Полученные результаты использованы авторами при разработке новых технических средств и технологий повышения продуктивности скважин и увеличения нефтеотдачи пластов с применением воздействия низкочастотными упругими колебаниями; создании системы мониторинга волновых технологических процессов в режиме обратной связи с обрабатываемой геологической средой; обосновании и оптимизации технологий СЛБО и СЛОЭ.

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THE ROLE OF NATURAL GASES IN SEISMICS OF HYDROCARBON RESERVOIRS

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Published data of passive seismic, vibration impact on residual oil production as well as selected frequency effect in oil exploration reveal the important role of resonances. If the wave length is much larger than the heterogeneity scale, the resonance appears to be internal one and it has to be accounted for in kinetic part of the dynamics equations. The model is developed to find a general form of dispersion curve, corresponding to the medium resonance at so-called dominant frequencies. The resonance is understood here as a negative dissipation limited by nonlinear generation of higher frequency oscillations. It includes the flux of energy from the Goldstone mode of extremely long waves with neutral stability towards dominant wave spectrum of flickering frequencies. The variants of small ganglia oscillations with surface tension as a restoring force and of gas/oil bubbles under high pressure are compared.

Types of the Biot – Frenkel waves, running through fluid – saturated rocks, possess different mechanisms of deformation. The 1st wave $\mathbf{P_1}$ is characterized by alternating cross of heterogeneous inclusions practically in undrained conditions. The latter means higher confining of strains leading to mineral grains damage. The 2nd wave **P_2 ,** as well as **S** (shear) wave, corresponds to the deformation as in dry matrix. So, from the point of view of the theory of elasticity the 1st Biot wave is anomalous but not the 2nd one. Usually another criterion is accepted: **P_1** is **fast** with small dissipation, but **P_2** is **slow** with high dissipation because deformation has to drain viscous fluid from a pore to neighboring ones.

The growth of rigidity of bounds between matrix grains, that is, of the ratio $\varepsilon = \beta K$ (β - grain compressibility, K – volume module of matrix) violates these features but in sedimentary basins is sufficiently small [1].

If rock is fully saturated with fluid, seismically observed is the **P_1** wave. Real (live) oil is gassy and its influence on seismics at a depth is very high [2]. Even small amounts (~ 5%) of gas release may change the wave type and make **P_2** visible. The practical consequence of discrimination of P-wave types is the following. It is known that the ratio of P and S wave velocity is determined by the Poisson ratio Pr ($0.25 < Pr < 0.5$):

$$\alpha = Vp / Vs = \sqrt{((K + 4G/3)/G)} = \sqrt{(2 - 2Pr)/(1 - 2Pr)} \quad (1)$$

Here G is the shear modulus.

If *vice versa*, one determines ***Pr*** by measuring the wave velocities, the proper answer will be obtained if P_2 and S waves are considered as relevant to the matrix properties. Use of P_1 wave data will give the "dynamic" value $\boldsymbol{Pr_d}$ (~ 0.4) which is higher than ***Pr*** data under drainage (~ 0.28)

$$Pr_d = \frac{1}{2}\frac{2-\alpha^2}{1-\alpha^2} = \frac{1}{2}\frac{2V_s^2-V_p^2}{V_s^2-V_p^2} \quad (2)$$

However, happens to be useful to find gas reservoir by anomalous low value $\boldsymbol{Pr_d} \sim 0.1$ [3]. It corresponds to $\alpha = 1.5$. This number is typical for fracturing of rocks in the vicinity of moving faults (invasion of water increases α to 2.38). The gas pressure growth is decreasing $\boldsymbol{Pr_d}$, for example, to 0.04. This "anti-dilatants" effect is an evident sign of gas blockade inside matrix pores during wave motions. Actually, these results were obtained by AVO-methods (Amplitude Variation with Offset analysis). The AVO method had shown [4] that some of the frequencies are preferable, specifically, *10 Hz* and *12 Hz* - in two other cases. The latter natural selection has a resonance feature also.

2. Hydrocarbon reservoirs are discriminated in water basins by the presence of gases in a free state or dissolved in "live" (gassy) oil. This is the most important feature for any seismic works in the field. Moreover, under the action of ultrasound, which is always present in seismic spectrum due to solid friction, these gases are released and create microbubbles cloud. Their concentration on oil – water contacts increases oil ganglia mobility in water fluxes and, consequently, Water-Oil Ratio (WOR) in production wells is decreasing [1]. **Fig. 1** shows that there are two resonances. The first is typical for passive seismics (2-4 Hz) and the second - at 12 Hz when the gas release in reservoir and WOR effects are much more essential than at all other frequencies. So, these resonances were mentioned in 1988 [5]. Dangel et al [6] found that such a passive resonance is common for hydrocarbon reservoirs.

