EGU2009-325-XY525

A new method for calculating the mean aperture of fractures in rocks: The dual mean

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INTRODUCTION

The intrinsic permeability or hydraulic aperture of single fractures can be determined with the Local Cubic Law,

$$F(x,y) = -\frac{H^3}{12\mu}\nabla P$$

where, F is the vector of the flow flux, H is the separation distance or local aperture of the fracture, ∇P is the local pressure gradient applied to the fluid and μ is the dynamic viscosity of the fluid. Fracture wall roughness should cause an overestimation of this permeability if it is of the same order of magnitude as fracture aperture variation. However, in laminar flow systems (to which the majority of subsurface flow belongs), roughness will not affect the mean flow velocity or flux as viscous drag near the fracture walls dampens the effect of roughness (Reynolds Number < 1). Predictions of the LCL worsen as the fracture surfaces are brought together due to an increase in in-plane tortuosity. Overestimations of fracture permeability are often due to inappropriate averaging of the separation between fracture walls, the mechanical aperture, H. All mean values depend upon the mean surface heights of the two surfaces used to define the fracture aperture. However, it is common to quote the mean aperture for the scenario where the relative mean surface heights of the two surfaces used to define the fracture aperture are such that the fracture surfaces just touch. The simple arithmetic mean aperture, H_a, is well defined, but of little practical use for fluid flow calculations. The geometric mean aperture, H_g, is well defined if the surfaces do not touch, but collapses to zero if the surfaces touch at one or more points even if the rest of the aperture is patent to flow. The harmonic mean aperture, H_h, is also well defined but again it collapses to zero if the surfaces touch. To overcome the problem, we define the dual mean, H_{dm}. This is the arithmetic mean of the geometric mean apertures along all fracture profiles in the direction of presumed fluid flow through the fracture. It has a physical basis, and is sensitive to anisotropy in the plane of the fracture, i.e., it has different values in different directions through the fracture. We use the dual mean in the two cartesian directions in the plane of the fracture x and y. For the x-direction this is defined as,

$$d_{mx} = \frac{1}{N_y}\sum_{j=1}^{N_y}\exp\left(\sum_{i=1}^{N_x}\frac{\log A_{ij}}{N_x}\right)$$

where N_x, N_y are the dimensions of the measurement grid in the x and y directions, respectively, A_{ij} is the value of the fracture aperture at the grid point with indexes (i; j), and Hdmx is the dual mean aperture computed with respect to x-direction (of the flow). We have tested the dual mean by finite element modelling and applied it to five rough fractures for which the physical and hydraulic aperture are known. The dual means in both directions across the fracture apertures show a much better correlation to the modelled hydraulic apertures than standard arithmetic mean apertures. We conclude that this is a pragmatic approach to calculating the mean aperture of a fracture where the surfaces touch at at least one point.

FINITE ELEMENT MODELLING

Fluid flow was modelled in 2D plan view in the measured rock fractures in a FEMLAB™ environment. The image analysed surface topography and aperture maps of Isakov et al (2001) and Ogilvie et al (2002) were used to define the physical boundaries of the model. Presuming validity of Local Cubic Law, *LCL,* for flow flux, Ge's equation was used to compute the pressure field (Ge, 1997).

$$\frac{Hc_x^2}{\tau_x^2}\frac{\partial H}{\partial x}\frac{\partial P}{\partial x} + \frac{1}{\tau_x}\frac{\partial}{\partial x}\left(\frac{H^2c_x^2}{\tau_x}\frac{\partial P}{\partial x}\right) + \frac{Hc_y^2}{\tau_y^2}\frac{\partial H}{\partial y}\frac{\partial P}{\partial y} + \frac{1}{\tau_y}\frac{\partial}{\partial y}\left(\frac{H^2c_y^2}{\tau_y}\frac{\partial P}{\partial y}\right) = 0$$

where, $P(x,y)$ is fluid pressure, $H(x,y)$ is the aperture of the fracture, c is a factor for effective aperture value, τ is the fracture tortuosity (Walsh & Brace, 1984). Constant pressure conditions were defined for both fluid input and output faces. Zero pressure was defined for fluid output face. As the equation is linear with respect to pressure P, the whole pressure field may be predicted from a single solution at any pressure difference between input and output faces. The Ge's equation does not account for Reynold's Numbers as it assumes that inertial effects are negligibly small. Non-slip boundary conditions were set up on the rough surfaces of the fracture, and the remaining sides of the fracture were given symmetrical (slip) boundary conditions. A fine triangular finite element grid was set-up in the fracture using iteratively refined Delaunay triangulation. A stationary linear solver was used to get the solution.

