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Formation Fracturing by Pore Pressure Drop (Laboratory Study)

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Abstract

Pore pressure increase in saturated porous rocks may result in its fracturing and corresponding microseismic event occurrences. Another type of the porous medium fracturing is related with rapid pore pressure drop at some boundary. If the porous saturated medium has a boundary where it directly contacted with fluid under the high pore pressure, and the pressure at that boundary is dropped, the conditions for tensile cracks can be achieved at some distance from the boundary. In the paper, the results of experimental study of fracturing of the saturated porous artificial material due to pore pressure rapid drop are presented. It was found that multiple microfracturing occurred during the pore pressure dropping, which is governed by pore pressure gradient. Repeated pressure drops result in subsequent increase of the sample permeability. The permeability was estimated on the basis of non-linear pore-elasticity equation with permeability dependent on pressure. The implementation of calculations to laboratory experiment data showed significant variation of the porous sample permeability during the initial non-stationary stage of the fluid pressure drop. The acoustic emission activity variation was found to be controlled by pore pressure gradient and changes of the number of potential fractures, which can be activated by the pore pressure gradient. It was found, that the probability distribution of these “potential fractures” could be approximated by a Weibull distribution. A way of solution of the inverse problem of local permeability defining from microseismic activity variation in a particular volume of porous medium was suggested.

1. Introduction

Pore pressure change in saturated porous rocks may result in the rocks deformations and fracturing [1] and corresponding microseismic event occurrences. Microseismicity due to fluid injection is considered in numerous papers [2]. Another type of the porous medium fracturing is related with rapid pore pressure drop at some boundary. The mechanism of such fracturing was considered by [3] as a model of sudden coal blowing and by [4] as a model of volcano eruptions. If the porous saturated medium has a boundary where it directly contacted with fluid under the high pore pressure (in a hydraulic fracture or in a borehole), and the pressure at that boundary is dropped, the conditions for tensile cracks can be achieved at some distance from the boundary as it was shown by [3]. The effective stresses in the solid matrix will change with the speed of elastic waves, while the pore pressure changes will be governed by a kind of pore pressure diffusivity law. The phenomenon was studied by [4] in laboratory experiments with artificial material with high porosity filled by gas.

In the paper, the results of experimental study of fracturing of the porous sample saturated by fluid due to pore pressure rapid drop are presented. It was found that multiple microfracturing occurred during the pore pressure dropping, which is governed by pore pressure gradient variation. The locations of microcracks were found with the help of acoustic pulses recording. It was found that repeated pressure drops result in subsequent increase of the sample permeability. The permeability was estimated on the basis of non-linear pore-elasticity equation.

A mathematical model of the pore pressure variations was constructed based on pore pressure diffusion equation with diffusivity coefficient dependent on space and time. The implementation of analytical estimates and numerical calculations to laboratory experiment data showed significant variation of the porous sample permeability during the initial non-stationary stage of the fluid pressure drop. The acoustic emission activity variation can be described as a triggering process controlled by pore pressure gradient and changes of the number of potential fractures, which can be activated by the pore pressure gradient. It was found, that the probability distribution of these “potential fractures” could be approximated by a Weibull distribution. It was shown that it is possible to solve the inverse problem of defining local permeability from registered microseismic activity variation in a particular volume of porous medium.

2. Experimental procedure

The diagram and the photo of the experimental setup are shown in Figure 1. The samples were made of quartz sand with grain sizes 0.3...0.4 mm, the sand was cemented by “liquid glass” glue with mass fraction 1%. To prepare the sample, the sand/“liquid glass”/water mixture was tamped to a height 82 mm into a mould with 60 mm in inner diameter. Then it was dried during a week. The sample porosity was 35%, uniaxial unconfined

compression strength was measured to be 2.5 MPa, p -wave velocity measured in the sample saturated by oil was 3100 m/s. The initial permeability measured by air blowing through the sample was about 2 D. To prevent the sample displacement during the experiments, a plastic ring was placed between lower end of the sample and the mould lid (see Figure 1). The upper end of the sample contacted directly with the mould upper lid. After vacuumization, the mould with sample was filled by mineral oil, which penetrates into the sample. Pressure in the mould was increased by means of oil injection through the bottom nipple up to 10 MPa and then discharged with the help of solenoid valve connected to the nipple. Injection-pressure drop cycles were repeated up to 40 times. Pressure release rate was controlled by a hydraulic resistor placed prior to the valve. The sample loading was related to oil pressurization at the bottom of the sample, there was no additional load.

