In-situ permeability from physics-based integration of poroelastic reflection coefficients

Karel van Dalen and Ranajit Ghose
Department of Geotechnology, Delft University of Technology, The Netherlands

Summary

A reliable estimate of the in-situ permeability of a porous layer in the subsurface is extremely difficult to obtain. We have observed that at the field seismic frequency band the poroelastic behaviour for different seismic wave modes can differ in such a way that their combination can give unique estimates of in-situ permeability and porosity simultaneously. We have integrated the angle- and frequency-dependent poroelastic reflection coefficients of different seismic wave modes, and have tested the results through numerical simulations. The estimated values of permeability and porosity appear to be robust against uncertainties in the employed poroelastic attenuation mechanism. Potential applications of this approach exist in hydrocarbon exploration, hydrogeology, and geotechnical engineering.

Introduction

There have been attempts to estimate in-situ Darcy permeability (k_0) from the attenuation of tube waves using poroelastic wave theory (e.g., Burns, 1990). More recently, poroelastic wave theory has been used for k_0 estimation using seismic body waves (de Barros and Dietrich, 2008; Lin et al., 2009). Poroelasticity predicts a motion of the pore fluid relative to the skeleton as waves propagate through the porous medium. However, at field seismic frequencies (10-100 Hz in soft soil) the relative fluid flow becomes negligible if the porous material is homogeneous or well cemented. The effects of relative fluid flow become quite substantial if there are heterogeneities like gas inclusions. Goloshubin et al. (2003) used both fluid flow and scattering mechanisms to derive a frequency-dependent seismic attribute which is proportional to fluid mobility, and estimated k_0.

Strong k_0 dependence can be observed in the mesoscopic-flow mechanisms that can explain the observed velocity dispersion and attenuation at field seismic frequencies (Pride et al., 2003). Accounting for mesoscopic-flow mechanisms opens the way for exploiting the frequency-dependent behavior of the seismic reflectivity (Chapman et al., 2006). The use of seismic reflection data seems particularly advantageous to obtain the spatial variations of k_0. A major difficulty, however, arises due to the relation of k_0 with porosity (ϕ): because many combinations of k_0 and ϕ can explain the observed velocity dispersion and attenuation data, no unique estimate of k_0 and ϕ can be reached.

Here we present the result of a quantitative integration of angle- and frequency-dependent reflection coefficients of different seismic wave modes at the interface between two fluid-saturated poroelastic layers containing small quantities of gas. This leads to a means, for the first time, to obtain a unique and reliable estimate for in-situ k_0 and ϕ simultaneously, even from the low frequency field seismic data. We discuss at first the relevant poroelastic wave propagation mechanisms. Then we illustrate the results through tests on synthetic data mimicking field observation, and finally we discuss the mechanism uncertainty and the scope of the method.

Poroelastic wave propagation mechanism at field seismic frequencies: a model

We first consider a poroelastic loss mechanism that offers a realistic description of the wave propagation at field seismic frequencies. For homogeneous porous materials (e.g., glass beads), the wave velocities as predicted by Biot's theory offer quite accurate values (Berryman, 1980). However, for fluid-saturated natural rocks or sediments, Biot's macroscopic flow mechanism cannot simultaneously explain the observed velocity dispersion and attenuation. Various attenuation mechanisms proposed in the framework of Biot's theory cannot coherently explain the experimental observations (Pride et al., 2003) Recent studies have shown that the major cause of intrinsic attenuation in porous media can be wave-induced fluid flow due to the presence of mesoscopic heterogeneities causing fluid-pressure gradients. The flow can be modeled by applying Biot's theory as the local mechanism. Inhomogeneities in the frame structure (e.g., pockets of weakly cemented grains) are modeled in the double-porosity theory (Pride et al., 2004). Inhomogeneities in the fluid (e.g., gas pockets larger than the grain size) can be modeled by considering an effective medium (White, 1975) or an effective fluid (Bedford and Stern, 1983). In the latter, all characteristics of Biot's theory remain intact on the macroscale, as in the double-porosity model.

