INVESTIGATION OF THE IMPACT OF FRACTURE INTERSECTION ON SOLUTE TRANSPORT IN FRACTURED CARBONATE

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ABSTRACT
A small scale characterization study has been conducted in a fractured limestone formation to identify hydraulic connections between boreholes, leading to the development of a conceptual model for the fractured limestone, for a volume of rock approximately equal to 35 000 m^3. The model contains a highly-fractured permeable zone for the upper 10 m of rock. Below, subhorizontal bedding planes with a spacing of 10 m form the main conductive units. Two sets of subvertical fractures are also observed. Preliminary tracer tests reveal that bedding planes lead to fast solute transport over short distance of a few meters. Numerical modelling indicates that vertical fractures can have a strong impact on solute transport. Further tracer tests are planned to investigate the impact of vertical fractures.

RÉSUMÉ
Une étude de caractérisation à petite échelle a été réalisée dans un calcaire fracturé, afin d'identifier les interconnexions hydrauliques entre divers puits. Un modèle conceptuel a ensuite été développé pour un volume d'environ 35 000 m^3. Sur une profondeur de 10 m à partir de la surface, le calcaire est très fracturé et sa perméabilité est élevée. Plus en profondeur, des plans de litage subhorizontaux espacés en moyenne de 10 m forment les unités les plus perméables. Deux familles de fractures subverticales sont aussi observées. Des essais de traçage indiquent un transport rapide de soluté le long de plans de litage. Des simulations numériques montrent aussi que les fractures verticales peuvent grandement influencer le transport de soluté entre les puits. Des essais de traçage additionnels sont prévus afin de mieux comprendre l'influence des fractures verticales sur le transport de masse.

1. INTRODUCTION

Solute transport in fractured rock formations has been a major research topic in the last few decades, for example in the areas of nuclear waste management and ground water contamination. Fracture networks are often very heterogeneous because stress fields that control fracture generation are nonuniform. The heterogeneity of fracture networks is further enhanced when several structural events have affected the rock. It is therefore difficult to characterize fracture networks in enough detail for prediction of fluid flow and contaminant transport (NRC 1996).

Transport mechanisms in a single fracture and/or in a fracture network can be difficult to estimate and simulate (Bodin et al. 2003). Recent studies have indicated that fractured rock masses should ideally be treated as a combination of rock matrix and discrete features, as opposed to an equivalent porous medium that can lead to erroneous approximations (Berkowitz 2002).

Bedding plane fractures have been shown to control flow in fractured sedimentary bedrocks (e.g. Novakowski and Lapcevic 1988; Michalski and Britton 1997; Muldoon et al. 2001). Since they are assumed to have a minor effect on flow, vertical features have often been neglected in flow and transport studies. However, vertical fractures that intersect major bedding planes could have an impact on solute transport. Mixing and solute transport at single fracture intersections have been studied by Berkowitz et al. (1994), Park and Lee (1999) and Park et al. (2001), among others, but site-scale studies of the impact of fracture intersections are still lacking.

This study concerns a structurally complex fractured carbonate formation, located in northern Maine. The objective of the work is to evaluate the influence of vertical fractures on solute transport, for small scales of approximately 10 m. We present here some preliminary field and modelling results.

2. SITE DESCRIPTION

The study site (Figure 1) is an abandoned quarry at the former Loring Air Force Base, Maine that was used for disposal of chlorinated solvents, oil and gasoline, among other products (SES 2002). LNAPL and DNAPL are present at the site, but their spatial distribution is poorly known (Stephenson and Novakowski 2003). Steam injection has been attempted for remediation but with little success because of significant heat losses to the rock matrix (Stephenson and Novakowski 2003).

Three topographic levels exist at the site (Figure 2). They are, from west to east: the lower level corresponding to a pond (216 masl), the middle level, called the upper tier where most of the contamination and boreholes are located (225 masl) and the upper level corresponding to the regional ground surface (230 masl).

