Study on quantitative characterization method of measurement accuracy of geostress technology and equipment

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Abstract. In view of the shortcomings of existing research, the definition, quantitative characterization of all elements and its application of geostress measurement accuracy are studied. On the basis of the summary and classification of the measurement accuracy research in past decades, the definition of geostress measurement and its accuracy are given from the perspective of closed-loop measurement, different from the definition of taking rock mass as measurement object. The function and significance of the measurement accuracy research is also clearly pointed out. The quantitative characterization idea and procedure of geostress measurement accuracy are introduced. A physical model test device is provided, and the coordinate setting and the method of reducing the uncertainty of measurement accuracy representation by coordinate conversion are explained. 2D and 3D accuracy characterization formulas of all stress component which including single indexes of average-mode and maximum-mode are given first in the world, and the calculation method of angle error is discussed, the relationship between characterization modes and technical requirements is explained. Taking the measurement accuracy characterization of the physical model test results of early USBM borehole deformation gauge(USBM-type gauge) and CSIRO hollow inclusion strain cells(CSIRO HI cells) as example, the quantitative characterization process of measurement accuracy is shown, the characterization indexes are compared with the original ones, and the overall measurement error of the single index of the maximum-mode of the two test technology is 10% and 27%, respectively. Accuracy indexes of different dimension test methods are calculated and compared for the first time, and the data show that the overall measurement accuracy of the former is much better than the latter.

1. Introduction

Geostress is the undisturbed natural stress in rock mass, the general term of crustal stress, and the basic data of underground engineering construction such as earthquake prediction, mining, water conservancy and hydropower engineering, civil construction and transportation. The geostress state of natural rock mass under specific time and space conditions is objective, and its value cannot be speculated, which can only be determined by in-situ measurement. U.S. scholar Lieurace first carried out the original rock stress measurement in 1932, and the geostress measurement method and technology have emerged. Up to now, there are more than ten main measurement methods and hundreds of measurement techniques
and equipment[1-8]. At present, the widely used geostress methods include hydraulic fracturing method and overcoring method. The latter includes borehole diameter deformation method and borehole wall strain method. In which the representative measuring elements are USBM borehole deformation gauges(USBM-type gauge), CSIR triaxial strain cell and CSIRO hollow inclusion strain cells(CSIRO HI cells).

There have been many tests on the accuracy of geostress measurement in history. Merrill R. H. et al.[9] conducted the measurement accuracy test on USBM-type gauge in specimens such as steel, lead, quartzite and sandstone and believed that the measurement error of the test technology was within 5%. According to the accumulated data of 10 years, E. R. Hoskings[10] drew the conclusion of the measurement error of USBM-type gauge is 20% ~ 100% in the stress value and 10 ~ 25% in the direction. Leeman E. R.[11] and Herget, G.[12] used steel and aluminum cubes to ascertain the accuracy of CSIR strain gauge. Worotnicki G. et al.[13] carried out the accuracy test of CSIRO HI cells by applying uniaxial pressure on cube aluminum block and bidirectional confining pressure on cylinder aluminum block. In the 1990s, Cai Meifeng[14] carried out large-scale simulation tests on a variety of representative measuring elements in the world. The measurement accuracy of the test technology was characterized only by the ratio index of the main stress value, that still did not give a overall data including all the angular and magnitude components. In terms of hydraulic fracturing method, Fairhurst[15], Haimson[16] and Hayash et al.[17] established and developed the measurement method. Ito et al.[18] studied the influence of hydraulic fracturing system flexibility on the measurement results. Liu Yunfang[19] studied the hypothesis and fracture criterion of in-situ stress measurement by hydro-fracturing method, and put forward the result verification and correction suggestions. Frash et al.[20] developed a true triaxial heating hydraulic fracturing device to study the hydraulic fracturing characteristics of dry and hot rocks. Yin Guangzhi et al.[21] conducted true triaxial hydraulic fracturing test of coal and rock mass by true triaxial fluid-solid coupling test system.

