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An experimental and numerical evaluation of continuous fracture permeability measurements during effective pressure cycles

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1. Introduction

Fluid transport within the Earth's crust is controlled by planar void space like crack networks and fractures unless flow through the rock matrix becomes important, e.g., in porous sedimentary systems. An understanding of the former rock structural elements and their hydro-mechanical properties therefore is of importance for a variety of both geoscientific and geotechnical themes like diagenesis, ore formation, metamorphic reactions, crustal deformation, and earthquake mechanics, as well as CO₂-sequestration, enhanced oil recovery, and nuclear waste storage, to name a few. Particularly, the efficiency of geothermal energy provision from deep geological formations predominantly relies on the hydraulic performance of cracks and fractures either preexisting or artificially created within a reservoir by hydraulic or thermal stimulation treatments. Central to all of these topics is the rock-type and scale dependent evolution of fracture permeability as a function of stress, temperature, time, and fluid chemistry. Consequently, various aspects of fracture hydro-mechanics have received attention in numerous theoretical, experimental, and field studies. Most recent reviews on the subject are provided in ^{1,2}.

Of fundamental interest in this context is finding the appropriate fluid transport equation with respect to fracture morphology e.g.,^{3–5}, understanding the relationship between aperture of

single rough fractures and normal stress e.g.,^{6–8}, and identifying processes that yield time dependence of fracture permeability e.g.,⁹. A rather limited number of experimental studies address the evolution of fracture permeability in selected rock types with time and feedbacks from stress and/or reactive chemical processes: on granite ^{2,10–12}, on limestone ^{13,14}, and on novaculite ¹⁵.

Here, we present results of fracture permeability measurements conducted on one carbonate rock sample during slow effective pressure cycles to distinguish and quantify different modes of brittle, elastic and time dependent mechanical response. However, the paper's prime purpose is to demonstrate that continuous fracture permeability measurements conducted during pressure cycling are feasible and meaningful when based on the steady state method. For this to evaluate, a numerical model was set up to calculate the dissipation time of induced pore pressure disturbances as a function of fracture aperture. Such disturbances, nominally, would yield a departure from steady state conditions and consequently errors in so derived permeability. Ultimately, the numerical simulation will constrain the minimum fracture aperture for which continuous measurements provide reasonable means for fracture permeability monitoring under dynamic loading conditions.

2. Sample material and experimental procedures

As sample material one type of Malm carbonate, Treuchtlinger

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Fig. 1. Artificially fractured sample TM-1. (a) Sample after fracturing in Brazilian test setup. (b) Optical micrograph of the single fracture with visible offset (arrow) of the two fracture walls.

Marmor (TM), was selected from an outcrop in the German Molasse Basin¹⁶. This rock is a Lower Malm, Middle Kimmeridgium (Delta) thick-bedded limestone with sponges. It consists predominantly of calcite and is only weakly dolomitized.

One specimen was prepared in cylindrical shape with 5 cm in diameter and 10 cm in length and was then split along the principal axis to create one defined artificial tensile fracture (Fig. 1a and b). Splitting was performed in a Brazilian test setup using an MTS uniaxial rock deformation apparatus. As evident from Fig. 1b and indicated by the arrow the two fracture walls experienced a small shear offset of approximately 80 µm in the direction perpendicular to the principal sample axis. During splitting the sample was maintained in a heat shrink tubing which was not removed but kept for the subsequent permeability measurements. In the following the sample will be denoted TM-1.

Before fracturing, the intact sample porosity ($\varphi=5\%$) and permeability ($k=1 \times 10^{-18} \text{ m}^2$) were determined. Porosity was measured by helium pycnometry and additionally by comparing dry and wet sample mass. Wet sample mass was determined after saturating the specimen in vacuum. Distilled water was used as the pore fluid in all experiments. Permeability was measured in a Hoek-cell¹⁷ with one high precision syringe Pump (Quizix Q6000) upstream and the downstream side of the sample open towards the atmosphere. The use of this type of cell permitted to determine the poroelastic response of sample permeability up to confining pressures of 20 MPa. Measurements were conducted at laboratory temperature approximating 20 °C.

