Estimation of in-situ stress – experiemtnal trials on Kaiser effect and hydrofracturing tests

In the present paper, an acoustic emission trend in the Kaiser effect of rocks was studied and possibility of its application in the estimation of in-situ rock mass stress was explored. Several methods have been proposed for estimating in-situ stress in the laboratory from rock core samples collected from the boreholes. Among them, acoustic emission (AE) method based on Kaiser effect is the simplest. Conventionally, in-situ stress is estimated by plotting cumulative events versus stress. The change in the slope of the curve is an indicator of the Kaiser stress. In the present study, borehole drilled samples from five sites were investigated in the laboratory by AE method for which the in-situ stress was already measured by hydrofracturing method. A plot of cumulative events versus stress indicated three types of trend and is named as type 1, 2 and 3. It is easy to identify the Kaiser stress if the trend is of type 1. Types 2 and 3 trends do not show any perceptible change in the slope of the curve and it is impossible to identify the Kaiser stress. Since most of the samples showed type 2 and type 3 trend, to estimate the Kaiser stress, other AE parameters namely ring down count, energy and absolute energy of the events were used. Among these parameters, absolute energy plot showed more significant change in the slope, and hence preferred for identification of the Kaiser stress.

1.0 Introduction

In-situ stress is one of the essential input parameter into models for underground design and stability analyses. A number of techniques have been proposed and developed to determine in-situ stress. The actual measurement of the stress is not an easy task and all suffer from limitations. The established techniques such as the over coring and the hydraulic fracturing methods are not only expensive and time-consuming, but also are not suitable for measuring the in-situ stress at depth in remote regions.Alternatively, several methods have been proposed for estimating in-situ stress in the laboratory from rock core samples collected from the boreholes; AE method (Kanagawa et al., 1977; Yoshikawa and Mogi, 1981, 1989), differential strain analysis (Simmons et al., 1974) or differential strain curve analysis (Ren and Roegiers, 1983), an elastic strain recovery method (Teufel, 1982; Wolter and Berckhermer, 1989), and deformation rate analysis (Yamamoto et al., 1990). Among them, acoustic emission (AE) method based on Kaiser effect is the simplest and inexpensive. A rock core from an underground site is used in determining the past stress history.

The Kaiser effect can be defined as the stress level at which acoustic emission does not occur until the stress exceeds the previously applied maximum stress. It is also defined as the recollection of the maximum previous stress, which a rock was subjected in-situ. This stress is identified as in-situ stress of the rock mass. This technique has been developed and tried by various researchers with the aim of providing a practical technique of estimating the in-situ stress in the laboratory (Hardy et al, 1985, 1992 and Lavrov, 2003).

Conventionally, the Kaiser stress is identified by plotting cumulative AE events vs. stress. A change in the slope of the curve is an indicator of the Kaiser stress. However, the experiments carried out at NIRM laboratory did not show any such perceptible change to identify the Kaiser stress. Therefore, AE results were analysed using other AE parameters such as ring down count, energy, and absolute energy of the events for identifying the Kaiser stress. The in-situ stresses estimated by the Kaiser method were compared to the stress measured by hydrofracturing method. The details of the experimental study are presented along with a new method of evaluation of Kaiser stress.

2.0 Laboratory investigations

Borehole drilled cores from five sites were chosen for the investigation because of availability of the in-situ stress values by hydrofracturing method. Test samples were prepared keeping the length to diameter ratio of 2.5 and loaded at a rate of 0.05 MPa/s up to about 50 MPa using the MTS compression-testing machine. The diameter of the samples varied from 54 mm to 60 mm. Wide band sensor (100kHz-1000kHz) was used for recording the acoustic emissions.

