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An experimental study on the validity of Kaiser effect for in-situ stress measurements by Acoustic Emission Method (AEM) in rocks subjected to cyclic loads

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Abstract

The acoustic emission method utilizes the Kaiser effect for inferring the stress state. Since stress tensor has 6 independent components, uniaxial or triaxial tests in 6 different directions are carried out to infer the components of the in-situ stress tensor. The acoustic emission response differs when the (deviatoric) stress level exceeds the one at which material was previously subjected to. The fundamental complexity is that the earth's crust has a stress history. As a result, one may find one or several stress levels during actual experiments. The question is how to select or define the one, which reflects the stress level that rock was subjected to. An experimental study on the acoustic emission responses of initially unstressed rock-like materials under uniaxial cyclic loading conditions was performed. On the basis of these experimental results, the validity of Kaiser effect for inferring stress state by considering the stress level with respect to its uniaxial compressive strength is checked and the applicability of the method for inferring the crustal stresses is discussed.

1. INTRODUCTION

The acoustic emission method was first suggested for inferring the in-situ stresses by Kanagawa et al. (1976, 1981). Since then many attempts were made to measure the stress state by this method. Nevertheless, the cost of acoustic emission measurement equipments was quite high and it could not become a widely accepted method. Furthermore, the validity of the method is always questioned as it is generally performed after other methods of in-situ stress measurements were already carried out. Recently, the cost of equipments becomes less and the experiments can be easily performed under laboratory conditions. As a result, there is a re-growing interest in stress measurements by this method (Holcomb, 1993; Hughson & Crawhord 1987; Seto et al., 1999; Tuncay et al., 2002; Villaescusa et al., 2002; Wang et al., 2000; Watanabe & Tano, 1999; Watanabe et al., 1994, 1999).

The acoustic emission method utilizes the Kaiser effect for inferring the stress state. Since the stress tensor is a symmetric second order tensor, it has 6 independent components. As a result, it is necessary to perform uniaxial or triaxial tests in six different directions. According to the Kaiser effect (Kaiser 1953), it is expected that acoustic emission response will differ when the (deviatoric) stress level exceeds the one at which material was previously subjected to as illustrated in Figure 1. The fundamental complexity in rock mechanics is that the earth's crust has a stress history. In actual experiments, one may find one or several stress levels. The question is how to select or define the one, which reflects the current stress level that rock was subjected to before unloading.

The authors have recently carried out a series of experiments on rock-like samples, which were initially non-stressed, using different cyclic loading paths in order

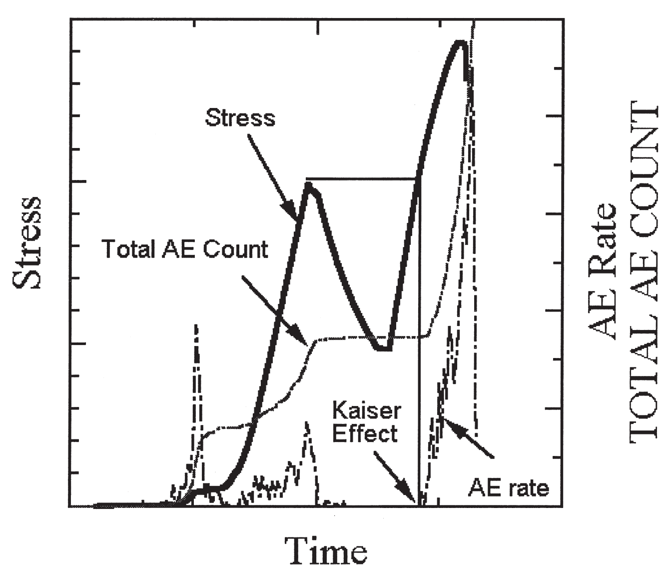

Figure 1: Illustration of Kaiser Effect

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to investigate the validity of the Kaiser effect and the applicability of in-situ stress inference by the acoustic emission method (AEM). The experimental results are presented and discussed in this article.

