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Characterization of Fracture Aperture and Spacing Using Radon Tracer and Well Tests

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ABSTRACT

Fracture aperture and spacing are normally concealed properties of undisturbed fractured rocks. These two properties are disturbed by exposure; therefore, an indirect method is required to evaluate the in-situ values of fracture aperture and spacing. This paper presents a quantitative method to characterize fracture aperture and spacing. Precursory radon data is used to determine fracture porosity in a naturally fractured aquifer. Well tests are used to estimate aquifer transmissivity and fracture permeability. Assuming three mutually orthogonal sets of fractures are common in nature, in-situ fracture aperture and spacing can be characterized from fracture porosity and permeability.

1. INTRODUCTION

Naturally fractured reservoirs hold large groundwater, geothermal, and hydrocarbon resources. Information for evaluating fracture porosity and permeability include drilling history, well logging, well tests, tracer tests, and production history. This paper presents a quantitative method to characterize fracture aperture and spacing using radon tracer and well tests with the help of a case study.

The 2003 Mw 6.8 Chengkung earthquake was the strongest earthquake near the Chengkung area in eastern Taiwan since 1951. The Antung radon-monitoring well D1 (Figure 1) was located 24 km from the epicenter. Precursory changes in the groundwater's radon concentration were observed prior to the 2003 Mw 6.8 Chengkung earthquake. The radon concentration was fairly stable (787 ± 42 pCi/L) from July 2003 to September 2003 (Figure 2). Sixty-five days before the magnitude Mw 6.8 earthquake (December 10, 2003), the radon concentration of ground water started to decrease and the trend continued to decrease for 45 days. Twenty days prior to the earthquake, the radon concentration reached a minimum (326 ± 9 pCi/L) before the trend started to increase. Just before the earthquake, the radon concentration recovered to the previous background level.

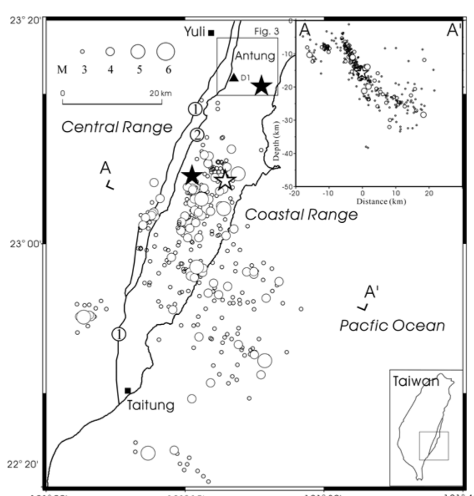

Figure 1: Map of the epicentral and hypocentral distributions of the mainshock and aftershocks of the 2003 Chengkung earthquake (open star: 2003 mainshock, open circles: 2003 aftershocks, filled stars: 1951 mainshocks, filled triangle: radon-monitoring well, ①: Chihshang, or, Longitudinal Valley Fault, ②: Yongfeng Fault). (From Kuo et al. 2006).

