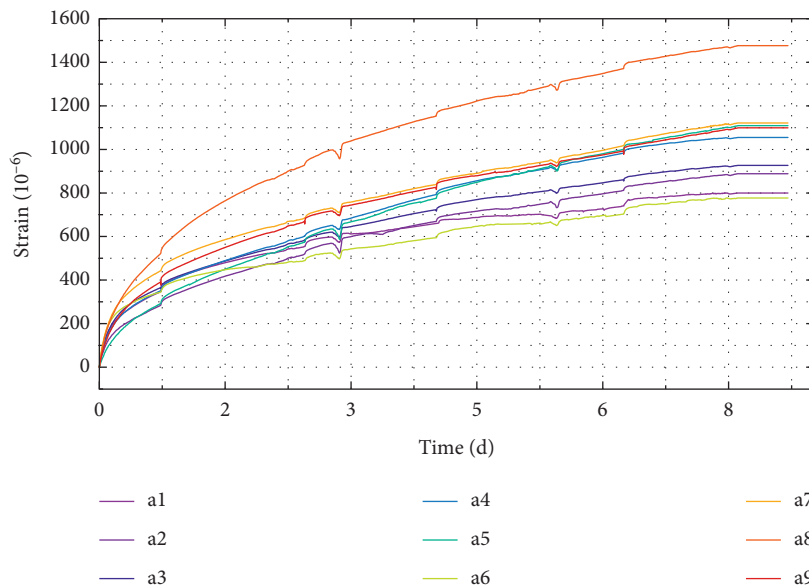


FIGURE 8: -1879 m core sample anelastic recovery strain curve.

about 1 hour. After that, the experimental preparation process such as pasting the strain gauges also takes about 1 hour, so the experimental measurement actually lags behind for a period of time. However, the rate of anelastic strain recovery during this period is still relatively large, resulting in the loss of some initial recovery amount, causing the anelastic strain recovery amount used in our calculation to be smaller than the actual strain amount, and the obtained stress results will also be smaller than the actual amount. To overcome the influence of time factors, it is necessary to ensure that the experiment can be carried out quickly after the core leaves the original position, so as to eliminate the error caused by the time factor as much as possible.

4.2. Discussion. The amount of anelastic strain recovery of cores at different depths is different. From the core strain recovery curves at different depths, we can see that the strain recovery is proportional to the depth, which also shows that the deep in situ stress is greater than the shallow in situ stress. Compared with the shallow part, the anelastic recovery value of the deep core is larger. In literature [18, 19], the ASR test depth is -746 m ~ -1173 m, and the maximum anelastic strain of the core reaches 600~1000 microstrains. In this experiment, the strain values measured in the -1180 m core sample ranged from 300 to 900 microstrains. However, the anelastic strain of the core at the depth of -2008 m obtained in this paper reaches 1600 microstrains, which

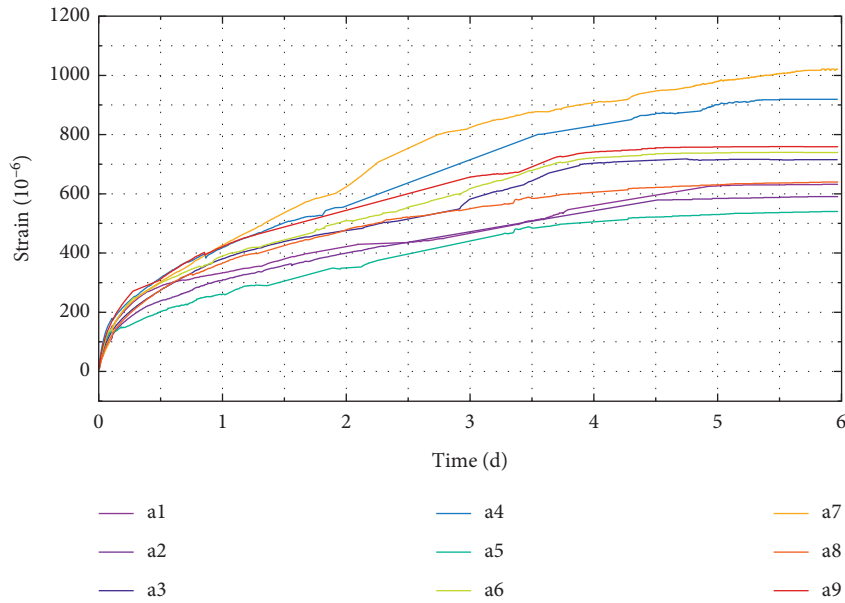


FIGURE 9: -1960 m core sample anelastic recovery deformation curve.

