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Experimental investigation of flow behavior in smooth and rough artificial fractures

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SUMMARY

The flow behavior in smooth and artificial rough fractures is experimentally investigated. The piezometric head is measured at several positions to determine experimentally the head gradient through a sophisticated procedure, and the hypothesis of one-dimensional flow is verified. It is demonstrated that both the Forchheimer and Izbash equations adequately describe the flow conditions, and proper coefficients for these equations are estimated. The experimental results are also used to construct a Moody-type diagram, where a non-monotonic dependence is shown to characterize the friction factor – Reynolds number relationship in the transition between laminar and weak turbulent flow.

1. Introduction and background

Flow in fractures is an important issue in several disciplines, including water resources management (Papadopoulou et al., 2010), contaminant pollution control (Masciopinto et al., 2010), exploitation of geothermal fields (Kohl et al., 1997; Cheng et al., 2001; Radilla et al., 2012), and radioactive waste sequestration (Fillion and Noyer, 1996), among others. Therefore, the mathematical description of the above mentioned flow processes is crucial in order to prevent pollution or to properly manage natural resources (Masciopinto et al., 2010).

The simplest approach is to assume that the fracture walls are two smooth parallel plates, creating a narrow gap. At the microscopic level, the flow between the plates is described by the Navier–Stokes equations, which, when neglecting the non-linear inertial terms in the case of creeping flows (i.e., flows for which the inertia effects are negligible), reduces to Stokes equations. It is easy to demonstrate (e.g., Munson et al., 1998; Polubarinova-Kochina, 1962) that for this problem, at the macroscopic level, the flow is described by a Darcy-type equation, which reads in the case of one-dimensional flow:

$$V = -KJ, \tag{1}$$

where V is the bulk velocity [m/s], J is the piezometric head gradient [–], and K is the hydraulic conductivity [m/s]. In the smooth plate case investigated herein, the hydraulic conductivity is given by $K = w^2 g/12\nu$ (Polubarinova-Kochina, 1962), where w is the plate aperture [m], B is the plate width ($w \ll B$), g is the gravity acceleration [m/s^2], and ν is the kinematic viscosity [m^2/s]. The gradient J can be expressed by the relation $J = \partial h/\partial x$, where h is the piezometric head [m], and x is the spatial coordinate [m].

Equivalently to Eq. (1), for creeping flows taking place between two smooth plates, the magnitude of the flow rate Q [m^3/s] is proportional to the cubic power of the fracture aperture, a relation which is described as the Local Cubic Law (LCL) (Polubarinova-Kochina, 1962; Brush and Thomson, 2003):

$$Q_{LCL} = -\frac{w^3 Bg}{12\nu} J. \tag{2}$$

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However, it is accepted that the LCL is not always adequate to describe the flow behavior in natural fractures. The reason for this is that at least one of the two conditions cited above (i.e., the channel geometry and the flow regime) does not usually hold.

Both Gutfraind and Hansen (1995), using the Lattice-Gas Automaton approach, and Skjetne et al. (1999), using the Finite Difference Method, solved the Navier–Stokes equations, and investigated numerically flow processes in fractures, assuming that they can be simulated as a rough conduit bounded by a self-affine surface, an approach that is compatible with the findings of Odling (1994) and Kulatilake et al. (2006). Gutfraind and Hansen (1995) concluded that at low velocities (i.e., small Reynolds numbers), *"pressure drop and velocity are linearly related"* (a conclusion that is compatible with the findings of Skjetne et al., 1999) or equivalently, the flow behavior could be described at the macroscopic scale by the Darcy law. At larger Reynolds numbers, deviations from this linear behavior occur, and Eqs. (1) and (2) do not hold. Skjetne et al. (1999) proposed the quadratic Forchheimer equation in order to describe this non-linear behavior:

$$-J = aV + bV|V|, \tag{3}$$

where a and b are appropriate coefficients. Eq. (3) is widely used to describe the inertial flow behavior in porous media (Venkataraman and Rao, 1998; Sidiropoulou et al., 2007; Moutsopoulos et al., 2009).

For creeping flow conditions, the quadratic term on the right hand side of Eq. (3) becomes negligible, and this equation reduces to the Darcy law (Eq. (1)), where $a = 1/K$. On the contrary, for high velocity flows, a fully developed turbulence regime is established, so that head losses induced by the linear term on the right hand side of Eq. (3) are not important (Burcharth and Andersen, 1995; Kohl et al., 1997; Moutsopoulos and Tsihrintzis, 2005; Moutsopoulos, 2007, 2009). Thus, by assuming that the flow occurs in the positive x-direction, the bulk velocity can be expressed by the following relation:

$$V = \sqrt{-J}/\sqrt{b}. \tag{4}$$

Moutsopoulos and Tsihrintzis (2005) and Moutsopoulos (2009) demonstrated that the use of Eq. (4) is pertinent, at small times, if an abrupt change of the head is imposed at one edge of a porous medium or fracture, or a flow rate is injected into an initially dry fracture.