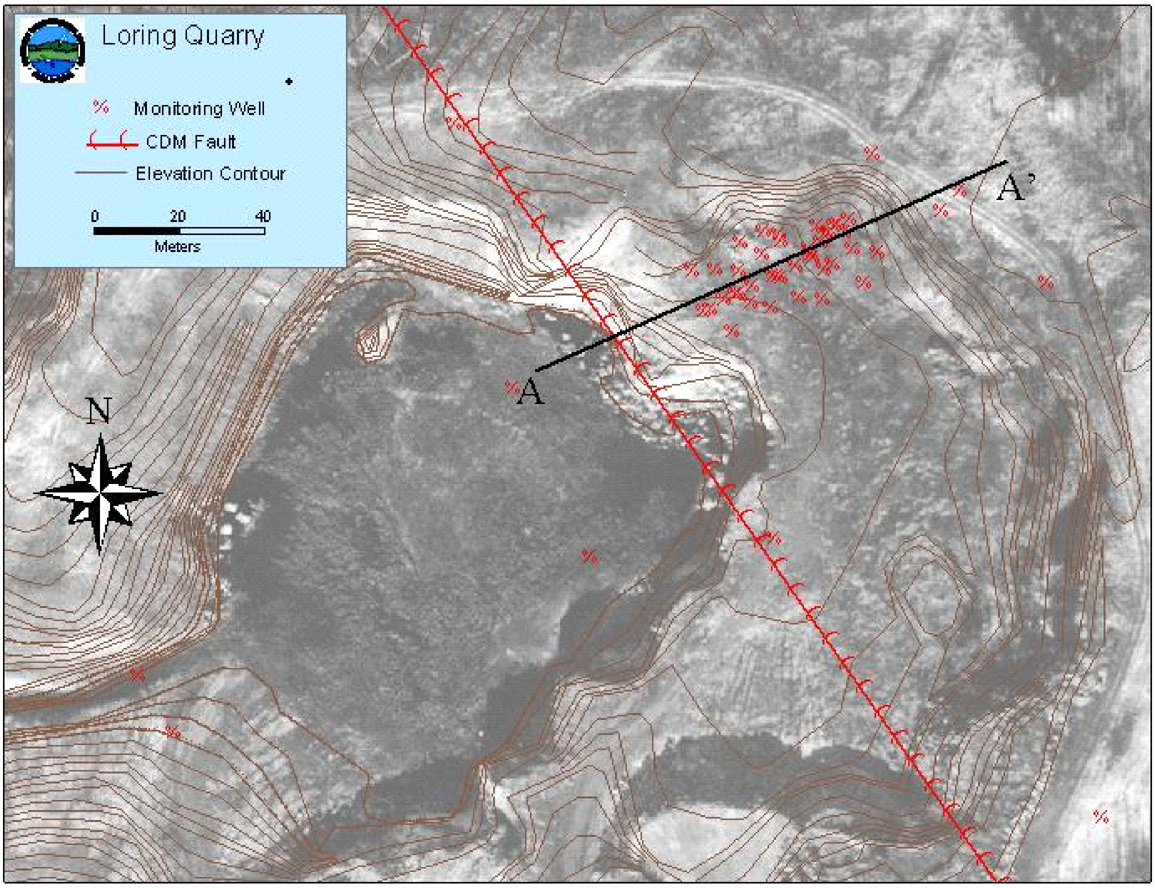

Figure 1: Aerial view of the study site.

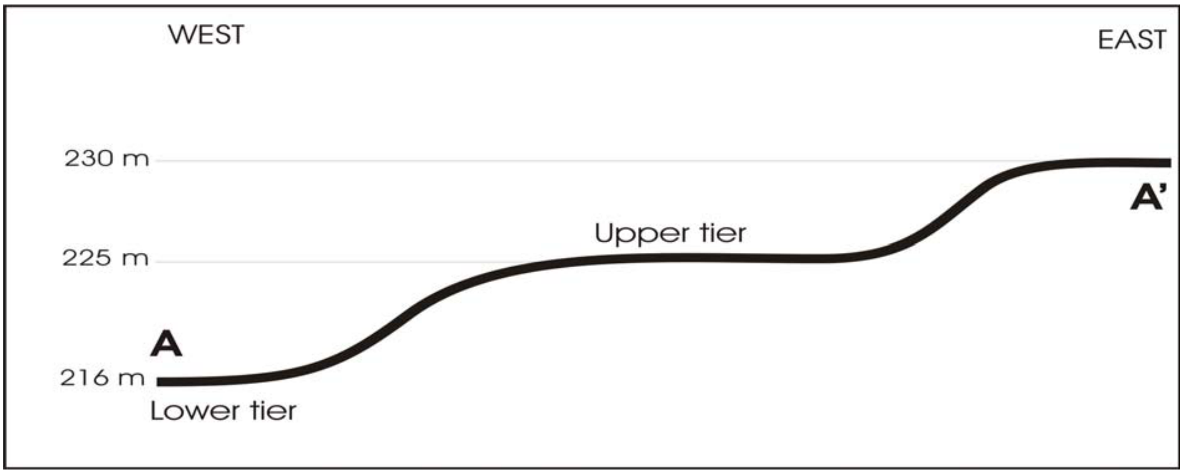

Figure 2: Cross-section A-A' (Figure 1) of the site topography.