Pore pressure transducers and acoustic emission (AE) transducers (of piezoceramic type) were mounted into upper and bottom lids of the mould, as it is shown in Figure 1. AE data were digitized with sampling frequency 2.5 MHz, the fluid pressure – with sampling frequency 50 kHz. The acoustic emission records were synchronized with the pressure records. Locations of AE events were estimated on the basis of measured p -wave velocity and onset time difference of AE pulses. The absolute peak amplitude of AE pulse was assumed as the amplitude of AE event. All localized AE events were characterized by onset time, location (distance from open boundary of the sample), and amplitude.

Figure 1. A diagram (left) and a photo of the laboratory setup.

3. Results

Figure 2 shows typical waveforms of AE pulses, registered by opposite transducers. These waveforms had onsets with the same signs as well as with opposite signs. In case of tensile fractures it can be explained by the sample unloading in the processes of pore pressure drop and fracturing, so at least one or both boundaries of the tensile fracture were moving in the open end direction. After some time, the onsets of the AE pulses registered at the closed end became mainly positive. AE pulse amplitudes became lower with time.

Figure 2. Examples of waveforms, registered at opposite sides of the sample. Amplitude is in arbitrary units.

Distributions of the AE pulse amplitudes summarized by 5 mm intervals along the sample are shown in Figure 3 for experiments after the 1st and 7th pressure drops. One can see, that microfracturing is spreading from the open end to the closed end with repeated pressure drops, and that maximal amplitudes registered at some distance from the opened end.

Variations of AE rate (the number of AE pulses per 0.1sec) are shown in Figure 4. The AE almost stops after 2 sec from the beginning of the pressure drop. The number of AE pulses increases with every next pressure drop, meanwhile the number of pulses with high amplitudes diminishes with next pressure drops. The last result can be explained by diminishing of pressure gradient due to the sample permeability increase in the course of subsequent fracturing of the sample.

Figure 3. Distributions of the AE pulse amplitudes along the sample in two experiments.

Figure 4. AE activity variations: a,b – registered at open (upper curve) and closed ends (lower curve) of the sample in experiments 1 and 6; c – registered in three different experiments (see Fig.5 legend)

Fluid pressure variations with time are shown in Figure 5 for both open and closed ends of the sample. Initially, the pore pressure decreases rapidly (in 0.1 sec), after that it slowly diminishes to atmospheric pressure. The AE rate is significant in first 2 sec, some of acoustic pulses occurred in up to 10 sec (Figure 4). The pressure gradient (estimated as pressure difference divided by the sample length) is shown in Figure 6. The prolongation of the pressure gradient maximal values is in agreement with AE maximal meanings.

Figure 5. Fluid pressure vs. time registered at the two ends of the sample

Figure 6. Linear estimation of the fluid pressure gradient for three experiments

4. Discussion

Shapiro et al. [5] proposed to consider an evolution of hydraulically induced microseismic event hypocenter locations as a diffusion process controlled by pore pressure diffusion in poro-elastic medium caused by fluid injection. In the presented experiments the fluid pressure decreased with time and AE maximum was registered when the pressure was dropped from its maximum. Let us compare AE variation and variation of pressure difference (Figure 4 and Figure 6). One can see that the AE began when the absolute value of the fluid pressure difference started to increase, and AE stops when the fluid pressure difference started to decrease. It is clear from physical point of view, that to produce tensile fracturing one should have tensile force, which could appear only in case of enough high pressure gradient.

Let us now try to estimate dynamic permeability variation during the fluid pressure drop. For it, we used fluid pressure data registered at the open end of the sample and calculated the fluid pressure at the closed end of the sample by means of simple pore-elastic equation (Schelkachev, [6]) for small time intervals (0.01 sec) and one-dimensional isotropic homogeneous case:

$$\frac{\partial p}{\partial t} = D \frac{\partial^2 p}{\partial x^2}$$

where D is hydraulic diffusivity

$$D=\frac{k}{\mu_0\beta m_0}$$

where k is permeability, β is an effective compressibility of the porous medium, μ_0 – viscosity, m_0 – initial porosity. Initial condition:

$$p(x, 0)=p_0$$

A zero fluid rate Q at the closed end of the sample and registered pressure at the open end were taken as boundary conditions:

$$\frac{\partial p}{\partial x}(t, l)=0$$

$$p(t, 0)=p_1(t)$$

Then we compared results of the calculations with experimental data and vary coefficient of diffusivity to obtain the best coincidence between calculated and registered pressure. The procedure was repeated for all the time of experiment. There was no difference between experimental and calculated pressures, obtained by that manner (Figure 7). The dependence of estimated permeability on fluid pressure is shown in Figure 8. The final permeability values after the pressure drop are shown in Table 1.

Figure 7. Measured (lab) and calculated for several diffusivity coefficients differential pore pressure.

Figure 8. Estimation of the permeability dependence on pore fluid pressure

Pressure drop #	6	22	32
Permeability k, D	4.9	7.4	9.5

Table 1. Permeability estimated by pore pressure difference diminishing in time.