In the present investigation, highly advanced PC based AE system from Physical Acoustics Corporation, U.S.A., was used. The trade name of the AE system is MISTRA's (Massively Instrumented Sensor Technology for Received

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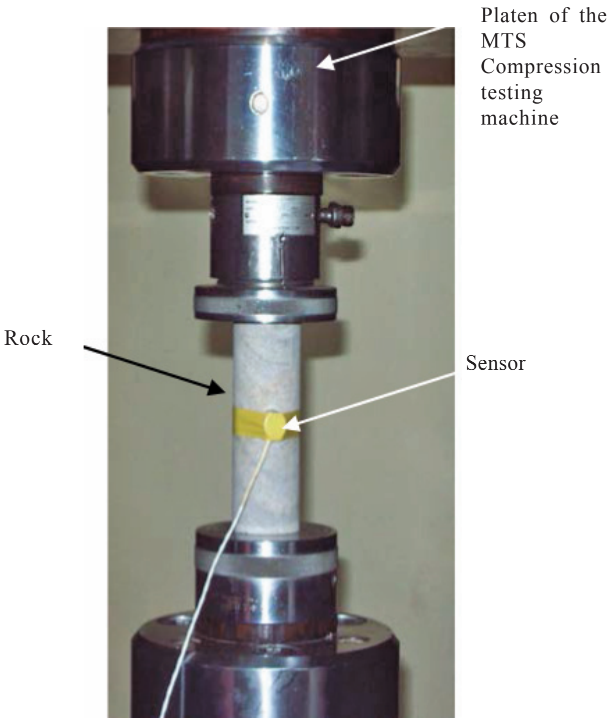

Fig.1 Rock sample with AE sensor

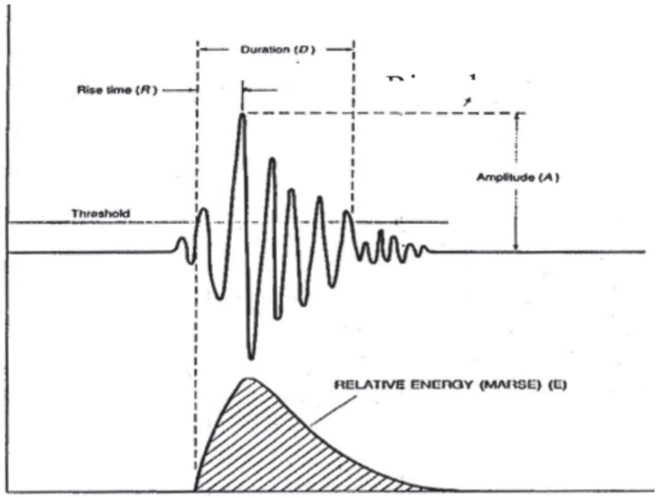

Fig.3 Acoustic emission waveform parameters (Pollock, 1980)

