Slow Wave Phenomenon at Seismic Frequencies

SL4.6

G.M. Goloshubin, Tymengeologia, Russia and Norsk Hydro, Norway;*
P.V. Krauklis and L.A. Molotkov, Academy of Sciences Math. Inst., Russia;
and H.B. Helle, Norsk Hydro, Norway

SUMMARY

The observation of slow wave phenomena within an oil-saturated layer at seismic frequencies is the main subject of our discussion. The theory of wave propagation cannot explain this phenomenon well enough. We develop a theory for a model of an oil-saturated layer which includes a two-phase medium consisting of a solid body with fluid-filled cracks. Solution within the framework of this model shows the possibility of slow wave formation with high amplitudes at low seismic frequencies. Results of the theoretical research correspond to the data of the cross-hole seismic experiment.

INTRODUCTION

Biot's theory (1956) predicts that wave propagation in a saturated porous medium involves three types of waves: two compressional waves and one shear wave. The two compressional waves are known as the fast P wave and the slow P wave. The slow P wave is the consequence of the fluid-solid coupling. Plona (1980) observed a compressional slow wave in a porous medium at ultrasonic frequencies. According to Biot's theory this wave attenuates very quickly and the attenuation is higher for low frequencies than for high frequencies. Thus, Biot's theory predicts that the low frequency slow waves cannot be observed at some distance from their origin. We discuss the possibility of slow wave observation in an oil-saturated layer at seismic frequencies using experimental data and the theoretical solution.

EXPERIMENTAL DATA

In West Siberia the wave fields in a cross-hole seismic experiment, with a well separation of 300 m, were carefully investigated. The source and receivers were located outside and within a 18 m thick oil-saturated sand layer at 2500 m depth. The main result of the investigations of the wave fields is the following: both the fast P wave and the slow wave were observed at seismic frequencies (Fig. 1). The ordinary fast P wave of high frequency (f≈100 Hz) and velocity of V≈3000 m/s was observed both inside the oil-saturated layer and outside. The slow wave is observed only inside the oil-saturated layer (Fig.1,b). This wave has very low frequency (f ≈10 Hz), very low velocity (V≈300 m/s) and high amplitude. We associate the slow wave with fluid-saturation.

THEORETICAL RESEARCH

As starting point we use a simple model of an oil-saturated layer. This consists of a liquid layer sandwiched between solid half-spaces. Corresponding analytical (Krauklis, 1962; Krauklis at al., 1992) and numerical solutions show the possibility of slow wave formation with high amplitudes. This wave dominates inside the layer and it attenuates very quickly outside it. The result of analytical and numerical solutions corresponds to the result of Chouet (1986) and Ferrazzini and Aki (1987) which they used for the interpretation of volcanic tremors. However the model of a liquid layer is too simple for the description of oil-saturated rock and only shows the principle of slow wave propagation with high amplitude at seismic frequencies. It cannot explain very low velocity of the slow wave in a finite thickness layer. We develop a theory for a model of an oil-saturated layer which includes a two-phase medium consisting of a solid body with fluid-filled cracks. We use the matrix method (Molotkov, 1984) and the principle of an equivalent model. The resulting solution describes wave propagation in an elastic-liquid cracked medium. The solution shows three P waves propagating along the cracks. The velocities of these waves are V_1, V_2, V_3:

$$V_{1,3}^2 = \frac{\tilde{\rho}_s + (ac+b^2)\tilde{\rho}_l \pm \sqrt{\left[\tilde{\rho}_s + (ac+b^2)\tilde{\rho}_l\right]^2 - 4ac\tilde{\rho}_s\tilde{\rho}_l}}{2c\tilde{\rho}_s\tilde{\rho}_l};$$

$$V_2^2 = a/\rho_s;$$

$$\tilde{\rho}_s = \rho_s(1-\phi);\quad \tilde{\rho}_l = \rho_l/\phi$$

where ρ_s is the density of the solid part of the medium; ρ_l is the density of the liquid part of the medium. Also

$$a = \frac{4\mu(\lambda+\mu)(1-\phi)}{\lambda+2\mu};\; b = \frac{\phi.(1-\phi)}{\lambda+2\mu};\; \ddagger = \frac{\;}{\lambda_l}\;\; \frac{1-\phi}{\lambda+2\mu}$$

where λ is the. Lame's constant of a solid part; λ_1 is the Lame's constant of a liquid part; μ is the shear modulus; ϕ is the porosity. Velocities V_1 and V_2 correspond to the quasi-compressional and plate-compressional waves accordingly. Velocity V_3 coresponds to the slow wave. If the porosity is very small (ϕ < 0.1) the velocity of the slow wave may be expressed as

$$V_3 = 2V_s\sqrt{\phi(1-V_s^2/V_p^2)\rho_l/\rho_s}$$

where $V_s = \sqrt{\mu/\rho_s}$, $V_p = \sqrt{(\lambda+2\mu)/\rho_s}$.

