Cross well radar and vertical radar profiling methods for time lapse monitoring of rainfall infiltration

Elmar Strobach*, Brett D. Harris,
J. Christian Dupuis, Anton W. Kepic
Dept. of Exploration Geophysics, Curtin University
26 Dick Perry Ave, Perth, Western Australia
**corresponding author: elmar.strobach@postgrad.curtin.edu.au*

Michael W. Martin
Water Corporation Ltd.
629 Newcastle Street, Leederville, WA

The relationship between electromagnetic velocities derived from in-hole radar surveying and soil saturation can be exploited to map changes in recharge from rainfall infiltration in the vadose zone against time. We have completed time-lapse cross-well radar and vertical radar Profiling (VRP) experiments with the objective of monitoring rainfall infiltration during the winter season at two sites on the Gnangara Mound in the Perth Basin, Western Australia. Depth-velocity profiles have been derived from the direct transmission measurements. Results obtained from Vertical Radar Profiling and Zero vertical offset cross well profiling are evaluated and the influence of different geometries and test-site conditions are discussed. We find that zero vertical offset cross well radar experiments were highly repeatable. Further changes in ground conditions such as an increase in moisture content can be observed with great confidence. The interpretation of vertical radar profiles was more challenging. However both techniques successfully reveal the time-lapse response of water migrating through the unsaturated soil profile for the two trial sites.

Key words: Vertical Radar Profiling, Zero vertical offset crosswell Profiling, water infiltration

INTRODUCTION

We performed borehole radar measurements on various sites at the Gnangara Mound, north of Perth, Western Australia. The main objective was to observe water infiltration during the natural precipitation and infiltration cycle. The outcomes of this study will be incorporated into a biophysical vertical flux model called WAVES developed by the Water Corporation Ltd. of Western Australia. Recharge rates and distributions are a critical component of numerical groundwater modelling such as Perth Regional Aquifer Modelling System PRAMS (Xu et al. (2008).

We compare different borehole acquisition geometries at two test-sites. In order to observe the infiltration front moving through the ground, time-lapse experiments were performed before and during winter rainfall events.

Ground-penetrating radar is a common technique for investigating the shallow subsurface. In hydrogeophysics, GPR can be used to estimate water content. This is because the propagation of electromagnetic waves at radar frequencies is strongly dependent on water content as the dielectric permittivity of water is one order of magnitude greater than permittivities of most earth materials (Huisman et al. (2003)). GPR is largely used as an imaging tool with antennas employed at the surface collecting data in common-offset mode along 2D lines. This geometry has limited ability to recover accurate velocity profiles. Velocity can be estimated from the shape of diffraction hyperbolae. However this method provides rough estimates only and depends on the often unknown azimuth and geometry of the diffractor. Velocity can also be inferred from the two-way travel-time of a reflected wave originating at a reflector of known depth such as the water table (Huisman et al. (2003). If two travel time from a know reflector depth is used, the resultant velocity is the average velocity between surface and point of reflection. The point of reflection must to be known with high certainty. This proves problematic for the water table as the electromagnetic waves are being reflected somewhere around the capillary fringe rather than the exact gravimetric water table level (Pyke et al. (2008)).

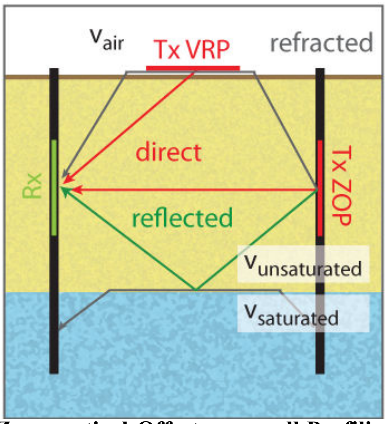

Figure 1: Zero vertical-Offset crosswell Profiling ZOP and Vertical Radar Profiling VRP acquisition geometries and possible raypaths. Note the refracted raypaths along the high contrast interfaces air-soil and unsaturated-saturated.

Multi-offset surface radar measurements can reveal a more accurate velocity-depth distribution by analysing direct ground arrival and reflection hyperbola. Their interpretation, however, can be challenging as the direct ground arrival can be altered due to a low-velocity waveguides and associated dispersion (Van der Kruk et al. (2009). Further the reflection hyperbola adaption or semblance analysis relies on reflections being present.

