INTERPRETATION OF BOREHOLD TIDES AND OTHER ELASTOMECHANICAL OSCILLATORY PHENOMENA IN GEOTHERMAL SYSTEMS

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Introduction

Ultralow to low-frequency oscillatory phenomena of elastomechanical nature have been observed in a number of geothermal areas. These include pressure and water level oscillations in the tidal frequency range 10^{-6} to 10^{-4} Hz (White, 1968), flow oscillations at around 10^{-3} Hz (Bodvarsson and Bjornsson, 1976) and ground noise in the range 10^{-1} to 10 Hz (Douze and Sorrel, 1972). The presence of such oscillations conveys certain information on the underlying geothermal systems which is of both theoretical and practical interest. In the following, we will very briefly discuss a few aspects relating to the interpretation of oscillatory field data with the main emphasis on borehole tides.

Oscillations of Tidal Origin

Pressure oscillations in the tidal frequency range, which may be observed either directly by pressure transducers emplaced in closed subsurface fluid spaces, or, as water level oscillations in boreholes, result from the straining of the surrounding formations by forces of tidal origin. The water level oscillations represent a breathing of the formations through the borehole. The volume amplitude of the oscillating fluid must therefore give clues as to the local strain amplitude and the formation volume in direct contact with the borehole. To obtain quantitative cause-effect relations, we have to consider the diffusion of low frequency pressure fields in natural formations.

Concentrating on the case of fluid-saturated Darcy-type porous media, the simplified linear pressure diffusion theory given by Bodvarsson (1970) can be applied to obtain useful relations. The oscillatory pressure field is then derived as a solution to a standard linear scalar diffusion equation. Applying the theory to the simple but practically relevant model shown in Figure 1, we consider a spherical volume V of radius R of a homogeneous and isotropic Darcy-type medium saturated by a fluid of density ρ and which is embedded in a formation of negligible permeability. The capacitivity or storage coefficient of the wet medium is s and its hydraulic conductivity $c = k/\nu$ where k is the permeability of the medium and ν the kinematic viscosity of the fluid. The skin depth d of a harmonic oscillatory pressure field with an angular frequency ω is then obtained by (Bodvarsson, 1970)

$$d = (2c/\rho s\omega)^{\frac{1}{2}} \tag{1}$$

A borehole of cross-section a has been drilled into the center of the porous formation and for convenience we assume that it is connected with V through a small spherical cavity of radius r. The borehole is cased all the way to the cavity and there is a free water surface at an elevation h. Moreover, we assume that tidal forces of angular frequency ω produce a homogeneous and isotropic strain of amplitude b in V. The formation matrix coefficient ε characterizes the relation between the imposed strain and the porosity (Bodvarsson, 1970).

Omitting details of derivation, we obtain by solving the pressure diffusion equation with appropriate boundary conditions at the inner and outer boundaries of the porous formation, the following relation for the amplitude of the water level

$$h = h_s T(1 + T)^{-1} \quad (2)$$

where h_s is the static amplitude (Bodvarsson, 1970)

$$h_s = -\varepsilon b/\rho g s, \quad (3)$$

g is the acceleration of gravity and T is the tidal factor

$$T = \rho g s V_d F/a \quad (4)$$

which is characterized by two quantities, the skin volume

$$V_d = \pi r^2 d \quad (5)$$

and the complex dimensionless reflection factor F which depends primarily on the ratio R/d.

The permeability of common Darcy-type reservoir formations is frequently of the order of 10^{-2} to 1 darcy and the skin depth at tidal frequencies is then 50 to 500 meters (Bodvarsson, 1970). Moreover, reasonable values for the cavity radius r are of the order of one meter. Cases where $r/d \gg 1$ and $d/r \gg 1$ are therefore of particular practical interest. An elementary derivation shows that in this case the coupling between the borehole and the formation is resistive and the tidal factor can then be approximated by

$$T = -i\rho g s \pi r d^2/2a = -ig\pi r c/\omega a \quad (6)$$

This expression which can be assumed for a number of Darcy-type porous reservoirs furnishes the main clues as to the problem of interpreting borehole tides in such cases.

