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Study on Acoustic Emission In-situ Stress Measurement Techniques Based on Plane Stress Condition

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Abstract

In-situ stress is the key parameter for underground and slope rock engineering design optimization. Hydraulic fracturing method and trepanning stress relieving method are the two main in-situ stress measurement methods for the present, but both of the two methods have some disadvantages such as strict operating conditions, complicated operations, high cost, etc. which have not been overcome till now. With a case of high-steep open pit slope, the paper begins with hydraulic fracturing method to measure the in-situ stress and then, on this basis, based on plane stress condition, the paper adopts acoustic emission method to measure the horizontal maximum principle stress and its direction. It indicates that the test results of acoustic emission are consistent with that of hydraulic fracturing method.

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Keywords: In-situ stress measurement; Acoustic emission; Plane stress; Hydraulic fracturing method; Trepanning stress relieving method

1. Summary

With the rapid development of the national economy, rock slope stability encountered in the construction projects such as mine exploration, transportation, construction of water conservancy has gradually emerged. Through large amount of slope works excises, of in-situ stress, the magnitude and

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direction of the principal stress, together with its relation to slope surface, have great influence on the stability of slope. And in several places, the horizontal in-situ stress is stronger than the vertical in-situ stress (CAI Mei-feng, He Man-chao＆LIU Dong-yan.2002).

In recent years, there are mainly two methods for in-situ stress measurement: hydraulic fracturing method and solid inclusion strain measurement technology (CAI Mei-feng, QIAO Lan＆LI Hua-bin. 1995). Solid inclusion strain measurement is often performed by measuring point by point. So in order to acquire the 3D stress condition in the rock mass to be excavated and its surroundings, it is necessary to bore three directional holes not parallel to each other and converging at the measuring point in deeper part (CAI Mei-feng. 1993.12(3):275-283.). However, due to the difficulty of directional construction and the special requirement of construction conditions, it is only applicable in underground mine. For surface mine, it obviously does not viable. The hydraulic fracturing method is to assume that the gravity stress is one of the principal stresses and coincide with one of the principal stresses, and he 3D in-situ stress condition is determined based on the results measured through borehole. The outstanding advantage is that it allows measuring of the ground pressure at deeper part. However in this method, it is simply considered that the initial fracturing of the rock mass is on the direction perpendicular to the minimum principal stress. If there is weakness plane such as beddings and joints, then the initial fissure may be along the weakness plane (CAI Mei-feng, He Man-chao＆LIU Dong-yan.2002) .So this method can only be used in relatively complete rock. Moreover, this method is very expensive, and complicated to operate, which, to some degree, limit its development. Therefore, it is urgent to find a cheap and applicable in-situ stress measurement to the open slope.

In the paper, a new acoustic emission measurement is proposed. This measurement is also to assume that the gravity stress is one of the principal stresses, and then solves the maximum principal stress and its direction on horizontal plane by acoustic emission method under plane stress condition. So this method has the characteristics of acoustic emission and hydraulic fracturing method, but more rational than hydraulic fracturing method in economical efficiency and applicability.

2. Theoretical Basis of Acoustic Emission Measurement under Plane Stress Condition

The measurement of in-situ stress is often based on the plane condition. The measuring borehole can be considered as a circular hole in an infinite sheet, and the direction of stress is parallel with the horizontal plane (WANG Lian-jie, PAN Li-lei.1991). According to the calculation formula of elastic mechanics, two pairs of horizontal principal stresses σ_1 and σ_2 are known, then normal stress and shear stress on any one of the sections is (as shown in Figure 1):

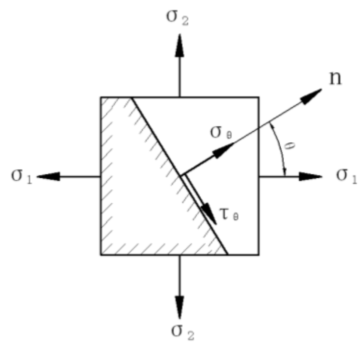

Figure 1

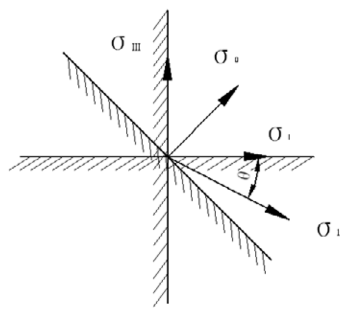

Figure 2

$$\begin{cases} \sigma_\theta = \frac{1}{2}(\sigma_1 + \sigma_2) + \frac{1}{2}(\sigma_1 - \sigma_2)\cos 2\theta \\ \tau_\theta = \frac{1}{2}(\sigma_1 - \sigma_2)\sin 2\theta \end{cases} \quad (1)$$

