Comparing Theoretical and Calculated Seismoelectric Transfer Functions at the Boise Hydrogeophysical Research Site

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Introduction

In August 2009, we conducted borehole seismoelectric experiments at the Boise Hydrogeophysical Research Site (BHRS) in order to investigate the frequency and permeability dependence of co-seismic electrical fields that accompany the propagation of seismic P-waves in water-saturated porous media. The BHRS functions like an outdoor laboratory as many of its physical properties have been measured in boreholes by previous investigators. Geologically the site consists of coarse cobble-and-sand fluvial deposits, underlain by a clay layer at approximately 20 m and overlain in some areas by an incised sand channel. The site is located along the shore of the Boise River and has a shallow water table that was 2 m below surface during our visit.

The objective of our borehole experiments was to determine if theoretical transfer functions predicting the amplitude and frequency-dependence of co-seismic seismoelectric effects as a function of several physical properties would prove consistent with calculated transfer functions based on in situ measurements made in a well-characterized natural environment.

Theory

The propagation of seismic waves through saturated poroelastic media can generate electric fields, known as seismoelectric effects, as a consequence of electrokinetic coupling associated with the movement of pore fluid relative to the solid matrix. Transfer functions derived by Neev and Yeatts (1989) and Garambois and Dietrich (2001) link various physical properties to the amplitudes of co-seismic electric fields that travel along with seismic P-waves. Neev and Yeatts' (1989) formulation, expressed in terms of elementary physical properties, is

$$\frac{E}{\dot{u}} \approx j\omega \frac{L_0}{\sigma} \frac{C}{v_c^2} \tag{1}$$

where E is the amplitude of the electric field (in the same direction as $\dot{u}$)
$\dot{u}$ is the amplitude of seismic particle velocity of the solid phase
ω is radian frequency
σ is the bulk electrical conductivity
C is one of Biot's poroelastic constants (equivalent to (Q+R)/ ϕ)
v_c is Biot's characteristic velocity (velocity in the case of no relative fluid flow)

L_0 in equation (1) above is known as the electrokinetic (streaming current) coupling coefficient for steady fluid flow and is postulated to be a function of several other basic physical properties (Ishido and Mizutani, 1981):

$$L_0 = -\phi \frac{\square}{\tau^2} \frac{\epsilon_f \zeta}{\eta}$$
(2)

where ϕ is porosity

ϵ_f is the permittivity of the pore fluid

ζ is the zeta potential for the rock-water system under study

τ is the tortuosity of the pore network

η is the viscosity of the pore fluid

It can be shown that the transfer function of Garambois and Dietrich (2001) is very similar to that given above at frequencies below Biot's critical frequency where fluid motion in the pores is dominated by viscous (as opposed to inertial) effects. Both functions predict that the ratio of co-seismic electric field to seismic particle velocity should increase linearly with frequency and coupling coefficient, and vary inversely with electrical conductivity. Furthermore, somewhat counter-intuitively, they do not predict any explicit dependence on permeability at such low frequencies. Garambois and Dietrich (2001), however, extend their transfer function into the higher frequency inertial flow regime by use of a frequency-dependent coupling coefficient $L(\omega)$ that causes E/ů to increase more slowly with frequency (as $\omega^{1/2}$ rather than ω). This transition occurs at the Biot critical frequency ω_c which depends on fluid flow permeability k_0 according to the equation (Garamabois and Dietrich, 2001),

$$\omega_c = \frac{\phi}{\tau^2 k_0} \frac{\eta}{\rho_f} \tag{3}$$

Identification of ω_c, by means of spectral analysis of field measurements thereby constitutes a possible method for the estimation of permeability provided that sufficiently broadband signals can be generated. Expected values for ω_c at the relatively coarse-grained and permeable BHRS are relatively low, in the range 200 to 4000 Hz.

Method

Measurements were carried out in two boreholes on site at the BHRS, located approximately 20 m apart. These boreholes (X4 and C5) were similar as they both intersect the same cobble dominated units and sand channel but differ as borehole C5 terminates in a volcanic unit while X4 terminates in a clay layer. A 100 lb accelerated weight drop functioned as our main seismic source although a sledgehammer source was also of adequate strength. The source struck a high-impact polyethylene plate set on the ground 2 – 3 m away from the borehole collars. To avoid crosstalk P-wave arrivals and co-seismic responses were recorded separately at 25 cm depth increments in each borehole. We recorded P-wave arrivals using a three component borehole geophone (with 40 Hz natural frequency) while the co-seismic responses were recorded using a ten channel electrode array configured to yield 10 grounded dipoles, each 2 m in length. Figure 1 shows the vertical seismic and seismoelectric profiles measured in borehole X4 following the removal of powerline harmonic noise from the latter.

