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

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Abstract A methodology is proposed for interpreting hydraulic and tracer tests in a discrete fracture network (DFN). To start off, an externally generated network of fractures (represented by 2-D disks) is embedded in a 3-D domain. Since each generated DFN is considered as one of the possible outcomes, a stochastic approach is adopted. In each DFN, the connections between the disks define a conductive network, modelled as a suite of 1-D elements. The hydraulic conductivity and specific storage coefficient for each element form the product resulting from an individual value multiplied by a parameter; this is the same for all the elements and corresponds to a disk belonging to a given family. These family parameters are fitted by means of an inverse problem solution using available pumping test data. Tracer tests are also used to inversely calibrate solute transport parameters (mobile and immobile porosities, dispersivity, and diffusion in the fractures and matrix). The methodology is illustrated with hydraulic and tracer tests performed at the El Berrocal site (Spain).

Keywords discrete fracture network; fractured media; hydraulic and tracer test interpretation

INTRODUCTION

Fractured geological media make groundwater modelling highly complex. The main reasons for this are the geometrical complexity at the location, and the extent and the hydraulic properties of the individual fractures. Groundwater flow and solute transport in fractured media can be modelled using four approaches arranged in groups: equivalent porous media (EPM), discrete fractured network (DFN), porous media with embedded fractures (mixed approach) and channel networks. All of these approaches have been applied widely to forward problems. For inverse problems, however, DFNs pose a fundamental dilemma, namely, the large number of parameters involved in the calibration process. In principle, each element in the network will have different associated hydraulic parameters, making inverse modelling a challenge.

Uncertainty in location, size and hydraulic parameters of each individual fracture makes the deterministic approach largely useless. The methodology proposed is based on the idea of reducing the number of values to be calibrated by casting the problem in a stochastic framework. The 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 allows one to conclude that DFN models are suitable to study flow and solute transport in fractured media, since their results are comparable to those obtained by calibration with a mixed approach model (Ruiz *et al.*, 2001).

METHODOLOGY

First, the conceptual model consists of a set of fracture families, defined *a priori* on the basis of tectonics. Each network is composed of a number of fractures whose location, size (radius) and orientation are geometrically defined by probability density functions supported by extensive field data (Nita *et al.*, 2004). The fracture apertures also come from a predefined probability function. Each individual fracture keeps track of the fracture family to which it belongs (this last point being of utmost importance in our methodology).

The next step corresponds to solving the governing equations of flow and transport in the DFN. The methodology (a modification of the channel model developed by Cacas *et al.*, 1990) is set to first find the conductive fracture network. This network is formed by the fractures that are interconnected and by those connected to the boundaries, which makes them capable of conducting water. Actually, just as in each disk, flow only takes place in channels associated with the most conductive features, while the three-dimensional (3-D) network is modelled by a suite of 1-D elements (see Fig. 1(a)). Using this approach, it is possible to associate each element, e_{ij}, with a given fracture family. Figure 1(b) shows the full procedure, going from a DFN to a mesh of 1-D elements.

The parameters associated with each element are hydraulic conductivity (K) and specific storage coefficient (S_s) when the flow equation is solved, and porosity (ϕ) and longitudinal dispersivity (α_L) for transport. In each individual element, actual parameter values are equal to the product of two terms: (a) one specific term, based on geometrical and connectivity considerations, and (b) a scaling factor ("family parameter") which is an unknown value that is the same for all elements associated with a given family. The latter value is the one calibrated by means of the inverse problem. Only a reduced number of parameters have to be estimated as an immediate consequence. The data used for calibration can be steady-state heads, or data coming from a pumping (heads) or a tracer test (concentrations). 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. In this type of mesh, numerical instabilities can prevent the inverse problem from converging. This might call for reducing the length of the 1-D finite elements, thus increasing the number of nodes, leading again to CPU problems.

Boundary conditions (BC) must be applied to all elements that intersect a given predefined geometry. In the flow problem, BC can be of a constant head, constant flow or mixed. In transport, BC depends on whether, in a given node, water flows in (with external concentration), or out, carrying the actual concentration in the system.

