A stable strain gauge measurement method for monitoring in-situ stress

Jiang Jingjie\(^1\), Sun Yao\(^1\), Peng Hua\(^1\), Ma Xiumin\(^1\)

\(^1\) Institute of Geomechanics, China Academy of Geological Science, MinzudaxueNanlu, No.11, Beijing 100081, China
\(^2\) Key Laboratory of Neotectonic Movement and Geohazard, Institute of Geomechanics, MinzudaxueNanlu, No.11, Beijing 100081, China
\(^3\) Observation and Research Station of Crustal Stress and Strain in Beijing, Ministry of Natural Resources, MinzudaxueNanlu, No.11, Beijing 100081, China

Corresponding email: jiangjingjie@mail.cgs.gov.cn

Abstract. In-situ stress exists in all rock mass or structures, which is reflected in the deformation and failure of various underground or ground excavation in geotechnical engineering. In-situ widely used in the engineering practice, in-situ stress monitoring plays an important role in many aspects, such as mine development, slope support, and geological disaster prevention and control, etc. Strain gauge has been used to record rock deformation using Differential strain analysis (DSA), Hollow Inclusion Technique (CSIRO Cells), and other in-situ stress measurement techniques. Limited by the volume, cost, power, and connection scheme of the measuring instruments, the test data are always influenced by various immeasurable factors, such as bend of the measuring cable and change in the ambient temperature. Majority of the gauge measurement technologies are not suitable for in-situ stress monitoring because of the stability of strain gauge measurement is poor, limits the application range of the gauge measurement. A stable strain gauge measurement method can be used for medium to high-precision in-situ stress monitoring to serve various engineering developments. We made a new measurement scheme by using high-precision constant current with independent signal transmission channels to achieve a high stability and high-resolution strain gauge measurement circuit with low power consumption and space cost. The temperature drift is as low as 0.3 με/°C in 0°C–60°C temperature range at 8000 με strain input, which can achieve the measurement effect of the traditional desktop strain gauge in about 1/10th volume and very low cost. The error caused by the change of cable resistance is reduced to 1 ppm, and the error caused by the disconnection and reconnection is less than 1 με, which avoids the failures caused by various environmental factors in the monitoring process, and the installation distance of monitoring strain gauge can reach tens of meters. This creates conducive conditions for using traditional in-situ stress measurement technology with in-situ stress monitoring and establishes an efficient and low-cost in-situ stress monitoring system.

1. Introduction

The resistive strain gauge, which can survey the deformation distribution of the object surface to measure the internal stress, is widely used in non-destructive detection technology and civil engineering. It can measure strain, stress, torque, acceleration, displacement, and other physical quantities combined with different elastic structures. At least nine independent strain components need
to be measured simultaneously to obtain 3-D stress tensor in rock mechanics field investigation. Each channel must be consistent in measurements as any errors might adversely affect the results, thus it is important to design a stable strain gauge measurement system to meet the requirement of field investigation.

In-situ stress measurement methods, such as DSA (Penghua et al., 2011), ASR (Wanglianjie et al., 2016), and borehole stress-relief method (Jingfeng, 2011), are used to measure 12 channel strain gauges simultaneously. The tests usually take almost an hour to a few days, and the interference can be ignored. But large measurement interference can be introduced due to environmental changes when the test needs a long time, the data cannot be analyzed in case of insufficient stability in the monitoring work.

We have analyzed the source and transmission process of interference in the resistance strain gauge measurement system in this paper and used a novel circuit structure to suppress the interference caused by environmental changes in the measurement process and create a stable strain gauge measurement method suitable for in-situ stress measurement and other field investigation and monitoring.

2. Interference in the process of resistance strain gauge testing
The signal processing of resistance strain gauge measurement system is shown in Figure 1. The mechanical deformation of the test object is transferred to the resistance strain gauge by binding with glue and transformed into the resistance change by the resistance strain gauge, then converted into voltage signal by the analog signal processing circuit, and lastly into a data stream by the analog-to-digital converter (ADC) for deformation analysis. The strain measurement system contains errors introduced by each signal processing segment.

![Figure 1. Flow diagram of the resistance strain gauge measurement](image)

The formation mechanism of interference is different in each signal processing segment, thus corresponding technologies are needed to eliminate the interference. The ineluctable change of resistance on the wires in the analog signal processing circuit cause certain measurement error, and the error value is positively correlated with the length of wires and the change in temperature. The arrangement of instruments and the effective measurement time are limited by the analog signal processing circuit’s performance. Appropriate measurement structure can greatly improve the stability of the measurement system, reduce the restrictions on the installation environment, and prolong the effective measurement time, making it more suitable for field investigation and monitoring.