The rock formation at the site is an early Paleozoic limestone from the Carys Mills formation. The two major structural features are a regional anticlinal fold (Aroostoock-Matapedia) dipping slightly to the north and a normal fault (CDM fault) dipping to the east (Figure 1). Three main sets of fractures have been identified: bedding planes dipping to the E-NE at approximately 20° and two subvertical fracture sets, one oriented NE-SW and the other oriented NW-SE (SES 2002). The subvertical fractures intersect the bedding planes at high angle.

Regional groundwater flow is controlled by topography, with flow oriented towards the pond, in a direction opposite to the bedding plane dip.

3. METHODOLOGY

A total of 44 boreholes have been drilled at the site. Work at the site involved description of fracture planes in cores, slug tests, pulse interference tests, constant head tests and pumping tests in the various boreholes. Hydraulic tests have been used since they are efficient for finding the principal hydraulic features (Earlougher, 1977). Using results from hydraulic testing, a series of tracer tests have been designed to investigate the impact of vertical fractures for solute transport and these tests will be further analyzed with a 3D discrete-fracture numerical model, HydroSphere, to gain better insight into the role of fracture intersections.

4. CONCEPTUAL MODEL

Figure 3 is a schematic of the vertical boreholes and wells that are located in the upper tier, showing the vertical extent of the boreholes and the water levels measured. These water levels show a trend of decreasing water level elevations from east to west.

Boreholes have been grouped in 3 zones in Figure 3, based on these water levels. These zones have been interpreted as blocks that have slipped, breaking the horizontal connections through bedding planes (SES 2002).

Another hydraulic feature observed at the site is the higher degree of fracturing and higher permeability for the upper part of the bedrock, typically from the ground surface to a depth of about 10 m. Shown in Figure 4 is a typical borehole transmissivity profile for the site, showing the higher permeability between ground surface and a depth of about 10 m. The permeability measured in individual boreholes becomes generally lower at depths greater than 10 m. Hydraulic testing has also shown that the average spacing between conductive bedding planes is 10 m. The density and extent of subvertical fractures are currently unknown.

Using structural and hydraulic observations, a simple conceptual model has been elaborated for the upper tier, where almost all boreholes are located. We consider a volume of rock 40 meters deep that covers an area of 40 meters in the east-west direction by 20 meters along the north-south direction (see Figure 5 and Figure 6). This volume of rock is divided in 3 zones, from east to west, based on water levels measured in boreholes.

