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# Analytical and Numerical Modeling of Flow in a Fractured Gneiss Aquifer

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## ABSTRACT

Investigating and modeling fluid flow in fractured aquifers is a challenge. This study presents the results of a series of packer tests conducted in a fractured aquifer in Freiberg, Germany, where gneiss is the dominant rock type. Two methods were applied to acquire hydraulic properties from the packer tests: analytical and numerical modeling. MLU (Multi-Layer Unsteady state) for Windows is the analytical model that was applied. ANSYS-FLOTRAN was used to build a two-dimensional numerical model of the geometry of the layered aquifer. A reasonable match between experimental data and simulated data was achieved with the 2D numerical model while the solution from the analytical model revealed significant deviations with respect to direction.

**Keywords:** Ansys/Flotran; MLU for Windows; Gneiss; Packer Test; Fractured Aquifer

## 1. Introduction

Fractured aquifers are very important for groundwater supply because about 75% of the earth's surface consists of fractured aquifers [1] and 25% of the global population is supplied by karst waters [2]. Flow velocity in fractured gneiss is known to be highly variable over a range of scales and uncertainties which arises from heterogeneous flow pattern in fissures and fractures. This has significant implications on water resource management from borehole to catchment scales. In addition, understanding flow heterogeneity in the aquifer is of great importance for groundwater protection and for predicting contaminant transport.

Theis [3] was the first scientist to conduct a transient analysis of the groundwater flow. After Theis, many researchers like Warren and Root [4], Kazemi [5], Odeh [6], Hantusch and Thomas [7], and Streltsova [8] studied the flow through fractured rocks in the context of petroleum and groundwater engineering. Jenkins and Prentice [9] described groundwater flow in a single fracture with a very large permeability. Sen [10] used an analytical solution to analyze fractured gneiss with a linear flow pattern. Cohen [11] used a two-dimensional numerical model to analyze an open-well test in fractured crystalline rock. Gernand and Heidtman [12] used the analytical model by Jenkins and Prentice to analyze a pumping test in a fractured gneiss aquifer. Schweisinger *et al.* [13] analyzed transient changes in a fracture aperture during hydraulic well tests in fractured gneiss. Wang and Cui [14] analyzed fluid flow and heat transfer by using the distributed resistance application in ANSYS FLOTRAN. Their analysis was done without comparing the modeled results with those from experiments (Gu *et al.* [15] and Cen and Chi [16]). Slack [17] proposed a theoretical analysis for the slug test which couples elastic deformation with fluid flow within a fracture. Molina-Aiz *et al.* [18] used ANYS FLOTRAN to simulate the velocity and temperature in a ventilated greenhouse. Crandall *et al.* [19] used ANSYS FLUENT to obtain the flow solution in a fractured aquifer.

Several analytical solutions are implemented in software packages like AQTESOLV, Aquifer Win32, AquiferTest Pro, StepMaster, and MODPUMP to determine the hydraulic parameters of aquifers. Some of these packages offer analytical solutions for fractured aquifers. However, these software packages have certain limitations due to the more or less arbitrary selection of analytical solutions that are implemented. MLU for Windows [20] is based on a completely different concept: It is a multi-layer analytical model for confined and unconfined aquifers and can thus be used for any kind of groundwater testing scenario.

Several numerical models have been developed to simulate the flow and transport in fractured aquifers. Examples are GeoSys/Rockflow and TOUGH2. Walsh *et al.* [21] modeled flow and mechanical deformation in fractured rock using Rockflow/GeoSys. McDermott *et al.* [22], Myrttinen *et al.* [23] and others used the numerical simulator GeoSys/Rockflow to simulate the flow and transport in fractured rocks. Also, Pruess *et al.* [24], Pruess and García [25], and others present results for multiphase flow in porous and fractured aquifers using TOUGH2. A detailed review on characterizing flow and transport in fractured geological media is presented by Berkowitz [26]. However, models such as Rockflow, Rockflow/Geosys, and TOUGH2 do not apply the well-known Navier-Stokes equation. They use the fact that the Navier-Stokes equation can be linearized as long as the Reynolds number is less than 10 and thus can be replaced by the much simpler Reynolds lubrication equation. However, there are some doubts that the local cubic law is valid in some cases and only a few publications used models based on Navier-Stokes Equation.