As the above equation is linear with respect to pressure field, $P(x,y)$, only one solution was computed for every combination of fracture type and flow direction. When this solution is multiplied by any factor, the result is also a solution of Ge's equation (Ge, 1997), corresponding to another value of pressure head applied to the fracture. After the pressure field was obtained, the map of the flow flux was computed from the Local Cubic Law. This law states a linear connection between the flow flux and the pressure gradient so the flow flux is also linearly proportional to the pressure head applied to the fracture (as long as the Reynold's Number is small and the above equation is valid).

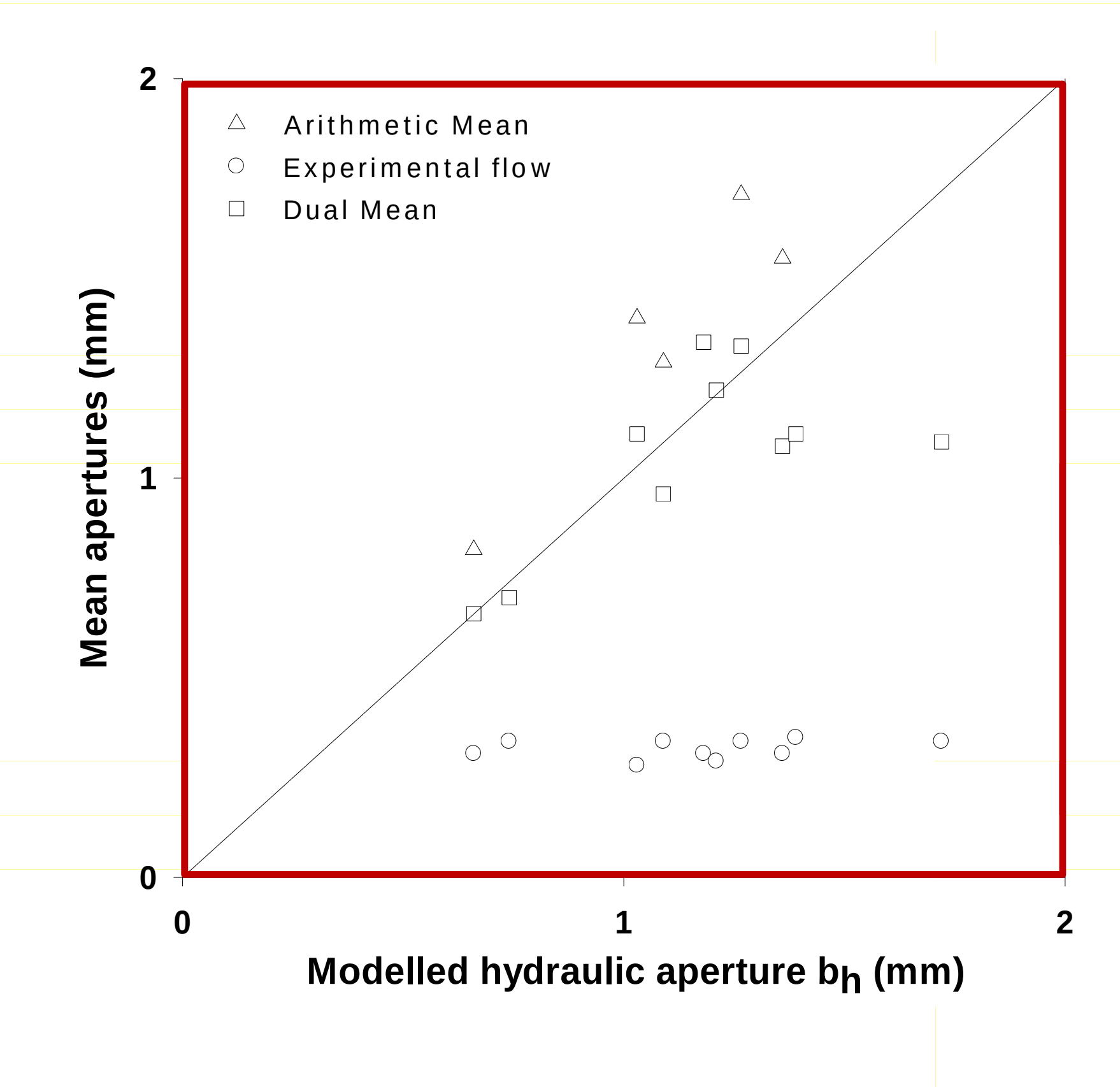
An integral of the flow flux across the flow direction yields overall flux or flow charge. The ratio of the flow charge to the pressure head applied to the fracture characterises the fracture transmissibility. This value was computed for every fracture type and for every flow direction in order to derive hydraulic aperture of the fracture.

