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A New Method Developed for Rock Stress Measurement at Deep Depth in High Temperature Environment

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ABSTRACT

Core samples expand radially in anisotropic manner at core drilling by relief of anisotropic rock stresses, and as a result, they become to have a very slight elliptical cross section. In this study, we proposed and verified experimentally a new concept to modify the way of core drilling so that a partial section of the core sample expands to have elliptical cross section as described above but the other section maintains circular cross section before expansion. From this core sample, we can measure how much the core expands in any direction due to the stress relief with drilling, and the measured amount of expansion allows to estimate the magnitudes of in-situ stresses. This method does not require any in-situ test such as hydraulic fracturing and over-coring, it should be applicable to high temperature environment even in supercritical geothermal field, as long as the core samples can be obtained.

1. INTRODUCTION

The rock stress is important to all subsurface energy activities and to geothermal energy development in particular (e.g., GeoVision Report, 2017). This is because stress state dictates the extent, orientation, and size of fracture networks which provide the required permeability for a geothermal reservoir. The rock stress has independent three components which are the vertical stress and the maximum and minimum stresses in the horizontal plane. The vertical stress can be estimated to be overburden stress from depth and rock density as hydrostatic pressure of pore water, but there is no way to estimate the magnitudes and directions of the maximum and minimum horizontal stresses, S_{Hmax} and S_{hmin}, other than measuring directly. On the other hand, the hydraulic fracturing and the over-coring stress relief methods are known as standard methods of stress measurements. They require to carry out in-situ tests using downhole tools in borehole at depth, but it is basically difficult to carry out those tests at depth of km order, and the downhole tool cannot survive in geothermal wells at high temperature exceeding 200 ^{o}C. There has not yet been established any methods that can be applied to measure rock stress directly at depth of km order in such high temperature environment.

In this situation, we have proposed a new method of stress measurement using core samples (Funato and Ito, 2017). The cores are generally thought to have circular cross sections. This idea is roughly correct but not exactly. By releasing the compressive strain of rock mass due to drilling, the cores expand radially in anisotropic manner associated with the anisotropic stress magnitudes, and as a result, they become to have a very slight elliptical cross section. The deformation can be represented theoretically. The rock stress originally subjected to the cores before drilling can be estimated from cross sectional shape of the core measured on ground after retrieving. Since this method does not require the in-situ test, it should be applicable to high temperature environment even in supercritical geothermal field, as long as the cores can be obtained. However, the original version of this method can measure only the difference between S_{Hmax} and S_{hmin}.

In this present study, we proposed a new idea to improve the method of Funato and Ito (2017) so that each magnitude of S_{Hmax} and S_{hmin} can be measured. To do this, we modify the way of coring so that a partial section of a core sample expands to have elliptical cross section due to stress relief but the other section maintains circular cross section before expansion. From the core sample drilled in this way, we can measure how much the core expands in any direction, and the measured amount of expansion allows us to estimate the stress magnitude in the measured direction including S_{Hmax} and S_{hmin}. This idea was verified successfully by laboratory experiments.

2. CORE DEFORMATION CAUSED BY STRESS RELIEF WITH DRILLING

We describe here briefly the theoretical relationship between the rock stress and the core deformation caused by the stress relief, which has been shown in Funato and Ito (2017). During the core drilling, a core bit cuts into the exposed surface of rock at the bottom of a borehole with a rotating motion, and as a result, a column of rock is cut out to be a core. The cross section of the column at the cutting edge should be perfectly circular in diameter d_0, since the column is cut out by a rotating bit and the column at the cutting edge should be restricted its deformation by the surrounding rock mass. However, the same cross section of the column being away from the cutting edge becomes able to expand freely from the surrounding rock mass in response to the relief of the rock stresses. Such deformation of the column occurs continuously with drilling. Then the core expands most and least in the directions of S_{Hmax} and S_{hmin} which are the maximum and minimum horizontal stresses in a plane perpendicular to the borehole, respectively. As a result, the core becomes uniform in cross sectional shape with the maximum and minimum diameters, d_{max} and d_{min}, as illustrated in Fig. 1. Assuming linear elastic deformation, the core diameter d_θ at a circumferential angle θ from a reference position is theoretically given by