If there are known normal stresses on three different sections, the magnitude and direction of the maximum principal stress on horizontal plane can be obtained according to the above formula. For the convenience of sample preparation of acoustic emission, only the condition that the three known sections are distributed in 45° by sequence is discussed (as shown in Figure 2), so:

$$\begin{cases} \sigma_{\mathrm{I}} = \frac{1}{2}(\sigma_1 + \sigma_2) + \frac{1}{2}(\sigma_1 - \sigma_2)\cos 2\theta \\ \sigma_{\mathrm{II}} = \frac{1}{2}(\sigma_1 + \sigma_2) + \frac{1}{2}(\sigma_1 - \sigma_2)\cos(90 + 2\theta) \\ \sigma_{\mathrm{III}} = \frac{1}{2}(\sigma_1 + \sigma_2) + \frac{1}{2}(\sigma_1 - \sigma_2)\cos(180 + 2\theta) \end{cases} \quad (2)$$

Solve the equations:

$$\begin{cases} \sigma_1 = \frac{1}{2}(\sigma_{\mathrm{I}} + \sigma_{\mathrm{III}}) + \frac{1}{2\cos 2\theta}(\sigma_{\mathrm{I}} - \sigma_{\mathrm{III}}) \\ \sigma_2 = \frac{1}{2}(\sigma_{\mathrm{I}} + \sigma_{\mathrm{III}}) - \frac{1}{2\cos 2\theta}(\sigma_{\mathrm{I}} - \sigma_{\mathrm{III}}) \\ \tan 2\theta = \frac{2\sigma_{\mathrm{II}} - \sigma_{\mathrm{I}} - \sigma_{\mathrm{III}}}{\sigma_{\mathrm{I}} - \sigma_{\mathrm{III}}} \end{cases} \quad (3)$$

So if three normal stresses on different sections can be obtained through horizontal test, the magnitude and direction of the maximum principal stress on horizontal plane can be obtained according to the formula deduced above.

3. In-situ Stress Measurement by Acoustic Emission Method under Plane Stress Condition

3.1. Test Equipment and Test Method

To be brief and for easy comparison with the in-situ stress measured with hydraulic fracturing method, the paper only lists the test results in four sample depth of 260m, 200m, 140m, and 110m, and conducts data processing analysis. The measurement of rock acoustic emission Kaiser Effect is performed jointly by SAEU2S digital acoustic emission inspection system and electro-universal tester. In the test, the loading velocity is controlled in 2×10^{-5}~5×10^{-5}/s for strain or 0.3~0.5MPa/s for stress; when there is residual strength of sample, loading and recording shall be stopped (LI Zao-ding, SONG Na-xin＆QIN Si-qing. 1994.15(3).(248-252).- LI Hong, ZHANG Bo-chong. 2004.23(8):1349-1352). The acoustic emission detector records and provides the energy accumulation count-time curve, while the data collecting system records and provides stress-time curve. The two groups of data taking time as the uniform coordinate axis are used to generate energy accumulation count-stress-time relation curve. Analysis of this curve shows that the corresponding stress of abrupt transition point of the energy accumulation count-time curve is the Kaiser Stress point (CAI Mei-feng, QIAO Lian & YU Bo.1997.16(3):233-239.).

The drill core obtained in the directional borehole shall be drilled for sample in 4 directions; their positions are:

Sample 1 is a cylinder sample with diameter of 30×60mm drilled along the drill core axial direction. (See Figure 3);

Sample 2~4 are cylinder samples with diameter of 25mm along the radial of the drill core from three different directions which are perpendicular to the axial direction, with rock samples in four directions and in 45° (See Figure 4) for each sample listed in a group.

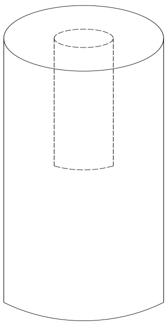

Figure 3 Axial sampling position (1 direction)

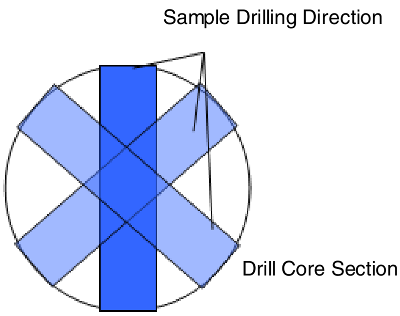

Figure 4 Radial sampling position (3 directions)

3.2. Test Result and Analysis of In-situ Stress Measurement by New Acoustic Emission Method

With the above test method, the Kaiser Point stresses measured at each measuring point are shown in Table 1. The magnitude and direction of the principal stress calculated at each measuring point through the above equation are shown in Table 2. With the data of Table 2, the curve of principal stress of K1 hole verifying with depth can be protracted as shown in Figure 5.

