Calibration of hydraulic and tracer tests in fractured media represented by a DFN Model

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Abstract A methodology to interpret hydraulic and tracer tests in a discrete fracture network (DFN) is proposed. The methodology starts with an externally generated network of fractures (represented by 2D disks) embedded in a 3D domain. Each generation of a DFN is considered one amongst the ensemble of all possible realizations, and so we adopt a stochastic approach. For each DFN, the connections between the disks define a conductive network, which is represented by a suite of 1-D elements, each one with an individual hydraulic conductivity and storage coefficients. Furthermore, each disk element belongs to a fracture family, so that it is possible to define the so-called family parameters, which are the coefficients that multiply all parameters of the elements belonging to a given family. The values of these family parameters are fitted by means of inverse problem solution of the flow equation, with available pumping tests. Tracer tests can be used to calibrate solute transport parameters (characterizing advection, longitudinal dispersion, and diffusion into a hypothetical immobile matrix). The methodology is illustrated with hydraulic and tracer tests performed in El Berrocal Site (Spain).
Key words fractured media; discrete fracture network (DFN); inverse problem; hydraulic and tracer tests.

INTRODUCTION

Fractured geological media present high complexity to groundwater modelling. The main reasons are geometrical complexity in the location and extent of fractures, plus heterogeneity and anisotropy in hydraulic parameters. Groundwater flow and solute transport in fractured media can be analyzed by four groups of models: equivalent porous media (EPM), discrete fractured network (DFN), porous media with embedded fractures (mixed approach), or channel networks. All of them have been applied widely in forward problems. For inverse problem, though, DFN pose a fundamental problem which is the large number of parameters involved in the calibration process, as due to heterogeneity, each element would have widely different hydraulic parameters associated making inverse modelling a challenging problem. Thus, DFN's must be cast in a statistical framework, as there is a large amount of uncertainty in the actual location, size and hydraulic parameters of each individual fracture.

We propose an alternative calibration method that can be applicable to DFN. The methodology is based on the idea of reducing the number of values to be calibrated based on the concept that a DFN is a realization of a Spatial Random Function. This method has been applied to the interpretation of hydraulic and tracer tests in the granitic batholith of El Berrocal (Spain), within the project HIDROBAP-II financed by ENRESA and the Nuclear Security Council of Spain.

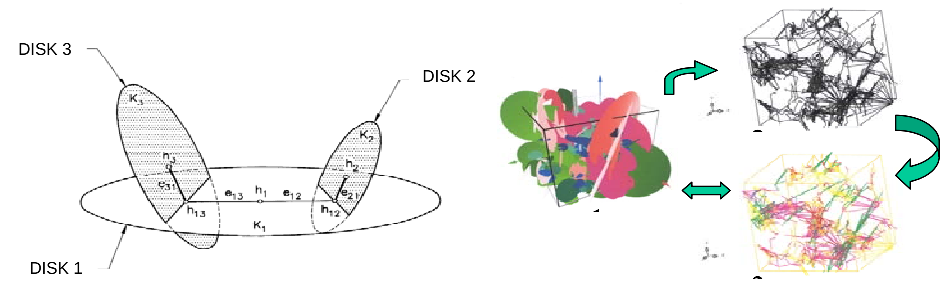
The quality of the fits obtained permits to conclude that DFN models are appropriated to study groundwater flow and solute transport in fractured media since its results are comparable with calibrations obtained using a mixed approach porous media model (Ruiz et al., 2001).

METHODOLOGY

The conceptual model consists of five (5) fracture families, defined a priori based on tectonical criteria. Each network is composed by a number of fractures whose location, size (radius) and orientation are geometrically defined by fractal distributions or probability density functions. These distributions are supported by extensive field data (Nita *et al*., 2004). Each fracture is associated an aperture value from a predefined probability function. Each individual fracture keeps track of the fracture family it belongs (this last point being of outmost importance in our methodology).

