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Application of the fiber optical oscillation sensor to AE measurement at the rock compression test

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ABSTRACT: This paper reports the experiment about newly-developed high sensitivity Fiber Optical Doppler sensor (FOD sensor). In this experiment, applicability of this sensor to monitoring system of rock cavern was estimated from the result of Acoustic Emission (AE) measurement during uniaxial compression loading with rectangular soft tuff rock. As the result, it was confirmed that the FOD sensor could be used in the same manner as conventional PZT type sensor, and growth process of cracks was observed by the elapsed time analysis with AE locations. By observing change in center frequency of AE waveform, there was a tendency that frequency decreased after failure of the rock. Further, while the hard rock showed a constant frequency of AE wave before failure, soft rock showed differently larger changing phenomena in frequency than the hard rock. And clearer changes was seen in seismic wave velocity (Vp) and amplitude. We suppose that these phenomena were caused by the growth of micro cracks in the rock, and that it is possible to know by using FOD sensor system, when and where the rock will reach the mechanical limit before failure.

1 INTRODUCTION

Fiber Optical Doppler sensor (FOD sensor) is a device that makes use of the laser Doppler effect. It can be manufactured as a compact disk-type device that is thin, lightweight, flexible, explosion-proof and nearly free from electromagnetic noise. Especially, wideband measurement is achievable because FOD sensor is hardly affected by frequency response of input wave. In addition, because of its extremely low damping characteristics, it can transmit optical signals to over 10km away. Now this device is expected to use in various fields.

We are now trying to develop the FOD sensor so as to be used for monitoring system of rock cavern. Then we carried out the test in which acoustic emission (AE) generated during uniaxial compression loading of the rock specimen was measured with FOD sensor. The specimen was rectangular shaped soft tuff rock. The following notes the result of the experiment especially focused on the change of the feature of AE waveform on the failure process.

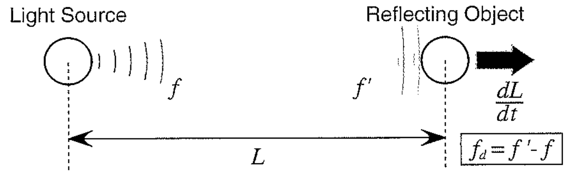


Figure 1. Schema of the optical Doppler effect.

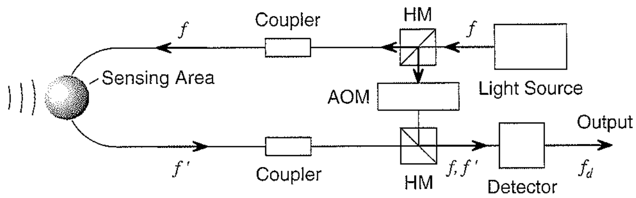


Figure 2. FOD measurement system.

2 FOD MEASUREMENT METHOD

2.1 *Principle of the FOD sensor*

Supposed that you watch a reflect point which is moving relatively to a viewpoint where light source is (see Figure 1), the frequency of light from the reflect point changes because of the Doppler effect which is described by the following formula.

$$f_d = -\frac{1}{\lambda}\frac{dL}{dt} \quad (1)$$

where λ is a wavelength of the light and dL/dt is a moving velocity of the reflect point (L indicates the distance between the viewpoint and the reflect point). This fomula means that the Doppler effect, that is, the shift of the frequency of light (f_d) arises in proportion to a moving velocity of the reflect point.

When an optical fiber expands and contracts, the Doppler effect as well arises on the light within the optical fiber. FOD sensor uses this mechanism.

2.2 *FOD measurement system*

FOD measurement system is shown in Figure 2. The interferometer detects modulation of optical frequency by use of the optical heterodynes interfering method. By connecting the both ends of a FOD sensor to this interferometer, frequency change of light within the sensor is converted to the change of voltage, and the deformation of the FOD sensor is detected.

If an optical fiber is pasted up with a solid, the expansion and the contraction speed of the solid are measurable. Frequency change of light is proportional to the transforming speed of the optical fiber, and its speed is proportional to the solid's displacement rate (strain velocity).