To illustrate our method of k_0 estimation, in this paper we consider an unconsolidated near-surface situation made of 2 layers, one on top of another, of water-saturated loose sands containing small quantities of gas (bubbles). We use the mechanism of an effective fluid in a homogeneous porous frame (Smeulders and van Dongen, 1997; Vogelaar, 2009). This mechanism, which uses the Rayleigh-Plesset equation for the gas-bubble behavior, is known to provide quite realistic results (e.g., van Wijngaarden, 1972). Both sand layers have identical grain bulk modulus, fluid bulk modulus, fluid viscosity, fluid density, gas fraction, gas bubble radiu, and gas bulk modulus. The two layers differ in shear shear modulus, bulk modulus, porosity, matrix density, tortuosity, and permeability. Realistic values were assigned to all these properties.

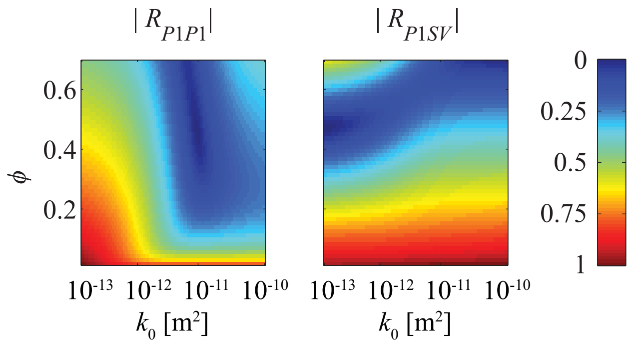

Figure 1: Normalized reflection coefficients for P1P1 and P1SV wave modes at the boundary between two saturated porous layers as a function of porosity and permeability.The reflection coefficients have been calculated using the poroelastic mechanism of an effective fluid in a homogeneous porous frame (Smelulders and van Dongen, 1997; Vogelaar, 2009). Note the very different behavior between the two wave modes.

Integration of poroelastic reflection coefficients: estimation of in-situ k_0

We assume that all parameters of layer 2 other than k_0 and ϕ are known a-priori by other experimental means or through processing operations. Then, using the poroelastic attenuation mechanism mentioned above, we calculate the velocity and attenuation of P and S waves in the two layers. For layer 2 we use varying values of k_0 and ϕ. Next, we calculate the frequency- and angle-dependent reflection coefficients (e.g., Dutta and Ode, 1983) for various wave modes P1P1 (P1 indicating the Biot fast compressional wave), P1SV, SVP1, SVSV and SHSH, where the second wavetype corresponds to the incident wave and the first wavetype corresponds to the reflected wave.

In practice, both 3-component seismic (particle velocity) data and the fluid-pressure data need to be acquired for different seismic wave modes at a given location. A reflection event present in these multiple datasets should represent a given interface or depth region in the subsurface, and should be related to the same reflection point (i.e., common-midpoint data). The data need to be preprocessed to minimize all surface-related effects, source-coherent and other noises, and then decomposed into P1, SV and SH waves. During all processing steps amplitudes should be preserved. The feasibility of such processing of angle-dependent reflection data has been reported earlier (e.g., Schalkwijk et al., 2003; Jocker et al., 2004; Ghose and Goudswaard, 2004).