Table 1 Kaiser Point stress measured at each measuring point

Sounding (m)	Sampling position	No.	Kaiser point stress (MPa)	Sounding (m)	Sampling position	No.	Kaiser point stress (MPa)
K1 (110)	Transverse	K1-135-1	5.19	K1 (200)	Transverse	K1-228-1	7.01
		K1-135-2	5.07			K1-228-2	6.01
		K1-135-3	7.46			K1-226-3	7.20
	Axial	K1-130	8.18		Axial	K1-229	6.72
K1 (140)	Transverse	K1-147-1	6.30	K1 (260)	Transverse	K1-295-1	6.79

		K1-147-2	7.60			K1-295-2	13.02
		K1-147-3	3.20			K1-295-3	13.17
	Axial	K1-151	9.52		Axial	K1-296-1	12.03

Table 2 Principal stresses measured at each measuring point

Sounding (m)	Vertical principal stress (MPa)	Horizontal principal stress 1 (MPa)	Horizontal principal stress 2 (MPa)	Direction of horizontal principal stress 1 (°)	Direction of horizontal principal stress 2 (°)
K1 (110)	3.06	5.64	4.11	5.40	95.40
K1 (140)	4.11	8.23	3.89	8.03	98.03
K1 (200)	5.36	10.22	4.72	8.02	98.02
K1 (260)	6.93	12.72	5.98	8.18	98.18

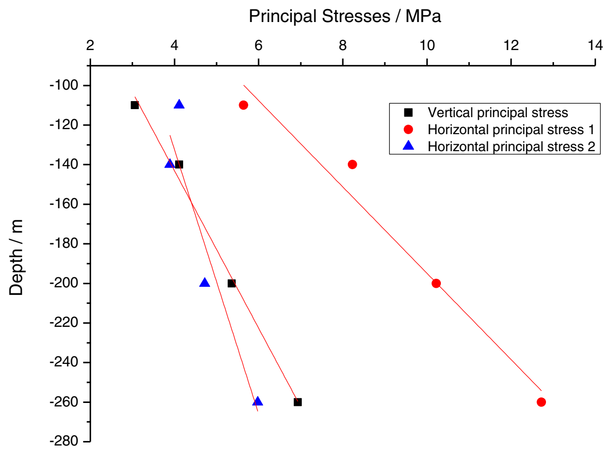

Figure 5 Curve of principal stress of K1 hole verifying with depth

(1) It can be known from Figure 5 that principal stresses in three directions are obtained in the in-situ stress measurement, including a vertical direction and two horizontal directions. With the increase of the measuring depth, the magnitude of stress at each direction increases.

(2) The test results indicates that both the maximum and the minimum horizontal principal stresses increase as the depth increases, basically in linear change, and the maximum horizontal principal stress increases faster than others as the measuring depth increases.

(3) The test results indicates that the maximum principal stress in on the horizontal direction. In the borehole of the whole measuring depth scope, the vertical principal stress shall be 3.06-6.93MPa, the maximum horizontal principal stress shall be 5.64-12.72MPa, and the minimum horizontal principal stress shall be 4.11-5.98MPa.

(4) It can be seen from the stress measured at each measuring point that the horizontal principal stress is 1.34-1.89 times of the vertical principal stress, which means that the measured area is affected by horizontal tectonic movement recently.

(5) The calculation result indicates that the direction of the maximum horizontal principal stress is close to EW direction, and the direction of the minimum horizontal stress is close to the SN direction. The inclination between the two directions is 90°.

4. In-situ Stress Measurement by Hydraulic Fracturing Method

4.1. Test Method

For ease of comparison, the paper lists only Hole K1 for analysis. Hole K1 is 270m deep and at 8m hydrostatic level. After core selection, 7 hole-sections of various depths were reserved as test sections. In actual measurement, since the equipment cannot reach the depth below 250m, only 5 sections were successfully measured. Depths of the 5 fractured sections were 83.36~83.96m, 116.07~116.67m, 155.38~155.98m, 181.53~182.13m and 232.54~233.14m respectively. The calculated results of fracture pressure P_b, reopening pressure P_r, closure pressure P_S, compressive strength of hydraulic fracturing T, pore water pressure P_0, maximum horizontal principal stress σ_1 and minimum horizontal principal stress σ_2 at the tested sections are shown in Table 3-2. The vertical stress is calculated by the measured overburden weight at each test point based on the formula $S_V = \gamma H$ (where γ is rock bulk weight and H is depth of measured section) and the rock bulk weight used is 2.7g/m^3.

