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A Practical Model to Estimate The Pore-Fracture Deformation in Dry/Wet Rocks and in Enhanced Geothermal Systems

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ABSTRACT

The world literature on rock mechanics describes the existence of subsidence in aquifers, in petroleum and gas fields, and in geothermal reservoirs. All these natural systems could be fractured or not. The phenomenon is a direct consequence of the deformation of the poro-elastic media. The fluid extraction causes the reduction of both the internal pore-fracture pressure and of the effective aperture of pores and fractures. On the other hand, the cohesive structure of rocks is weakened by the presence of liquid in the pores. As a consequence all the rock geomechanical parameters are influenced by that cohesion and are directly affected by the pressure and amount of liquid present in pores and fractures. Many naturally fractured systems had intense tectonic activity in their remote past and their original fracturing was equally intense. But some of them could contain fissured zones where most of the fractures appear closed. This phenomenon is partially explained by the fact that dry rock deformation and saturated rock deformation are very different. The first one can be anelastic or plastic, while the second one could be totally elastic. For example, if at the geological moment of being formed a volcanic reservoir was unable to store more than sufficient water, the lack of fluid could produce the collapse of fractures and faults, originating a low or zero global permeability with strong pressure gradients between the matrix blocks and the few open fissures. This effect can be accentuated by autosealing during the water-rock interaction. In that case the chemical equilibrium between water and rock cannot be attained. In this paper we present the development of a simple, practical poroelastic model to estimate, with few data, the deformation of fractured porous rock in dry or wet geothermal systems. These results can be useful in the study of enhanced hydrothermal reservoirs.

Introduction

The phenomenon of subsidence in rock mechanics is a direct consequence of fluid extraction from the underground porous media, causing the reduction of the internal pore pressure and of the effective diameter of the pores. A similar event occurs in fractures and fissures of naturally fractured reservoirs that had intense tectonic activity in their remote past and where the original fracturing was intense. Fractures in volcanic systems can also be closed because of fluid lost by natural means or through human activity.

Some volcanic hydrothermal systems contain portions of fractured rock where many fractures appear closed. This phenomenon could have two origins: the first one is caused by autosealing during water-rock chemical interactions at high temperature. The second one is a result of the action of rock and water compressibilities, combined with the deformation differences between dry rock and saturated rock. Studies carried out on a prototype of this type of systems (Los Humeros, Mexico geothermal field; Suarez & Samaniego, 1995) strongly suggest that at the moment of its formation, out of unknown reasons, the reservoir was unable to store abundant water. Our central hypothesis is that such lack of fluid caused the collapse and closing of many fissures, fractures and faults, originating a global drop in permeability and permitting, at the same time, the coexistence of very strong pressure gradients between the matrix blocks and the residual open fractures. The tectonic movements in this field, did not have enough intensity to produce faults of great penetrability into the underground. At the same time, the shortage of water prevented the fracturing to be more intense. The created fractures collapsed because of the lack of hydraulic support. From these conditions the low global permeability of the reservoir arose.

Effects of Fluid on Porous Rock Properties

In geothermal systems the rock properties are affected by the presence of fluid inside the pores and inside the fissures. This is generally called the *pore-water* effect (Terzaghi, 1943), which af-

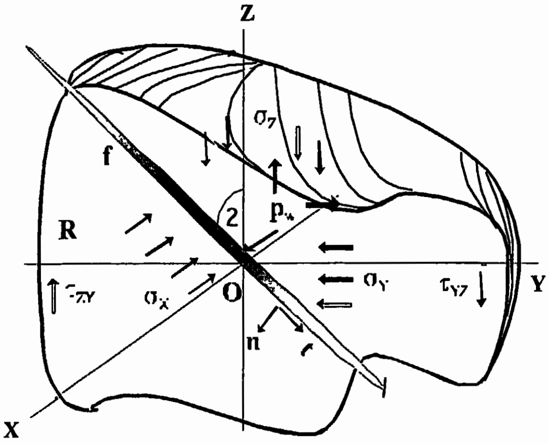

Figure 1. Stress tensor in a fractured porous rock.