The present study was motivated by the need of improving conceptualization of fractured gneiss through a combination of fieldwork and modeling. Studies of flow properties using packer techniques and geophysical readings were used to investigate groundwater flow in fractured gneiss. The major task of the paper was to model flow in fractures by means of Navier-Stokes equation on the one hand, and to assume fractured zones as a continuum and thus to apply Darcy's Law on the other hand. MLU for Windows was chosen as analytical model because it is an integrated tool to evaluate pumping tests for multi-layer confined aquifers. Finally, the analytical solution was compared to the numerical solution with respect to evaluating and estimating permeability of fractured aquifers.

## 2. Site Description

Gneiss is the dominant crystalline rock at the test site in Freiberg. All six wells at the test site of the TU Bergakademie Freiberg with a total depth of 50 m and 100 m, respectively, are lacking any kind of casing or screen (except for a upper protection casing (at 3 to 5 m)) and have diameters of 4 to 6 inch. The gneiss at the site is a medium- to coarse-grained Inner Gneiss. Major fractures were identified by geophysical borehole logging in six boreholes at depths of 11 to 11.5 m and minor fractures at 14 to 16, 22 to 23.6, 31.3 to 31.9, 37.5 to 38 and 47 to 47.6 m [27]. Caliper, Single-Point Resistance (SPR), High Resolution Detector (HRD), Gamma-gamma soundings, and neutron-neutron soundings were used to identify fracture zones [27]. Consequently, higher values of hydraulic conductivity are associated with the horizontal fracture zones.

The six wells serve as direct, vertical connection between the zones of higher permeability. Thus, the presence of wells intersecting with the six zones of higher hydraulic conductivity can significantly perturb fluid flow. The flow in the fractured gneiss aquifer is assumed to be extremely heterogeneous with high flow velocities in the fracture zones and very low velocities in the block matrix. Non-fractured gneiss itself is nearly impermeable.

## 3. Methods

Hydraulic properties of rock materials can be estimated in both: laboratory and field. However, hydraulic properties obtained in the laboratory are not a true representation of the aquifer. Therefore, especially in fractured rocks, packer tests and tracer tests are indispensable. Packer tests are a well-known method to determine aquifer properties in open boreholes [28-30]. They can be used in uncased boreholes to determine the hydraulic conductivity of the individual horizon by isolating a zone between two packers or isolating a certain part of the borehole with a single packer. The equipment needed for packer tests includes an air compressor, a submersible pump, inflatable packers, and pressure transducer probes (Diver, type CTD, Schlumberger).

Two general methods of hydraulic testing have been used: Double packer tests, and single packer tests. Single packer test provide hydraulic data either for the borehole above or below the packer. The double packer test was performed for the most dominant fault in the range 11 to 12 m. The pumping rate was kept constant at about 10 L/min until a steady drawdown was achieved. For the test, the submersible pump is mounted between the two packers and the resulting drawdown. The duration of the pumping test was 6 to 7 hours.

For the single packer test the packer was mounted 13 m below ground surface. The pumping rate in the single packer was held constant at about 16 L/min and was maintained for 6 hours until a steady state drawdown was achieved. In both cases recovery was monitored, too.

Two approaches are addressed in this paper to calculate and evaluate the hydraulic properties for a fractured gneiss aquifer:

- An analytical solution using MLU for Windows (based on Darcy's Law)
- A numerical solution using ANSYS-FLOTRAN (based on Navier-Stokes Equation)

### 3.1. Analytical Solution

MLU for Windows is a tool for single- and multi-layer aquifers (both, confined and unconfined), which combines Stehfest's method, the superposition principle, and the Levenberg-Marquardt algorithm. Stefest's method is performed in the numerical solution to convert the Laplace domain to the real domain. Parameter estimation is performed by applying the Levenberg-Marquardt algorithm [20]. MLU assumes a homogenous, isotropic, and uniform aquifer.

A one layer model was used to calculate the hydraulic conductivity for the first horizontal fault zone. There, the fractured layer is embedded in impermeable gneiss. The numerical values for the hydraulic conductivity are presented in **Table 1**. The values for the permeability were obtained from forward modeling using the Theis method assuming a thickness of 0.5 m and evaluating each single observation well individually.

Conductivity increases in direction of well 2 in comparison to well 3, and 4 (for spatial distribution see **Figure 1**).

