Stoneley wave dispersion in a high permeability sandstone: Perth Basin, Western Australia

Majed AlMalki*
Curtin university
Western Australia, Perth
m.almalki3@postgrad.curtin.edu.au

Brett Harris
Curtin university
Western Australia, Perth
b.harris@geophy.curtin.edu.au

J. Christian Dupuis
Curtin university
Western Australia, Perth
c.dupuis@curtin.edu.au

SUMMARY

There is increasing support for the existence of a relationship between Stoneley wave characteristics and permeability in sandstone formations. We evaluated monopole full waveform sonic data sets acquired in a mudded drill hole at the Mirrabooka Aquifer Storage and Recharge trial site in Perth, Western Australia. To increase the spectral range of the full wave form sonic data the hole was logged three times with transmitter centre frequencies at 1, 3 and 15 KHz. Data were recorded in four receivers spaced at 1ft intervals with the first receiver at 3ft from the transmitter. Stoneley waves were clearly identified in the low frequency range of 1–5 KHz, which is characteristic of Stoneley wave propagation in a slow formation.

A semblance slowness technique was used to determine the slowness of Stoneley wave. Slowness values ranged from 950 µs/m (V_{ST} = 1050 m/s) for sandstone to 1650 µs/m (V_{ST} = 600 m/s) for shaley sediments.

Observations of the dependence of phase velocity on frequency were made by using multi filter and phase shift transform techniques. The relationship between Stoneley wave dispersion and fast flow, high permeability pathways, as identified in flow and time lapse induction logging data, was clearly observed in an interval from 330 to 333m below ground level. This high permeability sandstone layer can be identified in dispersion curves by assessing frequency and phase velocity shifts. Our outcomes are significant, as they present the possibility of identifying narrow high permeability layers in wells where full waveform sonic logs have been completed.

Key words: Velocity dispersion, Stoneley waves.

INTRODUCTION

One relatively new and important application of full waveform acoustic logging is to determine fluid effects in poroelastic media. A Stoneley wave (tube wave) is a dispersive wave mode that dominates the monopole full waveform at low frequencies with large amplitudes and low velocities (Tang, 2004). A Stoneley wave can be generated in borehole fluid and involves particle motion propagation along the borehole wall (Bakulin *et al*., 2008). During propagation, the Stoneley wave compresses the fluid inside the borehole, which helps pass the fluid through the formation. When a Stoneley wave encounters a permeable bed, its slowness and attenuation increases (Williams *et al*., 1984; Winkler *et al*., 1989; Tang 2004; Bakulin *et al*., 2008). In an unconsolidated sandstone formation, Cheng *et al* (1987) numerically found two reasons why Stoneley waves are sensitive to the formation permeability. First, the Stoneley wave's frequency (up to 3 KHz) is low enough to the range of frequency where its sensitivity can increase with permeability. Secondly, in consolidated and unconsolidated sandstone sequences, permeability variation is high and such permeability typically falls into a range (from 10 to >3000 mD) where Stoneley wave dispersion should be sensitive to changes in permeability.

We present results of dispersion analysis for Stoneley waves from field data. We use multi-filter analysis and phase shift transform (Park *et al*., 1998) techniques to compute the dispersion curve. Flow logging in nearby production well combined with time lapse induction logging in monitoring wells clearly identify narrow fast flow high permeability pathways (Malajczuk, 2010). A comparison between these fast flow pathways and Stoneley wave dispersion curves is made.

METHOD AND RESULTS

The study site is located at the Mirrabooka Aquifer Storage and Recovery (ASR) Trial area on Gnangara Road approximately 15 km north Perth, Western Australia. The site consists of one injection and five monitoring boreholes (M345_207 and M345_208, _108, _109, _308, and _408, respectively) shown in Figure 1. All boreholes penetrate the Leederville aquifer (Rockwater Proprietary Limited, 2009). The full waveform sonic field experiment was performed in monitoring well M345_109. The purpose of the FWF sonic surveys was to improve the understanding of the strong heterogeneity in the Leederville aquifer within the injection interval (i.e., 320–428 m below surface). During the first cycle of the injection and recovery process, a total 190 ML of water was injected into the Leederville formation through borehole M345_207. The injection well M345_207 is approximately 40 m from monitoring well M345_109 (Prommer *et al*., 2011). Fast high permeability pathways for groundwater flow were identified by using time lapse induction logs at monitoring boreholes M345_109 and M345_408. According to Malajczuk (2010), the fast flow was identified in the layers located at: 330–333,350–356,366–373 and 398–401 m below ground level. These key intervals are located within the weakly consolidated sandstones of the Wanneroo member of the Leederville formation.

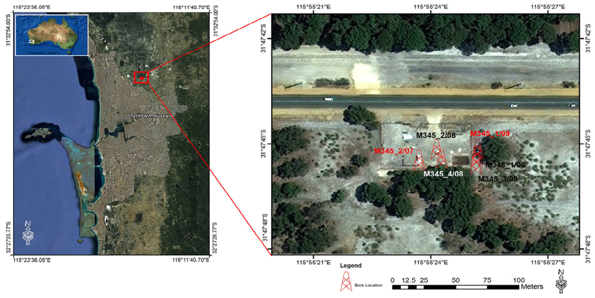

Figure 1: View of study site. Well M345_109 at Mirrabooka Aquifer Storage and Recovery (ASR) site is used for acoustic experiment.