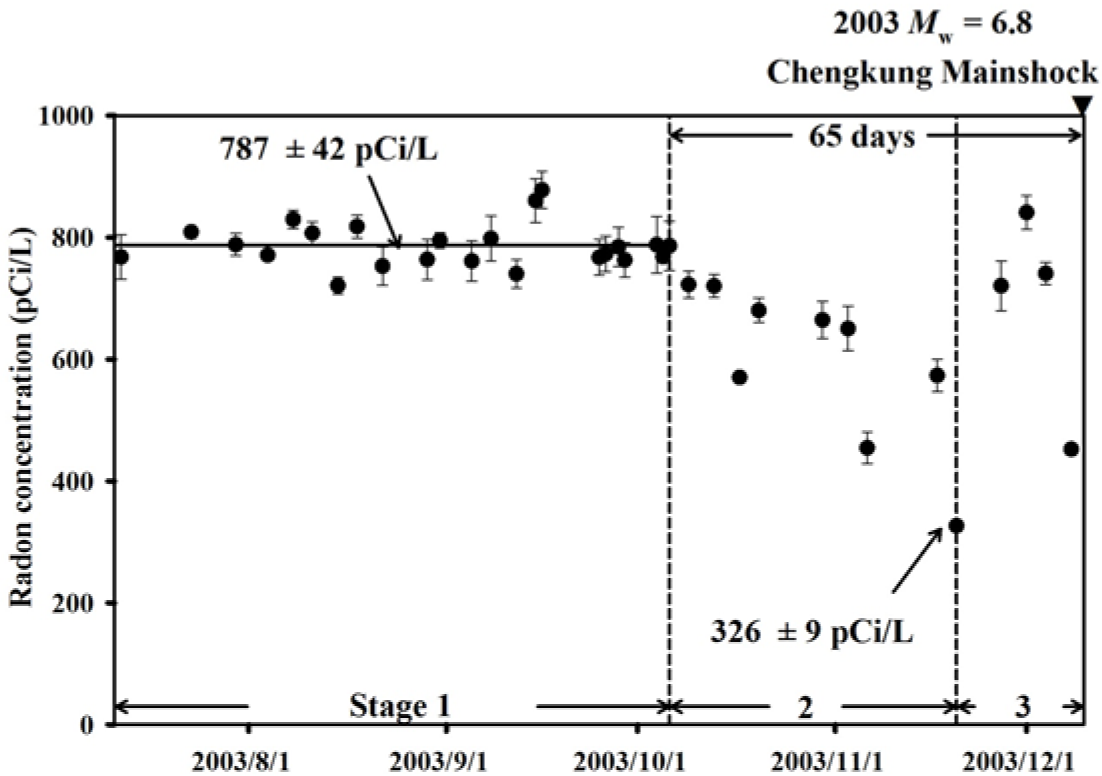

Figure 2: Radon concentration data at the monitoring well (D1) in the Antung hot spring (adapted from Kuo et al. 2006). Stage 1 is buildup of elastic strain. Stage 2 is dilatancy and development of cracks and gas saturation. Stage 3 is influx of ground water and diminishment of gas saturation.

In fractured aquifers under undrained conditions, the in-situ volatilization of dissolved radon could cause a decline of radon in groundwater precursory to an earthquake (Kuo et al. 2006). Using the radon data recorded at Antung well D1 precursory to the 2003 Mw 6.8 Chengkung earthquake, the model was applied to estimate fracture porosity.

From May 1, 2007 to August 19, 2008, 139 well tests were conducted to estimate aquifer transmissivity and fracture permeability near Antung well D1. The objective of this paper is to present a quantitative method to characterize fracture aperture and spacing using radon tracer and well tests. Some calculations of fracture aperture and spacing are given using radon data and 139 well tests at Antung well D1.

2. GEOLOGICAL SETTING

The geological map and cross section near Antung well D1 are shown in Figure 3. The Antung hot spring is situated in an andesitic tuffaceous sandstone block (Miocene) which is enclosed within the Paliwan Formation (Late Pliocene to Pleistocene mudstone with sandstone). The hot spring is formed nearby an eastward-dipping, high-angle reverse fault zone which contacts between the Lichi mélange and the Paliwan Formation. Some hot springs and mud volcanoes are scattered along the fault zone, indicating a Quaternary active fault. The Lichi mélange occurs as a highly deformed mudstone that is characterized by penetrative foliation visible in outcrop. The Tuluanshan Formation consists of Miocene volcanic rocks such as lava and volcanic breccia as well as tuffaceous sandstone (Chen and Wang 1996).

