DETERMINING RESERVOIR PRESSURE IN CLOSED RESERVOIR AND ELASTIC EXPULSION OF FLUID WHEN RESERVOIR IS OPENED

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The studies of Tkhostov [1] have shown that the reservoir pressures of fluid in closed reservoirs differ from the hydrostatic value. This has led to the determination of the pressure in such reservoirs and the solution of the problem of elastic expulsion of the fluid when the reservoir is opened.

1. Assume a closed reservoir is subjected to the confining pressure q. The equation of equilibrium (without account for inertial forces) is written in the form

$$\sigma + p = g \int_0^{x_1} [(1-m)(\rho_2 - \rho_1) + m\rho_1]\, dx_1 + q \tag{1.1}$$

$$\sigma = (1-m)\sigma^v - (1-m)p \tag{1.2}$$

Here σ = fictitious pressure in skeleton; σ^V = true stress [2] in the rock; p = pressure in fluid; g = gravitational acceleration; m = porosity; ρ_2 and ρ_1 = densities of rock particles and reservoir fluid; x_1 = depth of reservoir element measured from reservoir roof.

We assume that ρ_2 = const (particles do not compress) and under the action of the external loading there is only repacking of the particles (compaction), obeying Hooke's law

$$\varepsilon_2 E_2 = \sigma \tag{1.3}$$

where ε_2 is the relative volumetric compression of the skeleton, E_2 is the bulk modulus of elasticity of the skeleton. The elastic compression of the fluid is

$$\varepsilon_1 E_1 = p \tag{1.4}$$

Specifically, if a rock specimen which does not contain fluid is loaded, then p = 0 and from (1.2) we obtain $\sigma = (1-m)\sigma^V$, i.e., in this case the fictitious stress is the average normal stress distributed over the entire section of the specimen.

On the other hand, if a specimen saturated with fluid is entirely in a fluid with the pressure p, then the skeleton will not be loaded, $\sigma = 0$, and from (1.2) we obtain $\sigma^V = p$, i.e., the rock particles will be subjected to all-round hydraulic compression of intensity p.

In the case of a horizontally positioned reservoir, when its thickness can be neglected, (1.1) takes the form $\sigma + p = q$.

Let us find the load distribution in a horizontal reservoir in the static condition (σ = const, p = const). To this end we use the equation of compatibility of the skeleton and pore fluid deformations.

A closed reservoir can be modeled by a cylinder with absolutely rigid walls, filled with a porous medium and a fluid. An impermeable piston presses down on the two-phase medium from above with the intensity q.

In the unloaded condition the reservoir element with porosity m_0 occupies in the cylinder the volume v_0. The particles occupy the volume $(1-m_0)v_0$. After loading, the element volume becomes equal to

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$$v_1 = (1 - \varepsilon_2) v_0$$

By assumption the rock particles do not deform, therefore the pore volume occupied by the fluid will be

$$v_3 = (1 - \varepsilon_2) v_0 - (1 - m_0) v_0 = (m_0 - \varepsilon_2) v_0$$

The porosity of the element when loaded will be

$$m = \frac{m_0 - \varepsilon_2}{1 - \varepsilon_2} \tag{1.5}$$

Then

$$\varepsilon_1 = \frac{m_0 - m}{m_0} = \frac{(1 - m_0)\varepsilon_2}{m_0 (1 - \varepsilon_2)}$$

or neglecting the quantity $\varepsilon_1 \varepsilon_2$, we rewrite

$$\varepsilon_1 = \varepsilon_2 (1 - m_0) / m_0$$

Thus, using (1.3) and (1.4) we have

$$\frac{p}{E_1} = \frac{1 - m_0}{m_0} \frac{\sigma}{E_2} \tag{1.6}$$

Hence, using $\sigma = q - p$ we obtain

$$p = q [1 + m_0 E_2 E_1^{-1} (1 - m_0)^{-1}]^{-1} \tag{1.7}$$

We shall calculate the stresses in the water and the rock skeleton at the roof level for the following parameters: $E_1 = 0.2 \cdot 10^5$ at, $E_2 = 0.5 \cdot 10^5$ at, $q = 500$ at, rock specific weight $\rho_2 = 2.3$ g/cm^3, reservoir roof distance from the earth's surface $H = 2174$ m, $m_0 = 0.2$. For these parameters we have

$$p = 307 \text{ at}, \ \sigma = 193 \text{ at}$$

The fluid pressure in the pores in the confined reservoir at a depth of 2174 m for the selected E_1 and E_2 differs from the hydrostatic pressure by 1.4 times. The larger the modulus E_2, the lower the pressure inside the pores will be for a constant q.