The next step corresponds to the solution of the PDE's governing groundwater flow and solute transport in the DFN. The methodology presented here is a modification of the channel model developed by Cacas *et al.* (1990). It starts by finding the conductive fracture network that is the fractures that are connected among themselves and also connected to the boundaries, therefore capable of conducting water. Actually, despite the fracture is modelled as a disk; actual flow takes place only in a small part of it that is in channels associated to the most conductive features within a given fracture. The critical point is the way these channels are interconnected, forming a 3-D network of 1-D elements. A simplified way to consider channels is represented in Fig. 1(a) (HIDROBAP, 1998). One of the advantages of this methodology with respect to that of Cacas *et al.* (1990) is that with this scheme each element still belongs to a given disk, and therefore it is possible to associate each element to a given fracture family. Fig. 1(b) shows the full procedure of going from a DFN to a mesh of 1-D elements while keeping the concept of fracture family.

The parameters associated to any given 1-D element are hydraulic conductivity (K) and storage coefficient (S) in the case the groundwater flow equation is solved, and porosity (ϕ) and longitudinal dispersivity (α) for transport. In each individual element, the actual parameter is equal to the product of two terms: (1) a specific value that comes from a statistical distribution a priori (e.g. a lognormal distribution for K), and (2) a scaling factor ("zone" or "family parameter") which is an unknown value, the same for all elements associated to a given family. The latter value is the one calibrated by means of the inverse problem. As an immediate consequence, only a reduced number of parameters (one or two per family) are to be estimated. The data used for calibration can be steady-state head data, or that coming from a pump (heads) or a tracer test (concentrations).



(a) (b)

Fig. 1 Constructing the conductive network. (a) From individual fractures to 1-D elements. (b) Going from a 3-D DFN to a mesh of 1-D elements. Colours represent families.

Regarding boundary conditions (BC), they must be applied to all elements that intersect a given external volume used in the definition of the DFN. This can be done by using a given geometry (e.g. parallelepiped) and associating a boundary condition to every face. In the flow problem BC can be constant head, constant flow or mixed. In transport the BC depend whether in a given node water flows in (with external concentration), or flows out, carrying the actual concentration in the system.

Calibration is done using TRANSIN II (Medina *et al.,* 1996). The code requires observed values of heads and or concentrations at a given number of observation points and estimates the parameters that best fit the observed values. Observation points should belong to an element which is part of the conductive network.

In the transport problem it is possible to incorporate a number of processes to account for non-conservative species. These processes can be adsorption, first-order radioactive decay and matrix diffusion. Whenever one of the processes is incorporated to the conceptual model, some additional parameters arise. These new parameters are also associated to families, despite any given element could have a different coefficient drawn from an a priori statistical distribution if necessary.

In this type of meshes numerical instabilities can cause both the direct or inverse problems not to converge. This might call for reducing the length of the 1-D finite elements, therefore increasing the number of nodes, which leads again to CPU problems.

RESULTS

Flow Simulations

The methodology is tested by means of the calibration of a combination of hydraulic and tracer test carried out in the framework of the El Berrocal Project (Rivas *et al.,* 1997). Twenty different statistical equiprobabilistic representations of the media were generated and analyzed.

The DFN was modelled as defined by 5 fracture families. A pumping test was simulated and the interpretation was performed using the methodology presented in this paper. Initially only the flow parameters were calibrated. The parallelepiped block simulated was 600 m × 600 m × 300 m, with the pumping and observation points located around the mid point in the domain. Boundary conditions applied in the numerical model where no flow in the top and bottom boundaries and zero drawdown elsewhere indicating that the influence radius of the test was assumed to be less than 300m. The calibrated parameters were a single value for hydraulic conductivity (K) and storage coefficient (S) for each independent fracture family, leading to a total of 10 parameters to estimate. Amongst the 20 initial networks, all of them unconditional to the location of specific fractures, six of them produced excellent results in terms of fitting the transient head data. Fig. 2 shows one of the best fits obtained, compared to an average one.

