Tunnel in situ stress measurement by hydraulic fracturing based on the iS3 platform

Chen Ziyang 1*, Zhu Hehua1, Li Xiaojun 1, Liu Ruming2, Du Jinyi2

1 Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, Shanghai, China;
2 Yunnan Transportation Planning and Design Research Institute, Kunming, China
* zychen0404@tongji.edu.cn

Abstract: In situ stress is an important fundamental design and construction parameter in tunnel engineering as the external load of tunnels, especially in case of deep tunnels in which potential geological hazards caused by high in situ stress can be often observed. This paper describes the integration of the acquisition technique and analysis method of tunnel in situ stress measurement via hydraulic fracturing into the infrastructure smart service system (iS3) platform. The hydraulic fracturing method, which is recognized as the most reliable and effective means to measure in situ stress deep in the crust, is applied in iS3 to acquire the stress information of the rock. The transient pressure analysis (PTA) method is integrated as the analysis module of iS3 because of its advantage of accurately capturing the hydraulic fracture closure event and determining the shut-in pressure (equal to the minimum horizontal principal stress) through flow regime analysis of the fracturing fluid. The hydraulic fracturing measurement based on iS3 has been applied to a deep rock highway tunnel in south-western China (maximum depth: 1259 m). The iS3 integrated system provides a valuable reference for tunnel in situ stress measurement.

Keywords: rock tunnel, in situ stress, hydraulic fracturing, transient pressure analysis, iS3

1. Introduction

With the quick development of society, economy, and infrastructure around the world, deep tunnels are extensively constructed in transportation, energy, and many other fields because of their advantages of safety, convenience, environmental protection, and less sensitivity to the natural environment and human activities [1]. However, with the depths varying from hundreds of meters to several kilometers, deep rock tunnels encounter many complex and diverse geological environments when compared with shallow stratum conditions [2]. In situ stress, as the external load of tunnels, is an important fundamental design and construction parameter in tunnel engineering, especially deep tunnels in which potential geological hazards caused by high in situ stress can be often observed. High geostress is one of the most important features associated with deep crust [3-4], which directly influences the construction, operation, and maintenance of deep tunnels.

Geostress increases with the tunnel depth. An environment with high geostress (maximum principal stress $\sigma_{\text{max}} > 20$ MPa or strength–stress ratio of rock mass $S_0 = R_c / \sigma_{\text{max}} < 7$) significantly affects the pressure, deformation, and stability of the surrounding rock mass of the deep rock tunnels, primarily causing disasters, including rock bursts and large deformation. Two examples have been observed in China. First, in the diversion tunnel of the Jinping II Hydropower Station, the maximum depth becomes 2525 m and 75% of the tunnel exceeds 1500 m in depth. The measured maximum principal
stress $\sigma_{\text{max}}$ is 46 MPa, and the strength–stress ratio of the rock mass $S_0$ is approximately 2.13. More than 700 rock bursts occurred during construction. In particular, an extremely intense rock burst occurred on November 28, 2009, in which the support system was completely damaged within the 28-m section along the tunnel axis. The tunnel boring machine (TBM) was permanently buried in collapsed rock, causing tragic casualties. Another example is the Muzhailing tunnel of the Lanzhou-Chongqing Railway. The tunnel is 19.02 km long with a maximum depth of about 715 m. The measured maximum principal stress is 27.16 MPa, and the strength–stress ratio of rock mass is 2.13. The core section of the slate/carbonaceous slate stratum ridge that the tunnel passes through is 2000 m. During construction, large extrusion deformation was significant, and the lining structure was seriously damaged.

Currently, in situ measurement is the most direct and reliable way to obtain stress information of deep tunnels. Hydraulic fracturing is one of the recommended methods to determine rock stress by the ISRM [5] and ASTM [6] organizations, and is deemed to be the most reliable and effective testing method for in situ stress at deep depth. Hydraulic fracturing measurement does not need coring, rock constitutive equations or precise downhole instruments, and is theoretically unrestricted by the depth of measurement. Further, the PTA (transient pressure analysis) method adopted in this paper for data analysis has advantages of accurately capturing the hydraulic fracture closure event and determining the shut-in pressure (equal to the minimum horizontal principal stress) through flow regime analysis of fracturing fluid.

