8th. World Congress on Computational Mechanics (WCCM8)
5th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2008)
June 30 –July 5, 2008
Venice, Italy

WAVE PROPAGATION IN PARTIALLY-SATURATED ROCKS: THEORETICAL AND NUMERICAL INVESTIGATIONS

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Key Words: *Porous media, Mixture theory, Unsaturated rocks, Wave propagation*

ABSTRACT

In the present contribution we investigate seismic wave propagation in partially-saturated rocks, which is of great importance for example for the petroleum industry. While many studies investigated wave propagation in fully-saturated rocks (Biot theory) analytically and numerically, studies for partially-saturated rocks are rare [5-8]. With so-called patchy-saturation models, partial saturation is studied by using Biot's theory (2-phases) with a heterogeneous distribution of for example the fluid compressibility to mimic a partial saturation on the meso-scale, cf. White [1] and Dutta and Odé [2]. Such models have attracted considerable attention because they predict significant dispersion and attenuation for low, seismic frequencies ($\omega < 100$ Hz). However, they do not include the saturation as a primary model parameter. Partial-saturation models for 3 phases, as presented here, include saturation as primary model variable on the pore-scale. Understanding the impact of saturation on wave propagation is important for applications in the petroleum industry, because the saturation of oil or gas in a reservoir determines if the reservoir is economic or not. The partial-saturation model presented here allows studying the impact of saturation on parameters such as reflection coefficient, dispersion and attenuation. Additionally, the impact of different capillary pressure-saturation relations on wave propagation can be studied.

We propose a phenomenological three-phase continuum model based on the thermodynamical-consistent mixture theory extended by the concept of volume fractions. Commonly, it is denoted as the Theory of Porous Media (TPM), cf. de Boer [3] or Ehlers and Bluhm [4]. The mixture is composed of three constituents: A porous skeleton $\varphi^{\mathfrak{s}}$, a compressible wetting fluid $\varphi^{\mathfrak{l}}$ and a compressible non-wetting fluid $\varphi^{\mathfrak{g}}$. As in Biot's theory, a second slow and highly attenuated compressional wave is predicted by the three-phase model. Additionally, a third compressional wave taking into account a relative movement of all three phases is observed in this model. Capillary pressure depending on the degree of saturation is taking into account by the empirical van Genuchten equation. From the modelling point of view, it has to be remarked that the porosity $\phi(\mathbf{x}, t)$ and the saturation of the liquid phase $s^{\mathfrak{l}}(\mathbf{x}, t)$ depend on the volumetrical deformation of all inherent phases. Thus, on the one hand, these quantities stay not constant during the wave propagation process. On the other hand, they are dependent field variables. Besides the phase velocities and attenuation effects of monochromatic waves, cf.

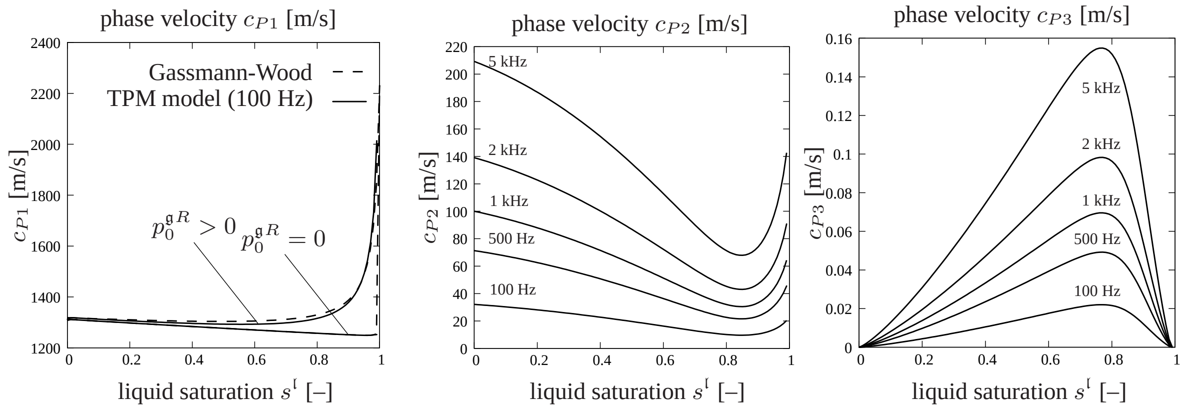

Figure 1: Variation of phase velocities P1-P3 with varying degree of liquid saturation $s^{\mathfrak{l}}$ at 3 km depth

Fig 1, we propose an efficient and stable finite element implementation of the three-phase model in the time domain. Finally, several numerical investigations show the distinct behavior of the model in comparison with classical one-phasic and bi-phasic approaches, respectively.

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