2. EXPERIMENTAL DEVICE AND SAMPLES

The experimental set-up used in experiments is illustrated in Figure 2 and Figure 3 shows the instrumentation of a typical sample. The compression test device made by SHIMADZU has the loading capacity of 2000kN and it is manually operated. The load and axial displacement of samples are measured automatically by using a load cell and two displacement transducers and data were sampled at time intervals through YOKOGAWA WE7000 A/D amplifier and data are monitored on a laptop computer. The AE system consist of a AE transducer made by NF and AE Tester which converts the AE signals into total AE count and AE count rate with a chosen sensitivity. The AE count is defined as the number of signals exceeding a chosen threshold value of acoustic waves. Accordingly, the AE count rate is the AE count for a given time interval.

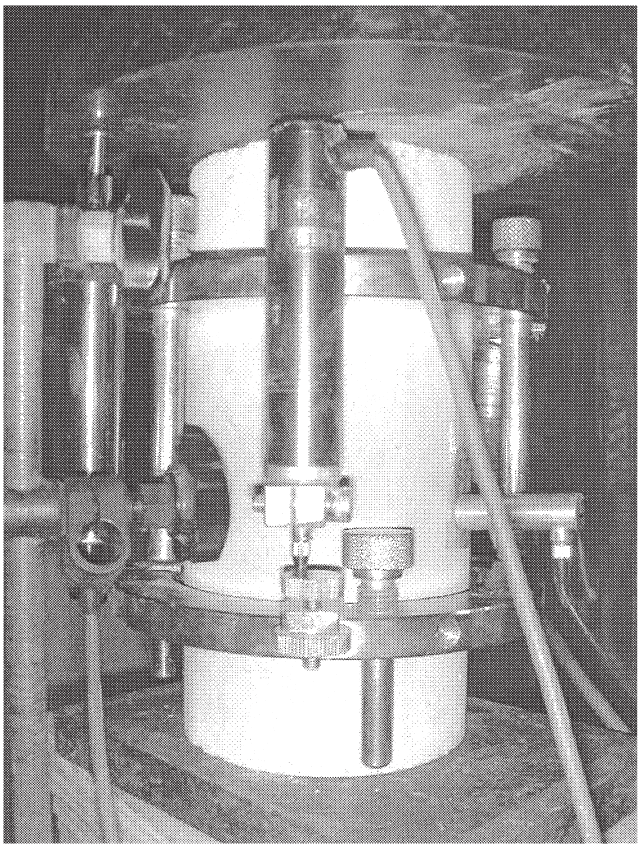

Figure 3: A view of instrumented sample

3. EXPERIMENTS

Two series of experiments on the acoustic emission responses of initially unstressed rock-like materials (specifically it is concrete, which resembles to conglomeratic sedimentary rocks) under different uniaxial loading paths were undertaken. The uniaxial compressive strength and elastic modulus of samples range between 13.2-44.4 MPa and 3.7-12.5 GPa, respectively. In the first series of experiments, 56 samples were tested and loaded up to three different stress levels as shown in Figure 4. For each loading-unloading-reloading cycle, the applied stress level and the stress level inferred by using the Kaiser effect concept are obtained and processed as illustrated in Figure 5.

In the second series of experiments, the number of cycles was increased and the minimum load level at each loading and unloading cycle was kept almost the same while the loading stress level was increased as the cycle

