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A discussion of scale effects on hydraulic conductivity at a granitic site (El Berrocal, Spain)

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Abstract. Scale effects on hydraulic conductivity (i.e. increase in the value of K with increasing scale of measurement) have been reported in the literature. Here, we summarize extensive tests performed at El Berrocal, a granitic site in Central Spain, to study whether such effects indeed appear. In fact, median hydraulic conductivities clearly increase with measurement scale. We argue, however, that large scale measurements may be biased towards high K values because they are performed in the most permeable zones, where pumping rates can be high. This is supported by the fact that cross-hole transmissivities and hydraulic conductivities consistently fall below the corresponding values at the pumping interval.

Introduction

Nature's heterogeneity accounts for several paradoxes in hydrogeological problems. The increase of hydraulic conductivity within an increase of the scale of measurement is one of the most striking ones. This increase has been reported by several authors, notably *Clauser* (1992), who summarized data from many sites.

Theoretically, effective K at large scales should be equal to the geometric average of local values in 2-D flow domains or to (*Gutjahr et al.,* 1978)

$$K_{eff} \simeq K_g(1 + \frac{\sigma_f^2}{6}) \quad (1)$$

in 3-D flow domains, where K_g is the geometric average of point values K, σ_f^2 is the variance of $\log K$ and K_{eff} is the effective hydraulic conductivity. For large σ_f^2 values, *Gelhar and Axness* (1983) suggested to consider (1) as the first two terms of an exponential expansion. Then, instead of (1) they propose to use

$$K_{eff} = K_g \exp(\frac{\sigma_f^2}{\sigma}) \quad (2)$$

Whenever the theoretical value given by (2) is significantly smaller than the actual effective conductivity, the field is said to display scale effects on K.

The present work intends to document the variability of hydraulic conductivity within the scale of measurement and to contrast values of K measured on the same fracture at different distances from the pumping well at El Berrocal site (central Spain).

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El Berrocal is the experimental site of an international project aimed at studying migration processes which have controlled the distribution of naturally ocurring radionuclides in a fractured granitic environment. The approach fully integrates the geochemical, structural and hydrogeological features of the site. Multiple fracture systems cut across the rock mass, some of them being of particular relevance (Figure 1). Several sets of quartz dykes are genetically related to these fractures. Dips of fracture systems and quartz dykes range from 65^o to vertical. *Pérez del Villar et al.* (1993) describe the site geology in detail.

The experimental layout consists of an old shaft at an average depth from the surface of 30 m and 19 boreholes ranging from 5 at 600 m deep. Single borehole testing by means of conventional straddle packers has been run in the deepest boreholes (more than 50 m). Table 1 summarizes the number of boreholes used in this work and details the number of tests performed at each well. It also includes the distances between those wells where cross-hole tests were conducted. Hydrochemical surveys have been used for characterizing groundwater composition and for unveiling the role of a uranium quartz dyke in the geochemistry of the system. Some tracer tests have also been performed to help in understanding the hydrogeology of the system.

The regional gradient is controlled by large scale topography (not shown in Figure 1) and points downwards. Locally, a large portion of the groundwater flow occurs at the weathered top of the rock mass, which displays an enhanced pemeability. However, for the purpose of this work, we have only concentrated on the rock mass below the weathered zone. Downwards flow concentrates in major fractures (1 and 2 in Figure 1) and dykes (uranium and barite quartz dykes). *Guimerà et al.* (1993) provide additional details on the hydrogeology of the site.

Results, data processing and interpretation

A large number of single borehole and cross-hole tests have been performed. Inflows at the shaft were also measured. These data were interpreted with several models. The results are summarized in Figure 2. Following is a brief description of data processing at each scale.

– **Single hole tests. Pulse, slug and constant head injection.** They were interpreted under the assumption of 2-D radial flow through a homogeneous

Table 1. Number of single-hole tests at every tested borehole, and distances betweeen boreholes at each multiple well test location.