We examine the solution for the case of a fluid-filled cracked layer sandwiched between two solid half-spaces. The dispersion equation for oscillations in this case is the same as in the case of the liquid layer (Krauklis et al., 1992) but the term a which defines the distribution of the slow wave energy inside fluid-filled cracked layers is quite different. In our case it is

$$\bar{\alpha} = i\sqrt{\frac{(V_{ph}^2-V_1^2)(V_{ph}^2-V_3^2)}{V_{ph}^2-V_2^2}c\left[\rho_l\phi+\rho_s(1-\phi)\right]}$$

where V_{ph} is the phase velocity of the slow wave. We can calculate V_{ph} from equation:

$$\tan\frac{kh\bar{\alpha}}{2} = \frac{\left[\rho_l\phi+\rho_s(1-\phi)\right]\sqrt{1-V_{ph}^2/V_{p0}^2}\,(V_{ph}/V_{s0})^4}{\left[\left(2-\frac{V_{ph}^2}{V_{s0}^2}\right)^2-4\sqrt{\left(1-\frac{V_{ph}^2}{V_{p0}^2}\right)\left(1-\frac{V_{ph}^2}{V_{s0}^2}\right)}\right]\bar{\alpha}\rho_0},$$

where k is the wavenumber; h is the thickness of the layer. Parameters of the medium outside fluid-filled layer are density ρ_0 , shear wave velocity V_{s0} , compressional wave velocity V_{p0}.

The phase velocity of the slow wave depends strongly on wavenumber and layer thickness and porosity (Fig.2). The vertical component of the slow wave amplitude is concentrated near the boundaries of the layer (Fig.3,a). The horizontal component of the slow wave amplitude is distributed inside the oil-filled layer (Fig.3.b). The amplitude of the wave decreases if the wavenumber and/or thickness of the oil-filled layer increases (Fig.4). Results of the theoretical research correspond to the data of the laboratory experiments which confirm the possibility of high amplitude slow wave formation (Fig.5).

CONCLUSIONS

Slow waves were observed inside an oil-saturated layer at seismic frequencies. This wave had very low frequency (10 Hz), very low velocity (300 m/s) and high amplitude. Known theories of the wave propagation in a two-phase medium cannot explain this phenomenon. We have developed a theory for the wave propagation in an elastic cracked solid which contains a fluid. The solution for the case of a fluid-filled cracked layer sandwiched between two solid half-spaces shows the possibility of slow wave formation with high amplitude and low velocity at low frequences.

ACKNOWLEDGMENTS

We thank INFING of ZapSibNIIGeofizika and Geophysics Department of Norsk Hydro Research Centre for support in the investigation of slow wave phenomenon.

REFERENCES

Biot, M. A., 1956, Theory of propagation of elastic waves in a fluid-saturated porous solid. 1. Low-frequency range: J. Acoust. Soc. Amer., 28(2), 168-178.

Chouet, B., 1986, Dynamics of a fluid-driven crack in three dimensions by the finite-difference method: J. Geophys. Res., 91(B14), 13967-13992.

Ferrazzini, V., and Aki, K., 1987, Slow wave trapped in a fluid-filled infinite crack: Implication for volcanic tremor: J. Geophys. Res., 92(B9), 9215-9223.

Krauklis, P. V., 1962, About some low frequency oscillations of a liquid layer in elastic medium: PMM, V01.26, N6, 1111-1115 (in Russian).

Krauklis, P. V., Goloshubin, G. M., and Krauklis, L. A., 1992, Slow wave in a fluid-filled layer which imitates an oil collector: Transactions of LOMI Scientific seminars, 22, l0l-112 (in Russian).

Molotkov, L. A., 1984, Matrix method in theory of wave propagation in elastic and liquid layered media, Nauka (in Russian).

Plona, T. J., 1980, Observation of a second bulk compressional wave in a porous medium at ultrasonic frequencies. Appl. Phys. Let., 36, 259-261.

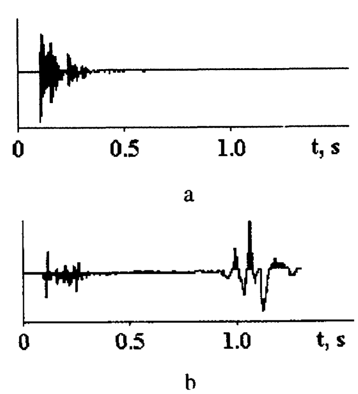

Fig. 1 Seismic response outside (a) and inside (b) oil-saturated layer.

