Proc. National Seminar on
Non-Destructive Evaluation
Dec. 7 - 9, 2006, Hyderabad

Importance of AE Study for Fracture Process of Heterogeneous Solid Material - High-Speed, Multi-channel AE Measurement System in Geological Survey of Japan/AIST

T. Satoh and X. Lei
Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, Tsukuba, 305-8567, Japan
e-mail: xinglin-lei@aist.go.jp

Abstract

In order to investigate detailed features of the space-time distributions of microfractures generated during rock fracture experiments, we have developed a high-speed, multi-channel acoustic emission (AE) waveform measurement system. This system consists of 32 channels of transient-memory controlled by a microcomputer. The transient-memory has a 16 MB RAM buffer in each channel, which enables us to record the waveform data for more than 8000 AE events. AE waveform is digitized with a sampling interval of 50 nanoseconds and a resolution of 12 bits, and is recorded on the RAM buffer with a very short system dead-time of about 200 microseconds.

We have also developed a visual and interactive processing system for dealing with a huge amount of AE waveform data. From AE waveform data, P-wave first arrival time is automatically picked, and AE hypocenter is determined. The AE data processing system also has functions of manual re-location of AE hypocenters, focal mechanism determination, some statistical analysis of AE time series, and so on.

Using this system, we clearly found clustering of AE hypocenters around a macroscopic fracture plane during a 10 second interval before final fracture of a granite sample under triaxial compression. This demonstrates that the system could be a very powerful tool for studying the space-time distribution of AE events, especially when the AE activity is very high.

Keywords: *Acoustic emission (AE), Microfracturing, Heterogeneity, AE Measurement system*

1. Introduction

A large number of prefailure microfractures are generated during deformation of a stressed heterogeneous solid material like rock, while few microfractures are generated in a homogeneous material like glass. Interaction between microcracks play major role in fracture of heterogeneous material, and thus it is very important to study the evolution of spatial distribution of microfracturings during deformation process of heterogeneous materials. When a microfracture occurs, a high frequency elastic wave called an acoustic emission (AE) is radiated. AE can provide us much information about the microfracturing activity, e.g. location of a microfracture and its fracture mode. An earthquake represents a brittle fracturing in the Earth's crust, which shows a heterogeneous structure on all scales. Various precursory phenomena of large earthquakes such as foreshock and pre-slip should result from this heterogeneity. Thus, a detailed investigation of AE activity leading up to the ultimate fracture of rock sample is also very important for understanding the preparation processes of a large earthquake.

When a brittle rock sample is traxially compressed, the sample will commonly fracture with an ultimate shear fault whose orientation is about 30 degree from the maximum compression axis. The process of the fault growth usually occurs unstably in a very short time, often less than a few seconds. During this process, a large number of AE events occur progressively along the fault plane. One can realize the faulting process stably by controlling axial stress to maintain, for examples, AE rate [1] or increasing rate of circumferential strain [2] constant. However, in order to investigate the fault nucleation and development process under loading conditions similar with real problems, such as constant stress or strain rate, by using AE, an AE measurement system that can detect enough number of AE events during this short time period is needed. For this purpose, we have developed a high-speed, multi-channel AE waveform measurement system as well as a visual and interactive data processing system for dealing with a huge amount of the AE waveform data. In this paper, we show the AE waveform measurement and processing system in Geological Survey of Japan/AIST as well as some experimental results. Some recent results based on more advanced analysis are shown in another paper in this issue [3].

2. AE Waveform Measurement System

A block diagram of the AE waveform measurement system is shown in Fig. 1 [4]. The system consists of pre-amplifiers, a trigger pulse generator (TPG), four transient-memory (TM) units, a controller, a peak detector (PD) and a PC. Each TM unit has eight inputs, and thus the total number of channels of this system is thirty-two.

AE signals detected by PZT transducers are, after amplification by the pre-amplifiers, fed into TMs, in which the analogue AE signals are digitized with the minimum sampling interval of 50 nanoseconds and a resolution of 12 bits. Some of the pre-amplifier outputs are also fed into TPG. When TPG detects an AE event, it emits a single TTL pulse. The TTL pulse is input into TMs and the controller. When the TM receives the pulse, the AE waveform is recorded in a RAM buffer based on the pre-set sampling rate, delay time and record length. Each TM has a 16 MB RAM buffer, and can record 8192 AE events for a typical measurement condition, i.e., record length of 1024 words. The AE waveform data in the RAM buffer are transferred to the PC through a GP-IB bus in order of occurrence, and then finally recorded on a hard disk. The transferred AE waveform data is deleted from the RAM buffer to increase free space for future AE events. When a new AE event is detected, the system immediately stops the data transfer and starts recording the waveform data of the new AE event on the RAM buffer. This procedure realizes a short dead-time and a larger number of recordable AE events. The peak detector had been developed to study the time series of AE activity in detail [5]. It can record the occurrence time of AE events with a 10 microsecond resolution and digitize their maximum amplitudes into twelve equally spaced levels on a logarithmic scale. The PD has been incorporated as a part of the AE waveform measurement system. The controller has been introduced to realize synchronized behavior between the 4 TM units and the PD.

