Paper 110

Signal to Noise Improvements in Seismoelectric Data Acquisition

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ABSTRACT

Electrokinetic effects induced by seismic waves are of interest for their sensitivity to the pore fluid content, porosity and permeability of porous and fractured rocks and sediments. Two dominant types of signals, known as co-seismic and interfacial seismoelectric effects, have been predicted by theoretical modeling and confirmed by measurements since the early 1990's. The development of practical applications for these phenomena has progressed more slowly as a result of the challenges involved in their routine measurement. We discuss the common sources of noise encountered and approaches that have been developed to deal with them. Recent trends in surface and borehole field experiments are also briefly discussed.

INTRODUCTION

Seismoelectric effects of electrokinetic origin have potential to reveal information about the fluid saturation, pore fluid type and permeability of subsurface formations with the relatively high resolution of seismic methods. Since the early 1990's several groups of investigators have confirmed that the effects are real and measurable in the field and great strides have been made in theoretical modeling of the signals expected in layered, porous media. The development of practical applications and validation of theory remains a work in progress however due to the challenges involved in developing robust instrumentation and methods to allow reliable and interpretable measurements to be made a routine basis. The difficulty in making the measurements relates to an inherently low signal-to-noise (S/N) ratio. In this work, we discuss the common sources of noise encountered and some of the strategies that have been used to combat them. We also address some of the benefits of vertical seismoelectric profiling in boreholes, as an alternative to the more conventional surface survey geometries that have been the focus of more research to date.

BACKGROUND

Seismically induced electrokinetic effects arise in porous media because of the electric double layer that exists at a solid-liquid interface – a layer of ions adsorbed on the solid matrix, and a parallel, diffuse layer of counter-ions in the pore fluid. Part of the diffuse layer is free to move with the pore fluid. Thus, the motion of pore fluid relative to solid that accompanies P-wave propagation leads to a macroscopic separation of electrical charge between compressed and rarefied regions in the seismic wavefront. This charge separation gives rise to *co-seismic* electrical fields that are contained within the traveling seismic wave and exhibit amplitudes dependent on the electrical and mechanical properties of the host medium. In addition, abrupt distortions in the charge distribution caused by the P-wave impinging on a boundary can give rise to a second type of seismoelectric effect which is distinct in that it radiates as an EM field (Thompson and Gist, 1993). Such *interfacial* seismoelectric effects will be received essentially simultaneously by widely separated antennas at an arrival time given by the one-way seismic traveltime to the interface. In the case of a horizontal interface, the source can be approximated as a vertical electrical dipole centered on the interface directly below the shot. Horizontal grounded dipole receivers located on the earth's surface will therefore observe a signal with opposite polarity on opposite sides of the shot, and with a maximum amplitude at an offset equal to one half of the interface depth.

Of the two types of seismoelectric signals, the one which has received the most attention as a potential exploration tool is the interfacial effect. Although the weaker of the two, it can provide important information about formations at depth, while the co-seismic can only provide information about the soil or rock properties in the vicinity of the electrical receivers. Measurements of interfacial effects have been reported by several investigators and a handful of reports (Thompson and Gist, 1993; Butler et al., 1996; Haines et al., 2007; Dupuis et al., 2007a) have demonstrated that they can indeed be used to map boundaries. The reported amplitudes of interfacial effects measured using grounded dipoles on the earth's surface have ranged from an exceptionally strong 1 mV/m for the case of an interface at 3 m depth and a sledgehammer source (Butler et al.,

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1996), to as low as 60 nV/m for the case of an interface at 68 m depth and a 1 kg explosive source (Thompson and Gist, 1993). Most recently, we have used a 40 kg accelerated weight drop source and a 26 channel recording system to map the water table and interfaces in the overlying vadose zone in a sandy aquifer near Perth, Australia (Dupuis et al., 2007a). The clear interfacial signals emanating from the water table at about 14 m depth had amplitudes on the order of 1 μV/m. In our experience, it is desirable and presently possible to achieve background noise levels of 0.1 μV/m or less in stacked, processed shot records acquired for near-surface applications. Thompson and Gist (1993) have postulated that a much lower noise floor of 0.1 nV/m might eventually be achievable in final stacked seismoelectric sections.

