International Geotechnics Symposium cum International Meeting of CSRME 14th Biennial National Congress

Rheological Stress Recovery (RSR) Method for Geostress Measurement in Deep Soft Rock

Quansheng LIU, Professor School of Civil Engineering Wuhan University 16 December 2016 Hong Kong, China

CONTENTS







PRINCIPLE OF RSR METHOD





→ 漢 × 学 WUHAN UNIVERSITY

• Surrounding rocks at depth are usually fractured and broken, due to repeated tectonic movements and excavation unloading effect, so that soft and weak enough to show strong rheological behavior.

• The classic methods for in-situ stress measurement such as both hydraulic fracturing and overcoring is difficult to be successful in deep soft and weak rock.



Background



Hydraulic fracturing method

- It assumes that gravity is one of principal stresses, which induces severe error in most cases especially in mountain area, and only 2D principal stresses can be measured in the plane vertical to borehole.
- Hydraulic fractures very often initiate in pre-existing natural joints, not necessarily in direction of minor principal stress.
- Yeakers used to seal the water usually are broken by sharp rock block and become leaky when high hydraulic pressure is applied.



Background

Overcoring method

- Difficult to overcore intact thick walled cylinder cores with sensor inclusion in the fractured rock masses under high stress.
- The test error is too large to estimate by substituting solid cylinder specimen for overcored thick walled cores, because Young's modulus of rock is more than one order of magnitude in different specimen sizes, shapes and stress states.



武漢大学

Background

High stress acting on soft rock at depth \rightarrow Strong rheological bevaviour \rightarrow The borehole shrinkage gradually to closure, in situ stress recovery to ultimately stable \rightarrow Measured stress will gradually increase over time if a pressure transducer is embedded into the borehole \uparrow



2 Principle of RSR Method States WUHAN UNIVERSITY

The Rheological Stress Recovery (RSR) Method is proposed The in situ stress at depth can be measured over time by embedding pressure transducers into rock mass, by taking the advantage of the strong rheological behavior of soft rock masses.



Embedding two 3 component transducers at one measure point



$$\begin{split} \sigma_{x}^{'} &= \sigma_{x}l_{1}^{2} + \sigma_{y}m_{1}^{2} + \sigma_{z}n_{1}^{2} + 2\tau_{xy}l_{1}m_{1} + 2\tau_{yz}m_{1}n_{1} + 2\tau_{zx}n_{1}l_{1} \\ \sigma_{y}^{'} &= \sigma_{x}l_{2}^{2} + \sigma_{y}m_{2}^{2} + \sigma_{z}n_{2}^{2} + 2\tau_{xy}l_{2}m_{2} + 2\tau_{yz}m_{2}n_{2} + 2\tau_{zx}n_{2}l_{2} \\ \sigma_{z}^{'} &= \sigma_{x}l_{3}^{2} + \sigma_{y}m_{3}^{2} + \sigma_{z}n_{3}^{2} + 2\tau_{xy}l_{3}m_{3} + 2\tau_{yz}m_{3}n_{3} + 2\tau_{zx}n_{3}l_{3} \\ \tau_{xy}^{'} &= \sigma_{x}l_{1}l_{2} + \sigma_{y}m_{1}m_{2} + \sigma_{z}n_{1}n_{2} + \tau_{xy}(l_{1}m_{2} + l_{2}m_{1}) + \tau_{yz}(m_{1}n_{2} + m_{2}n_{1}) + \tau_{zx}(n_{1}l_{2} + n_{2}l_{1}) \\ \tau_{yz}^{'} &= \sigma_{x}l_{2}l_{3} + \sigma_{y}m_{2}m_{3} + \sigma_{z}n_{2}n_{3} + \tau_{xy}(l_{2}m_{3} + l_{3}m_{2}) + \tau_{yz}(m_{2}n_{3} + m_{3}n_{2}) + \tau_{zx}(n_{2}l_{3} + n_{3}l_{2}) \\ \tau_{zx}^{'} &= \sigma_{x}l_{3}l_{1} + \sigma_{y}m_{3}m_{1} + \sigma_{z}n_{3}n_{1} + \tau_{xy}(l_{3}m_{1} + l_{1}m_{3}) + \tau_{yz}(m_{3}n_{1} + m_{1}n_{3}) + \tau_{zx}(n_{3}l_{1} + n_{1}l_{3}) \end{split}$$

2 Principle of RSR Method States wuthan university

Two key problems to be solved:

- The development of 3 component pressure transducer
- Whether the measured stress of pressure transducer
 equals to the original stress of surrounding rock before
 drilling ?





of dual-coil.

