Prediction of hydro-mechanical responses of a long – term pump test in Sellafield site

A. REJEB and D. BRUEL*

IPSN/DPRE/SERGD, B.P. 6, 92265 Fontenay-aux-Roses CEDEX,France
** Paris School of Mines, CGI, 35 rue Saint Honoré, 77305 Fontainebleau, France*

Abstract: Under the auspices of the DECOVALEX[1] II international project, the coupled hydromechanical responses, in the fractured volcanic rocks at Sellafield site, to a pump test and shaft sinking were studied. The aim of this paper is to describe the methodology for analysing the hydromechanical responses of a long-term pump test in borehole RCF3 drilled on the centreline of one of the proposed shafts. This methodology is based on the Discrete Fracture Network (DFN) approach for hydraulic analysis and the discrete approach, where the main discontinuities are explicitly represented in model. The principal advantage of using the DFN approach is to change easily the scale of the study without important modifications of the network. Hydraulic properties of the different types of discontinuities were evaluated by calibration of the flow rates measured in the site.

1. INTRODUCTION

The rock mass response to storage of radioactive waste may be a coupled phenomenon involving thermal, hydrogeological, mechanical and chemical processes. The overall objective of the DECOVALEX II international project is to increase the understanding of various thermo-hydro-mechanical processes and how they can be described by mathematical models. The most important transport mechanism of radionuclides from a repository to the biosphere is through the groundwater present in the rock. The host rock will be subjected to *in situ* stresses, excavation-induced stresses and thermo-mechanical stresses resulting from radiogenic heat of the wastes. Because there is a strong relationship between fracture aperture and permeability, these stresses can cause changes in hydraulic properties of the jointed rock masses. For the safety of the disposal system, it is important to quantify these changes during the excavation, operational and post-closure stages.

The excavation of the repository causes a major perturbation of the rock mass by the creation of a large cavity. At this stage, the mechanical perturbation of the hydraulic system dominates. The excavation will concentrate stress changes around the cavity, which in turn will change the local fracture aperture and permeability. In general the question is how to determine the nature and extent of anisotropic changes in hydraulic conductivity around the repository cavity.

In this~~the~~ context, the Institute of Protection and Nuclear Safety, in collaboration with Paris School of Mines, studied Task 1 of the DECOVALEX II project. This task concerns the prediction and model calibration of the RCF3 pump test and the proposed shaft excavation at Sellafield site by United Kingdom Nirex Limited. At Sellafield, Nirex have investigated at different scales the geology and hydrogeology of a Potential Repository Zone (PRZ) which included the rock volume in which it was happened to construct an underground Rock Characterisation Facility (RCF). In the PRZ the stratigraphic sequence comprises from the top downwards - St Bees Sandstone Formation of the Herwood Sandstone Group, the Brockram Formation and the Borrowdale Volcanic Group (BVG). Only the BVG is studied in the framework of task 1. Details of the hydrogeological testing at Sellafield has been given in [1]. The aim of this paper is to describe the methodology used to analyse the hydromechanical responses of a long-term pump test.

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[1] **DE**velopment of **CO**upled models and their **VAL**idations against **EX**periments in nuclear waste isolation.

2. CHOISE OF METHODOLOGY

The hydrogeological properties of the potential host rock, known as BVG, were investigated from an extensive hydraulic testing programme. A variety of experiments were designed to address the rock mass at different length scales. Major outcomes of this research are (i) that groundwater flow through this fractured rock mass is controlled by a number of flowing zones, that might be assembled into a connected network, and (ii) that the properties of the fracture sub-network between the flowing zones is distinct from those of this larger scale network [2]. This observation fits with more general observations made on crystalline rocks, where the overall fluid flow is often very heterogeneous and concentrated in a few fractures, as a result of complex geometry made by the superposition of structures of various sizes. A consequence of the broad distribution of fracture size is discussed in [3] in terms of network connectivity. Theoretical developments assuming a power law distribution for the fracture sizes, lead these two authors to state that for most natural systems, fracture networks are connected at large scales, whatever the fracture density, and that permeability is therefore increasing with the domain size as the consequence of the increase of connectivity. A direct conclusion might be that the only relevant scale is the size of the system under consideration, which in turn raises the question concerning the pertinence of an equivalent porous medium description for such geological systems. Furthermore, when mechanical effects are considered, it has been demonstrated from numerical simulations [4] and from *in situ* observations [5] that, if it exists, a critical flow path does not necessarily remain the same as fluid pressure is increased or decreased. Therefore, conclusions drawn from pump test responses obtained within a given range of fluid pressures might not be extrapolated to other hydromechanical regimes without great caution.

