



## Linear dynamic model for porous media saturated by two immiscible fluids

Jian-Fei Lu <sup>a,b,\*</sup>, Andrzej Hanyga <sup>b</sup>

<sup>a</sup> *Mathematics and Physics College of Jiangsu University, Zhenjiang, Jiangsu 212013, PR China*

<sup>b</sup> *Department of Earth Science, University of Bergen, Allegaten 41, N5007 Bergen, Norway*

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### Abstract

A linear isothermal dynamic model for a porous medium saturated by two immiscible fluids is developed in the paper. In contrast to the mixture theory, phase separation is avoided by introducing one energy for the porous medium. It is an important advantage of the model based on one energy approach that it can account for the couplings between the phases. The volume fraction of each phase is characterized by the porosity of the porous medium and the saturation of the wetting phase. The mass and momentum balance equations are constructed according to the generalized mixture theory. Constitutive relations for the stress, pore pressure are derived from the free energy function. A capillary pressure relaxation model characterizing one attenuation mechanism of the two-fluid saturated porous medium is introduced under the constraint of the entropy inequality. In order to describe the momentum interaction between the fluids and the solid, a frequency independent drag force model is introduced. The details of parameter estimation are discussed in the paper. It is demonstrated that all the material parameters in our model can be calculated by the phenomenological parameters, which are measurable. The equations of motion in the frequency domain are obtained in terms of the Fourier transformation. In terms of the equations of motion in the frequency domain, the wave velocities and the attenuations for three P waves and one S wave are calculated. The influences of the capillary pressure relaxation coefficient and the saturation of the wetting phase on the velocities and attenuation coefficients for the four wave modes are discussed in the numerical examples.

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*Keywords:* Porous media; Immiscible fluids; Dynamic model; Capillary pressure; Entropy inequality

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\* Corresponding author. Present address: Mathematics and Physics College of Jiangsu University, Zhenjiang, Jiangsu 212013, PR China. Tel./fax: +86 511 8791011.

E-mail addresses: [ljfdoctor@yahoo.com](mailto:ljfdoctor@yahoo.com) (J.-F. Lu), [andrzej.hanyga@geo.uib.no](mailto:andrzej.hanyga@geo.uib.no) (A. Hanyga).

## 1. Introduction

The dynamic response of porous media is of interest in various areas such as geophysics, civil engineering, ocean engineering, petroleum engineering and environmental engineering. It is pointed out in a historical review (de Boer, 1996) of the subject that two kinds of theories have been developed and used up to now, namely, Biot's theory (Biot, 1956a,b, 1962) and the mixture theory (Morland, 1972; Bedford and Drumheller, 1978; Bowen, 1980, 1982; Passman et al., 1984). The important difference between Biot's theory and the mixture theory is the coupling between state variables of the solid and the fluid phases. Bowen (1982) showed that if the coupling parameter  $Q$  introduced by Biot (1956a) is neglected, then, the mixture theory is equivalent to Biot's theory. A comparative study by Schanz and Diebels (2003) shows good agreement between Biot's theory and the mixture theory in the case of incompressible constituents, while for the case of compressible constituents there is significant discrepancy between the two theories. Clearly, this is due to the fact that in the incompressible case the constitutive coupling terms in Biot's theory vanish and thus, the two approaches are equivalent.

Based on the work of von Terzaghi (1923), Biot (1956a,b, 1962) presented a theoretical description of a porous medium saturated by one fluid. In deriving the equations of motion for the porous medium, Biot introduced the Lagrangian viewpoint and the concept of generalized coordinates. Biot derived the constitutive relation of the porous medium from a single free energy. Biot also extended his theory to the anisotropic medium (Biot, 1955), poro-viscoelastic medium (Biot, 1956c) and non-linear poroelastic medium (Biot, 1972). Besides, Biot's theory was extended to the unsaturated porous medium by Brutsaert (1964), Berryman et al. (1988) and Santos et al. (1990), Hanyga (2004), Hanyga and Lu (2004). As mentioned above, a striking characteristic of Biot's theory is the constitutive coupling between the solid skeleton and the pore fluid, which can account for both mechanical interactions between bulk components and the complex interface phenomena in the porous medium. Furthermore, in contrast to some recent model (Hassanizadeh and Gray, 1990), since the coupling parameter in Biot's model can be determined by appropriate ideal experiments (Biot and Willis, 1957), the phase interaction effects can be taken into account without an explicit reference to the interfaces. However, since Biot introduced his theory in the frame of the Lagrangian mechanics, the restrictions on the dissipative mechanisms such as drag force and capillary pressure hysteresis have to be imposed by intuitive consideration.

The generalized mixture theory can also be used to describe the behavior of porous media saturated by fluids. An important feature of the generalized mixture theory is the introduction of the concept of volume fraction to characterize the microstructure of the porous medium (Morland, 1972). According to the mixture theory, at the macro-scale level, each phase can occupy the same point simultaneously in an amount determined by its volume fraction. Each phase is also characterized locally by two independent densities: a true density with respect to the true volume occupied by the phase and an bulk density with respect to the total volume occupied by the porous medium. Another important assumption of the generalized mixture theory is phase separation, which has the following implications: (1) the total energy and entropy are a sum of all the partial energies and entropies associated with the phases; (2) the partial energy and entropy of each phase depend only on the state of that phase. In effect, phase separation is only reasonable for some special cases such as particulate media. The assumption of phase separation is too restrictive in the context of general porous media since it ignores the interface energy generated by the coupling between the fluids and the solid. To circumvent the limitation of phase separation in the mixture theory, Hassanizadeh and Gray (1990), Muraleetharan and Wei (1999), Wei and Muraleetharan (2002) treated the interfaces and the common contact lines as separate phases endowed with mass, density and energy. In this way, the interaction effect between each phase can be taken into account. However, this approach introduces additional thermodynamical variables such as volume density of interface area, which is beyond the reach of the current experiments.

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