At the present time in the gas and oil fields the magnitude of the reservoir pressure is usually considered equal to the magnitude of the hydrostatic pressure of the liquid column at the depth in question, although this condition is not always satisfied in the presence of a closed reservoir compressed by tectonic forces.

As noted in [1], the fluid pressure within reservoirs varies from 0.7 to 2 times the hydrostatic pressure. The variations of the reservoir pressure within closed reservoirs depend on the ratio E_2/E_1. Anomalously high pressures within the reservoirs may appear as a result of the action of tectonic forces, which are difficult to take into account at the earth's surface.

Let us find the load distribution in a closed reservoir having some thickness. With account for (1.4) we obtain the relation $\rho_1(p)$ in the form

$$\rho_1 = \rho_0 (1 + p / E_1) \tag{1.8}$$

Considering q = const, we write (1.1) in the form

$$\frac{d\sigma}{dx_1} + \frac{dp}{dx_1} = g\rho_2 [1 - m(x_1)] - g\rho_1 [1 - 2m(x_1)]$$

or taking (1.3), (1.5), (1.6), (1.8) into account and introducing the dimensionless pressure and coordinate,

$$\frac{a - p_1}{\alpha - \beta p_1} dp_1 = dx$$

where

$$p_1 = p / E_1, \quad x = m_0 \rho_0 a (E_2 / a + E_1)^{-1} \int_0^{x_1} g(x_1)\, dx_1$$

$$a = (1 - m_0) / m_0, \quad \alpha = a(\rho_2 / \rho_0 - 1) + 1$$

$$\beta = a - 1 + (a m_0)^{-1}.$$

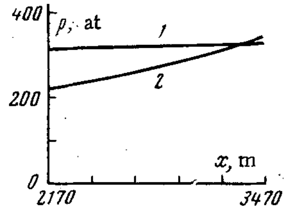

Fig. 1

We integrate the differential equation written above:

$$x = p_1 / \beta + \beta^{-2} (\alpha - a\beta) \ln | \alpha - \beta p_1 | + c$$

From the condition

$$x = 0, \; p_1 = p_0 = aq (a + E_2 / E_1)^{-1} E_1^{-1}$$

we find

$$c = - p_0 / \beta - \beta^{-2} (\alpha - a\beta) \ln | \alpha - \beta p_0 |$$

Consequently

$$x = (p_1 - p_0) \beta^{-1} + \beta^{-2} (\alpha - a\beta) \ln [(\alpha - \beta p_1) / (\alpha - \beta p_0)] \quad (1.9)$$

The relation $p_1(x)$ is easily constructed graphically.

Let us compare the magnitude of the reservoir pressure calculated using (1.9) with the magnitude of the hydrostatic pressure, satisfying the following differential equation:

$$dp / dx_1 = g\rho_1$$

Considering (1.8), we represent this equation in the form

$$dp / dx_1 = g (x_1) \rho_0 (1 + p / E_1)$$

Solving the equation in dimensionless quantities, we find

$$x = \ln (1 + p_1) + c, \quad p_1 = p / E_1, \quad x = \rho_0 E_1^{-1} \int_0^{x_1} g (x_1) \, dx_1$$

Since $p_1 = 0$ for $x = 0$, the constant of integration $c = 0$. Finally

$$p_1 = e^x - 1 \quad (1.10)$$

The comparison of the pressures at the same depth from the earth's surface is made on the basis of (1.9) and (1.10).

Figure 1 shows reservoir pressure as a function of depth for a closed reservoir and a reservoir with hydrostatic pressure: 1 = pressure distribution in closed reservoir, 2 = distribution in open reservoir.

2. Upon the appearance of a crack in the impermeable wall of the closed reservoir the equilibrium state of the two-phase system is disturbed until the fluid flowing out of the reservoir lowers the pressure therein to the hydrostatic value.