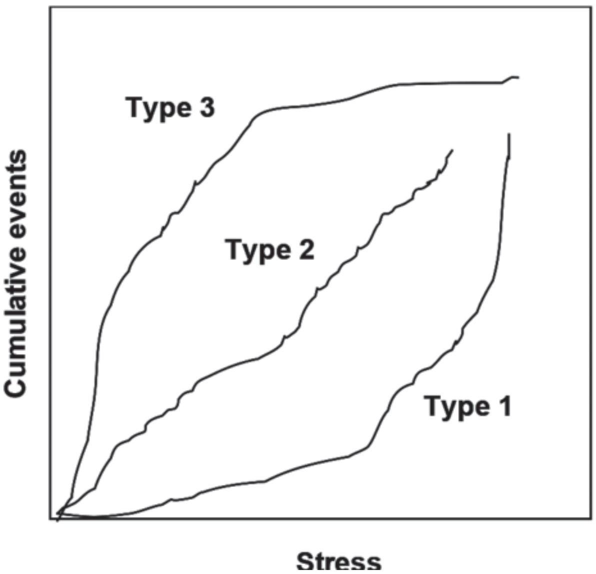

Fig.2 Trend of AE events

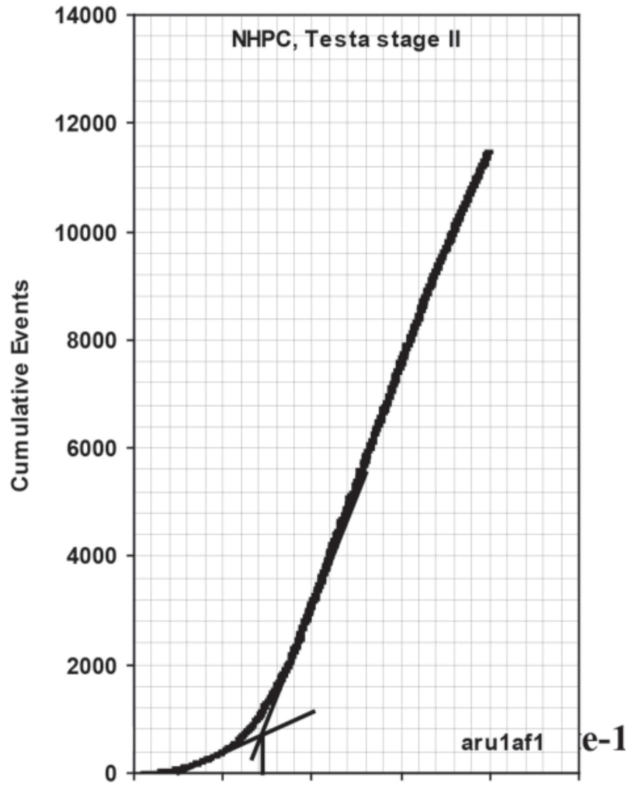

Fig.4. AE parameter plots for site-1

Acoustic Signals) (Users manual, 2001). The Mistra's system is a fully digital, multi channel, computerized, acoustic emission system that performs AE waveform and signal measurement and stores, displays and analyzes the resulting data. Sample was placed between the platens of the MTS compression-testing machine and loaded at a rate of 0.05 MPa/sec. All the AE data are stored in the computer and analysed. Fig.1 shows the photograph of the experimental arrangement at NIRM laboratory (NIRM, 2005). Conventionally, Kaiser stress is determined by subjecting a sample to two cycles of loading (Seto et al, 1998). In the first cycle, the sample is loaded to stress level to remove the AE events due to crack closure, pore collapse, crack propagation etc. The AE events due to these activities have amplitude less than 50 dB. In the second cycle, the sample is loaded to a stress level greater than the first cycle stress. In the second cycle, low amplitude events of first cycle, in general, do not appear again. This approach of determining the in-situ stress may have serious drawbacks. Application of stress in the first cycle may appear as memorized stress in the second cycle.

