A new method for stress orientation measurements by using borehole deformation and its applications to the active faults

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A new sensor tool for borehole deformation using a laser displacement sensor has been developed for stress orientation measurement at shallow depths. The new method for estimation of stress field using this tool is based on following principles: 1) The borehole drilled in a stress field is quasistatically deformed due to viscous property of rock around a borehole. 2) The orientation of maximum horizontal compressive stress (SHmax) is determined from a minor axis of an ellipse fitted to a deformed shape of borehole cross section. One of the advantages of this method to estimate stress orientation is a remarkably lower cost than existing methods, such as stress release and hydraulic fracturing methods. Radial displacements of the borehole wall under creep deformation are measured with the laser displacement sensor rotating continuously around a borehole axis. A total resolution of $0.7\ \mu\text{m}$ is achieved by stacking of several thousands data. A field performance test confirms that the new tool can detect the creep deformation, about ten μm increasing of the borehole radius in a measurement of half a day just after drilling. After the performance test, we applied this new method to active faults in order to evaluate stress state of the faults. In the measurement for the Kego fault in Fukuoka Prefecture, western Japan, the average orientation of SHmax is about N60°E for the two measurement point around the southern edge of the fault. The estimated orientation is found to be unfavorable for a strike slip on the Kego fault. In the application to the Atotsugawa fault, central Japan, the orientation of SHmax is estimated to be ENE-WSW by the measurements in a mine cavity near the fault. This orientation is consistent with the trend of the directions of P-axes of the focal mechanism solutions of ultra-micro earthquakes along the fault.

1. INTRODUCTION

In-situ stress measurement has a very important role to many fields related to the Earth's crust or rock structure. For example, it is essential to evaluate stress field of active faults in seismogenic region in order to study a prediction of earthquake occurrence. Initial stress measurement is necessary for constructing underground openings.

The existing methods, such as stress release and hydraulic fracturing methods are generally used for stress measurement. However, these methods have some fundamental and/or technical problems, and various proposals are still performed to solve the problems. In addition, a common problem on applying the existing methods is very high cost for the measurements. Because of the high cost, the number of measurement points tends to be limited. This limitation makes it difficult to evaluate a typical stress state of inhomogeneous field.

To overcome these problems of the existing methods, we have developed a simple and low cost method based on new principal and a borehole tool

used in depth up to about 20 m. In this paper, we describe the development of the new method and tool, the results of field performance test and the applications to two active faults in Japan, the Kego fault and the Atotsugawa fault.

2. NEW METHOD AND TOOL FOR STRESS ORIENTATION MEASUREMENTS

A principle of the new method is to measure the creep deformation of the borehole just after drilled in the anisotropic stress field. The orientation of SHmax is able to be determined from a minor axis of an ellipse fitted to a deformed shape of borehole cross section. This direct measurement for the anisotropic deformation in the proposed method does not need to conduct an overcoring or to pump up a hydraulic pressure after drilling. Therefore the new method has an advantage of remarkably easier and lower cost than the existing methods.

For designing a new tool for the measurement,

we estimated the creep strain at 10 m depth in 24 hours just after drilling to be about $1.0\text{E-}6$. Laser displacement sensor is chosen to measure the above strain. Stacking of several thousands data obtained by laser sensor makes the resolution of about $0.1\text{ }\mu\text{ m}$ possible.

Figure 1 System diagram of the new tool of the laser scanner for borehole deformation (LAS-BD). The downhole tool is composed of a laser sensor with rotary mechanism, a digital compass for a tool direction measurement and centralizers. The data is transferred to the control and recording unit and the PC for data store and tool control.

System diagram of the new tool is shown in Fig.1. The laser displacement sensor located at the bottom of the downhole tool is rotated around 360 degrees continuously to measure radial displacement of borehole wall. Two centralizers are located to fix the tool in a borehole during measurement. The tool is designed to be applicable to the borehole of 116 mm in diameter because of the focus distance and a size of laser displacement sensor. The radial displacement is measured at each 2 degrees in rotation and the maximum stacking number is 7500 at $200\text{ }\mu\text{ s}$ sampling rate. It takes 6 minutes to rotate the laser sensor in one cycle. As the results of several operation tests in the laboratory, total resolution of the tool is estimated to be about $0.7\text{ }\mu\text{ m}$. The measurement using this tool will be conducted at the depth of about 10 - 20 m where the disturbance caused by thermally induced stress from surface is negligibly small. Table 1 shows the specification of the downhole tool.