For the above reasons, we decided to take advantage of a Discrete Fracture Network (DFN) model, which has capabilities to include the superposition of a variety of geometrical structures and a hydromechanical compliant flow rule for the pressurised fractures. This was used to model the RCF3 pump test, by considering in an explicit way the different observed geometric features at their appropriate scales. Hydrogeological properties such as the hydraulic conductivity or storativity were derived for each class of discontinuities using the appropriate field tests. The approach consists of starting from modelling the smallest type of discontinuities and gradually merging the fracture networks into larger volume of rock, up to the field scale pump test simulation that incorporates the largest identified faults.

3. TEST DATA AND ANALYSIS

The hydrogeological data base has been obtained as part of the site characterisation programme but detailed knowledge related to small-scale flow properties was mostly collected along the RCF3 borehole. Geometrical information concerning the discontinuities, such as the distribution of fracture orientation and fracture spacing, were derived from the analysis of wireline logs. Four different directional sets, mostly subvertical, are identified (see Table 1). No fracture length scale can be obtained from borehole data. However, outcrops exhibiting similar morphological characteristics exist in the area and are helpful to better constraint the smaller scale fracture pattern. Observed fracture trace-lengths ranged from 2 m to 10 m. For larger structures, typical length scales have to be quantified using flow test responses in a trial and error matching process. It was recognised that several possibilities might satisfy the data and that no unique solution will come out from the modelling.

Table 1. Characteristics of the four identified fracture sets in the BVG, corrected for borehole deviation from vertical as discussed in [2].

Joint set	*Orientation*	*Frequency [frac/m]*
1	North 56, dip75	0.42
2	North148,dip65	0.29
3	North352,dip70	0.12
4	North254,dip70	0.13

Structural logs also exhibit a number of apparently open fractures, that might be significantly conductive for flow with an average spacing of the order of 25 m, while the full network of discontinuities along RCF3 results in a mean spacing of the order of 1 m. To investigate the connectivity of these possibly flowing features and the resulting overall permeability in between the depth of the potential repository and the overlying sedimentary pile, two types of flow tests were performed, respectively and referred in Nirex terminology as Short Intervals Tests (SIT) over an interval of 1 – 2 m and Fracture Network Tests (FNT) in 20 m open hole sections. SIT consisted in the instantaneous injection of a constant fluid volume of 20 cm^3 in single fracture isolated by a double packer system. The response is characterised by two quantities, namely the pulse height and the remaining overpressure after one hour and half of pressure decay. One hundred measurements were made available and the responses are depicted as histograms in Figure 1. In the FNT, an interval of 20 m in length is isolated and the hydraulic head is subject to a 100 m initial drawdown. The measurements are the integrated volume after one hour of rising head back to the initial level. Seventeen responses were available with an average produced volume of 1 l. Figure 2 shows how these discharged volumes are distributed.

Both types of tests were used in the first stage of the present work to calibrate the hydraulic properties, e.g. the equivalent aperture and the fracture stiffness of the small scale fractures and intermediate scale fractures, respectively. Among these open fractures, some can be identified or correlated at different boreholes. They were given a name and treated explicitly with their deterministic set of parameters (location, orientation, infinite extension) in the analysis of the three month long pump RCF3 test. Because these experiments basically consist of prescribing local hydraulic head perturbations, the analysis deals with transient responses and hydromechanical interactions are concerned, since storativity is governed by the compliance of the fractures that allows some fluid to be stored or expelled from the fracture void space. Accordingly, stress magnitudes described in [6] must be accounted for.