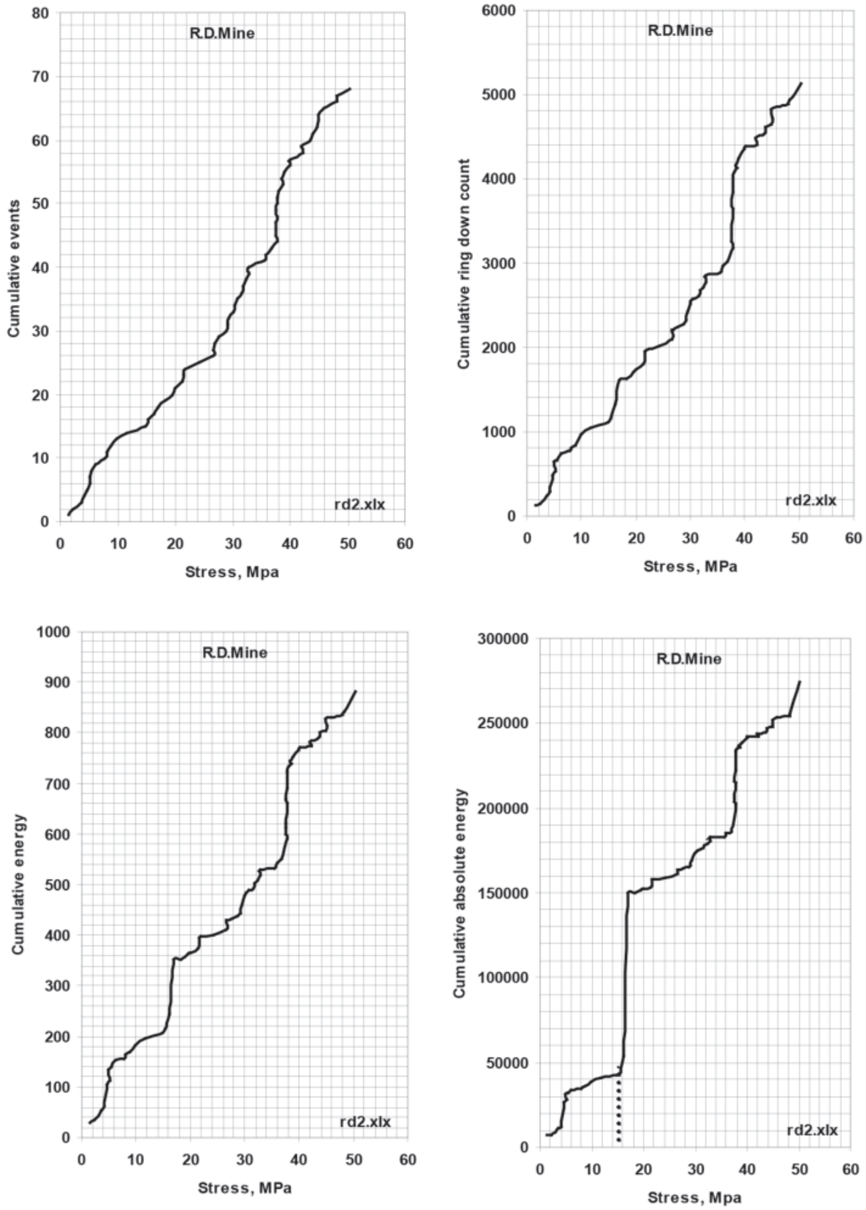

Fig.5 AE parameter plots for site-2

There is no clear procedure to what stress level the sample has to be subjected in the first cycle.

To avoid the ambiguity in the present study, the following method was adopted under uniaxial compressive stress conditions for conducting the experiment in the laboratory:

(a) Since, the samples belong to depth covers within 500 m, it is assumed that the maximum stress would not exceed 50 MPa. In view of this, the samples were loaded only once up to about 50 MPa and acoustic emissions were recorded. In doing so, the question of memorized stress due to more than one cycle of loading does not arise.

(b) Low amplitude events that mask the estimation of Kaiser stress were removed by graphical filtering method using AE software. Only the AE events greater than 50 dB were considered, whereas lower amplitude events were rejected as noise.

3.0 Analysis of the AE data – an innovative approach

Conventionally, in-situ stress is estimated by plotting cumulative events versus stress. The change in the slope of the curve is an indicator of the Kaiser stress. For estimation of in-situ stress by Kaiser method, borehole drilled rock samples from five different sites were investigated. A plot of cumulative events versus stress indicated three types of trend and is named as type 1, 2 and 3 (Fig.2). Type 1 shows an exponential trend of increase of AE events with increase of stress. Type 2 indicates a linear trend, whereas, logarithmic trend was observed in type 3. It is easy to identify the Kaiser stress if the trend is of type 1. Types 2 and 3 trends do not show any perceptible change in the slope of the curve and it is impossible to identify the Kaiser stress. In the present study, most of the samples showed types 2 and 3 trend. Therefore, a new method was proposed to estimate the Kaiser stress considering other AE waveform parameters namely; ring down count, energy and absolute energy. The definition of these parameters is given below.

Acoustic emission events (AE event) are individual signal bursts produced by local material changes. The nature of AE event is shown in the Fig.3.

Ring Down Count (RDC): RDC is the number of times a signal crosses a preset threshold limit

Acoustic emission activity is attributed to the rapid release of energy in a material. The energy content of the acoustic emission can be related to this energy release and can be measured. Mistra's software calculates two types of energy.

Energy: Energy is the area under the rectified signal envelope as shown in the Fig.3. It is sensitive to amplitude and duration.

