Application of the Ultrasonic Propagation Time of a Core Sample for Stress Measurement of Underground Rocks*

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1. Introduction

It is important to know the stress state in underground rock mass for the design and evaluation of the stability of underground constructions. Various instruments for rock stress have been developed, and the local stress state underground has been estimated. Yamamoto et al.1) experimentally investigate the phenomenon of inelastic strain in a rock specimen increasing when the compressive stress applied to the rock specimen exceeded the previous maximum stress exerted underground. Based on this phenomenon, they proposed a method, called deformation rate analysis (DRA), for estimating rock stress acting in underground rock using boring core samples. This method is useful for estimating rock stress by easy measurements in the laboratory, although it has a poor theoretical basis2).3).

DRA is an application of the stress memory effect of rock, i.e., the rock stress to be exerted underground is evaluated by measuring the difference in deformation behaviors between the loading process up to the underground stress state and the higher loading level during the time when the rock sample is released from the underground stress state. This stress memory effect of rock is thought to be closely related to changes in the microstructures such as microcrack opening and closing, and rearrangement of components in rock.

Ultrasonic propagation has been used as a technique for indirect measurement of the structural changes inside a rock during loading. With the recent progress in measurement technology, a system that can measure propagation time with a nano-order accuracy has been developed, and this system has been applied to many engineering fields4). Therefore, this technique is applicable, as is the DRA method, for estimating stress in underground rock using core samples of rock.

In order to prove the applicability of the ultrasonic propagation time method for estimating rock stress, we conducted laboratory experiments using sandstone samples collected from Taiheiyo Coal Mine. After each specimen was loaded to memorize the artificial stress, the ultrasonic propagation time in the horizontal direction to the loading axis was measured during the cyclic loading process. The deformation rate was also recorded at the same time for a comparison of the results.

The experimental results confirmed that the propagation time of ultrasonic waves through a specimen under stress could be accurately measured and that a drastic change in the propagation time occurred when the loading level reached the previous maximum stress. This stress coincided with the stress obtained from the DRA method. These results indicated that it is possible to estimate the rock stress memorized in a rock sample by accurate measurement of ultrasonic
propagation time as an indirect method during the loading process. In this paper, we describe the experimental techniques and results.

2. Measurement System of Ultrasonic Propagation Time

Ultrasonic propagation time was measured by an apparatus (UVM-2, Ultrasonic Ind. Co., Ltd.) that uses the sing-around method. The sing-around method makes it possible to measure ultrasonic propagation with an accuracy in the nano-order. By this method, an accurate mean value of propagation times, calculated from the integration of propagation times, can be obtained by the repetition of a large number of ultrasonic transmission and reception cycles. The offset function of this instrument can eliminate noise in received signals and adjust the alternation of the sensor’s characteristics.

Fig. 1 shows a block diagram of the sing-around method. An incident ultrasonic wave, corresponding to an electric pulse generated by the pulse generator, was transmitted into the sample and detected by the receiver sensor. The received signal was fed into the gate-amp, and the signal was amplified up to a constant amplitude level by the auto-amp. The trigger was then set to the amplified signal to detect the zero-crossing time, and a trigger signal was generated by the trigger-amp. A certain delay time was set until the reverberation of the ultrasonic wave in the sample was extinct in the trigger-amp. This cycle of signal flow was repeated. In the experiments, the repetition of sing-around was set to 10,000 times, and the accuracy of the propagation time measurement became \(10^{-2}\) nsec.

3. Specimens and Experimental Procedures

To compare the reliability of rock stress estimation by ultrasonic measurement with that by DRA, Inada granite and Taiheiyo sandstone specimens were prepared for uniaxial compression tests. A specimen of Inada granite was cut in a square prism shape of about 30 mm \(\times\) 30 mm \(\times\) 60 mm from a cubic block of about 20 cm in side length. The sandstone sample was collected from an area of 6\`7 m above the roof rock of the roadway in Taiheiyo coal mine (-500 m sea level) by boring a section of 45 mm in diameter. From the boring core, the sandstone specimen was cut into the same shape as that of the granite specimen. The ends of these specimens were ground parallel and flat to within \(\pm 1/50\) mm. Before the loading tests, the specimens were dried in a desiccator for several weeks.