The final step in this preliminary analysis was to apply a tapered window function to the seismic and seismoelectric data sets so as to isolate the first P-wave related pulses and then calculate simple periodogram estimates of their spectral content. Division of one spectrum by the other yielded a calculated transfer function for comparison to that predicted by theory.

Results

Co-seismic signals accompanying P-wave arrivals demonstrated excellent signal-to-noise ratios with amplitudes of 10 to 100 microVolts/m. Amplitudes generally decreased with depth but also increased with the compaction of sediment beneath the seismic source resulting in variations in source coupling. A normalization factor, calculated using initial P-wave amplitudes measured by a distant geophone on surface, was applied to compensate for the source coupling variations. The co-seismic signals had a dominant frequency of approximately 250 Hz with a useable bandwidth reaching nearly 800 Hz.

An averaged seismoelectric transfer function from borehole X4 (fig. 2b) displays results falling between two bounding theoretical transfer functions calculated using Neev and Yeatts (1989) formulation. The theoretical transfer functions are determined using physical property values measured in borehole X4 to show a full range of results which we would expect our measured data to fall within. From these results we can see that Neev and Yeatts (1989) transfer function shows the potential for predicting co-seismic responses although our measured results do not display the linearity expected from theory. The measured transfer function deviates from linearity at approximately 250 Hz as a consequence of notches found in the seismic spectra which were attenuated (but not completely removed) by the averaging process. At this stage we have yet to determine the cause of these notches but they may be a consequence of the relatively crude spectral analysis technique we have employed to date.

Conclusions

The preliminary analyses presented here show that theoretical transfer functions for the co-seismic seismoelectric effect in the low-frequency regime predict signal amplitudes and frequency dependence that are comparable to those observed in borehole experiments at the BHRS. Observed frequency dependence does, however, seem to be adversely affected by notches in the spectra of the seismic P-wave arrivals, thereby preventing us from commenting on whether changes in frequency response, related to permeability are present in the upper part of the seismoelectric spectrum. More advanced spectral analysis techniques will be applied in an effort to overcome this problem and extend the useable bandwidth for transfer function comparison.

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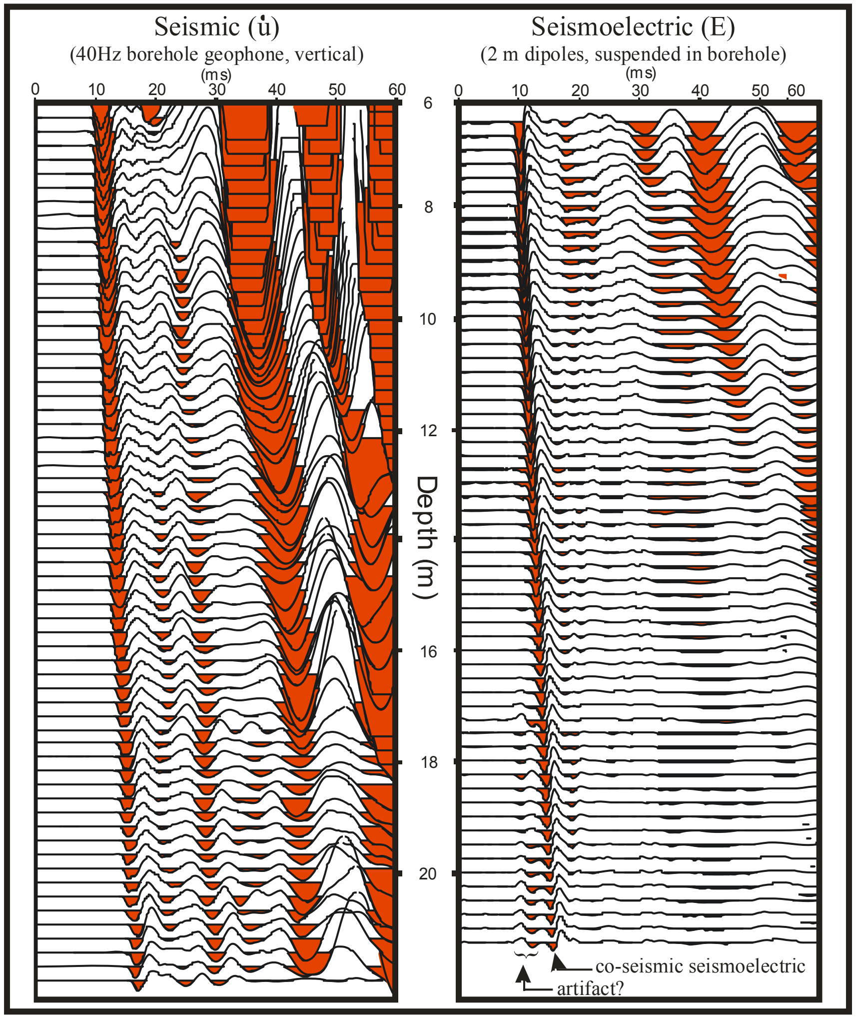

