Shallow seismic AVO variations related to partial water saturation during a pumping test

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[1] High-resolution shallow seismic reflection experiments were conducted during and after a pumping test of an agricultural irrigation well to image the cone of depression. Although variations in the reflection time from the top of the saturated zone were not observed, amplitude-versus-offset (AVO) analysis revealed changes in reflection amplitude responses that correlate temporally and spatially to expected changes to the partially saturated zone induced by the pumping and recovery of the aquifer. The AVO responses exhibit dependence on aquifer drawdown and recovery cycles and the distance from the pumping well. We propose that near-surface soil heterogeneity and relatively rapid changes in the water table elevation during irrigation cycles caused a thickening of the partially saturated zone above the water table, which resulted in detectable changes in seismic reflection amplitudes. This study offers insights about the response of shallow seismic reflections to changes in subsurface water saturation and the potential application of seismic techniques to hydrogeophysical problems.
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1. Introduction

[2] Multiple attempts have been made to image the cone of depression around an agricultural pumping well using shallow seismic reflection (SSR) techniques [*Birkelo et al.*, 1987; *Johnson*, 2003; *Sloan*, 2005], however none have been successful. The study described here was intended to image the cone of depression by conducting multiple SSR surveys during and after a pumping test. Despite water table fluctuations of ~0.5 m, which were within the resolution limits, we were unable to observe temporal changes in the reflection from the top of the saturated zone (TSZ) that were attributable to pumping. However, AVO analysis of the data revealed seismic amplitude variations that correspond to differences in the applied pumping stresses and distances from the pumping well. We suggest that the thickness of the partially saturated zone (PSZ) above the water table is affected by a continuous cycle of pumping and recovery of an unconfined aquifer. Relatively rapid changes in the height of the water table in concert with small scale soil heterogeneities have caused a thickening of the PSZ, which results in detectable changes in the AVO response of the TSZ reflection. Figure 1 illustrates the zone affected by pumping where (A) represents the water table surface prior to pumping and (B) is the water table during pumping once it has reached steady-state conditions, forming the cone of depression.

[3] In order to relate the observed changes in reflection amplitude to the subsurface, we consider how the seismic properties of the subsurface might change as a result of the pumping cycles. The water table represents the fully saturated interface where water pressure is equal to atmospheric pressure. Immediately above the water table is the fully saturated capillary fringe, which underlies the PSZ. At steady-state conditions the thicknesses of the capillary fringe and PSZ are controlled by the grain size of the surrounding sediments. The enlarged section in Figure 1 depicts the increase in water saturation (S_w) from some residual value in the unsaturated zone to 100% in the fully saturated zone. During pumping, pore-bound water may remain above the drawn-down water table and as water levels return to pre-pumping conditions air can be trapped in the pore space beneath the water table. Such conditions would be expected to influence the seismic-velocity profile of the PSZ.

[4] *Knight and Nolen-Hoeksema* [1990] showed the effects of partial saturation on *P*-wave velocity (V_p) in a sandstone using two different methods of varying water saturations (Figure 2). One method increased S_w through imbibition, yielding velocities similar to those predicted by the Biot-Gassman-Domenico equations [*Domenico*, 1976] where velocities remain relatively constant with increasing saturation and increase very rapidly at saturations greater than ~90%. The second method achieved partial saturation through drainage, where velocities follow more of a curved path on the graph and increase exponentially with increased water saturation. These observations were made at the pore scale using ultra-sonic frequencies and consolidated sandstone samples under laboratory conditions. We suggest that analogous seismic velocity behavior, although not at the pore scale, will result in the PSZ from drainage and imbibition during irrigation cycles.

[5] *Mavko and Mukerji* [1998] relate this difference in velocity response to patchy and uniform saturation. They define uniform saturation as fine-scale, uniform mixing and patchy saturation as heterogeneous saturation on a coarser scale. They determined that patchy saturations always lead to higher velocities than uniform saturations. Saturation scales separating uniform from patchy behavior may be from 0.1–1 cm in the laboratory to tens of centimeters in the field.