The subsequent experiment on the fractured sample was performed in an MTS conventional triaxial deformation apparatus

under hydrostatic loading conditions with oil used as the confining pressure medium. Permeability was measured at $30 \pm 1 \text{ °C}$ to avoid disturbances by laboratory temperature variations. A background pore pressure of 0.1 MPa was applied and confining pressure was cycled twice between 2 and 40 MPa, i.e. two times up and down, at a rate of approximately 0.5 MPa/h. During the second cycle effective pressure was maintained constant at 40 MPa for approximately 10 h to investigate potential time dependent effects in mechanical response of the fractured sample. One full cycle including the time required for permeability measurements therefore took approximately one week. In the following, the term “effective pressure” relates to the difference between confining and pore pressures as defined by Terzaghi¹⁸.

Permeability of the fractured sample was measured either step-wise (during the first pressure cycle) at defined effective pressure levels or continuously (during the second pressure cycle), in both cases with one upstream pump maintained in constant flow mode and one downstream pump operated in constant pressure mode at 0.1 MPa. For step-wise measurements a flow rate of 5 ml/min was applied limiting the maximum pore pressure upstream to 1 MPa at minimum fracture aperture. Continuous measurements were conducted by imposing the same, constant flow rate throughout confining pressure ramping and recording the differential pore pressure as it developed with time. In both cases, permeability was then calculated by applying Darcy's Law directly e.g.,¹⁹. In the following, results for the fractured sample will be reported as either sample or fracture permeability with reference to the sample's and the fracture's cross-sectional areas, respectively. This is an important point to distinguish as sample permeability is precisely derived from the measurement itself. In contrast, fracture permeability is a secondary quantity that relies on the assumed geometry of the fracture, e.g. parallel plates, as outlined in Section 4.2.

3. Numerical model setup

To investigate the applicability of continuous permeability measurements based on the steady state method a three dimensional finite element (FE) model of the experiment was set up using the multiphysics simulator Comsol.^c The modeled rock specimen consists of two different domains. A two dimensional plane with a given aperture representing the fracture (5 cm wide and 10 cm long) was embedded in a cylindrical 3D mesh (5 cm in diameter and 10 cm in length) representing the rock matrix. In addition to the rock specimen, the capillary in the lower end cap of the triaxial cell was explicitly modeled by a squared cross section with 1 mm edge length. The model consists of 9752 tetrahedral elements with edge lengths between 1 mm and 1.2 cm.

Fluid flow was modeled with Darcy's law in both the matrix and the capillary and the “cubic law” [e.g.,³] in the fracture assuming smooth laminar flow between two parallel plates. Additionally, storage was considered for all three model domains, i.e., matrix, capillary, and fracture.

The model parameters of the three domains are given in Table 1. The injected fluid was pure water at 30 °C with a dynamic viscosity of 0.796 mPa s, a density of 996.66 kg/m³ and a compressibility, i.e. storage, of $4.6 \times 10^{-10} \text{ 1/Pa}$. While all other parameters were kept constant, models with different fracture apertures between $1 \times 10^{-8} \text{ m}$ and $5 \times 10^{-5} \text{ m}$ were set up.

As starting condition, a homogeneous pore pressure of 0.1 MPa was set within all three domains of the model. Afterwards, this pressure was maintained at the top of the sample (downstream) as

^c <https://www.comsol.com>.

Table 1
Parameterization of the three domains in the numerical model.

Domain	Rock matrix	Fracture	Capillary
Porosity, ϕ (%)	5	100	100
Permeability, k (m^2)	1×10^{-18}	8.3×10^{-18} – 2.1×10^{-10} ($k=a^2/12$)	1×10^{-8}
Aperture, a (m)	–	1×10^{-8} – 5×10^{-5}	–
Density, ρ (kg/m^3)	Fluid: 996.66 Solid: 2650	Fluid: 996.66 Solid: –	Fluid: 996.66 Solid: –
Storage, S (1/Pa)	Fluid: 4.6×10^{-10} Solid: 3×10^{-10}	Fluid: 4.6×10^{-10} Solid: –	Fluid: 4.6×10^{-10} Solid: –

Viscosity, $\eta = 7.96 \times 10^{-4}$ Pa s.

Temperature, $T = 30$ °C.

a constant fluid pressure boundary. At the bottom of the sample (upstream) a constant fluid injection rate of 5 ml/min was applied by imposing a constant mass flux of $83.33 \text{ kg}/(\text{m}^2 \text{ s})$ at the end of the capillary. All other outer boundaries of the model were no flow boundaries. Each of the models was run for 10^5 s, thus approximately 28 h.

