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SIGNIFICANCE OF CRACK OPENING MONITORING FOR DETERMINING THE GROWTH BEHAVIOR OF HYDROFRACTURES

Toshiyuki Hashida, Kazushi Sato and Hideaki Takahashi

Research Institute for Fracture Technology
Tohoku University
Sendai/980, Japan

ABSTRACT

A method for determining the size of a crack induced by hydraulic fracturing is presented. The procedure is based on the measurement of the crack opening displacement and the fracture mechanics approach. The proposed method has been tested by conducting laboratory small-scale hydraulic fracturing tests on a granite. It is shown from the preliminary tests that the method provides a reasonable prediction of experimentally observed crack sizes.

INTRODUCTION

Massive hydraulic fracturing is one of the most promising means for enhanced recovery of geothermal energy from a deep rock mass. In this application of hydraulic fracturing, it is useful to develop a methodology for the design and control of an artificial crack to be used as heat exchanging surfaces. The evaluation of the size of the crack should be based on the fracture mechanics (Abe, H. et al, 1976, Simonson, E.R., 1976, Takahashi, H. and Abe, H., 1987). Conventionally, the size of the crack by means of hydraulic fracturing has been predicted using the fracture toughness and the volume of the fluid injected, assuming that an estimate of the volume of the induced crack is provided from the fluid volume injected. However, no established method for determining the in-situ fluid loss during hydraulic fracturing exists. It is known that the fluid permeation into a surrounding rock mass strongly depends on pre-existing fractures in actual geothermal reservoirs.

In this paper, we propose a method, which is based on the monitoring of the crack opening displacement and the fracture mechanics approach, to evaluate the size of hydrofractures. Firstly, laboratory small-scale hydraulic fracturing tests were conducted on various sized specimens of a granite, and the results were analyzed in terms of the crack propagation resistance in order to determine a suitable fracture toughness. Secondly, a specially designed deformation gage was applied to preliminary hydraulic fracturing tests to monitor the crack opening behavior. Based on the measured crack opening displacement and fracture toughness, the size of the crack was predicted and compared with experimental observations. It is suggested form the preliminary result that the proposed method provides a potential means for analyzing the crack growth behavior in hydraulic fracturing.

EXPERIMENTAL PROCEDURE

(1) Laboratory small-scale hydraulic fracturing tests

The rock tested in this study was a granite from a quarry in Iidate, Fukushima prefecture, Japan. Iidate granite is a light gray biotite granite. The rock has a rift plane typical of granites. As described below, all the hydrofractures propagated along the rift plane.

A series of hydraulic fracturing tests were conducted on rectangular specimens of various sizes. The geometry and dimensions of the specimens are shown in Fig. 1 and Table1, respectively. Hereafter, the size of the specimens are nominally designated by 15 cm, 20 cm, 30 cm, 50 cm, and 1 m. Simulated vertical boreholes were drilled in the center of all specimens, and bilobed pre-notch was introduced on the borehole to facilitate the analysis of crack propagation resistance. The depth of the pre-notches a_i/λ was approximately 0.5. In most tests the diameter of the holes was 15 mm, but diameter of 29 mm was used for crack opening monitoring experiments. Hydraulic fracturing was achieved by pressurizing the borehole using rubber packers. The pressurization was provided by a plunger pump at a flow rate of approximately 0.2 ml/sec. The rubber packers were made of hard rubber belt-shaped O-rings mounted on a steel shaft through which injection fluid was pumped into the open hole. Dyed hydraulic oil was used as the injection fluid to delineate the shape of the hydraulically induced crack. The viscosity of the injection fluid was 14 cSt. In order to analyze the crack growth behavior rubber packers with different pressurization intervals were utilized to extend the crack step by step in such a way that the subsequent injection interval enclosed the crack created at the preceding stage. During fracturing tests, the borehole pressure vs time was recorded in an X-Y plotter. After the tests, the specimen was broken open along the dyed crack plane, and the fracture surfaces were examined in detail. To determine the fracture toughness of the granite, J-based fracture tests were conducted on 3 inch compact tension specimens. For the experimental procedure of the J-based method, see the literature (Li, V.C. et al, 1987)