[6] In a homogenous medium, such as a clean, well-sorted sand, water will drain evenly as the water table is lowered, resulting in a vertical translation of the PSZ [*Bevan et al.*, 2005]. However, at our field site, thin, discontinuous

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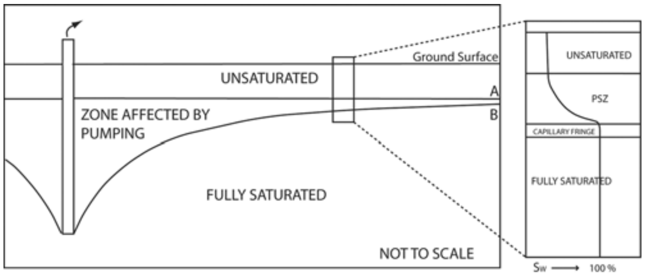

Figure 1. Illustration showing the water table before pumping (A), during pumping (B), and the zone affected by the raising and lowering of the water table. The enlarged section illustrates the soil-moisture profile.

clay layers interbedded with fine- and medium-grain sands form small scale heterogeneities. These varying near-surface soils have different field capacities, i.e. different abilities to retain moisture under gravity drainage. As the water table is drawn down, clays and silts will retain greater amounts of water than well-sorted sands causing patchy saturation. Localized areas of higher water saturation, which can be on the scale of 10 s of centimeters, will influence the seismic response. During imbibition, sediments will saturate more evenly, which is akin to uniform saturation. Although it is possible that the TSZ reflection coincides with a change in stratigraphy, we do not believe that a stratigraphic boundary is the controlling factor of the AVO response that we are observing in the data. Similar to our study, prior shallow seismic reflection experiments of fluctuating water table surfaces did not show changes in reflection times [*Birkelo et al.*, 1987; *Johnson*, 2003].

[7] We propose that we are observing a hysteretic effect analogous to that of *Knight and Nolen-Hoeksema* [1990], but on a larger scale due to patchy saturation caused by small scale subsurface heterogeneities. At the pore scale, hysteresis is possible because no interpore communication occurs with ultrasonic frequencies and seismic velocities are affected by fluid distribution [*Endres and Knight*, 1989]. At lower frequencies interpore communication does occur and the pore contents act as a single effective pore fluid [*Endres and Knight*, 1997]. Therefore a homogeneous medium will not exhibit a hysteretic velocity behavior. At our field site we suggest that lower frequencies respond to a velocity hysteretic effect caused by patchy saturations. *Endres et al.* [2000] also reported localized areas where, as the soil-moisture profile translated downward, sediments had higher water saturation and were detectable by GPR.

[8] *Sengbush et al.* [1961] describe the effects of various velocity functions on a reflected wavelet as a process of linear filtering. A sharp interface represented by a step-velocity function produces a reflection having the same waveform as the source pulse. A gradational interface represented by a ramp-velocity function produces a reflection that is the integrated source pulse. The effect of moving from a step-velocity function to a ramp-velocity function on a reflected wavelet is an overall lowering of the wavelet frequency and decrease in amplitude. Velocity changes related to imbibition would correlate with uniform saturation, approximated by a step-velocity function, and those related to drainage would correlate to patchy saturation, approximated by a ramp-velocity function.

2. Data Acquisition and Processing

[9] Common mid-point (CMP) seismic reflection surveys were conducted to image changes in the TSZ reflection during pumping of a shallow unconfined aquifer. Pre-pumping water table depth was ~4.7 m, measured at an observation well [*Sloan et al.*, 2007]. The first survey was conducted after the irrigation pump had been allowed to run continuously for three days at a rate of ~3785 L/min (1000 gal/min). Following aquifer recovery, ~18 hours after the pump was turned off, a second survey was acquired. A third survey was shot the following summer when, due to cooler temperatures, the pump had not been run for at least two weeks and water table fluctuations were limited to natural processes. The pumping well was located 5 m away from the east end of each of the surveys.

[10] Each survey was conducted using 144 Mark Products L-40A 100-Hz geophones planted at a 10-cm interval. The source was a .22-caliber rifle firing into 15-cm deep holes every 10 cm beginning and ending 5 m off of each end of the spread. Data were recorded using two Geometrics 72-channel StrataView seismographs with 24-bit A/D conversion, 256-ms record lengths, and 0.25-ms sampling interval. Acquisition parameters were identical for each survey. Data were processed using commonly applied techniques for AVO data, as described by *Castagna* [1995] and *Resnick* [1995]. Processing included geometry definition, elevation corrections, spherical spreading corrections, *f-k* filtering, CMP sorting, NMO corrections, and partial stacking.