In all practical cases, the density ρ and cross-section $\underline{a}$ are well known. The capacitivity can generally be estimated with sufficient accuracy on the basis of core samples. Moreover, although boreholes rarely open into spherical cavities, most practical cases involving irregular cavities of small dimension compared with the skin depth d can be approximated by spherical cavities with an equivalent radius r which can be estimated within reasonable limits. The skin depth d is therefore the principal unknown on the right of equation (6).

Moreover, the static amplitude h_s given by equation (3) can in principle often be determined experimentally by closing the borehole with packers at appropriate levels and placing instrumentation to record the tidal pressure amplitude in the enclosed space. Provided that such observation can be made, we can conclude that the skin depth is the principal unknown on the right of equation (2). Hence, observing the tidal water level amplitude h, we can obtain data on the skin depth d and thereby because of (6) information on the hydraulic conductivity c. These two quantities, d and c, are therefore the principal targets of most interpretive efforts involving borehole tides.

Local Enhancement of the Tidal Dilatation

Elementary considerations indicate that the local tidal dilatation is generally modified by variations in the subsurface elastic parameters. The effect is most obvious at very abrupt inhomogeneities such as in the case of open subsurface spaces. Consider, for example, an open very flat penny-shaped cavity of radius r and width w. The cavity is placed in homogeneous solid rock at a depth which is substantially greater than the diameter 2r and such that its axis is parallel to the direction of maximum principal tidal strain. A simple argument (Bodvarsson, 1977) indicates that the cavity will breathe in response to the tidal stresses and that the dilatation amplitude of the open space is enhanced by a factor of approximately r/w relative to the undisturbed dilatation at a distance from the cavity. In specific cases, the local dilatation amplification can thus attain very large values. Moreover, there is also a substantial enhancement of the tidal stresses along the edge of the cavity. This is a typical notch effect.

Analog effects, but generally of a more complex nature, are obtained in the cases of other types of inhomogeneities (Bodvarsson, 1977). Inclusions of porous fluid-saturated material in solid rock will also breathe in response to the solid earth tides, and there will be notch type stress concentrations in particular locations. The theory of these phenomena is somewhat complex, in particular, when the dimensions of the inclusions exceed the hydraulic skin depth at tidal frequencies of the porous material.

The case of fracture zones with a permeable fluid-saturated gouge is of particular interest. We assume that the fluid can breathe freely through the surface of the gouge. Although very little is known about the fluid conductivity characteristics of gouge materials, we can on the basis of rather simple theoretical modeling (Bodvarsson, 1977) infer that the tidal fluid pressure amplitude within the gouge may in some cases, at least, vary along the fracture zone as indicated in Figure 2. There is an upper zone, the depth of which is of the order of the hydraulic skin depth in the gouge, where the breathing through the open surface causes a reduction of the tidal pressure amplitude. Further below is a zone of an enhanced pressure amplitude. This is a notch type effect caused by the reduced pressure amplitude in the surface zone. Deeper in the fracture zone, where the effect of the open surface is negligible, the pressure amplitude attains the local static value given by equation (3).

The above considerations indicate that data on the local tidal pressure amplitude, as measured in closed boreholes, can be of some value as an exploration tool. Some characteristics of the local geological structure and material properties can be reflected in the observational data.

Hydroelastic Oscillations

Helmholtz type borehole-cavity oscillations. Small amplitude temperature oscillations of frequency around 10^{-3} Hz have been observed in a thermal borehole in Southwestern Iceland. The hole flows about 0.5 kg/s at 43°C. Bodvarsson and Bjornsson (1976) have discussed this phenomenon and have concluded that it may be caused by weak flow oscillations due to a hydroelastic Helmholtz type borehole-cavity resonance excited by pressure fluctuations of turbulent origin.