Apart from ambient and instrumentation-related noise sources, co-seismic effects can be a significant source of interference in surveys targeting interfacial effects. The co-seismic effects are broadly analogous to surface wave interference in seismic reflection records. They may be attenuated relative to interfacial effects that appear flat on shot records by using wavefield separation (velocity) filtering and multi-channel stacking provided an adequate number of channels is available. Alternatively, in some applications, such as borehole or cross-hole surveys, source-receiver geometries may be selected to ensure co-seismic effects do not arrive until after the interfacial signals of interest (e.g., see Haines et al., 2007; Dupuis et al., 2007b). In the last section of this paper we discuss benefits of vertical seismoelectric profiling in boreholes as a complement or alternative to surface surveys. The approach offers several advantages in S/N and can additionally make use of the co-seismic signal for borehole logging.

DATA ACQUISITION

The most common type of data acquisition systems used to acquire seismoelectric signals are seismographs. The high dynamic range and channel capacity of modern exploration seismographs open up many avenues for S/N improvement through post-processing. These systems on their own however are not suitable for systematic acquisition of high quality seismoelectric data.

Seismographs are designed to be interfaced to geophones, which present low source impedances of a few hundred ohms. As such, the input impedance of the seismograph is commonly no higher than about 20 kΩ. Unfortunately, electrode contact resistances in most soils are significantly greater than geophone impedances, and thus a voltage divider problem, as shown in Figure 1, can arise as earth currents are partially shunted through the seismograph inputs. For a source impedance of 20 kΩ at the dipole, not uncommon at many sites, only half the voltage will be seen at the acquisition system. Furthermore, as the source impedance rises, bandwidth is reduced due to the low-pass filter formed by the source impedance and the combined input capacitance of the cable and seismograph. In Figure 1 we show typical filter responses we would expect given our Geode seismograph's input impedance of 20 kΩ in parallel with 20 nF, and a seismic cable capacitance of 100 pF/m. The upper plot shows how the filter would vary with dipole source impedances of 1 to 50 kΩ for a 100 m length of cable, while the lower plot shows the more subtle effect of cable lengths ranging from 5 to 100 m.

It is also important to ensure good isolation between channels, which can be a challenge given the normal design of the input stage of seismographs if the contact impedance is much larger than the input impedance. The use of buffering amplifiers resolves these problems, and thus offers a signal with consistent spectrum, greater channel isolation and better signal strength.

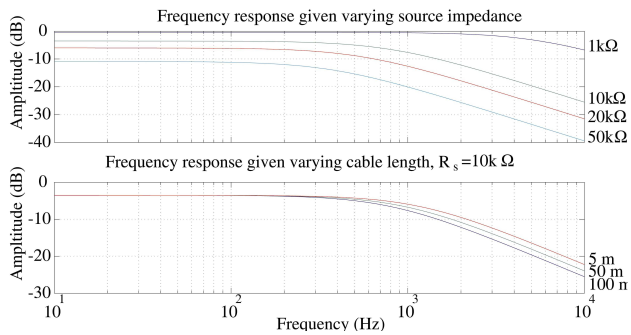

Figure 1: Importance of proper buffering of dipoles.

NOISE SOURCES

Harmonic noise

Harmonic noise associated with electrical power systems is commonly the largest source of noise we have encountered in Canada. Amplitudes on the order of 1 mV/m are common even in rural areas. The noise is strongest at the fundamental frequency of power transmission (60 Hz) and at odd harmonics which arise from non-linearities in transformers and other loads. It appears to be a consequence of the common practice of using the earth to accept any residual current that is not perfectly balanced between the phases of a transmission line. In contrast, powerline noise has been minimal at several field sites in Australia where we have observed a fourth conductor (presumably a ground line) running between the towers of three phase transmission lines.

Powerline harmonics, like other distant noise sources, can be suppressed by the subtraction of a noise reference recorded by a remote dipole. In practice we have found the improvement offered by this method to be limited to about 20 dB, although we suspect further improvement could be realized by developing adaptive filtering algorithms to match individual harmonic components more closely. Harmonic noise may also be suppressed by taking the difference between traces recorded by dipole receivers symmetrically placed on opposite sides of the shot; Thompson and Gist (1993) noted that this approach tends to cancel noise from distant sources while theoretically doubling the signal from interfacial seismoelectric effects generated below the shot.