This paper describes the integration of the acquisition technique and analysis method of tunnel in situ stress measurement by hydraulic fracturing into the iS3 platform (infrastructure smart service system). The hydraulic fracturing method is applied in iS3 to acquire the stress information of the rock. The PTA method is integrated as the analysis module of iS3. Hydraulic fracturing measurement based on iS3 has been applied to a deep rock highway tunnel in south-western China (maximum depth 1259 m). Additionally, a comparison with traditional analysis methods is presented. The research results provide an effective reference for the construction of deep rock tunnels.

2. iS3 (infrastructure smart service system)

The concept of iS3 was first proposed from the perspective of information flow. iS3 is composed of data acquisition, processing, representation, analysis, and integrated decision services and covers the whole life cycle of different information flow nodes in planning, survey, design, construction, and maintenance [7-9], as shown in Fig. 1.

![Figure 1. Conceptual sketch of iS3](image)

iS3 can be seen as the integration of Building Information Modeling (BIM) and Geographic Information System (GIS), meanwhile providing an open interface for the integration of other software, such as modeling, simulation, and analysis, enabling the implementation of a variety of analytical and integrated decision services. iS3 abstracts data and analysis services from information flow level and devotes information application integration to the whole life cycle of infrastructure, which is suitable for information flow in most engineering applications as shown in Fig. 2.
3. In situ stress information acquisition: hydraulic fracturing

Hydraulic fracturing measurement is one of the recommended methods to determine rock stress by ISRM [5] and ASTM [6] and is deemed as the most reliable and effective testing method for in situ stress at deep depth.

Hydraulic fracturing measurements inject a small volume of high pressure fluid into the test stratigraphic horizon, producing an extensional fracture extending to the original formation away from the influence of stress concentration around the well [10]. When the pump is shut off and injection stopped, fluid enters the formation through the fracture surface, causing the pressure drawdown within the fracture (Fig. 3). When the fluid pressure in the fracture is equal to the minimum horizontal principal stress of the formation, the fracture closes up. Theoretically, the fracture closure pressure ($P_c$) is equal to the in situ minimum horizontal principal stress ($\sigma_h$), which is perpendicular to the fracture [11-12], as shown in Fig. 4 and Fig. 5.
Hydraulic fracturing measurement is conducted mainly in two steps. First, for the measurement of in situ stress magnitude, a pair of expandable rubber packers is sent to the test position in the borehole through the drill pipes of the drilling rig. Then, fracturing liquid is injected and released into the fracturing section for several cycles, and the pressure change is monitored with time. Second, for the stress direction measurement, an impression rubber packer and electronic compass is sent to the test position in the borehole through the drill pipe of the drilling rig.

4. In situ stress analysis: pressure transient analysis (PTA)

The analysis of measurement data to determine the fracture shut-in point and pressure is a key procedure in hydraulic fracturing measurement, directly affecting the measuring precision since the shut-in pressure equals the minimum horizontal principal stress \( \sigma_h \) [13-15].

This paper introduces the pressure transient analysis (PTA) method from the oil/gas field into hydraulic fracturing analysis for tunnel engineering. PTA originates from oil well testing, in which petroleum engineers analyze the seepage model of the oil well, accurately capturing the crack closure event by flow state transformation in the pressure derivative logarithmic diagram to accurately determine the minimum horizontal principal stress \( \sigma_h \). Hence it could be expected that the PTA method has considerable potential to improve the accuracy and efficiency of hydraulic fracturing measurement.