We take the fluid equation of motion in the form

$$v = - K \left(\frac{1}{g\rho_1} \frac{\partial p}{\partial x_1} - 1 \right), \qquad K = g\rho_1 k / \mu \quad (2.1)$$

Using the Slichter-Kozeny equation, the permeability k is expressed in terms of the porosity m

$$k = A m^3 / (1 - m)^2$$

Here A is a constant which depends on the grain size.

Since the grains, by assumption, do not deform, A is an absolute constant. Therefore

$$k \approx k_0 [1 - (3 - m_0) \sigma m_0^{-1} E_2^{-1}] \quad (2.2)$$

With increase of the pressure the fluid viscosity (particularly fluids of complex molecular structure) increases markedly:

$$\mu = \mu_0 (1 + \alpha_1 p) \quad (2.3)$$

Then

$$\mu^{-1} \approx \mu_0^{-1} (1 - \alpha_1 p) \quad (2.4)$$

Consequently

$$K \approx K_0 (1 + p / E_1)(1 - \alpha_2\sigma)(1 - \alpha_1 p), \qquad K_0 = \rho_0 g k_0 / \mu_0 \qquad \alpha_2 = (3 - m_0) / (m_0 E_2)$$

Using (1.1) and setting $\alpha_3 = 1/E_1$, we rewrite

$$K \approx K_0 \Big[1 - \alpha_2 q + p(\alpha_3 + \alpha_2 - \alpha_1) - \alpha_2\rho_2 g \int_0^{x_1} (1 - m)\, dx_1 - \alpha_2 g \int_0^{x_1} m\rho_1 dx_1 + \alpha_2 g \int_0^{x_1} (1 - m)\rho_1 dx_1\Big]^0$$

If in this equation we limit ourselves to small quantities of first order, then we must set

$$\int_0^{x_1} (1 - m)\, dx_1 = (1 - m_0)\, x_1, \qquad \int_0^{x_1} m\rho_1 dx_1 = m_0\rho_0 x_1, \qquad \int_0^{x_1} (1 - m)\rho_1 dx_1 = (1 - m_0)\rho_0 x_1$$

Then, setting

$$\varepsilon_3 = \alpha_3 + \alpha_2 - \alpha_1, \quad \varepsilon_4 = \alpha_2 g\rho_0 \, [(1 - m_0)\rho_2 / \rho_0 + 2m_0 - 1]$$

we obtain

$$K \approx K_0 (1 - \alpha_2 q + \varepsilon_3 p - \varepsilon_4 x_1)$$

Thus

$$v = -K_0 (1 - \alpha_2 q + \varepsilon_3 p - \varepsilon_4 x_1)\left(\frac{1}{\rho_1 g}\frac{\partial p}{\partial x_1} - 1\right)$$

The equation of continuity of the fluid flowing out of the rock has the form

$$\frac{\partial}{\partial t}(m\rho_1) = -\frac{\partial}{\partial x_1}(\rho_1 v)$$

Making the substitutions

$$m\rho_1 = (m_0 - \varepsilon_2)(1 - \varepsilon_2)^{-1}\rho_0 (1 + \alpha_3 p) \approx \rho_0 m_0 (1 + \alpha_3 p - a\sigma E_2^{-1})$$

$$= \rho_0 m_0 \Big[1 + \alpha_3 p - aE_2^{-1}\Big(q - p + g\int_0^{x_1} [(1 - m)(\rho_2 - \rho_1) + m\rho_1]\, dx_1\Big)\Big]$$

$$-\rho_1 v = K_0 (1 - \alpha_2 q + \varepsilon_3 p - \varepsilon_4 x_1)\left(\frac{1}{g}\frac{\partial p}{\partial x_1} - \rho_1\right)$$

and denoting

$$\tau = K_0 t\, [g m_0 \rho_0 (\alpha_3 + a / E_2)]^{-1}$$

we write the continuity equation in the form

$$\frac{\partial p}{\partial \tau} = \frac{\partial}{\partial x_1}\left\{(1 - \alpha_2 q + \varepsilon_3 p - \varepsilon_4 x_1)\left[\frac{\partial p}{\partial x_1} - g\rho_0 (1 + \alpha_3 p)\right]\right\}$$