As stated by Yeo et al. (1998), a drawback of the 2D approach used by Gutfraind and Hansen (1995) and Skjetne et al. (1999) is that the aperture of natural fractures varies in all directions. Therefore, the head losses occurring at narrow restrictions of the conduits predicted by two-dimensional geometries are overestimated. Skjetne et al. (1999) admitted that for 3D geometries, "*narrow constrictions have less importance as the flow simply passes around them*". Therefore, a more realistic, 3D description of the flow domain was adopted by Brush and Thomson (2003), who used knowledge obtained from modern laboratory methods concerning geometric characteristics of void spaces to develop a random fracture generation algorithm. They solved both the Navier–Stokes and Stokes equations for flow in "synthetic" 3D conduits by the finite-volume-method. Flow covered a large spectrum of Reynolds numbers ranging from 10^{-2} to 10^{3}. They also concluded that the influence of the inertial terms can be neglected (and subsequently the Stokes equation is valid) in the case when three geometric and kinematic conditions are satisfied, which include the constraint that the Reynolds number is smaller than one. The simulation results also demonstrated that the total flow rates predicted by the corrected LCL (where an adequate mean value for the aperture was used) were within 10% of those computed using the Stokes equation. Nevertheless, the authors pointed out that in cases of high Reynolds numbers, the flow rates obtained using the full Navier–Stokes equations (Q_{NS}) were smaller than the corresponding values obtained by using the Stokes equation (Q_S). This effect was most pronounced in cases of high values of the fracture roughness. The minimum computed value of Q_{NS}/Q_S was approximately 0.4.

The findings of Brush and Thomson (2003), that according to the flow conditions the pressure drop in fractures can be described by either a linear or a non-linear relation (i.e., either Eq. (1) or Eq. (3)), are confirmed by in-situ observations. Cappa et al. (2005) conducted field experiments in a shallow fractured carbonate reservoir rock, in order to investigate hydromechanical coupled processes, and demonstrated that the flow behavior inside fractures can be simulated by a Darcy-type linear law. Explicit values for the hydraulic conductivity of fractures are provided by the authors. On the contrary, non-linear, non-Darcy flow conditions were observed by Kohl et al. (1997), who analyzed injection tests at a geothermal research site in France. They reported that fully developed turbulent flow conditions occurred and that the flow behavior in a single fracture could be described by Eq. (4).

In experiments conducted in situ, detailed knowledge of the geometric features of fractures is not possible, and also knowledge of hydraulic characteristics are often limited, because measurements are possible at only a few points. For this reason, several laboratory experiments have been conducted in order to investigate flow processes in fractures.

For the description of fluid flow behavior in replicas of the surface of a natural fracture in a red Permian sandstone, Zimmerman et al. (2004) proposed the use of the Forchheimer equation at Reynolds numbers above 10. Their experimental results were confirmed by solving numerically the Navier–Stokes equation for the same flow regime.

The adequacy of the Forchheimer law to describe flow in fractures was reported by Nowamooz et al. (2009) on the basis of results obtained in a replica of a fracture. Radilla et al. (2013) investigated experimentally the flow in transparent replicas of a granite fracture and a Vosges sandstone fracture. In the case of single-phase flow and for relatively small Reynolds numbers ($Re < 1$), the existence of a "weak inertial regime" was confirmed, where the energy losses due to inertia effects are proportional to the third power of velocity, a result which is compatible with the numerical study of Skjetne et al. (1999). Nevertheless, the experimental results indicated that, at higher values of Re, the use of the Forchheimer equation is adequate. The adequacy of the Forchheimer law to describe the flow behavior inside artificially created fractures in a bench-scale experiment was also reported by Cherubini et al. (2012).

Zhang and Nemcik (2013) investigated the flow behavior in fractures, which were created in the laboratory by splitting into half initially intact samples of a fine grain sandstone block. The hydraulic behavior of both "mated" and "non-mated" fracture samples was investigated. Non-mated samples involved two fracture halves displaced by 2 mm along the flow direction, creating a reduced number of contact asperities. The effects of both confining stress and velocity were also examined. They found that a non-linear flow regime is more likely to occur in non-mated fractures, due to enlarged apertures, in comparison to mated fractures. Zhang and Nemcik (2013) used the Izbash law, in addition to the Forchheimer equation, to describe the inertial flow effects. The Izbash law, usually used to describe flow processes in porous media (Yamada et al., 2005; Moutsopoulos et al., 2009; Sedghi-Asl et al., 2014), is:

$$J = -\lambda V^n. \tag{5}$$

Eq. (5) reduces to the Darcy law (Eq. (1)) for $n = 1$, and to Eq. (4), describing fully developed turbulent flow, for $n = 2$. The coefficient λ can be thought to be an equivalent hydraulic resistance coefficient. For $n = 1$ (Darcy flow case) $\lambda = 1/K$, while for $n = 2$ (fully