This approach mimics the experiment in a way that confining pressure induced changes in fracture aperture and thus any departure from linearity of the pore pressure gradient are represented by instantaneously applying flow at one side of the sample inducing a fluid pressure disturbance that would dissipate at a rate that is directly correlated with fracture permeability.

For continuous permeability measurements to be valid, a steady state pressure distribution between top and bottom of the sample needs to be achieved within reasonable time (e.g. 1 s) after some pore pressure disturbance was induced either by changing flow rate (as in the model) or aperture (as in the experiment). To investigate the time span for steady state conditions to redevelop a relative dissipation of the pore pressure disturbance (RD) was calculated for each time step at a point in the center of the fracture 1 cm above the constant flow rate boundary using the following equation:

$$RD = (P_{\text{current}} - P_{\text{initial}}) / (P_{\text{final}} - P_{\text{initial}}) \times 100\% \quad (1)$$

where P_{current} is the current pore pressure at the investigated time step, P_{initial} is the initial pore pressure of 0.1 MPa and P_{final} is the final pore pressure at the last time step and at which steady state conditions are reached.

Based on this procedure and for each fracture aperture the time span to reach a level of 95% and 99% RD, respectively, was calculated implying that, e.g., at 99% the difference between the measured differential pressure between inlet and outlet and the differential pressure at full steady state conditions is 1%.

4. Results and discussion

4.1. Experimental results

The intact rock material of sample TM-1 is characterized by a porosity ϕ of 5%, a permeability k of $1 \times 10^{-18} \text{ m}^2$, an unconfined compressive strength UCS of 230 MPa, a tensile strength TS of 13 MPa, and a Young's modulus E of 33 GPa. Permeability relates to 2 MPa which was the lowest confining pressure applied. Strength and elastic properties have been measured elsewhere and are reported in ¹⁶.

As a result of splitting the sample experienced a significant permeability enhancement by more than five orders of magnitude from $1 \times 10^{-18} \text{ m}^2$ to $600 \times 10^{-15} \text{ m}^2$ at the start of the first pressure ramp (Fig. 2). After the first cycle, sample permeability was approximately one order of magnitude lower ($60 \times 10^{-15} \text{ m}^2$) but obviously stabilized at that level as permeability decreased significantly less during the second one. Sample permeability, then monitored continuously, changed rather reversibly from $60 \times 10^{-15} \text{ m}^2$ at 2 MPa to $8 \times 10^{-15} \text{ m}^2$ at 40 MPa and back to $40 \times 10^{-15} \text{ m}^2$ at 2 MPa effective pressure.

Fig. 2 demonstrates an excellent match between permeability measured step-wise during the first pressure down ramp and the

Fig. 2. Sample permeability as a function of effective pressure. During the first pressure cycle (red) permeability was measured step-wise at defined pressures (squares) and during the second one continuously (black). One notices a significant decrease in sample permeability by one order of magnitude during the first cycle. During the second cycle permeability responded rather elastically to changes in effective pressure although some transient behavior is evident as permeability did not fully recover upon unloading. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 3. Optical micrographs taken on one face of the sample after pressure cycling: (a) center, (b) edge. The fracture is held open by bridging asperities displaying brittle features. The offset the two fracture walls experienced during initial fracturing is clearly visible on (b).

one monitored continuously during the second pressure up ramp. As will be evidenced by the numerical model results outlined and discussed in Section 4.4 this indicates the applicability of the steady state method also in cases when fracture aperture dynamically changes provided that any pore pressure disturbance can dissipate rapidly with respect to the loading rate.

Displayed in Fig. 3 are two optical micrographs (a, b) taken on one of the sample faces after the experiment. In this figure, along the fracture plane, asperities as bridging solid contacts can be observed. The fracture is clearly visible and still open to some degree but had decreased in aperture with respect to the one before pressure cycling (Fig. 1b). The asperities display features of brittle deformation like microcracks and crushing of matrix material.