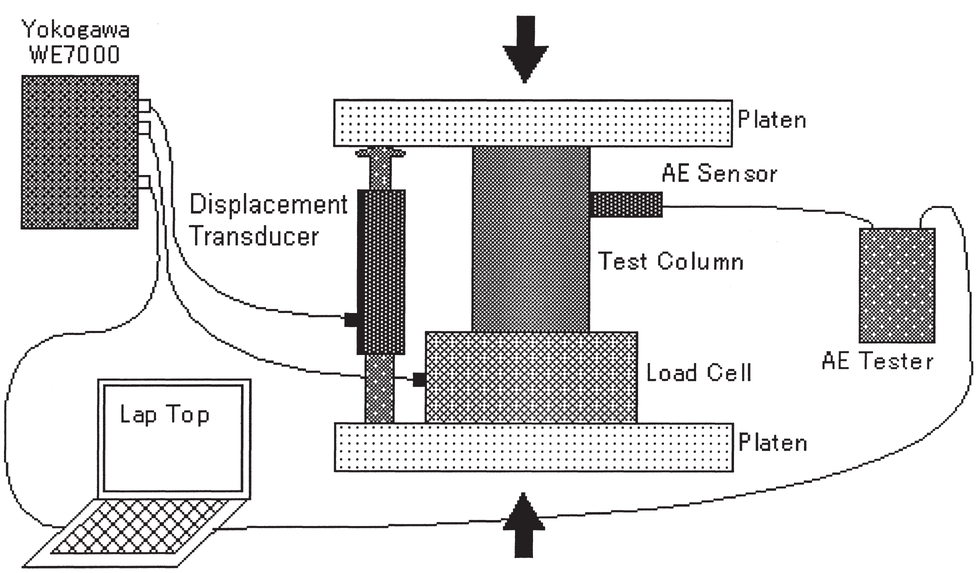

Figure 2: Experimental set-up

number was increased. Figure 6 shows the loading-unloading procedure adopted in a typical test of the second series of experiments.

In the first series of experiments, the unloading stress level was kept greater than the peak stress level of the previous cycle. However, in the second series of experiments, the unloading stress level at each cycle was chosen so that it would be less than the peak stress level of the first cycle. The reason for such a procedure was to see if the material memorizes the peak stress levels to which it was subjected in previous cycles.