[Preceding paragraph continues:] fects more or less all rock geomechanical parameters. Compared with steam or with air, liquid water is almost incompressible and this property tends to reduce both rock elasticity and stiffness. For example, saturated rock density and speed of wave propagation are increased, while strength is reduced. In geothermal reservoirs, the different values in parameters of dry rock and wet rock are determined by the amount of liquid water saturation, porosity, permeability, pressure and temperature.

A Simple Model for the Poroelastic Deformation

On the basis of the classical elastic continuum theory of rock mechanics (Farmer, 1968; Asszonyi & Richter, 1979; Blès & Feuga, 1986) we can calculate approximately how the internal stresses are affected by the fluid in a fractured rock matrix. Let **R** be a rock portion of a geothermal reservoir saturated with water in liquid phase. The rock is confined and crossed by a single fracture **f** in the plane YZ (Figure 1). The fracture is inclined at an angle θ with respect to the Z axis. The water in **R** has very low compressibility and the pore-water pressure is almost equal to the hydraulic pressure p_w in **R**, which can be represented by a spherical tensor $p_w\,\delta_{ij}$ (the unit tensor is δ_{ij}). Let us assume that X, Y, Z are the principal axes and **R** is subject to the stresses (σ_X, σ_Y, σ_Z) as shown in Figure 1.

To simplify, we also assume that the main effective pressure actions are contained in the plane YZ and that σ_Y (lateral confining stress) and σ_Z (vertical stress) are the principal stresses, minimum and maximum respectively, having a zero shear stress on this plane $\tau_{YZ} = \tau_{ZY} = 0$. A compressive stress σ_Z is applied to **R** originating the fracture shown in Figure 1. The plane YZ is orthogonal to the plane of failure. The stress tensor inside the fracture can be simplified if it is represented in an orthonormal principal system of coordinates (**t**, **n**), where **t** is a unit vector tangential to **f** and **n** is a unit vector orthogonal to **f**. In this reference frame, if the rock is dry, the normal stress σ and the shear stress τ acting in the direction θ of the fracture are given by the following equations:

$$\tau = \frac{\sigma_Z - \sigma_Y}{2}\,\mathrm{Sin}\;2\,\theta,\ and\ : \qquad (1)$$

$$\sigma = \frac{\sigma_Z + \sigma_Y}{2} + \frac{\sigma_Z - \sigma_Y}{2}\,\mathrm{Cos}\;2\,\theta$$

On the other hand, in saturated rock the effective stresses acting in the fracture will be decreased by p_w. This effect was discovered by Terzaghi (1943) when he showed experimentally that the effective stress tensor acting in saturated rocks is reduced by p_w: $\sigma_I - p_w\,\delta_{ij}$ (I = X, Y, Z) in every principal stress component. Replacing these effective stresses in equation (1) we obtain the shear or tangential stress τ_w and the normal stress σ_w acting in the fracture saturated with water in liquid state. Notice, in the following formulas, that the shear stresses in dry rock or in wet rock are the same; while the effective normal stress is reduced by an amount equal to p_w:

$$\sigma_w = \frac{\sigma_Z + \sigma_Y}{2} - \frac{\sigma_Z - \sigma_Y}{2}\,\mathrm{Cos}\;2\,\theta - p_w \qquad (2)$$

$$\tau_w = \frac{(\sigma_Z - p_w) - (\sigma_Y - p_w)}{2}\,\mathrm{Sin}\;2\,\theta = \tau$$

