P-waves behavior at transition from liquid to gas-saturated porous media

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Summary The comparing of *P*-wave behavior for water and gas - saturated porous media is made. It is shown that in gas-saturated media the 2nd wave has low attenuation. Moreover, in this case at low frequencies the wave characteristics radically differ from ones for water - saturated media. It is obtained that *P*-waves transformation happens if gas pressure exceeds some threshold value, the expression for this value is given.

According to the Frenkel - Biot theory, two *P*-waves can propagate in saturated porous medium [1]. The 1st wave is faster wave and has small attenuation. The 2nd wave is slower, extremely damped wave. But, for gas-saturated media the situation can be changed. As Nikolaevskiy had shown [2], the 2nd wave is determined mainly by rock matrix deformation. For liquid-saturated media, porous matrix can be deformed only if saturating fluid can flow through a pore system, leaving a room for volume repacking. The Darcy resistance creates so high attenuation that this wave can spread at extremely short distances. However, a saturating gas has high compressibility and therefore the matrix volume deformation becomes possible without flow along the pore system. Correspondingly, such 2nd wave can have small attenuation.

The total system of equations of the porous media dynamics in linear approximation looks as [2]:

$$\beta_\Sigma \frac{\partial p}{\partial t} - \beta_1 \frac{\partial \sigma^{eff}}{\partial t} + (1-m_0)\frac{\partial v_1}{\partial x} + m_0 \frac{\partial v_2}{\partial x} = 0 \tag{1}$$

$$(1-m_0)\rho_{10}\frac{\partial v_1}{\partial t} + (1-m_0)\frac{\partial}{\partial x}p = \frac{\partial}{\partial x}\sigma_{eff} + \frac{m_0^{\,2}\mu_2}{k}(v_2 - v_1) \tag{2}$$

$$m_0\rho_{20}\frac{\partial v_2}{\partial t} + m_0\frac{\partial}{\partial x}p = -\frac{m_0^{\,2}\mu}{k}(v_2 - v_1) \tag{3}$$

$$\sigma_{eff} = K_p e_1 + \varepsilon p \tag{4}$$

here v_i is phase velocity (1 – solid, 2 – saturating fluid); σ_{eff} - effective stress; p - fluid pressure; $K_p = K_b + (4/3)G$, K_b is bulk modulus of a porous skeleton and β_1 is compressibility of its material, G is shear modulus of a skeleton; β_2 is liquid compressibility; m_0 is porosity; μ is viscosity and k is permeability; $\beta = (1-m_0)\cdot\beta_1 + m_0\cdot\beta_2$; $\varepsilon = K_b\beta_1$.

The following parameter values are chosen: $k = 1.8\cdot10^{-11}\ m^2$, $\beta_1 = 2\cdot10^{-10}\ Pa^{-1}$, $K_p = 10^8\ Pa$, $m_0 = 0.25$; and gas parameters $\mu = 2\cdot10^{-5}\ Pa\cdot sec$, $\rho_{20} = 1000\ kg/m^3$, $\beta_2 = 2.4\cdot10^{-6}\ Pa^{-1}$. Let us note that these parameters correspond to "weak" rocks ($\varepsilon << 1$).

The numerical calculations of *P*-wave characteristics on the base of system (1) – (4) confirmed that really in gas-saturated media the 2nd wave has low attenuation, but 1st wave becomes extremely damped. Moreover, for gas-saturated media the wave characteristics depend essentially on frequency (in the contrast to a water - saturated medium). It is important that for gas-saturated media at low frequencies the wave dispersion radically differs from ones for liquid-saturated media. But, at high frequencies the wave behavior does not change. The 2nd wave is "slow" and shows out-of-phase behavior of gas-solid motions only at high frequencies and it becomes "fast" wave and shows in-phase behavior at low frequencies.

On the contrary, gas-bubbles effects on high frequency waves above bubble resonance. It was shown recently by Dunin, Mikhailov and Nikolaevskiy [3].

It is important to note that mentioned effect appears only for "weak" matrix ($\varepsilon << 1$). Calculations made for "cemented" formations, show that wave behavior did not change essentially.

It is also shown that *P*-wave behavior transformation happens only if compressibility of a saturated fluid exceeds some critical value. The expression for this value is obtained:

$$\beta_{2cr}^{-1} = \frac{1-m_0}{m_0}\left\{\frac{\rho_*}{\rho_0}K_p^{-1} - \beta_1\right\} \tag{5}$$

Taking into account that gas compressibility and its density depend on the pressure, and considering the gas behavior as adiabatic, we can find from (5) that at our parameter values, the critical pressure value is approximately $6\cdot10^6\ Pa$. The transformation of wave behavior at variation of the pressure is shown at the **fig. 1**.