To find AE relation with the pore pressure gradient the following assumption can be used [5, 7]:

- AE event occurred when the pore pressure gradient reaches some critical value;
- The critical value varies spatially and can be described by a probability distribution.

One can suggest that the critical value distribution can be described by Weibull distribution which is often used to describe fragment size distributions in fractured rock [8];

$$N((dp/dx)^*) = N * ba^{-b}((-dp/dx)^*)^{b-1} e^{\left(\frac{(dp/dx)^*}{a}\right)^b}, \quad (1)$$

where parameters a and b are the scale and the shape parameters, respectively, $(dp/dx)^*$ is the critical value of pore pressure gradient.

Variation of AE rate in time can be described with the help of Weibull distribution

$$N(t) = N * \frac{c}{t} \left(\frac{t}{t_0}\right)^c e^{-\left(\frac{t}{t_0}\right)^c} \quad (2)$$

The parameters of the distribution calculated to fit experimental data of the experiment 22 (Figure 9) are $N^*=120$, $c=1,7$, $t_0=0,6$. The coupled use of distribution (2) and pore pressure measurement allows to calculate parameters of the distribution (1) to best fit experimental data of $(dp/dx)^*(t)$.

Figure 9. Variation of AE rate and fitted Weibull function (experiment 22).

Figure 10. Dependence of AE event numbers on pore pressure gradient calculated in accordance with relation (1) with parameters of best fit curve shown in Figure 9.

Figure 11. Experimental and calculated pore pressure gradient variation in time (experiment 22).

The comparison of experimental pore pressure gradient (estimated as pressure difference between two points of pressure measurements) and critical pore pressure gradient calculated based on AE variations is shown in Figure 11. Experimental and calculated data start to be in agreement when the fluid pressure become respectively low and the sample permeability is more or less constant.

So, if one gets to know variation of AE (or microseismic activity in real case) in time and the relation between number of events and critical values of pore pressure gradient is known, it is possible to calculate the porous medium permeability.

Let's now consider once more one-dimensional pore-elasticity equation with constant coefficient of diffusivity

$$\frac{\partial p}{\partial x} = D \frac{\partial^2 p}{\partial x^2} \quad (3)$$

The solution can be written as

$$p(x, t) = A + \sum_{i=0}^{\infty} C_i e^{-\mu_i^2 D t} \sin(\mu_i x) + \sum_{i=0}^{\infty} B_i e^{-\mu_i^2 D t} \cos(\mu_i x) \quad (4)$$

Use of initial and boundary conditions of the experiment (which were described early) the solution can be written as

$$p(x, t) = p_{atm} + A(x) \sum_{i=0}^{\infty} \frac{1}{\mu_i^2} e^{-\mu_i^2 D t} \cos(\mu_i x) \quad (5)$$

where

$$A(x) = \frac{p(x, 0) - p_{atm}}{\sum_{i=0}^{\infty} \frac{1}{\mu_i^2} \cos(\mu_i x)}, \quad \mu_i = \pi i + \frac{\pi}{2}$$

The series

$$\sum_{i=0}^{\infty} \frac{1}{\mu_i^2} \cos(\mu_i x)$$

converges and majorizes the series in (5). Let's consider a function $f(x)$:

$$f(x + T) = f(x), \quad T = 4;$$

$$f(-x) = f(x);$$

$$\forall x \in [0; 2]: f(x) = \frac{1-x}{2}.$$

For $f(x)$ defined at $[-l, l]$ with period $2l$ which satisfies the Dirichlet conditions, the Fourier series expansion looks like

$$f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} \left(a_n \cos \frac{\pi n x}{l} + b_n \sin \frac{\pi n x}{l} \right),$$

$$a_n = \frac{1}{l} \int_{-l}^l f(x) \cos \frac{\pi n x}{l} dx$$

$$b_n = \frac{1}{l} \int_{-l}^l f(x) \sin \frac{\pi n x}{l} dx$$

The function $f(x)$ is even, so

$$b_n = 0$$

$$a_0 = \frac{1}{2} \int_0^2 \frac{1-x}{2} dx = 0$$

$$a_n = \frac{1}{2} \int_0^2 \frac{1-x}{2} \cos\left(\frac{\pi n x}{2}\right) dx = \frac{1}{2} \left[(1-x) \frac{2}{\pi n} \sin\left(\frac{\pi n x}{2}\right) \right]_0^2 - \int_0^2 (-1) \frac{2}{\pi n} \sin\left(\frac{\pi n x}{2}\right) dx =$$

$$= \frac{1}{\pi n} \int_0^2 \sin\left(\frac{\pi n x}{2}\right) dx = \frac{2}{\pi^2 n^2} (-1) \cos\left(\frac{\pi n x}{2}\right) \Big|_0^2 = \frac{2}{\pi^2 n^2} (1 - (-1)^n)$$

$$f(x) = \sum_{n=1}^{\infty} \frac{2}{\pi^2 n^2} (1 - (-1)^n) \cos\left(\frac{\pi n x}{2}\right)$$