After differentiating in the right side we obtain

$$\frac{\partial p}{\partial \tau} = (1 - \alpha_2 q + \varepsilon_3 p - \varepsilon_4 x_1)\frac{\partial^2 p}{\partial x_1^2} - \{g\rho_0 [\varepsilon_3 + \alpha_3 (1 - \alpha_2 q)] + \varepsilon_4\}\frac{\partial p}{\partial x_1} + \varepsilon_3 (\partial p / \partial x_1)^2 + g\rho_0 \varepsilon_4$$

Converting in this equation to dimensionless quantities, we have

$$\frac{\partial p_1}{\partial \tau_1} = (\alpha_4 + \varepsilon_5 p_1 - \varepsilon_6 x)\frac{\partial^2 p_1}{\partial x^2} - \alpha_5 \frac{\partial p_1}{\partial x} + \varepsilon_5 \left(\frac{\partial p_1}{\partial x}\right)^2 + \alpha_6$$

$$p_1 = p / q, \ \tau_1 = \tau / L^2, \quad \alpha_4 = 1 - \alpha_2 q, \ \varepsilon_5 = q\varepsilon_3, \quad \varepsilon_6 = \varepsilon_4 L$$

$$x = x_1 / L, \qquad \alpha_0 = \alpha_3 q, \qquad (g\rho_0)_1 = g\rho_0 L / q \tag{2.5}$$

$$\alpha_5 = (g\rho_0)_1 (\varepsilon_5 + \alpha_0\alpha_4) + \varepsilon_6, \qquad \alpha_6 = (g\rho_0)_1 \varepsilon_6$$

Here L is the length of the rock from which the fluid is expelled. Using the approximate method in theory of one-dimensional unsteady fluid filtration in the elastic regime, presented in [3], we seek the solution of (2.5) in the form

$$p = c_0 + c_1 \frac{x_1}{l(\tau)} + c_2 \frac{x_1^2}{l^2(\tau)} \tag{2.6}$$

The boundary conditions are: fluid pressure at the withdrawal boundary at the moment of initiation of expulsion

$$x_1 = 0,\ p = p_0, \tag{2.7}$$

the pressure outside the disturbance zone

$$x_1 = l,\ p = p^\circ \tag{2.8}$$

The initial condition is

$$\tau = 0,\ l = 0 \tag{2.9}$$

Still another condition must be satisfied until the boundary of the disturbance zone reaches the impermeable wall of the confirmed reservoir:

$$\partial p / \partial x_1 = 0, \quad \text{for} \quad x_1 = l \tag{2.10}$$

Bearing in mind (2.6)-(2.10), we obtain

$$c_0 = p_0,\ c_1 = 2(p^\circ - p_0),\ c_2 = -(p^\circ - p_0)$$

Then (2.6) is written as

$$p = p_0 + 2(p^\circ - p_0)\frac{x_1}{l(\tau)} - (p^\circ - p_0)\frac{x_1^2}{l^2(\tau)} \tag{2.11}$$

We reduce (2.11) to dimensionless quantities

$$p_{11} = p_{01} + 2c\frac{x}{l_1} - c\frac{x^2}{l_1^2}$$

$$p_{11} = p/q,\ p_{01} = p_0/q,\ c = (p^\circ - p_0)/q,\ x = x_1/L,\ l_1 = l/L$$

Integrating (2.5) with respect to x in the limits from 0 to l_1 and using (2.6), we obtain the differential equation

$$d\tau_1 = (al_1^2 + bl_1 + i)^{-1} l_1 dl_1$$

$$a = -3\alpha_6 / c,\quad b = -3(\varepsilon_6 - \alpha_5),\ i = 6(\alpha_4 + \varepsilon_5 p_{01}) \tag{2.12}$$

Integrating with account for $b^2 - 4ai > 0$ and also using (2.9), we obtain

$$\tau_1 = -\frac{1}{2a}\ln\left|\frac{a}{i}l_1^2 + \frac{b}{i}l_1 + 1\right| + \frac{b}{2a\sqrt{b^2 - 4ai}}\ln\left|\frac{2al_1/\varkappa_2 + 1}{2al_1/\varkappa_1 + 1}\right| \tag{2.13}$$

$$\varkappa_1 = b - \sqrt{b^2 - 4ai},\qquad \varkappa_2 = b + \sqrt{b^2 - 4ai}$$

Then the relation $l_1(\tau_1)$ can be obtained graphically.

