EGU2012-6394

Unraveling seismic attenuation mechanisms in saturated alluvial sediments

Marco Milani, Germán Rubino, Ludovic Baron and Klaus Holliger

Institute of Geophysics, University of Lausanne, Switzerland

UNIL | Université de Lausanne

Institute of Geophysics

1 - Introduction

The attenuation of seismic waves is an important material parameter, which contains potentially valuable information on key hydraulic and geomechanical properties of the probed medium. An inherent and important complication arising in the interpretation of such measurements is, however, that there are multiple physical mechanisms contributing to the dissipation of seismic energy, such as wave-induced fluid flow at the micro-, meso-, and macroscopic scales as well as scattering and inelastic effects. Moreover, the relative contributions of the various attenuation mechanisms are generally unknown and difficult to unravel.

In this work, we analyze the role played by the attenuation mechanisms related to wave-induced fluid flow effects by comparing the predicted phase velocity and attenuation characteristics with those of a comprehensive dataset.

2 - Database

The dataset considered in this study was acquired along a borehole penetrating unconsolidated Pleistocene glaciofluvial sediments. The prevailing mineralogy is dominated by calcite with minor amounts of quartz and clay. The groundwater table is located at a depth of 4 m.

A comprehensive suite of logging data, including P- and S-wave full waveform logs, allowed us to parameterize the governing equations. The P-wave data is collected using a multi-frequency slim-hole sonic tool, with dominant source frequencies ranging roughly between 1 and 30 KHz (Figure 1).

The solid grain properties are characterized by ρ_s=2.71 g/cm^3, K_s=70.2 GPa and μ_s=29.0 GPa, while water properties are taken to be ρ_f=1.0 g/cm^3, K_f=2.10 GPa, and η=0.0013 Pa·s.