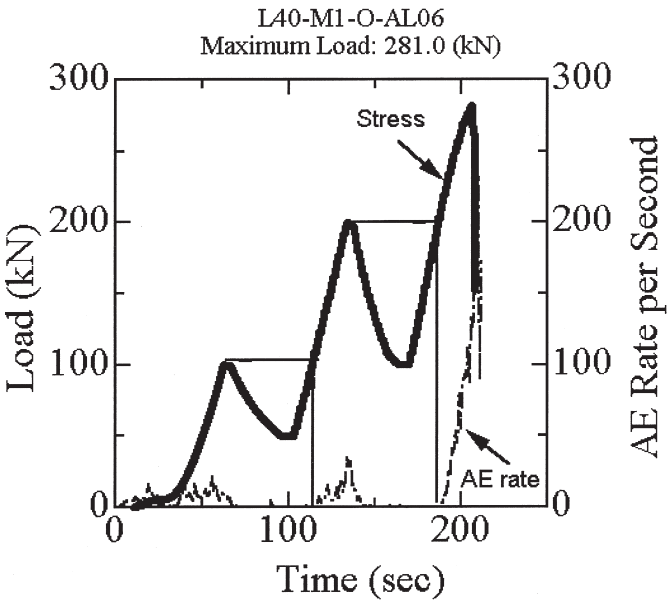

Figure 4: Typical stress and AE responses

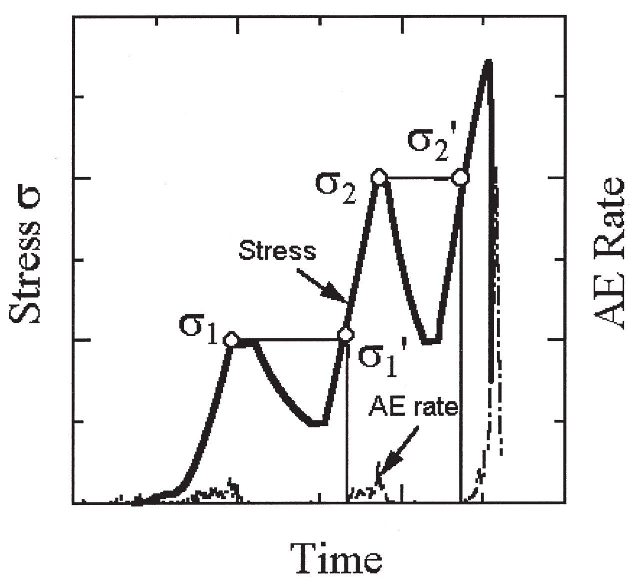

Figure 5: Procedure for inferring the stress level and some definitions

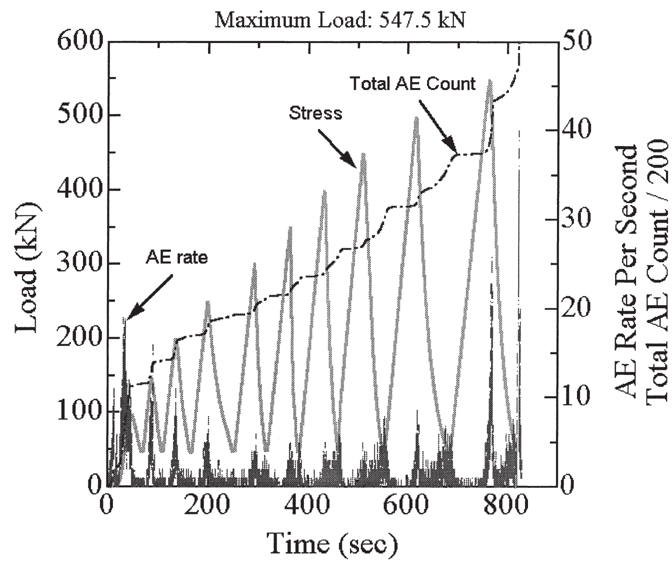

Figure 6: Typical stress and AE responses

4. RESULTS AND DISCUSSIONS

Figure 7 shows a plot of the normalized stress level by its uniaxial strength and the ratio of inferred stress to applied stress by using the procedure for inferring the stress levels in an experiment as shown in Figure 4. Although some scattering exists, it can be firmly stated that Kaiser effect concept perfectly holds for rocks and it would be appropriate for inferring the stress level in rock masses. The experimental results indicate that when the applied stress level is below 70-85% of their uniaxial strength, the inferred stress level from the Kaiser effect is slightly less than the applied stress level. The stress level of 70-85% of their uniaxial strength is well known to be corresponding to the threshold value of stress level for initiating unstable cracking in Rock Mechanics (Bieniawski, 1967). On the other hand, if the applied stress level exceeds the stress level of 70-85% of their uniaxial strength, the inferred stress level is slightly greater than the applied ones. Figure 8 compares the relation between normal distribution (Gaussian) function and experimental frequency and normalized inferred stress ratio for the first series of experiments.

Next the results of the second series of experiments are presented and discussed. Figure 9 shows a plot of the normalized stress level by its uniaxial strength and the ratio of inferred stress to applied stress. Compared to the first series of experiments, the scattering band of the second series experiments is much narrower and the deviation is limited to 10%.

Figure 10 shows an enlarged section of the last load-

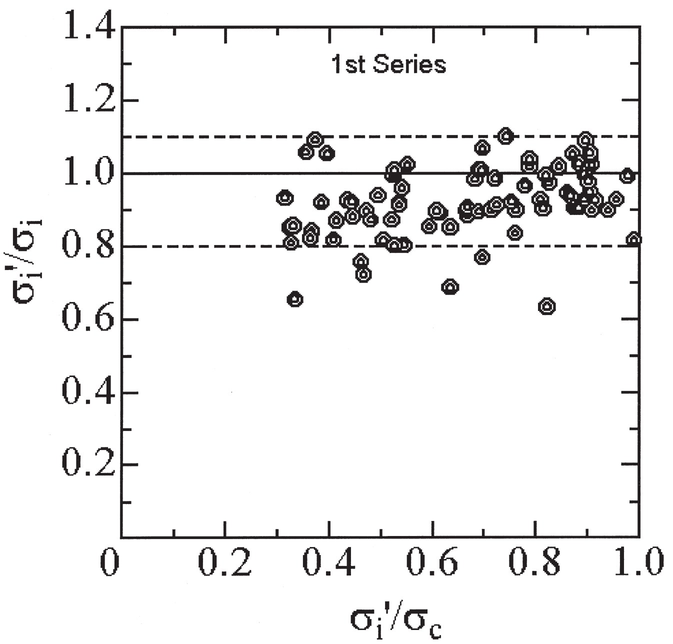

Figure 7 : Comparison of inferred stress levels as a function of normalized stress level by its uniaxial strength (σ_i : applied stress level at loading cycle i; σ'_i : inferred stress level at loading cycle i; σ_c : uniaxial compressive strength of specimen)

