Anelastic strain recovery in situ stress measurement method and its application prospect in underground mines

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Abstract. Current stress state data are important in underground mine construction, analysis of tunnel stability, the forecasting of coal and gas rock bursts in underground mines. At present, the hollow inclusion gauge is primarily used for in situ stress measurement in underground mines. However, the sensors of these gauges often fail to fully adhere to the borehole wall, which can reduce the reliability of the measurement results. In this study, the anelastic strain recovery (ASR) in situ stress measurement method based on oriented cores is introduced. The effectiveness of this technique is analyzed by comparing the test results with those obtained by the hydraulic fracturing method. In addition, the reliability of the ASR method is evaluated by repeatability testing. The ASR results indicate a horizontal minimum principal stress error of less than 10% compared with those obtained by the hydraulic fracturing method. The repeatability test results show good consistency in the in situ stress measurement results of two back-to-back test samples. The ASR method is a safe and highly efficient technique that is not limited by the depth and measurement environment. Therefore, it is expected to have broad application for underground mine in situ stress measurement.

1. Introduction
The in situ stress state is an important factor in underground mine construction, analysis of tunnel stability, and the forecasting of coal and gas rock bursts [1-2]. At present, hollow inclusion gauges are primarily used for in situ stress measurement in underground mines. The representative measuring sensors include KX-81 developed by Institute of Geomechanics, Chinese Academy of Geosciences, and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) hollow core inclusion stress meter developed in Australia [3-5]. However, the variations in measurement technology and construction environment cause limitations with respect to the usage of the hollow inclusion gauge method. For example, due to the influence of gravity and borehole conditions during the installation process, it is difficult for the sensor to adhere to the borehole wall rock completely. In such cases, the gauges are unable to effectively obtain elastic deformation information. Although the cores obtained during the measurement process are required to be at least 40 cm in length, this process frequently results in measurement failure in rocks with poor integrity. Moreover, a waiting period is required for the strain gauges to adhere completely to the rock after the stress meter is adhered to the borehole wall. The measurement period and labor intensity are higher when using the hollow inclusion gauge method in underground mines. Thus, the development of a safe, efficient, and reliable method for in situ stress measurement is an urgent requirement in current underground mine construction projects.

The newly developed anelastic strain recovery (ASR) method is an oriented core-based technique used to determine the three-dimensional (3D) in situ stress present at deep levels. This method can be used
to estimate the original inelastic strain close to the original state because it recovers the anelastic strain measured in the drilling field [6-12]. In addition, the ASR method has a relatively explicit theoretical basis in comparison to other core-based methods. In the present study, we briefly introduce the basic principles and related procedures of the ASR method. Then, the method’s effectiveness is evaluated by comparing its measurement results with those obtained by hydraulic fracturing in situ stress measurement. Moreover, the reliability of ASR method is analyzed through repeated measurement of the same samples. Finally, the application prospects of the ASR method are discussed for measuring the in situ stress in underground mines.

2. ASR in situ stress measurement method

For an isotropic viscoelastic material, when in situ stresses and pore pressure are released step-wise at \( t = 0 \), anelastic normal strain \( \varepsilon_a(t) \) recovers during the elapsed time from 0 to \( t \) in an arbitrary direction. The directions of the cosines of this arbitrary direction, defined as \( l \), \( m \), and \( n \) corresponding to the \( x \)-, \( y \)-, and \( z \)-axes, respectively, are given by the following equation (Lin et al., 2006; Sun et al., 2014):

\[
\varepsilon_a(t) = \frac{1}{3} \left[ (3l^2 - 1)\sigma_x + (3m^2 - 1)\sigma_y + (3n^2 - 1)\sigma_z \right]
\times J_{as}(t) + \left( \sigma_n - p_o \right) J_{av}(t) + \alpha_T \Delta T(t)
\]

where \( \sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{yz}, \) and \( \tau_{xz} \) are the components of the in situ stress tensor released by drilling; \( \sigma_m \) is the constant mean normal stress, \( p_o \) is the pore pressure, \( \alpha_T \) is the linear thermal expansion coefficient, \( \Delta T(t) \) is the temperature change, and \( J_{as}(t) \) and \( J_{av}(t) \) are the ASR compliances of the shear and volumetric deformation modes, respectively. The magnitudes of the three principal stresses can be simplified as

\[
\sigma_i = \frac{e_i(t)}{J_{as}(t)} + \left\{ \frac{e_{\sigma_i}(t) - \alpha_T \Delta T(t)}{J_{av}(t) + p_o} \right\} \quad i = 1, 2, 3
\]