The pressure-time recording curves of each section are shown in Figure 6, which indicates that the fracturing curves are rather complete and the fracture pressure is obvious. Calculated results in Table 3 show that the in-situ stress value at level 0~120m is small because stress is released due to pit excavation near the bore hole, and the stress value below 120m increases relatively, which reflects the in-situ rock stress state due to less excavation disturbance in deep rocks.

It is seen from Table 3 that in the measured range of Hole K1, the maximum and minimum horizontal principal stresses increase as the bore hole depth increases. The maximum horizontal principal stress goes up gradually from 2.16MPa to 14.79MPa and the minimum horizontal principal stress increases gradually from 1.66MPa to 9.25MPa. It can be seen from the principal stress values at deep hole that the horizontal principal stress is greater than the vertical one.

Table 3 In-situ Stress Measurement of Hole K1 by Hydraulic Fracturing Method

S.N.	Fracture Depth	Fracture Parameter (MPa)						Stress (MPa)			Fracture Direction (°)
		P_b	P_r	P_s	P_H	P_0	T	σ_1	σ_2	σ_v	
1	83.36～83.96	2.83	2.08	1.66	0.82	0.74	0.76	2.16	1.66	2.21	
2	116.07～116.67	5.93	4.5	4.08	1.14	1.06	1.43	6.68	4.08	3.07	N77°E
3	155.38～155.98	12.6	7.57	6.98	1.52	1.44	5	11.9	6.98	4.11	N88°E
4	181.53～182.13	12.9	9.13	7.83	1.78	1.7	3.78	12.7	7.83	4.8	
5	232.54～233.14		10.8	9.25	2.28	2.2		14.8	9.25	6.15	

Notes: P_b: in-situ rock fracture pressure
P_r: fracture reopening pressure
P_s: instantaneous closure pressure
P_H: water column pressure at the tested depth
P_0: pore column pressure at the tested depth
T: rock tensile strength
σ_1: maximum horizontal principal stress
σ_2: minimum horizontal principal stress
σ_v: vertical stress estimated by rock thickness; water column in drill hole is 8m

According to stress measurement theory by hydraulic fracturing method, the crack generated by hydraulic fracturing is of the same direction with the maximum horizontal stress. Therefore, when the fracturing is finished, the comprehensive analysis of fracturing test curve is used to select 2 tested sections of obvious fracturing pressure for impression direction test. The 2 tested sections are 116.07~116.67m and 155.38~155.98m deep respectively. The impression results are shown in Figure 7. Based on baseline orientation, it is calculated that the induced fracture directions of the above sections, i.e. directions maximum horizontal principal stress, are N77°E and N88°E (see Table 3).

In order to get a visual impression of the measurement results of the 5 different depths in the bore hole, the magnitudes of maximum horizontal principal stress, minimum horizontal principal stress, and vertical stress of various depths were drawn in Figure 8. It can be seen from the Figure that all the horizontal principal stresses in Hole K1 increase with depth of bore hole. The stress value of two test points in shallow part deviates from the track of three points in deep part, which can be attributed to the release of stress in shallow part.