Absolute energy: This is not the conventional AE parameter. This value is available in the Mistra's software. It is calculated as the integral of the squared voltage signal divided by the reference resistance (10k ohm) over the duration of the AE waveform packet (Users manual, 2001).

In the present investigation, acoustic emission data is available from five sites. Low amplitude events (< 50 dB) were

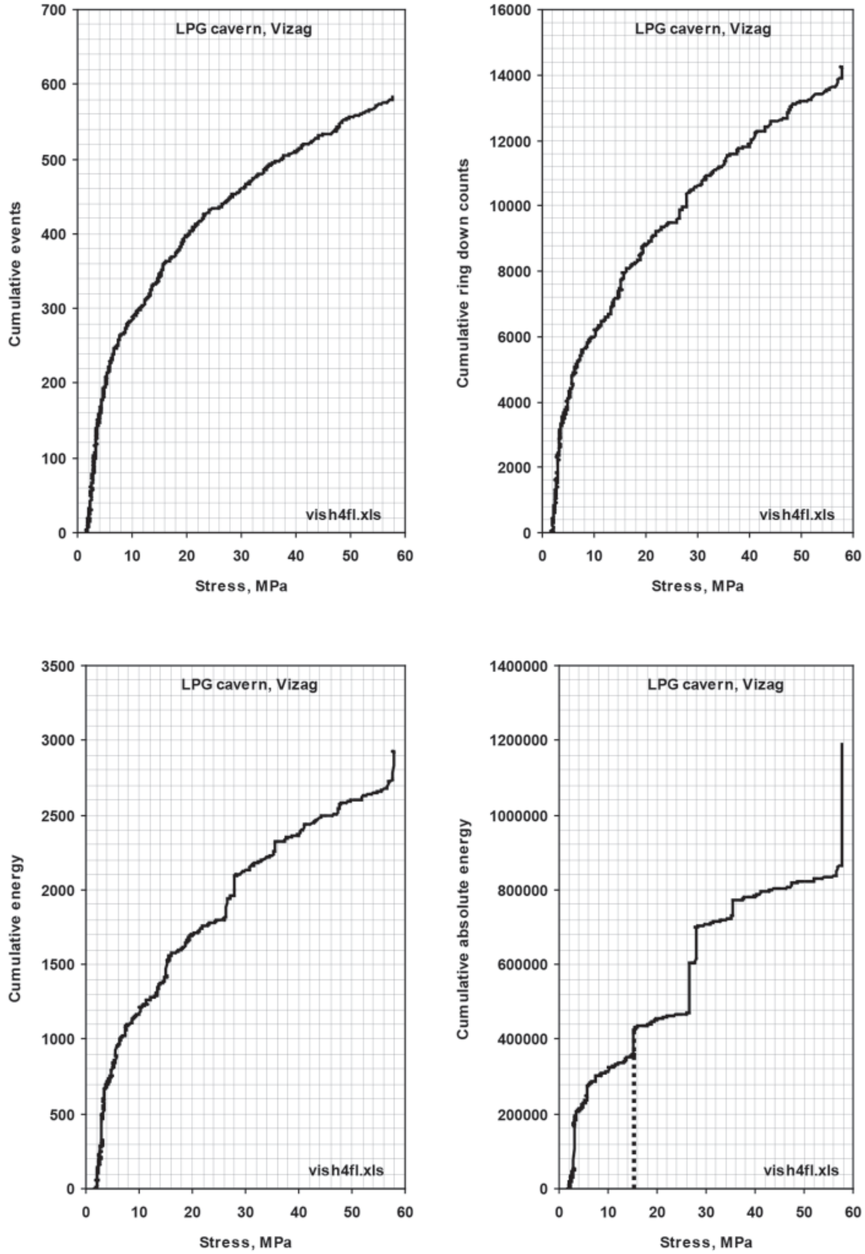

Fig.6 AE parameter plots for site-3

removed by graphical filtering method. Fig.4 shows the type 1 trend for a typical site, wherein the Kaiser stress could be easily identified. Kaiser stress is easily identifiable by drawing tangents. Kaiser stress is 7.0 MPa and in-situ stress from hydrofracturing method is 8.59 MPa.