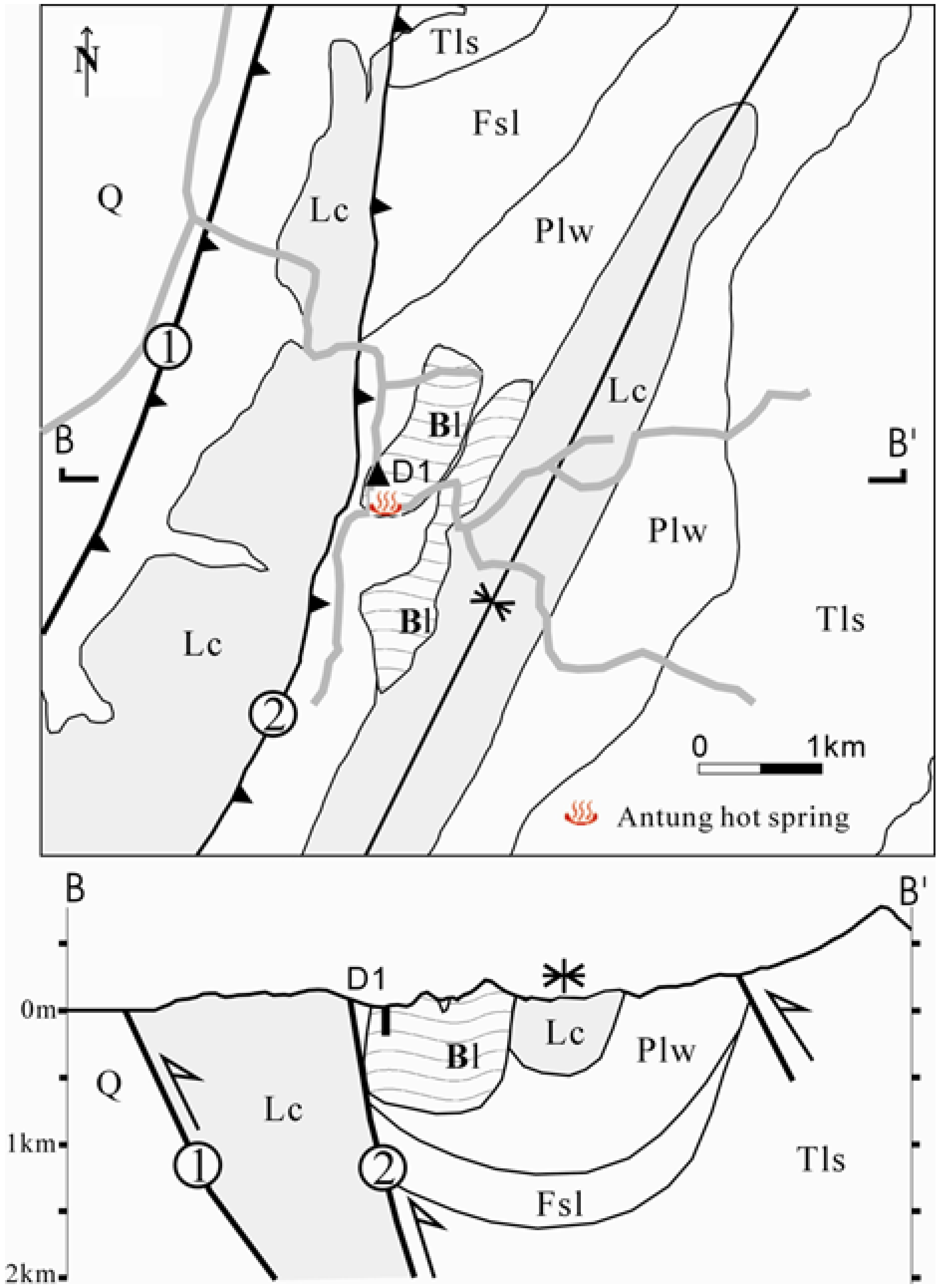

Figure 3: Geological map and cross section near the radon-monitoring well in the area of Antung hot spring (adapted from Kuo et al. 2006) (Q: Holocene deposits, Lc: Lichi mélange, Plw: Paliwan Formation, Fsl: Fanshuliao Formation, Tls: Tuluanshan Formation, Bl: tuffaceous fault block, D1: radon-monitoring well, ①: Chihshang, or, Longitudinal Valley Fault, ②: Yongfeng Fault).

Well-developed minor faults and joints are common in the tuffaceous-sandstone block displaying brittle deformation. It is possible that these fractures reflect deformation and disruption by the nearby faults. Ground water flows through the fault zone and then into the block along the minor fractures. The recharge rate is very slow and can be negligible. Geological evidence suggests that the Antung hot spring at well D1 is a small low-porosity fractured aquifer in undrained conditions.

Prior to local large earthquakes, two physical processes, rock dilatancy and water diffusion, are likely to take place at the Antung hot spring with the above geological conditions. When the regional stress increases to about half the fracture stress, rock dilatancy initiates and cracks develop in aquifer rock. Laboratory experiments have shown that dilatancy can be a stable and repeatable process, and the onset of dilatancy is essentially unaffected by the repeated cycling of compressive stress. According to the dilatancy-diffusion model, the development of new cracks in a small aquifer rock could occur at a rate faster than the recharge of pore water. In a small aquifer with un-drained conditions, gas saturation could develop in the rock cracks. When gas phase develops in aquifer rock, the radon in groundwater volatilizes into the gas phase and the radon concentration in groundwater decreases. The above mechanism is referred to as “in-situ radon volatilization” (Kuo el al. 2006). The mechanism is also the basis to apply radon as a tracer to determine the gas saturation in a naturally fractured aquifer.