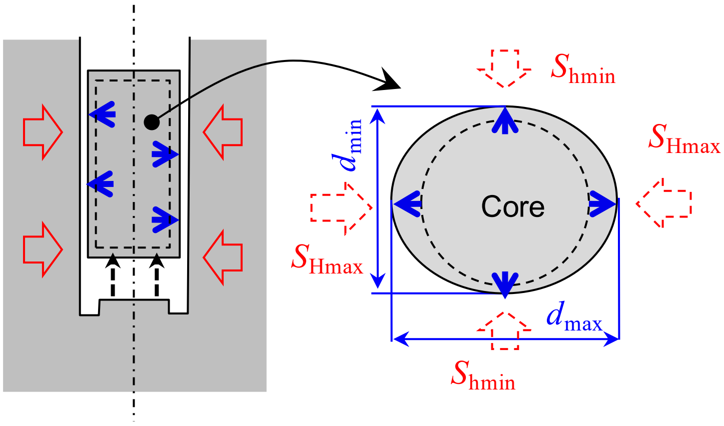

Figure 1: Core expansion caused by stress relief with drilling.

$$d_\theta = \frac{d_{max} + d_{min}}{2} + \frac{d_{max} - d_{min}}{2}\cos 2(\theta - \alpha) \tag{1}$$

where α is the value of θ at the direction of d_{max}.

The stress relief with coring induces strains in the core, which is the same as those induced in the rock mass when it is fully relieved from the in-situ stresses. The strains ε_{max} and ε_{min} in the directions of d_{max} and d_{min} respectively are given as a function of the in-situ stresses of horizontal and vertical components S_{Hmax} and S_{hmin} and S_v as follows,

$$\varepsilon_{max} = \frac{d_{max} - d_0}{d_0} = \frac{1}{E}\{S_{Hmax} - \nu(S_{hmin} + S_v)\} \tag{2}$$

$$\varepsilon_{min} = \frac{d_{min} - d_0}{d_0} = \frac{1}{E}\{S_{hmin} - \nu(S_{Hmax} + S_v)\} \tag{3}$$

where d_0 is the original core diameter before expansion, and E and ν are the Young's modulus and Poisson's ratio of the rock, respectively. From those equations, we have

$$S_{Hmax} - S_{hmin} = \frac{E}{1+\nu}\frac{d_{max} - d_{min}}{d_0} \approx \frac{E}{1+\nu}\frac{d_{max} - d_{min}}{d_{min}} \tag{4}$$

This equation gives the original idea of Funato and Ito (2017) that the differential stress (S_{Hmax} - S_{hmin}) is determined from the measured core diameters of d_{max} and d_{min} assuming known elastic properties E and ν.

3. CONCEPT OF DUAL BIT CORING

The reason for stress estimation limited to the difference (S_{Hmax} - S_{hmin}) in the method of Funato and Ito (2017) is come from the difficulty to measure the original core diameter d_0 before expansion. If d_0 is known, each one of the horizontal stresses S_{Hmax} and S_{hmin} can be estimated from the measured d_{max} and d_{min} and Eqs. (2) and (3) assuming S_v to be estimated from rock density and depth as usual. However, the core becomes d_0 in diameter momentarily at the cutting edge as described above, and it is obviously impossible to measure d_0 there directly. To address this problem, we propose a new concept of Fig. 2.

In the new concept, we modify the way of core drilling. First, a core bit 1 cuts a circular groove into the exposed surface of rock at the bottom of a borehole and stops when the groove reaches a depth L_1 which is equivalent to the borehole diameter. There remains a column inside the groove, and its upper part A should expand in response to the relief of the rock stresses. Next, another bit 2 cuts another circular groove with a smaller diameter until the groove reaches a depth L_2 which is few times larger than L_1. In this case, the upper part B of the secondary cut-out column should not expand anymore, since the stresses has been relieved there already by cutting the first groove. Therefore, the upper part of the second column should be maintained at d_0 in diameter. Contrary to this, the lower part of the second column should expand in response to the relief of the rock stresses. Finally, the second column is cut out from the surrounding rock mass and retrieved to the ground surface with coring bits. The grooves cut at first and second are hereafter referred to the outer and inner grooves, respectively.