Borehole	Number of single hole tests	distance between boreholes (m)							
		2	13	15	11	12	14	16	18
2	5	–							
13	17	19	–						
15	39	22	30	–					
11	11				–				
12	2				14.5	–			
14	38						–		
16	21						20	–	
18	15						11	16	–

medium because the interval length (3-10 m) is much longer than the thickness affected by the test. We used the formulations proposed by *Papadopoulos et al.* (1973) for slug tests and by *Bredehoeft and Papadopoulos* (1980) for pulse tests. The general formulation of *Baker* (1988) was used in some cases as well. We consider a scale of sample or affected rock mass on the order of decimeters around the test section. Each dot in Figure 2 represents the median of a set of measurements made in each hole with a single packer spacing. We use the median and not the mean of the log$K$ values because many of them fall below 10^{-11} m/s, the threshold of the device. We group the values by borehole and packer spacing for the sake of comprehensiveness. The highest value of K belongs to a shallow borehole which may have been drilled in the most permeable zone of the rock mass.

– **Single hole tests. Recovery tests.** Volumes withdrawn for hydrochemical sampling were on the order of hundreds of litres, usually by means of a gas-lift system. The recovery curve measured at the pumping borehole was chosen to be representative of a measurement scale of metres. Interpretation of such tests was done using homogeneous models. In spite of the vast amount of samplings, Figure 2 only displays the results of the best controlled ones (constant rate and proper head recoveries). The highest value (-5.5) belongs to the intersection of Fracture 1, the uranium quartz dyke and the barite dyke, and may not be comparable to the others.

– **Cross-hole tests.** The distance between boreholes is on the order of 10 to 80 m and therefore K values are representative of a scale of "tens" of meters. These tests were interpreted using 3-D models with embedded 2-D fractures and 1-D strings to represent fracture intersections and boreholes short-circuits, a methodology described by *Carrera et al.* (1990). The code TRANSIN-III (*Galarza et al.,* 1995) was used for the automatic interpretations. In what follows, we will refer to these as heterogeneous models. The values displayed in Figure 2, however, represent the results obtained for homogeneous models, taking into account only the observation boreholes. We choose this approach in order to obtain results comparable to smaller scale values.

– **Site scale.** Three estimates of site effective K were made. The horizontal size of the site and borehole depth are on the order of hundreds of meters and represent another order of magnitude of measurement scale in Figure 2. The highest value comes from calibrating a numerical model. The other two values were derived from (1) applying Thiem's equation to shaft in-

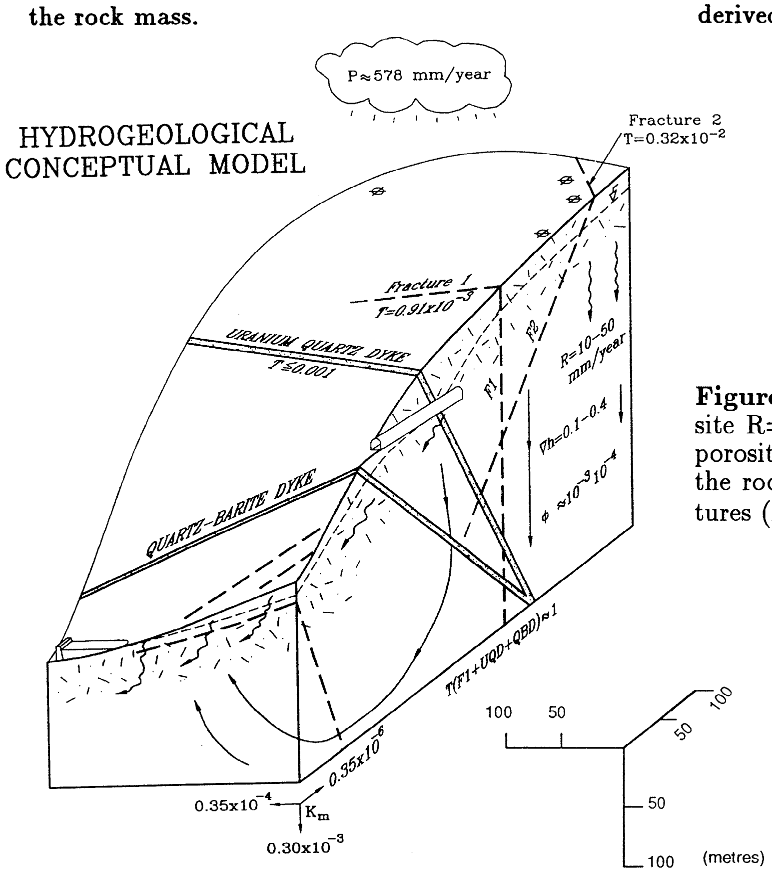

Figure 1. Hydrogeological conceptual model of the site R=recharge; ∇h= vertical hydraulic gradient; ϕ= porosity; K_m= anisotropic hydraulic conductivity of the rock mass (m/d); T= transmissivity of main fractures (m^2/d).