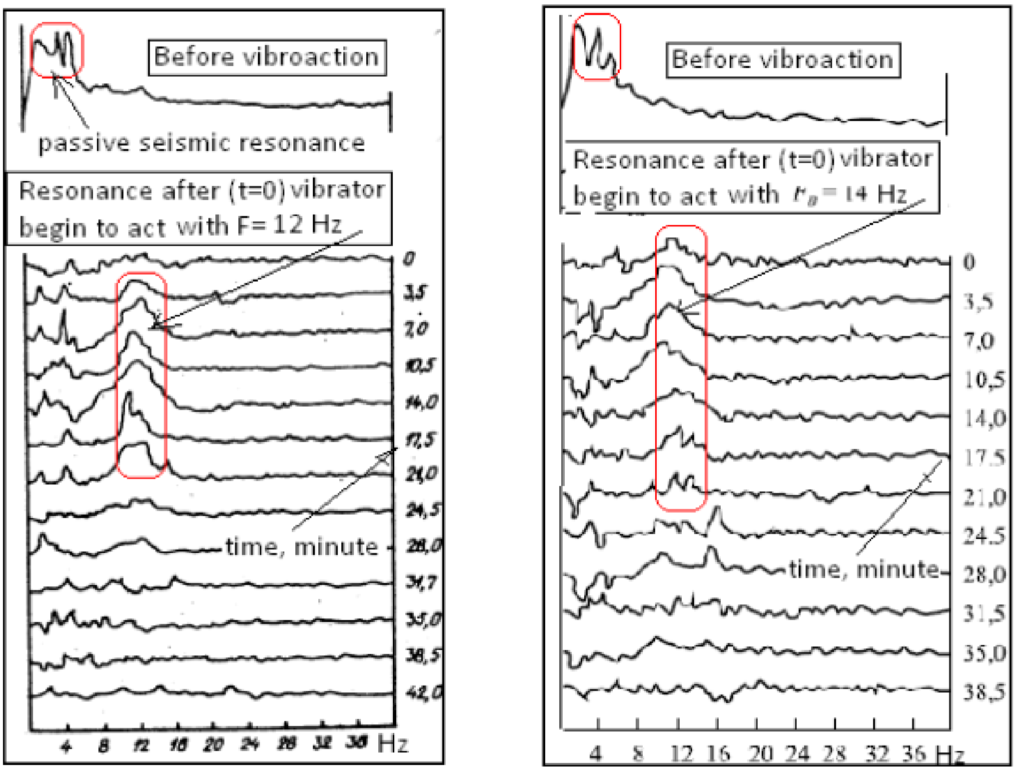

Fig. 1. Initial spectra difference in oil well at 750 m and at oil reservoir (North Caucasus) and in water basin shows passive seismic signal. Vibrations for 20 min at 12 (and 14) Hz reveal resonance at 10 -12 Hz.

The passive seismic signal is explained in literature by resonance oscillations of oil ganglia of radius ***R*** limited by surface tension γ at its contact with gas. This corresponds to NAPL contaminations (dead oil drops are surrounded by air) in surface soils. The control factor has the order of $20\ Pa = \gamma / \boldsymbol{R}\ (0.02 / 10^{-3}\ N/m^2)$ [7].

Deep hydrocarbons are under action of hydrostatic pressure $p_0 \sim 10^7\ Pa$ at depth of *1 km* and this number shows definitely that the surface tension is negligible for oscillations in gassy oil.

In linear form the oscillations of the gas object surrounded by fluid or solid isolating shell of density $\rho \sim 900\ kg/m^3$ are described [8] by the equation $R_{tt} + \omega_0^2 R + \xi R_t = \varpi$, where $\omega_0^2 = (3\chi p_0 / \rho R_0)$, $\xi = (4/R_0^2 + m_0/k)\nu$, $R = \varphi e$, χ - adiabatic power, *k* – permeability, *e* – deformation, φ - porosity with correction for saturation, ν - kinematic fluid viscosity and ϖ - driving force. Considering ω_o, see that the length scale of oscillating species in a rock massive is ~ *10 m*, that is, the whole layer with the compressed gas bubbles is our object.