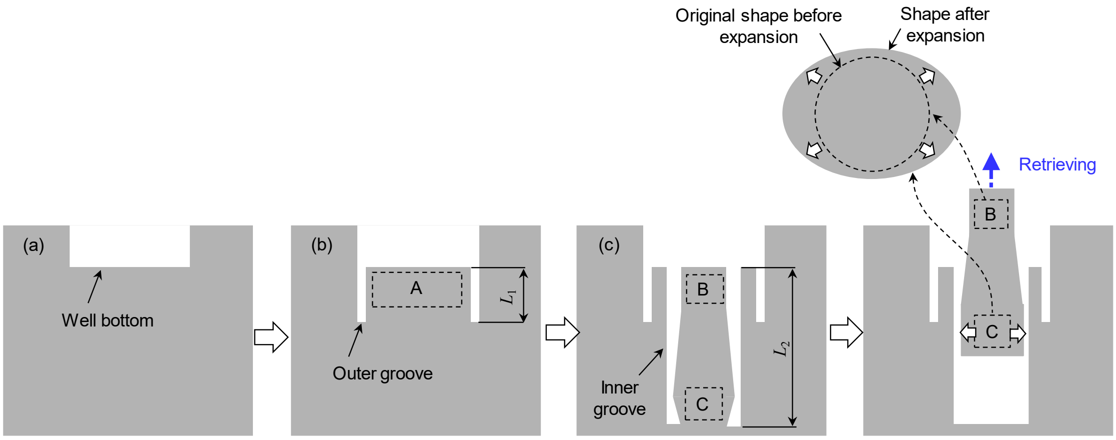

Figure 2: A Newly proposed procedure of core drilling by dual core bit.

Figure 3 shows an idea of coring tool to realize the concept described above. This tool has a special feature to have dual coring bits with large and small diameters, which are used for cutting the outer and inner grooves, respectively. The large bit is initially fixed with a drill rod for cutting the outer groove, and it is unfixed for cutting the inner groove by the small bit. The fixing and unfixing the large bit with a drill rod can be realized for example by the mechanism of "J-slot" which is well-known as a simple yet reliable means of downhole tool activation. This tool works mechanically and does not require basically any electric devices which are sensitive to high temperature. Therefore, this tool is expected to be used even in a high temperature rock at geothermal fields.

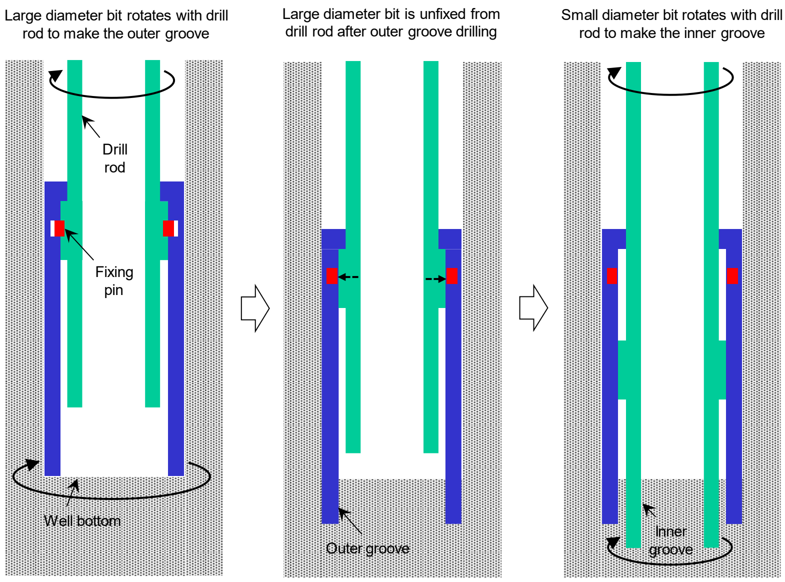

Figure 3: An idea of dual core bit and its operation.