However, the following problems still exist in the accuracy of geostress measurement: (a) There is no authoritative answer and comparison for the measurement accuracy of different technologies and equipment, and sometimes the measurement results are questioned. (b) New methods and technologies’ measurement accuracy cannot be given a clear answer. (c) Independent laboratory can only verify the acquisition equipment, sensor parts and other components, and cannot give the measurement accuracy of the whole process. The reasons for the above problems are as follows: (a) There is no clear definition of geostress measurement accuracy, and there is no unified and clear measurement accuracy characterization regulations within the industry. (b) The measured rock mass does not conform to the principle setting of the measurement method and there is no correction technology, resulting in large measurement error. (c) The measurement error levels of technical schemes and measuring equipment of different organizations are uneven, and the technical differences are significant.

Based on existing studies[23], the paper proposed the definition of the closed-loop concept of geostress measurement accuracy, the suggestion of the characterization setup, the characterization index and calculation formula of the measurement accuracy of all elements, and demonstrated the quantitative characterization process of measurement accuracy of USBM-type gauge and CSIRO HI cells technologies.

2. Definition, characterization system suggestion and research significance of geostress measurement accuracy
Measurement refers to the process of test for the purpose of determining the value of the measured object, while measurement accuracy refers to the quantity that reflects the proximity of the measured result and the true value. Based on the above concepts, geostress measurement is a process in which the initial stress state of the measured rock mass is taken as the measured object and the initial input of the measurement, the signal output and collection are realized by the measurement program and the test operation, and then the measurement results are obtained through the auxiliary test and result calculation programs. It can be regarded as the definition of the geostress measurement accuracy by giving feedback.
to the process of geostress measurement, comparing the measurement result with the initial input, and using appropriate indexes to obtain the characterization of the approximate degree of the two.

Different from the definition of rock mass as the measurement object, the above mentioned geostress measurement process and accuracy definition form a closed loop, which is the whole process and absolute definition. In this definition, the accuracy of geostress measurement is related to the measurement as well as feedback process, and the error factors of all the stages of the measurement process and the special influence factors of the measured rock mass are included into the research scope. In particular, the concept of accuracy and correctness can be derived from the measurement accuracy. Measurement error is used to represent the degree of deviation between measured value and true value, and to reflect measurement accuracy from the facet of error. Based on the above definition and analysis, the research on the accuracy of geostress measurement can be divided into three aspects: (1) the measurement principle; (2) the accuracy of measurement technology and equipment; (3) the correction technique of special rock mass measurement. Once the measurement method is established, the latter two aspects are main objectives of research, and the foregoing citation reflects the above classification.

Three conditions are required to determine the measurement accuracy of a set of measurement technical and equipment: (1) Unified measurement accuracy quantitative characterization method; (2) Standard test facilities that simulate the field test environment and conform to the test principle; (3) Technical scheme and equipment to be inspected and tested. On the basis of that, two levels of organization system can be formed. One is the authoritative data release system, which can be composed of several laboratories or technical verification laboratories. This system can provide authoritative data of measurement accuracy of a set of test technology and equipment, and its program and data processing can refer to ISO 5725-1994 standard[22]. The other is the laboratory system for evaluating the accuracy of geostress measurement independently by each test organization.

The above characterization system can give the measurement accuracy of a set of technical and equipment, which shall include specific measurement equipment composition and detailed technology. The quantitative characterization data of measurement accuracy is the basis for the study of technical correction scheme of specific rock mass, the error evaluation of field measurement results, and the assessment of measurement accuracy of technical innovation scheme. The accuracy assessment can promote the survival of the fittest of geostress measurement methods and techniques.

3. Quantitative characterization of geostress measurement accuracy of all elements

The quantitative characterization of geostress measurement accuracy of all elements is proposed based on the known stress state and measurement results.