A two layer model was used to calculate the hydraulic conductivity from the single packer test for the fracture zones below the packer. Only two fracture zones were modeled because they are assumed to be the most significant ones regarding depth and permeability. The values determined for the hydraulic conductivity of the different monitoring wells are presented in **Table 2**.

The hydraulic conductivity of well 2 and well 4 is higher than that of well 3 and well 6. Concerning technical issues, it was difficult to measure the drawdown in the pumping well (well 5). So, no parameter was calculated for it.

**Table 1. Hydraulic conductivity (double packer test) for the upper fracture zone.**

| Well No. | Hydraulic Conductivity (m/sec) |
|---|---|
| Well 2 | $5.83 \times 10^{-4}$ |
| Well 3 | $1.17 \times 10^{-4}$ |
| Well 4 | $1.17 \times 10^{-4}$ |
| Well 6 | $1.25 \times 10^{-4}$ |

**Table 2. Hydraulic conductivity (single packer) for the fracture zones below the packer at a depth of 14 m.**

| Well No. | Hydraulic Conductivity (m/s) |
|---|---|
| Well 2 | $1.25 \times 10^{-4}$ |
| Well 3 | $8.33 \times 10^{-5}$ |
| Well 4 | $1.25 \times 10^{-4}$ |
| Well 6 | $2.5 \times 10^{-5}$ |

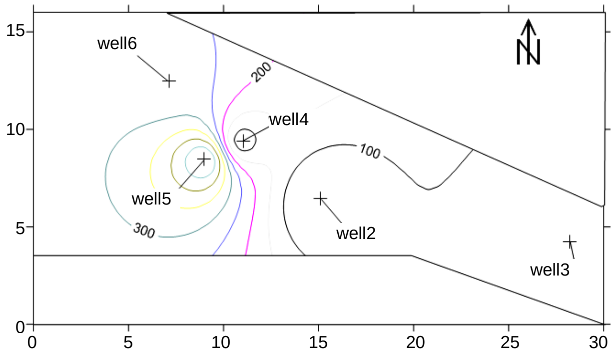

**Figure 1. Drawdown at the Freiberg test site at the end of the double packer test.**

### 3.2. Numerical Model

The ANSYS/FLOTRAN CFD (Computational Fluid Dynamics) software package offers comprehensive tools for analyzing two-dimensional and three-dimensional fluid flow fields. FLOTRAN is a finite element analysis program for solving fluid flow and conjugate heat transfer problems. The governing equations solved by FLOTRAN are the Navier-Stokes equations combined with the continuity equation, and the thermal transport equation. The general purpose of the CFD modul of ANSYS FEA systems is to solve a large variety of fluid flow problems. ANSYS/FLOTRAN simulates laminar and turbulent compressible and incompressible flows, single or multiple fluids, and thermal/fluid coupling [31]. FLUID141 and FLUID142 are two element models in ANSYS/FLOTRAN [32,33]. In this paper, FLUID141 was utilized for the 2D model.

In FLOTRAN CFD elements, the velocities are obtained from the conservation of momentum principle, and the pressure is obtained from the conservation of mass principle [34]. The matrix system derived from the finite element discretization of the governing equation is solved separately for each degree of freedom. The flow problem is nonlinear and the governing equations are coupled. The number of global iterations requires achieving a converged solution that may vary considerably, depending on the size and stability of the problem. The degrees of freedom are velocity, pressure, and temperature [35].

**Figure 2** shows the geometry, node locations, and the coordinate system for a typical quadrilateral and triangular element. The element is defined by three nodes (triangle) or four nodes (quadrilateral) and by isotropic material properties.

The fluid properties density and viscosity were specified for the element and were then meshed automatically in ANSYS. The smaller the size of elements is defined, the more accurate is the result that can be achieved by the model. However, very fine element sizes result in high CPU time. In the current study, models with different meshing sizes were applied and evaluated.

