GEOTHERMAL RESERVOIR TESTING BASED ON SIGNALS OF TIDAL ORIGIN

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Introduction

The theory of pressure and water level oscillations of tidal origin in Darcy type aquifers and petroleum reservoirs has been discussed in a number of recent publications (see for example, Bredehoeft, 1967; Bodvarsson, 1970, 1977, 1978a, 1978b; and Arditty et al., 1978). There is a general agreement that observational data on the tidal pressure phenomena may be applied to obtain useful estimates of important reservoir parameters such as the permeability.

A Simple Basic Model

In the simplest setting involving a single open well connected by a small spherical cavity to a large homogeneous and isotropic reservoir, the mechanism of the tidal well test is easily comprehended on the basis of the model illustrated in Fig. 1 below. Let the permeability of the porous medium be k, the density of the fluid by ρ, its kinematic viscosity be ν and hence the fluid conductivity of the medium be $c=k/\nu$. Moreover, let s be the hydraulic capacitivity or storage coefficient of the medium and the diffusivity therefore $a=c/\rho s=k/\mu s$ where μ is the absolute viscosity of the fluid. The skin depth of the medium at an angular frequency ω is then $d=(a/2\omega)^{\frac{1}{2}}$ (Bodvarsson, 1970). For the present purpose, concentrating first on cases where boundary effects can be ignored, we assume that the skin depth of the reservoir material at tidal frequencies is smaller than the extent of the reservoir including the depth of the well. In other words, the reservoir can be assumed to be infinite as viewed from the well-cavity. Introducing a spherical coordinate system with the radial coordinate r and with the origin placed at the center of the cavity, the fluid pressure field $p(r,t)$ in the porous medium is governed by the diffusion equation (Bodvarsson, 1970).

$$\partial_t p - a[\partial_{rr} + (2/r)\partial_r]p = -(\varepsilon/s)\partial_t b \qquad (1)$$

where t is time, $b(t)$ the tidal dilatation of the medium and ε is the formation matrix coefficient. Let r_0 be the radius of the cavity, f the cross section of the well and g the acceleration of gravity. The boundary condition at $r = r_0$ is then

$$(f/g)\partial_t p - Fc\partial_r p = 0, \qquad (2)$$

where $F = 4\pi r_0^2$ is the surface area of the cavity.

The expression for the oscillations of the water level in the well in response to the dilatation is obtained by solving equation (1) with the boundary condition (2) and deriving the pressure at the cavity which is equal to the pressure at the well bottom. To simplify our results without any appreciable loss of generality, we can in most cases assume that the skin depth of the medium is much larger than the dimensions of the cavity, that is, $d >> r_0$. Assuming therefore an infinite medium and that b and $p \propto \exp(i\omega t)$, the solution of (1) in terms of amplitudes is (Bodvarsson, 1970)

$$p = (B/r)\exp[-(1+i)r/d] - (\epsilon b/s), \qquad (3)$$

where B is a constant to be determined by the boundary condition (2). Inserting (3) into (2), we finally obtain for the amplitude of the water level in the well

$$h = -(\epsilon b/\rho g s)T/(1+T), \qquad (4)$$

where b is the dilatation amplitude and T is the tidal factor,

$$T = -4i\pi g s c r_0/f\omega, \qquad (5)$$

An elementary potential theoretical argument shows that the admittance or conductance of the cavity is

$$A = 4\pi c r_0, \qquad (6)$$

and we can define the mass stiffness of the well

$$S = dp/dm = g/f, \qquad (7)$$

This quantity measures the increase in well bottom pressure when a unit mass of liquid is added to the well, Using these expressions, the tidal factor can be expressed

$$T = -iAS/\omega \qquad (8)$$

which along with (4) is our final result for the above simple mode illustrated in Fig. 1.

It is to be noted that the above expression (8) will also hold for a closed well situation. We have then only to redefine the mass stiffness

$$S = dp/dm = 1/\beta M \qquad (9)$$

where M is the liquid mass in the well and β is the compressibility of the liquid. In the case of a gas cap, (9) will have to be adjusted accordingly. In the case of a closed well equation (4) will have to be expressed in terms of the well-head pressure rather than a water level.

Interpretation of Well Data

In the relatively simple situation described above, the interpretation of well data is based on equations (4) and (8). Invariably, ρ and f can be taken to be known. Since in most practical cases, the effective dilatation εb and formation capacitivity s are of less interest than the formation fluid conductivity c, the latter quantity is generally the primary target of any interpretation of observational tidal well data. Equations (4), (8) and (6) show that c has to be derived from the tidal factor T and that this factor can be separated if we are able to observe the water level amplitude at two different tidal frequencies. Since the tidal force field includes a number of frequencies this will generally be possible. Being, in principle, able to obtain T and thus on the basis of (8) the admittance A, the fluid conductivity will have to be derived with the help of (6). In the rather idealistic situation with a spherical well-cavity of known radius r_0, we are therefore, in principle, able to reach our goal of obtaining a numerical estimate of c.