- (a) Pressure plate
 (b) Sealing washer
 (c) Column
 (d) Sensor diaphragm
 (e) Coil
 (f) Pillars
 (g) Vibration wire
- (h) Supporting body

Scomponent pressure transducer



- One sensor can measure 3 orthogonal stress components
- ✓ Range: 0~35MPa
- ✓ Waterproof: 8MPa
- ✓ Borehole diameter:120mm

Calibration test result shows good linearity and repeatability



2 Principle of RSR Method 😂 或 漢 * 導 wurlan UNIVE

6 *component pressure transducer*

- ✓ FBG sensing for one sensor to measure 6 independent stress components to obtain stress state at the measure point
- ✓ 6 channel parallel gratings access demodulator in single channel by a coupler so that installation and testing is simple and signal can be transmitted by long distance

Sensing plate

Output channel



- Diameter: 80mmRange: 0-35MPa
- ✓ linearity: good

2 Principle of RSR Method 😂 或 演 * 孝 wuhan UNIVERSITY

6 *component pressure transducer*



Stress state calculation

| $\int \sigma_x$ | -3.8850 | 0.94280 | 0.94280 | 4.4136 | -0.70710 | -0.70710 | (σ_{n1}) |
|------------------|---------|---------|---------|----------|----------|----------|-------------------------------|
| σ_{y} | 2.5527 | -2.2761 | -2.2761 | -2.4147 | 2.7070 | 2.7070 | σ_{n2} |
| $\int \sigma_z$ | 1.3328 | 1.3333 | 1.3333 | -0.99946 | -0.99997 | -0.99997 | σ_{n3} |
| $\int \tau_{xy}$ | 0 | -2.7870 | 2.7870 | 0 | -2.9560 | 2.9560 | σ_{n4} |
| τ_{yz} | 0 | -1.9709 | 1.9709 | 0 | -1.4780 | 1.4780 | σ_{n5} |
| τ_{zx} | 2.2761 | -1.1380 | -1.1380 | -1.7071 | 0.85353 | 0.85353 | $\left[\sigma_{_{n6}}\right]$ |

2 Principle of RSR Method States wurden university

Pushing and positioning apparatus

Pushing apparatus :

Rapid assembling pushrod + Three-direction equiangular pulley

Positioning apparatus :

- Using the scale on the pushrod to determine the depth of sensor
- Using the electronic goniometer to determine the azimuthal angle of sensor



Influence of Different Factors on Stress Recovery
 Considering two typical models of rocks





Three-parameter solid model

2 Principle of RSR Method 😂 🛪 🎼 * 🤻 wuhan UNIVERSITY

Influence of in-situ stress states on measured stress



Stress recovery is effected by stress states in borehole direction. Stress recovery is hardly effected by stress states in tunnel axis and vertical directions.

Three-parameter solid model



Stress recovery is not effected by stress states in any directions. Burger's fluid model

2 Principle of RSR Method States wurden university

Influence of Grout solidification time





Stress recovery is not related to grout solidification time, ultimately reaches 100%

Burger's fluid model

The shorter the solidification time, the higher the degree of stress recovery. The maximum can be restored to 55%

Three-parameter solid model

The shorter the grout solidification time is, the more favorable the stress recovery is.

Influence of modulus of surrounding rock





Stress recovery is not related to rock modulus, ultimately reaches 100%

With increment of ratio of instantaneous to long term modulus, the recovered stress increases. Stress recovery > 40 % when modulus ratio≥1.2

Burger's fluid model

Three-parameter solid model

The stress recovery of the extremely weak rock is up to 100%, and the stress recovery of the hard rock varies greatly.

2 Principle of RSR Method ^会 或 演 * 導 wuHan UNIVERSITY

0.7

Influence of modulus ratio of grout stone to the sensor



 $\begin{array}{c} 0.6 \\ 0.5 \\ 0.4 \\ 0.3 \\ 0.2 \\ 0.1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 100 \\ 200 \\ G_T/G_c \\ \end{array}$

٠X

The recovered stress increases with increment of modulus ratio. When modulus ratio exceeds 50, recovery level=100% With increment of modulus ratio, the recovered stress firstly increases then decreases. When modulus ratio =50, maximum stress recovery level=70%

Burger's fluid model Three-parameters solid model The best modulus ratio of grout stone to the sensor is 50.