where \( e_i(t) \) denotes the principal strain deviator components, and \( e_{\sigma_i}(t) \) is the constant mean normal strain. Eq. 1 shows that the recovered anelastic strain depends on the in situ stress tensor components, pore pressure, temperature change during the measurement, the thermal expansion coefficient, and the compliances of both deformation modes. Therefore, if the material constants \( (J_{as}(t), J_{av}(t), \alpha_T) \), pore pressure, and temperature change are known, the six stress components, i.e., 3D in situ stress tensor, can be obtained by measuring the anelastic normal strains in the six independent directions. For isotropic viscoelastic materials, the directions of the three principal axes of the in situ stresses coincide with the directions of the three principal axes of the anelastic strain tensor. Thus, the directions of the 3D principal in situ stresses can be determined by calculating the principal directions of the measured anelastic strain data in at least six independent directions.

For the measurement using the ASR method, a core sample with an appropriate length of about 10–15 cm was first obtained. The core was cleaned and marked with orientations, and the special strain gauges (C1, C2, … C18) were glued along the baseline (\( x^\prime \)-axis) and lines oriented 45°, 90°, and -45° from the baseline, with the clockwise direction being negative. The layout of strain gauges used here is shown in Fig. 1. The sample containing the strain gauges was wrapped using a Fresco Bag sealed by silicon rubber to prevent the pore water from evaporating during the test. The sample was placed in a water chamber equipped with an electronically controlled constant temperature device. Three wire-resistance strain gauges and a precision data recorder were employed to record the strains and changes in temperature. In addition, a dummy specimen was employed under the same conditions to monitor the data drift. It should be noted that according to the testing protocol, the measurement should begin as soon as possible after the core is prepared.
3. Effectiveness and the reliability analysis

3.1 Effectiveness analysis

The hydraulic fracturing method is the most reliable technique currently used to obtain horizontal minimum principal stress. Owing to its simple operation and repeatable measurement results, this method has been widely applied in past decades in the fields of oil and gas field (dry hot rock) development, deep tunnel stability analysis, and geodynamic basic research. To verify the effectiveness of the ASR stress measurement method, the stress measurement results obtained by ASR and hydraulic fracturing were compared and analyzed. The borehole of the stress measurement is located in Mayang Miao Autonomous County, Huaihua City, Hunan Province, at a depth of 2043.91 m and a borehole diameter of 98 mm. The ASR and the hydraulic fracturing methods were applied to measure the stress state of the borehole. Fig. 2a shows the anelastic recovery strain curves obtained after drilling siliceous rock to a depth of 1260 m. Axes 1 to 9 in the figure represent the anelastic recovery strain curves in different directions, and the red curve indicates the temperature change in the sample during the measurement process. Fig. 2b shows the downhole pressure versus time curve obtained by hydraulic fracturing measurement at a depth of 1267 m. The breakdown, reopen, and closed pressure are clearly indicated on the curve. The repeatability of the reopen and closed pressures was very good, which relates to reliable closing pressure, i.e., horizontal minimum principal stress (Chen et al., 2019).

Figure 1. Layout of strain gauges on the surface of the rock core.

Figure 2. Test curves of ASR and hydraulic fracturing methods at Xuefengshan borehole.
The in situ stress measurement results of the ASR and hydraulic fracturing methods at depths of 1260–1267 m are shown in Table 1. The horizontal minimum principal stress measured by the ASR method was 3.43 MPa lower than that obtained by hydraulic fracturing method. Moreover, the temperature was about 56 ℃ at 1260 m. The results obtained by in situ measurement using hydraulic fracturing were higher than the actual stress state. Thus, the difference in results between the two methods might be caused by thermal stress. Generally, the horizontal minimum principal stress error obtained by the two methods was about 10%, which verifies the effectiveness of the ASR method to a certain extent.

Table 1. Repeated measurement results of ASR method.

| Sample                  | Depth (m) | $\sigma_H$ (MPa) | $\sigma_h$ (MPa) | $\sigma_v$ (MPa) |
|-------------------------|-----------|------------------|------------------|------------------|
| ASR method              | 1260.00   | 42.03            | 29.09            | 33.40            |
| Hydraulic fracturing    | 1267.00   | 50.79            | 32.52            | 33.58            |
| Average                 | 1263.50   | 46.41            | 30.81            | 33.49            |

$\sigma_H$: horizontal maximum principal stress; $\sigma_h$: horizontal minimum principal stress; $\sigma_v$: vertical stress

3.2 Reliability analysis

To verify the reliability of the ASR in situ stress measurement method, a repeatability test of the ASR in situ stress measurement results was conducted using back-to-back granite samples, as shown in Fig. 3. The granites were obtained from a dry hot rock borehole in the eastern Hebei Province. The lengths of the samples were 14 cm and 12 cm, and the diameter of each was 10 cm. The internal depths of the samples were 3620.61–3620.75 m and 3621.05–3621.17 m, respectively. Fig. 4 shows the ASR curves of the two granite samples. Axes 1–9 indicate the ASR curves in different directions, and the red curve indicates the temperature change of the sample during the measurement process. The ASR curves of the two samples were nearly identical. The minor differences between the two might have been induced by differences in the fixed position of the strain gauges or those in the time from drilling to the start of the measurement.