Adding of the oscillator equation to the continuum system is nontrivial. In our case the wave length is so long that all oscillating motions are internal. So, its proper place is between the kinetic completing set [9]. The total stress $\sigma = \sigma^f + p + \varpi$ includes the Terzaghi stress σ^f, besides *p* in oil and ϖ - force, acting on gas bubbles. In paper [10] it is shown how to combine the rheology with the Biot – Frenkel equations.

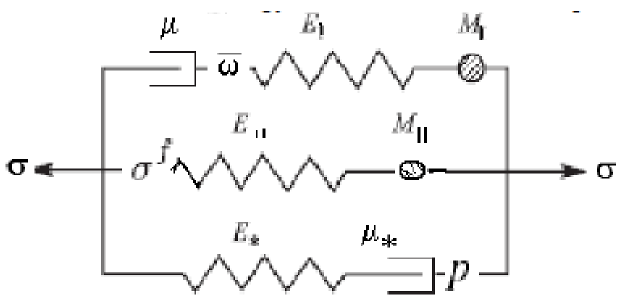

Fig. 2. Stress distributions in oil/gas element of elastic porous media

Figure 2 corresponds to the following rheology law (σ - total stress; $de = de^e + de^p$ - total strain):

$$\sigma + \sum_q^n a_q \frac{D^q \sigma}{d\tau^q} = Ee + \sum_q^m a_q \frac{D^q e}{d\tau^q} \qquad (3)$$

Here ($n = 3$, $m = 6$). In the running coordinates the resulting evolution for particle velocity v is valid for both types of the Biot waves [10]:

$$\frac{\partial v}{\partial t} + Nv\frac{\partial v}{\partial \xi} + \zeta v = \sum_{q=1}^n A_{q+1} \frac{\partial^{q+1}}{\partial \xi^{q+1}} v \qquad (4)$$

This is generalization (of the sixth order!) of the equation BKDV where A_{2q} are positive, as well as N - factor of nonlinearity, $A_{2q=1}$ - negative. The dispersion curve for rolls $v = v_0 \exp(\lambda t + ikx)$ is the following one and shown in **Fig. 3**.

$$\lambda = -\zeta - i|A_3|k^3 + i|A_5|k^5 + k^2(|A_2| + |A_4|k^2 - |A_6|k^4)$$

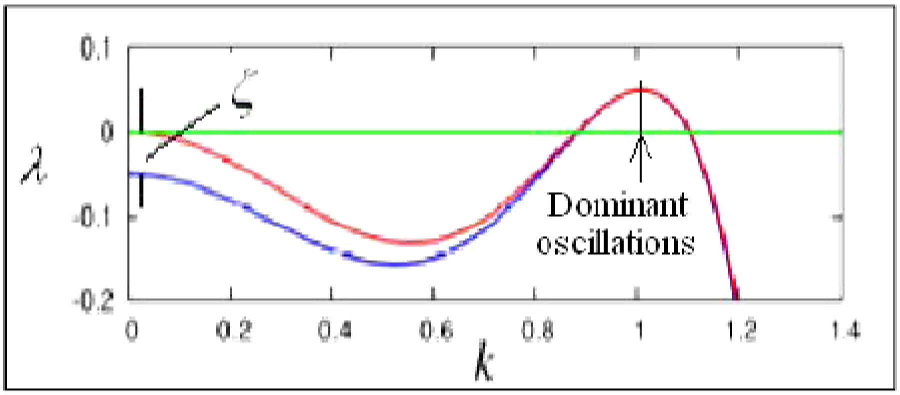

Fig. 3. Dispersion curve is moved down if the Darcy term is included.

The interval between the two roots of k corresponds to negative dissipation, that is, to the resonance frequencies. The resonance amplitude growth is limited by nonlinear generation of higher frequency oscillations. This interval may correspond to a reservoir dominant frequency $\omega \sim (10 - 12)$ *Hz* or the passive seismic case $\omega \sim (2 - 6)$ *Hz*. This depends on the values of the coefficients because $k_2 \sim (1/2)(A_4/A_6)$ and corresponds to the interval center:

$$A_2 = \frac{E_{\rm I}\theta + E_*\theta_*}{\rho_0}, \qquad A_3 = -c\left(\frac{E_{\rm I} + E_*}{\rho_0}\theta\theta_* + \varkappa_{\rm II}^2\right), \qquad A_4 = c^2\left[\varkappa_{\rm I}^2 \frac{E_*\theta_* + E_{\rm I}\theta}{E_{\rm I}} + \varkappa_{\rm II}^2(\theta + \theta_*)\right],$$

$$A_5 = -c\varkappa_{\rm I}^2(c^2\theta\theta_* + \varkappa_{\rm II}^2), \qquad c^2 = \frac{E_{\rm II}}{\rho_0}, \qquad A_6 = c^2\theta_*\varkappa_{\rm I}^2\varkappa_{\rm II}^2\frac{E_{\rm II}}{E_{\rm I}}.$$