3.1. Quantitative representation ideas

The geostress state of rock mass is a second-order tensor in 3D space, and the results can only be compared between its magnitude value and its angular component. The state of geostress can be expressed by the stress and angle components of 2D or 3D orthogonal coordinate system. Therefore, the magnitude and angle of principal stress of 2D stress measurement, the magnitude, azimuth angle and dip angle of principal stress of 3D stress measurement can be used as comparable terms and the quantitative index results can be given.

This quantitative characterization, which includes the characteristics of the measured rock mass and all the influence factors of the error in the measurement, for all the magnitude values and angles, is called the all elements quantitative characterization of measurement accuracy. The single index reflects the influence of single or multiple error factors in the measurement process, and the single index reflects the measurement error caused by all error factors in the whole measurement process. The quantitative characterization of the accuracy of geostress measurement should be carried out by physical simulation test in laboratory environment, and some sessions can be carried out by computer simulation.
3.2. Quantitative characterization method

The quantitative characterization procedures for the accuracy of geostress measurement are as follows:
(1) carry out the simulation test in the original coordinate system and obtain the measurement results;
(2) convert the loading stress and measurement results under the original coordinate system to the geodetic coordinate system; (3) calculate the principal stress magnitude and angle in the geodetic coordinate system; (4) calculate the measurement accuracy of simulation test technology.

Figure 1 shows a geostress simulation test device [23] for overcoring method in the chamber, which mainly includes test rig, test model, three-dimensional prestressing loading device, drill and auxiliary equipment used in lifting test, stress testing components and test instruments, etc. The test coordinate system is set as shown in Figure 2: O-XYZ is the geodetic coordinate system, positive X axis is due north, positive Y axis is due east, and positive Z axis is vertically downward. The positive z axis of the original coordinate system o-xyz points from the hole bottom to the hole top, and the positive x axis is horizontal to the right facing the hole top, with the right-hand coordinate system.

For the convenience of expression, the principal stress values 3D test methods of the true value of geostress are specified as $\sigma_1$, $\sigma_2$ and $\sigma_3$, respectively. The dip angle and azimuth angle are $\alpha_1$, $\alpha_2$, $\alpha_3$ and $\beta_1$, $\beta_2$ and $\beta_3$, respectively. The dip angle ranges from $\pm 90^\circ$ and the down dip is positive. The measured value, that is, the calculated value of the principal stress of the simulation result, is distinguished by the '0' superscript.

In order to avoid small error and large variation of azimuth of near vertical principal stress, the test coordinate system can be converted to make it have a large included angle with the geodetic coordinate system axis. It is suggested that the z-axis of the adjusted original coordinate system o-xyz should point from the bottom of the hole to the top with an inclination of $45^\circ$ and an azimuth of $315^\circ$. x-axis forward is horizontal (inclination is $0^\circ$), azimuth angle N$45^\circ$E; y-axis is perpendicular to xz plane and is inclined upward. The dip angle and azimuth angle are -$45^\circ$ and $315^\circ$, respectively.

Figure 1. Schematic diagram of 3D physical model test device of overcoring method

Figure 2. Coordinate system diagram of measurement accuracy characterization

Under the above settings, the stress value error of single test is given by equation (1), the angle error of two-dimensional and three-dimensional stress is given by equation (2) and equation (3), equation (4) is the single characterization index formula of average mode, and equations (5) and (6) are the single
characterization index formula of maximum mode of two-dimensional test and three-dimensional test respectively.

\[
\delta_k = \frac{\sigma_k - \sigma^0_k}{\sigma^0_k}, \quad \bar{\delta} = \left( \frac{1}{k} \sum_{k=1}^{4} (\delta_k)^2 \right)^{1/2}, \quad \delta_{max} = \max\{\delta_1, \delta_2, \Delta, \delta_k\}; \quad k = 20r3
\]  

\[
\zeta_k = \frac{\alpha_k - \alpha^0_k}{180^\circ}, \quad \bar{\zeta} = \frac{1}{2} \left( \zeta_1^2 + \zeta_2^2 \right)^{1/2}, \quad \zeta_{max} = \max\{\zeta_1, \zeta_2\}; \quad \zeta = 2
\]  