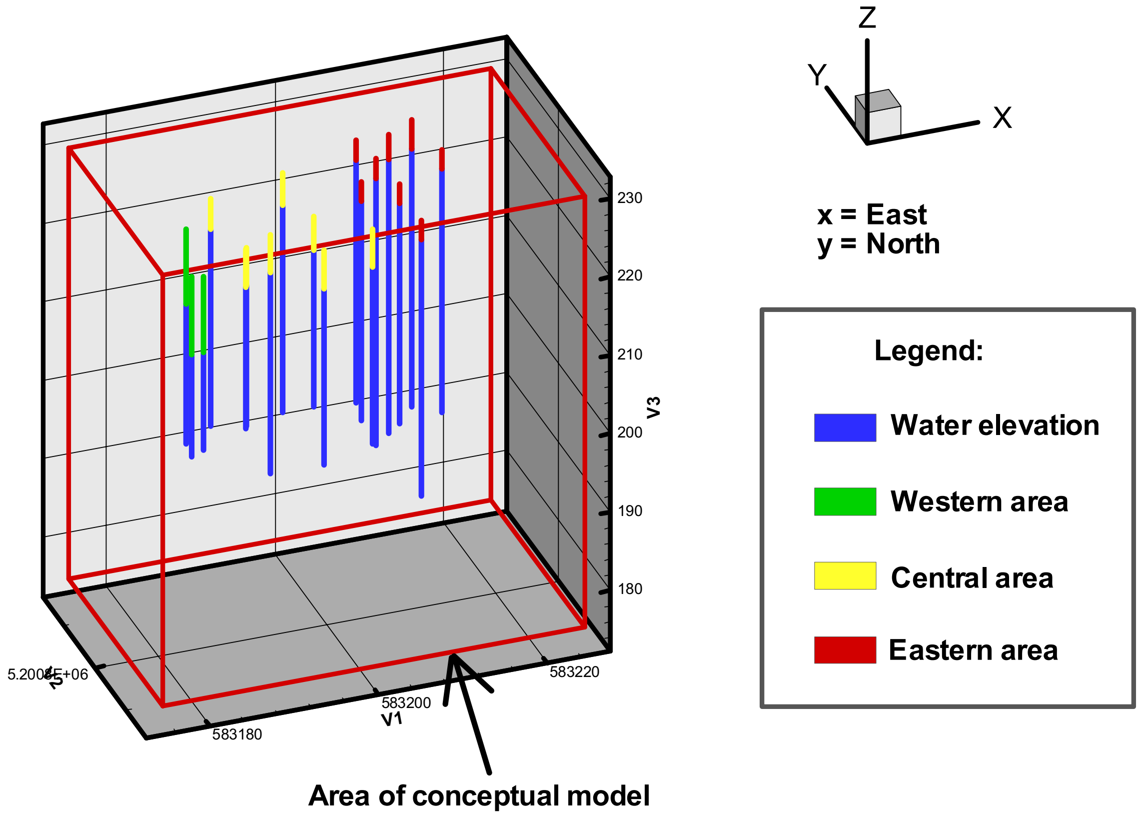

Figure 3: Water table elevations in boreholes, showing three different hydraulic zones.

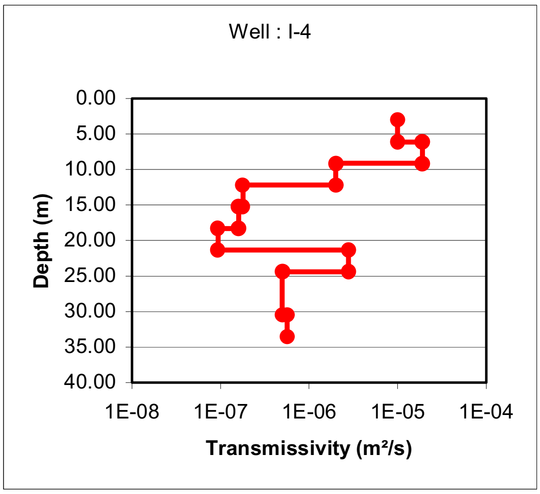

Figure 4: Example of transmissivities measured with pulse interference tests (from Stephenson and Novakowski 2003)

The upper zone is represented by a highly fractured and permeable region and is assumed to behave as an equivalent porous medium (Figure 5). This upper zone is connected to deeper bedding planes through vertical features. An average spacing of 10 m has been used to represent the discrete bedding planes (see Figure 5). The bedding plane fractures are represented in the model at average observed locations, dipping at angles close to the average for the bedding planes (10°-30°). Because of the current lack of detailed knowledge on the density of vertical fractures, they are represented randomly in the conceptual model (Figure 6). However, the vertical fractures shown respect the observed orientation and the vertical dip. Furthermore, some of these vertical fractures shown in Figure 6 terminate on bedding planes, as observed at the site. For the sake of clarity, we show the vertical fractures separately in Figure 6, but it is understood that the conceptual model is the combination of Figure 5 and Figure 6.

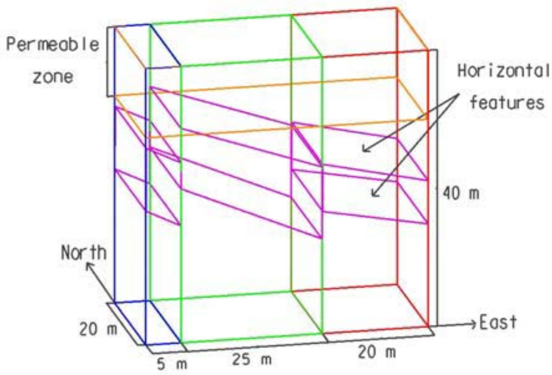

Figure 5: Conceptual model for the fractured rock highlighting the permeable zone near the surface and the horizontal fractures.