Fig. 2 shows the measurement system of ultrasonic propagation time and deformation rate. The diameter of the transmitter and receiver for ultrasonic waves was 25 mm, and the resonance frequency was 0.5 MHz. As shown in the figure, the ultrasonic sensors were cramped at the center of the right and left faces of the specimen by soft springs (reaction force is approximately 1.5 N) to decrease the constraint of lateral direction as far as possible. Thus, the ultrasonic propagation time was measured in the lateral direction of the specimen. During the tests, the transmitting pulses and receiving waveforms were continuously monitored by an oscilloscope. The recording interval of propagation time was set to 2.5 sec, and the time data was stored in a hard disk of a personal computer.

Ultrasonic propagation velocity has been used by some researchers to evaluate changes in the microstructure of rock samples. The reason for using ultrasonic propagation time in the present study, however, was because the length of the specimen was difficult to measure accurately with the same order of significant figures of the propagation time (nano-order).

The deformation rate was also measured by detecting strains. Two cross-type strain gages were cemented onto the side faces of the specimen to detect axial and lateral strains. The stain data were recorded on a hard disk of a personal computer after being amplified by a strain amplifier and digitized with a sampling frequency of 2 Hz.

All specimens were loaded under uniaxial stress conditions controlling the strain rate \(1.5 \times 10^{-5}/\sec\) of the specimens. The loading direction for the sandstone specimen was parallel to the core-boring axis at the sampling site in the coal mine, and the vertical direction to the grain-plane was chosen for the granite specimen.

4. Experimental Results

Figs. 3 and 4 show typical stress-strain and stress-
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ultrasonic propagation time curves for the sandstone specimens and the granite specimens, respectively. In these figures, strains are expressed by axial, lateral and volumetric strain curves. In both experiments, the propagation time became shorter with increases in stress and longer before the failure of specimens. These variations in propagation time almost coincided with the behavior of volumetric strain. Furthermore, the points of the time at which propagation time changed from decreasing to increasing corresponded to the beginning of dilatancy in the sandstone specimen, and appeared before dilatancy in the granite. These results agreed with the measurements by Kaneko et al.\(^5\).

Simultaneous measurements of the deformation rate and ultrasonic propagation time were conducted only for the sandstone specimen, considering the linearity of the propagation time prior to the failure as shown in Fig. 3 and that the depth of sampling site was known in the sandstone. In the next experiment, a cyclic loading pattern was used in order to make the sandstone specimen memorize a certain stress. Fig. 5 shows the loading pattern, divided into three stages. In the first stage, a maximum stress of 20 MPa was applied with 10 cycles of loading in order for the specimen to memorize a stress of 20 MPa. For estimating the maximum stress in the first stage and for memorizing the new stress, a stress of up to 35 MPa was applied with 5 cycles of loading in the second stage. For the same purpose, the specimen was loaded up to 50 MPa of stress with 5 cycles in the third stage.

Fig. 3 Stress-strain and stress-propagation time curves obtained under conditions of uniaxial compression on Taiheiyo sandstone.

Fig. 4 Stress-strain and stress-propagation time curves obtained under conditions of uniaxial compression on Inada granite.

Fig. 5 Loading pattern consisting of three stages to measure propagation time and deformation rate.

Fig. 6 Diagram of stress-strain and stress-propagation time curves obtained in the 1st, 4th and 9th cycles of 10 loading cycles in the first stage of the loading pattern.
different because propagation time reflects microstructural changes that occur inside the specimen much more than does the strain detected on the surface of the specimen.