(2) Method for monitoring the crack opening displacement

In order to measure the crack opening displacement of hydrofractures, a special displacement gage was made in this study. A schematic of the displacement gage installed between the two rubber packers is given in Fig. 2. The displacement gage consists of three pairs of double cantilever beams. Strain gages are cemented to the both surfaces of each beam and connected as a Wheatsone bridge. The displacement gage monitors the displacement of the borehole wall in three orientations through a sensing steel rod. As indicated in Fig. 3, the instrumented packer with the displacement gage was set in the borehole such that the borehole deformation perpendicular to the rift plane can be monitored during hydraulic fracturing tests. Two specimens of 50 cm size were used for this series of tests. The pressurization interval was 15 cm.

STRESS INTENSITY FACTORS FOR THE FRACTURE MECHANICS ANALYSIS

As shown below, the shape of the hydraulically induced fracture can be approximated by an elliptical crack. In this section, the stress intensity factor of semi-elliptical surface cracks on a borehole is presented.

For semi-elliptical surface cracks on a cylindrical cavity in an infinite elastic body subjected to a constant pressure P acting on the crack surfaces and on the surface of the cavity (see Fig. 4), the stress intensity factor at the deepest point of the crack is written as follows

$$K= M_o P(\pi a)^{1/2}/E(k), \qquad k=[1-(a/c)^2]^{1/2} \qquad (1)$$

where M_o is a correction factor, and E(k) is the complete elliptical integral of second kind. Abē et al have found that an approximate estimate of the stress intensity factor at the deepest point can be obtained from a solution for a two dimensional crack irrespective of different aspect ratios (Abē, H., et al, 1985). The relation is given by

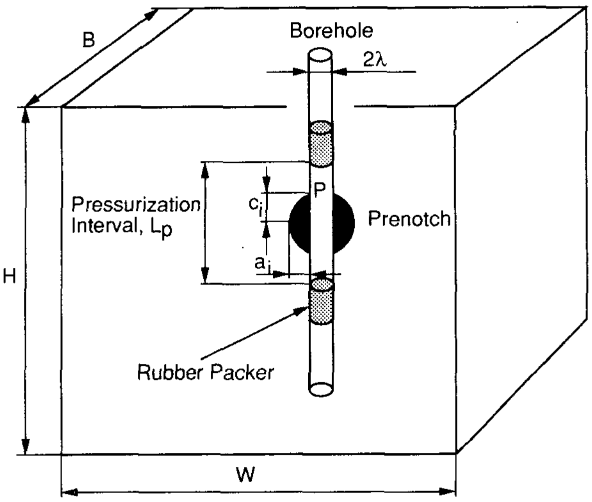

Fig. 1. Specimen used for hydraulic fracturing tests.

Table 1. Dimensions of specimens used.

Nominal Specimen Size	W (cm)	B (cm)	H (cm)	Borehole Diameter 2λ (mm)
15 cm	15	15	15	15
20 cm	20	20	20	15
30 cm	30	30	30	15
50 cm	50	50	50	15
50 cm *	70	50	50	29
1 m	100	100	100	15

* Borehole deformation was measured during the hydraulic fracturing tests

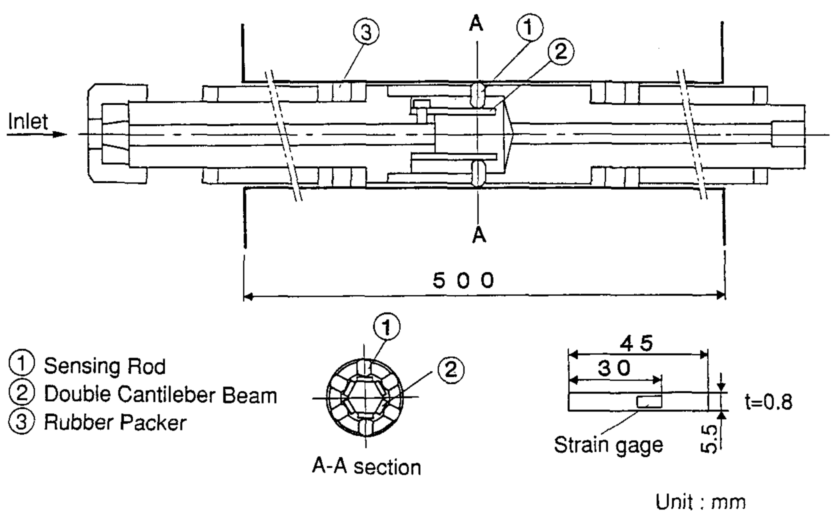

Fig. 2. Displacement gage for monitoring borehole deformation.

