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Nonlinear groundwater flow during a slug test in fractured rock

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SUMMARY

A series of slug tests with various initial head displacements was carried out to investigate the influence of nonlinear groundwater flow on a slug test in fractured rock. To identify the nonlinear flow regime during a slug test, a representative Reynolds number (Re) was calculated using the slug test results and the fractures identified from geophysical logging and core logs. The Forchheimer equation and cubic law were used to determine the critical Re where nonlinear flow arose in the test zone. Our results showed that nonlinear flow arose when the initial displacement was over 1.0 m. Then, the degree of nonlinearity increased and the estimated hydraulic conductivity from the test results decreased with increasing initial displacement. The study also suggested that the Forchheimer and cubic law can be used to estimate the hydraulic conductivity in a linear flow regime using data from the slug tests in a nonlinear flow regime.

1. Introduction

When radioactive contaminants leak from a subsurface repository, they generally migrate into the biosphere through groundwater flow. Thus, an accurate characterization of the groundwater flow system at a disposal site is important because the estimated safety of a repository can be distorted by inaccurate characterization results. Groundwater flow in a crystalline fractured rock, which is one of the preferred host rocks for radioactive waste disposal repositories, is quite different from that in a porous medium. The major pathway for groundwater flow in a crystalline rock is fractures set in a low permeable rock matrix, and the variation of fracture spacing and interconnectivity of the fracture network make crystalline rock very heterogeneous. Moreover, several reported phenomena such as the nonlinear groundwater flow in a fracture (Zimmerman and Bodvarsson, 1996), the directional anisotropy of groundwater flow in a fracture (Boutt et al., 2006) and the aperture change during a hydraulic test (Ji et al., 2013) can make the characterization more uncertain.

Nonlinear groundwater flow in a single fracture is a phenomenon in which the relation between the hydraulic gradient and the flux deviates from a linear relation at sufficiently high Reynolds numbers (Re). The transition from a linear to nonlinear flow was observed in many laboratory experiments with various single fracture models, most of which suggested that nonlinear flow was significant at Reynolds number greater than 1–10 (e.g. Skjetne et al., 1999; Zimmerman et al., 2004; Ranjith and Darlington, 2007; Ji et al., 2008). It indicates that a nonlinear flow generally becomes significant in a fracture when the Reynolds number is over 10. Many theoretical and numerical studies, which used the Navier–Stokes equations to describe groundwater flow in a single fracture, suggested that nonlinear flow originates from the roughness of the fracture plane, the fracture aperture variations, directional variations caused by the contact area, and inertial effects (e.g. Zimmerman and Bodvarsson, 1996; Yeo and Ge, 2001; Brush and Thomson, 2003). In spite of many laboratory and numerical studies, minimal attention was directed to the identification of nonlinear flow during hydraulic tests in fractured rock in field studies. Quinn et al. (2011) conducted constant-rate injection step tests at various injection rates (Q) in a fractured sedimentary rock using a packer system. They identified the nonlinear flow regime in the test zone by analyzing the relationship between the imposed Q and the stabilized head change (dH). They suggested the critical injection rate below which the linear flow regime was guaranteed during a steady-state hydraulic test in the test zone. Quinn et al. (2013) also examined the influence of non-linear flow on slug tests conducted in the same field site. From a constant-head step test the critical flow rate, at which the groundwater flow deviated from linearity, was determined and was used to identify nonlinear flow in the slug tests by comparing the monitored flow rates with the critical flow rate. Finally, they stated that slug tests with initial displacements less than 20 cm had minimal interference from nonlinear flow in their study site.

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A slug test is a common hydraulic test to estimate aquifer hydraulic parameters using the monitored recovery after a sudden change in hydraulic head at a borehole. Compared to other hydraulic tests such as a constant-rate pumping or constant head injection/withdrawal tests, a slug test is a simple procedure with logistical and economic advantages, leading to its frequent application for obtaining in-situ estimates of hydraulic properties in tight rocks (Butler, 1998). It has another advantage at contaminated sites because no water is injected or withdrawn. In this study, we identified a nonlinear flow regime during a slug test by estimating Re using the geophysical logging results and the core logs, and examined its influence on the estimated hydraulic conductivity for a fractured granite aquifer. A series of slug tests with various initial head displacements were conducted in an experimental borehole at Korea Atomic Energy Research Institute (KAERI) Underground Research Tunnel (URT), hereafter called KURT, while monitoring the heads. The evolution of Re at a single fracture in the packed-off test zone during the test was estimated using the geophysical logging data and measured hydraulic heads to identify the nonlinear flow regime according to the estimated Re. After a discussion on the influence of the nonlinear flow on the slug test results, the hydraulic properties of the test zones in a linear flow regime were estimated using the Forchheimer equation and cubic law, and compared to the measured values in a linear flow regime.