In the second stage of fluid expulsion from the rock, after the boundary of the disturbance zone contacts the impermeable reservoir wall at the time τ_{10}, we seek the pressure function in the form

$$p_{12} = P_1(\tau_1) + P_2(\tau_1)x + P_3(\tau_1)x^2,\ p_{12} = p/q,\ x = x_1/L$$

Here P_1, P_2, P_3, p_{12}, and x are dimensionless variables; then

$$p_{12}|_{x=0} = p_{01},\quad \left.\frac{\partial p_{12}}{\partial x}\right|_{x=1} = 0 \tag{2.14}$$

From (2.14) we have

$$P_1(\tau_1) = p_{01},\quad P_2(\tau_1) = -2P_3(\tau_1),\quad p_{12} = p_{01} - 2P_3x + P_3x^2 \tag{2.15}$$

Integrating (2.5) with respect to x from 0 to $L_1 = 1$ and using (2.15), we obtain

$$dP_3 / d\tau_1 = a_1P_3 + a_0$$

$$a_1 = 1.5(\varepsilon_6 - \alpha_5 - 2\alpha_4 - 2\varepsilon_5 p_{10})\ (a_1 < 0),\quad a_0 = -1.5\alpha_6\quad (a_0 < 0) \tag{2.16}$$

Solving (2.16), we obtain

$$P_3 = (G_1a_1)^{-1}\exp(a_1\tau_1) - a_0/a_1$$

where G_1 is the constant of integration, found from the condition of continuous transition of the pressure p_{11} into p_{12} at the time τ_{10} for x = 1.

From the condition $p_{11}(\tau_{10}) = p_{12}(\tau_{10})$ at the point x = 1 with account for $l_1(\tau_{10}) = 1$ we have

$$P_3(\tau_{10}) = -c, \quad G_1^{-1} = (a_0 - a_1 c) \exp(-a_1 \tau_{10});$$

therefore

$$P_3(\tau_1) = (a_0/a_1 - c) \exp[a_1(\tau_1 - \tau_{10})] - a_0/a_1$$

Thus, the pressure function in the second stage

$$p_{12} = p_{01} - 2[(a_0/a_1 - c)\exp[a_1(\tau_1 - \tau_{10})] - a_0/a_1]x + [(a_0/a_1 - c)\exp[a_1(\tau_1 - \tau_{10}) - a_0/a_1]x^2 \quad (2.17)$$

We assume that elastic fluid expulsion from the rock follows the Darcy law

$$Q = \frac{k(\sigma)}{\mu(p)} F(\sigma) \left(\frac{\partial p}{\partial x_1}\right)_{x_1=0} \quad (2.18)$$

Here Q = discharge; F = reservoir section area; σ = effective rock pressure.

We write (2.18) in dimensionless quantities

$$Q_1 = k_1 \mu_1^{-1} F_1 \left(\frac{\partial p_1}{\partial x}\right)_{x=0} \quad (2.19)$$

$$Q_1 = \mu_0 LQ/(k_0 F_0 q), \quad k_1 = k(\sigma)/k_0, \quad \mu_1 = \mu(p)/\mu_0, \quad F_1 = F(\sigma)/F_0,$$

The quantities k_0, μ_0, F_0 are measured under atmospheric conditions.

Using (1.3) and (1.5), we express F_1 through σ,

$$F_1 = 1 - \sigma/E_2 \quad (2.20)$$

The fluid volume v_{11} leaving the reservoir through the section x = 0 during the first expulsion stage with account for (2.2), (2.3), (2.20), and p_{11} is expressed by the integral

$$v_{11} = \int_0^{\tau_{10}} Q_1 d\tau_1 = 2c(1 - \beta_1\sigma_1)(1 - \sigma_1)(1 + \alpha_{11})^{-1} \int_0^{\tau_{10}} l_1^{-1}(\tau_1)\, d\tau_1$$

$$\beta_1 = (3 - m_0)/m_0, \quad \sigma_1 = \sigma/E_2, \quad \alpha_{11} = \alpha_1 p_0$$

Let us find the second expulsion stage termination time τ_1^* from the condition $p_{12} - p_{01} \to a_0/a_1$ for x = 1; then $\tau_1^* \to \infty$.