Figure 1 illustrates the normalized reflection coefficients for P1P1 and P1SV wave modes, for vaying k_0 and ϕ in layer 2. It is is evident that the behaviour of these two reflection coefficients at the interface between two given poroelastic layers as a function of k_0 and ϕ is very different. This is due to the difference between the two wave modes in the local (at the reflection point) poroelastic behaviour. We take advantage of this difference and in that pursuit, we integrate the two reflection coefficients via a cost function (Ghose and Slob, 2006), which is illustrated below for P1P1 and P1SV wave modes:

$$C_{P1P1,P1SV} = \left(C_{P1P1}^{\beta} + C_{P1SV}^{\beta}\right)^{1/\beta} = \left(\frac{\sum_{f,p} |\Delta_{P1P1}|^{\beta}}{\left(\sum_{f,p} |\Delta_{P1P1}|^{\beta}\right)_{\max}} + \frac{\sum_{f,p} |\Delta_{P1SV}|^{\beta}}{\left(\sum_{f,p} |\Delta_{P1SV}|^{\beta}\right)_{\max}} \right)^{1/\beta}, \quad (1)$$

where C represents the integrated cost function, f and p are respectively frequency and ray-parameter, and Δ represents the difference between the observed reflection coefficient and the theoretically predicted (from poroelastic mechanism or model) reflection coefficient. The observed reflection coefficient is a function of f and p, while the estimated reflection coefficient is a function f, p, k_0 *and* ϕ. β=2 is used in case of noise-free data, if the data has noise with zero mean then β=1 can be used. Each term on the right hand side of equation (1) represents the cost function of an individual wave

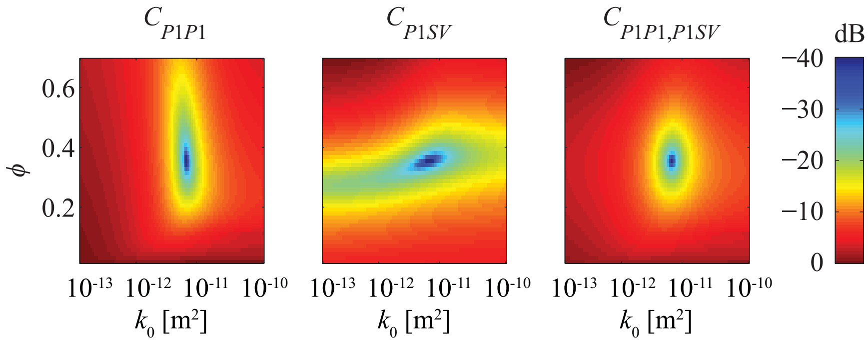

Figure 2: Individual (P1P1 and P1SV) and integrated (P1P1 + P1SV) cost functions in the k_0-ϕ domain. Because the P1P1 and P1SV cost functions are nearly orthogonal to each other due to the difference in their underlying physics, their integration results in a good convexity in the k_0-ϕ domain, and hence stable and unique estimates for k_0 and ϕ.

mode (P1P1 and P1SV), where the denominator takes care of the sensitivity. To simulate the realistic constraint of field seismic data on soft soil, we have used only two end frequencies for each wavetype: 40 and 100 Hz for P1, and 10 and 50 Hz for S, and 40 and 50 Hz for P1SV. In absence of field data at this moment, we have simulated the observed reflection coefficients using the same poroelastic mechanism/model and using the exact values of k_0 and ϕ in layer 2. Finally, the integrated cost function ($C_{P1P1,P1SV}$) is minimized in order to obtain the estimates of k_0 and ϕ. This is illustrated in Figure 2, for P1P1 and P1SV wave modes. The individual cost function for these wave modes is shown together with the integrated one. Remarkably, while the individual functions do not offer a clear minimum, the integrated cost function gives a very sharp minimum. Therefore unique estimates of k_0 and ϕ can be simultaneously obtained in the field seismic frequency band. The integration of P1P1 and P1SV reflection coefficients is successful because the local minima lines of their cost functions are nearly orthogonal to each other. This is due to the underlying physics: The P1P1 reflection coefficient is significantly affected by the presence of gas bubbles and has a strong k_0 sensitivity, while the P1SV reflection coefficient is primarily sensitive to ϕ. Therefore the integration of these two wave modes offers a good convexity in the k_0 -ϕ domain.