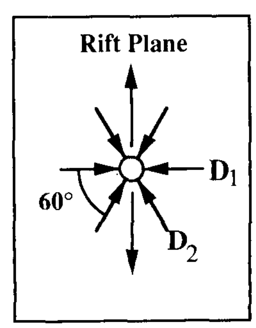

Fig. 3. Orientations for crack opening displacement measurements

$$K \simeq K_2 / E(k) \qquad (2)$$

where K_2 is the stress intensity factor of the two dimensional crack which can be found in the literature (Paris, P.C. and Shih, G.C., 1965). The correction factor calculated using Eqs. (1) and (2) is shown in Fig. 5. In order to correct Eq. (1) for the finite size of the rectangular specimens tested, a method proposed by Nishimura et al is used (Nishimura, A. et al, 1977). Approximating the specimen geometry by a thick-walled cylinder yields the following expression

$$K=[W^2/(W^2-1)]\, M_B\, M_o P(\pi a)^{1/2}/E(k) \qquad (3)$$

where $W= \lambda_o / \lambda$, and λ, λ_o are the radius of the borehole, and the outer radius of the approximated thick-walled cylinder. Data for M_B can be found in the literature (Shah, R.C. and Kobayashi, A.S., 1972).

CRACK PROPAGATION RESISTANCE BEHAVIOR IN HYDROFRACTURE GROWTH

The small-scale hydraulic fracturing tests showed that the crack extended both the sides of the pre-notches within the amount of the crack growth observed in this study ($\Delta a <$ 25 cm). Thus, the induced crack was bilobed, and its shape was nearly circular.

In the following, we describe an evaluation method to determine the crack propagation resistance based on results of the hydraulic fracturing tests. Schematics of crack propagation process and corresponding borehole pressure vs crack length (P- Δa) are shown in Fig. 6. We consider the pressure variation with the crack growth during the stepwise pressurization. The locations, A and B represents the positions of the rubber packer. The pressurization interval for the first cycle is A-A, and B-B for the subsequent cycle, respectively. The point 1 on the P- Δ a curve denotes the crack initiation at the notch tip. When the crack tip along the borehole reaches the location A, the pressure decreases due to the leakage of the injection fluid without significant crack growth. At the subsequent cycle, where the borehole interval B-B is subjected to fluid injection, the crack starts to propagate after the pressure corresponding to the point 2 is reached. When the fluid

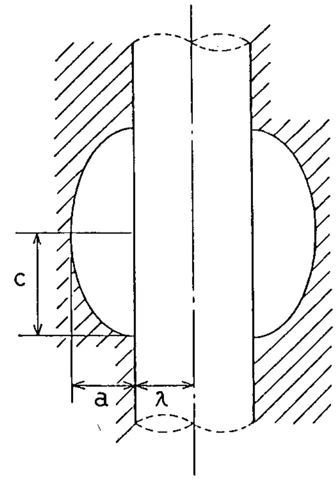

Fig. 4. Two semi-elliptical cracks on a borehole.

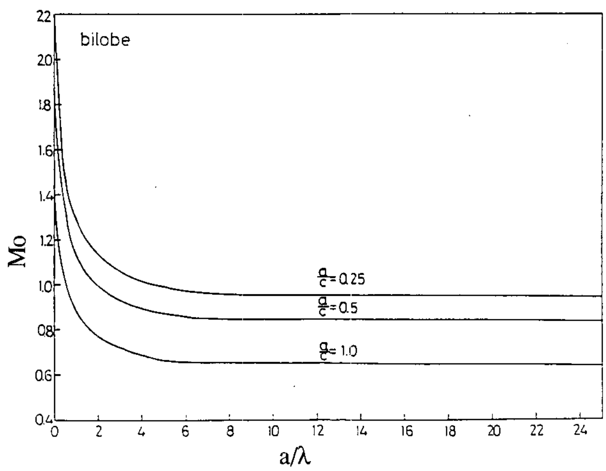

Fig. 5. Correction factor of the stress intensity factor.