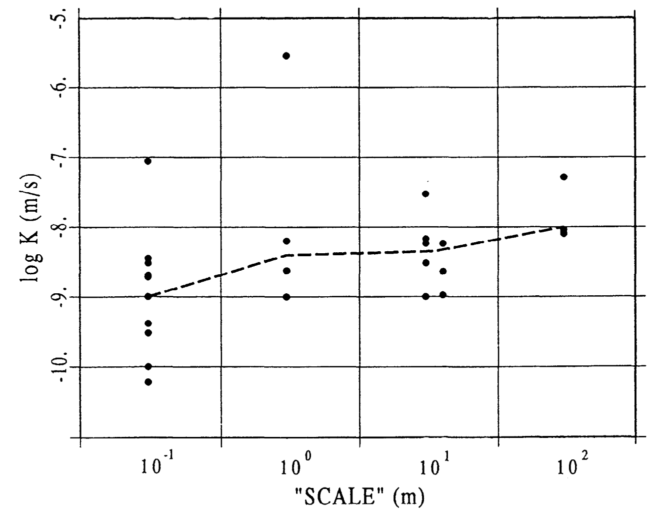

Figure 2. Summary of K values obtained at different scales. The dotted line links median values at each scale. Each dot at the 0.1 m scale represents median values of K measurements obtained with the same packer spacing at each well.

flows and (2) using Darcy's law to couple the recharge and vertical gradient shown in Figure 1.

The variances tend to decrease with the scale, which is hardly surprising. The variance of single hole log-K values is 1.9 (this was computed using only data above the median). Using equation 1, we would have obteined a large scale log-K of -8.7, much smaller than that obtained either with cross-hole or at the site scale. This would support that scale effects are indeed present, specially when considering that the variances of log-K at these scales are of only 0.2, the reduction being caused by the volume averaging induced by the increase in test support.

We take advantage of the use of heterogeneous models to study the scale dependence of fracture transmissivity or rock mass hydraulic conductivity. Figure 3 displays the comparison between K values obtained with a 3D homogeneous model and K and T values obtained by means of heterogeneous models of cross-hole tests. The parameters returned by the two models do not display

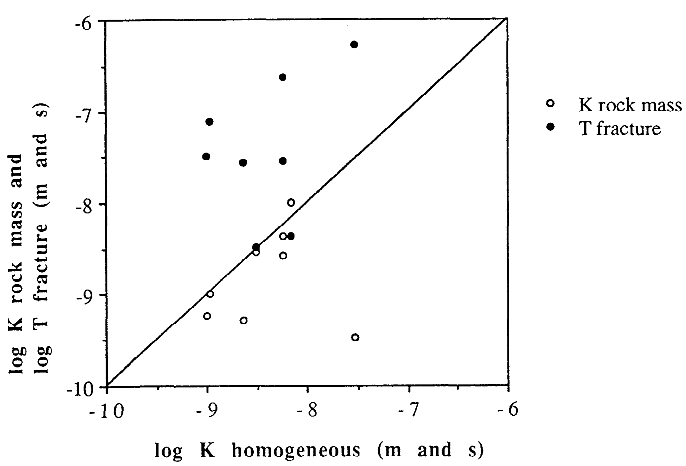

Figure 3. Summary of cross-hole interpretations: Values returned by homogeneous models (K apparent) vs. K and T from heterogeneous models. T is divided by pumping interval thickness in order to facilitate comparison with K values.

clear trends. Rock mass permeabilities of the heterogeneous models are smaller than those of the homogeneous models because part of the water flows through fractures in the heterogeneous models. Given that we know the T or K value from single-hole tests and the same parameter from cross-hole tests in the same interval, we can compare both. Figure 4 contains hydraulic conductivity values obtained from single-hole tests at pumping intervals (vertical axis) versus values from cross-hole tests (horizontal axis). Each dot corresponds to the parameter value obtained with one single hole test and one cross hole test at the same borehole interval. Transmissivity was divided by the test section lenght, to obtain the hydraulic conductivity for homogeneous single-hole tests in the left graph of Figure 4. Cross-hole values in the left graph were obtained under the assumption of a homogeneous medium (apparent K). On the other hand, those in the right graph were obtained assuming that a homogeneous 2-D fracture, embedded in a conductive 3-D medium, connects pumping and observation intervals. The same model was used to evaluate the homogeneous and heterogeneous hypotheses, they only differ on the presence of embedded fractures and therefore, the representative volume remains the same. It should be noticed that, contrary to what is suggested by Figure 2, cross-hole values (both K or T) are consistently smaller than those derived from single-hole tests at the pumping interval.