4. LABORATORY VERIFICATION

In order to verify the new concept, we carried out laboratory experiments as shown in Fig. 4a. We used a cubic specimen made of Honkomatsu andesite with side lengths of 200 mm. The Young's modulus E and Poisson's ratio ν of the rock are 31 GPa and 0.16, respectively. The specimen was set to a steel frame and biaxial compressive stresses S_{max} and S_{min} were applied horizontally using a pair of flat jacks. While applying S_{max} and S_{min}, the specimen was drilled vertically by using each one of two coring bits with ϕ50 and ϕ32 inner diameters. Figure 4b illustrates a vertical cross section of specimen after drilling by the two coring bits. There are two grooves which correspond to the outer and inner grooves described in the previous section. First, the outer groove of 65 mm deep (=L_1) was cut by the bit with ϕ50 inner diameter. Second, the inner groove was cut by the bit with ϕ32 inner diameters, where this groove passed through the specimen. Figure 4c shows top view of a specimen after the core drilling. The obtained core was subjected to diameter measurement using an originally-designed apparatus. The apparatus allows to measure the core diameter by an optical micrometer with the accuracy of 3 μm and the repeatability of 0.2 μm, and this measurement is carried out continuously while a core sample is rotated on two rollers at a constant speed to obtain circumferential distribution of the core diameter. The micrometer has a function to give the diameter averaged over an arbitrary width w_m in the axial direction of core between a few and several tens of mm. In this experiment, no vertical stress was applied to the specimen. Therefore, from Eqs. (2) and (3) substituting S_{Hmax}, S_{hmin} and S_v with S_{max}, S_{min} and zero, respectively, the magnitudes of S_{max} and S_{min} are given as follows,

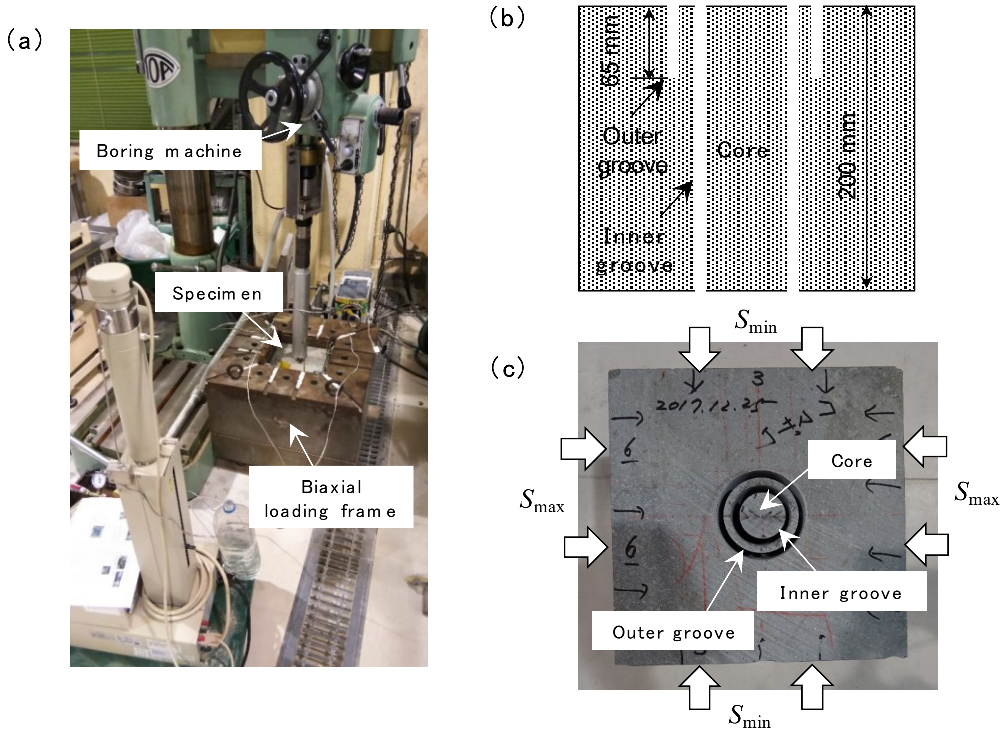

Figure 4: (a) Set up of laboratory experiment, (b) vertical cross-section of specimen and (c) top view of specimen after core drilling.

$$\boldsymbol{S}_{\mathbf{max}} = \frac{\boldsymbol{E}}{(\mathbf{1}-\boldsymbol{\nu}^{\mathbf{2}})}(\boldsymbol{\varepsilon}_{\mathbf{max}} + \boldsymbol{\nu}\boldsymbol{\varepsilon}_{\mathbf{min}}) \tag{5}$$

$$\boldsymbol{S}_{\mathbf{min}} = \frac{\boldsymbol{E}}{(\mathbf{1}-\boldsymbol{\nu}^{\mathbf{2}})}(\boldsymbol{\varepsilon}_{\mathbf{min}} + \boldsymbol{\nu}\boldsymbol{\varepsilon}_{\mathbf{max}}) \tag{6}$$

where ε_{max} and ε_{min} are determined from the measured d_{max}, d_{min} and d_0 (see Eqs. (2) and (3)).