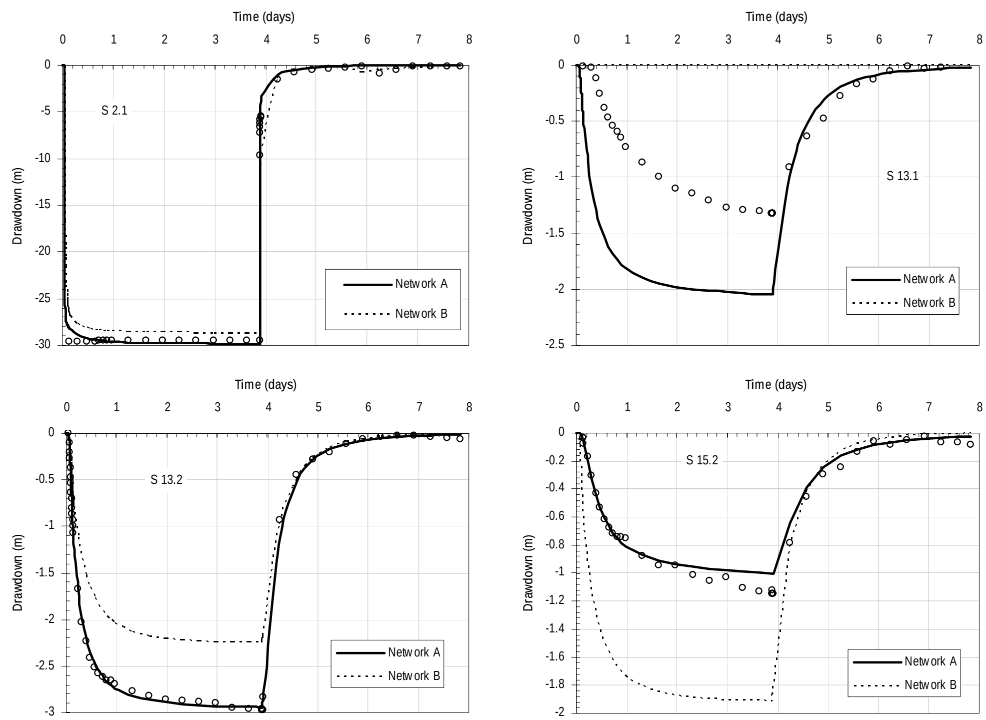


Fig. 2 Observed (dots) vs. computed drawdown (lines) after calibration of a pumping test (pumping in S14.2 and three additional observation points) in El Berrocal using a DFN approach. Two different fits (amongst the 20 networks available) are presented; Network A, corresponding to <u>one of the best</u> ones, and Network B, which provides an <u>average</u> fitting.

The match between computed and observed drawdown is similar to the one that was obtained in Rivas *et al*. (1997) applying a <u>mixed approach</u>, indicating that the methodology presented could compete in terms of data matching. In the observation point S13.1 it was impossible to get a good fitting, either by means of a DFN or a porous equivalent model. During the process of flow calibration the fracture family number 4 was insensible, meaning that the same fits were obtained independently of the zone value used. This means that in the vicinity of the test area very few, if any, of the conducting elements belong to that particular family. This result was repeated in most of the 20 DFN analyzed.

Transport Simulations

The proposed methodology was extended to transport analysis in the six networks which provided the best fit in the flow simulation. A tracer test with two different tracers (uranine and deuterium) was analized. The flow configuration is the result of a dipole, with pumping at the well (0.1 m^3 d^{-1}) and simultaneous pumping (0.2 m^3 d^{-1}) at the injection point. Boundaries were checked so that no mass was leaving the domain.

A double porosity model was considered. The processes considered were advection, dispersion and matrix diffusion. The total number of estimated zonal parameters was nine (the longitudinal dispersivity, six porosities: one for each family (5) and that of the immobile zone; and two diffusivities corresponding to the mobile and immobile zones). The fitting between observed (HIDROBAP, 1998) and computed concentrations at the extraction point is acceptable and also comparable with the one obtained using an equivalent porous media for conceptualization.