Fig. 8 shows the stress-strain and the stress-propagation time curves of the 10th cycle in the first stage and the 1st cycle in the second loading stage. A comparison of the curves of the 10th cycle and 1st cycle shows that the slopes of the stress-strain curves up to 20 MPa were almost the same. Also, both curves of propagation time up to 20 MPa were nearly parallel except at the initial stress. However, the slopes of propagation time changed at the stress of 20 MPa, and the magnitude of hysteresis in the 1st cycle of the second loading stage was larger than that in the 10th cycle of the first stage. Furthermore, the initial propagation time in the 1st cycle of the second stage was different from the time curve at the end of the 10th cycle. This difference might be due to the time lag of about 30 minutes from the end of unloading in the 10th cycle to the beginning of the 1st cycle of the second loading stage.

Fig. 9 shows the results from the second loading stage. This figure shows that the strains increased slightly near the point of maximum stress in the 1st to 3rd cycle, although significant changes in strain were not seen throughout all the cycles. However, the propagation time in the 1st and the 2nd cycles was different. The propagation time curve of the 2nd cycle was non-linear at the initial stress, and the slope up to 20 MPa became almost same as that of the 1st cycle. Finally, the propagation time of the 2nd cycle became approximately the same value of the first loading at the maximum stress. On the other hand, the propagation time of the 2nd cycle during the unloading process (broken line) was not different from that of the 1st cycle. In the 3rd to 5th cycle, although the propagation time curves showed slight differences around the maximum stress, the hysteresis curves did not change.

Fig. 10 shows the stress-strain and the stress-propagation time curves of the 1st cycle in the third loading stage. The stress-propagation time curve of the 5th cycle in the second loading stage is also shown for reference. The slope of the propagation time changed at the maximum stress of the last loading stage in the same manner as that in the second loading stage as shown in Fig. 8. In other words, the curve was deflected at the memorized stress. The propagation time curve during unloading was similar to the curve of the loading-up process below the memorized stress. The propagation time curves of loading and unloading crossed at the memorized stress point. The magnitude of the hysteresis curve in Fig. 10 is smaller than that in Fig. 8. This may be due to the difference in the number of cycles required to memorize the maximum stress. The slopes of the axial and lateral strain curves tended to be slightly smaller above 35 MPa.
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5. Ultrasonic Propagation Time and DRA

Based on the strain data obtained from the experiment, estimation of memorized stress was tried by deformation rate analysis. In this analysis, the linear interpolating method developed by Fuji et al. was used with a stress-strain difference diagram instead of the strain difference function.

Fig. 12 shows the stress-axial strain difference diagram calculated from the axial strain data of the 1st cycle in the second loading stage. The vertical axis shows the axial strain difference, and the horizontal axis is the stress. The figure clearly shows that the axial strain difference curve changes to a negative slope near the memorized stress (20 MPa), and the memorized stress can be estimated satisfactorily.

However, as the propagation time was measured in a vertical direction to the loading axis of the specimen, it was necessary to calculate propagation time by DRA in the same manner using lateral strain. Fig. 13 shows the results of DRA using lateral strain based on the 1st cycle of the second loading stage. Although the curves fluctuated, the minimum points basically corresponded to the memorized stress.

Fig. 14 shows the results of DRA based on the axial and the lateral strain of the 1st cycle in the third loading stage. The peak points in the axial strain difference and the mini-
thought to be dependent on the characteristics of microcracks and the magnitude of the overburden stress at the sampling site. As a result, the followings are considered on the estimation of the stress along the horizontal direction of the specimens. Based on this estimation, the changes of ultrasonic propagation time enable the memorized stress in the direction of loading axis could be estimated by the deflection point on the propagation time curves shown in Fig. 7. As was the case with the DRA method, that is, the deflection point corresponds to the memorized stress point. However, the numerical order of the changing rate in propagation time at the memorized stress was very small. If the change in the propagation time at the memorized stress point was induced by progress of microcracks inside the rock specimen, it is expected that the slope of the lateral strain curve will also change at the memorized stress point. However, the degree of change in the present experiment was too small for it to be detected in the stress-strain curves. DRA could clearly show small changes in the lateral strain. However, as no change was found in the propagation time and lateral strains after the 2nd cycle in each loading stage, the memorized stress could not be estimated by DRA based on the lateral strain curves of the 2nd to 5th cycles in each loading stage. One possible reason for this was that new microcrack openings inside the rock specimen did not occur after the 2nd cycle loading.