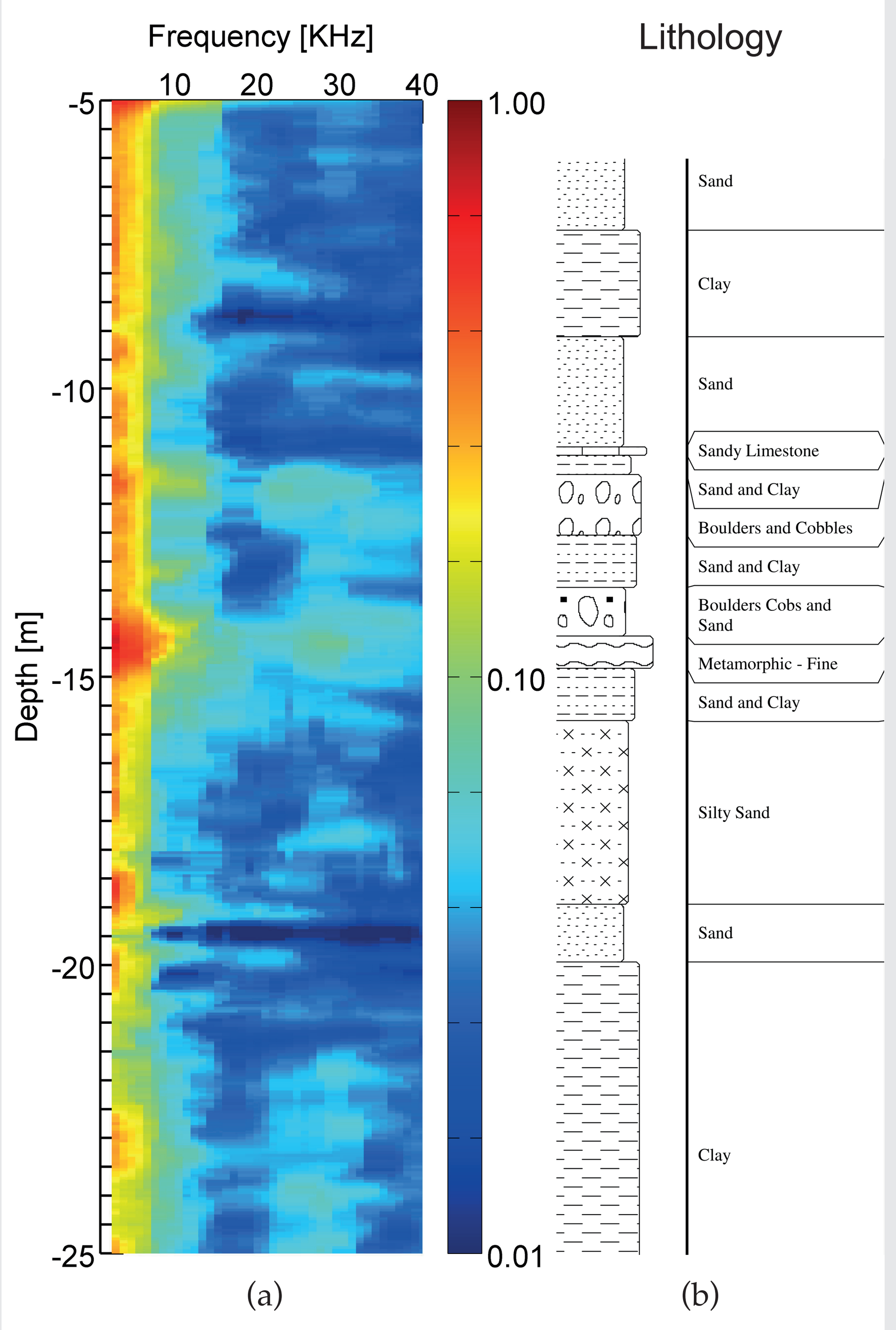

FIGURE 1: (a) Measured attenuation as a function of frequency and depth and (b) prevailing lithology along the considered borehole.

3 - Mesoscopic fluid flow

Attenuation produced by this phenomenon is due to heterogeneities larger than the pore size but smaller than the prevailing wavelengths. This attenuation mechanism can be important in certain geological environments and can be caused by local variations of the lithological and/or fluid properties of the probed medium.

In order to assess the relative contribution of this mechanism in the sediments under consideration, we proceed as follows:

1) We calibrate a rock physics model based on the Hertz-Mindlin approach [1] using Gassmann's equation [2].

2) Assuming the simplest and most attenuating form of mesoscopic heterogeneity for the considered environment, as defined by two adjacent layers with the strongest conceivable porosity contrast (Figure 2), we compute White's solutions [3].

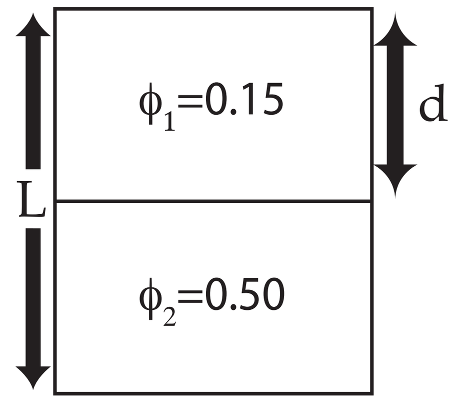

FIGURE 2: Schematic representation of the porosity contrast used to evaluate mesoscopic effects. While L is constant and d is variable and ranges between 0 and L.

3.1 - Rock physics model

The modified Hertz-Mindlin model proposed by Bachrach *et al.* [4] allows us to express the dry frame elastic moduli as functions of the porosity. It involves the calculation of the normal and shear stiffnesses of two adjacent grains followed by statistical averaging. The model requires the knowledge of the fraction of sliping contacts, where the tangential stiffness is zero, as well as the ratio between the effective contact radius and the average grain radius.

Using Gassmann's equation, we calibrate the model based on the P- and S-wave velocities and porosity data by minimizing the L^2-norm of the error with regard to the model's two free parameters. In doing so, we obtain an excellent match with regard to the observed velocities (Figure 3).

