Ocean Engineering 147 (2018) 195–205

Contents lists available at ScienceDirect

Ocean Engineering

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

# Effect of local fluid flow on the propagation of plane waves at an interface of water/double-porosity solid with underlying uniform elastic solid

M.S. Barak [a], M. Kumari [a,*], M. Kumar [b]

[a] Department of Mathematics, Indira Gandhi University Meerpur, Rewari, 122503, India
[b] Department of Mathematics, C.M.R.J Govt. College, Ellenabad, 125102, India

ARTICLE INFO

*Keywords:*
Plane wave
Sandwiched layer
Double-porosity
Reflection and transmission

ABSTRACT

This study deliberates the propagation of acoustic wave at water/double-porosity sediment interface with an underlying uniform elastic solid substrate. A mathematical model is constituted through three layers with distinct elastic properties. This layered structure contains an isotropic double-porosity solid sandwiched between an overlying water and underlying uniform elastic solid. The sandwiched layer is of finite thickness. Two types of boundary conditions (impermeable and permeable) at the interface of double-porosity solid and elastic solid substrate are considered. The closed form analytical expressions for reflection and transmission coefficients are derived theoretically for appropriate boundary conditions. These expressions are calculated as a non-singular system of linear algebraic equations. This non-singular system depends on various material parameters. Therefore, a numerical example is used to determine the effects of various properties of sandwiched layer on reflection and transmission coefficients. Essences of wave frequency, incident direction, layer thickness, pore fluid viscosity, wave-induced fluid flow and sealing of boundary pores on reflection and transmission coefficients are depicted graphically and discussed elaborately. It is revealed that the presence of double-porosity layer has a significant effect on reflection and transmission coefficients.

## 1. Introduction

It is commonly observed that situ rocks are generally heterogeneous. The non-uniform rock pores and cracks contain multiple fluids such as oil, gas, water, or CO2. The key issue in seismic exploration and reservoir monitoring is how to distinguishing these fluids by their seismic signatures. In exploration geophysics and seismology, seismic (reflection and transmission) methods are used to analyze the fluid content in subsurface reservoirs. On the basis of wave reflection signals the feedback about ocean floor is carried out. In environmental clean-up processes, contaminants to be removed from ground-water or earth are the traces of harmful chemicals, dissolved in typical liquids such as gasoline or oil. In general, earth is a layered structure with different elastic properties. The study of reservoir characteristics such as layer thickness, pore-fluid viscosity, radius of spherical inclusions, wave-induced fluid flow (i.e., LFF) and sealing of boundary pores through seismic method is helpful in detecting the hydrocarbon and minerals present inside the fissured rock of the ocean floor. The phenomenon of wave propagation at ocean floor is of great importance (practically as well as theoretically) in the various scientific fields, such as hydrogeology, engineering geology, seismology, seismology and petroleum geophysics. On the basis of Biot theory, the phenomenon of reflection and refraction (transmission) at water/porous interface is investigated by various authors including Stoll and Kan (1981), Wu et al. (1990), Santos et al. (1992), Albert (1993), Yang (1999), Williams (2001), Williams et al. (2001), Cui and Wang (2003), Denneman et al. (2002), Sharma (2004), Ohkawa et al. (2005), Sharma and Saini (2012) etc. The latest book by Carcione (2014) is also referred for relevant references and detailed procedures. However, to the best of our knowledge, the wave propagation through double porosity solid is limited. The extension of Biot's poroelasticity to double-porosity porous solid is carried out by Berryman and Wang (1995, 2000). They derived the phenomenological equations for double-porosity/dual-permeability medium. They found that three longitudinal and one shear wave exist in the double porosity medium. Later, Pride and Berryman (2003a, b) derived the governing equations for fluid saturated double-porosity media by using the volume averaging technique. Based on the Berryman and Wang theory, the wave propagation at the boundary of double-porosity media is investigated by Dai and Kuang (2006a, b, 2008). In the recent years, the main credit goes to Sharma (Sharma, 2013, 2014, 2015a, b, 2016, 2017) for comprehensive discussion on