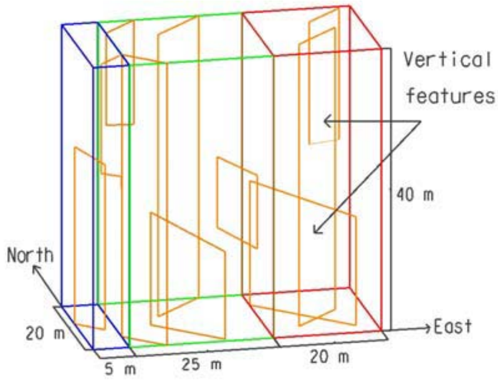

Figure 6: Conceptual model for the fractured rock highlighting the vertical fractures.

5. TRACER TESTS

Tracer tests are planned between boreholes that are hydraulically interconnected, at depths corresponding to either a single bedding plane fracture or two bedding planes connected through vertical fractures (see Figure 7). The objective of the tests is to identify if differences in tracer breakthrough at a given extraction well can be related to the presence of vertical fractures. The distances between boreholes used for the test will be between 6 m and 10 m, at a scale where we assume that there is a good probability that a single horizontal bedding plane connects 2 boreholes and where vertical fractures should also be present. The tests will be performed in a divergent flow configuration, which is easier to analyse, compared to convergent flow or two-well configurations (NRC 1996).

Interconnections between wells have been determined with pulse interference tests, either in a slug (e.g. Novakowski 1989) or pumping (e.g. Grader 1990) configuration, with observation of the pressure response in both the injecting/pumping well and in observation wells. Intervals containing bedding plane features are isolated by straddle packers in both pumping and injection wells. Since the first 10 meters of rock are considered highly fractured and permeable, the tests are planned for lower elevations, to enhance the probability of intersecting discrete features. They are also going to be conducted between boreholes of the same hydraulic zone, except for one interconnection that has been found between boreholes from two different zones. This exception is explained by the fact that the wells are located at the northern border of the upper tier, where the hydraulic gradient between the zones is much lower.

Since this study aims on evaluating solute transport through discrete features, matrix diffusion or adsorption on rock or instruments has to be minimised. The tracer chosen for the tests is the green fluorescent tracer named Lissamine FF. It shows good resistance to adsorption onto limestone and organic matter and no adsorption at all on instruments tested (Smart and Laidlaw 1977). It has proven to be the most resistant to adsorption amongst several other fluorescent dyes (Smart and Smith 1976). Lissamine FF is also stable under a wide range of pH (100% recovery from pH=3.5 to pH=10.5) and almost not affected by temperature changes or salinity (Smart and Laidlaw 1977). Photochemical decay would only affect this dye in tests lasting several days (Smart and Laidlaw 1977), which is not the case here, since the separation distances between boreholes chosen for the tests are short (6-10 m). These properties make Lissamine FF a good quantitative tracer. Background concentrations of the dye in the water of the quarry will be evaluated and calibration curves will allow accurate estimates of the concentrations obtained. Compared to other kinds of tracers (e.g. salt), fluorescent dyes are detectable at very low concentrations, so very little amount of Lissamine FF needs to be injected in the aquifer.

5.1 Preliminary tracer tests

The more detailed tracer tests to investigate fracture intersection are planned for June and July 2004. However, some preliminary tracer tests have already been conducted to verify the methodology and also check if hydraulic connections observed between some boreholes result in preferential solute transport.

Figure 8 shows measured tracer breakthrough during a test conducted between 2 vertical boreholes that have a horizontal separation equal to 1.7 m. The withdrawal interval is an open borehole having a length equal to 19 m, while the open interval in the packed off injection well has a length of 1.4 m. The tracer test was conducted in a radially-convergent flow field. A constant pumping rate equal to 6 x 10^{-4} m^3/min was maintained at the withdrawal well prior to tracer injection, to establish steady-state flow conditions and was maintained for the whole duration of the tracer test, after injection of the tracer. A salt tracer was then injected at a concentration of 7000 mg/l for 6 minutes at an injection rate equal to 2 x 10^{-3} m^3/min. Formation water was injected at the same injection flow rate for another 5 minutes and fluid injection was then stopped.