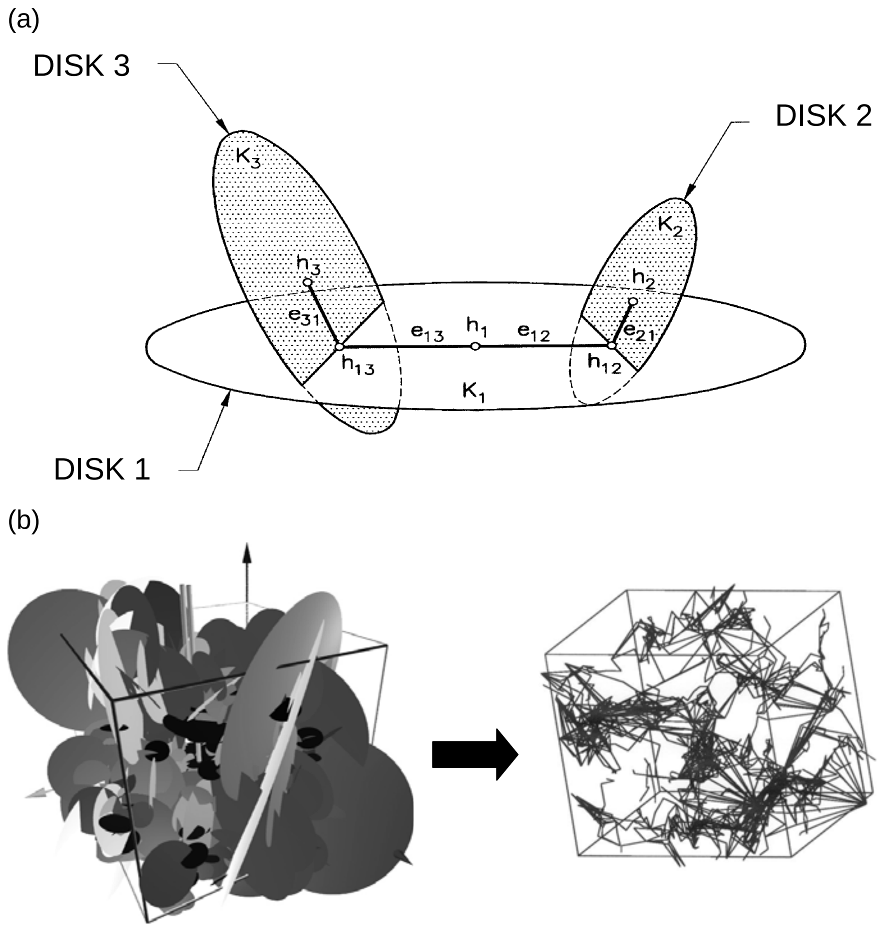


Fig. 1 Constructing the conductive network: (a) from individual fractures to 1-D elements; (b) from a 3-D DFN to a mesh of 1-D elements. Grey scale represents the families.

In the transport problem, it is possible to incorporate a number of processes such as sorption, first-order radioactive decay, and matrix diffusion to account for non-conservative species. Whenever one of the processes is incorporated into the concept-tual model, some additional parameters arise. If necessary, these new parameters will also be associated with families, despite the fact that any given element could have a different coefficient from an *a priori* statistical distribution.

RESULTS

Flow simulations

The methodology was tested by means of calibrating a combination of hydraulic and tracer tests carried out in the framework of the El Berrocal Project (Rivas *et al.*, 1997). The DFN was modelled according to five defined fracture families. A pumping test was simulated and the interpretation was performed using the methodology presented in this paper. In the first step, only flow parameters were calibrated. The block simulated was 600 × 600 × 300 m, with the pumping and observation points located around the middle of the domain. Boundary conditions applied where there is “no flow in the top and bottom boundaries” and “zero drawdown” elsewhere, indicating an influence radius of the test assumed to be less than 300 m. The calibrated parameters represented a single value for hydraulic conductivity (K) and a specific storage coefficient (S_s) for each independent fracture family, leading to a total of 10 parameters to estimate. Twenty different statistical equi-probabilistic representations of the media were generated and analysed. Six of these produced excellent results in terms of a very small head objective function (OF) when fitting the transient head data. Figure 2 shows one of the best fits obtained in comparison to the average (larger OF).

The match between computed and observed drawdown is similar or even better than the drawdown presented by Rivas *et al*. (1997) applying a mixed approach, thus indicating that the methodology presented could compete in terms of data matching. At the observation point S13.1 it was impossible to get a good fit, either by means of a DFN or a porous equivalent model. During the process of flow calibration, fracture-family number 4 was insensitive, meaning that the same fits were obtained independently of the value used for this particular zone. So, in the vicinity of the test area very few, if any, of the conducting elements belong to that particular family.