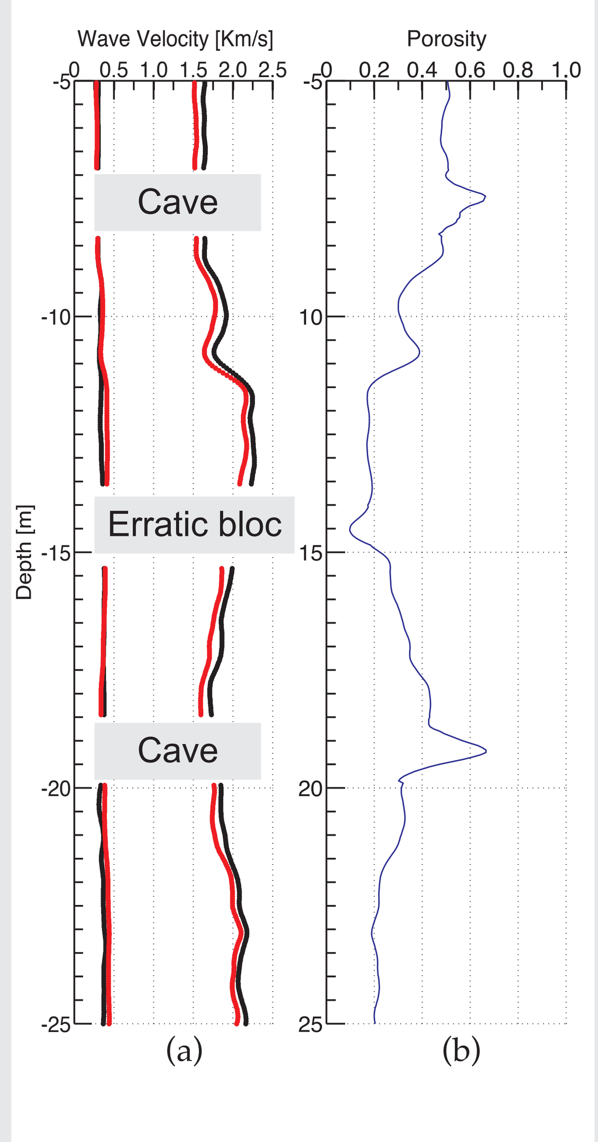

FIGURE 3: (a) P- and S-wave velocities and (b) porosity as functions of depth. Black and red points denote measured and modeled velocities, respectively.

3.2 - Attenuation analysis

Many different studies have demonstrated that mesoscopic fluid flow can be an important attenuation mechanism. However, Figure 4 reveals the complete ineffectiveness of this mechanism in our case, even in the presence of very strong porosity contrasts.

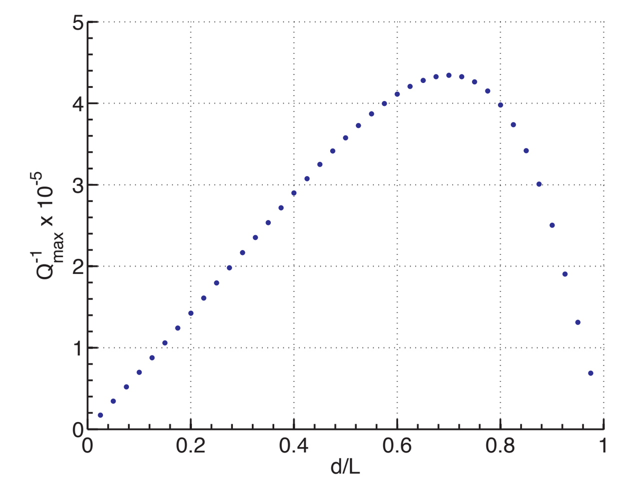

FIGURE 4: Mesoscopic attenuation produced by the porosity contrast shown in Figure 2 as a function of d/L. The Q-values were evaluated at the corresponding transition frequencies.

4 - Biot's theory

In the framework of Biot's theory [5], attenuation is produced by fluid flow between the peaks and troughs of the passing seismic waves. Biot's critical frequency, which strongly depends on the permeability, separates the so-called low- and high-frequency regimes. In consolidated rocks it is usually possible to work in the low-frequency regime, while a frequency correction term [6] associated with the high-frequency regime must be used for the unconsolidated sediments considered in this study.

We estimate the dry frame elastic moduli values as well as the permeability based on a joint inversion of the P-wave phase velocity and attenuation data (Figure 5). The inversion process is based on a Monte Carlo approach and the data considered for this analysis correspond to a depth of 20.05 m.

Unlike mesoscopic fluid flow, Biot's theory can produce significant attenuation and is able to explain most of the measured attenuation levels, especially at higher frequencies. However, as already pointed out by Baron and Holliger [7], Biot's theory does not seem to produce enough loss to completely explain the recorded level of attenuation over the entire frequency range considered in this study.