ANSYS-FLOTRAN can account for fractures influenced by the concept of distributed resistanceand was applied in the element 141 through the use of real constants. The distributed resistance refers to the macroscopic representation of geometric features that are not directly concerned with the region of interest. This concept is a convenient way to approximate the effect of porous media (such as a filter) or other flow domain features without actually modeling the geometry of those

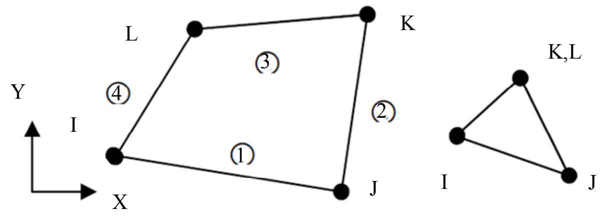

**Figure 2. FLUID141 2D Fluid-FLOTRAN Element (modified after ANSYS, 2009).**

features. Also, it can be used to simulate the flow in a fractured aquifer. A distributed resistance is an artificially imposed, unrecoverable loss associated with the geometry that is not explicitly modeled. Any fluid element with a distributed resistance will have a real constant set number greater than 1 [36].

The flow resistance, modeled as a distributed resistance, is caused by one or a combination of these factors: localized head loss (*k*), friction factor (*f*), and permeability (*C*). The equation for the total pressure gradient in x direction is shown below (1) [31]. It is a sum of the factors mentioned before.

$$\frac{\partial P}{\partial x} = -k \cdot \rho \cdot u_x \left|u\right| + \frac{f}{D_h} \rho u \left|u\right| + C\mu \cdot u_x \qquad (1)$$

where:

$\rho$ = is the density (mass/length³)

$\mu$ = is the viscosity (mass/(length*time))

$f$ = is a friction coefficient (dimension-less; calculated by the program): $f = a\ RE\text{-}b$

$RE$ = is the local value of the Reynolds Number (calculated by the program): $RE = (\rho u Dh)/\mu$

$a$, $b$ = are the coefficient and exponent of Reynolds number, respectively, used in fraction factor calculation

$C$ = is the FLOTRAN permeability ($1/\text{length}^2$).

FLOTRAN permeability is the inverse of the intrinsic or physical permeability.

The unit of the distributed resistance is $1/\text{length}^2$. The permeability of the cells in fracture zone 1 was found to be in the range of 0.00003 to 3e−8 m/s. This value has to be converted into a value that can be put into ANSYS. The flow rate of water through fractured gneiss is proportional to the hydrostatic pressure difference ($\delta P$). The hydrostatic pressure is normally expressed as a pressure potential $h = p/(\rho \cdot g)$, where $\rho$ is the liquid density $\text{M}/\text{L}^3$, $g$ is geravical accelarion $\text{L}/\text{T}^2$, $h$ has the dimension L and is equivalent to the hydrostatic head. The calculation was carried out using ANSYS V.12.1.

The permeability value depends both on the material and the fluid. The permeability for Newtonian liquids during laminar flow through inert non-swelling media is inversely proportional to the fluid viscosity $\eta$. Therefore, the intrinsic permeability for the material is defined as $k' = k \cdot \eta$. In this equation $k'$ is a material property independent from the fluid and with a dimension of $\text{L}^2$ [36].

The results from numerical modeling using ANSYS-FLOTRAN were calibrated with data from the packer test. The horizontal hydraulic conductivity was assumed to be anisotropic within a model cell. Heterogeneity was simulated by varying the horizontal hydraulic conductiveity between individual model cells or layers. The vertical hydraulic conductivity is based on specified values of the horizontal hydraulic conductivity.

**Figure 1** illustrates high drawdown in observation well 6. Moreover, the shape of the drawdown and the high hydraulic gradients between wells 5 and 6, imply that there is a fault between them. Pumping generates a cone of depression in the hydraulic potential field that both expands outward and deepens with time. Drawdown values were obtained from packer tests using double packers (**Figure 1**). A higher drawdown was observed at monitoring well 6 with about 2.7 m and a lower one at monitoring well 2 and well 3 with about 30 cm. Inverse distance weight interpolation was used to generate the contour lines. Drawdown at the pumping well (No. 5) could not be monitored, because a double packer system with the submersible pump between both packers was used. Thus the drawdown shown in **Figure 1** was estimated to be 5 m.

For the double packer test the first fracture zones were modeled as a confined aquifer with constant head boundary zones on both sides and no recharge. The mesh size used was 0.04 m around the pumping well and 0.1 m close to the margin of the model. Due to the geometry the mesh used comprised over 40,000 elements. The pressure equation was solved using a pre-conditioned conjugate gradient method for the incompressible flow. Preconditioned Conjugate Gradient (PCG) is the most robust iterative solver in ANSYS. The exact method is the semi-direct conjugate direction method that iterates until a specified convergence criterion is reached.