Figure 3. Back-to-back samples of ASR in situ stress measurement.
Figure 4. Anelastic strain recovery curves of samples obtained at depths of 3620.9 m and 3621.1 m.

Table 2 shows the calculation results of the ASR measurement samples using the calculation software employed in the ASR method. The average difference coefficient between the two methods was 6.29%, which shows good consistency. The average value of the two samples also demonstrates this point. Therefore, the repeatability of the ASR method was verified.

Table 2. Repeatability measurement results using the ASR method.

| Sample | Depth (m) | $\sigma_1$ (MPa) | $\sigma_2$ (MPa) | $\sigma_3$ (MPa) | $\sigma_h$ (MPa) | $\sigma_v$ (MPa) |
|--------|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|
| ASR1   | 3620.9    | 120.6           | 79.3            | 69.2            | 112.3           | 79.1            | 97.7            |
| ASR2   | 3621.1    | 126.4           | 89.0            | 78.5            | 117.2           | 78.9            | 97.8            |
| Average| 2621.0    | 123.5           | 84.2            | 73.9            | 114.8           | 79              | 97.8            |
| Average difference coefficient | —         | 2.35%           | 5.76%           | 6.29%           | 2.13%           | 0.13%           | 0.05%           |

$\sigma_1$: maximum principal stress; $\sigma_2$: medium principal stress; $\sigma_3$: minimum principal stress; $\sigma_h$: horizontal maximum principal stress; $\sigma_v$: horizontal minimum principal stress; $\sigma_v$: vertical stress (density of rock is 2.70 g/cm$^3$). The average difference coefficient is the ratio of the average difference to the average value.

4. Application prospects of ASR method in underground mine stress measurement

The ASR method is similar to the hollow inclusion gauge method in that the two have relatively complete theoretical basis in 3D in situ stress measurement methods. Both can be used to obtain in situ stress information by measuring the deformation of rock using strain gauges. The difference between the two methods is that the hollow inclusion gauge method measures the elastic deformation, and the ASR method measures the anelastic deformation of rock after unloading. The strain measured by the hollow inclusion gauge method is larger than that measured by ASR method. Compared with the hollow inclusion gauge method, the advantages of the ASR method for underground mine stress measurement are listed below.

1. In the ASR method, the strain gauges are adhered to the surface of the rock core. The strain gauge has good adhesion quality with the rock sample and can avoid the obvious joint fracture sections. Moreover, the core temperature is kept constant during the measurement to avoid the influence of temperature change.
(2) The ASR method can be used to measure a plurality of samples at the same time, and the reliability of the measurement results can be improved through multi-point data averaging and comparative analysis.

(3) The ASR method is not limited by the depth and environment of the borehole. As long as a directional core can be obtained within the underground mine, ASR stress measurement can be conducted to obtain accurate stress information.

(4) The ASR method is conducted in the surface laboratory using an underground directional core. It should be noted, however, that the ASR method also has limitations in its application. For rocks with high clay mineral content, such as shale, mineral water loss will produce shrinkage deformation during the measurement period, which is generally five to seven days. The shrinkage deformation is opposite the expansion deformation caused by stress release. Therefore, samples with low shale content are preferred for measurement using the ASR method. Because it offers safety and high efficiency and is not limited by the measurement depth and environment, this method is expected to have a wide application for underground mine stress measurement.

5. Conclusions
The basic principle and measurement procedure of ASR method are introduced, and the effectiveness and reliability of ASR method are shown combined with the measured data. The application prospect of ASR stress measurement method in underground mine is analyzed. The conclusions are as follows.

(1) ASR is a 3D in situ stress measurement method with relatively complete theoretical basis. The adhesive quality of strain gauge and temperature stability of samples can be guaranteed during the period of measurement. The test is conducted after the core was taken out from underground as soon as possible. Then the cores are at the near the original state, and the reliable stress information can be obtained.

(2) The reliability of the ASR method is verified by comparing the measurement results with those obtained using the hydraulic fracturing method. The repeatability of ASR method shows that the average difference coefficient of ASR stress measurement results with the back-to-back samples is 6.29%, which proves the effectiveness of the ASR method.

(3) The ASR method will have a wide application prospect in underground mine stress measurement with its safety, high efficiency, and no limitation of measuring depth and environment.

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