\[
\xi_k = \left| \frac{\alpha_k - \alpha^0_k}{90^\circ} \right|, \quad \xi_1 = \left| \frac{\beta_k - \beta^0_k}{90^\circ} \right|, \quad \bar{\xi} = \frac{1}{6} \sum_{k=1}^{4} (\xi_k^2 + 3 \xi_2^2)^{1/2}, \quad \xi_{max} = \max\{\xi_1, \xi_2, \xi_3, \xi_4\}; \quad \xi = 3
\]  

where \( k \) is the dimension, with a value of 2 or 3, corresponding to the two-dimensional and three-dimensional measurement methods, respectively. \( \delta_k \) is the relative error of a single principal stress magnitude, \( \bar{\delta} \) is the average magnitude error, and \( \delta_{max} \) is the maximum magnitude error. \( \zeta_k \) and \( \zeta \) are the relative errors of angle difference between the measured value and the true value of the principal stress angle relative to its half of value field, and \( \zeta_{max} \) is the maximum angle error. The value range of the azimuth of the principal stress is \( 0 \sim 360^\circ \) in the plane, but force are interactive. It can be considered that the variation range of the force is \( 180^\circ \), so it is reasonable to take \( 180^\circ \) as the denominator of the calculation formula of plane stress and azimuth error in equations (2) and (3). After the azimuth of a single principal stress is determined, the variation range of inclination angle is \( \pm 90^\circ \). Refer to the relationship between the value range of azimuth angle and its denominator of error calculation, the denominator of error calculation of \( \zeta_k \) is set to \( 90^\circ \). Through the above processing, the measurement errors of all principal stress components of values and angular can be characterized.

The author refers to \( \bar{\delta}, \bar{\zeta} \) and \( \bar{\xi} \) as the single index of average mode of measurement accuracy. The average mode index has an average effect on the quantity value and angle error, while the same accuracy index requires a loose requirement on the accuracy of the implementation technology. Taking \( A_{max}, A_{max} \) and \( \epsilon_{max} \) as the representation index is called the maximum mode, and \( \epsilon_{max} \) is the single index of this method, which is calculated by Equation (5) for 2D test and Equation (6) for 3D test. The index of maximum mode is strict to the realization technology. Under the condition of the same final accuracy index, the development and realization technology has higher accuracy requirements for all processes. The single error of measurement accuracy characterization results comes from one or several measurement steps, which is of great significance for the evaluation of technical improvement effect. A single simulation test can give the overall error estimation of a single index of applied technology, and multiple experiments can analyze the accuracy and correctness of measurement technology. It is suggested that the single index of maximum value mode should be used as the result of technical evaluation and verification.

4. Examples applications of quantitative characterization

In the 1990s, Cai Meifeng et al. [14] carried out several groups of physical model simulation tests on technologies which measuring elements of USBM-type gauge, CSIR three-axis hole wall strain gauge and CSIRO HI cells. They made a 2D loading stress relief test device to demonstrate and verified the application of the size effect, material characteristics and confining pressure test results of test block. This simulation is the largest simulation test of geostress measurement technology of overcoring method in the field, and the measurement accuracy represented by comparative coefficient of the principal stress...
absolute values of the difference between the original comparison coefficient and 1 as a comparison item, stress or the angle component, so it cannot reflect the measurement accuracy completely. Taking the measured plane divided by the loading value. This evaluation method does not evaluate the shear comparative coefficient n of the stress value, which is equal to the measured value of the axial stress in the test. (3) Through the coordinate conversion processing, the true value of each principal stress component of the test technology is obtained. (4) The original measurement accuracy evaluation index of the test is the azimuth is located at the quadrant center of the geodetic coordinate system, which makes it possible to verify all angular errors. (4) The original measurement accuracy evaluation index of the test is the included angle between the first measuring arm and the x axis, and the error is the difference between the angle and the measurement result. (2) 2D loading was adopted in the simulation test, and σ₁ direction in z-axis was not loaded, thus error calculation and accuracy characterization were not carried out. (3) Through the coordinate conversion processing, the true value of each principal stress azimuth is located at the quadrant center of the geodetic coordinate system, which makes it possible to verify all angular errors. (4) The original measurement accuracy evaluation index of the test is the included angle between the first measuring arm and the x axis, and the error is the difference between the angle and the measurement result. (2) The same below.

