Bifurcation of the P2 wave and its influence on fluid-induced micro earthquakes in porous rocks: long wave asymptotics of the Biot model

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The focus of this work is on the investigation of the bifurcation behavior of the Biot slow (P2) wave and its influence on the pore pressure distribution in a fluid-saturated rock. It is a well-known fact that an injection of the borehole fluids into surrounding rocks often results in small-magnitude earthquakes controlled by the changes in the pore pressure, which, in turn, is influenced mainly by the low-frequency Biot slow wave. Thus, the correct description of the properties of the P2 wave can provide an explanation for the occurrence of the fluid-induced micro earthquakes.

The classical Biot theory, which describes a wave dynamics of a fluid-saturated porous medium, assumes that the slow wave is highly dispersive and strongly attenuated below some critical frequency, which depends on the pore size in the skeleton and the viscosity of the fluid.

In this work the classical Biot system of equations is studied. The dispersion relation for the longitudinal P1 and P2 waves is derived and investigated by asymptotic methods. It is proven analytically that the Biot wave has a bifurcation behavior depending on its wave number. The bifurcation occurs in a neighborhood of the critical value k_{cr}, which indeed depends on the permeability of a medium and the viscosity of a fluid. The P2 wave is fully attenuated if its wave number is smaller than k_{cr} and it becomes propagatory with wave numbers bigger than k_{cr}. The bifurcation point describes the transition from low to high frequency regimes of propagation of the P2 mode. The estimates of the critical values for wave number and wavelength in real rocks show that the critical wave number is rather large and, consequently, the Biot slow wave becomes propagatory with a short enough wavelength. Thus, in the low frequency range of interest in seismology $(1 - 100\ Hz)$ the P2 modes behave like diffusive waves.

Although the long wavelength P2 waves are not propagatory and have a diffusive behavior, they influence significantly the pore pressure state in a medium. In order to analyze the pore pressure evolution in a porous rock during and after the injection of a borehole fluid the following problem is considered: the Biot system of equations is formulated for the radial symmetry case and is supplemented by the relevant boundary conditions at the borehole. The latter are the given pore pressure and stresses distributions at the borehole. The solution to this problem is very complicated because of the fact that the equations constituting the Biot model are coupled. The solution is constructed analytically. It has the integral form (it is an analogy of the Fourier integral) and, to some degree, resembles the solution of the corresponding boundary value problem to the diffusion equation. The "generalized diffusion coefficient" is a complicated combination of the parameters of a fluid and solid phases including the permeability of a medium and the viscosity of a fluid. It is proven that the main contribution to this integral is due to the P2 wave within the k-domain of diffusive behavior.

The constructed solution can be applied to the interpretation of the fluid-induced micro earthquakes. Obviously, an injection of a liquid into the borehole leads to an increase of the fluid pressure in a reservoir that causes a growth of the pore pressure in a fluid-filled rock. Pore pressure changes may lead to the occurrence of the micro earthquakes if the value of the pressure exceeds some threshold. The critical values of the pore pressure can be evaluated on the base of the obtained solution. This allows one to describe the microseismic cloud (spatial-time distribution of the micro earthquakes) and to estimate the threshold values of the pore pressure for a real rock. Moreover, this approach allows one to assess the permeability of the fluid-saturated rocks. The described method is best illustrated by examples of practical importance. The Soultz-sous-Forets (1993) and the Fenton Hill (1983) experiments on the fluid-induced earthquakes are considered.