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PHYSICAL ACOUSTICS

A Modified Biot/Squirt Model of Sound Propagation in Water-Saturated Sedment[1]

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Abstract—A modified Biot/Squirt flow model was developed. The difference between MBISQ and BISQ models is the expression for the porosity differential. Numerical analysis shows that the acoustic dispersion predicted by MBISQ is much higher than by BISQ. Investigations of the effects of permeability, viscosity, and squirt flow length on velocity and attenuation indicate that the behavior of MBISQ agrees with that of the BISQ model. The result of sediment acoustic inversion based on MBISQ was more reasonable than the result of BISQ model.

Keywords: acoustic model, sediment, BISQ, dispersion, porous media

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INTRODUCTION

The propagation of acoustic wave in marine sediments has captured a lot of interest from researchers. Marine sediments can be described by the porous media theory. An earlier study on the wave propagation in porous media was done in the 1940s by Biot [1]. Gassmann equation is applied widely in the field of oil and gas reservoir exploration [2]. Biot theory predicted three kinds of waves in porous media [3–5]. White [6] confirmed that relative motion of the fluid in pore is the main mechanism of wave attenuation in the laboratory. Plona [7] observed the slow compression wave (SP wave) in artificial porous material. McCann and Yamamoto [8–10] developed the Biot theory which can be applied to distributed pore size. Stoll [11–14] has modified the Biot theory. Biot theory only considers Poiseuile flow, and researchers have found that this theory faces difficulties in explaining the high wave dispersion and attenuation. Squirt flow mechanisms were considered as the main reason for strong attenuation and acoustic dispersion [15–19]. Squirt flow or macroscopic flow mechanisms cannot explain the complex wave propagation in porous media alone. The BISQ model was proposed by considering the Biot and squirt flow mechanisms in a generalized model [20, 21]. Goloshubin tried to replace the squirt flow length by the filtration radius [22]. The BISQ model has been extended to the three-dimensional isotropic case [23]. Diallo and Appel put forward a reformulated BISQ model (RBISQ), which had no squirt flow length [24]. Chotiros Nicholas considered this problem and tried to establish a new model, which considered the shear drag force [25]. Markov studied the propagation of longitudinal elastic waves in a fluid-saturated porous medium with spherical inclusions and Rayleigh wave propagation in fluid-saturated porous media [26, 27]. Tao and Li [28, 29] studied the acoustic characteristics of the gas bearing sediments, and a simplified model was derived. Bagdoev [30] established the wave dynamics of generalized continua. In this paper, a modified Biot/Squirt flow model was developed by using a new expression for the porosity differential in BISQ model.

BIOT/SQUIRT FLOW THEORY

The wave propagation equations based on BISQ are

$$\begin{aligned}\mu\nabla^2\mathbf{u} + (\lambda+\mu)\nabla(\nabla\mathbf{u}) - \alpha_0\nabla P &= \frac{\partial^2}{\partial t^2}(\rho_1\mathbf{u} + \rho_2\mathbf{U}),\\ -\phi\nabla P &= \frac{\partial^2}{\partial t^2}(\rho_{11}\mathbf{u} + \rho_{22}\mathbf{U}) - b\frac{\partial}{\partial t}(\mathbf{u}-\mathbf{U}),\end{aligned} \quad (1)$$

[1] The article is published in the original.

Table 1. Parameters of model

Parameter	ϕ	ρ_s	ρ_f	K_f	η	κ	K_s	μ	λ	a	R
Units	–	kg/m^3	kg/m^3	GPa	Pa s	md	GPa	GPa	GPa	–	mm
Value	0.15	2650	1000	2.25	0.001	1	38	14.6	6.3	2	1

$$P = -FS\left[\nabla \mathbf{U} + \frac{\alpha_0 - \phi}{\phi}\nabla \mathbf{u}\right], \tag{2}$$

where λ, μ are elastic moduli of the drained skeleton, α_0 is pore-elastic coefficient, b is the dissipation coefficient, $\mathbf{u}$ is the displacement vector of solid, $\mathbf{U}$ is the displacement vector of fluid, P is the fluid pressure, F is the Biot flow coefficient, S is the squirt flow coefficient, $\rho_1 = (1-\phi)\rho_s$, $\rho_2 = \phi\rho_f$, $\rho_{12} = -\rho_a$, $\rho_{11} = \rho_1 + \rho_{12}$, $\rho_{22} = \rho_2 + \rho_{12}$, ρ_s is the solid density, ρ_f is the density of fluid, ρ_a is the coupling density and ϕ is the porosity.