In order to simulate the hydraulic pressure drop process during the measurement, we build a theoretical model including the stratum, fracture, and well. We then consider a vertically fractured well producing a constant flow rate, \( q \), in an infinite, isotropic, homogeneous, horizontal stratum. Assume the well is intercepted by an undeformable and fully penetrating vertical fracture, as shown in Fig. 6. Two fluid equations are used to describe the hydraulic pressure drop: flow inside the fracture and flow from the fracture surface into the stratum. The governing equations was solved through Laplace transform and inverse transformation, with the results revealing four flow regimes [16], namely fracture linear, bilinear, formation linear and pseudo-radial flow (Fig. 7).
Figure 6. Conceptual model for a vertical well intersected by a vertical fracture

Figure 7. Fracture evolution state and corresponding flow regimes

From the hydraulic pressure derivative logarithmic diagram:

\[ \frac{\partial (\Delta p)}{\partial \ln(\Delta t_D)} \sim \ln(\Delta t_D) \]

Initially, in the pressure derivative logarithmic diagram, there is fracture linear flow characterized by a half-slope straight line; after a transition flow period, the system may or may not exhibit a bilinear flow period, indicated by a one-fourth-slope straight line. As time increases, the formation of a linear flow period might develop. Eventually, in all cases, the system reaches a pseudo-radial flow period. The solution [17] shows that, for fracture or formation linear flow, the pressure drop \( \Delta p \) is directly proportional to the square root of the dimensionless shut-in time \( \Delta t_D \); for bilinear flow, \( \Delta p \) is direct proportional to the forth root of the dimensionless shut-in time \( \Delta t_D \). Hence, in the pressure derivative logarithmic graph, a straight line with a slope of 0.5 represents fracture or formation linear flow, and a straight line with a slope of 0.25 represents bilinear flow. The ultimate regime is pseudo-radial flow, as the fracture has closed at this time, and corresponds to a horizontal line (slope of 0). Ultimately, in the pressure derivative logarithmic graph the fracture closes between lines of slope 0.5 or 0.25 and a line of slope 0. This important feature of pressure derivative logarithmic diagrams helps to determine the fracture close point precisely.

| Flow regime       | curve       | \( \frac{\partial (\Delta p)}{\partial \ln(\Delta t_D)} \sim \ln(\Delta t_D) \) |
|-------------------|-------------|---------------------------------------------------------------------------------|
| Fracture Linear Flow | \( \frac{1}{2} \) |                                                                                  |
| Bilinear Flow     | \( \frac{1}{4} \) |                                                                                  |
| Formation Linear Flow | 0.25        |                                                                                  |
| Pseudo-Radial Flow | 0           |                                                                                  |

Table 1. Forms of different flow regimes in the pressure derivative logarithmic diagram
PTA has the advantage in determining the shut-in pressure. In the pressure derivative logarithmic diagram, liquid flow regimes can be intuitively identified. As flow regime analysis correlates fracture states to flow regimes, the shut-in point and shut-in pressure can be identified more objectively and precisely.

5. Engineering application

We apply the iS3 tunnel in situ stress measurement by hydraulic fracturing to a highway tunnel in Yunnan Province, southwest China. With a maximum depth of approximately 1100 m and the tunnel length of 11.52 km, it is the longest highway tunnel in the Yunnan Province. During the investigation stage, hydraulic fracturing was performed based on the CZK8 vertical exploration hole (Fig. 9, 10). The borehole diameter is 75 mm, the test section between two packers is 0.7 m, and four sections were selected according to the quality and integrity of borehole core, namely 272.7–273.4, 262.7–263.4, 227.7–228.4, and 190.4–191.1 m. We use the 262.7–263.4 m section for analysis. Six fracturing cycles were conducted at the section, and for comparison three methods were used to analyze the test data simultaneously, including the proposed PTA method (Fig. 8) and traditional methods including the inflection point method and tangent method (Fig. 11).
Figure 9. Tunnel in situ stress measurement by hydraulic fracturing

Figure 10. Pressure (red) / flow rate (green) vs. time curve

Figure 11. Results of inflection point and tangent methods
Because there were six fracturing cycles in the testing section 262.7–263.4 m, there are six analysis values (the minimum horizontal principal stress) corresponding to each cycle of each method. The results are listed in Table 2.