For this test, there is a rapid arrival of the tracer at the pumping well. The peak concentration indicates a transit time equal to approximately 81 minutes. After the peak arrival, concentrations decline rapidly but do not go back to pre-test values. The background salt concentration in the formation water is equal to 0.23 g/L and it has been subtracted from the measured salt concentration shown in Figure 8.

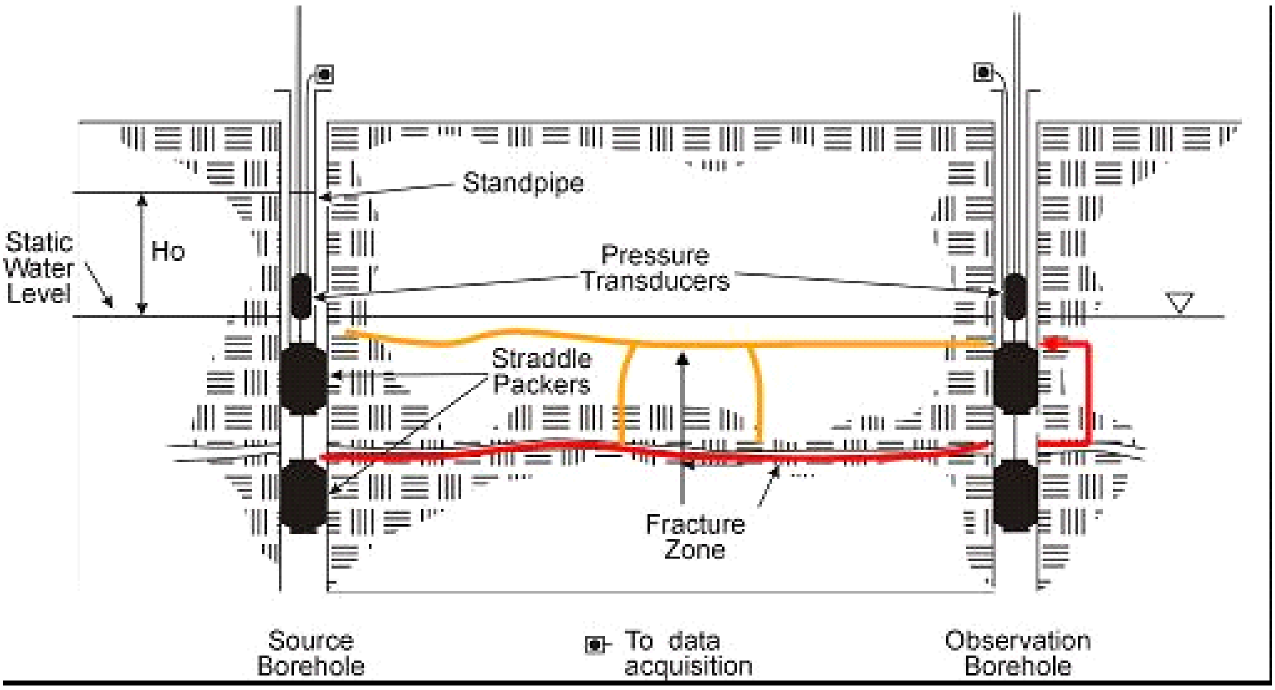

Figure 7: Planned configuration for the tracer tests (Modified from Stephenson and Novakowski 2003).

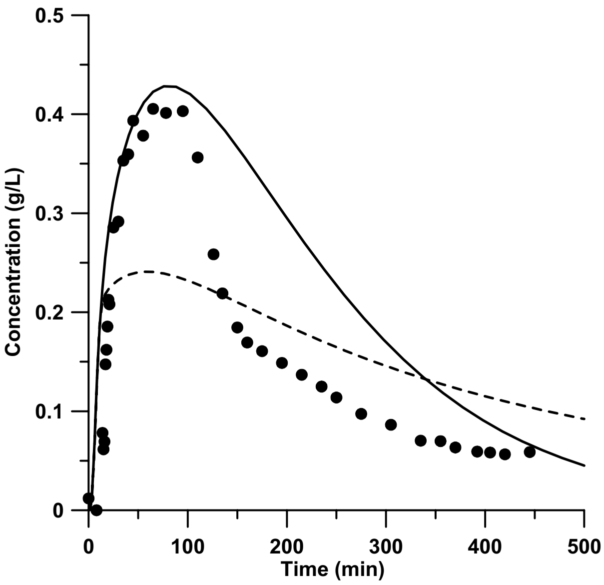

Figure 8: Solute breakthrough for a radially-convergent tracer test. Symbols are measured concentration, the solid line shows simulated concentration with horizontal bedding planes but without vertical fracture and the dashed line shows simulated concentration with horizontal bedding planes and a single vertical fracture.

