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Hydrology and Earth System Sciences Discussions

Interactive comment on "Bench scale laboratory tests to analyze non-linear flow in fractured media" *by* C. Cherubini et al.

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1) Fracture apertures of up to 3 mm are reported. What is generating these apertures? Since these were created by hitting the slab, I would expect that much smaller apertures would result if the pieces were fitted together as closely as possible. Please explain how these apertures were generated. Fractures have been generated by means of hammer blows. Given the nature of the rock block, when each fracture has been generated the rock is pulverized near to damage zones. Therefore fracture faces do not fit perfectly.

2) Fractal dimensions are reported in Table 2 which were estimated using the box counting method. I assume that the box counting method was applied to the fracture

pattern, although this is not stated and this should be clarified. The box counting methods gives results which are scale dependent (i.e. dependent on the number of fractures in the system) unless a large part of the fracture network with a large number of fractures is analysed. Since the experiment contains only 5 fractures, this effect will be present. In addition, these fractal dimensions are not mentioned again in the paper and do not seem to contribute, so I would recommend that they be dropped from the paper. Fractal dimension of fractures reported in table 2 has been evaluated on profiles of fracture traces supposing that the one-dimensional profile of fracture traces is a self – affine fractal (Hernàndez et al. 2010; Campos et al., 2005; Mourzenko et al. 2000). Box-counting technique has been applied in order to estimate fractal dimension utilizing the method illustrated in Turcotte (1997), pag. 135. Fractal dimension of fracture trace presents a value intermediate between 1 and 2. Fractal dimension of fracture surfaces has been calculated adding the unit to the fractal dimension of fracture traces. However according to the reviewer the fractal dimension values reported in table 2 have been dropped.

3) The letter A is used several times in equations as A1, A2 and A (equation 12,13 and 14) which is rather confusing. Also you seem to use A1 to mean both cross-sectional area of the flow cell and storage of the upstream tank (page 5584). Can different letters be use to avoid confusion? The letters S1 and S2 have been used to mean, respectively, cross-sectional area (equal to storage property) of the flow cell and of the upstream tank.

4) Flow through the fracture system is modelled using a finite element model. The modelling is steady state whereas the experiments (if I have understood the procedures correctly) are transient, so how can you compare the results? It is not clear how parameters af and bf are incorporated into the modelling at present. How was the fracture roughness incorporated? The detail of roughness included will depend on the size of the finite elements so this should be given. Do the modeling results depend on the discretization of the fractures? Experiments procedure is transient and permits to

obtain for each inlet – outlet ports configuration a relationship between hydraulic head difference dH and the flow rate Q of polynomial kind (equation 12). Therefore once assigned a ports configuration and a dH we are able to obtain an estimate of Q for steady-state condition. A finite element model has been carried out in order to estimate af and bf coefficients. Fracture trasmissivity is function of af , bf and the hydraulic gradient by the equation (7). In the reported flow simulations the aperture variability and roughness in space for each fracture have not been modeled. The geometry of the finite element model presents only the shape of fracture network and the geometry of holes. af and bf coefficients are representative of each configuration of ports. In other words for each configuration of ports we have obtained by means of flow simulation the equivalent parameters (af and bf) constant for the whole geometry of fracture networks. These parameters are representative of linear and non linear pressure drops due to not only the roughness of fractures faces but they are also representative of drops due to: the shape of fractures (curvature), contact area of fracture, fracture intersections, the geometry of in-let and out-let ports. Therefore the found parameters are equivalent parameters which characterize each single path. For each ports configuration several steady state simulations have been conducted varying the hydraulic head difference between the inlet and outlet ports. For each imposed hydraulic difference it is possible to compare the flow rate obtained from polynomial equation (12) and the flow rate that results from numerical model in correspondence of the inlet port. In figure 7 a) of the paper the mesh of finite element model is shown. The mesh is finer in correspondence of the hole where the hydraulic gradient is higher.

5) Figure 8 shows a clear division of the experiments into two groups with steep and shallow slopes but this is not discussed in the text. In the text you say that steep slopes of this graph correspond to more linear flow behaviour, so I guess that the shallow slopes are those with non-linear flow effects. What is causing the difference between these two sets of experiments and why is there such a clear separation between them? Effectively the experiments could be divided in two sets. The set with shallow slope has in common the outlet port 7 (that is to say ports 1-7, 2-7, 3-7, 4-7, 5-7, 6-7). In figure

9 (added to the paper) is showed the shape of fracture in correspondence of the port 7. The particular shape of this fracture gives rise to a higher contact between fracture surfaces if compared with the others. In fact the path that contains this fracture presents a very high hydraulic loss.

6) The Forchheimer equation has been used to analyse the experiment results, but two other equations (equations 1 and 3) are also given in the introduction. Their fit to the experimental data is not tested. Some justification of this should be made in the paper. Equation 1 does not fit the experimental results, probably a weak inertia regime is not evidenced in the experiments (in figure 5 the relationship between flow rate and resistance to flow does not present a change in slope). Equation 3 could be used to represent experimental data. However it has not been taken into account because it is an empirical law in which it is difficult to distinguish the linear contribution to hydraulic loss from the non-linear. 7) It would be interesting to have some discussion about the implications of the findings. What is dependence on fluid velocity here? The head difference across the model is not very large (around 1m) and it would seem that head gradients of this sort are larger than you would expect under natural conditions but could certainly occur during pumping. What implications does the presence of non-linear flow have for determination of hydraulic parameters from pump test results which assume Darcian flow, for instance?

In the conclusion the following part has been added: "The experimental results showed that the dependence of hydraulic conductivity on specific discharge cannot be neglected in fractured media. For instance during pumping tests a linear flow model can cause errors in the determination of transmissivity in fractured rock aquifers because much of the data collected can be non-linear due to flow occurring in transition between linear and fully turbulent flow. On the other hand, potential errors induced by non-linear flow model in constant pressure tests have also been recognized in the engineering literature (Louis & Maini, 1970) Elsworth and Doe (1986) used mathematical modeling of packer tests in fractured rock to show that calculation of transmissivity using non-Darcian constant head data can lead to underestimation errors as much as an order of magnitude. In our study the effective hydraulic transmissivity proves to be less than 46.59% (average value) of the Darcian (linear) flow hydraulic transmissivity. In particular way in correspondence of path 3-4 the variation reaches the maximum value equal to 59.38%. In pumping tests multiple pressure steps (i.e. higher flow rates resulting in a much greater dP) should be used for a more accurate identification of the Darcian range and the quantification of the linear to nonlinear flow relations resulting in better T estimates as non-linear function of gradient. This concept has to be taken into account in cases of anthropogenic stresses in the aquifer that might give rise to high hydraulic gradients".

Please also note the supplement to this comment:
http://www.hydrol-earth-syst-sci-discuss.net/9/C2677/2012/hessd-9-C2677-2012-supplement.zip

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Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 9, 5575, 2012.