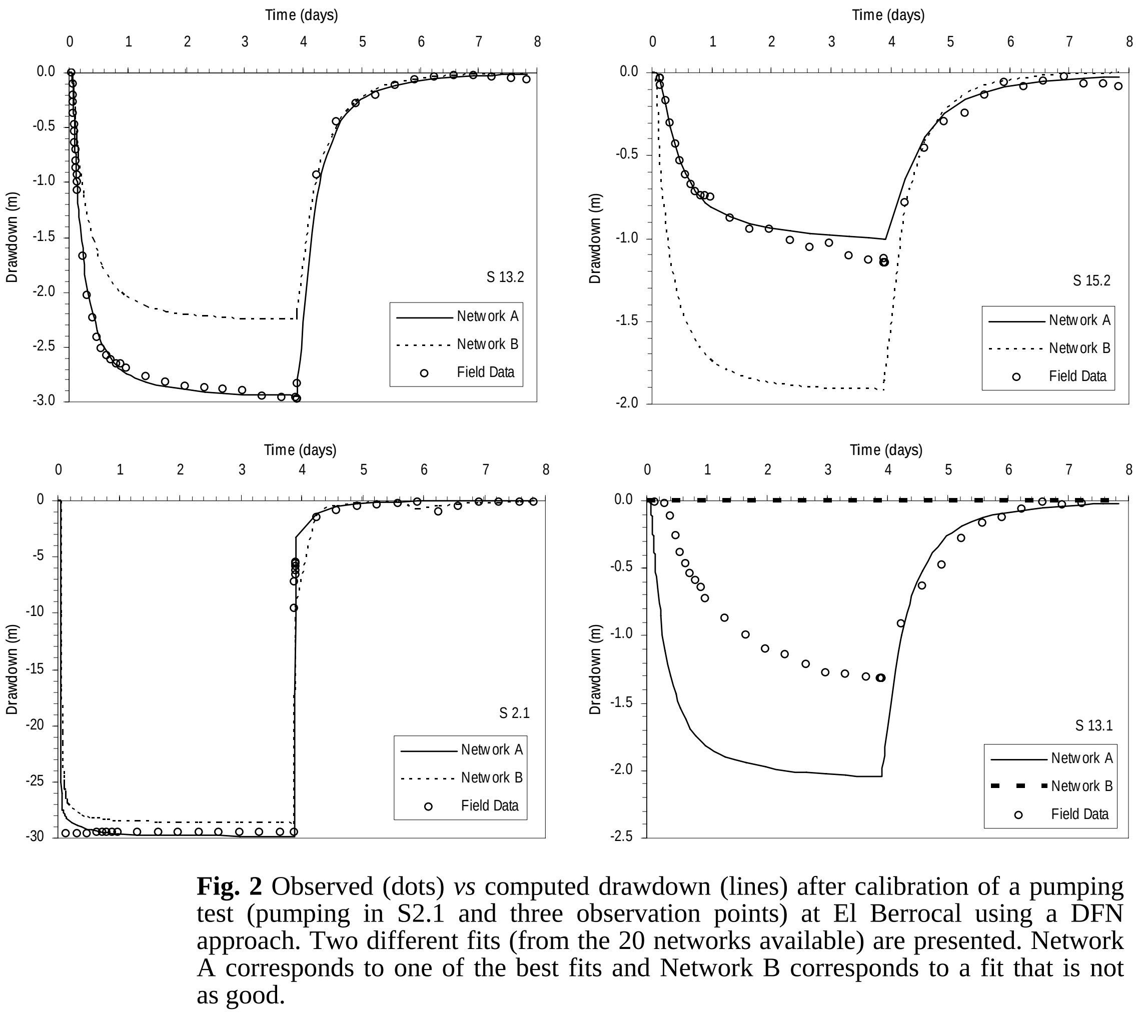


Fig. 2 Observed (dots) *vs* computed drawdown (lines) after calibration of a pumping test (pumping in S2.1 and three observation points) at El Berrocal using a DFN approach. Two different fits (from the 20 networks available) are presented. Network A corresponds to one of the best fits and Network B corresponds to a fit that is not as good.