Table 2. Hydraulic fracturing measurement results at 262.7 m–263.4 m of CZK8 borehole

| Cycle | PTA method | Inflection point method | Tangent method |
|-------|------------|-------------------------|----------------|
| 1     | 6.979      | 7.067                   | 11.292         |
| 2     | 6.682      | 7.240                   | 11.419         |
| 3     | 6.872      | 8.014                   | 12.145         |
| 4     | 6.942      | 7.910                   | 11.030         |
| 5     | 7.025      | 7.853                   | 11.160         |
| 6     | 6.827      | 7.235                   | 10.683         |
| Average | 6.888    | 7.553                   | 11.288         |
| Standard deviation | 0.113 | 0.379                   | 0.447          |

The regional in situ stress of the tunnel area from geological survey showed that the minimum horizontal principal in situ stress was 6.5–7.0 MPa, and of the results in Table 2 the PTA results are closest to the regional value. The standard deviation of PTA is the minimum among the three methods, showing that it had the highest consistency.

Hence, our preliminary conclusion is that PTA method has a much higher accuracy for hydraulic fracturing analysis, as in theory the fracture closes between linear and radial flow and is defined more accurately through flow regime transformation. Also, in practice, the closure point can be clearly obtained in the pressure derivative logarithmic graph by the intersection of two lines with different slopes.

6. Discussion

In tunnel engineering, pressure curve analysis usually uses the inflection point [18] and tangent methods [19] to determine the fracture shut-in pressure.

The inflection point method assumes that after pump shut-in, the pressure curve shows a significant inflection point during the descent, and the pressure value corresponding to the inflection point is the fracture closure pressure. In practice, however, the inflection point is affected by multiple factors, such as natural fractures and stratum heterogeneity around the well. The uncertainty of the inflection point selection is relatively large, which may easily lead to incorrect closure pressure interpretation, especially in fracture developed stratum. Moreover, the inflection point is not particularly obvious from the pressure curves in many hydraulic fracturing measurements. Selecting the inflection point from pressure-time curve alone can easily introduce subjective error, leading to erroneous or inaccurate test results.

The tangent method assumes that the instantaneous shut-in pressure (ISIP) corresponds to the inflection point on the curve. By drawing a straight line tangent to the pressure curve from the shut-in point, the deviation point of the line from the curve is the ISIP value. What is not clear is how one distinguishes ISIP from the $P_c$ of a fracture. Obviously, using ISIP as the closure pressure will result in an excessively high in situ stress measurement.

Compared to traditional analysis methods, PTA has the advantage of accurately capturing the hydraulic fracture shut-in event, because theoretically, the fracture closes between the linear flow and radial flow, and through flow regime transformation the fracture closure event can be defined more precisely, and; practically, through the pressure derivative logarithmic diagram, the shut-in point can be clearly obtained by the intersection of two lines with different slopes.

7. Conclusions

This paper describes the integration of the acquisition technique and analysis method of tunnel in situ stress measurement by hydraulic fracturing into the iS3 platform (infrastructure smart service system), with the following main conclusions:

(1) iS3 is composed of data acquisition, processing, representation, analysis, and integrated decision services and covers the whole life cycle of information flow nodes in planning, survey, design, construction, and maintenance. The integration of acquisition and analysis of tunnel in situ stress measurement into iS3 is preliminary and an important exploration of information capture and digitization of in situ stress research.
(2) The hydraulic fracturing method which is recognized as the most reliable and effective means to measure in situ stress deep in the crust is integrated into iS3 as the in situ stress information acquisition module.

(3) The PTA method is integrated into iS3 as the analysis module, due to its advantage compared to traditional methods of accurately capturing the hydraulic fracture shut-in event and determining the shut-in pressure (equal to the minimum horizontal principal stress) through flow regime analysis of fracturing fluid. In the pressure derivative logarithmic diagram, liquid flow regimes can be intuitively identified. As flow regime analysis correlates fracture states to flow regimes, the shut-in point and pressure can be identified more objectively and precisely.

(4) Hydraulic fracturing measurement based on iS3 has been applied to a deep rock highway tunnel in south-western China (maximum depth 1259 m), with the results validated by regional in situ stress data.

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