3. AVO Analysis

[11] Although AVO methods and techniques are widely used in hydrocarbon exploration, little work has been done in shallow subsurface investigations. The near surface presents complexities that must be overcome to provide a data set of high enough quality to perform AVO analysis. The airwave, refractions, direct wave, and surface waves often prevent a wide range of offsets from being used due to

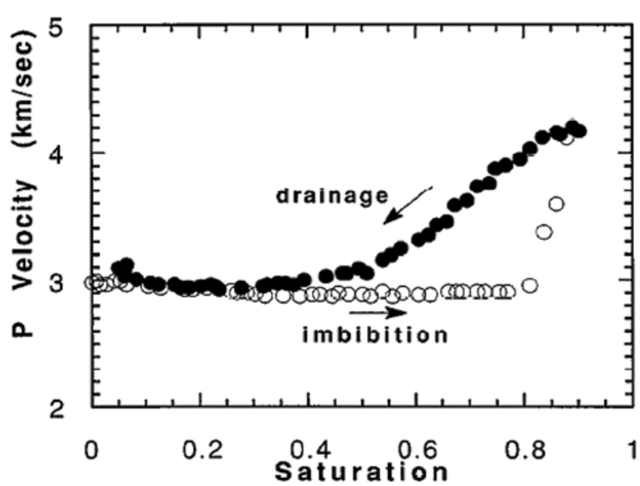

Figure 2. Plot displaying the changes in *P*-wave velocity with water saturation (from *Knight and Nolen-Hoeksema* [1990]).

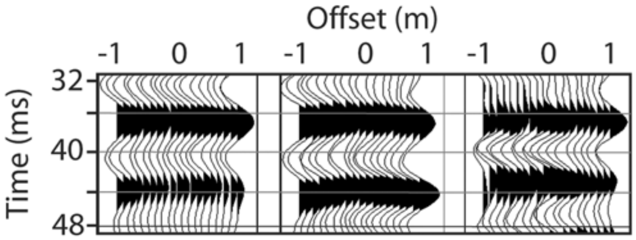

Figure 3. CMP supergathers from data collected (left) during pumping, (middle) during recovery, and (right) with no pumping.

interference with the reflections. Despite the associated problems, there are a few examples of SSR AVO studies [*Bradford et al.*, 1997; *Bachrach and Mukerji*, 2001; *Waddell et al.*, 2001]. *Bachrach and Mukerji* [2001] showed that the unsaturated/saturated sand interface exhibits an increase in reflection amplitude with increasing offset.

[12] Supergathers were created by partially stacking the common offsets of five adjacent CMP gathers (Figure 3). Each CMP gather was separated by 5 cm, covering a distance of 20 cm. Each of the three data sets was normalized to its respective RMS amplitude. The RMS amplitudes were calculated for each trace from a window around the TSZ reflection from 32–48 ms for offsets ranging from −1 to +1 m in 10-cm increments. The supergathers displayed in Figure 3 show data collected during pumping (drainage), after aquifer recovery (imbibition), and from the following summer when the pump was not used. The TSZ reflection consistently occurs at ~35 ms; however, the data collected during drainage (left) exhibit noticeably lower amplitudes and lower frequencies.

[13] Figures 4a, 4b, and 4c show plots of the relative amplitude versus CMP offset within a supergather for a range of distances from the pumping well during drainage and imbibition. The AVO response is represented by exponential curves fit to the data points using least-squares regression. For all distances from the pumping well, imbibition reflection amplitudes are greater than drainage reflection amplitudes, and reflection amplitudes increase overall with increasing offset. As the distance of the CMP supergather from the pumping well increases, the relative amplitude of each curve increases. Furthermore, the separation between the two amplitude curves in each plot is greatest near the pumping well. This effect is illustrated in Figure 4d using the difference of the two curves for each distance.

[14] Figures 4e and 4f show plots of relative amplitude versus CMP offset within a supergather for a range of distances from the pumping well for data collected during drainage and data from the following summer when the pump had not been used, respectively. During drainage, the relative amplitudes increase as the distance from the pumping well increases. In comparison, the amplitudes of the data acquired without pumping remain relatively consistent despite changes in the distance from the pumping well and display higher amplitudes than the drainage data.