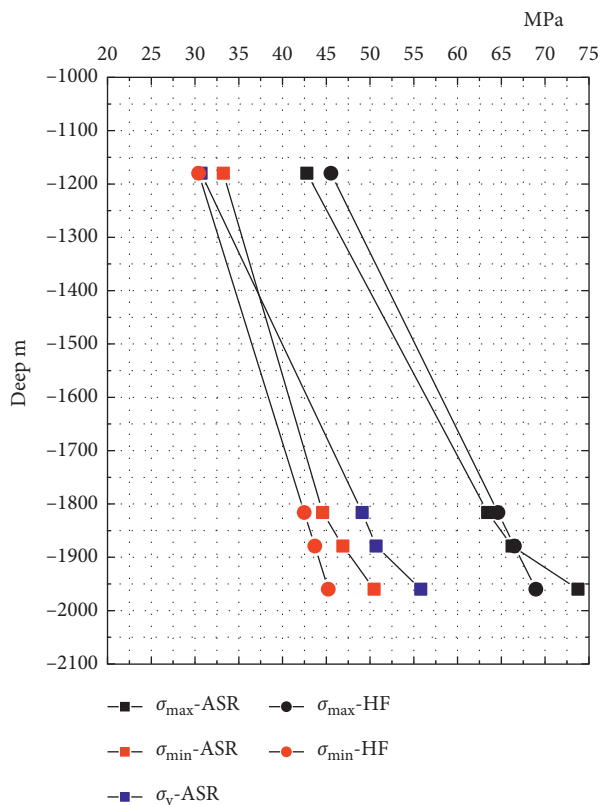


FIGURE 10: Comparison of test results of ASR and hydraulic fracturing.

shows that with the increase of depth, the anelastic strain recovery of the core is larger. Of course, this difference may also be caused by different lithology, and the anelastic characteristics of different mineral compositions are different. And the larger the anelastic strain recovery is, the

smaller the measurement error is, and the influence on the results is relatively small. Therefore, the ASR method is more suitable for deep hole cores.

The hydraulic fracturing method has many unique characteristics in testing stress in shallow holes and has been widely used in rock engineering, oil drilling, and seismic research. There are few hydraulic fracturing tests in the literature with a depth of more than 1000 m, and most of them are concentrated in shallow formations [30, 31]. During deep hole testing, the research team found that hydraulic fracturing is affected by many factors. Deep boreholes often appear necking, collapsed, and setback, causing the test instrument to get stuck or fall off. The increase in the number of test reciprocations also causes damage to the hole wall, which ultimately results in a significant increase in the hydraulic fracturing test cycle and an increase in economic costs. In contrast, the ASR method can be performed simultaneously during the drilling process and has the advantages of simple operation, short construction period, and low cost [32, 33].

In this paper, the exploration and application of the ASR method in deep hole drilling is carried out. Under the conditions of deep well extension engineering (such as roadways and chambers with a depth of -1500 m), the test can be carried out simultaneously with the stress relief method. In addition to the paleomagnetic method, the initial orientation of the core sample can also use the borehole wall imaging technology. In the next step, when the ASR method experiment is carried out in the deep hole, the ultrasonic borehole imaging technology can be used to determine the core orientation, so as to obtain the principal stress direction. The drilling depth required by the stress relief method is shallow, generally in the range of 8 m to 12 m. Due to the short coring time, while making full use of the stress relief method to drill the core, the core orientation can also be determined by drilling TV and other techniques in this

TABLE 2: Strain recovery of different strain axes in deep core.

Strain axis (m)	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
-1180	443	513	328	347	563	432	402	497	935
-1816	611	681	651	776	882	871	825	902	1058
-1879	800	888	927	1055	1109	777	1121	1476	1099
-1960	632	590	715	919	539	739	1021	639	759

TABLE 3: In situ stress measurement results by ASR method and hydraulic fracturing method.

Depth (m)	ASR			Hydraulic fracturing	
	σ_{\max} (MPa)	σ_{\min} (MPa)	σ_v (MPa)	σ_{\max} (MPa)	σ_{\min} (MPa)
-1180	42.78	33.24	30.7	45.54	30.41
-1816	63.45	44.58	49.1	64.62	42.49
-1879	66.24	46.91	50.7	66.51	43.69
-1960	73.76	50.46	55.8	68.94	45.23

depth range. Therefore, the accuracy and difference of the above two methods are compared within the same surrounding rock area, and the engineering experience and scientific research data foundation are further accumulated for the improvement of the ASR method [34–36].

5. Conclusion

- (1) Taking the -2000 m deep shaft of the Sanshandao Gold Mine as the engineering background, the ASR method was used to measure the deep in situ stress. The maximum principal stress values σ_{\max} of -1180 m, -1816 m, -1879 m, and -1960 m are 42.78~73.76 MPa, and the minimum principal stress values σ_{\min} are 33.24~50.46 MPa, respectively, which provide important basic data for shaft engineering construction, surrounding rock stability, wellbore, and roadway support design.
- (2) Comparing the in situ stress measurement results of the ASR method with the hydraulic fracturing method, the two are basically consistent, and the absolute error is in the range of 0.4~10.4%. This proves the reliability of in situ stress measurement by ASR method, which can reduce the error and further improve the accuracy of ASR method by controlling the influence of time.
- (3) The ASR method is more suitable for in situ stress measurement of deep rock formations with good integrity. The in situ stress level increases with depth. At the same time, the measurement error decreases with the increase of elastic strain recovery, which makes the applicability of the ASR method better.
- (4) Disadvantages such as hole collapse and shrinkage can be avoided using the ASR method. It can be carried out simultaneously with the engineering exploration and drilling process in the early stage of engineering construction. The ASR method is easy to operate, does not affect the construction period, and has significant advantages in the measurement of deep in situ stress.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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