Harmonic noise estimation and subtraction algorithms have also proven very effective. We routinely employ the algorithm of Butler and Russell (2003) to reduce harmonic noise levels by up to 45 dB. The ability to obtain precise estimates of the fundamental frequency (to within ~ 0.01 Hz) is critical to optimizing the performance of such routines. It is advisable to apply the routine to individual shot records (prior to stacking) so that the performance is less likely to be compromised by frequency, amplitude or phase changes before multiple shots are completed; individual records that exhibit excessive residual noise (due to such non-stationarities) can then be excluded from the stack – an approach that is also used to improve stacks of time domain EM decay curves. The best estimates of harmonic noise are obtained from data recorded immediately before the shot – using the pre-trigger recording capability of some modern acquisition systems. Users should be aware however that some such systems employ sub-sample trigger synchronization which must be disabled to avoid introducing a significant phase change in the harmonic noise train at time zero.

Although the post-processing techniques described above are very beneficial there would still be great benefit in developing methods for real-time suppression of harmonic noise in order to allow other, more subtle sources of noise (and signal) to be recognized and diagnosed during data acquisition.

Trigger and impact-related 'cross talk'

Most people familiar with making seismoelectric measurements have seen early source-generated noise that can obscure the first several ms of the record. This is particularly problematic when trying to resolve very shallow interfaces. Butler et al. (1996) concluded that one source of this noise was related to the deformation of metal and noted that it could be avoided by using a non-metallic base plate with sledgehammer sources. Recently, Haines et al. (2007) suggested that the signal may be related to the Lorentz field of the metal base plate moving in the earth's magnetic field. Although this is a plausible explanation, we have found that inserting a piece of cardboard between the plate and the hammer can also eliminate this interference and thus it seems that the impact between two metals may be a stronger contributor.

Our experiments have also shed light on the origin of interference that seems to be related to triggering systems commonly used with sledgehammer sources. We generally use piezoelectric transducers rather than the contact-closure switches to avoid the strong transient field that can be associated with the latter. The link that is often overlooked is the cable linking the piezoelectric transducer to the triggering circuit on the seismograph. The problem arises from a phenomenon called triboelectric noise which amounts to the charge buildup caused by friction or deformation of the cable insulation (Klijn and Kloprogge, 1974). Special "low noise" microphone cables are made with conductive polymers and fillers used to discharge the charge buildup and limit this type of spurious effect.

The use of this type of cable and re-location of the accelerometer from the sledgehammer to the impact plate, where it experiences less movement, vibration and strain, allowed us to greatly reduce this noise source (Figure 2).

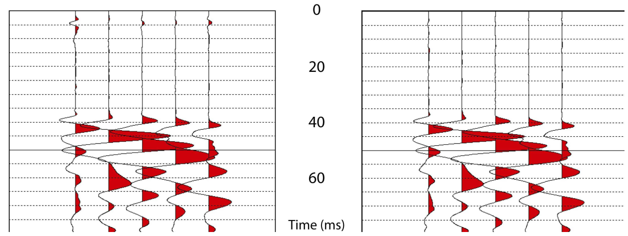

Figure 2: Seismoelectric shot records acquired at the same position with same sledgehammer source. Noise transients appearing in the first 10 ms on the left hand panel were eliminated in a repeat shot (right) by striking the baseplate in such a way as to minimize strain on the trigger cable.

Electrode Contact Impedance and AM Demodulation

Electrode contact impedance plays an important role in the overall attainable noise floor of the acquisition system. At the lower attainable limit sits the Johnson noise which is related to the thermal agitation of charge conductors within the resistors. At sites where contact impedance is high, this may be the dominating factor in determining the best achievable signal to noise ratio.

High contact impedance also makes the acquisition system more susceptible to stray field capacitance. In particular, we have observed that Amplitude Modulated (AM) radio broadcasts can be capacitively coupled to the electrodes and wires and be demodulated by non-linearities in our data acquisition system. This type of interference (Kepic and Butler, 2002) is very difficult to remove from the data because it is pseudo-continuous in time and selective stacking of records or filtering offers only limited improvements (e.g. see the shot record in Figure 3).

At one site where we faced high contact impedance, it was useful to dig holes about 50 cm deep and hammer in our 40 cm stainless steel stake or insert aluminium foil before backfilling and watering of the electrode with a mixture of water and soil-wetting agent. These measures reduced the contact impedance, the AM demodulation and Johnson noise (Dupuis et al., 2007a).