For the branches, shown in Figure 2, the following expressions are suggested:

$E_I = 3\chi p_0$; $M_I = \rho_g \kappa_I^2$; $\kappa_I = R_0$; $\mu = \rho_g \nu$; $\sigma^f = E_{II} e + M_{II}\, \partial^2 e/\partial t^2$; $M_{II} = \rho_s \kappa_{II}^2$

$p + \theta_* \partial p/\partial t = \eta_* \partial e/\partial t$, $\eta_* = (\mu_* m d^2/k)$, $\theta_* = (\mu_* m \beta_{oil} d^2/k)$, $E_* = 1/\beta_{oil}$, $\mu_* = \mu_{oil}$

Then $\kappa_I \sim k \sim 10^2 - 10^3$ *m* (branch ϖ) and gas inclusions, collectively responding to wave disturbances, have a scale (branch p) ~ *10* m.

If $\zeta = A_3 = A_5 = 0$, the oscillation at $\omega \to 0$ has neutral stability. It is shown that due to the interaction with this mode (known as Goldstone) of zero frequency the running waves may be unstable. This results in wave spectra flickering around the dominant frequency. Moreover, as it was found [11], the oscillations with negative dissipations are excited by the Gladstone mode (for example, by ocean tides). This is illustrated by **Fig. 4**.

Growth of the Darcy bulk term ($\zeta \neq 0$) introduces the effect of stability threshold, That means transformation of equation (4) into the Ginzburg – Landau one [12,13]. The saving non-zero odd terms in the analyses is showing [14, 15] that dispersion A_3; $A_5 \neq 0$ may stabilize waves.

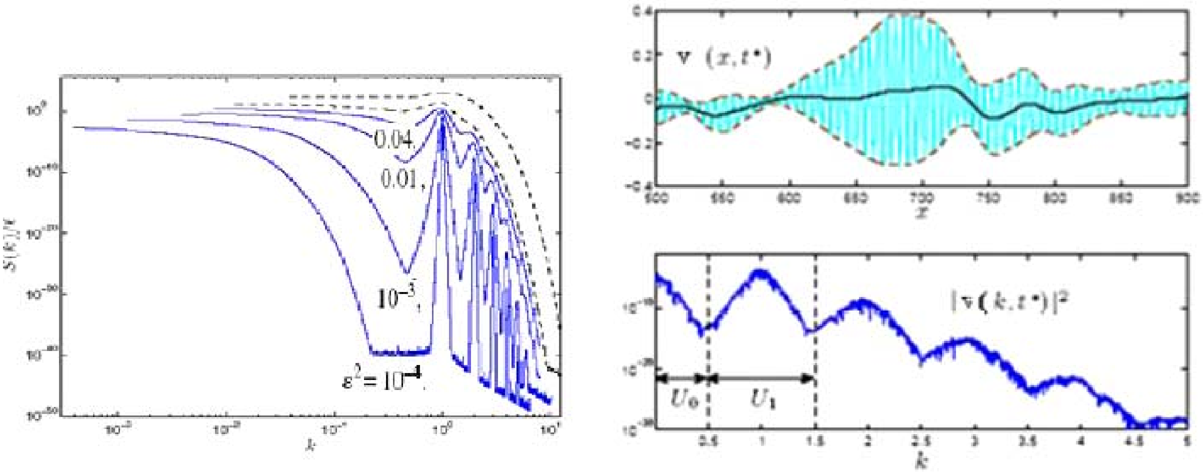

Fig.4. Oscillations v *(x,t)* and Fourier spectra *S(k)* at interaction of resonance ($k \sim 1$, $U_1 \pm 2 |U_0|$ - black dashed curves) by long waves U_0 ($k \sim 0$, black). Numerical results [10] and ε^2 – scaled width of resonance interval

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