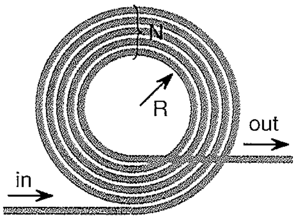
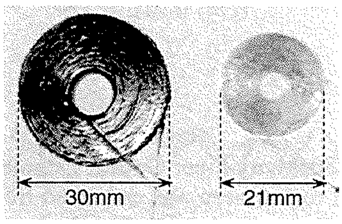


Figure 3. Schema of the disk-type FOD sensor.



Photograph 1. Developed disk-type FOD sensors.

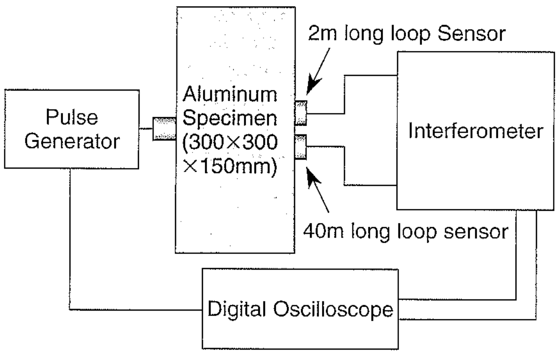


Figure 4. Schema of the sensitivity test for FOD sensors.

3 APPLICATION OF FOD SENSOR SYSTEM TO AE MEASUREMENT

3.1 *Development of the FOD sensor*

AE is a phenomenon whereby external stimuli such as mechanical loading generate sources of elastic waves. As the AE wave is extremely small, very high sensitive sensor is essential to detect these signals. So special disk-type sensors shown in Figure 3 and Photograph 1 had been developed for this test. The right-sided 21mm diameter sensor had been designed so that a long length optical fiber (2 m loop) was put into compact volume to improve the sensitivity by increasing dL/dt. Further, having optical fiber multi-layered, the 30 mm diameter sensor that was a 40 m long loop was developed.

3.2 *Sensitivity test of the developed FOD sensor*

In order to compare these two sensors, a sensitivity test was carried out. The test system is shown in Figure 4, in which the sensitivity of each sensor is checked by receiving the pulse wave that has been generated by PZT transmitter (150 kHz, 60 V) set on the opposite side of the aluminum specimen. Waveform is shown in Figure 5. From the comparison of the signal-to-noise (SN) ratio, 40 m-long loop sensor is more than ten times as sensitive as 2 m-long one. So 40 m-long type sensors were used in the following experiment.

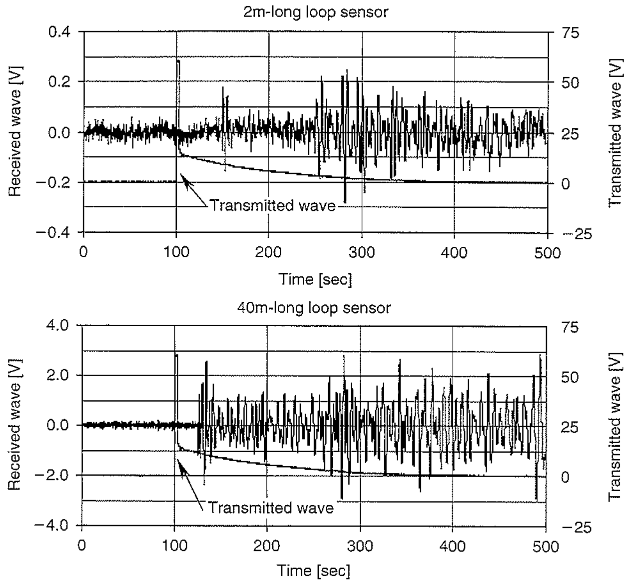


Figure 5. The result of sensitivity test.