3. IN-SITU RADON-VOLATILIZATION MODEL

For a fractured confined aquifer in undrained conditions, in-situ radon-volatilization model was developed to correlate the precursory decline in groundwater radon with the gas saturation (Kuo et al. 2006). The radon-volatilization model can be expressed as follows.

$$C_0 = C_w \left(H \times S_g + 1\right) \tag{1}$$

where C_0 is initial radon concentration in groundwater before gas phase develops, pCi/L; C_w is equilibrium radon concentration in the groundwater, pCi/L after gas phase develops; S_g is gas saturation, %; H is Henry’s coefficient for radon, dimensionless.

The gas saturation can be expressed in terms of the fracture porosity and the volumetric strain change in naturally fractured rocks under undrained conditions as follows (Kuo and Tsunomori 2014).

$$S_g \cong \frac{de}{\emptyset} \tag{2}$$

where de is volumetric strain in naturally fractured rocks, dimensionless; $\emptyset$ is facture porosity, fraction; S_g is gas saturation, %.

Equations (1) and (2) can be employed to calculate fracture porosity from the precursory radon decline and volumetric strain change associated with earthquake occurrence.

4. ESTIMATION OF FRACTURE POROSITY USING RADON TRACER

An anomalous radon decline from a background level of 787 ± 42 pCi/L to a minimum of 326 ± 9 pCi/L was observed at the well D1 in the Antung hot spring prior to the 2003 Mw 6.8 Chengkung earthquake in eastern Taiwan (Figure 2). Well D1 is completed in a fractured confined aquifer of weak recharge. Under such geological conditions, the micro-cracks of brittle rock mass and in-situ volatilization of radon could cause the anomalous declines of radon in groundwater precursory to nearby earthquakes (Kuo et al. 2006).

Given aquifer temperature at 60 °C, Henry’s coefficient (H) for radon is 7.91. Based on equation (1), it requires a gas saturation (S_g) of 17.9 % developed in rock cracks for the above anomalous radon decline from 787 to 326 pCi/L. The calculated compression strain (de) is about 20 ppm near the Antung hot spring for the 2003 Mw 6.8 Chengkung earthquake (Kuo et al. 2006). Given the above gas saturation (S_g) and compression strain (de), the fracture porosity ($\emptyset$) at Well D1 can then be calculated as 0.0001117 using equation (2).

5. ESTIMATION OF FRACTURE PERMEABILITY USING WELL TESTS

A total of 139 pumping tests were conducted to catch an earthquake precursor at Antung well D1 between May 1, 2007 and August 19, 2008. Drawdown was observed at well B which is 46 meter from pumping well D1. A submersible pump was used in well D1 for ground water sampling at a fairly constant flow rate of 205 L/min.

The Cooper-Jacob (1946) solution, which is a large time approximate solution of Theis (1935) solution, was used to analyze drawdown data recorded at Antung well B. Jacob first introduced a graphical method for evaluating aquifer properties, transmissivity and coefficient of storage. Figure 4 shows an example of the drawdown data and Jacob semi-log straight line for the pumping test conducted on May 15, 2007. For large values of pumping time (when $t > \frac{25r^2S}{T}$),

$$s = \frac{2.30Q}{4\pi T}\log t - \frac{2.30Q}{4\pi T}\log\frac{r^2S}{2.25T} \tag{3}$$

where

s = drawdown, in meter, measured in an observation well due to constant discharge of a pumped well

Q = discharge of a pumped well, in m^3/min

T = transmissivity, in m^2/min

r = distance, in meter, from pumped well to observation well

S = coefficient of storage, dimensionless

t = time in minutes since pumping started

Figure 4 also shows the Jacob semi-log straight with a slope of 1.0156 meter per log cycle. From equation (3),

$$\frac{2.30Q}{4\pi T} = 1.0156 \text{ m}$$

Given Q = 0.205 m^3/min for the pumping test, the aquifer transmissivity on May 15, 2007 is 0.0369 m^2/min.