4. CALIBRATION AGAINST SIT AND FNT EXPERIMENTS

4.1 Short Interval Test

The numerical procedure is similar for both type of tests. Dealing with the SIT, we first generate a fracture network within a cubic volume 25 m along each side, populated with small scale fractures according to densities extracted from Table 1. This volume was found to be large enough since a few fractures only experienced the test. Outer boundaries were kept hydrostatic, while the inner boundary, a vertical segment 1.56 m in length, 28 l in volume represents the tested zone where the pulse SIT test applies. Stress components were chosen to represent the regime at 650 m bOD depth (below Ordnance Datum = mean sea level). The 20 cm^3 volume is injected in 1 s, and we simulated the shut in phase for 5400 s. Pulse height and remaining pressure at the end of the period were stored. Fitting parameters are the ones of the Bandis normal closure law, e.g. the initial stiffness coefficient k_{n0}, the maximum aperture e_0 of the fracture under zero effective stress. For reliability of the results, 250 numerical tests are performed leading to the results presented in Figure 1. Best agreement is found for a lognormal distribution of aperture, with mean value -10.44 and standard deviation 0.25, which corresponds to an average maximum closure of $30\ 10^{-6}$ m, associated to a stiffness value at zero effective normal stress equal to 20 GPa/m.

4.2 Fracture Network Test

The main assumption in this analysis was that the fractures of intermediate scale, that possibly form a conductive network, follow the same distribution of orientation as those of the smaller scale. Only the relative density of each set and the sizes have to be corrected so that the total density reflects the 25 m spacing observed along the RCF3 scan line. The criterion is met with an average fracture area of ~ 700 m^2 and a total density of $1.7\ 10^{-4}$ fracture/m^3, which corresponds to fracture sizes ranging from 10 m to 50 m. Then the transient response was simulated. One hundred equally consistent network alternatives were performed, by filling a cube of rock, 150 m in size, centred at the depth of 650 m bOD, with fractures of the intermediate scale. Outer boundaries remain fixed at hydrostatic conditions while a 20 m vertical segment represents the inner boundary. A linear pressure decrease was prescribed in such a way that the 100 m hydraulic head drop is reached within 2 s. Pressure recovery was then calculated and flow coming out at the well was summed over time. The distribution of recovered volume was compared to the experimental results as shown in Figure 2. Reasonable agreement was found for stiffness coefficients under zero normal effective stress and aperture respectively of the order of 25 GPa/m and 100 10^{-6} m. The large volume values are not properly simulated but this discrepancy is likely to be linked for some of the FNT to the vicinity of faults with larger size that might have more efficient connections to the far field. This was addressed by an analysis the RCF3 pump test.

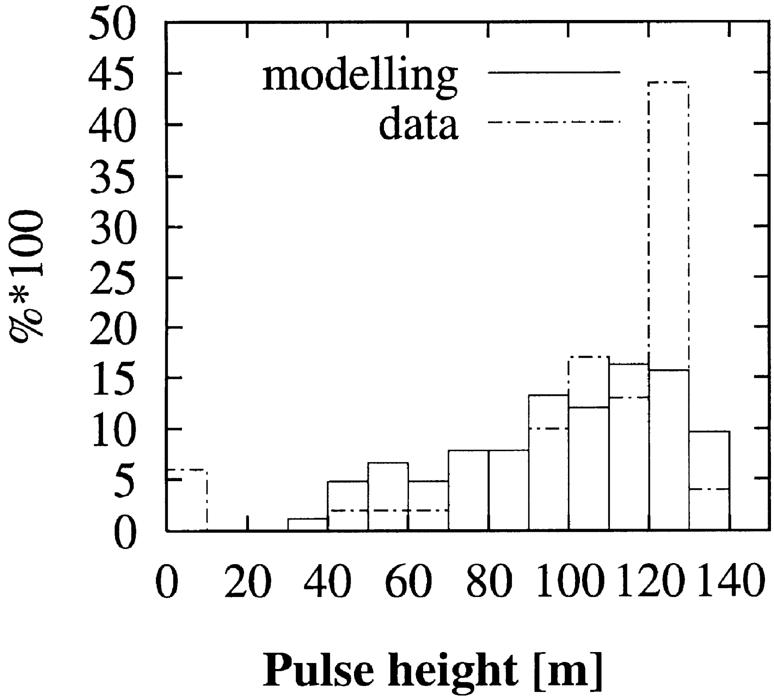

Figure 1: Pressure peak distribution of the SIT pulse tests, after the instantaneous injection of 20 cm^3 of water.