The compressibility of saturating fluid also depends on gas fraction. So, for studying of the gas saturation effects on transformation of *P*-waves behavior the generalized system of equations was used. This system takes into account both liquid-solid and gas-solid relative motions (see, for example [2,4,5]). New system consist of mass and momentum balance equations for solid, liquid and gas plus the constitutive laws. The terms, describing the viscous interaction between liquid phase and solid phase (R_2) and gas phase and solid phase (R_3), are introduced according to the generalized Darcy law [2]:

$$R_2 = -\frac{m^2(1-s_0)^2\mu_2}{kf_2(s_0)}(v_2 - v_1); \quad R_3 = -\frac{m^2 s_0^2 \mu_3}{kf_3(s_0)}(v_3 - v_1) \tag{6}$$

here s_0 is gas fraction and $f_i(s_0)$ is phase relative permeability (2 – liquid; 3 - gas).
The numerical calculations of P-wave characteristics on the base of the generalized model have shown that the radical changing of wave behavior takes place at high gas fraction $s_0 \sim 90 - 98$ %.
It is also obtained that the phase velocity of the 1st Biot wave sharply decreases as gas fraction changes from zero to 5 – 8% (velocity decreases essentially even at small gas fraction value (~0.01%)).

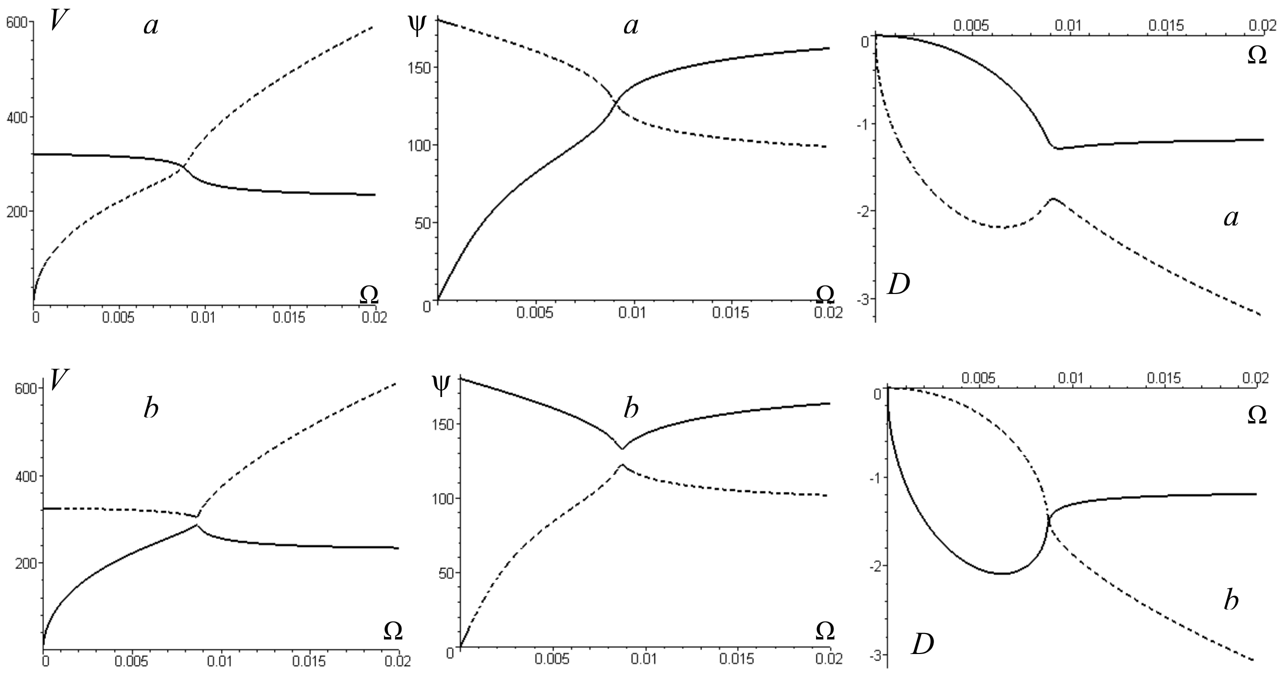

Fig. 1. Change of frequency - depended wave behavior at variation the pressure from $5{\cdot}10^6$ *Pa* (*a*) to $6{\cdot}10^6$ *Pa* (*b*). The firm line corresponds to 2nd wave and dash line corresponds to 1st wave.
Here V is wave velocity; D is attenuation coefficient; Ψ is "phase shift" between solid and gas relative motions; $\Omega = \omega/\omega_c$ is reduced frequency, ω_c is critical Biot frequency.

References

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