We summarized here the results of experiment at setting S_{max} and S_{min} of 6 and 3 MPa, respectively. Figure 5 shows circumferential distribution of the measured diameter at distance 150 mm in the axial direction away from the upper end of the core. The measurements were carried out at every 0.4° in the rotation angle and the width w_m of averaging window was fixed to be 5 mm. The horizontal axis θ is defined as the clockwise angle taken from the direction of S_{min}. The measured diameter variation in blue is well fitted to a sinusoidal curve in pink of Eq. (1) by least square regression resulting in the best estimations of d_{max}, d_{min} and α to be 31.64372, 31.63937 mm and 81.4 deg., respectively. The diameter measurement was repeated for entire body of the core at every 5 mm in the axial distance x from the upper end. The resulted best estimations of d_{max}, d_{min} and α are summarized in Figs. 6a and b. Note that the bottom of the outer groove is located at the distance $x = 65$ mm. Whereas the diameter seems to increase continuously with x, the diameter variation should be characterized separately in four regions I, II, III and IV shown in Fig. 6a from the view point of the rock stress subjected to the rock portion to be cut out as the core at drilling. In I, the rock portion was located inside the outer groove. The stress should be there nearly zero, and the core should not expand at drilling. In II, the stress should be magnified by stress concentration due to the bottom shape of the outer groove, and the core should expand significantly in response to the stress relief with drilling. In III, the stress should be equal to S_{max} and S_{min} applied to the specimen, the core should expand accordingly with drilling. In IV, the stress should be disturbed by the interaction between the bottom surface of the specimen and the bottom shape of the inner groove, which should be significant as the inner groove approaches the bottom surface with drilling. Based upon these considerations, we measured the diameter averaged over the distance between 15 and 35 mm within the region I and that between 125 and 155 mm within III. The results for I and III are shown in Fig. 7a and b, respectively. Figure 7a shows that the diameter is almost constant at any direction angle, as we expected. The diameter is 31.6369 mm on overage, which is shown by a green line in the figure. The diameter should correspond to the original diameter d_0 before expansion. On the other hand, Fig. 7b shows that the core diameter varies with direction angle in sinusoidal manner, and the theoretical curve fitting gives the best estimations of d_{max}, d_{min} and α of 31.6434, 31.6393 mm and 91.6 deg., respectively. The theoretical curve is shown in pink in the figure. The estimated value of α is almost equal to the actual value of 90 deg.. By putting those estimated values of d_0, d_{max}, d_{min} into Eqs. (5) and (6), we obtain the stress magnitudes S_{max} and S_{min} of 6.9 and 3.4 MPa, which are close to the actual values of 6 and 3 MPa, respectively.

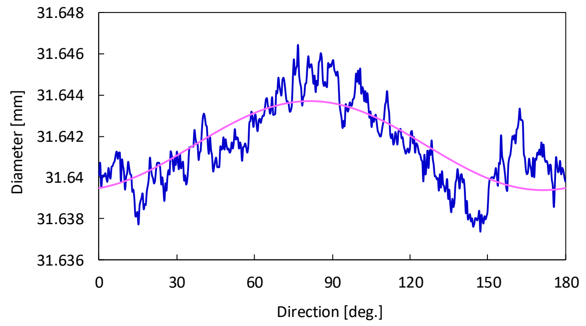

Figure 5: Circumferential distribution of measured core diameter at distance 150 mm in axial direction away from upper end of core.