3. Method of restraining interference of the analog signal processing circuit
Strain gauge measures the strain by measuring the change in the resistance value, the analog signal processing circuit changes the resistance to voltage, and the interference caused by the connection wires can be calculated by the following formula:
\[ E_{\text{strain}} = \left( \frac{l_{\text{wire}} \times \Delta r_{\text{wire}}}{K \times l_{\text{sensor}} \times R_{\text{typical}}} + \sigma_{\text{in}} \right) \times \frac{l_{\text{sensor}}}{l_{\text{standard}}} \]  

where

- \( E_{\text{strain}} \) ....... Interference on output data, \( \epsilon \);
- \( l_{\text{wire}} \) ........ Value of current through the wire which be connected in series to the strain gauge, A;
- \( \Delta r_{\text{wire}} \) ......... Change in the resistance of the wire connected in series with the strain gauge during the test, \( \Omega \);
- \( K \) .............. Sensitivity coefficient of the resistance strain gauge;
- \( l_{\text{standard}} \) ............. Theoretical value of current through the strain gauge, A;
- \( R_{\text{typical}} \) ............ Typical resistance of the strain gauge, \( \Omega \);
- \( l_{\text{sensor}} \) ............. Actual value of current through the strain gauge, A;
- \( \sigma_{\text{in}} \) ............. Actual value of strain in the test, \( \epsilon \);

Resistance change of the line includes the change on cable, connecting terminals, etc. in which the change on cable is primary. The formula for calculating the resistance of the copper conductor is as follows:

\[ r_t = R_{20} \times \frac{L}{1000} \times (1 + 0.00393 \times (t - 20)) \]
\[ \Delta r_{\Delta t} = R_{20} \times \frac{L}{1000} \times 0.00393 \times \Delta t \]  

where

- \( r_t \) ......... Copper conductor resistance at \( t \) °C, \( \Omega \);
- \( R_{20} \) ......... Conductor resistance per kilometer at 20°C, \( \Omega/km \);
- \( L \) ............. Connecting wire length, m;
- \( \Delta r_{\Delta t} \) ......... Change in the resistance of the copper conductor with the temperature change \( \Delta t \) °C, \( \Omega \);
- \( \Delta t \) ............. Temperature change during the test, °C;

We can get strain interference as per the following formula:

\[ E_{\text{strain}} = \sigma_{\text{in}} \times \frac{l_{\text{sensor}}}{l_{\text{standard}}} + \frac{0.00393 \times R_{20}}{1000 \times K \times R_{\text{typical}}} \times \frac{l_{\text{wire}}}{l_{\text{sensor}}} \times L \times \Delta t \]  

We can get that:

1. The abnormal driving current through the strain gauge causes measurement gain interference. More errors are introduced when the measurement value changes greatly;
2. The coefficient of strain gauge affects the introduction interference;
3. The change of environmental temperature causes interference on measurement;
4. The longer the connecting wire, the greater the interference caused by the resistance thermal effect of the wires;
5. The typical parameters of the strain gauge, connect structure and cable affect the interference via the connecting wire.

By analyzing and comparing 2-wire 1/4 bridge , 3-wire 1/4 bridge, and 1/2 bridge connect structures, a new connection structure avoiding errors caused by wire resistance is introduced.

3.1. Interference in the strain measurement of 1/4 bridge

The wire connection circuit and equivalent circuit of the common 2-wire 1/4 bridge resistance strain gauge measurement scheme are shown in Figure 2. The connecting wires, the terminals and the channel switch are directly connected in series with the strain gauge, \( I_{\text{wire}} \approx I_{\text{sensor}} \) in formula 3. The wire resistance thermal effect interference is an important factor in the measurement.

The maximum \( R_{20} \) of frequently-used 0.20 mm² copper wire is 92.3 \( \Omega/km \) according to (JB/T 8734.4-2016). The thermal effect of copper cable is about \( 3.6 \times 10^{-4} \Omega/m°C \) and the strain interference introduced is about 1.5 \( \mu \Omega/m°C \) for the frequently used 120 ohm resistance strain gauge. The resistance change of the connecting wire connected in series with the resistance strain gauge can cause obvious interference to the measurement.
Figure 2. The wire connection circuit and equivalent circuit of 2-wire 1/4 bridge

The relationship among the allowable cable length, the temperature change in the test, and allowable error is shown in Figure 3. It was found that the length of the wire connected in series with the strain gauge must be limited when the change of ambient temperature is determined to improve the measurement stability. Only 1.7 m length cable is allowed to be connected when the environment temperature change is 10°C when the allowable error is 50 με, and much shorter when the allowable error is smaller. However, in the process of field investigation or monitoring, there must be a considerable distance between the measure instrument and the strain gauge, and the range of environmental temperature change is difficult to control when the environment is complex, or the monitoring time is long. It is necessary to improve the measurement scheme to suppress the measurement interference caused by the thermal effect of the wire resistance to achieve a highly stable strain gauge measurement system, making it suitable for field investigation and monitoring.