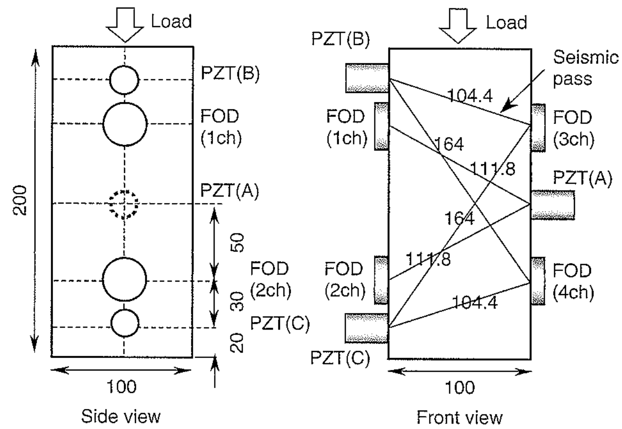


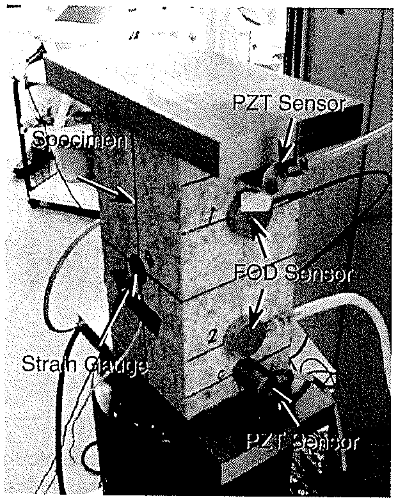
Figure 6. Installation of the measurement system components.

4 AE MEASUREMENT WITH FOD SENSOR

4.1 *Measurement system components*

To observe whether the developed sensor was applicable to AE measurement, AE measurement was carried out during uniaxial compression loading. In this test rectangular soft tuff rock called "Tage tuff" was used, and seismic waves generated during uniaxial compression of this specimen were recorded. In general, the amplitude of seismic waves from soft rock are much smaller than those from hard rock, and the total number of seismic waves is still less because of its high attenuation rate. So the condition of this test can be tough for AE measurement.

The system components are shown in Figure 6 and Photograph 2. Four FOD sensors (1 ch–4 ch) were attached on two opposite sides of specimen so that they were on a same vertical plane and formed plane-symmetric. In some other place three piezo transformers (PZT) were attached to generate pulses. They were resonant-type with central frequency of 30 kHz and used to obtain seismic wave velocity (V_p). During loading process, this investigation was periodically performed and the changes of V_p and more parameters such as amplitude and frequency were analyzed. The specimen was



Phograph 2. Rock specimen and AE sensors formation.

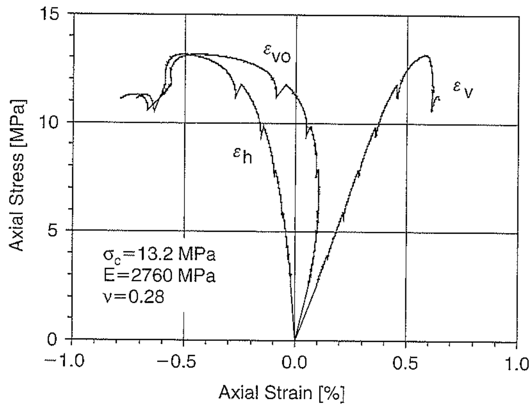


Figure 7. Uniaxial strength of test piece (Tage tuff).

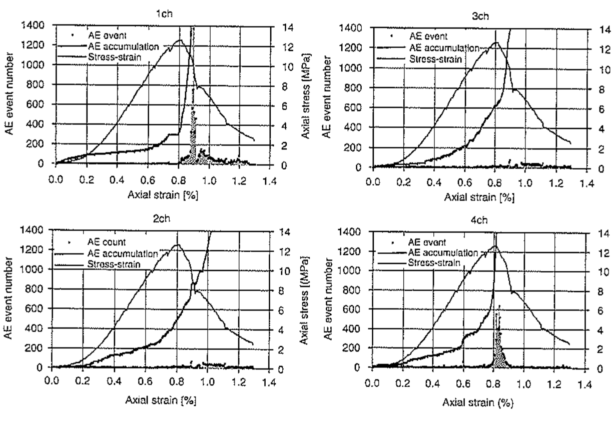


Figure 8. AE events on the loading process.

H200 × W100 × D100 size tuff rock whose uniaxial compression strength was 13 MPa, Young's modulus was 2.8 GPa and Poisson's ratio was 0.28 (see Figure 7).