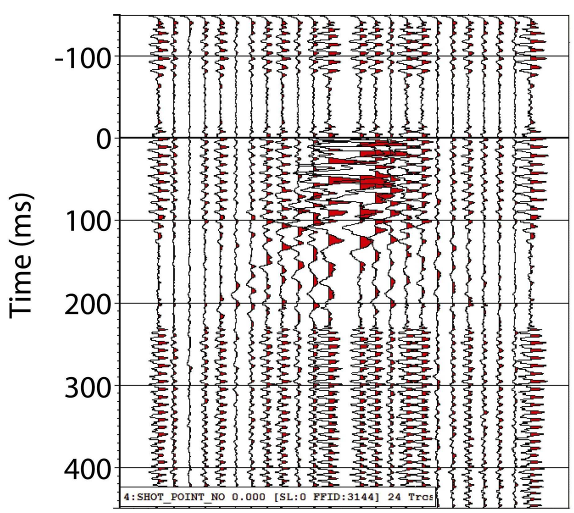

Figure 3: Example of AM demodulation noise in a seismoelectric shot record.

Increasing Trace Density by Composite Shot Gathers

After all other forms of noise have been mitigated to the best of our ability, the co-seismic signal remains an important obstacle. This is similar to surface wave interference in seismic reflection surveys. The co-seismic signal is commonly much stronger than the interfacial signals sought and must therefore be attenuated by multichannel filtering if the two cannot be adequately separated in time.

The channel capacity of our current seismoelectric acquisition system, like that of most other researchers, is relatively limited as we currently have only 26 preamplifiers. On a split-spread shot record consisting of only 26 traces it can be difficult to obtain a sufficiently wide range of offsets to differentiate the various seismoelectric arrivals while also retaining small enough dipole spacing to prevent spatial aliasing of very low velocity events. To tackle this problem and enable us to use wavefield separation algorithms we have found it beneficial to combine traces from adjacent closely spaced shotpoints following an approach suggested Kepic and Rosid (2004) in order to form composite shot gathers, or “super gathers” with great trace density. Inconsistencies in source strength, triggering, near-surface conditions, or noise levels from one shotpoint to the next can introduce some undesirable trace-to-trace variations within super gathers. Nonetheless, it is a relatively efficient way to acquire pre-stack records with high trace density using a limited number of channels.

ADVANTAGES OF VERTICAL SEISMOELECTRIC PROFILING

Much of the noise that affects seismoelectric measurements made on surface can be significantly reduced by deploying antennas in water-filled boreholes that are either uncased (e.g. open holes in rock) or lined with slotted PVC casing so as to allow electrical contact with the surrounding formation. This is partly because of the inherent shielding provided by the earth. In addition, the lower contact impedance associated with the immersion of electrodes in water reduces the Johnson noise and usually completely eliminates AM demodulation interference.

Experiments can be conducted in boreholes to determine whether particular subsurface contacts will yield a measurable interfacial effect and such effects can be observed free of co-seismic signal interference by placing the electrodes below the interface of interest (Dupuis et al., 2007b). In addition there is a signal amplitude advantage since the signals are measured closer to their origin. Finally, borehole surveys are also of interest for their ability to log variations in the amplitude or character of the co-seismic signal as a function of depth that are related to fluid flow, electrical and mechanical properties of the surrounding formation (Mikhailov et al., 2000; Hunt and Worthington, 2000; Dupuis and Butler, 2006).

CONCLUSIONS

Improvements in instrumentation and field techniques are making it possible to record seismoelectric signals on surface and in boreholes more reliably and with higher success rates than ever before. Lessons learned with respect to preamplification, harmonic noise characteristics, trigger cross-talk, hammer impact noise, electrode contact resistance and AM radio demodulation have all combined to lower ambient noise levels. Techniques such as the acquisition of composite shot gathers and vertical seismoelectric profiles help to differentiate co-seismic and interfacial seismoelectric effects.

The development of robust commercial low-noise preamplifiers, with a cost comparable to that of geophones would help to accelerate progress by facilitating the use of the very large recording systems containing hundreds of channels that are now used to great advantage in CMP seismic reflection surveying. New processing algorithms and instrumentation capable of applying real-time harmonic noise cancellation should also be contemplated in combination with ongoing field efforts designed to investigate the geological environments more amenable to investigation by seismoelectric methods.

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