Figure 3. Relationship between the allowable cable length and the temperature change using 2-wire 1/4 bridge

3.2. Measuring method of long wire compensation resistance strain gauge
The 3-wire resistance strain gauge measurement scheme is an important technique to suppress the thermal effect of wire resistance. Their connection circuit and equivalent circuit are shown in Figure 4.
The same size and length of measuring wire are used for both the strain gauge and the bridge resistance (R1). The connecting terminals are in the same environment, and the thermal interference values on both lines are similar and compensate each other. A more stable measurement scheme of resistance strain gauge is obtained, and the thermal interference source on the connecting channel is proportional to $\Delta r_w = (r_{w1} - r_{w2})$. Relative to 2-wire 1/4 bridge measurement mode, the interference is reduced to $\Delta r_w/r_w$. When the typical reduction ratio is about 10%, the allowable cable length becomes 10 times longer.

![Figure 4. The wire connection circuit and equivalent circuit of 3-wire 1/4 bridge](image)

The 1/2 bridge measurement mode or remote compensating strain gauge connection has the same equivalent circuit with a similar effect. About 17 m connecting cable is allowed if the allowable error is 50 με when the temperature change is 10°C, which can meet the needs of some field investigations. However, the line length is still limited when the precision requirement is higher i.e., within 3 m to ensure that the allowable error is less than 10 με and 0.3 m for 1 με. It is necessary to customize the cable with higher impedance consistency or use the strain gauge measurement scheme with better interference suppression performance for monitoring.

### 3.3. Other methods to improve the stability of resistance strain gauge measurement

The stability of measurement can be improved by installing bridge measuring instrument near strain gauge to short the connect wires. However, most instruments are large and the application environment is demanding, making the instruments difficult to install near the gauges for field investigation.

The full bridge measuring circuit can greatly improve the stability of measurement but each channel needs three high-precision resistors and four wires to connect to the measuring instrument. The increasing complexity of sensor installation, measuring instrument connection, and the risk of test failure limit their use in practical work in the field investigation.

### 3.4. Design of high stability resistance strain gauge measurement method

There is a measurement method that avoids errors caused by wire resistance, called the Kelvin or 4-wire method, the equivalent circuit is shown in Figure 5. Voltmeter’s wires carry minuscule current, thus the ammeter indication, nearly the same as the current through the subject resistance ($R_g$), and the wires ($R_{w2}$ and $R_{w3}$) connecting the voltmeter across the subject resistance, will drop insignificant amounts of voltage, resulting in a voltmeter indication that is very

![Figure 5. Equivalent circuit of Kelvin (4-wire) Resistance Measurement](image)
nearly the same as if it were connected directly across the subject resistance. We can get more accurate resistance value through Ohm’s Law in which resistance is equal to voltage divided by current \((R = U/I)\). In other words, using appropriate constant current the accurate resistance can be obtained by detecting the voltage, which is a simple and more reliable method. In most strain gauge measurement circuits, the driving current for the sensor is at \(10^{-3}\)A, and the current on the voltage measurement wire is as low as \(10^{-9}\)A, thus the interference caused by thermal effect of connecting wires is reduced to less than one millionth of that of the 2-wire connection mode. Using 0.20 mm² copper wire (theoretical length of 30 m) with the ambient temperature change within 10°C, we can ensure that the thermal interference on the wire is less than 1 μV.

Kelvin circuit not only reduces the requirements of the connecting wire but also reduces the demand of other electronic components, such as connection terminal, channel switch, and so on. The monolithic CMOS analog multiplexers can be used to replace the MOSFET transistors to save more space. The optimized design principle is conducive to the design of miniaturization and high stability resistance strain gauge acquisition circuit, which is convenient for the field deployment of resistance strain gauge acquisition equipment.

Different from direct resistance measurement, the resistance variation range \((\Delta R_g)\) of strain gauge is about 4% of the typical resistance \((R_g)\), and the output voltage of the Kelvin circuit varies from 0.96 \(\times\) \(I_g\) \(\times\) \(R_g\) to 1.04 \(\times\) \(I_g\) \(\times\) \(R_g\). When full-scale input voltage range of the ADC is \(\pm V_{\text{ref}}\) or 0~\(V_{\text{ref}}\), the efficiency of the converter (ADC) is only 7.7% of the device performance, resulting in the decrease of the sensitivity coefficient of the ADC used in the measurement system.