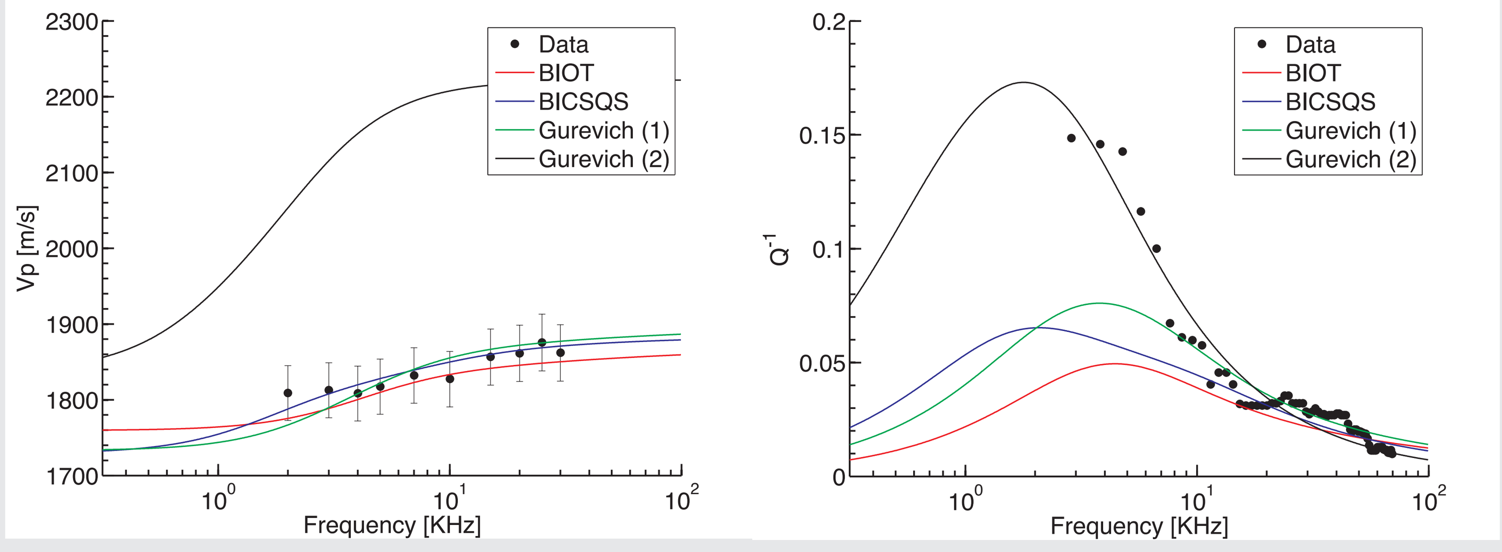

FIGURE 5: (a) Measured and predicted phase velocities and (b) attenuation curves.

5 - Biot's theory + squirt flow

A natural extension of Biot's theory can be obtained by considering fluid flow occurring at microscopic scales. When a wave squeezes a medium, it can produce fluid flow at broken grain contacts as well as in micro-fractures due to local variations in stiffness. Hence, the so called "squirt flow" is an additional attenuation mechanism which can be studied in the context of Biot's theory by taking the dry frame elastic moduli as being complex and frequency dependent.
For the purpose of this study, we consider and compare the two physics-based squirt flow models proposed by Chotiros and Isakson [8] (BICSQS) and Gurevich *et al.* [9]. Both of these models require the knowledge of parameters in addition to those involved in classical Biot's theory.

To this end, we estimate the values for the unknown parameters following the same philosophy as in the case of Biot's theory. Based on an exhaustive analysis we observe that, in general, squirt flow models improve the attenuation prediction with respect to Biot's theory (Figure 5). In fact, the observed attenuation levels can be completely reproduced by considering any of the two squirt flow models, but the corresponding phase velocities and their dispersion behaviour then turn out to be entirely incompatible with our observations (Figure 5).

6 - Permeability estimation

One of the most important aspects of the inverse procedures considered in this study, is that they allow us to obtain first-order estimates of permeability. Comparing the three different permeability distributions obtained in the course of the Monte Carlo inversion processes (Figure 6), we notice that the Biot's, and, to a lesser extent, Gurevich and BICSQS models produce consistent and realistic permeability estimations, albeit with the squirt flow models generally predicting higher permeability values than Biot's theory [10].