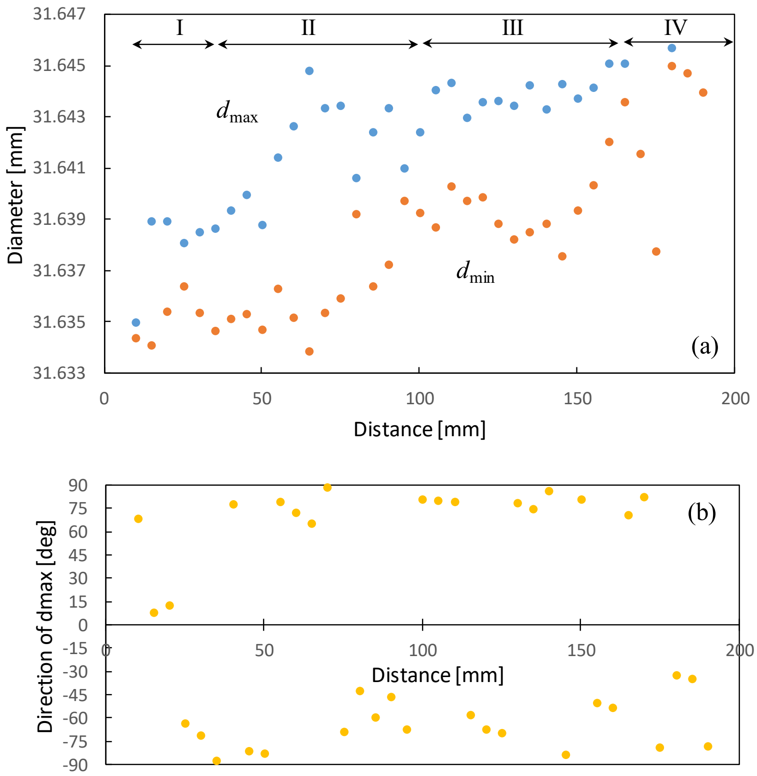

Figure 6: Variation of d_{max}, d_{min} and α with distance along core axis.

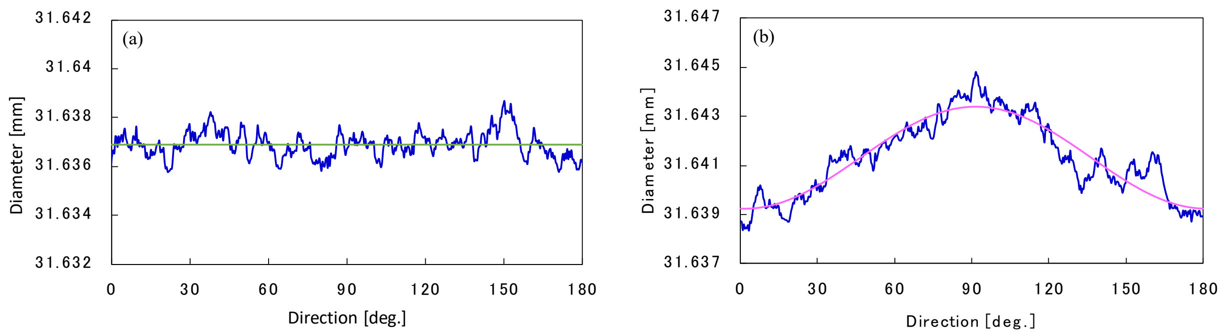

Figure 7: Circumferential distribution of measured core diameter averaged over the distance between (a) 15 and 35 mm and (b) 125 and 155 mm, respectively.

5. CONCLUSIONS

The reason for stress estimation limited to the difference (S_{Hmax} - S_{hmin}) in the method of Funato and Ito (2017) is come from the difficulty to measure the original core diameter d_0 before expansion, where S_{Hmax} and S_{hmin} are the maximum and minimum horizontal stresses. If d_0 is known, each one of S_{Hmax} and S_{hmin} can be estimated from the measured maximum and minimum core diameters d_{max} and d_{min}. To realize this, we modified the way of core drilling. First, a core bit cuts a circular groove into the exposed surface of rock at the bottom of a borehole. Next, another bit cuts another circular groove with a smaller diameter until the groove reaches a depth which is few times larger than the first groove depth. In this case, the upper part of the secondary cut-out column should not expand anymore, since the stresses has been relieved there already by cutting the first groove. Therefore, the upper part of the second column should be maintained at d_0 in diameter. Contrary to this, the lower part of the second column should expand to have d_{max} and d_{min} in response to the relief of rock stresses. In order to verify the new concept, we carried out laboratory experiments. Being subjected to biaxial compressive stresses S_{max} and S_{min}, the specimen was drilled vertically by using each one of two coring bits with ϕ50 and ϕ32 inner diameters to get a core. We detected successfully the values of d_0, d_{max} and d_{min} from the core. The S_{max} and S_{min} estimated from those detected values were very close to those actually applied to the specimen.

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