Wave Motion 51 (2014) 1225–1236

Contents lists available at ScienceDirect

Wave Motion

journal homepage: www.elsevier.com/locate/wavemoti

On dispersive propagation of surface waves in patchy saturated porous media

Yu Zhang [a,b,e,*], Yixian Xu [c,d,e], Jianghai Xia [c,e], Ping Ping [c], Shuangxi Zhang [a,b]

[a] School of Geodesy and Geomatics, Wuhan University, Wuhan, 430079, PR China
[b] Key Laboratory of Geospace Environment and Geodesy, Ministry of Education, Wuhan, 430079, PR China
[c] Institute of Geophysics and Geomatics, China University of Geosciences, Wuhan, Hubei 430074, PR China
[d] State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, Hubei 430074, PR China
[e] Subsurface Multi-scale Imaging Laboratory, China University of Geosciences, Wuhan, Hubei 430074, PR China

HIGHLIGHTS

- We present numerical results for Rayleigh wave in patchy saturated media.
- Rayleigh wave shows a significant transition behavior at low frequencies.
- The dispersive characteristics in the frequency and time domains depend on the gas fraction.

ARTICLE INFO

Article history:
Received 4 October 2013
Received in revised form 9 July 2014
Accepted 17 July 2014
Available online 25 July 2014

Keywords:
Surface wave
Patchy saturation
Dispersion
Attenuation

ABSTRACT

Frequency-dependent velocity and attenuation for Rayleigh-wave propagation along a vacuum/patchy saturated porous medium interface are investigated in the low frequency band (0.1–1000 Hz). Conventional patchy saturation models for compressional waves are extended to account for Rayleigh wave propagation along a free surface. The mesoscopic interaction of fluid and solid phases, as a dominant loss mechanism in patchy saturated media, significantly affects Rayleigh-wave propagation and attenuation. Researches on the dispersion characteristics at low frequencies with different gas fractions in patchy saturated media also demonstrate a strong correlation between the Rayleigh-wave mode and the fast compressional wave. Especially, the strongest attenuation with the maximum value of $1/Q$ for Rayleigh waves are obtained in the frequency range of 1–200 Hz. Numerical results show that the significant dependence of velocity and attenuation on frequencies and gas fractions presents a distinctive dynamical response of Rayleigh waves in the time domain.

1. Introduction

The presence of pore fluid can dramatically influence the wave properties of a porous medium, such as subsurface unconsolidated sedimentary material. The elastic modulus of the medium becomes frequency-dependent and attenuation effects arise due to distributions of the fluid in pore space. It is particularly interesting to consider the problem of a gas–liquid mixture saturated medium. In this case, even more dissipative mechanisms have to be considered beyond the

* Corresponding author at: School of Geodesy and Geomatics, Wuhan University, Wuhan 430079, PR China. Tel.: +86 13545353790.
E-mail addresses: yuz124@gmail.com, yuzhang@sgg.whu.edu.cn (Y. Zhang), xyxian65@aliyun.com (Y. Xu), jianghai_xia@yahoo.com (J. Xia), ppingapple@gmail.com (P. Ping), shxzhang@sgg.whu.edu.cn (S. Zhang).

http://dx.doi.org/10.1016/j.wavemoti.2014.07.007
0165-2125/

global interaction between the fluid and solid frame that occurs when the pore space saturated only by one fluid [1]. Recent studies [2] have shown that in the low frequency band (seismic frequencies), the mesoscopic distribution of fluids patchy saturation is the major cause of attenuation in porous media. The effects due to mesoscopic wave-induced fluid motion were first modeled by isolated spherical gas pockets in liquid saturated matrix background by White [3]. During the underground liquid motion, the pressure variation might lead to the diffusive formation of free gas pockets [4], which induces fluid flow between the pocket and matrix and causes the intrinsic attenuation [4,5].