Figure 1: Vertical seismic profile (left) and vertical seismoelectric profile (right) acquired with weight drop source at BHRS borehole X4. Note the higher dominant frequency of the seismoelectric arrival (in agreement with theory).

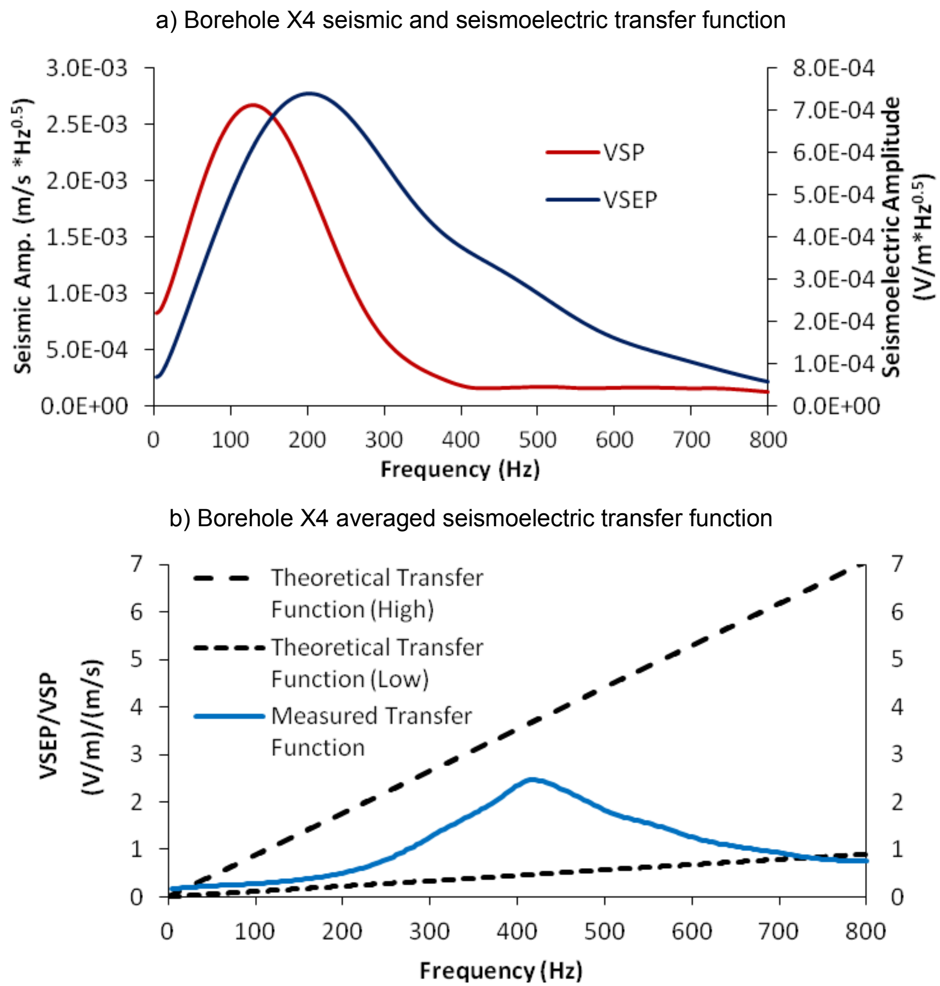

Figure 2: a) Averaged seismic and seismoelectric spectra from borehole X4 and b) the averaged seismoelectric transfer function (blue) plotted between theoretical transfer functions calculated using Neev and Yeatts (1989) formulation. The theoretical transfer functions shown above are calculated using physical property values chosen to display maximum and minimum acceptable values for our measured results.