4.2 *Result of the test*

4.2.1 *AE event*

The time history of the number of AE events measured by each FOD sensor at every loading step is shown in Figure 8. High rate (the number of events per time) zone can be observed when the axial stress achieved at its maximum, and then the rate at 1 ch and 4 ch were particularly high. Furthermore, by elapsed time analysis with event histories of 1 ch and 4 ch, the fact that the rate at 4ch previously achieved at peak before 1 ch can be found. It is expected that these time histories should rely on the fracture mode, that is, such a destruction formation that local mechanical fractures propagated from zone around 4 ch to 1 ch would occurred.

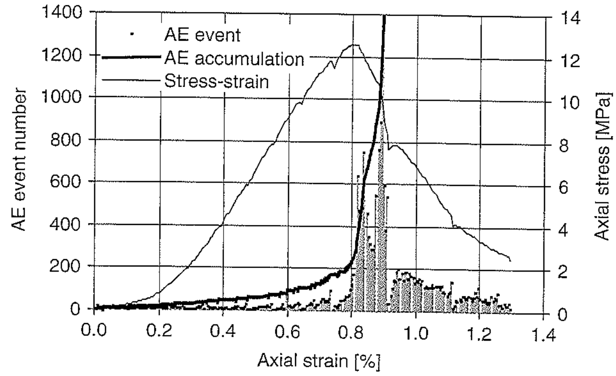


Figure 9. Total AE events on the loading process.

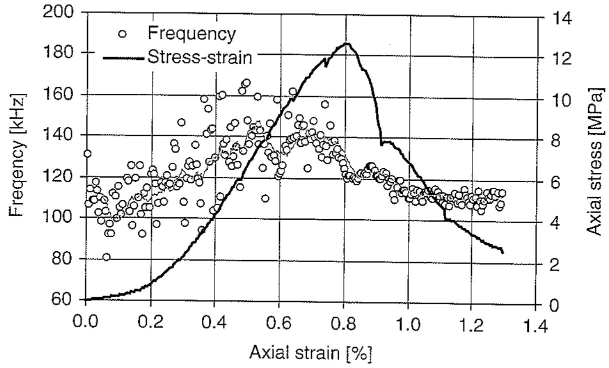


Figure 10. Frequency of AE wave on the loading process.

The total AE events measured by all of the four FOD sensors is shown in Figure 9. By the observation of AE accumulation, you can find that AE event had already begun to increase around the step of 0.6% axial strain, that is, 70% stress level of maximum.

4.2.2 *Frequency of AE wave*

Frequency of AE wave is shown in Figure 10. Before failure, the center frequency of AE became higher gradually along with the larger loading. And after fracture, the frequency of AE wave decreased again. These phenomena are explicable by strain-growing and softening mechanism in response to internal stress. What we should pay attention to is the fact that we can know when softening has begun by detecting the change of frequency of AE wave.

4.2.3 *b-value*

The change of b-value is shown in Figure 11. b-value is an statistical indicator calculated by following equation.

$$\log N(M) = a - bM \qquad (2)$$

where M is magnitude of seismic wave and $n(M)$ means the number of times of wave of which magnitude is M. You can find that b-value sharply decreased after failure. It is supposed that this change was caused by the influence of big and long period waves frequently arose after failure through the deformation along cracks.

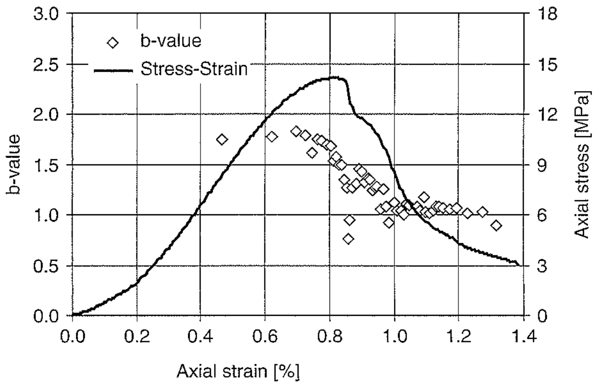


Figure 11. b-value of AE wave on the loading process.