In a vertical fracture θ= 0° and $\sigma_w = \sigma_Y - p_w$. If the fracture is horizontal θ= 90° and $\sigma_w = \sigma_Z - p_w$. If the fracture is inclined at an angle $\theta = 45°$, $\sigma_w = (\sigma_Z + \sigma_Y)/2 - p_w$. In order to illustrate an application of this model to the case of the Los Humeros reservoir, we consider the general properties of well H-27 and use the parameters of Table 1. At a depth of 1500 m the rock density is $\rho_R = 2400\ \mathrm{kg/m^3}$, and the pore-water pressure p_w is 125 bar; the corresponding temperature is 310 °C and liquid density is 700 kg/m^3. The numerical values of the principal stresses σ_Y and σ_Z are given by the confining lateral pressure and the lithostatic load respectively:

$$\sigma_Z = \rho_R\, g\, z + p_0 = 354\ \mathrm{bar} \qquad (3)$$

$$\sigma_Y = \alpha\rho_R\, g\, z = \alpha\, 354\ \mathrm{bar} \qquad (4)$$

Here g = 9.8 m/s^2 is the acceleration of gravity, p_0 = 1 bar is atmospheric pressure, z =1500 m represents depth and α is an experimental correction coefficient, which ranges between 0.5 and 0.9; the first value corresponds to rock with high porosity while the second one is for almost dry rock with little porosity. Assuming an angle $\theta = 60°$ for the fracture's inclination and the preceding numerical values we obtain in dry rock, from equation (1):

$$\sigma_{dry} = 327\ \mathrm{bar}\ ,\ \tau_{dry} = 78.6\ \mathrm{bar} \qquad (5)$$

The same data applied to equation (2) for saturated rock give:

$$\sigma_w = 184.7\ \mathrm{bar}\ ,\ \tau_w = 78.6\ \mathrm{bar} \qquad (6)$$

In the same reference frame (**t**, **n**) the strain tensor ε is given by:

$$\varepsilon_t = -\frac{\nu\,\tau}{E}\ ,\ \varepsilon_n = \frac{\sigma}{E} \qquad (7)$$

Average modulus of elasticity and Poisson's ratio can be estimated from Table 1. They are equal to E = 3.0 10^5 bar and ν = 0.23. Elastic strain is also different in each case. For the practical purpose of estimating fracture deformation in the orthogonal direction we define $\delta z_n = z\ \varepsilon_n$, as the small normal compression experienced by the fracture relative to a perpendicular dimension z in the direction **n**. We also assumed that fractures are separated by a distance z = 1 m. We obtain from the application of results (5) into equations (7) for dry rock:

$$\varepsilon_t = -(0.23)\ 78.6/(3\ 10^5) = -\ 6.03\ 10^{-5} \tag{8}$$

$$\varepsilon_n = 327/3\ 10^5 = 10.9\ 10^{-4} \Rightarrow \delta z_n = 1.1 \text{ mm} \tag{9}$$

Substituting results (6) in equation (7) we obtain for the case of saturated rock:

$$\varepsilon_w = 184.7/3\ 10^5 = 6.2\ 10^{-4} \Rightarrow \delta z_n = 0.6 \text{ mm} \tag{10}$$

In the previous example we assumed that elasticity modulus E is not affected by the presence of water. But practical experience shows that in porous rocks, liquid saturation affects the value of E. The effect of pore-water pressure p_w on the elasticity of the rock would lead to an equivalent decrease in strain that could be approximated by the next formula (Farmer, 1968), which suggests a decreased modulus of elasticity:

$$\varepsilon_w = \frac{0.5\ p_w}{E} = \frac{0.5 \cdot 125}{3 \cdot 10^5} = 2.1 \cdot 10^{-4} \Rightarrow \delta z_n = 0.21 \ mm \tag{11}$$

We infer that in dry, low porous rocks, natural fractures present a clear tendency to be closed by normal lithostatic stresses. Under the same loading conditions, fractures filled with water will not collapse because of the presence of a pore-water pressure opposing the normal stress. This analysis is also supported by other experimental results obtained, for example, by Colback & Wiid (1965), when they measured a strength reduction of 50% in saturated sandstone. As a general conclusion, we observe that high porosity saturated rocks will be considerable weakened by the presence of water even at low pressure, facilitating the formation of fractures. This is the case for geothermal rocks having porosities greater than 10%. The Rehbinder effect (Farmer, 1968) postulates that all phenomena due to p_w, are caused by a reduction of the cohesive structure of the rock, because it is weakened by the presence of liquid in the pores.