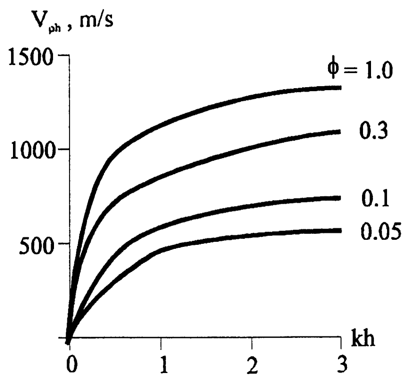

Fig.2 The phase velocity of slow wave vs. porosity (ϕ), wavenumber (k) and thickness of layer (h).

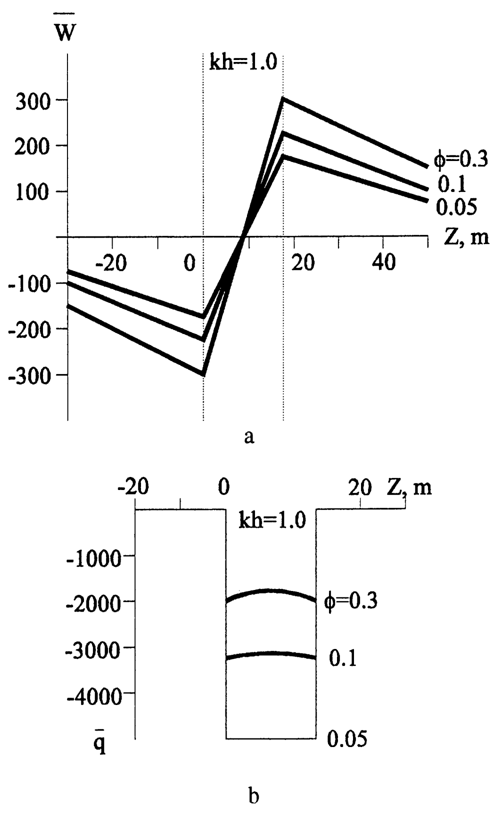

Fig.3 Distribution of the vertical (a) and horizontal (b) components of slow wave amplitude in the liquid-filled cracked layer: ϕ is porosity.

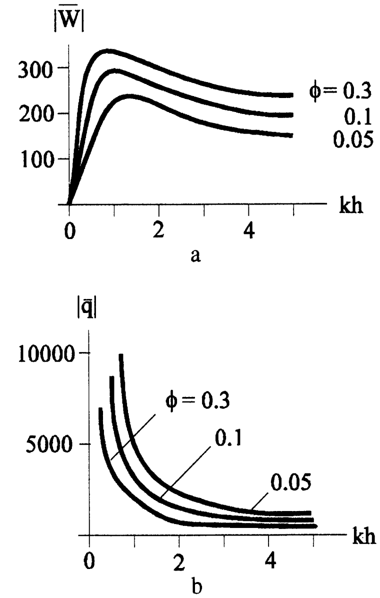

Fig.4 The vertical (a) and the horizontal (b) components of slow wave amplitude vs. porosity (ϕ), wavenumber (k) and thickness of layer (h).

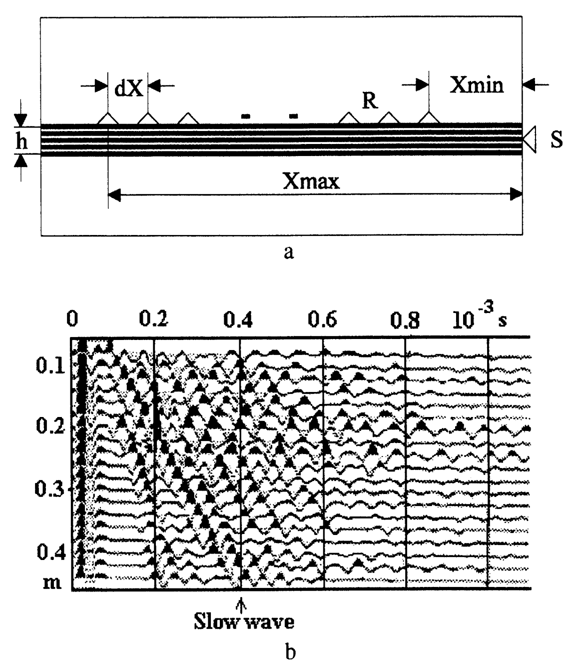

Fig.5 Model (a) and data of the laboratory experiments (b): Xmin is the distance between source (S) and the first receiver (Xmin=0.08 m); Xmax is the distance between S and the last receiver (Xmax=0.44 m); dX is the distance between receivers R (dX=0.02 m); h is thickness of the layer (h=0.005 m).