4. Discussion

[15] The graphs in Figures 4a–4f show that seismic data collected during drainage exhibit lower amplitudes than those acquired both during imbibition and at no pumping conditions. This seismic amplitude relationship to pumping condition is observed at all distances from the pumping well and at all offsets within the supergathers. This observation is consistent with the seismic response expected from a patchy saturation velocity profile formed by drainage. Furthermore, the lowest amplitudes are observed at the supergather closest to the pumping well. As the distance of the supergather from the pumping well increases, so do the amplitudes, suggesting an increasingly sharper velocity transition away from the pumping well. As illustrated in Figure 1, drawdown will decrease as the distance from the pumping well increases. This response is illustrated by Figure 4d where as the distance from the pumping well increases, the separation between the curves decreases. Thus, as the distance from the pumping well increases, both hydrologic and geophysical responses decrease, suggesting a causal relationship. Figure 4e shows that as the distance from the pumping well increases, the amplitude increases while the pump is running. However, when the pump was not used and the water table was not drawn down, as in Figure 4f, the curves are clustered together and display higher amplitudes. These results further suggest that changes in the thickness of the PSZ due to elevation changes of the water table result in corresponding detectable seismic reflection amplitude changes.

[16] At undisturbed water table conditions (no pumping) it is expected that the PSZ will exhibit the most abrupt seismic velocity transition from unsaturated to fully-saturated conditions. As the water table is drawn down (drainage) and the thickness of the PSZ increases, the slope of the seismic velocity profile will also increase. The increase in the slope of the ramp-velocity function leads to lower seismic reflection amplitudes and frequencies [*Sengbush et al.*, 1961]. As the water table returns to equilibrium (imbibition) and the thickness of the PSZ decreases, the slope of the velocity ramp also decreases. This leads to an increase in reflection amplitudes and frequencies relative to those during drainage. The same PSZ disturbance behavior explains the seismic response as the distance from the pumping well increases and the drawdown of the water table decreases. At distances farther from the pumping well there are smaller changes in the elevation of the water table and a lesser effect on the thickness of the PSZ, which would lead to increasingly higher reflection amplitudes at farther distances. The observations of shallow seismic reflection amplitude response during pumping cycles are in agreement with the suggested PSZ thickness changes and analogous to the seismic velocity response to varying water saturation presented by *Knight and Nolen-Hoeksema* [1990] and *Mavko and Mukerji* [1998].

[17] Changes in the TSZ reflection amplitude may serve as an indicator of permeability near the water table. A more homogeneous and permeable material, such as a clean or well-sorted sand, would allow more uniform drainage during drawdown. Uniform drainage would have a lesser or no effect on the thickness of the PSZ, resulting in a smaller change in seismic amplitude. Conversely, lowering the water table in poorly-sorted heterogeneous soils would increase the thickness of the PSZ and exhibit a larger variation in amplitude. The results of this study could yield a more accurate representation of subsurface hydraulic