The most direct and accurate method of obtaining a velocity profile is by zero vertical offset crosswell profiling or constant-offset crosswell tomography. Note that Rucker and Ferre (2003) called the method zero-offset profiling ZOP which has been widely accepted and despite the similarity to zero-offset seismic profiling, we will use the abbreviation ZOP in the following. Crosswell measurements require a pair of vertical boreholes (see Figure 1) and two borehole radar antennas. The antennas are lowered into each well separately (e.g. Rucker and Ferre (2003). For zero vertical offset profiling, both antennae are lowered at the same speed so their midpoint positions remain at the same depth. The accuracy of this method depends on borehole separation and how accurate it is known, and the frequency of the antenna.

Another second method that can be used to obtain a 1D velocity profile is Vertical Radar Profiling (e.g. (Tronicke and Knoll (2005); Clement and Knoll (2006)). In this configuration only a single hole is needed. One borehole antenna is lowered in the hole while a second antenna (i.e. typically the transmitter), remains at constant position on the surface with horizontal offset x.

METHOD

We measured VRPs and ZOPs at several test-sites throughout the Gnangara Mound. The sites were originally chosen for shallow groundwater system investigation by the Department of Water, Western Australia (Searle and Bathols (2009)). We present data from the High Hill Road West (HHW) and Whiteman Park shallow groundwater monitoring sites. All datasets were acquired with the Mala's 100 MHz slimhole antennas and the ProEx system linked with a field laptop that runs the acquisition software GroundVision 2.0. The trace spacing was 1.5 cm for all measurements and The sample interval is 0.2 ns.

.At the High Hill Road West (HHW) test site we performed three time-lapse ZOP and three multi-offset VRP experiments. The experiments were completed in 2011 at; (i) the beginning of May before rainfall events (ii) the end of June after approximately 100 mm of precipitation, and (iii) at the beginning of August after another approximately 100 mm of rainfall.

For HHW the May and August VRP data was collected with a 2 m transmitter offset (i.e. on the surface), while the June dataset was collected at zero-offset only. The stratigraphy at HHW consists of unsaturated layered sands of the Bassendean Formation. The water table is at 11.8 m below ground level and remained approximately constant until August. Within theses sands some heterogeneities are present such as silty sections and a "[...] strong brown [...] weakly cohesive and consolidated" silty sand horizon between 1.4 – 2 m (Searle and Bathols (2009)).

WP

The Whiteman Park test site is co-located with a winter pumping trial. The site is also the subject of vegetation monitoring and research being completed by a team lead by Froend and Davies from Edith Cowen University. The site has been geophysically characterised by means of 3D GPR and 2D electrical resistivity tomography by Strobach et al. (2011). Time-lapse Neutron measurements are compared to the crosshole radar experiments (Figure 3). A dark cemented soil horizon is present at approximately 2 m depth which is known to contain elevated water content (Bertuch and Froend (2006). Strobach et al. (2011)) characterized the spatial variability and estimated water content of that layer from surface GPR to be between 0.8 v% and 0.15 v%. Depth to water varied between 4.8 mbgl (metre below ground level) in May and 5.4 mbgl in August. Here, ZOPs and VRPs are presented that have been acquired on two occasions in early July and August. The VRPs were acquired with a transmitter offset of 1 m. The distance between the holes is 11.5 m and so facilitate a substantially different geometry compared to the HHW.

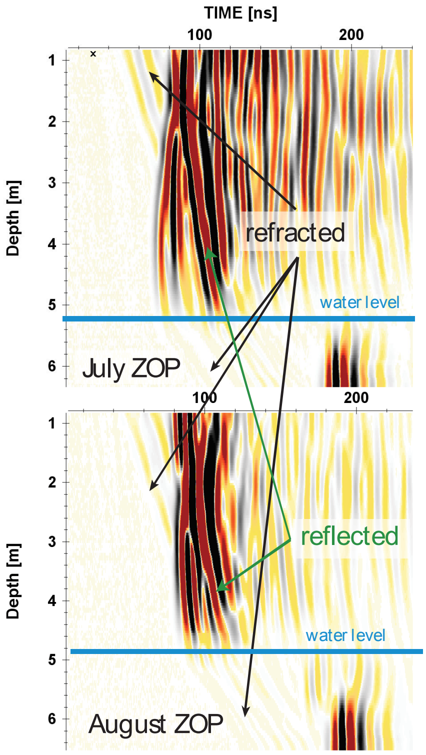

Figure 2: Zero vertical-Offset crosswell Profiles ZOPs at Whiteman Park acquired in July (upper) and August (lower). Borehole separation is 11.5 m. Note the change in traveltime of waves arriving at 2 – 5 m depth due to moisture increase at depth in August.