MEAN APERTURES

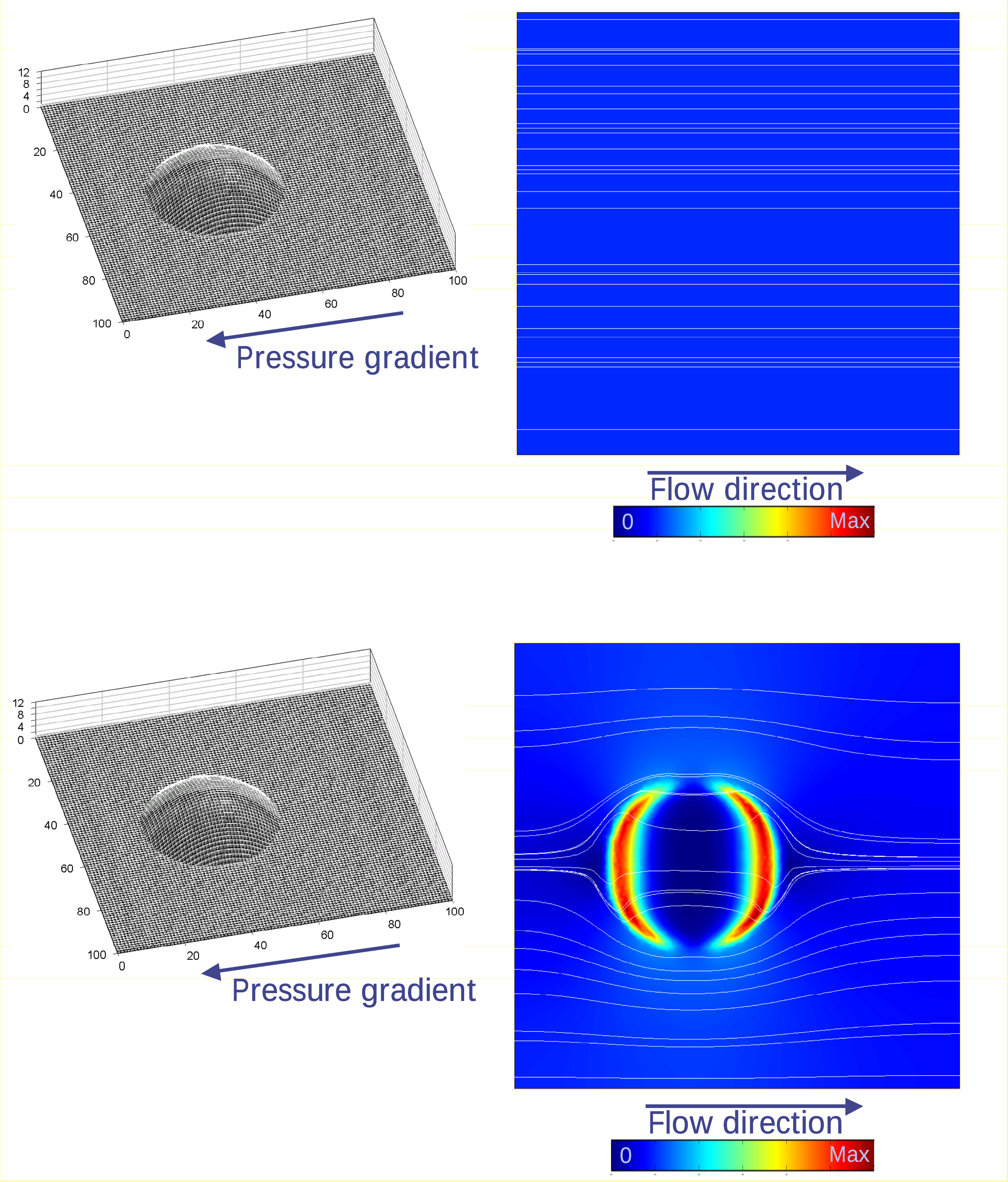
Modelled hydraulic aperture versus mechanical aperture averages for 5 single rough fracture apertures.