Referring to the principle of Wheatstone bridge measurement, the Kelvin circuit is improved by adding reference strain gauge \((R_{\text{ref}})\) as shown in Figure 6, using two constant current sources with five wires to realize differential voltage inputs for the ADC. It improves the matching between analog circuit output and ADC input, the common mode interference voltage on \(R_{\text{w1}}\) is effectively suppressed by the high Common Mode Rejection Ratio(CMRR) of ADC. The 5-wire structure can achieve high measurement accuracy and highly effective resolution of the data acquisition system.

3.5. 5-wire dual constant current source strain gauge test circuit performance test

According to the design of 5-wire dual constant current source strain gauge, a set of test circuit is made to check the stability and resolution of the measurement circuit. The high-precision constant current sources are designed by using INA114, two DG407 are used as switches for 16 channels, and MSC1210 is used for analog-to-digital acquisition. The final PCB area is about 10 cm\(\times\)10 cm and can be smaller when using smaller terminals. BZ2209-5 standard strain simulator is connected to the test circuit using a DPDT mechanical switch to test the performance of the designed strain gauge measurement circuit, and the DPDT is used to simulate the disconnection and reconnection of the connecting wires. The test circuit is put into the programmable constant temperature and humidity test chamber to simulate the temperature change from 20°C to 50°C.

Some test results are shown in Figure 7. The test results show that the short-term output change of the test data is less than 1 μV, the change of adjacent channel is less than 1 μV, switch the DPDT to
disconnection and reconnection the wire output change is also less than 1 με, and the noise in 5 minutes is less than 4 με. It means that the matching between channels (8 Ω) and on-resistance flatness (9Ω) of DG407 multiplexers is effectively suppressed, the suppression efficiency of interference caused by the resistance of the wire conforms to the theoretical calculation (about 1 ppm). The temperature interference coefficient is less than 0.3 με/°C with the output at approximately 8000 με, the temperature stability of the measurement scheme is very good.

![Graphs showing temperature drift and noise](image)

(a). Difference between channels vs temperature. (b). The temperature drift of 20~50 °C

**Figure 7. Test results of the sample circuit**

**4. Discussion and Conclusions**

There are several ways to provide highly stable strain gauge test in which 5-wire dual constant current source strain gauge effective suppression of the interference of environmental changes on the test data, has several advantages, such as stable data output, lower space occupation, and less power consumption. It makes a stable strain gauge measurement method suitable for strain monitoring in complex environments for a long time. It can provide services for civil engineering, mining, water
conservancy construction, and other important industries, and is highly suitable for field investigation work.

5. References

[1] LI Yuan, QIAO Lan, SUN Xinshuo. ANALYSES OF SOME FACTORS AFFECTING PRECISION IN IN-SITU STRESS MEASUREMENT WITH METHOD OF CSIRO CELLS. Chinese Journal of Rock Mechanics and Engineering, 2006, 25(10):2140-2144.

[2] PengHua, Maxiumin, JiangJingJie. IN-SITU STRESS MEASUREMENT BY DIFFERENTIAL STRAIN ANALYSIS METHOD IN WFSD-1. Journal of Geomechanics, 2011, 17(3):249-261.

[3] WANG Lian-jie, CUI Jun-wen, SUN Dong-sheng, ZHAO Wei-hua, QIAN Hua-shan. Determination of Three-dimensional in Situ Stresses by Anelastic Strain Recovery in Tengchung Scientific Drilling Hole. Acta Geoscientica Sinica, 2016, 37(1):111-115.

[4] Cai Meifeng. STUDIES OF TEMPERATURE COMPENSATION TECHNIQUES IN ROCK STRESS MEASUREMENTS. Chinese Journal of Rock Mechanics and Engineering, 1991, 10(3):227-235.

[5] CAI Yuanqi, ZHANG Yue, SHI Xiangyu, LI Yang, LI Jinguang. Method of in-situ temperature compensation for resistance strain gauge. Engineering Journal of Wuhan University, 2020, 53(7):591-596.

[6] HUANG Jiarong, WANG Xing. A method for strain measurement with the three-wire system. Protective Engineering, 2013, 35(4):37-40.

[7] Yan Haokui, Ren Jianguo. Working Principle of Electric Resistance Strain Gauge. Metrology & Measurement Technique, 2013, 40(4):12.

[8] Standardization Administration of the P.R.C., 2008. GB/T 3956-2008. Conductors of insulated cables. Standards Press of China (China: Bei Jing).

[9] Ministry of Industry and Information Technology of the P.R.C., 2016. JB/T 8734.4-2016 Polyvinyl chloride insulated cables and wires and cords of rated voltages up to and including 450/750 V-Part 4: Insulated wires for internal wiring of equipment. China Machine Press (China: Bei Jing).

Acknowledgments

This study was supported by Geological survey project of China Geological Survey (DD20190546) and (DD20190290).