6. NUMERICAL MODELLING

A 3D discrete-fracture numerical model, HydroSphere (Therrien et al. 2004), is used to simulate the tracer tests conducted at the site. The model allows the analysis of the field tests as well as simulations to investigate the sensitivity of fracture parameters on breakthrough curves. It uses the control volume finite element method to solve flow and transport equations in a 3D porous medium that contains 2D discrete fractures (see Therrien and Sudicky 1996). One-dimensional line elements are used to represent pumping or injection wells in the domain, allowing inclusion of wellbore storage (Therrien and Sudicky 2000). Details on the governing equations and numerical formulation are found in (Therrien et al. 2004).

Simulations based on the preliminary tracer test shown previously have been conducted to highlight the features of the model. The extent of the simulation domain is 20 m in both horizontal x- and y-directions, and 30 m in the vertical z-direction (with the domain extending from z = 20 m to z = 50 m). Shown in Figure 9 are the discrete fractures included in the model, as well as the pumping and injection wells. The pumping well is located at x = 10.5 m and y = 14.2 m and extends from z = 31 m to z = 50 m. The injection well is located at x = 11.1 m and y = 15.8 m and it is much shorter, extending from z = 37.3 m to z = 38.7 m. We assume that two horizontal bedding planes are located in the domain, with a vertical spacing equal to 10 m. The lower bedding plane extends over the whole domain in the xy plane and it is located at z = 38.0 m. It directly connects the pumping and injection interval. The upper bedding plane has a smaller extent in the xy plane. It is located at z = 48 m and only intersects the pumping interval. Figure 9 also shows the location of a vertical fracture that connects the 2 bedding planes. The vertical fracture is assumed present in one of the two simulations presented here.

The domain is discretized with 3D block elements, using 21 nodes in the x-direction, and 25 nodes and 52 nodes in the y- and z-directions, respectively, for a total of 27 300 nodes and 24 480 elements. The nodal spacing is reduced near the fractures and wells. The fractures are represented as 2D planar elements and 1D line elements discretize the pumping and injection wells.

The material properties used for the simulation are based on measured or estimated values for the study site and have not been calibrated (Stephenson and Novakowski, 2003). The limestone rock matrix has a hydraulic conductivity equal to 10^{-10} m/s, its porosity is equal to 0.01 and its tortuosity is 0.01. All fractures have a uniform aperture equal to 150 μm, which corresponds to a hydraulic conductivity of about 1 m/s. The longitudinal and lateral dispersivities of the fractures are equal to 0.5 m and 0.05 m, respectively. The salt tracer is assumed non-reactive and its free-diffusion coefficient is equal to 1.3 x 10^{-9} m^2/s.

Transient flow and transport simulations have been performed, without adjusting the material properties, to reproduce the preliminary tracer test results shown in Figure 8. For the simulation, the top and bottom boundaries are impermeable and the lateral boundaries are assigned a uniform hydraulic head, which assumes that they are not affected by pumping or injection. The initial hydraulic head distribution is obtained from a steady-state flow simulation, where only the pumping well is in operation, with the above boundary conditions. For transport, all boundaries are assigned zero-dispersive flux and the initial solute concentration is zero everywhere in the domain. At time equal to zero, the injection well is turned on and solute is injected at a concentration equal to 0.7 g/L for 6 minutes. From 6 to 11 minutes, the injection well is still in operation but the injection concentration is zero. The injection well is then turned off at 11 minutes and the simulation is continued until the final time equal to 500 minutes. Variable time-stepping is used for the simulation, with an initial time step equal to 1 minutes that increases by a factor equal to 1.15 until a maximum time step equal to 20 minutes is reached.

Shown in Figure 9 are simulated solute concentrations at the pumping well for 2 cases, one where only the 2 bedding are included in the model, and the second case where the vertical fracture is added, effectively connecting the 2 bedding planes. Although no calibration has been attempted with the model, the first simulation without a vertical fracture reproduces quite well the early tracer arrival and the peak concentration. After the peak arrival, the simulated concentrations remain higher than measured ones and the quality of the fit decreases.

Although the simulated values are higher than measured ones, they do become lower after about 450 minutes, indicating longer persistence of the tracer for the experiment.