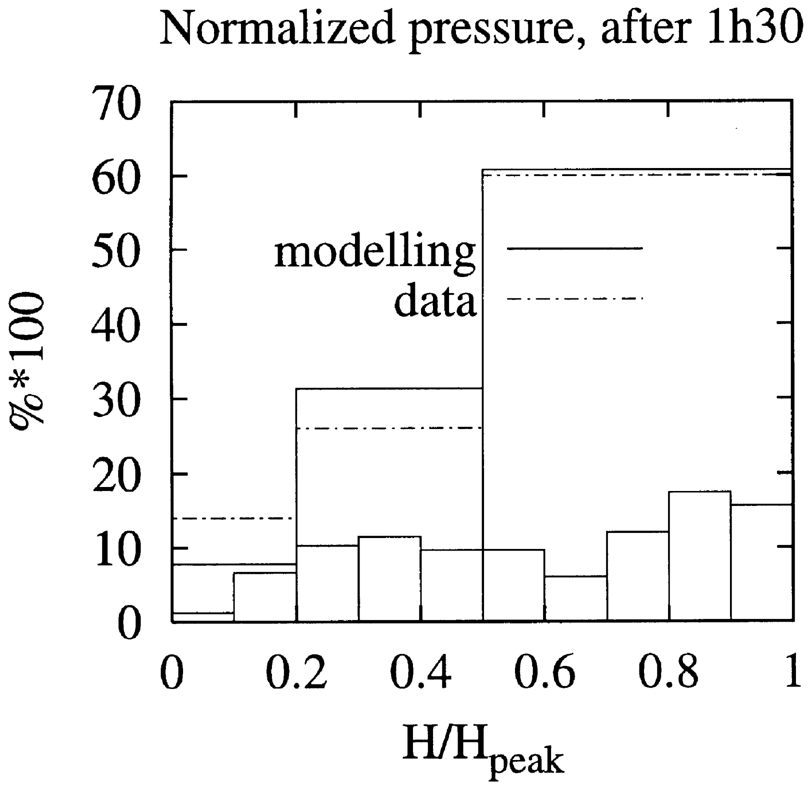

Figure 2: Remaining pressure at the source after 1h30 of pressure decay, normalised with regard to the peak value. Measurements are sorted into three classes while numerical results are distributed into 10 classes, and then summed to compare with the experimental data.

5. INDIVIDUAL FAULTS PARAMETERS AND RCF3 PUMP TEST SIMULATION

The RCF3 pump test is basically a simple test where the hydraulic head at the source zone is kept constant. The total time of the fluid abstraction was 2110 h with a drawdown of 1553 kPa applied in the RCF3 well, from 640 m down to 680 m bOD. The responses were monitored in packed sections at different places, either in the RCF3 borehole or in one of the five other boreholes (namely RCF1, RCF2, RCM1, RCM2, RCM3). Their exact location was provided in [6]. Pressure changes were calculated and compared at 25 different zones, of which 10 of these zones were used for calibration purposes. The discharged flow produced at the source zone was also compared to measurements.

The domain of the study was dimensioned so that it includes all the monitoring zones. A cylindrical volume, with RCF3 as the central axis, was chosen, with a radius of 250 m, extending from the top of the BVG, e.g. ~ 400 m bOD, down to a depth of 950 m bOD. The vertical boundary, as well as the top boundary, was prescribed by a hydrostatic head profile.