By inputting artificial AE signals into this system from a pulse generator, it was

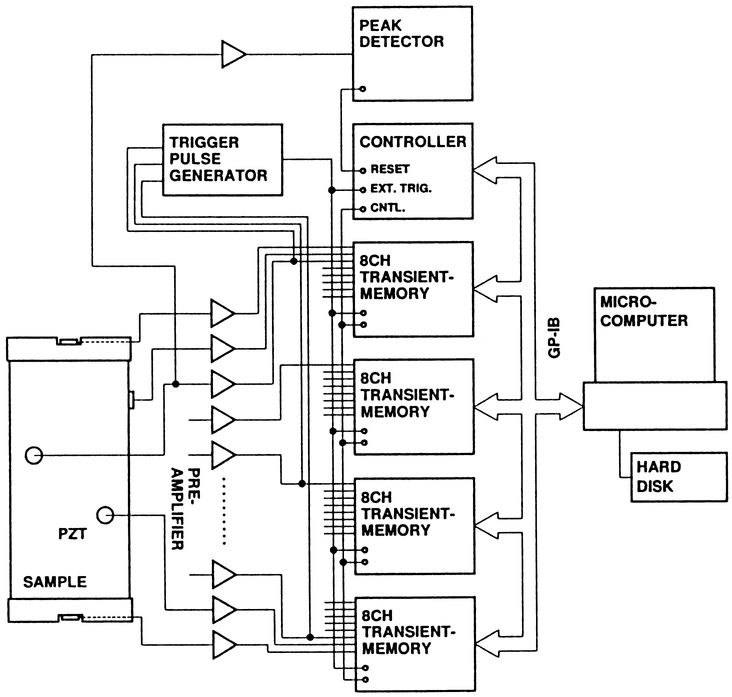

Fig. 1**:** Block diagram of the AE waveform measurement system

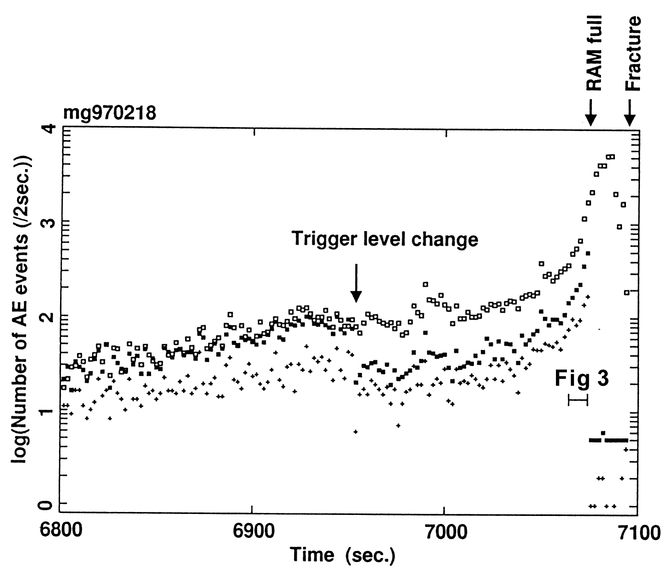

Fig. 2: Numbers of AE events in every 2 second interval detected by PD (open squares), and those detected (solid suares) and located (crosses) by the TM system. The data are shown for the last 5 minutes before the final fracture

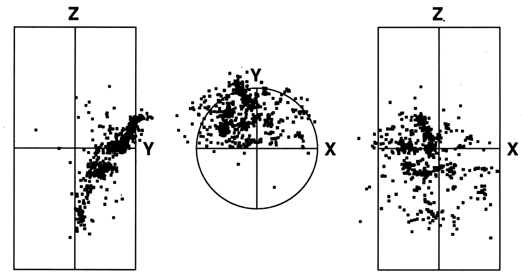

Fig. 3: AE hypocenter distribution for a 10 second interval indicated in Fig.2 by the horizontal bar labeled by "Fig.3"

found that the dead-time was about 200 microseconds when the RAM buffer wasnot full. It is considered that the 200 microseconds dead-time is practically short enough because, in our experience, the duration of locatable AE events is longer than several tens of microseconds. It was also found that the system is stable with a 0.4 second dead-time even when the RAM buffer is full.

3. AE Waveform Data Processing System

An automatic AE hypocenter determination program was developed for the efficient processing of a huge amount of AE waveform data [6]. The algorithm for picking the first arrival time is based on that proposed for earthquake hypocenter determination [7]. In this method, a waveform record is represented by two stationary parts, background noise and AE signal, using the auto-regressive model. The first arrival time is picked as the best dividing point by minimizing AIC [8].