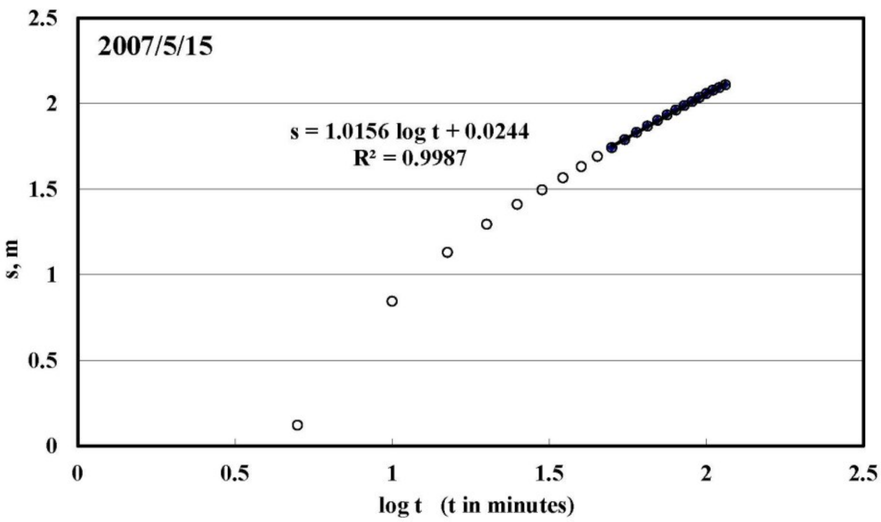

Figure 4: Jacob method for well test analysis. The slope of the semi-log straight line is 1.0156 meter per log cycle.

Figure 5 shows the estimated transmissivity versus date. The transmissivity estimated from 139 well tests is 0.035 ± 0.006 m^2/min. Given aquifer temperature at 60 °C and aquifer thickness of 15 m estimated from well logs, the calculated fracture permeability is about 2 darcy.

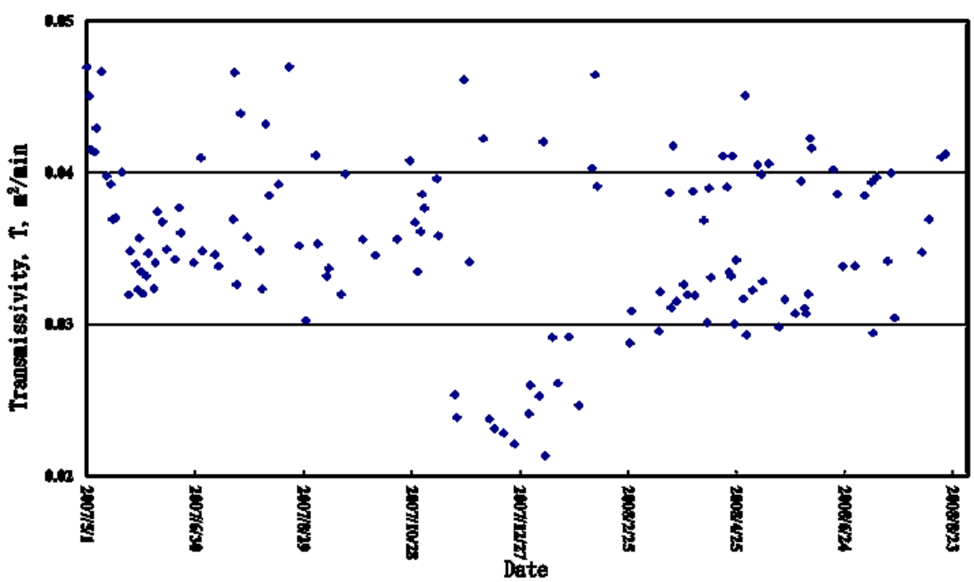

Figure 5: Aquifer transmissivity estimated from 139 pumping tests at Antung well D1 versus date.

6. CHARACTERIZATION OF FRACTURE APERTURE AND SPACING

Assuming that three mutually orthogonal sets of fractures are common in nature, Snow (1968) derived the following equations to estimate the fracture porosity ($\emptyset$) from a measured permeability (k) for a cubic arrangement of plane fractures with an average spacing (Δ) and an average aperture (2B).

$$\emptyset = 5.45\left(\frac{k}{\Delta^2}\right)^{\frac{1}{3}} \tag{4}$$

and

$$2B = \emptyset\frac{\Delta}{3} \tag{5}$$

Given fracture porosity ($\emptyset$) of 0.0001117 and fracture permeability (k) of 2 darcy, we can calculate fracture aperture (2B) and fracture spacing (Δ) using equations (4) and (5). The estimated fracture aperture (2B) and fracture spacing (Δ) at Antung well D1 are 560 microns and 15 m, respectively.

7. CONCLUSIONS

(1) With the help of a case study, this paper presents a quantitative method to characterize fracture aperture and spacing using radon tracer and well tests.

(2) The fracture porosity at Antung well D1 estimated from radon tracer is 0.0001117. The fracture permeability estimated from well tests is 2 darcy. The estimated fracture aperture and spacing are 560 microns and 15 m, respectively.

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