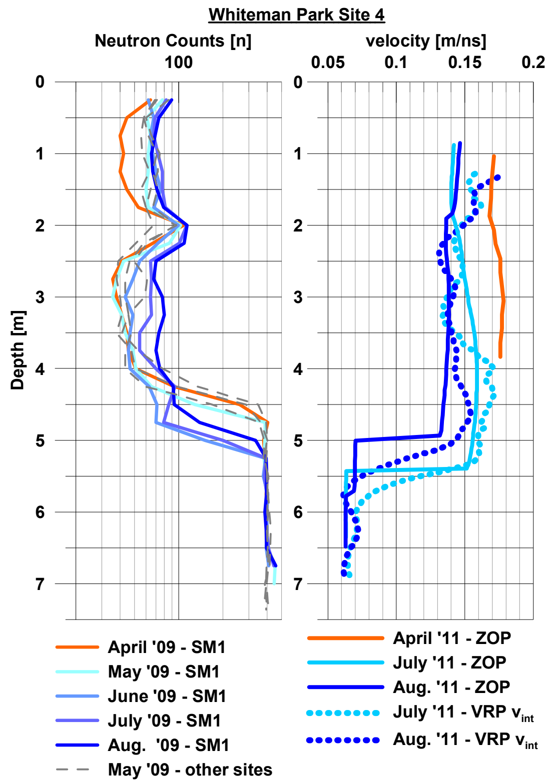

Figure 3: Raw time-lapse Neutron counts (left) and radar wave velocity (right) from Whiteman Park. Both techniques are a direct indicator for moisture content. The time-lapse response shows water infiltration through the

Processing
Data was processed with ReflexW 6.0 and VRPs interpreted with RadExPro 3.95. There were two peculiarities in the data. Firstly there were spikes and secondly clipped amplitudes. Both are not uncommon in radar data. Clipping was most severe for the cross well survey in the very close holes at HHW. While the clipping ruled out any prospect of recovering full amplitude information it did not affect picking of travel times. After considerable testing it was concluded that picking the zero crossing was most repeatable and robust location for recovering of travel times. The first processing step was to identify time-zero. This was done by placing the antenna at a known distance in an upright position (air-launched dipole in full-space). The zero-crossing was then picked and taken to be first-arrival time. That is, the time shift can be determined because travel velocity and distance are well known in air. Other processing steps included, short de-spiking 2D-Median filter, DC-removal, re-sampling to 0.1 ns and stacking over 0.1 m of traces.
Velocity-depth profiles for the ZOPs were calculated from direct-ground arrival travel-times assuming straight rays. For ZOPs the problem is simple, provided the direct ground arrival time (i.e. not the refracted wave) is. For the VRPs we used the interval velocity calculation in the 'Advanced VSP Display' of RadExPro with a regularization of 0.25 and a window of 1.2 m. The window was chosen close to the estimated resolution power according to the length of the antenna and the Fresnel zone. Those parameters comply in effect with Occam's principle which is a reasonable approach as first-arrival travel-times can be quite noisy (Clement and Knoll (2006)).

RESULTS

The resultant ZOP – and VRP – velocity profiles are presented in Figure 3 and Figure 5 for WP and HHW, respectively. HHW shows a very good repeatability for the ZOP velocities below 3 – 4 m, while drastic changes are obvious in the first few meters due to infiltration events. Note that we adjusted the static correction for the time lapse ZOPs so absolute values in the saturated zone are identical. In June after the first ~100 mm of rainfall, the infiltration front reached a depth of approx. 1.8 m (Figure 3, dashed grey line) according to the ZOPs. This depth correlates well with a low-velocity horizon already present in the May data (Figure 3, dashed pink line). This layer is the slightly cohesive, cemented silty sand as described earlier. The wetting front then continued to migrate through the profile and reached a depth of ~3.5 m in August (dashed blue line) after another ~100 mm of rainfall.
VRPs show similar infiltration behaviour, but are less repeatable at greater depth. In the first few meters, the VRP curves seem to be shifted to greater depth relative to the ZOP data while displaying the same curvature. At greater depth the curvatures between ZOP and VRP match again, but the absolute values of the VRP are higher than the ZOP velocities (0.135 m/ns vs. 0.155 m/ns → 25%). In the saturated zone below 11.8 m, the VRPs give slower results. Their repeatability, however, is increased.
At WP both techniques reveal similar results. As no VRPs and ZOPs were performed before rainfall, we show the dry result extracted from a dataset acquired for tomography from April. The plots show the ZOPs as smooth curves. A decrease in velocity with time and depth, however, depict the infiltration between the two wells. While the VRPs show more vertical heterogeneity, they do not resolve the cemented horizon which is expected to have a lower velocity.The raw neutron counts presented in Figure 3 show the general infiltration behaviour around borehole SM1 at WP, which is one of the ZOP holes.