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There are other important thermo-mechanical effects in geothermal reservoirs. High pressure and temperature increase ductility and lower the yield point of the rock. The high confining pressure effects induce plastic flow. We have observed that fissures, fractures and microfractures are more numerous in the vicinity of large or regional faults. Similar experiences were reported by different authors (Blès & Feuga, 1986). This phenomenon occurs because when a fault is generated within massive rocks, original stress distribution is modified around the fault, producing the development of different tension fractures, especially near to the end of the fault. Faults and fractures in volcanic geothermal systems were produced by several tectonic events, during discontinuous deformations beyond the limit of elastic strain, in rocks composed of brittle materials. The main natural mechanisms forming the faults and fractures are compression, extension, shearing and shortening. These mechanisms act all together and are also influenced by the previous presence of stratification , cleavage, joints and fractures. Fissures and faults derived from an earlier tectonism can already be present as rock discontinuities and become active in a new tectonic event. That is why in volcanic reservoirs very complex structural systems can be developed.

Conclusions

- There exist natural systems that presently have low permeability and contain small amounts of liquid water, but whose original permeability was high.
- The lack of fluid allowed the collapse of fissures because their internal hydraulic stresses could not balance the lithostatic load. Water-rock interaction facilitated the selfsealing of faults and fractures, especially in shallow strata.
- Our model shows that under these natural conditions every fracture, having one milimeter or smaller aperture, can be closed by the vertical compression, unless an opposite local force is present to balance the lithostatic load.

Table 1. Petrophysical Properties from Los Humeros, Mexico Reservoir (*Contreras et al, 1990*).

(Superscript m/f means absolute permeability in matrix and microfractures, respectively. K_{ter} is rock thermal conductivity, C_P is rock specific heat at constant pressure, E is the modulus of elasticity, v is Poisson's ratio and C_R is rock compressibility measured at a confining pressure of 350 bar. Measurements are reported in saturated rock, and (*) means uniaxial tests.)

well	depth (m)	density (kg/m^3)	porosity (%)	permeability (milidarcy)	E (10^5 bar)	v	C_R (10^{-6} bar^{-1})	K_{Ter} (W/m/°C)	C_P (J/kg/°C)
H02	616	2160	19.7	0.019	2.09 *	0.27	-	1.54	1046.7
H04	907	2240	19.4	0.086	1.60*	0.39	9.2	1.96	1046.7
H10	1469	2620	6.1	0.026	1.99 *	0.18	7.3	1.61	1088.6
H18	1750	2340	14.7	0.005	2.69	0.20	8.5	2.42	921.1
H19	1769	2460	11.5	0.147^f	2.05 *	0.31	7.7	1.91	1172.3
H20	1403	2270	15.8	0.059	2.88	0.19	-	2.19	1046.7
H22	663	2250	18.1	0.096	2.08 *	0.28	8.6	1.96	1088.6
H23	1924	2370	13.9	1.252^f	3.19 *	0.37	6.5	1.82	1088.6
H24	2297	2370	11.6	0.070	4.11 *	0.42	4.8	2.14	1130.4
H26	1810	2670	4.5	1.873^f	2.77 *	0.42	7.7	1.95	1004.8
H27	1500	2400	10.1	0.145^f	3.32 *	0.23	-	1.89	1130.4
H29	1200	2250	18.4	0.334^f	2.53	0.30	12.5	1.86	1046.7

- A practical solution for these problems is simply to inject external water into the reservoir. Volcanic rocks are brittle, easily fractured rocks. This action will increase rock permeability and allow different portions of the reservoir to communicate with each other.

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