4.2. Relating sample to fracture permeability

For the permeability values reported before, k was calculated relative to the cross sectional area $A = \pi R^2$ of the cylindrical sample, where $R = 2.5$ cm is the sample radius. Using the well known relation between the flow velocity v through parallel plates and the pressure gradient applied e.g.,^{3–5} one has to account for porosity ϕ when comparing the former to the Darcy velocity q by applying the relationship attributed to Dupuit and Forchheimer e.g.,¹⁹, where $q = v \phi$. When, as in the present case, overall sample permeability is determined by the portion of porosity that relates to the fracture, $\phi = (2Ra)/A$, then, a relationship can directly be derived that permits to calculate fracture aperture a from measured permeability k where the fracture is idealized as a rectangular slit bounded by parallel plates:

$$a = \sqrt[3]{6 \pi k R}. \quad (2)$$

This implies that average or effective hydraulic fracture aperture can be calculated directly from sample permeability measurements for each point on the permeability-effective pressure curves in Fig. 2. As an example, for the data at maximum and minimum effective pressures shown in this figure Eq. (2) yields: $a = 66 \mu\text{m}$ for $k = 600 \times 10^{-15} \text{ m}^2$, $a = 31 \mu\text{m}$ for $k = 60 \times 10^{-15} \text{ m}^2$, $a = 27 \mu\text{m}$ for $k = 40 \times 10^{-15} \text{ m}^2$, and $a = 16 \mu\text{m}$ for $k = 8 \times 10^{-15} \text{ m}^2$.

The so derived hydraulic apertures a can then finally be applied to calculate fracture permeability k_f , e.g., using the “cubic law” e.g.,³ assuming laminar flow between two parallel plates:

$$k_f = \frac{a^2}{12}. \quad (3)$$

For the examples provided before, Eq. (3) yields, in the same order, the corresponding fracture permeability values:

$$k_f = 363 \times 10^{-12} \text{ m}^2, \quad 80 \times 10^{-12} \text{ m}^2, \quad 61 \times 10^{-12} \text{ m}^2, \quad \text{and} \quad 21 \times 10^{-12} \text{ m}^2, \text{ respectively.}$$

4.3. Mechanical sample response during the pressure cycles

After the first pressure cycle in Fig. 2 sample permeability had irreversibly decreased by approximately one order of magnitude from $600 \times 10^{-15} \text{ m}^2$ to $60 \times 10^{-15} \text{ m}^2$. It is suggested that this decrease relates to partial fracture closure by brittle destruction of asperities yielding an increase in fracture contact area A_c . For the calculation of this increase a force balance between the applied effective pressure p_{eff} and unconfined compressive strength UCS of the material can be applied:

$$A_c = (p_{eff}/UCS)A_s, \quad (4)$$

where $A_s = 50 \text{ cm}^2$ is the apparent contact area of the fracture. With $UCS = 230 \text{ MPa}$ (Section 4.1) and Eq. (4) one calculates $A_c = 0.44 \text{ cm}^2$ for $p_{eff} = 2 \text{ MPa}$ and $A_c = 8.70 \text{ cm}^2$ for $p_{eff} = 40 \text{ MPa}$, respectively. This finally implies an increase in fracture contact area during the first pressure up ramp by $\Delta A_c = 8.26 \text{ cm}^2$.

It is suggested that the fracture contact area adjusts itself to the highest effective pressure applied and that the fracture concurrently stabilizes (Fig. 3). The response of sample permeability to further changes in effective pressure during the subsequent pressure cycle then was rather elastic with transient effects being significantly less important. However, during the second cycle effective pressure was held constant at 40 MPa for approximately 10 h and permeability was monitored simultaneously (Fig. 4). As evident from this figure sample permeability decreased by approximately $0.4 \times 10^{-15} \text{ m}^2$ indicating slow fracture closure by $\Delta a = 0.26 \mu\text{m}$ (Eq. (2); Section 4.2).

4.4. Numerical simulation

Fluid flow through the synthetic fractured samples was simulated for different fracture apertures. The pore pressure evolution for the lowest fracture aperture observed during the experiment (16 μm) is shown in Fig. 5. One notices that after flow is initiated (a) a steady state pressure distribution develops quasi instantaneously (i.e., in less than 1 s) within the fracture (b). This pore pressure gradient then remains constant. In contrast, within the weakly permeable matrix the pore pressure increases significantly slower from the high pressure side towards the low pressure side of the sample. Steady state within both the fracture and the matrix is reached only after approximately 100–1000 s as indicated by the time sequences (c) through (e).

Fig. 4. Sample permeability as a function of time measured continuously during the second pressure cycle at 40 MPa constant effective pressure indicating creep-like fracture closure.