Discussion and conclusions

The most striking feature of the results presented here is the apparent contradiction between Figures 2 and 4. Figure 2 shows a trend of increasing K values with the scale of the measurement. On the other hand, K values at small scales are consistently higher than K values at large scales in Figure 4.

We contend that, to a large extent, this apparent contradiction is a result of the way cross-hole tests are planned and performed. Pumping intervals for cross-hole tests are chosen so as to ensure that pumping rates are as large as possible. If pumping intervals were chosen at random, chances are that pumping rates at many intervals would be small and corresponding response at observation intervals would be negligible, hence resulting in hard to interpret tests. The effect of choosing the most permeable intervals for pumping is two fold. On one hand, hydraulic conductivities obtained from such tests will tend to be larger than the average, hence biasing graphs such as Figure 2. In fact, geochemical sampling, which led to the "meters" scale K's in Figure 2, was also performed preferentially at the most permeable intervals. These two observations cast a shadow of doubt on the implications of Figure 2 and other similar often presented to support the existence of scale effects. On the other hand, if pumping intervals do indeed represent the most permeable zones, one should expect fracture transmissivities (or rock mass conductivities) between pumping and observation intervals to be smaller. Hence, it is not surprising that, as shown in Figure 4, hydraulic conductivities derived from these tests are smaller than those of the pumping intervals.

The discussion of scale effects is further complicated by the varied nature of flow field geometries. If scale ef-

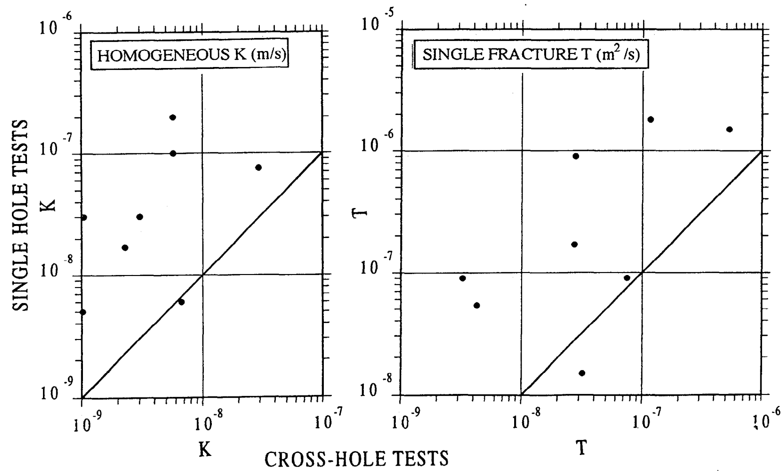

Figure 4. Results from interpretation of cross-hole tests under the assumption of either homogeneous medium (left) or single fracture embedded in a homogeneous medium (right). Vertical axis represents K or T derived from single hole test.

fects are indeed present, apparent conductivities would be a function of distance (i.e., support volume), they may also be affected by the flow field geometry. Radial flow (2-D) is assumed for single hole tests; its 3-D counterpart was used for interpreting cross-hole tests and one of the site scale estimates was based on the assumption of parallel flow.

In summary, we conclude that it is unclear whether scale effects take place at El Berrocal. Site scale conductivities are large than derived from equation 1, but their estimation is quite uncertain. Actually, such question may be irrelevant at this stage. By performing a detailed characterization, we feel we may be able to piece together a model reproducing the most important features of the site. If this task, curently underway, is succesful, then it would no longer be necessary to define an effective hydraulic conductivity, inherently an equivalent porous medium concept.

Finally, it may be worth to mention that the use of rank statistics (i.e. median) has allowed us to overcome the ever tedious task of accounting for data below measurement threshold.

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