This program, first developed on a mini-computer, has been ported in an integrated AE data processing program for Windows (WinAE) [9]. WinAE has also functions of 1) AE waveform data acquisition, 2) manual relocation of AE hypocenter, 3) space and time distribution plots of AE events, 4) focal mechanism determination, and 5) some statistical analysis of the space and time distributions of AEs. More recently, the automatic hypocenter determination program has been linked to the AE waveform data acquisition program (AESolpro) to develop a system which can monitor the AE hypocenter distribution in quasi-real-time during a rock fracture experiment [10].

4. Example -a Triaxial Fracture Experiment of Granite

The performance of this AE measurement system is evaluated through a triaxial fracture experiment of a coarse grained granite. The sample was a cylinder 50 mm in diameter and 100 mm in length, and contained some pre-existing healed joints and veins. Eighteen longitudinal type PZT transducers 5 mm in diameter with resonance frequency of 2 MHz were pasted to the sample side surface. Two transducers of the same type were installed in the steel end-pieces attached to the top and the bottom of the sample. One of the PZT signals was, after amplification by 20 dB, input into PD. Three of the pre-amplifier outputs were fed into the TPG. A trigger pulse was generated when one of the three inputs exceeded the threshold level.

Figure 2 shows the numbers of AE events detected in every 2 seconds for the final 5 minutes of the experiment. Open and solid squares are the numbers of events detected by PD and TM, respectively. The numbers of located events are indicated by crosses. The PD data are plotted for events with amplitude larger than one of the twelve threshold levels. The threshold level was so defined that the numbers of AE events detected by PD might be comparable to those by the TM system at the earlier stage of the experiment. In this experiment, the threshold level was 8.9 mV. The RAM buffer became full at about 20 seconds before the final fracture, although the trigger level of TM had been increased from 20 mV to 50 mV to avoid it. Even after that, the system was controlled stably and 5 AE events were detected in each 2 second interval. The hypocenters were located for 30 % of the detected events.

Figure 3 shows the AE hypocenter distribution for a 10 second interval indicated in Fig.2 by a horizontal bar labeled by "Fig.3". A planar distribution which has a strike in the x direction and a dip in the negative y direction is identified. This planar distribution coincides well with a pre-existing natural fracture plane. Looking at the hypocenter distribution more closely, the AE events are distributed not uniformly on the plane but in clusters. Such kind of image could not be obtained by the previous systems due to the long dead-time in waveform recording. This demonstrates that the new system is a powerful tool for studying the space-time distribution of AE events, especially when the AE activity is very high.

5. Conclusion

In order to investigate detailed features of the space-time distributions of microfractures generated during rock fracture experiments, we have developed a high-speed, multi-channel AE waveform measurement system. We have also developed a visual and interactive data processing system for dealing with a huge amount of the AE waveform data. Through a number of rock fracture experiments, we confirmed that this system is a very powerful tool for studying the space-time distribution of microfracturings using AE, especially when the AE activity is very high, at an order of several thousands events per second.

6. References

1. Lockner D.A., Byerlee J.D., Kuksenko V., Ponomarev A., and Sidorin A., “Quasi-static fault growth and shear fracture energy in granite”, Nature, 350, 39-42, 1991.
2. Kawakata, H., Cho, A., Yanagidani, T., and Shimada, M., "The observations of faulting in Westerly granite under triaxial compression by X-ray CT scan", Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., 34, 375, 1997.
3. Lei, X., Satoh, T., and Nishizawa, O., "Experimental study on stress-induced pre-failure damage in rocks and its applications to earthquake source-process research based on AE", this issue, 2006.
4. Satoh, T., and Nishizawa, O., "A high-speed, multi-channel waveform recording system for AE measurement", Bull. Geol. Surv. Japan, 48, 439-446, 1997.
5. Nishizawa, O., and Noro, H., "A self-exciting process of acoustic emission occurrence in steady creep of granite under uniaxial stress", Geophys. Res. Lett., 17, 1521-1524, 1990.
6. Satoh, T., Kusunose, K., and Nishizawa, O., “A minicomputer system for measuring and processing AE waveforms -High speed digital recording and automatic hypocenter determination-“, Bull. Geol. Surv. Japan, 38, 295-303, 1987.
7. Yokota, T., Zhou, S., Mizoue, M., and Nakamura, I., "An automatic measurement of arrival time of seismic waves and its application to an on-line processing system", Bull. Earthq. Res. Inst. Univ. Tokyo, 56, 449-484, 1981.
8. Akaike, H., "A new look at the statistical model identification", IEEE Trans. Autom. Control., AC-19, 716-723, 1974.
9. Lei, X., Nishizawa, O., Satoh, T., and Kusunose, K., "An AE data processing program for Windows", Bull. Geol. Surv. Japan, 48, 447-457, 1997.
10. Lei, X., Satoh, T., Nishizawa, O., Masuda, K., and Kusunose, K., "A real time AE hypocenter monitoring system for laboratory rock fracture experiment", Bull. Geol. Surv. Japan, 49, 353-363, 1998.