The fluid volume v_{12} leaving the reservoir during the second stage with account for (2.2), (2.3), (2.20), (2.17) is

$$v_{12} = \int_{\tau_{10}}^{\infty} Q_1 d\tau_1 = -2(1 - \beta_1\sigma_1)(1 - \sigma_1)(1 + \alpha_{11})^{-1} \int_{\tau_{10}}^{\infty} P_3(\tau_1)\, d\tau_1$$

The total fluid volume v expelled from the reservoir in the elastic regime is

$$v = v_{11} + v_{12}$$

Specifically, let us calculate the amount of water expelled from a rock specimen of length L = 5 cm, diameter 3 cm (depth of specimen withdrawal H = 2174 m) for the following values of the parameters

$$p_0 = 220 \text{ at}, \; \alpha_3 = 5\cdot10^{-5} \text{ at}^{-1}, \; \alpha_2 = 2.8\cdot10^{-4} \text{ at}^{-1}$$
$$\alpha_1 = 10\cdot10^{-5} \text{ at}^{-1}, \; \rho_2 = 2.3 \text{ g/cm}^3, \; \rho_0 = 1 \text{ g/cm}^3$$
$$E_2^{-1} = 2\cdot10^{-5} \text{ at}^{-1}, \; m_0 = 0{,}2, \; g = 9.8 \text{ m/sec}^2, \; q = 500 \text{ at}$$
$$\varepsilon_5 = 0.0983, \; \varepsilon_6 = 0.153\cdot10^{-5}, \; \alpha_4 = 0.8767, \; \alpha_5 = 0.2732\cdot10^{-5}, \; \alpha_6 = 0.153\cdot10^{-10},$$
$$a_0 = 0.025, \; (g\rho_0) = 10^{-5}$$
$$p_{01} = 0.44, \; k_0 = 100 \text{ mDarcies}, \; \mu_0 = 0.3 \text{ cp}$$

The fluid pressure $p°$ developed in the specimen as a result of applying the instantaneous load q is calculated using (1.7)

$$p° = 307 \text{ at}$$

The time required to create the load q is negligibly small in comparison with the duration of the process of water expulsion from the specimen.

In (2.12) we evaluate the denominator

$$a = -2.638 \cdot 10^{-10}, \ b = 0.3606 \cdot 10^{-5}, \ i = 5.52, \ |al_1^2 + bl_1| \ll i$$

Therefore we have from (2.12)

$$id\tau_1 = l_1 dl_1, \quad \text{or} \quad l_1 = \sqrt{2i\tau_1}$$

Here the initial condition has been taken into account.

The pressure function of the fluid in the specimen in the first stage has the form

$$p_{11} = 0.44 + 0.105 \ x\tau_1^{-1/2} - 0.016 \ x^2\tau_1^{-1}$$

$$\tau_{10} = 0.09, \ \beta_1 = 14, \ \sigma = 313 \ \text{at}, \ \sigma_1 = 62.6 \cdot 10^{-4}, \ \alpha_{11} = 22 \cdot 10^{-3}, \ v_{11} = 0.014$$

Converting to dimensional quantities, we find

$$v_1 = 3 \cdot 10^{-4} \ \text{cm}^3$$

We find the volume v_{12}

$$a_0 = -1.5 \cdot 0.153 \cdot 10^{-10} \sim 0, \quad a_1 = -2.76, \quad c = 0.174, \quad v_{12} = 0.112$$

Converting to dimensional variables we find

$$v_2 \approx 0.066 \ \text{cm}^3 \qquad v = v_1 + v_2 \approx 0.0663 \ \text{cm}^3$$

An experimental setup [4] was used to test a rock specimen (taken in the Sobolin field from well 172-R from a depth of 2172-2176 m with specific weight 2.3 g/cm^3, open porosity 0.2, aleurolite) with the properties indicated above under conditions similar to those used in the calculation. The volume of water expelled from the specimen was equal to 0.08 cm^3, i.e., somewhat greater than the calculated value, which is explained by inelastic deformations in the specimen in the course of the experiment.

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