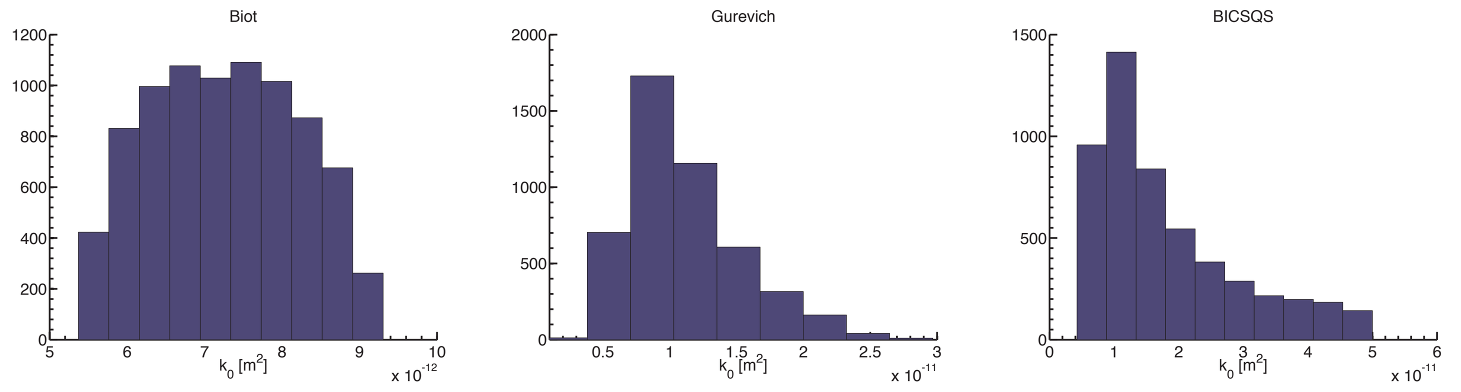

FIGURE 6: Permeability distributions resulting from the Monte Carlo inversion process.

7 - Conclusions

We have analyzed a comprehensive suite of logging data in unconsolidated glaciofluvial sediments to explore the physical mechanisms contributing to the attenuation of seismic waves in such environments. To do so, we considered different theoretical models based on wave-induced fluid flow effects at the micro-, meso- and macroscopic scales and verified whether they permit to explain the P-wave attenuation and phase velocity behaviour observed in the sediments. We found that while the levels of attenuation due to the presence of mesoscopic heterogeneities is negligible, the energy losses produced by fluid flow at macro- and microscopic scales can be very significant. These models are able to explain most of the measured attenuation and velocity dispersion, especially for the higher frequencies considered in this analysis.

8 - References

[1] G. Mavko, T. Mukerji and J. Dvorkin 2009. *Rock Physics Handbook, Cambridge University Press*
[2] F. Gassmann, 1951. Über die Elastizität poröser Medien, *Vierteljahresschr. Naturforsch. Ges. Zurich*, **96**, 1-23.
[3] J.E. White, N.G. Mikhaylova and F.M. Lyakhovitskiy, 1975. Low-frequency seismic waves in fluid saturated layered rocks, *Izvestija, Academy of Sciences, USSR: Physics of the Solid Earth*, **11**, 654–659.
[4] R. Bachrach and P. Avseth, 2008. Rock physics modeling of unconsolidated sands: Accounting for nonuniform contacts and heterogeneous stress fields in the effective media approximation with applications to hydrocarbon exploration, *Geophysics*, **73**, E197-E209.
[5] M.A. Biot, 1956. Theory of propagation of elastic waves in a fluid-saturated porous solid. II. Higher frequency range, *Journal of the Acoustical Society of America*, **28**, 179-191.
[6] D.L. Johnson, J. Koplik and R. Dashen, 1987. Theory of dynamic permeability and tortuosity in fluid-saturated porous media, *Journal of Fluid Mechanics*, **402**, 176-379.
[7] L. Baron and K. Holliger, 2011. Constraint on the permeability structure of alluvial aquifers from the poro-elastic inversion of multifrequency P-wave sonic velocity logs, *IEEE Transactions on Geoscience and Remote Sensing*, **49**, 1937-1948.
[8] N.P. Chotiros and M.J. Isakson, 2004. A broadband model of sandy ocean sediments: Biot–Stoll with contact squirt flow and shear drag, *Journal of the Acoustical Society of America*, **116**, 2011-2022.
[9] B. Gurevich, D. Makarynska, O. Bastos de Paula, and M. Pervukhina, 2010. A simple model for squirt-flow dispersion and attenuation in fluid-saturated granular rocks, *Geophysics*, **75**, N109-N120.
[10] J.L. Buchanan, 2006. A comparison of broadband models for sand sediments, *Journal of the Acoustical Society of America*, **120**, 3584-3598.

E-mail contact: marco.milani@unil.ch, german.rubino@unil.ch, ludovic.baron@unil.ch and klaus.holliger@unil.ch