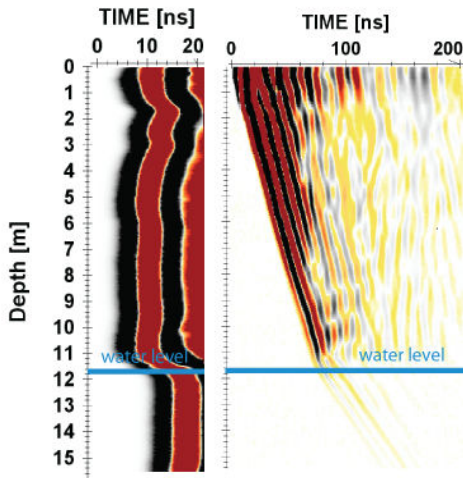

Figure 4: Examples of Zero vertical-Offset crosswell Profile (left) and Vertical Radar Profile (right) at High Hill Rd West where boreholes are at 1 m distance.

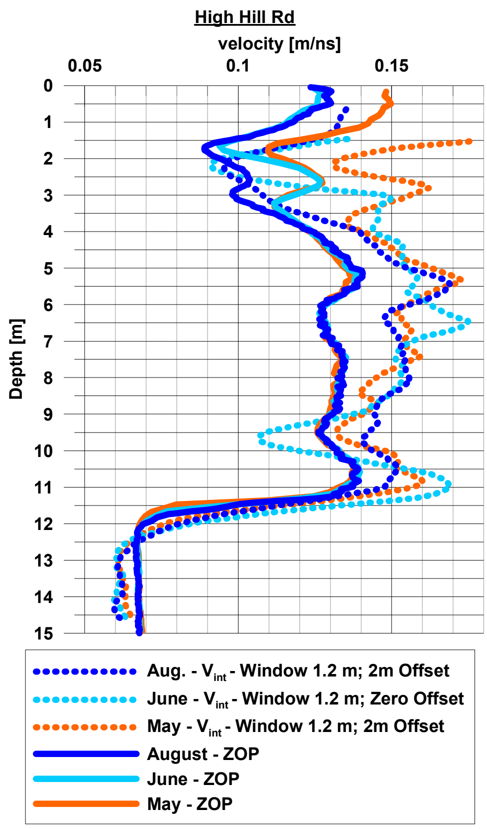

Figure 5: Time-lapse zero vertical-offset crosswell profiling (solid) and vertical radar profiling (dotted) velocities obtained at the High Hill Rd West test-site. Note the good agreement of time-lapse velocity changes due to infiltration between the two methods.

DISCUSSION

The calculation of velocity-depth profiles is straightforward for the ZOPs at 1 m separation at HHW, as almost no refracted energy has to be expected from the air-soil or between unsaturated-saturated interfaces, and the Fresnel-zone R_f is small ($R_f \sim 0.6$ m). The only limiting factor for resolution is the length of the antenna and the frequency, which are linked. For the 11.5 m separated holes, not only the Fresnel-zone increases which leads to lower resolution power ($R_f \sim 2$ m), but also refraction at high-contrast interfaces occurs. At large separation, major refractions can be identified due to their relatively small amplitudes and because of their linear characteristic. Refractions in ZOPs are discussed in Rucker and Ferre (2003). Here, we decided to pick the large amplitude direct arrival zero-crossing as it did not seem to be interfering with the refracted arrivals from the large contrast interfaces (air-soil, unsaturated-saturated). The known cementation horizon at WP is noticeable in the ZOP as a kink in the curve. Its low-velocity property cannot be identified due to refracted waves above and below the layer. The low-velocity layer behaves as a waveguide with a wave train arriving at later times. Also reflections above and below the layer are identifiable as hyberbolic events. The VRPs have no problem with refracted air waves as they are proximate to the hole (x = 1 m). Potential problems occur in the VRP data due to reflected upgoing waves that interfere with the direct wavefield. Zero-offset VRPs were difficult to pick as polarities seemingly changed, so we discarded them and used 1 m offset data instead.