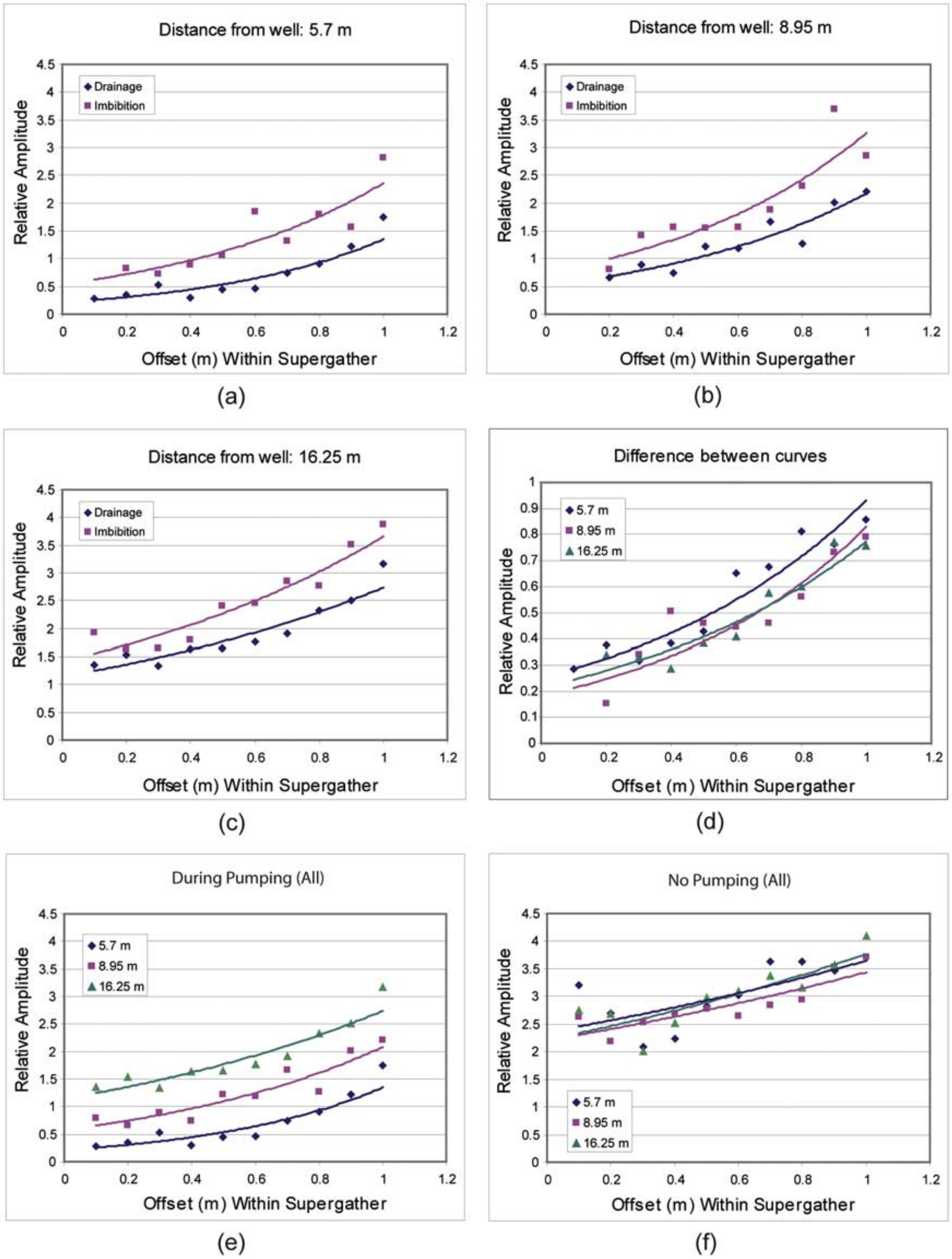

Figure 4. (a, b, c) AVO curves from data collected during (drainage) and after (imbibition) pumping for CMP supergathers at three different distances from the pumping well. (d) The difference between the two curves for each distance. AVO curves for all data collected (e) during pumping and (f) without any pumping.

properties when used in tandem with techniques that are sensitive to pore fluids, such as ground-penetrating radar and electrical methods. These techniques may also prove useful in understanding changes in water table and saturation fluctuations, which may be desirable in time-lapse studies at contaminated sites where non-invasive techniques might be necessary. Future work will focus on quantitatively relating the changes in amplitude to the thickness of the PSZ by monitoring soil moisture content.

5. Conclusions

[18] Imaging the cone of depression using shallow seismic reflection during a pumping test may be possible; however, it has not been documented in the literature to our knowledge, despite several attempts. Without prolonged drainage time, the length of which will vary with subsurface properties, some amount of pore-bound water will remain above the drawn-down water table. If there is a sufficient amount of water to produce a seismic reflection, temporal changes in the TSZ reflection will not be observed.

[19] The data presented here show that detectable changes in the AVO response of the TSZ reflection are observed in field data during a pumping test of an unconfined aquifer. The AVO responses correspond to different pumping conditions and varying distances from the pumping well, which can be explained by changes in partial water saturation above the water table. We show that lower seismic amplitudes observed during pumping (drainage) are consistent with the expected response of a thicker partially saturated zone. Recovery of the water table (imbibition) results in higher seismic amplitudes indicative of a thinner partially saturated zone. The techniques described here may be beneficial in observing changes in saturation and water table fluctuations and may help to constrain interpretations when combined with other geophysical and hydrogeologic data.

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