Fracture oscillations and geothermal ground noise. When properly excited, fluid filled fracture spaces can perform hydroelastic oscillations and radiate very low frequency seismic signals. A simple approximate theory of such oscillations has been given by Bodvarsson (1978). The frequency f of the basic oscillation mode of a very thin fracture space of constant width w, vertical dimension L, and which is open to the surface as shown in Figure 3, can be estimated by the following relation

$$f = (\mu w/\rho L^3)^{\frac{1}{2}} \qquad (7)$$

where μ is the shear modulus of the rock and ρ is the density of the fluid.

The above result indicates that fracture spaces of width 10^{-3} m and vertical dimension of 10 to 100 m have basic frequencies in the range 0.2 to 5.0 Hz. This is the frequency range of seismic ground noise which has been observed in many geothermal areas (Douze and Sorrels, 1972). The observed seismic signals may thus result from hydroelastic oscillations of thin fracture spaces. As in the above case of Helmholtz type oscillations, the excitation may again be provided by pressure fluctuations of turbulent nature in the convecting geothermal fluid.

Provided the above interpretations are correct, the observed frequencies give some clues as to the dimensions of the oscillating spaces.

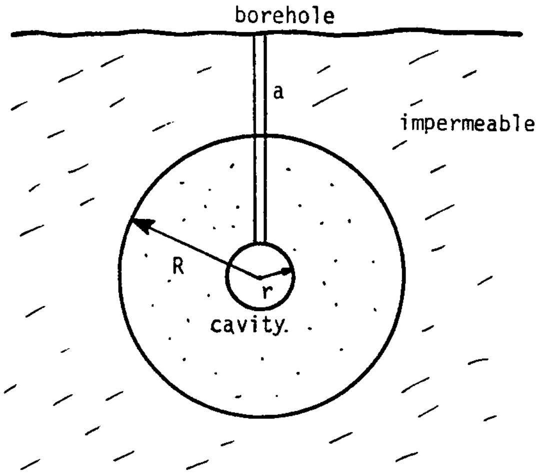

Figure 1. Spherical volume of a porous Darcy type material.

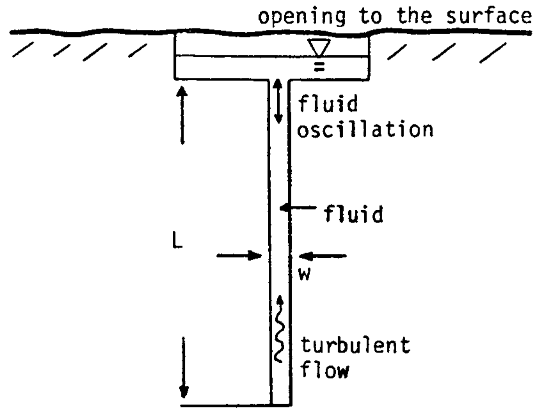

Figure 3. Open vertical fracture.

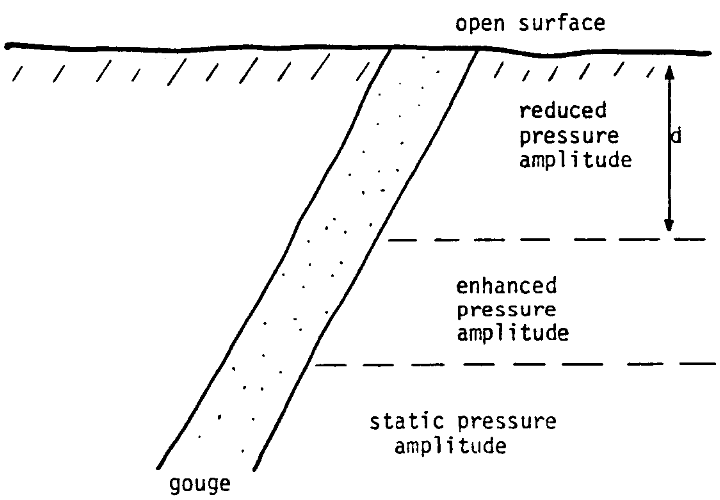

Figure 2. Fracture zone containing a permeable gouge.

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