Individual faults, that crosscut the simulated domain were extracted from the data base with their own geometrical characteristics and superimposed to the network made of small and intermediate scale fractures. These are respectively referred as F200, F201, F203, F209, F210, F211A, F212, F2low and F2up. In order to better reflect the geometry, the model was conditioned to include a known flowing feature that intersects the source zone at a depth of 672 m bOD, (FZ20 and FZ21). The immediate vicinity of the source zone was further described up to a distance of 25 m by combining fractures of the smallest scale to fractures of the intermediate scale in the generation of the random networks. Unknown parameters that needed to be calibrated were the aperture and stiffness for the large structures and also their extension, since we found that non persistent structures allow more variable behaviours which is useful to understand significantly different responses at neighbouring locations. It has to be noted that each monitoring zone is connected to a piece of the network, either by a fracture belonging to a random set or by one of the faults.

During this calibration phase, we found that the FZ20 must not have a large extension (less than 35 m in radius), otherwise it would connect to other large structures and produce to fast responses in the nearby monitoring zones. It must also have a large aperture, 10^{-4} m, and a stiffness comparable to the stiffness of the fractures belonging to the intermediate class. Fluid produced during the first minutes of the pump test at a rate of many litres per minute seems to be expelled from this structure.

Also, we had to use large storativity coefficients for the faults that would not fit with those derived from a conventional Bandis compliant model. For this reason, the normal compliance law was redefined using two other parameters, namely the aperture e_i and the equivalent normal stiffness k_{ni} defined at the *in situ* effective stress level. Apertures values e_i were found to range in between $25.\ 10^{-6}$ m to $1.\ 10^{-4}$ m, while the equivalent hydraulic stiffness values fall into the range 5 GPa/m to 40 GPa/m. These apparently low values can be explained by the combination of (i) the mechanical stiffness of the fracture, which should be of the order of 100 GPa/m for effective stress in the order of 15 MPa and (ii) the deformation of a metric damaged/alterated zone in addition to the open conductive zone of the faults with an equivalent Young's modulus of 40 GPa. This is in agreement with what was suggested by [7], where the storativity value S was derived according to the following formulation:

$$S = \rho\ g\ (1/k_{ni} + 2\ L/E + \beta\ e_i) \qquad (1)$$

E being the Young's modulus of the surrounding rock layer, with thickness 2L, β the fluid compressibility, ρ the fluid density, g the gravity, k_{ni} and e_i the Bandis parameters at a given normal effective stress. Thus, with regard to the relative magnitude of both terms in equation (1), the stiffness k_{ni} we found for the large structures, seems to be controlled by the mechanical properties of the surrounding rock mass, characterised by two other quantities E and L.

Reliability of the results was achieved by averaging 20 different but equi-probable numerical realisations of this pumping test. This sampling might be insufficient to reach a representative average value and to accurately reflect the variability of the responses. Figure 3 shows the average calculated flow discharged versus time at the source zone in the RCF3 borehole which is compared to the measured flow. Figure 4 gives the final piezometric change at the various observation zones. The first ten monitoring zones were used for the calibration of the mean simulated values. The variability obtained from the 20 different simulations is shown with the help of error bars.