The anisotropic stress field causes the cross

Table 1 Specification of the downhole tool.

Tool length	1500 mm
Tool diameter	100 mm
Tool weight	25 kg
Applicable hole size	116 mm
Maximum depth	20 m
Rotation speed of sensor	1 degree / s
Total resolution	$0.7\text{ }\mu\text{ m}$

section of the borehole to deform elliptically. We can fit the ellipse to the borehole cross section and determine the direction of axes of the ellipse, which coincide with the stress orientations. For the present the new method is applied to estimate a stress orientation, although magnitude and orientation of stress are needed to evaluate a stress field completely.

3. FIELD PERFORMANCE TEST

After the operational tests in the laboratory, we have conducted a field performance test in a former stone quarry in Tsukuba city, eastern Japan. The main purpose of the field test is to confirm that the new tool detects the creep deformation of the borehole just after drilling, which is predicted from the principal of this method. The borehole was drilled by the bit of 116 mm diameter and, fresh and hard granite were present at depths deeper than 3.3 m. The borehole deformation was measured at the depth of 11.4 m where the fracture is not detected by core inspection. The results of the measurement are shown as follows.

Radial displacements of the borehole for 137 laps were continuously obtained during about 14 hours in the night after drilling. We calculated the lengths of major and minor axes of an ellipse fitted to the borehole cross section at each lap. Time variations of the lengths are displayed in Fig.2. This figure indicates that the length of a major axis increased in half a day, although the value of the length at each lap has a perturbation of about $10\text{ }\mu\text{ m}$. As exponential curve is fitted to the variation of a major axis length, the length of major axis increased about $5\text{ }\mu\text{ m}$ from first to 20th lap, and increased about $5\text{ }\mu\text{ m}$ during the rest laps. The length of minor axis seems to increase slightly during the measurement, but the amount of increase is not clear because of the large error.

Figure 2 Time variations of the lengths of major and minor axes of an ellipse fitted to the borehole cross section at each lap in field performance test. Closed circles and open squares denote lengths of major axis and of minor axis, respectively. It is confirmed that length of a major axis increased about ten μ m in half a day. The exponential curve is to show fitting to the variation of a major axis length. The dashed curve is an extrapolation of the variation of major axis if the measurement was started just after borehole drilling.

Figure 3 The relative change of the borehole shape estimated from the difference between the averaged radius for the data from the first to the fifth lap and that from the 128th to the 137th lap in field performance test. Moving average for 20 degrees is applied to this data. The thick circle indicates the radius change of zero. The orientation of major axis is obtained by the elliptic approximation. The SHmax orientation can be determined as N45.0° E.

We analyzed to fit the ellipse to the relative change of the borehole cross section from just after drilling to about 14 hours after drilling in order to estimate the orientation of SHmax. The borehole cross section just after drilling and that at 14 hours after drilling were obtained from the averaged data from first to 5th lap and from 128th to 137th lap, respectively. Fig.3 shows the relative change of the borehole shape and orientation of SHmax estimated from elliptic approximation. The orientation of SHmax at this measurement point can be determined as N45.0°E. There is some possibility that this orientation of SHmax is not due to a tectonic stress field, considering the effect of isostasy caused by the unloading act in the former stone quarry and the topographic effect near the measurement point.

4. APPLICATION TO THE KEGO FAULT

The Kego fault is a NW-SE trending left-lateral strike slip fault with a west-raised component, running through the central part of the densely populated Fukuoka city, western Japan. The length of the fault is estimated to be 22 km. The 20 March 2005 West off Fukuoka Prefecture Earthquake (Mj 7.0) occurred in northwestward of the Kego fault and the aftershock region of the earthquake was roughly parallel to the strike of the fault (Fig.4). Toda and Horikawa (2005) calculated Coulomb stress change on the Kego fault caused by the earthquake and indicated the possibility that the earthquake probability along the Kego fault for the next 30 years was raised up to about 7 % due to the stress increase from the 2005 earthquake. Therefore, we have measured the stress orientation around the Kego fault in order to evaluate the stress state on the fault (Kiguchi and Kuwahara, 2006).