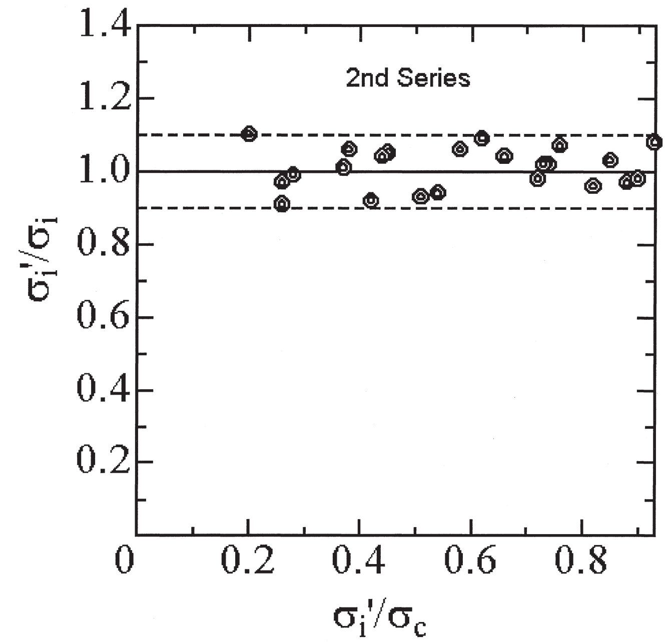

Figure 9 : Comparison of inferred stress levels as a function of normalized stress level by its uniaxial strength

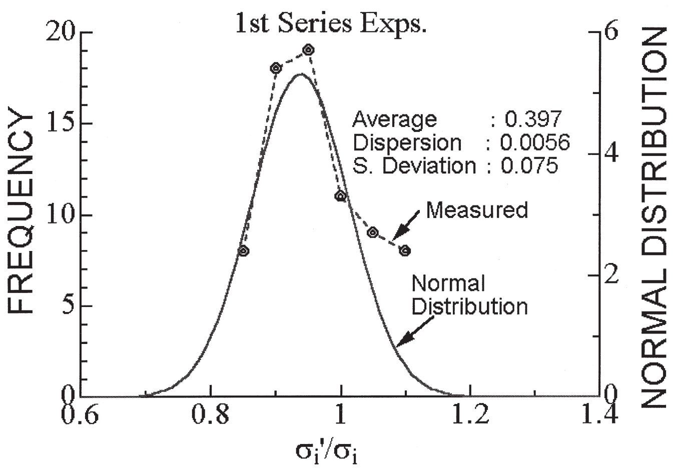

Figure 8 : Comparison of the relation between the normal distribution function and experimental frequency and normalized inferred stress ratio for the first series of experiments

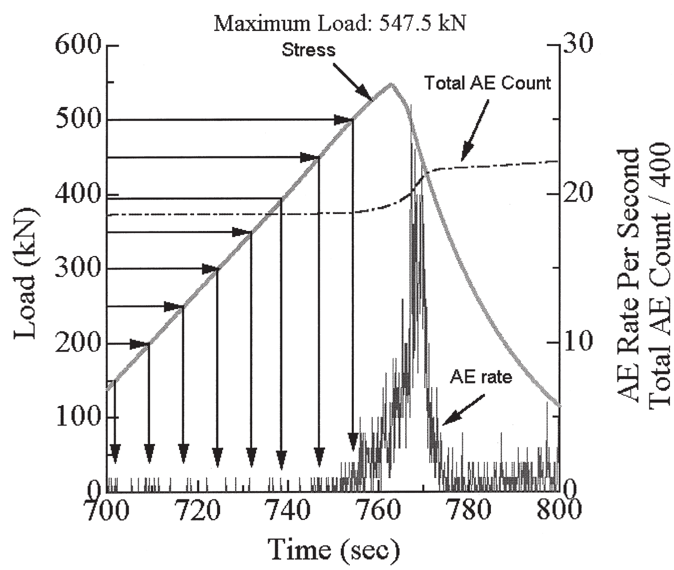

Figure 10 : The enlarged plot of the responses at the last cycle of loading shown in Figure 6.