From the practical point of view, the procedure will, however, break down if T >> 1. The factor T/(1+T) is then approximately equal to unity and the water level amplitude h will be independent of the fluid conductivity. In practice, we can expect this difficulty to become serious when about T > 3. Since in most cases the factor $4\pi g/f\omega$ will be of the order of 10^7 (MKS), we see that the above inequality implies $r_0 c > 3\times10^{-7}$ (MKS). For water at 100°C with $\nu = 3.10^{-7} m^2/s$ we obtain then in terms of permeability $r_0 k > 3\times10^{-7} \times 3\times10^{-7} \approx 0.1$ darcy-meters. Therefore, taking, for example, $r_0 = 0.5$ m, we find that the above difficulty becomes serious for permeabilities in excess of 200 millidarcy. In other words, the tidal test based on open well situations is sensitive only to small to medium permeabilities. Due to increased stiffness S, the applicability in the case of closed wells is more restricted.

Deviations from the basic model

Non-spherical well-reservoir connection. The assumption of a spherical cavity is perhaps to most obvious idealization in the above basic model. Unfortunately, the symmetry of the pressure field will be broken in the case of a non-spherical cavity, and the above simple relations may, in principle, not apply. However, provided the dimensions of a non-spherical cavity are much smaller than the skin depth d of the medium, and this will mostly be the case, the difficulties arising are not too important from the more global point of view. The global pressure field at some proper distance from the cavity will be approximately spherically symmetric and the above analysis will largely be valid. The most serious casualty is that the cavity admittance is not given by the simple relation (6) and other analog relations have to be relied on. In practical cases, there may be difficulties in establishing the form of the cavity. Most frequently, however, the well-reservoir connection consists of an open section of the well. Let the radius of the well be r_1 and the length of the open section be L. An elementary potential theoretical exercise shows that when $L >> r_1$ the admittance can then be (Sunde, 1968) approximated by

$$A = 2\pi cL/\ln(L/r_1) \qquad (9)$$

It is of interest to point out that an open section of $L = 10m$ and $r_1 = 0.1m$ has approximately the same admittance as a spherical cavity of $r_0 = 1.1$ m.

Multi-well setting. Another important deviation from the basic model involves cases where there is more than one well opening into the reservoir. This situation may lead to a well-well interaction and pressure field scattering. The practical criterion for interaction is obtained by comparing the well-well distance to the skin depth d of the medium. In general, two wells will interact noticeably if the distance between the well-reservoir cavities is approximately equal or less than the skin depth at tidal frequencies.

The analysis of multi-well situations is more complex than the results given above. In the case of spherical cavities,, the solution for the pressure amplitude field will then have to be constructed as a sum over solutions of the type (3), that is

$$p = \sum_j (B_j/r_j)\exp[-(1+i)r_j/d] - (\varepsilon b/s), \qquad (10)$$

where the j^{th} summand is centered at the j^{th} well-cavity, r_j is the distance from the field point to the center of the j^{th} cavity and the B_js are integration constants. A boundary condition of the type (2) applies at each well-cavity and the constants B_j are obtained by solving a set of linear algebraic equations. An estimate for the fluid conductivity can then be obtained along similar lines as indicated above. We will, however, refrain from a further discussion. Obviously, neglecting well-well interaction M multi-well situations leads to an underestimate of the formation fluid conductivity c.

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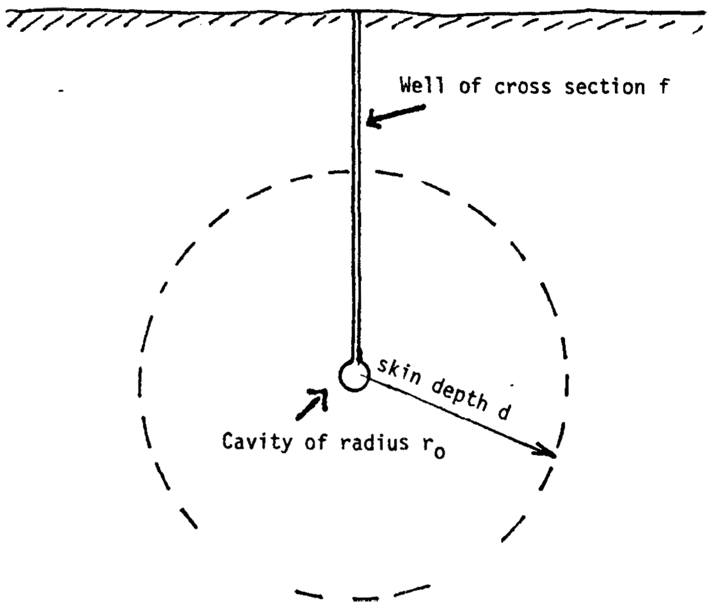

Figure 1. Single well model.