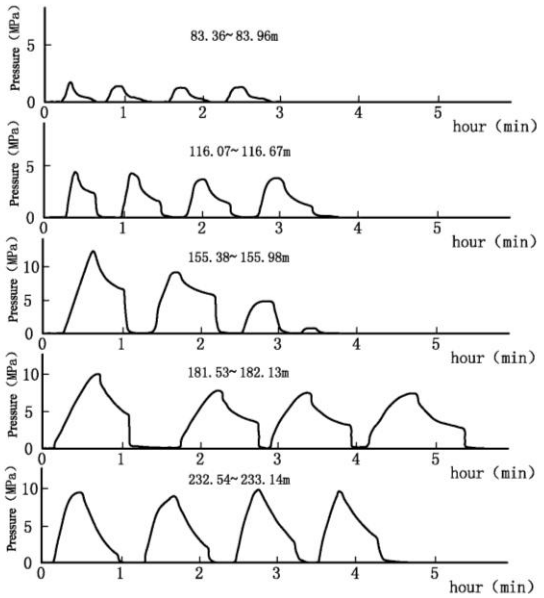

Figure 6 Pressure-Time Recording Curve of Hole K1

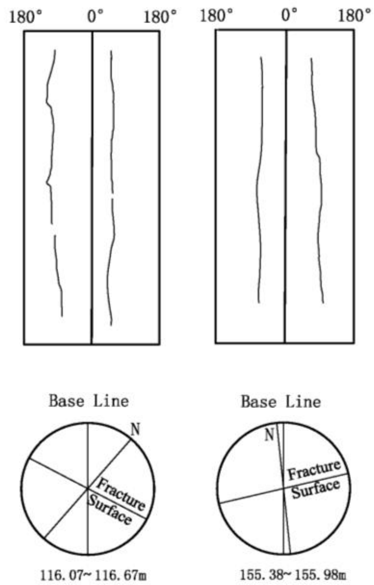

Figure7 Impression Result of Hole K1

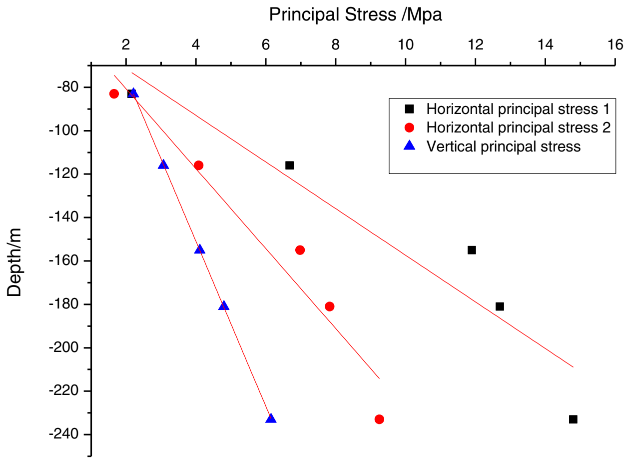

Figure 8 Principal Stress Variation Curve of Hole KB with Depth

4.2. Test Result and Analysis of In-situ Stress Measurement by Hydraulic Fracturing Method

(1) Both maximum and minimum horizontal principle stress increase with depth, basically in linear change. The increment with depth of maximum horizontal principle stress is greater than that of others, and generally greater than that of minimum horizontal principle stress.

(2) On average, the ratio of maximum principle stress and minimum principle stress is approximately 1.5.

(3) In the range of test depth, the maximum horizontal principle stress value is between 2.16-14.79MPa and the minimum horizontal principle stress value is between 1.66-8.00MPa. Both of the two values are in the medium range.

(4) It can be seen from the stress measured at each measuring point that the horizontal principal stress is 0.97-2.89 times of the vertical principal stress, which means that the measured area is affected by horizontal tectonic movement recently..

(5) The calculation result indicates that the direction of the maximum horizontal principal stress is N82^{0}E direction on average, close to EW direction, basically the same with the principal stress direction in North China

(6) Horizontal principle stress is 0.57-2.9 times of vertical stress.

5. Conclusions and Expectations

(1) New acoustic emission method obtains consistent results with hydraulic fracturing method in measuring in-situ stress, which proves that it is feasible to use new acoustic emission method to measure in-situ stress. Besides, new acoustic emission method is more economical than hydraulic fracturing method. The new acoustic emission method is simple for operation. The actual measurement is mainly completed in laboratory and easy to be done. Due to its superiority over hydraulic fracturing method and solid inclusion stress meter, the new acoustic emission method is worth learning and popularizing in in-situ stress measurement.

(2) Both of the two test methods indicate that the tested results are in accordance with $\sigma_{h,max}$(MPa)=0.054×depth (m)+0.678; $\sigma_{h,min}$(MPa）=0.064×depth (m)+0.378; σ_v(MPa)=0.0255×depth

(m)+0.218. However, in order to obtain more accurate linear regression coefficient, the authors need to make a large quantity of field test verification.

(3) New acoustic emission method only assumes that vertical stress is one of the directions of principal stress and then calculates maximum and minimum horizontal principal stresses, which is limited. In the future, the authors will research into the sampling and measurement method of vertical stress, so as to make the method more perfect and calculate and obtain accurate the status of three-dimensional in-situ stress.

(4) Uniaxial acoustic emission in-situ test neglects the important influence of ambient pressure upon results. The authors will try to make acoustic emission in-situ measurement study of rock on stress memory effects under tri-axial condition.

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