Transport simulations

The proposed methodology was extended to transport analysis in six networks, thus providing the best fit in the flow simulation. A tracer test with two different tracers (uranine and deuterium) was analysed. The flow configuration is the result of a dipole, with pumping at the well (0.1 m^3 day^{-1}) and simultaneous pumping (0.001 m^3 day^{-1}) at the injection point. Boundaries were checked to see that no mass was leaving the domain.

A double porosity model was considered, along with the processes of advection, dispersion and matrix diffusion (ADE + MD). The total number of estimated zonal parameters was nine:

- longitudinal dispersivity,
- six porosities (one for each family, i.e. five, and one for the immobile zone), and
- two diffusivities corresponding to the mobile (fractures) and immobile (matrix zone).

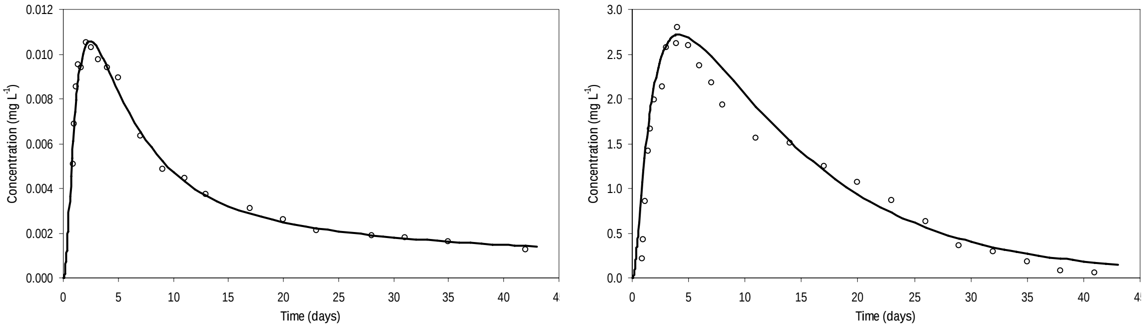
The fitting between observed and computed concentrations at the extraction point is acceptable and also comparable with the fitting obtained using a model based on an equivalent porous media approach.

The inverse problem technique is not so easy to apply to transport as it is to flow. It must be applied after a manual adjustment of the parameters to get an approximated shape of the breakthrough curve (BTC). First of all, the molecular diffusion coefficients of the matrix (1×10^{-5} m day^{-2}) and of the fracture families (1×10^{-1} m day^{-2}) were fixed to typical values. In this case an initial guess of the different parameters can be obtained as follows: the immobile porosity affects primarily the BTC tail shape, the mobile porosities influence the time corresponding to the peak, and the dispersivity conditions the shape of the BTC. The total injected mass must also be calibrated to account for partial recovery of the tracer.

Figure 3 shows the fitted BTC for the network that provided the best fit in relation to the flow problem. The deuterium curve was best fitted using an advection–dispersion–matrix diffusion model (Fig. 3(a)), while a model without matrix diffusion would fit the uranine BTC very well (Fig. 3(b)). This indicates the need for a retention process in the former. Consistency in the parameters comes from having the same parameter values for porosities in both curves. The values calibrated for longitudinal dispersivity and diffusivity are different for each tracer, as the processes accounted for are also different.

CONCLUSIONS

Twenty different realizations of a DFN were used to calibrate pumping and tracer tests in fractured media. Eighty per cent (80%) of the DFN analysed present the objective functions of head with acceptable values, and from these, 30% provide an excellent fitting in terms of heads. The fittings are comparable with and, in some cases, better than those obtained by means of an approach based on an equivalent porous media with embedded fractures. The methodology allows one to calibrate a relatively small number of parameters, making the calibration process possible. The actual fitted



(a) (b)

Fig. 3 Observed (dots) *vs* computed concentrations (solid lines) after calibrating tracer tests in El Berrocal using a DFN approach using (a) deuterium with an advection–dispersion–matrix diffusion (ADE + MD) model: and (b) uranine with an advection–dispersion (ADE) model.

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 test interpretation allows additional parameters to be estimated, such as porosity and dispersivity, along with the porosity and dispersion coefficient of the immobile zone if a double porosity model is adopted.

In conclusion, the methodology presented allows us to calibrate the parameters corresponding to a DFN. The definite advantage of the method is that the DFN simulated is not unique, so this methodology can be easily and immediately applied in a geostatistical framework, thus making it easier to give physical meaning to the calibrated values.

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