* Corresponding author.
*E-mail addresses:* ms_barak@igu.ac.in (M.S. Barak), manjeet.aryan17@gmail.com (M. Kumari), manjit.msc@gmail.com (M. Kumar).

https://doi.org/10.1016/j.oceaneng.2017.10.030
Received 21 May 2017; Received in revised form 14 August 2017; Accepted 16 October 2017

wave propagation in double-porosity solid. Sharma (2013) studied the essence of wave-induced fluid flow (i.e., LFF) on the wave characteristics (i.e., phase velocity and attenuation) and on the reflection of plane wave for two kinds of boundary (i.e., permeable and impermeable) of double-porosity porous solid, based on Biot-Rayleigh theory (Ba et al., 2011). Sharma (2014) studied the essences of LFF, wave frequency, pore-fluid viscosity and opening of surface pores on Rayleigh waves characteristics and, on their particle motion in double-porosity solid. Sharma (2015a) studied the essence of LFF on the wave characterizes in a transversely isotropic double-porosity medium. Sharma (2015b) modified the constitutive relations derived by Berryman and Wang (2000) for double-porosity solid. The essences of incident direction, permeability, wave frequency, radius of spherical inclusions, pore fluid viscosity and sealing of boundary pores on the wave-induced flow of pore at the interface of double-porosity solid under inviscid liquid layer are analyzed by Sharma (2016). Sharma (2017) analyzed the essences of wave-inhomogeneity, pore-fluid viscosity and composition of double porosity on inhomogeneous propagation in double-porosity dual--permeability materials.

In the aforementioned research, the phenomenon of reflection and refraction (transmission) is carried out at the single interface (i.e., there is no sandwiched layer). Therefore, keeping in view the importance of the transition layer, few limited efforts have been made to study the phenomenon of reflection and refraction (transmission) of plane wave at a layer sandwiched between two dissimilar media. Some of the recent studies on reflection and transmission of seismic waves through transition layer have been carried out by various authors including Sinha (1964), Cerveny and Vanek (1974), Kuo (1992), Ainslie (1996), Wang et al. (2013), Lyu et al. (2014), Corredor et al. (2014), Chen et al. (2015), Sahu et al. (2015), Bai et al. (2015), Paswan et al. (2016), Feng et al. (2016), Bai et al. (2016), Chen et al. (2017) etc. Lyu et al. (2014) studied the reflection and transmission of wave at water/porous sediment with a double porosity substrate without taking LFF into account. They found that the presence of double-porosity substrate significantly affect the reflected wave in overlying water.

Keeping the importance of wave-induced fluid flow (i.e., LFF) in mind, present study considers the propagation of plane waves at water/double-porosity sediment interface with an underlying uniform elastic solid substrate. A mathematical model is constituted through three layers with distinct elastic properties. This layered structure contains an isotropic double-porosity solid sandwiched between an overlying water and underlying uniform elastic solid. The sandwiched layer is of finite thickness. Two types of boundary conditions (impermeable and permeable) at the interface of double-porosity solid and elastic solid substrate are considered. The closed form analytical expressions for reflection and transmission coefficients are derived theoretically for appropriate boundary conditions. These expressions are calculated as a non-singular system of linear algebraic equations. This non-singular system depends on various material parameters. Therefore, a numerical example is used to determine the essences of various properties of sandwiched layer on reflection and transmission coefficients. Essences of wave frequency, incident direction, layer thickness, radius of spherical inclusions, pore-fluid viscosity, wave-induced fluid flow (i.e., LFF) and sealing of boundary pores on reflection and transmission coefficients are depicted graphically and discussed elaborately. It is revealed that the presence of double-porosity layer has s significant essence on reflection and transmission coefficients. This study is motivated by the problem faced by oil excavation industries where desired products in the form of multiple fluids such as oil, gas, water, or $CO_2$ are found within the layered structure.