Influence of modulus ratio of grout stone to surrounding rock





With the increment of modulus ratio, the recovered stress increases at first then decreases. (Maximum recovery level=50%)

Burger's fluid model

Three-parameter solid model

The best modulus ratio of grout stone to surrounding rock is 2-3.





→ 漢大学 wUHAN UNIVERSITY

Influence of sensor inclusion effect on measured stress



✓ Numerical Simulation of Inclusion Effect





 C^{D} is related to stress ratio; C^{e} is related to modulus ratio.

2 Principle of RSR Method States wurden university

✓ Model Test of Inclusion Effect





The model test of 3D pressure transducer in large mortar specimens indicates the relation between measured and original stresses suggested by simulation is applicable.





Pingdingshan Coal Mine







Testing process



● 武漢大学

Testing result of rheological stress recovery method



Principal stress / MPa

| | Magnitude | Azimuthal angle | Dip angel |
|------------|-----------|-----------------|-----------|
| σ_1 | 30.56 | 109.6 | 15.11 |
| σ_2 | 21.42 | 45.83 | 74.84 |
| σ_3 | 19.94 | 19.29 | 1.17 |

Measured stress curves

Stress components / MPa

| σ_{x} | σ_{y} | σ_{z} | $	au_{xy}$ | $	au_{yz}$ | $	au_{zx}$ |
|--------------|--------------|--------------|------------|------------|------------|
| 27.78 | 23.56 | 22.15 | -5.32 | -1.54 | 2.21 |





D Testing result of overcoring method

| E=8GPa, μ=0.31 /MPa | | | | | | | E = | 100 | FPa, j | 1= 0.31 | /MPa | | |
|---------------------|----------------------|--------------|------------------|------------|------------|--------------|------------------|------|--------------|------------------|------------|------------|--|
| σ_{x} | σ_{y} | σ_{z} | $	au_{xy}$ | $	au_{yz}$ | $	au_{zx}$ | σ_{x} | σ | y | σ_{z} | $	au_{xy}$ | $	au_{yz}$ | $	au_{zx}$ | |
| 22.48 | 23.09 | 20.91 | 0.03 | -0.12 | 0.28 | 27.3 | 8 28 | .11 | 25.75 | 0.35 | -1.59 | 3.40 | |
| | | | | | | | | | | | | | |
| Magnitude | | le Azi | imuthal angle | Dip | angel | | Magn | itud | e Azi | imuthal angle | Dip | angel | |
| σ_1 | σ ₁ 25.40 | | 20.96 | 27 | .65 | σ_1 | σ_1 30.32 | | , | 26.52 | 39.35 | | |
| σ_2 | 22.16 | - | 19.71 | 56 | 56.89 | | 28. | 24 | 2 | 295.68 | | 1.03 | |
| σ_3 | 18.92 | - | 18.45 | 43 | 43.71 | | 22. | 67 | 3 | 35.57 | 50 | .63 | |





Applications

Descriptions

Pingmei coal mine, No.1

Pingmei coal mine, No.5

Pingmei coal mine, No.11

Panyidong coal mine

Guqiao coal mine

LXB diversion project

880m depth, mudstone, fair intact

760m depth, sandy mudstone, blocky

780m depth, mudstone, blocky

820m depth, sandy mudstone, fair intact

900m depth, sandy mudstone, crushed

300m depth, granite porphyry, fair intact



→ 漢大学 WUHAN UNIVERSI

- The hydraulic fracturing method assumes that gravity is one of principal stresses, It is not reasonable in most cases, especially in such mountain area as west of China. RSR method does not need this assumption, it is more reliable according to the test data.
- As the incomplete slag discharge and broken core, overcoring method is difficult to be successfully applied in deep soft rock. However, RSR method is easily performed due to the low requirement for drilling and grouting.
- ✓ Rheological stress recovery method is an effective rock stress measurement method for deep soft surrounding rock.



Thanks for your Attention !

Email: liuqs@whu.edu.cn