The measurement accuracy of the elastic material test results of the USBM-type gauge and the CSIRO HI cells in this test was characterized, and the accuracy data of the test technology was obtained. The basic information and characterization results of the test are listed in Table 1 to Table 3. Figure 3 shows the comparison of the comparative coefficient index and the measurement accuracy index defined in this paper.

Note: (1) α is the included angle between the first measuring arm and the x axis, and the error is the difference between the angle and the measurement result. (2) The unit of stress is MPa and the unit of angle is °.

| Test No. | Applied stress | Angle | Measurement result | Comparison coefficient | Relative error | Quantitative characterization index |
|---------|----------------|-------|--------------------|------------------------|---------------|-------------------------------------|
| 3#      | 2.6           | 2.2   | 90                 | 103                    | 4             | 11                                  |
| 5#      | 3.2           | 2.5   | 75                 | 66                     | 0             | 14                                  |
| 10#     | 2.3           | 1.8   | 165                | 160                    | 1             | 6                                   |
| 11#     | 3.1           | 2.4   | 90                 | 105                    | 8             | 8                                   |

- The unit of stress is MPa and the unit of angle is °.
- The same below.

| Test No. | Initial measurement results | Comparison coefficient | Results in geodetic coordinate system after coordinate transformation |
|----------|-----------------------------|-------------------------|---------------------------------------------------------------|
| 6#       | 2.8 3.2 2.9 -0.1 0.4 0.1 0.3 2.9 | 34 39 259              | 2.6 -9 176 -0.1 49 96                                      |
| 7#       | 2.6 3.1 3.2 -0.2 0.1 0.1 0.1 3.2 | 32 32 -43              | 2.5 -24 31 -0.2 48 91                                      |
| 8#       | 2.9 3.2 3.1 0.1 0.2 0.1 0.2 3.1 | 32 32 -0.64            | 2.6 -12 16 0.0 48 93                                      |
| 9#       | 2.9 3.2 3.2 -0.1 0.2 0.1 0.0 3.2 | 33 38 -54              | 2.5 -20 20 -0.1 46 89                                      |
### Table 3. Measurement accuracy characterization results of CSIRO HI cells

| Test No. | Applied stress in geodetic coordinate system | Comparison coefficient/% | Quantitative characterization index/% |
|----------|---------------------------------------------|--------------------------|--------------------------------------|
|          | $\sigma_1$, $\alpha_1$, $\beta_1$, $\sigma_2$, $\alpha_2$, $\beta_2$, $\delta_1$, $\xi_1$, $\zeta_1$, $\delta_2$, $\xi_2$, $\zeta_2$, $\delta_3$, $\xi_3$, $\zeta_3$, $\delta_{\text{max}}$, $\Delta_{\text{max}}$, $\varepsilon$, $\epsilon_{\text{max}}$ |
| 6#       | 3.2 45 -45 2.8 0 45 45 135 5 6 31 7 10 27 5 22 6 7 22 31 16 31 |
| 7#       | 3.1 45 -45 2.6 0 45 45 135 4 14 1 3 27 8 3 24 4 4 18 27 13 27 |
| 8#       | 3.2 45 -45 2.9 0 45 45 135 1 6 10 11 13 16 3 23 8 11 15 23 12 23 |
| 9#       | 3.2 45 -45 2.9 0 45 45 135 2 8 5 15 22 14 1 26 11 15 17 26 14 26 |

#### Figure 3. Comparison of measurement accuracy characterization index

It can be seen from table 1 that the measurement error of average mode measured by USBM-type gauge is 4% ~ 10%, the measurement error of maximum mode is 6% ~ 14%, and the angle error is 3% ~ 8%; The overall error is characterized by comparison coefficient, the measurement error is 0 ~ 14%, the measurement error of single index of average method is 4% ~ 8%, and the measurement error of single index of maximum method is 6% ~ 14%; The angle error close to the magnitude error, and the magnitude error is generally greater than the angle error.