A comparison of the propagation time and lateral strain curves of each loading stage showed that their behaviors had a linear relationship to increases and decreases in stress, except for the 1st cycle. The propagation time showed more complicated behavior than the lateral strain. The difference between them in the 1st cycle was thought to be caused by the difference in measurable area. While the propagation time reflects the microstructural change along the ultrasonic propagation path in the lateral direction, the strain gage detects local deformation on the surface of the specimen.

Originally, DRA was used as a method to estimate unknown stress received in the past time. In the present study, artificial stress memorized by loading could be estimated as a deflection point on the propagation time curves shown in Fig. 8 and Fig. 10, as was the case with the DRA method. That is, the memorized stress in the direction of loading axis could be estimated by the changes of ultrasonic propagation time along the horizontal direction of the specimens. Based on this result, the followings are considered on the estimation of the magnitude of the overburden stress at the sampling site.

The variation of ultrasonic propagation time was thought to be dependent on the characteristics of microcracks inside the specimen such as the number of cracks, the dimensions and the orientations. After the core sample was released from the field stress state by core drilling, it may have been deformed, depending on the three-dimensional stress condition accompanying microcrack generation inside the core. These microcracks, which have an anisotropic distribution in size and orientation, would affect the ultrasonic propagation time. In Fig. 7, the deflection point was not found clearly in the stress-propagation time curve of the 1st cycle in the first loading stage. This reason was considered to be caused by the above mentioned mechanism. Therefore, the another experiments using the sandstone specimens sampled at the same site of the previous experiments were carried out changing the direction of the propagation path of the ultrasonic wave.

Fig. 15 shows typical stress-propagation time curves obtained from these experiments. The direction of the loading axis was confirmed by the cyclic loading test shown in Fig. 7. A comparison of these three curves in Fig. 15 and Fig. 7 showed that the behaviors of the propagation time were dependent on the direction of the propagation path of the ultrasonic wave. In Fig. 15, the deflection points of the propagation time were found at the stress of about 135 MPa in the top figure and about 10 MPa in the bottom figure. It was confirmed that the former stress (135 MPa) estimated from the propagation time curve were approximately agreed with the overburden stress at the site estimated theoretically to be about 13 MPa. However, as the relationship between the variation of the ultrasonic propagation time and the characteristics of microcracks inside the specimen is not clear quantitatively,
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we are planning further experiments.

The results of this study showed that accurate measurement of ultrasonic propagation time allowed detection of delicate changes in the inner microstructure of a rock specimen undergoing a deformation process. This method could be useful for measuring rock stress from a core sample. More experimental data on the relationship between ultrasonic propagation time and stress memory effect of rocks are needed to clarify the mechanisms of microstructures inside rocks.

6. Conclusions

Ultrasonic propagation and axial and lateral strains were measured during uniaxial compression tests on Taiheiyo sandstone and Inada granite specimens. Using the single-around method, the propagation time could be measured with an accuracy in the order of 10^-2 nsec. Sandstone, which showed a relatively linear relationship between propagation time and strain with increases in stress up to failure, was used for the next cyclic loading test with stepwise increases in stress in order for the specimen to memorize the maximum stress in each stepwise stage. The ultrasonic propagation time in a horizontal direction to the loading axis was measured as well as the strains during loading.

The propagation time curve showed similar behavior to that of the lateral strain curve in all loading process except for the 1st cycle in each stress stage. The deflection points of the propagation time curves coincided with the memorized stress values and with the estimation points by DRA. This indicated that estimation of rock stress that had been exerted in the past was possible by accurate measurement of the propagation time during loading. Thus, accurate measurement of propagation time can also be a useful method for evaluating changes in the microstructure inside a rock specimen undergoing deformation.

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References