The second simulated breakthrough curve shown in Figure 8 is for the case where a vertical fracture is added to the system, with all other simulation parameters remaining constant with respect to the first simulation. In that case, the first arrival of the tracer is similar to the case without the vertical fracture. However, after about 10 minutes, the concentration starts levelling off. Simulated concentrations then start declining after about 75 minutes. Compared to the first case, the peak concentration is lower and the peak arrival is shifted to earlier times. For that second case, there is rapid tracer migration from injection to pumping well, along the lower bedding plane, which produces early breakthrough. However, the vertical fracture provides an alternate flowpath from injection to pumping well, which causes an equivalent retardation of the solute breakthrough. Retardation originates from the longer flow path created, with solute moving up along the vertical fracture and then laterally along the upper bedding plane until it reaches the pumping well. Furthermore, there is an increased potential for diffusion into the matrix since the solute is spreading over a larger volume in the rock mass. The concentration isosurface for a value equal to 0.01 g/L, shown in Figure 10, reveals that the tracer has diffused into the matrix along the lower bedding plane, as well as along the vertical fracture. The late-time concentration tail shown in Figure 8 is explained by the tracer diffusing back from the matrix into the fractures.

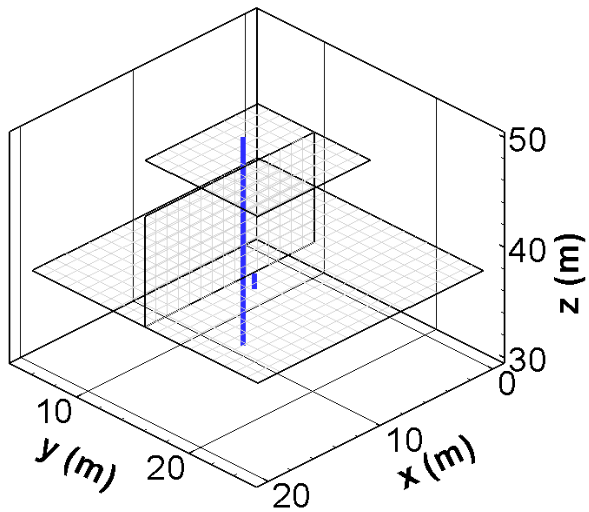

Figure 9: Location of the bedding planes, vertical fracture, pumping well (long interval) and injection well (short interval) for the simulation.

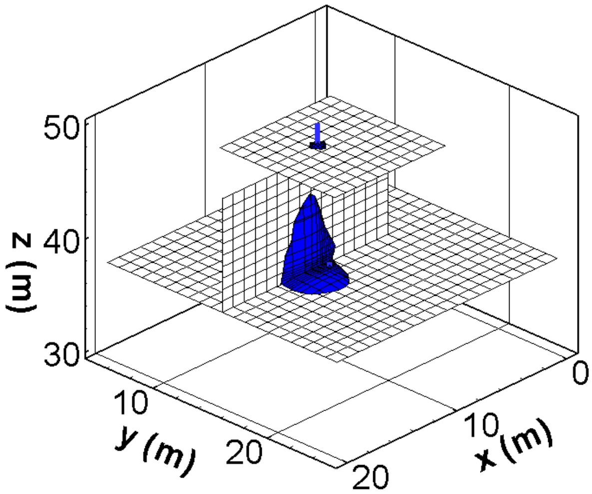

Figure 10: Simulated concentration isosurface equal to 0.01 g/L for the vertical fracture case, 500 minutes after start of injection.

The preliminary simulations presented here show the modelling capabilities for reproducing the tracer tests. Further work will involve varying input parameters to determine the sensitivity of simulated breakthrough to these parameters.

7. CONCLUSION

We present here some preliminary results on the characterization of flow and transport properties in a fractured limestone formation, as well as modelling results for a preliminary tracer test. More detailed tracer tests are planned in June and July 2004 to investigate small-scale transport in discrete fractures, and evaluate the impact of fracture connectivity on solute breakthrough

The coupled results of the tracer experiments and the numerical simulations should allow the evaluation of the impact of vertical features on solute transport in a discrete horizontal fracture for the site studied. This coupling method could also be applied to other sites where a similar study takes place. Also, the knowledge learned here about the role that vertical features play in solute transport could be of interest to several other studies in fractured carbonates in the future.

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