MODIFIED BIOT/SQUIRT FLOW THEORY

According to the study of Dvorkin [20],

$$\frac{\phi}{\rho_f}\frac{\partial \rho_f}{\partial t} + \frac{\partial \phi}{\partial t} + \phi\frac{\partial^2 (U_x - u_x)}{\partial x \partial t} + \phi\left(\frac{\partial^2 U_r}{\partial r \partial t} + \frac{1}{r}\frac{\partial U_r}{\partial t}\right) = 0. \tag{3}$$

The porosity differential is written as [3–5]:

$$d\phi = \alpha_0 de + dP/Q, \tag{4}$$

where $Q = \left[\frac{1}{K_s}\left(1 - \phi - \frac{K_b}{K_s}\right)\right]^{-1}$, K_b and K_s are the bulk moduli of the drained skeleton and the solid phase correspondingly. The e is expressed by $e = \frac{\partial u_x}{\partial x}$ in BISQ model. But the last item of Eq. (3) is expressed in cylindrical coordinates. So, the solid dilatation porosity differential should be expressed in cylindrical coordinates too. That means the de in Eq. (4) should be expressed by

$$e = \frac{\partial u_r}{\partial r} + \frac{u_r}{r} + \frac{\partial u_x}{\partial x}. \tag{5}$$

Then Eq. (4) can be written as

$$\frac{\partial \phi}{\partial t} = \alpha_0 \frac{\partial}{\partial t}\left(\frac{\partial u_r}{\partial r} + \frac{u_r}{r} + \frac{\partial u_x}{\partial x}\right) + \frac{1}{Q}\frac{\partial P}{\partial t} = \alpha_0 \frac{\partial}{\partial t}(\nabla \mathbf{u}) + \frac{1}{Q}\frac{\partial P}{\partial t}. \tag{6}$$

In an isotropic medium, Eq. (6) can be rewritten by

$$\frac{\partial \phi}{\partial t} = 3\alpha_0 \frac{\partial}{\partial t}\left(\frac{\partial u_x}{\partial x}\right) + \frac{1}{Q}\frac{\partial P}{\partial t}. \tag{7}$$

Similarly to the calculation process in BISQ model [20], the fluid pressure equation of the modified BISQ (MBISQ) model can be expressed by

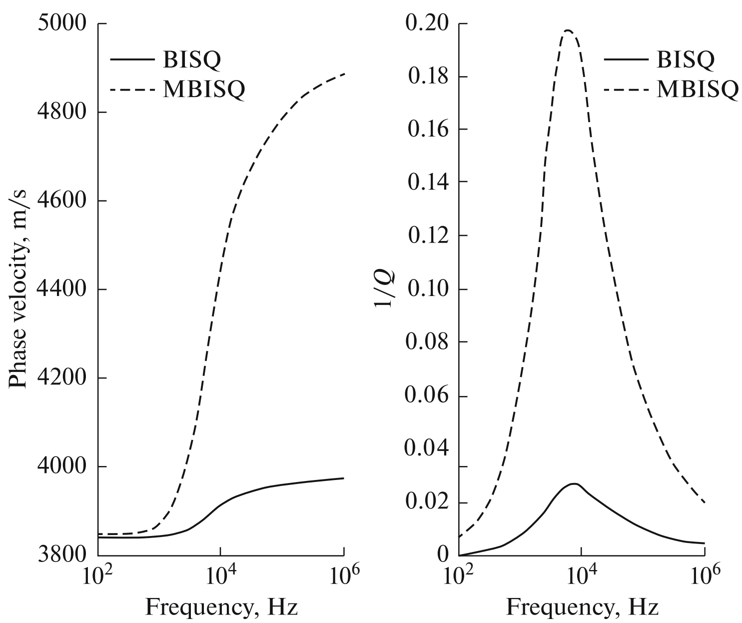

Fig. 1. Velocity and attenuation predicted by BISQ and MBISQ.