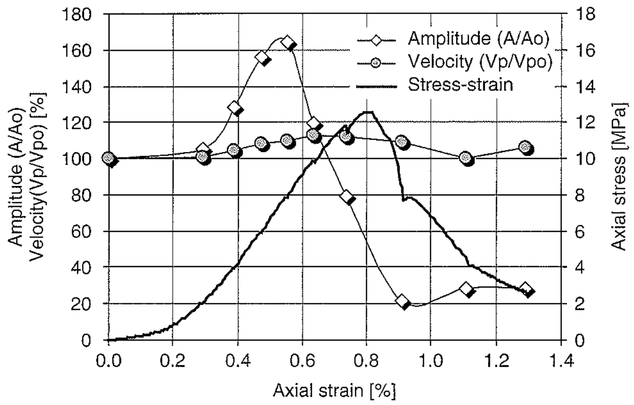


Figure 12. Velocity and amplitude of AE on the loading process.

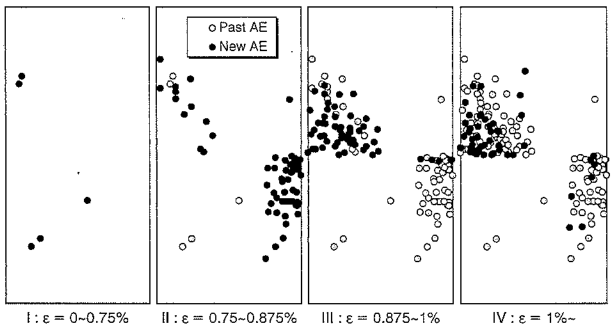


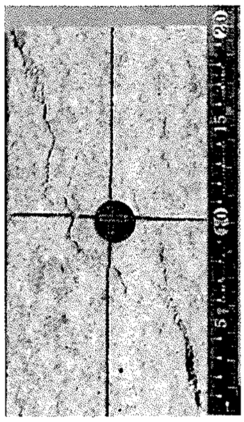
Figure 13. Estimation of the AE locations.

4.2.4 *Seismic wave parameters*

Velocity (V_p) and amplitude of AE wave during uniaxial compression are shown in Figure 12. There is a tendency for V_p to increase in response to loading, but the percentage of increase was 10% at most. On the other hand, amplitude (maximum amplitude value) of AE wave increased in response to loading, and the percentage of the increase reached 60%. Further, it decreased remarkably after failure. These phenomena mean that the rock hardening or softening arose whereby the crack growth or the change of the void generates in the specimen on the loading process.

4.2.5 *Source location of AE signal*

The result of estimation of AE locations is shown in Figure 13. At the early step of loading process most of location were concentrated in the right bottom zone near to the 4 ch FOD sensor. But as the fracture zone shifted to the left upper zone near to the 1 ch FOD sensor, the number of AE location near the 1 ch FOD sensor increased. It seems possible to capture the process of destruction of specimen using the time-scale estimation of AE locations.



Photograph 3. Test piece after failure.

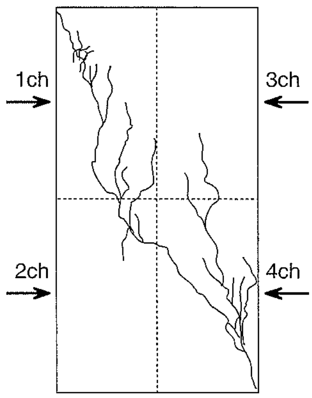


Figure 14. Sketch of the cracks generated on the test piece.

The photograph of the test piece after the experiment and the sketch of the cracks appeared on the surface of specimen are shown in Photograph 3 and Figure 14, respectively. By comparing the time-scale estimation of AE locations (see Figure 13) with these photograph and sketch, we can easily know seismic waves were frequently occurred along cracks. And from the result that AE event had already begun to increase around the step of 70% stress level of maximum (see Figure 9), it is possible to know by using FOD sensor system, when and where the rock will reach the mechanical limit before failure.

5 CONCLUSION

- AE measurement using newly-developed high sensitivity FOD sensor was performed at the rock compression experiment.
- The tendency for the frequency of AE wave to decrease during the destructive process was obtained.
- The velocity of seismic wave (V_p) slightly increased during the destructive process.
- The amplitude value of seismic wave jumped 60% during early loading step, and it decreased remarkably quite before axial stress achieved at its maximum. It is supposed that these phenomena were caused by such a mechanical change as crack growth.

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