Substitution $n = 2k + 1$ (for even n $f(x) = 0$)

$$f(x) = \sum_{k=0}^{\infty} \frac{4}{\pi^2(2k+1)^2} \cos\left(\frac{\pi(2k+1)x}{2}\right) = \sum_{k=0}^{\infty} \frac{1}{(\pi k + \frac{\pi}{2})^2} \cos\left((\pi k + \frac{\pi}{2})x\right)$$

$$A(x) = \frac{p(x, 0) - p_{atm}}{\sum_{i=0}^{\infty} \frac{1}{\mu_i^2} \cos(\mu_i x)}, \quad \mu_i = \pi i + \frac{\pi}{2}$$

so:

$$A(x) = \frac{p(x, 0) - p_{atm}}{\frac{1}{2}(1-x)} \quad (6)$$

To estimate the permeability one can adopt that

$$\frac{\partial A}{\partial x}(x) = 0$$

because in considered experiments

$$\frac{\partial p}{\partial x}(x, 0) = 0$$

and denominator in (6) is almost constant when x is small. In that case:

$$\frac{\partial p}{\partial x} = -A(x) \sum_{i=0}^{\infty} \frac{1}{\mu_i} e^{-\mu_i^2 D t} \sin(\mu_i x) \quad (7)$$

The diminishing part of the pore pressure gradient dependence on time (which is shown by ellipse in Figure 12) can be approximated by exponential function be^{at} (as it is shown in Figure 13), which corresponds to $i=0$ in (7), and the diffusivity coefficient can be estimated as

$$D = \frac{a}{(\pi/2)^2}$$

exp.6

exp.6

exp.22

Figure 13. Approximation of pressure difference variation in time by exponential low.

The results of the permeability estimations are shown in Table 2.

Pressure drop #	6	22	32
$D, \text{ m}^2/\text{sec}$	0.4	0.99	0.785
k, D	3.8	9.2	7.3

Table 2. Estimated values of diffusivity coefficient and permeability

The obtained values of permeability were compared with permeability estimated by permeability dependence on pore pressure drop (Table 1) and with permeability obtained with the help of r-t method suggested by Serge Shapiro and colleagues ([5, 9-11]). Diagram of distance

from the sample boundary dependence on time of AE event occurrences is shown in figure 14. An envelope curve.

$$r=\sqrt{4\pi D(t-t_s)},$$

which is a solution of one-dimensional porous elasticity equation, is shown in Figure 14 by red curve. It should be noted that the sample length was 83 mm, which is shown in the diagram by dotted line. The number of registered AE events was not high, it restricts an accuracy of the method.

exp.6

exp.22

Figure 14. Dependence of distance from the sample boundary on time of AE event occurrences.

If we compare Table 1, Table 2 and Table 3 we will see, that the permeability based on AE variation in time estimation gives values which are close to that obtained using data on pore pressure drop; nevertheless, r-t method gives values which are not contradict other results but differ from them significantly.

Experiment #	2	6	22	32
D, m ² /sec	0.003	0.17	0.2	2
k, D	0.03	1.6	1.9	18.6

Table 3. Permeability estimated by r-t method

5. Conclusions

In the paper, the results of experimental study of saturated porous sample fracturing due to pore pressure rapid drop are discussed. It was found, that acoustic emission AE (corresponded to microfracturing) was spreading from the end of the pressure drop to the closed end of the sample, and that maximal number of AE events was registered at some distance from the opened end.

The number of AE pulses increased with every next pressure drop, meanwhile the number of pulses with high amplitudes diminished. The prolongation of the pressure gradient maximal values is in agreement with AE maximal rate.

It was found that multiple microfracturing occurred during the pore pressure drop; the microfracturing is governed by pore pressure gradient.

The model of AE relation with the pore pressure gradient was considered based on the following assumptions: AE event occurred when the pore pressure gradient reaches some critical value; the critical value varies and can be described by Weibull distribution, which is often used to describe fragment size distributions in fractured rocks.

Permeability variation during the fluid pressure drop was estimated by means of fluid pressure data and pore-elastic equation solution for small time intervals (0.01 sec). It was found that the sample permeability is high in initial stage of the pressure discharge and decrease during pore pressure drop.

It is shown that if the change in microseismic activity in time is measured, the distribution of the critical pressure gradient is known for the considered material and the boundary conditions are given (for example, the change in pressure in the well), it is possible to calculate the pressure gradient, and on this basis, the permeability of the porous medium.

The study showed possibility to solve an inverse problem of defining permeability by registering microseismic activity variation in particular volume of porous medium alongside with pore pressure measurements at some point.

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