Possible explanations for the discrepancy between ZOPs and VRPs at HHW below 3 m include: a) dispersion in the VRP which leads to phase shifts, b) changing antenna radiation pattern due to varying ground conditions between transmitter and receiver, c) unidentified systematic error e.g. due to distance variations. Explanations a) would have a change in waveform, i.e. frequency content as a consequence, which we could not observe. Also the zero-crossing as it resembles group velocity would be less influenced. Point b) would have a small impact on travel-times as the variations in dielectric permittivity are not large. Especially group velocities would not be as affected as amplitudes. An unidentified systematic error is possible. A change in borehole separation of 10 – 20 % equates to 10 – 20 cm at HHW, which at 10 m depth equates to 0.5° - 1° deviation from the vertical axis which would explain the observed difference. Below the water table, however, we find larger values for the ZOP which would mean that the boreholes diverge at first and converge again below the water table.

CONCLUSIONS

We have measured time-lapse zero vertical-offset crosswell radar profiles and vertical radar profiles at two test-sites with borehole distances of 1 m and 11.5 m. At both sites we were able to observe infiltration due to natural rainfall within a period of 3 month. The ZOPs proved superior for holes at proximate distance (High Hill Rd HHW, 1 m separation) in terms of vertical resolution compared to VRPs. Especially the repeatability at the lower borehole interval where no relative change was observed made the ZOP results more credible. The absolute ZOP velocities, however, carry errors due to variations in borehole separation or inaccurate zero-time correction. At large borehole separations (Whiteman Park, 11.5 m separation), calculated velocities represent averaged subsurface properties due to the increased Fresnel zone and refracted energy. At WP ZOPs and VRPs reveal similar absolute velocities. The time-lapse neutron logging data from winter 2009 and our investigation show very similar infiltration behaviour and the borehole radar measurements are therefore a potentially powerful tool to monitor water infiltration in a natural setting. Borehole radar measurements have some advantages over neutron measurements such as GPR being an innocuous technology and that it characterizes the subsurface in the far field between wells.

ACKNOWLEDGMENTS

We would like to thank Andrew Greenwood, Konstantin Tertyshnikov and Eva Caspari for assistance in the field. Neutron data is provided by the Water Corporation. Elmar Strobach is funded by a Curtin University international postgraduate research scholarship and a student research grant by the Australian Society of Exploration Geophysics. The research was taken out under a Centre of High Definition Geophysics (CHDG) project and research grants provided by the Water Corporation.

REFERENCES

Muriel Bertuch and Ray Froend. Winter drawdown trial - whiteman park, soil characterisation report. Technical report, Edith-Cowan University, School of Natural Sciences, Perth, Western Australia, July 2006.

William P. Clement and Michael D. Knoll. Traveltime inversion of vertical radar profiles. *Geophysics*, 71 (3): K67–76, 2006. doi: 10.1190/1.2194527.

J. A. Huisman, S. S. Hubbard, J. D. Redman, and A. P. Annan. Measuring soil water content with ground penetrating radar: A review. *Vadose Zone J.*, 2 (4): 476–491, 2003. doi: 10.2113/2.4.476.

Kendra Pyke, Sami Eyuboglu, Jeffrey J. Daniels, and Mark Vendl. A controlled experiment to determine the water table response using ground penetrating radar. *Journal of Environmental and Engineering Geophysics*, Volume 13, Issue 4: 335 – 342, 2008.

Dale F. Rucker and Ty P. A. Ferre. Near-surface water content estimation with borehole ground penetrating radar using critically refracted waves. *Vadose Zone Journal*, 2 (2): 247–252, 2003. doi: 10.2113/2.2.247.

J. Searle and G. Bathols. Bore completion report for the shallow groundwater system investigation stage 2. *Department of Water, Western Australia, Hydrogeological record series*, HR 276, 2009.

E. Strobach, B. D. Harris, J. C. Dupuis, A. W. Kepic, and M. W. Martin. Estimation of water content in partially saturated soil horizons with ground-penetrating radar. In *73rd EAGE Conference and Exhibition, 23-25 May 2011, Vienna*, 2011.

Jens Tronicke and Michael D. Knoll. Vertical radar profiling; influence of survey geometry on first-arrival traveltimes and amplitudes. *Journal of Applied Geophysics*, 57 (3): 179–191, April 2005.

Jan Van der Kruk, H. Vereecken, and Robert W. Jacob. Identifying dispersive gpr signals and inverting for surface wave-guide properties. *The Leading Edge*, 28 (10): 1234–1239, 2009. doi: 10.1190/1.3249780.

C. Xu, M. Canci, M. Martin, M. Donnelly, and R. Stokes. Perth regional aquifer modelling system (prams) model development: Application of the vertical flux model. *Department of Water, Western Australia, Hydrogeological record series*, HG 27, 2008