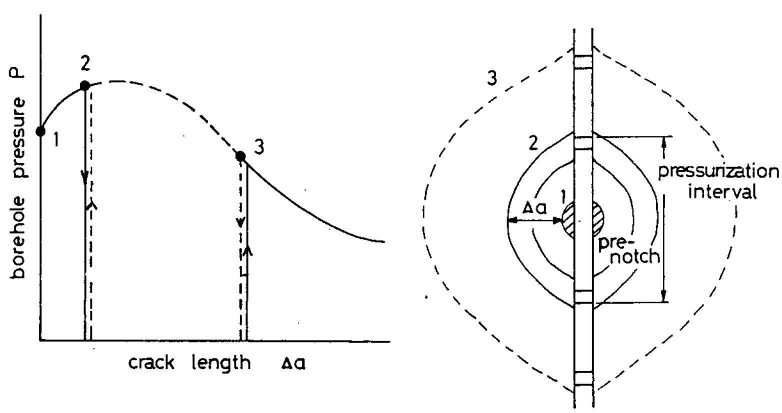

Fig. 6. Procedure for the analysis of crack propagation resistance.

gets over the straddle packer at the location B, the pressure decreases again as mentioned for the first cycle. Thus, the borehole pressure corresponding to the crack length induced at a pressure cycle $P(\Delta a)$ can be found by comparing the magnitude of the maximum pressure achieved at the the cycle P_{pre} and that at the subsequent cycle P_{sub}. Namely, $P(\Delta a) = P_{pre}$, if $P_{pre} \leq P_{sub}$, and $P(\Delta a) = P_{sub}$, if $P_{pre} > P_{sub}$. This discussion enables us to determine the borehole pressure and the corresponding crack size which are needed to construct crack propagation resistance curves.

Fig. 7 shows an example of the borehole pressure vs time curve recorded for the cyclic hydraulic fracturing tests of the 1 m sized specimens. Based on the method illustrated in Fig. 6, the evaluation point to be used for the crack propagation analysis is indicated on the pressure vs time curve by a solid circle. The pressurization was discontinued and unloaded at the end of the tests. Post-test examination showed that the crack propagation at the final pressure cycle was within the pressurization interval. The

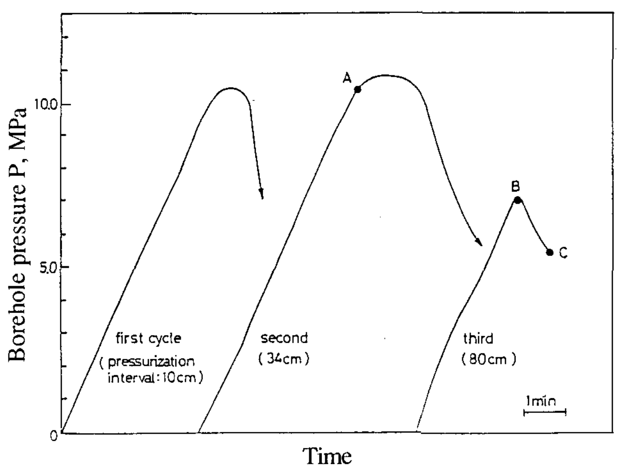

Fig. 7. Pressure vs time record.

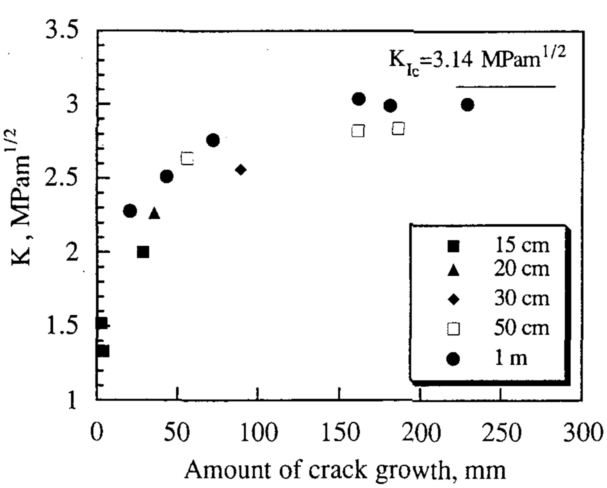

Fig. 8. Crack propagation resistance curve.