## 2. Governing equations

In this study, we consider a mathematical model constituted through three layers with distinct elastic properties. This layered structure contains an isotropic double-porosity solid sandwiched between an overlying water and underlying uniform elastic solid as shown in Fig. 1. In Cartesian coordinate system $(x, y, z)$, $z$-axis ($x$-axis) is placed downward (rightward). Let $z = 0$ be the interface separating water and double-porosity solid, and $z = h$ represent the boundary between double-porosity and uniform elastic solid, where $h$ represent the width of sandwiched layer.

### 2.1. Double-porosity solid

The double-porosity medium is presumed to be a spherical porous solid (inclusion) within another spherical porous solid (host medium). Hence, there are two phases in system i.e., host and inclusions. The pores in both phases are filled by same fluid. Let $\psi_1(\psi_2(= 1 - \psi_1))$ is the volume fraction of host (inclusion) medium. The total porosity is given by $\phi = \psi_1\phi_{10} + \psi_2\phi_{20}$, where, $\phi_{10}(\phi_{20})$ is the local porosity of host (inclusion). It is commonly accepted that the presence of fluids in the pore space of rocks causes attenuation and dispersion by the mechanism broadly known as wave-induced fluid flow (LFF). LFF occurs as a passing wave creates the regions of different fluid pressures in saturated porous rock and thus induces a flow of pore fluid. The wave-induced fluid flow is caused by the fluid-pressures difference between two regions of a saturated porous solid. This pressure gradient results from the different compressibilities of these regions. The LFF mechanism provides a link between fluid-transport properties and seismic wave signatures.

The wave-induced flow of fluid ($\gamma$) across the pores in a double-porosity solid is defined as (Ba et al., 2011; Sharma, 2013)

$$\gamma = e_0\nabla\cdot\mathbf{u} + e_1\nabla\cdot\mathbf{v} + e_2\nabla\cdot\mathbf{w}; \quad (e_0, e_1, e_2) = (\lambda_2 - \lambda_1, -\lambda_3, \lambda_4)/\left(\lambda_3 + \lambda_4 + \varepsilon\omega^2\right). \tag{1}$$

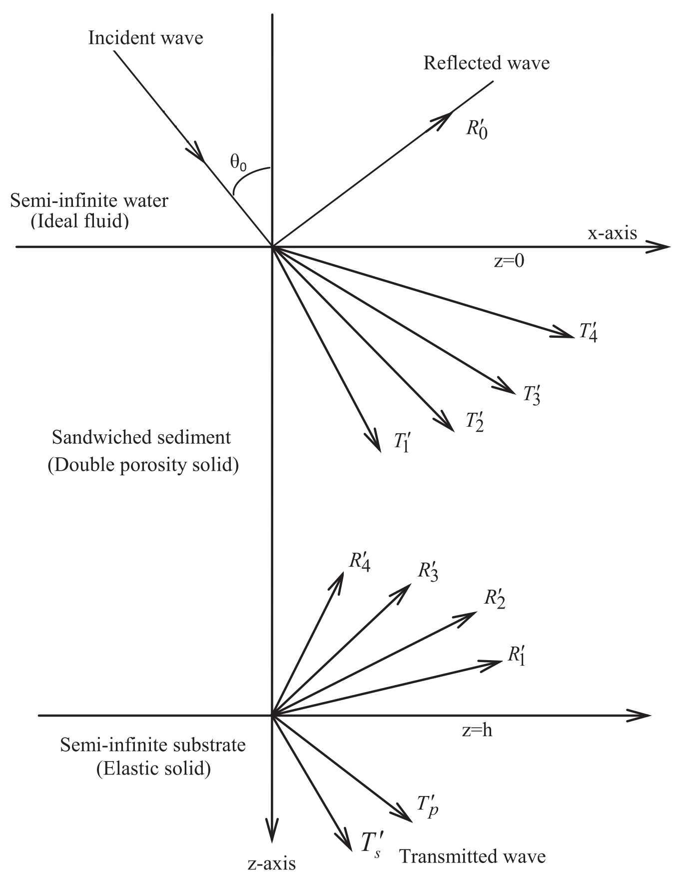


**Fig. 1.** Geometry of the problem.