Surface-wave propagation along a free-surface interface is one of the fundamental problems that needs to be understood for surface-wave applications in ground-water, engineering, environmental, geological and geophysical studies. The solid and fluid interactions in real media lead to complex surface-wave properties. The simple elastic theoretical model for surface-wave modeling is insufficient. Therefore, finding the dispersion characteristics of surface wave in porous media in the low frequency band (seismic frequencies) is a key issue in improving the precision of surface-wave in real-world applications. The frequency-dependent dispersion properties of surface waves in fully saturated media have been progressing under different interface conditions, such as a vacuum/solid interface (e.g., [6–8]), a fluid/solid interface (e.g., [9–12]), and a solid/solid interface (e.g. [13,14]). Analyses on a mixture of multiple fluids on surface waves are also found in [15–17]. However, to our best knowledge, there is no study concerning the influence of patchy saturation, which is regarded as the dominant attenuation mechanism for wave propagation in porous media at low frequencies, on the surface waves. Therefore, in the present work, we investigate the patchy-saturation effects of gas pockets on the propagation of surface waves along a free surface boundary. Understanding the patchy-saturation effects will help us to estimate wave velocity and attenuation more accurately.

This paper is organized as follows. In Section 2 we review the theoretical models of patchy saturation of a gas–liquid mixture for acoustic wave propagation in porous media. The bulk properties of the porous medium containing gas pockets are described in the model of [3]. In Section 3 the velocity and attenuation dispersion of Rayleigh surface wave along a vacuum/patchy saturated porous medium interface for typical near surface applications are presented and discussed. The wave-form responses of the surface wave in these patchy saturated porous media in the time domain are also plotted and analyzed. The discussion and conclusions are summarized in Section 4.

2. Acoustical properties of a patchy saturated medium

The mesoscopic scale of patchy saturation is larger than the pore size but smaller than the wavelength (typically tens of centimeters), which is large enough so that the wave-induced pore-pressure changes cannot equilibrate during a wave period. Patches of non-uniform saturation always occur at the gas–liquid contacts. Between full gas and full liquid saturation, typically a transition zone exists. When the wave impulse propagates, the wave induced fluid flow might lead to pressure gradient in this zone and makes diffusivity at the gas–liquid contacts [2].

The patchy-saturation theories apply to a nonrigid porous medium fully saturated by a fluid that contains gas pockets (radius a) larger than the typical pore size. The interaction among the individual gas pocket is neglected by defining a liquid influence shell (radius b) surrounding each pocket. The gas fraction is $S_1 = a^3/b^3$, and $S_2 = 1 - S_1$ is the liquid fraction [3]. The radius b is chosen so that the volume of the sphere $\frac{4}{3}\pi b^3$ equals the volume of the unit cell of the cubic lattice (Fig. 1).

The external pressure field is assumed to be spatially homogeneous at the scale of the inhomogeneity. We presume the wave frequency f is low enough that the Biot theory [1] is around its low-frequency limit, i.e. $f \ll f_c$, where the Biot critical frequency is defined by $f_c = \frac{\phi\eta}{2\pi C\kappa\rho_f}$. The physical properties related to the rock frame are porosity ϕ, tortuosity C, and the permeability κ; those related to the pore fluid are viscosity η and density ρ_f.

The starting conditions are essentially the Biot theory at low frequencies by setting the all higher order inertial terms to zero and by taking the dynamical permeability equal to its steady one [5]. The quasi-static Biot equations in the frequency domain are written by

$$\nabla \cdot \tau = 0, \tag{1}$$

$$\frac{\kappa}{\eta}\nabla \cdot p = -i \cdot \omega \mathbf{w}, \tag{2}$$

where $\mathbf{w}$ is the relative displacement of the fluid, defined as $\mathbf{w} = \phi(\mathbf{U} - \mathbf{u})$. $\mathbf{u}$ and $\mathbf{U}$ are the solid and the fluid displacements, respectively. The solid stress τ and the pore fluid pressure p are written by

$$\tau = 2\mu e_{i,j} + \delta_{i,j}(\lambda_c - \alpha M\varsigma), \tag{3}$$

$$p = -\alpha Me + M\varsigma, \tag{4}$$

where $e_{i,j} = \frac{1}{2}(\partial_j u_i + \partial_i u_j)$, $e = \nabla \cdot \mathbf{u}$ and $\varsigma = -\nabla \cdot \mathbf{w}$. λ_c and μ are lame coefficients. α and M are the Biot coefficients. Explicit expressions are given in terms of the bulk modulus of the pore fluid, the solid, and the matrix $K_{f,s,m}$, respectively [18]

$$\alpha = 1 - \frac{K_m}{K_s}, \tag{5}$$

$$\frac{1}{M} = \frac{\alpha - \phi}{K_s} + \frac{\phi}{K_f}. \tag{6}$$