stress intensity factor along the periphery of the growing crack may be essentially constant. Abē et al carried out boundary element analyses for a pair of semi-elliptical cracks around a borehole and found the crack shape giving almost constant stress intensity factor along the crack periphery (Abē, H. et al, 1988). It has been shown that the aspect ratio of the crack is close to 1.0. This theoretical prediction agrees with the experimental observation mentioned above. Therefore, the amount of the crack growth at each pressure cycle is estimated from the aspect ratio a/c (=1.0) and the pressurization interval Lp using the following equation

$$a/c=2(a_i+\Delta a)/Lp=1.0 \qquad (4)$$

The crack propagation resistance curves obtained from the hydraulic fracturing tests are summarized in Fig. 8. It is shown that the crack propagation resistance initially increases and levels off at the crack length of approximately 15 cm. It is particularly noted that the curve gives a nearly constant crack propagation resistance at the larger crack growth stage and steady-state crack growth condition is achieved. The fracture toughness value determined by the J-based testing method K_{Ic} is also indicated in Fig. 8. Note that the constant crack propagation resistance is close to the K_{Ic}. In order to assess the crack growth process in large-scale rock masses, it is required to evaluate an upper limit of fracture toughness values. The result of Fig. 8 suggests that the J-based method can be used to predict the constant value of the crack propagation resistance. Furthermore, it has been demonstrated previously that the J-based method can determine a fracture toughness which is independent of specimen size and confining pressure (Hashida, T., 1990, Hashida, T. et al, 1993). These results show that the K_{Ic} is judged to be an appropriate fracture toughness value which can be applied to the analysis of crack growth behavior during hydraulic fracturing.

CRACK OPENING DISPLACEMENT AND PREDICTION OF HYDROFRACTURE GROWTH BEHAVIOR

Pressure vs borehole deformation curves obtained from a hydraulic fracturing test are shown in Fig. 9. The curve labelled D_1 shows the deformation recorded for the orientation perpendicular to the rift plane, and the data obtained in the direction inclined at 30° to the rift plane is labelled D_2 (see Fig. 3). Note that the D_1-curve gives a larger displacement compared to the D_2-curve. This is because the crack propagation has occurred along the rift plane, as mentioned previously. The relation exhibits significant nonlinear deformation behavior below the breakdown pressure. It has been shown that the development of localized fracture process zone precedes the macroscopic crack propagation in fracture tests of the granite (Hashida, T., 1990, Hashida, T. et al, 1993). The nonlinear displacement prior to the breakdown process can be taken as reflecting the planar fracture process zone along the rift plane. Thus, the pressure vs borehole deformation curve of Fig. 9 allows the crack opening displacement to be evaluated. From Fig. 9, the measured borehole deformation is 58 μm at the last stage of the crack propagation, and the corresponding linear elastic borehole deformation at this stage is 8 μm. Therefore, by substracting the elastic deformation from the total borehole deformation, the crack opening displacement is obtained to be 50 μm for this hydraulic fracturing experiment. The crack opening displacement data as obtained above are used in the following analysis.

Based on the measurements of the crack opening displacement and the fracture mechanics approach, we predict the length of the crack induced by the hydraulic fracturing tests. The opening displacement of a penny shaped crack at the center, w is written as follows

$$w=8(P-S)a/\pi E' \qquad (5)$$

where S is the tectonic stress perpendicular to the crack plane, and $E'(=E/(1-\nu^2))$ is the effective Young's modulus. The stress intensity factor for the penny shaped crack is given by