## 4. Results and Discussion

The uppermost fractured zone located at between 11 and 12 m depth has an average thickness of 0.5 m. The simulation period of 402 minutes was chosen according to the time of the packer test. The differences between the measured and computed values are mainly due to the strong dependence of the coefficients on hydraulic conductivity which is not constant in the aquifer but highly heterogeneous. The horizontal hydraulic conductivity is assumed to be isotropic within a single model cell (**Figures 3** and **4**).

The simulation period was 6 hours. Concerning boundary conditions it was assumed that there is no drawdown at the left and right margin. The pressure is continuous across the fracture from block to block. Five fracture layers were included in this model. Moreover, hydraulic

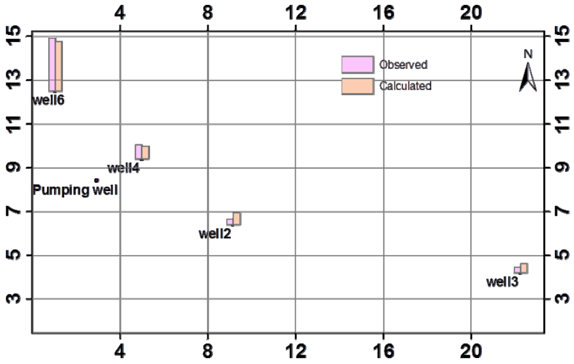

**Figure 3. Map with arbitrary numbers in meter of observed drawdown during double packer test versus drawdown modeled with ANSYS-FLOTRAN.**

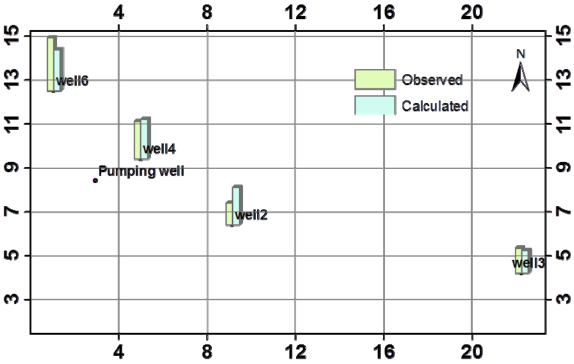

**Figure 4. Map with arbitrary numbers in meter of observed drawdown during single packer test versus drawdown modeled with ANSYS-FLOTRAN.**

conductivity was determined in the fracture zones between $3 \times 10^{-6}$ to $9 \times 10^{-6}$ m/s. In fact, the magnitude of the response of groundwater levels in the gneiss aquifer spatially varied indicating heterogeneity in the fractured gneiss. Similar to the first model, a simplified 2D-groundwater flow model was built to simulate the single packer test in the fractured gneiss.

**Figure 4** depicts the difference between the observed and the calculated head for the single packer test. Good matching was observed at well 3 and well 4. In contrast, only sufficient matching can be seen at well 2 and well 6.

Calibration was performed by trial and error. The hydraulic conductivity of the fracture layer was between $3 \times 10^{-5}$ to $3 \times 10^{-8}$ m/s and $10^{-15}$ m/s or less for the non-fractured gneiss. The hydraulic conductivity of the two-dimensional model decreases with increasing depth. As stated before, having more and better information about the fracture's geometry, roughness and the network would give better matching between the observed and simulated heads.

## 5. Conclusion

Navier-Stokes equation is essential to predict the groundwater flow in the fractured gneiss aquifer at this scale and when turbulent flow is likely to occur. The two methods used to identify the permeability of the aquifer were analytical and numerical modeling. They are reasonable but care should be taken with respect to the interpretation of the results because of the uncertainties in the characterization of aquifer properties. In general it can be concluded that it is recommendable to carry out tracer tests in order to increase the accuracy of the model. At the investigated test site, hydraulic conductivity decreases from the right side to the left side due to the decrease in fracture thickness. The hydraulic conductivity decreases with increased distance from the ground surface (depth) because the number and width of fracture openings decrease with depth. Generally, the hydraulic conductivity values of the analytical solution were higher than the values obtained using the numerical approach. Finally, both the analytical and the numerical model proved to be useful tools for improving the knowledge of the fractured gneiss aquifer and for identifying the various flow components. ANSYS-FLOTRAN will give a better prediction of aquifer response than MLU for Windows because it is based on a non-linear equation.

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