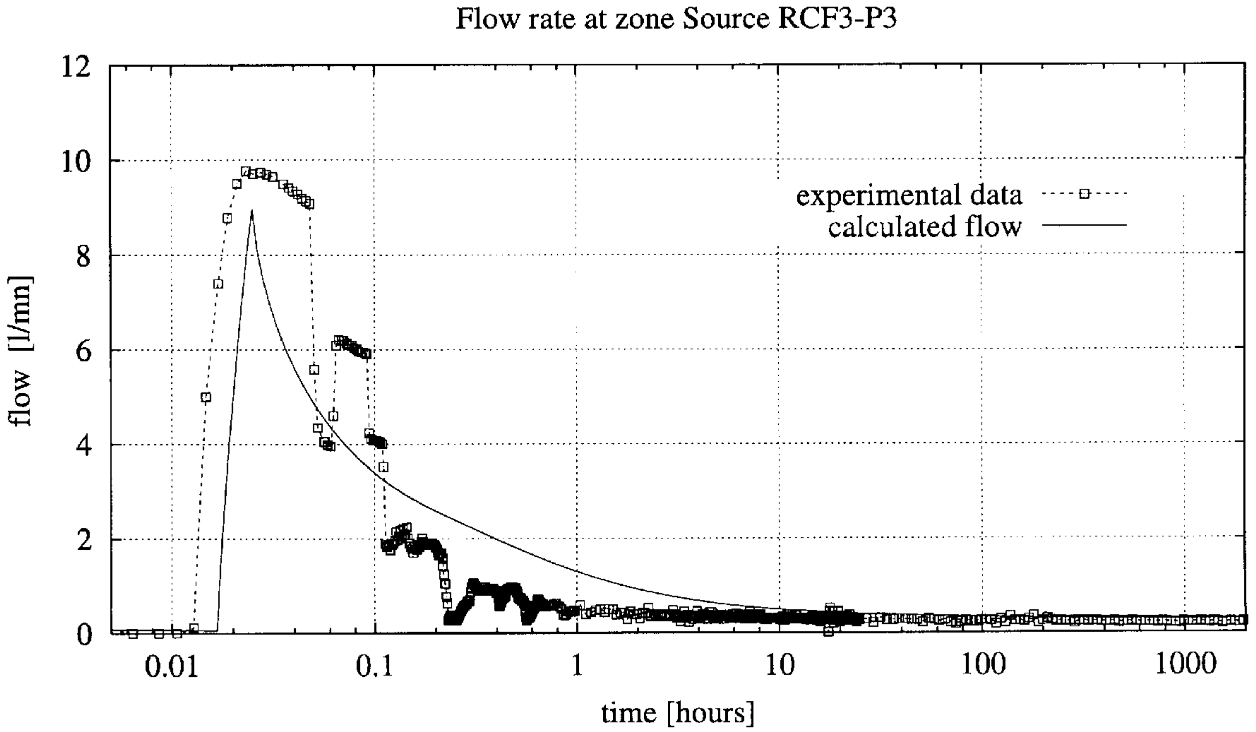

Figure 3: Comparison between calculated and measured discharged flow versus time during the pump test.