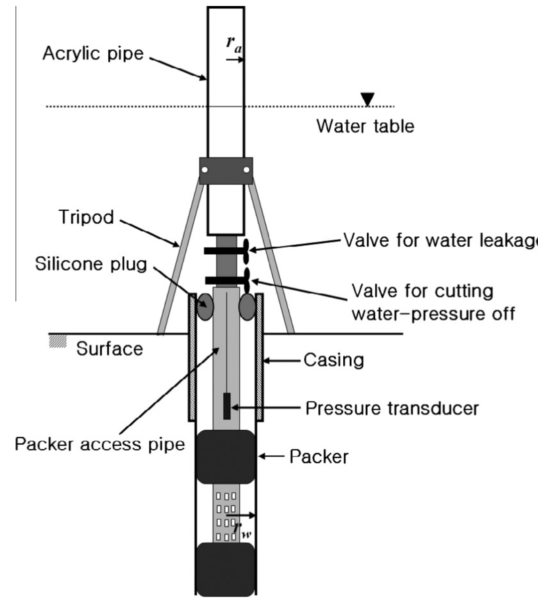

Fig. 1. Slug test system allowing a sudden change in hydraulic head at the test zone under artesian conditions.

2. Approach

2.1. Test borehole and slug test

The study site (KURT), located in Daejeon, a midwest region of the Korean peninsula, is a small-scale underground research facility whose maximum depth is 90 m below ground surface. Details on the site characteristics of KURT are described by Ji et al. (2013). The host rock is a Mesozoic two-mica granite. The test borehole TB-5 is an open vertical borehole 30 m deep with a diameter of 7.6 cm (3 in.) under artesian conditions. Since it is completed in competent rock, no skin effect is expected after developing.

For intensive observation, the zones with small number of fractures were selected as the test zones, and slug tests were conducted in the packed-off sections 17.1–20.0 m and 22.1–25.0 m below the top of the casing (TOC), hereafter called Zones A and B, respectively. The static groundwater levels at Zones A and B were ~4.1 m and ~3.8 m higher than the test borehole TOC, respectively. We designed a special slug test system that allowed a sudden change of hydraulic head at the test zone under artesian conditions (Fig. 1). In this system, a double packer system, which isolated the test zone in a borehole, was connected to an acrylic pipe, which was located above the ground surface and supported by a tripod, through a packer access pipe. Between the acrylic and packer access pipes, there were two valves for discharging water and severing the hydraulic connection between the acrylic and packer access pipes. The diameters of the packer access pipe, valve and acrylic pipe were 2.5 cm, 1.3 cm and 2.6 cm, respectively. We next summarize the slug test procedures using this system. First, the acrylic pipe was connected to the packed-off test zone until the hydraulic head stabilized. Then, the second valve was activated to sever the hydraulic connection between the acrylic and packer access pipes. According to the designated initial head displacement, water in the acrylic pipe was bled off using the valve for discharging water for a rising head slug test or mounts up for a falling head slug test. Then, a sudden change of hydraulic head was introduced by reconnecting the acrylic pipe and the test zone, and the recovery was monitored using a transducer located in the packer access pipe. The test borehole was plugged after installation of the slug test system to prevent an overflow of groundwater (Fig. 1). As KURT is a horseshoe-shaped tunnel with maximum height of 6 m, the length of the acrylic pipe was limited to 5 m. We thus conducted only rising head slug tests with initial head displacements ranging from 0.5 to 4.0 m, and the hydraulic heads were measured every 3 s.

2.2. Identification of flow regime

To identify the flow regimes at fractures during slug tests, a representative Re for each fracture was estimated. First, an acoustic televiewer was used to identify fractures crossing the test borehole, and the identified fractures were classified into open and closed fractures based on the core logging results. The open fracture was defined as the fracture where the core was separated although the closed fracture as the fracture where the core was not separated. As the open fractures can be hydraulically active, the number and characteristics of the open fractures were considered to estimate a representative Re for the fractures in the test zone. The Re at a single fracture is defined as:

$$\mathrm{Re} = \frac{\rho v e}{\mu} = \frac{\rho Q}{w \mu}, \tag{1}$$

where ρ [M/L^3] is the fluid density, v [L/T] is the flow velocity, e [L] is the fracture aperture, μ [M/L T] is the fluid viscosity, Q [L^3/T] is the flow rate, and w [L] is the fracture width perpendicular to flow (Ji et al., 2008). During a slug test, groundwater flow is radial with a maximum velocity at the borehole wall, and velocity decreases as the distance from the borehole increases. As observed heads at a borehole are controlled by groundwater flow near a borehole, the maximum groundwater velocity near the borehole wall was used as v in this study. Then, the circumferences of fracture traces at the borehole wall were used as w. To calculate the representative Re for the fractures in the test zone during a slug test, we assumed that groundwater flowed into the test zone only through the open fractures during a slug test. Then, we estimated the mean flow rate (Q_m) and mean fracture width (w_m) for a fracture in the test zone as:

$$Q_m = \frac{\sum_i^{N_f} Q_i}{N_f}, \tag{2}$$