The dissipation times of a pore pressure disturbance caused by an imposed constant flow rate of 5 ml/min is shown in Fig. 6 for different fracture apertures. From the experiment detailed before hydraulic fracture apertures were determined to range between 16 μm and 66 μm . Within this range 99% of the pore pressure disturbance dissipated in less than 1 s within the fracture. The transition between reasonable dissipation times (e.g., less than 1 s for more than 95% of the pore pressure disturbance to be dissipated) and very high dissipation times close to the values for an unfractured rock matrix can be related to approximate fracture apertures ranging between 1 μm and 10 μm . Below 0.3 μm fracture aperture it takes approximately 1 h for most (95%) of the pressure disturbance to be dissipated as in this case the fracture permeability approaches the permeability of the rock matrix. For very large fracture apertures, i.e. above 50 μm , the pressure increase caused by a constant flow rate of 5 ml/min was below the resolution of the model.

4.5. The steady state method in comparison to other techniques

The advantage of the steady state method applied in this study is that flow is smooth, continuous and undisturbed with very precisely controlled flow-rate over the full confining pressure interval investigated and for every confining pressure increment. The evolution of the upstream pore pressure then is a direct measure of sample permeability within experimental precision.

In contrast, this is not the case for transient methods to determine permeability continuously, i.e., pore pressure pulse²⁰ and oscillatory (sinusoidal) fluid flow e.g.,^{21–24}. For both techniques any disturbance in confining pressure affects the signals to be evaluated via concurrent changes in pore pressure.

For pore pressure pulse (1) the analyzable time and thus confining pressure step is determined by sample permeability, (2) the method requires repeated pulsing with each pulse to be evaluated individually and (3), most importantly, the signals to be explored in accordance with theory²⁰, which are the respective time

Fig. 5. Model setup and pore pressure evolution between 1 s and 1000 s for the smallest hydraulic fracture aperture observed during the experiment (16 μm). After start (a) a steady state pressure distribution develops after less than 1 s within the fracture (b). In the rock matrix pore pressure becomes steady state only after more than 100 s (time sequences labeled c, d, and e).

Fig. 6. Numerically simulated time span for a steady state pressure distribution to redevelop in the fracture after some pore pressure disturbance was induced by changing flow rate, shown as a function of effective fracture aperture. Within the range of experimentally observed fracture apertures (dashed interval) it takes less than 1 s for 99% of the pressure disturbance to be dissipated.

dependent pressures in some up and downstream pore fluid reservoir, are overprinted by the deformation induced pore pressure disturbance.

Similarly, for oscillatory fluid flow (1) the analyzable time and thus confining pressure step is determined by sample permeability as it defines the oscillation frequency required and (2), again, the signals to be explored in accordance with theory^{21,23}, which are the attenuation and the phase shift of a sinusoidal pore pressure signal downstream with respect to the one upstream, are overprinted by the deformation induced pore pressure disturbance yielding erroneous permeability values.

In summary, these two methods are hardly applicable when continuous measurements of confining pressure induced changes in fracture permeability are intended to be performed and therefore do not provide any advantage over the method applied in the present study.

5. Conclusions

For the example of a carbonate rock containing one single, artificial fracture with an 80 μm shear offset the transient response of fracture permeability to cyclic changes in effective pressure was experimentally investigated. Permeability measurements were conducted step-wise during a first pressure cycle and continuous during the second one.

Several modes of deformational response to pressure changes were distinguished and quantified. It showed that fracture stability and thus permeability evolution were primarily dependent on the inherent mechanical properties of the rock matrix within the pressure limits applied. During first pressurization, the fracture asperities are interpreted to undergo irreversible brittle deformation only until the true contact area counterbalances the maximum effective pressure applied and the unconfined compressive strength of the material. The pressure response of fracture permeability then is quasi-elastic and reversible, at least at the short term. However, at elevated effective pressures a slow decrease in fracture permeability was observed induced by time dependent creep-like fracture closure. This not only has implications for the time scales of fluid transport within natural fracture systems but also for geotechnical applications that involve hydraulic fracturing in carbonate lithologies.

Additionally, a numerical FEM-model was set up to constrain the applicability of the steady state method for continuous

monitoring of permeability changes under dynamic loading conditions. More precisely, the model was aimed to investigate the time span for a steady state pressure distribution to develop in a single-fractured sample of low matrix permeability displaying a wide range of fracture apertures. The results of this simulation suggest that the permeability of fractured samples subject to dynamic changes in fracture aperture, as observed for the experiment, can be measured continuously for fracture apertures larger than 10 μm as steady state conditions were found to redevelop almost instantaneously within the fracture. Therefore, neither a step-wise permeability determination nor the application of other methods (e.g., pore pressure pulse or oscillating flow) is required for these conditions.

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