The Dual Mean in both directions across the fracture aperture shows a better correlation to the modelled hydraulic aperture than a standard arithmetic mean aperture.

Experimentally obtained hydraulic aperture b_h shows no correlation to mechanical apertures



RESULTS



The performance of Reynold's equation for flow within a channel of constant aperture in which there is embedded a constriction. The effect of the pore is not taken into account by Reynold's equation.

A comparison of streamline prediction for a fracture of constant aperture using the Reynold's and Ge's equation is given in Figure 1. Unlike the Reynold's equation prediction, the Ge's equation streamlines follow the topography. Hydraulic aperture, b_h, calculated from the modelled data (i.e., from the integral of flux and pressure head) is in close agreement with the profiled mechanical apertures, b_m resulting from a dual mean (Figure 1). This is a better correlation than when using an arithmetic mean. It is therefore possible to continue using the LCL to predict hydraulic aperture when prescribing a dual mean mechanical aperture. This constant ratio allows large-scale fracture networks to be populated with parallel plates with the effect of roughness (Brush & Thomson, 2003).

The performance of Ge's equation for flow within a channel of constant aperture in which there is embedded a constriction. The effect of the pore is taken into account by Ge's equation.

REFERENCES

S. Brown, Fluid Flow through rock joints: The effect of surface roughness, J. Geophys. Res. **92**, (1987), 1337-1347.

Brush, D.J. & Thomson, N.R. 2003. Fluid flow in synthetic rough-walled fractures: Navier-Stokes, Stokes, and the local cubic law simulations. *Water Resources Research,* 39, (4).

S. Ge, A governing equation for fluid flow in rough fractures. Water Resour. Res. 33 (1) (1997) 53-61.

E. Isakov, S.R. Ogilvie, C.W. Taylor, P.W.J. Glover. 2001. Fluid Flow Through Rough Fractures in Rocks I: High Resolution Aperture Determinations, Earth Planet. Sci. Lett. 191, 267-282.

Ogilvie, S.R., Isakov, E, Glover, P.W.J. 2006. Fluid flow through rough fractures in rocks II: A new matching model for rough rock fractures. EPSL, 241, 454 – 465.

C.E. Renshaw, J.S. Dadakis, S.R. Brown. Measuring fracture apertures: A comparison of methods, Geophys. Res. Lett. **27** (2000) 2, 289-292.

J.B. Walsh, W.F. Brace. The effect of pressure on porosity and the transport-properties of rock. J Geophys Res, 89 (NB11), (1984), 9425-9431.

CONCLUSIONS

1. There exist a number of ways of obtaining an average value for the aperture of a rock fracture (e.g., arithmetic, geometric, harmonic).
2. Each of these methods has its disadvantages when used in flow modelling.
3. One of the most important disadvantages is that these averages are independent of direction whereas the effective mean aperture of a fracture should be dependent upon the flow direction for anisotropic fractures.
4. We have defined a new type of average (the dual mean) that takes into account the requirements of flow modelling, particularly that (a) the average does not collapse when the fracture surfaces touch (i.e., the aperture is zero) at one or more points, and (b) the average has different values depending upon the direction of fluid flow.
5. We have tested the dual mean by finite element modelling and applied it to five rough fractures for which the physical and hydraulic apertures are known.
6. The dual means in both directions across the fracture apertures show a much better correlation to the modelled hydraulic apertures than standard arithmetic mean apertures.
7. We conclude that this is a pragmatic approach to calculating the mean aperture of a fracture where the surfaces touch at at least one point.

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