We tried to choose the locations for the measurement to estimate a degree of a present effect of stress release due to a former earthquake on the fault. First we calculated distributions of stress orientation around the southern edge of the Kego fault due to a far field stress with the direction of N80°E. Fig.5 (a) shows the stress orientation for the case of 100 % stress relief on the fault. The classified area in Fig.5 corresponds to the perturbation of stress orientation compared with far field. Fig.5 (a) indicates quite a large perturbation near the fault. As shown in Fig.5 (a), (b) and (c), the smaller the amount of stress relief on the fault is, the less the perturbation of stress orientation is. As the results of the calculation, the change of the stress orientation corresponded to the amount of the

stress relief on the fault is remarkable around the edge of the fault. The change rate of the orientation is considered to be large near the fault, while the stress orientation far away from the fault is almost same of the far field stress. Therefore, it will be possible to evaluate the amount of the stress relief on the Kego fault by compared the relationship of the measured stress orientation and the distance from the fault with the result of the calculations. We chose three locations for the measurement around the southern edge of the fault, where the distance from the fault is 1 km, 2 km, and 4 km, respectively.

The measurements were conducted at three depths with 1 – 3 m intervals in each location. The measurements were successful in two locations, while the third one was not perfect because of an unexpected thick weathering layer where the measurement was difficult. The orientations of the SHmax were determined to be NE to ENE for the locations with distances of 2 km and 4 km, respectively, from the fault (Fig.4). Data scatter even in one location was about 20°, which is too large to evaluate the perturbation of the stress orientation field around fault edges due to a former earthquake. The average orientation of SHmax is about N60°E for the both locations. The estimated orientation is found to be unfavorable for a strike

Figure 4 Location of The 2005 west off Fukuoka Prefecture earthquake, aftershock region and Kego fault. SHmax orientation estimated at No.2 and No.3 measurement points are indicated as bold lines. The orientation estimated at 3 depths in each location is overlaid on the map. Estimated orientation has a large angle to the strike of the Kego fault.

slip on the Kego fault. One of possibilities of tectonic meanings of the present result is a considerable component of reverse faulting on the fault. However, further studies on various data such as geodetic measurement and stress at large depths are necessary.

Figure 5 Example of stress field calculation around the south edge of the Kego fault. (a) Distribution of stress orientation for the case of 100 % stress relief on the fault. The classified area corresponds to the perturbation of stress orientation compared with far field. There is quite a large perturbation near the fault. (b) The same as (a) for 70 % stress relief. (c) The same as (a) for 30 % stress relief.

5. APPLICATION TO THE ATOTSUGAWA FAULT

The Atotsugawa fault in central Japan is an

ENE-SWS trending right-lateral strike slip fault with the length of about 60 km. A recurrence interval of large earthquake of the fault is considered to be about 2000 years by paleoseismological observations and latest activity is thought to have occurred in 1858. Several observations indicate that the fault can be divided into two types of segment, the rocky segment and the creep one. The amount of this creep was measured as about 1 mm / year by optical distance method. The stress state on the creep segment of the fault is a fundamental problem to understand the mechanics and strength of fault.

The measurements of stress orientation have been performed at two depths of 16.8m and 17.7m in a vertical borehole (Kuwahara et al., 2005). The borehole was drilled in a mine cavity near the creep segment of the Atotsugawa fault in Gifu Prefecture. The results of the measurements are summarized as follows:

1) A theoretical elliptic borehole deformation has been successfully observed. Major and minor axes are elongated by 3-5 μ m and shortened about by 5 μ m, respectively. Almost all the amount of the deformations is achieved in a first few hours.

2) An orientation of the minor axis is ENE-WSW, which can be regarded as SHmax direction (Fig.6). This orientation is consistent with the trend of the directions of P-axes of the focal mechanism solutions of ultra-micro earthquakes along the fault.

Figure 6 Orientation of SHmax estimated in the vicinity of the creep segment of the Atotsugawa fault, central Japan (thick line). Thin lines along the Atotsugawa fault show the directions of P-axes of the focal mechanism solutions of ultra-micro earthquakes. Rose diagram indicates the distribution of the directions of the P-axes.

3) Other creep deformations with various shorter wavelengths than the theoretical anisotropic deformation have been observed. The amplitude of the short wavelength deformations is compatible with the anisotropic deformation. These deformations are probably due to nonuniform distribution of viscoelastic properties of rock.

In addition to this new method, several methods to measure in-situ stress were applied in the same borehole, such as hydraulic fracturing, stress relief and ASR. The direction of SHmax estimated by the borehole deformation will be compared with the results of other methods.

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