Figs.5 and 6 show the plot of cumulative event, ring down count, energy and absolute energy versus stress for typical sites showing types 2 and 3 trends, respectively. For each site all these graphs are shown on the same page to observe the variation in the trend. For estimating the Kaiser stress, the following method was adopted:

Fig.5 shows type-2 trend for a typical site. In this case, cumulative AE events (Fig.5a) increase with the increase of stress following a linear trend. Although, the variation of slope was apparent in ring down count (Fig.5b) and energy curves (Fig.5c), comparatively more significant variation in the slope of absolute energy curve (Fig.5d) was noticed. Therefore, the first predominant change in the slope of the absolute energy curve was preferred for identifying the Kaiser stress. The in-situ stress estimate by AE method is 16 MPa, and by hydrofracturing method it was measured as 18.2 MPa.

Type 3 trend for a typical site is presented in Fig.6. In this case, initially cumulative AE events increases with the increase of stress up to a certain stress level, beyond which the increase in total number of AE events is reduced (Fig.6a). Ring down counts and energy plots do not show any significant change in the slope of the curve (Fig.6b and 6c). However, absolute energy curve shows a significant change beyond a stress level, which is considered for estimating the Kaiser stress (Fig.6d). Absolute energy plot shows a significant change in the slope of the curve at about 15 MPa, which is inferred as Kaiser stress. In-situ stress determined by hydrofracturing method is 14.13 MPa.

Results from five sites were compared for the value of in-situ stress determined by Kaiser method and hydrofracturing method (Table 1). For these sites, the difference in the value determined by both the methods is about 2 MPa. Kanagawa et al (1976), and Hyashi et al (1979) reported that the Kaiser method over estimated the in-situ stress by about 10 MPa as compared to the value estimated from over-coring method. Whereas, Momeyez and Hassani (1992a, 1992b) stated that the insitu stress estimated by Kaiser method is in agreement with the value obtained by over-coring method. Thus in the present investigations, the in-situ stress estimated by both the methods are comparable.

Conclusions

Detailed laboratory investigations were carried out for estimating the in-situ stress of rock mass using the rock core based on AE method (Kaiser effect). Conventionally, Kaiser stress is estimated by two cycles of loading. Stress induced in the first cycle may appear as the Kaiser stress in the second cycle. Therefore, in the present study, the sample was loaded once up to 50 MPa and the acoustic emissions were recorded. A plot of cumulative event versus stress from AE data of eight

TABLE 1 COMPARISON OF IN-SITU STRESS ESTIMATED BY KAISER METHOD AND HYDROFRACTURING METHOD

Location of sample	Trend	Kaiser stress (MPa)	In-situ stress from hydrofracturing method (MPa)	Difference
Site-1	Type 1	7.5	8.59	-1.59
Site-2	Type 2	16	18.28	-2.28
Site-3	Type 3	15	14.13	0.87
Site-4	Type 3	8	9.77	-1.77
Site-5	Type 2	7.0	6.73	0.27

sites indicated three types of trend and is named as types 1, 2 and 3. It is easy to identify the Kaiser stress if the trend is of type 1 due to significant change in the slope of the curve. In the present study, most of the samples showed types 2 and 3 trend. These two trends do not show any perceptible change in the slope of the curve, and Kaiser stress could not be estimated. In order to identify the Kaiser stress, besides the AE events, three other parameters namely; ring down count, energy and absolute energy of the events were considered. A plot of cumulative ring down count/energy/ absolute energy versus stress showed a change in the slope of the curve, which is identified as Kaiser stress. Among these parameters, absolute energy of the events is noticed as a better AE parameter for the estimation of the Kaiser stress. These parameters may be used whenever cumulative events plot show type 2 or type 3 trend. In-situ stress estimated by laboratory method was compared to the in-situ value determined by hydrofracturing method. Data from five sites were compared, and there was a good agreement between the two methods.

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