It can be seen from table 2 and table 3 that the magnitude error of CSIRO HI cells in measuring average mode is 4% ~ 11%, the magnitude error of maximum mode is 4% ~ 15%, the angular error of average mode is 15% ~ 22%, and the angular error of maximum mode is 23% ~ 31%, which is obviously greater than the magnitude error. The overall measurement error characterized by comparison coefficient is 1% ~ 11%, the measurement error of single index of average method is 12% ~ 16%, and the measurement error of maximum method is 23% ~ 31%; The angle error is obviously larger than the magnitude error.

Figure 3 and comprehensive analysis show that: (1) The measurement accuracy of all elements measurement contains measurement errors of magnitude and angle, and its quantitative index reflects the measurement accuracy under all error factors in the measurement of rock mass and the whole measurement process. This index is more representative than comparative coefficient method. (2) The single index of average mode has the effect of average measurement error, and the single index of maximum mode has the largest measurement error. The same technical index of preset indicators will put forward higher requirements for the accuracy of the test technology. (3) The mean of the overall measurement errors of the test technique scheme used in USBM-type gauge is 10% ($\epsilon_{\text{max}}$ index). (4) The average measurement error of CSIRO HI cells technology is 27% ($\epsilon_{\text{max}}$ index), and the angle error is obviously greater than the magnitude error. The angle error is caused by the position error of strain gauge in the process of strain gauge making and the angle error of strain gauge installation, etc. Therefore, improving the technical accuracy of relevant steps can improve the overall measurement accuracy. The mismatch between the CSIRO HI cells and the 2D test loading may result in significantly
larger angle error of the 3rd principal stress. (5) Comparison of single index data shows that the measurement accuracy of USBM-type gauge used in the test is higher than that of CSIRO HI cells.

Note: (1) The technologies used in the above tests are still used in engineering, and new improvement based on digital technology has emerged. The accuracy evaluation can be carried out by referring to the above procedures. (2) The above simulation test condition is the maximum 2D loading of 3.2MPa, which does not conform to the real geostress state of the current mainstream engineering rock mass. Therefore, more advanced and accurate test conditions are needed to evaluate the accuracy of geostress measurement.

5. Conclusion
The geostress measurement technology and the evaluation system of geostress measurement results are not perfect, a unified and all elements measurement accuracy quantitative characterization system is thus urgently needed.

The accuracy of geostress measurement refers to the quantity that takes the initial stress state as the input, obtains the measurement result from the measurement process, compares the measurement result with the initial stress state, and uses the appropriate index to represent the approximate degree of the two.

Using physical model simulation test to characterize the measurement accuracy of measurement technology and equipment is a necessary way to verify the measurement principle, measurement accuracy and technical improvement effect. A layered characterization system can be established on the basis of the established characterization method of measurement accuracy.

The quantitative characterization of measurement accuracy can provide quantitative data of the accuracy of geostress measurement technology, which is helpful to conduct the research of technological improvements on specific rock mass, instruct the error evaluation of in-situ measurement results, evaluate the effect of measurement technology innovation, and promote the survival of the fittest of measurement technology.

The accuracy index of all elements geostress measurement is composed of magnitude error and angle error, and average mode has the characteristic of averaging all component errors. The maximum mode is a representation of the strict requirements of the implementation technology, in which single index is the most stringent characterization.

The average measurement errors of index $\epsilon_{\text{max}}$ of USBM-type gauge and CSIRO HI cells used in application examples are 10% and 27%, respectively. The all factor measurement accuracy results of the two test methods are calculated and compared for the first time, and the data show that the overall measurement accuracy of the former is much better than the latter.

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