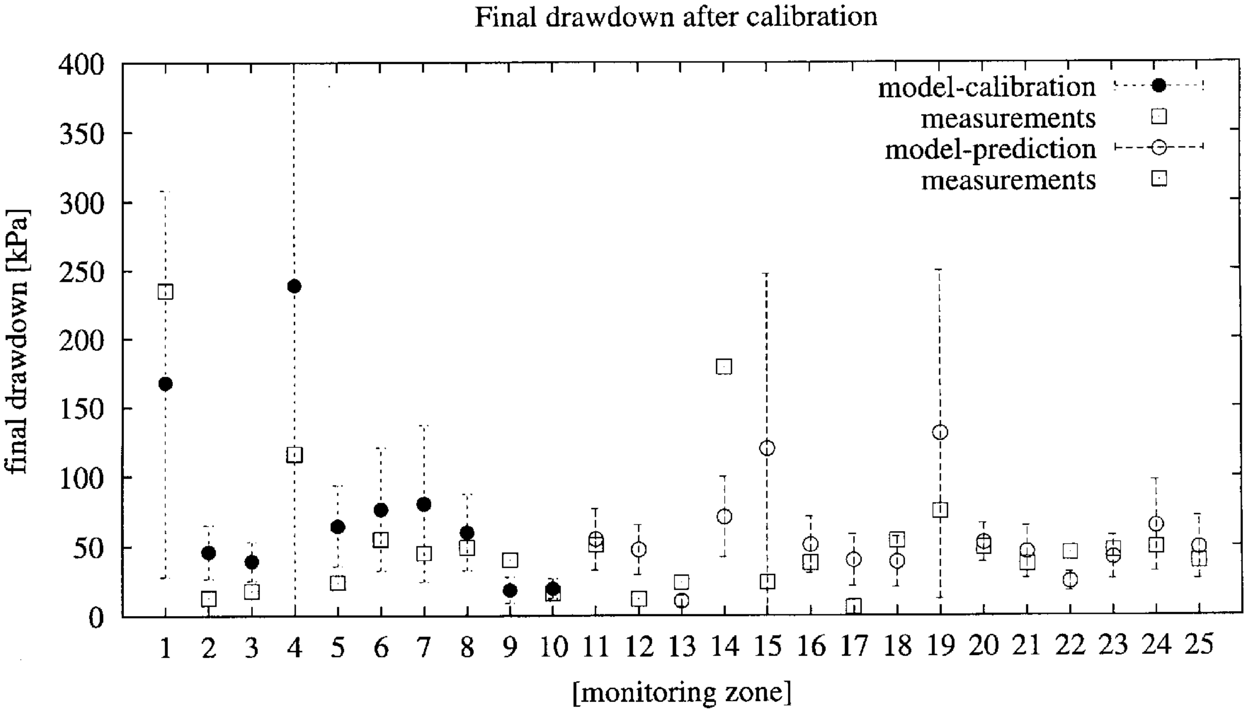

Figure 4: Final pressure changes at the 25 different monitoring zones.

6. DISCUSSION

This section described the current progress on hydromechanical coupling in a densely fractured rock that exhibits an heterogeneous fracture pattern. It is shown that a discrete approach for the fracture network description can provide valuable results in terms of flow prediction at the source zone and hydraulic drawdown at monitoring zones. The integration of geological structures of different length-scale seems well suited for analysing piezometric responses that can fluctuate a lot in immediately adjacent zones. However, a large spreading in predicted pressure change is obtained at some monitoring zones, probably due to connectivity effects with the large scale conductive structures. Conditioning the fracture network at the monitoring zones would have been desirable in this respect.

Dealing with the hydro-mechanical coupling involved in the various hydraulic tests, we successfully introduced the fracture normal compliance that simultaneously controls the hydraulic conductivity as well as the fracture storativity.

We have to point out that the prescribed pressure changes were relatively small with regard to the *in situ* stresses, so that any further use of the calibrated stiffness coefficient and maximum closure may be questionable for cases involving very different fluid pressure ranges.

Another interesting output of the pump test simulation is that the large faults may behave differently than fractures of intermediate and small scale. They seem to be much more capacitive, and their behaviour is likely to reflect the response of a rock-fracture system. Indeed these must have experienced successive shearing events and alteration phases, during their geological history.

7. CONCLUSION

Task 1 is a typical situation which will be encountered in selection and characterisation of potential sites in fractured rocks for underground radioactive waste repositories. It is a very useful exercise for developing the methodology to determine the key hydrogeological properties by using prediction-calibration cycles of a long-term pump test. The real achievement of all numerical investigations is the gain in understanding the distribution of the permeability field of the site and the mechanical factors affecting it. This exercise also has yielded a fruitful— experience on how to do the interpretation of the information package of site geology and hydrogeology of the RCF3 pumping test area provided by Nirex. It should be noticed that the extraction of the necessary input data from this large set of different documents needed a lot of time.

This study shows, that the discrete approach for the fracture network description can provide valuable results in terms of flow predictions. So we can be reasonably confident about our ability to provide acceptable estimations of the pressure field and drawdown on a large scale, and for long term purposes like the RCF3 pump test performed at Sellafield.

The Discrete Fracture Network (DFN) approach has the capability to allow the superposition of a variety of geometrical structures with a large variation in the geometrical characteristics and it is shown here that the calculations are tractable at the relevant scale for a long term pump test. The advantage is, that changing the scale of the studied area becomes easy and does not imply important modifications in the fracture network, since it only requires to reduce the size of the modelled area and if necessary to add details of smaller scale at some particular places. This was done when modelling the pump test and the shaft excavation, which have respectively two different scales.

Finally, the hydromechanical modelling of Sellafield site confirms again that an extensive hydraulic testing programme at different length and time scales is the most important ingredient to understand the hydrogeology system in any other potential site.

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