The strength of this approach lies in exploiting the physical difference in the poroelastic behaviour of the different seismic wave modes reflected at an interface of two saturated, porous layers. Any mechanism of poroelasticity that reliably captures this difference at field seismic frequencies will successfully allow such integration. Because the poroelastic reflection coefficients incorporate the effects of both frequency-dependent velocity and attenuation, the integration of these reflection coefficients is promising. It has been so far impossible to obtain estimates of k_0 and ϕ that individually and simultaneously satisfy the field observations. The present approach, for the first time, provides a solution to this problem.

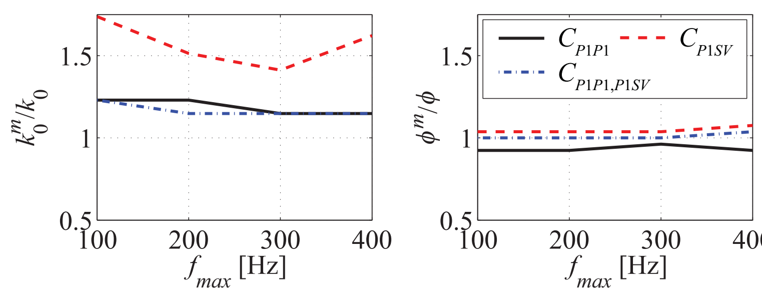

Figure 3: The effect of model uncertainty on the estimated k_0 and ϕ. The vertical axis represent the ratio of the estimated permeability or porosity using the integration approach (in this case the data representing the field observation is generated by the mechanism proposed by Pride et al. (2004), while the model prediction uses the mechanism of Smeulders and van Dongen, 1997; Vogelaar, 2009) to the true values. The results of individual cost function (P1P1 and P1SV) minimization and the integrated cost function (P1P1 + P1SV) minimization are shown.

Discussion

In this paper we have restricted ourselves to only two unknowns - k_0 and ϕ; however, the approach can very well be extended to incorporate more unknown parameters in the lower layer. Further, the methodology can be adapted to a stack of layers by progressively going downwards. The approach is general and can be useful in different disciplines.

In order to evaluate the effect of mechanism uncertainty on the estimated values of k_0 and ϕ, we have tested two very different mechanisms. We have synthesized the reflection coefficients representing the field observation using the patchy saturation mechanism of Pride et al. (2004), which also considers mesoscopic gas inclusions in the pore fluid, but based on an energy variation principle. On the other hand, for model predictions, we have, as before, used the the mechanism of Smeulders and van Dongen (1997); Vogelaar (2009). The dispersive regime and the frequency corresponding to the maximum attenuation are quite different between the two mechanisms. Next, we have minimized the integrated cost function. We find that the effect of mechanism uncertainty on the estimated values is small (Figure 3). The value of ϕ can be retrieved very accurately (< 1%). For $k_{0,}$ the error in the retrieved value is less than 25%, which is quite acceptable for in-situ k_0. When the frequency restrictions are slightly relaxed, for instance 300 Hz for maximum P1 frequency and 150 Hz for maximum P1SV frequency, then the inaccuracy in the k_0 estimate is less than 15%.

Conclusions.

We have presented a concept for the estimation of in-situ permeability (k_0) and porosity (ϕ) at the interface between two fluid-saturated porous layers by integration of local angle- and frequency-dependent reflection coefficients of different seismic wavetypes. Obtaining simultaneously permeability and porosity estimates from field seismic data using poroelasticity has so far not been possible. Our approach presented here promises a solution to this problem. It takes advantage of the physical difference in the poroelastic behavior of the different seismic wavetypes reflected at the boundary between two porous layers. One needs a poroelastic attenuation mechanism that explains data at the field seismic frequencies, and for this reason mesoscopic inhomogeneity is incorporated. The validity of the integration approach, however, is not dependent on a specific mechanism. Tests on synthetic data illustrate that the approach is robust against uncertainties in the employed poroelastic attenuation mechanism.

Acknowledgements

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