$$K=(2/\pi)(P-S)(\pi a)^{1/2} \qquad (6)$$

The combination of the above two equations provides the following relation

$$a=(E'w\pi^{1/2}/4K) \qquad (7)$$

As described in the preceding session, the observation on the shape of the hydrofractures supports the approximation of the penny shaped crack and then the use of Eq. (7) in the prediction of the crack length. The E' of the granite used for the tests is 60 GPa and the fracture toughness K_{Ic} determined by the J-based method is 3.14 MPa·m$^{1/2}$. The crack lengths predicted by Eq. (7) with the measured crack opening displacement value are shown in Table 2, together with the experimental results obtained from post-test observations. The predicted crack length compares well with the experimental results. Though this comparison should be taken as preliminary and further tests are needed, the result demonstrates the feasibility of the present technique to analyze the crack growth behavior in hydraulic fracturing treatments. The method proposed in this study is summarized in Fig. 10. The technique is being currently applied to field hydraulic fracturing experiment.

CONCLUDING REMARKS

A method for determining the size of hydrofractures was proposed, which is based on the measurement of the crack opening displacement and the fracture mechanics approach. The method was applied to laboratory small-scale hydraulic fracturing tests. The results in this paper can be summarized as follows:

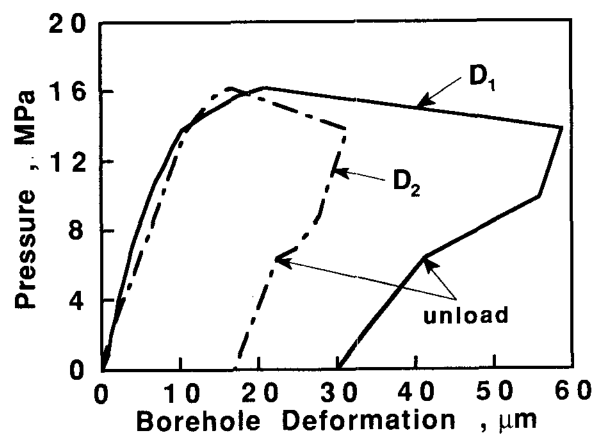

Fig. 9. Pressure vs borehole deformation.

Table 2. Comparison of predicted and experimental results

Specimen No.	Experimental Results			Predicted Results
	a (cm)	c (cm)	w (μm)	a (cm)
H1	13.0	12.0	50	18
H2	12.5	12.0	51	18

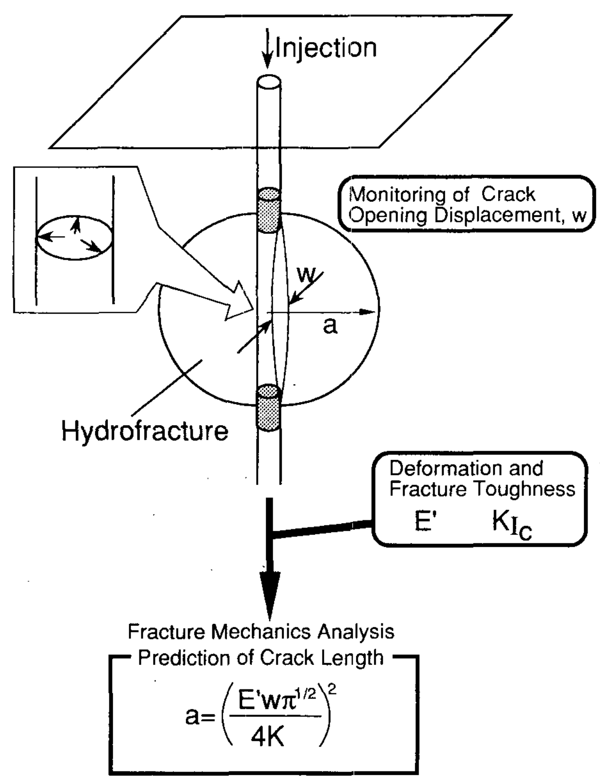

Fig. 10. Method proposed for the analysis of hydraulic fracturing.

(1) Cyclic hydraulic fracturing tests were conducted to determine the crack propagation resistance of a granite. The fracture mechanics analysis of the hydraulic fracturing tests revealed that the crack propagation resistance initially increased with the crack extension and then showed a constant value after the crack extension of 15 cm.
(2) The constant crack propagation resistance in the hydrofracture growth can be predicted by the J-based fracture testing method.
(3) The size of the hyrofractures predicted by the proposed method compares well with the experimental results.

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