The inverse problem technique is not so easy to apply in transport solution. It must be applied after a manual adjust for the parameters to get an approximated shape of the breakthrough curve (BTC) (Fig. 3). First of all, the molecular diffusion coefficients of the matrix (1×10^{-5} m d^{-1}) and the fracture families (1×10^{-1} m d^{-1}) were fixed to typical values. Second, the immobile porosity was fixed to represent the BTC tail (1), while the mobile porosity (the same value for all the families) was settled to reach the peak position (2). In addition, the dispersion coefficient was increased to shape properly the BTC (3). To start the process, mass tracer and the dispersion coefficient were only calibrated (4), then, the porosities (mobile and immobile) were calibrated automatically (5).

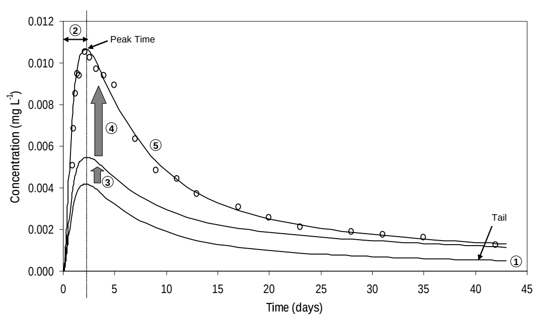


Fig. 3 Steps for a semiautomatic calibration of a BTC in a DFN model

Fig. 4 shows the fitted BTC for the network number 10 (which provides also the best fit of the flow problem). The Deuterium curve was best fitted using an advection – dispersion – matrix diffusion model (Fig. 4(a)), while a model without matrix diffusion could fit very well the Uranine BTC (Fig. 4(b)). This indicates the need for a retention process in the former. Consistency in the parameters comes from the same parameter values for porosities in both curves. The values calibrated for longitudinal dispersivity and diffusivity are different for both tracers.

CONCLUSIONS

Twenty different realizations of a DFN were used to simulate pumping and tracer tests in fractured media. Eighty percent (80%) of the DFN analyzed present head objective functions with acceptable values, thirty percent (30%) with objective function values that can be considered excellent from the head fitting standpoint. The methodology adopted allows calibration a relatively short number of parameters, deeming the calibration process possible. The actual fitted parameters (zonal T and S values) vary with each simulation. Families that do not contribute to flow can be detected by this method. The tracer tests interpretation allows estimating additional parameters, such as porosity, longitudinal dispersivity, as well as matrix diffusion parameters (ϕ_m, D_m).

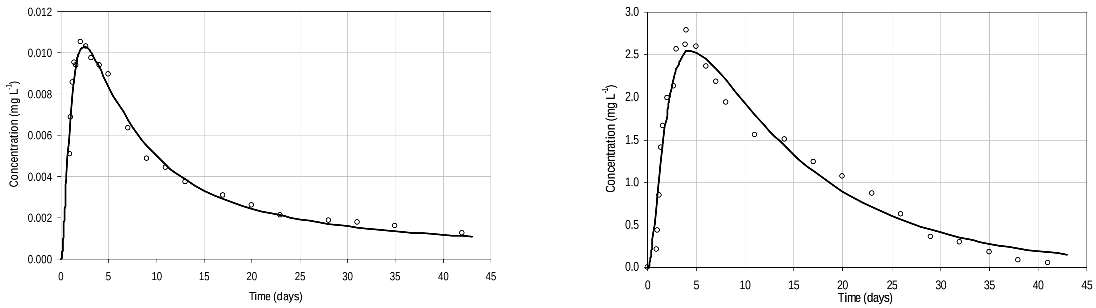


Fig. 4 Observed (dots) vs. computed concentrations (lines) after calibration of a tracer test in El Berrocal using a DFN approach. (a) Deuterium: Advection – Dispersion – Matrix Diffusion model. (b) Uranine: Advection – Dispersion model.

In conclusion, the methodology presented allows calibrating the parameters corresponding to a DFN obtaining matches qualitatively and quantitatively as good, or better, as those obtained using a conceptual model of an equivalent porous medium. The definite advantage of the method is that the DFN simulated is not unique, and therefore this methodology is easily and immediately casted in a geostatistical framework, and therefore it is easier to find a physical meaning to the calibrated values.

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