ing step shown in Figure 6. These experimental results clearly showed that the samples memorize the previous peak stress levels if the threshold value for acoustic emission signals set at smaller levels. Nevertheless, the responses at previous peak stress levels are not very much distinct as that of the last highest peak stress level. Although there are still some fundamental issues to be dealt with, the authors feel that this method may be quite useful tool for geo-engineers and geo-scientists for inferring the stress state and stress history in rock. Figure 11 compares the relation between the normal distribution (Gaussian) function and experimental frequency and normalized inferred stress ratio for the second series of experiments.

5. CONCLUSIONS

Two series of experiments were carried out to check the validity of Kaiser effect used for inferring in-situ stress state in rock masses. The experimental results clearly indicated that the Kaiser effect is a sound concept to infer the stress state to which rock subjected previously.

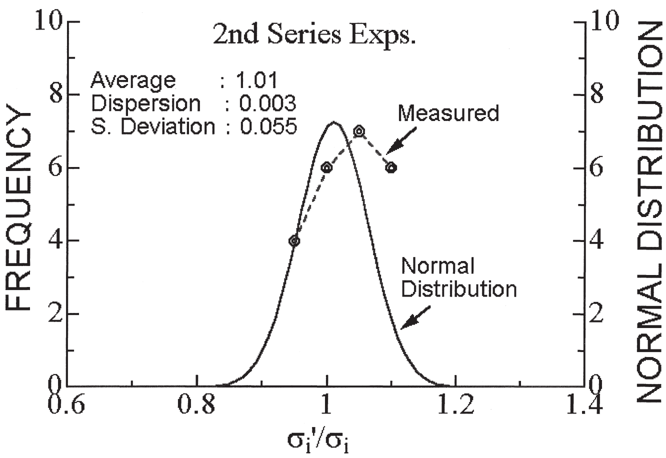

Figure 11: Comparison of the relation between the normal distribution function and experimental frequency and normalized inferred stress ratio for the second series of experiments

However, there may be some deviations depending upon the stress level with respect to the strength of rock. Particularly, if the stress level is less than the unstable crack threshold value defined by Bieniawski (1967), the inferred stresses may be less than the actual level to rock was subjected. On the other, the inferred stress levels may be greater than the actual ones if the stress level is greater than the unstable crack propagation threshold stress level. However, the deviations are generally limited to $\pm 20\%$ of the actual stress level which would be quite acceptable error in rock engineering projects. Therefore, the acoustic emission method should be a useful tool for engineers for inferring the stress state in rock masses. Nevertheless, some further theoretical developments are necessary for the utilization of the acoustic emission method as a universally accepted technique of in-situ stress inference in rock masses.

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要　旨

繰り返し荷重履歴を受けた岩盤の AE 法による初期応力の推定における Kaiser 効果の妥当性に関する実験的研究

大洞光央・アイダン・オメル・桑江ひとみ・迫田恵三

地殻の初期応力推定法の一つとして，カイザー効果に基づく AE（Acoustic Emission）法がある。応力テンソルは 2 階の対象テンソルであるため，6 つの独立な成分を持つ。したがって，6 つの異なる方向に対して 1 軸や 3 軸圧縮試験を行い応力テンソルの各成分を推定する必要がある。カイザー効果により，AE の応答は岩盤が以前に受けた応力レベルを超えた時に変化する。実際に，岩盤から取り出した岩石を用いて実験を行うと，いくつかの応力レベルで AE の応答に変化が見られるケースが多数存在する。これは地殻が様々な応力履歴を受けているのことに起因する。したがって，その岩石が受けていた応力はどれかという疑問が発生する。そこで，無応力状態で作成した擬似岩石供試体を使用して繰り返し載荷試験を行い AE の応答を実験的に確認した。本論文で，実験結果に基づき応力推定法に対するカイザー効果の妥当性を調査し，さらに，地殻の初期応力推定法として AE 法の適用性について議論する。