The injection interval can be simplified into several thin (i.e. typically <10 m thick), high hydraulic conductivity (i.e. often >10 m/day) sandstones and low-permeability siltstone/shale layers. The transition between high and low hydraulic conductivity layers is often sharp (Harris *et al.*, 2010). This hydraulic characteristic suggests that the study site is ideal for studying the link between Stoneley wave dispersion and permeability in sandstones. In particular we focus on the interval between 330 and 333 m where very high hydraulic conductivity was observed.

Full waveform sonic logging

Three multi-frequency full waveform sonic data sets were recorded at borehole M345_109. They were acquired at a selected transmitter centre frequencies of 1, 3 and 15 KHz. Data was recorded by four receivers spaced a 3,4,5 and 6 ft from the transmitter. A recording length of 4.25 ms was used for the 1 KHz dataset such that low frequency Stoneley waves could be identified (Figure 2).

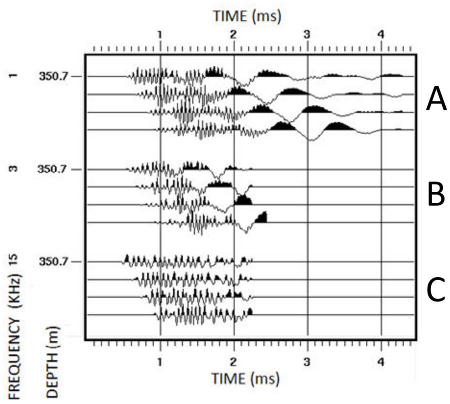

Figure 2. An example of full waveform sonic logs acquired at transmitter frequencies of 1, 3 and 15 KHz. (A) 1 KHz data set with recording length was over 4 msec. (B) and (C) are 3 KHz and 15 KHz logs, respectively. Recording length for B and C was approximately 2.45 msec.

Slowness and frequency of Stoneley wave

A multichannel semblance algorithm was used to determine Stoneley wave slowness. Semblance S_T is calculated from the ratio of the total energy (g) of the stacked amplitude within a window of length ($1+m\Delta$) to the sum of the energy of the individual traces within the same time window. The S_T algorithm given by Neidell and Taner, (1971) is;

$$S_T = \sum_{t}^{t+m\Delta} \left(\sum_{i=1}^{N} a_{ti} \right)^2 \Big/ N \sum_{t}^{t+m\Delta} \sum_{i=1}^{N} (a_{ti})^2$$

Figure 3 shows that Stoneley wave slowness is sensitive to the formation’s properties. For example, for sandstone and shale layers, the slowness variation is in the range of 950 to 1650 µs/m. On that basis, it is expected that the sandstone/clay sequences have *S*-wave velocity less than the acoustic velocity of the borehole fluid (water) which results in a Stoneley wave energy of up to 5 KHz. In this example well, the porosities of the weakly consolidated sandstone ranged from 25 to 35 percent and the permeability ranged from 10 to greater than18000 mD. These ranges are suitable for using Stoneley wave dispersion to investigate permeability effects at low frequency up to 5 KHz.

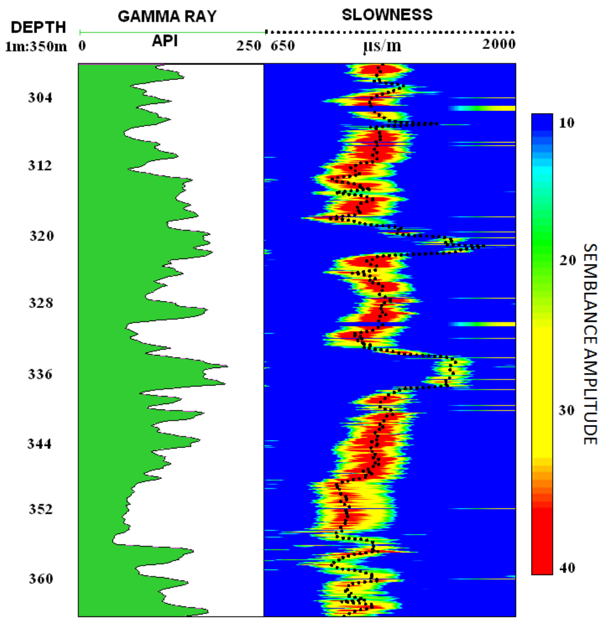

Figure 3. Semblance analysis of Stoneley wave events. The dotted line represents the slowness values. The red and blue denote strong and weak coherence amplitudes, respectively. The green track on the left depicts gamma ray values.

As seen in Figure 4, Stoneley wave energy is highest in the low frequency range of 1–5 KHz; which is a characteristic of Stoneley waves in a slow formation where *S*-wave velocity is less than the acoustic velocity of the borehole fluid. In Figure 4, the transmitter centre frequency was set to 1 KHz in order to investigate Stoneley wave energy at FWF sonic logging low frequencies.

Although the specified source frequency was 1 KHz, the resulting amplitude spectra show that a pulse with a wide spectral energy is generated, with a maximum energy level near to the selected transmitter centre frequency.

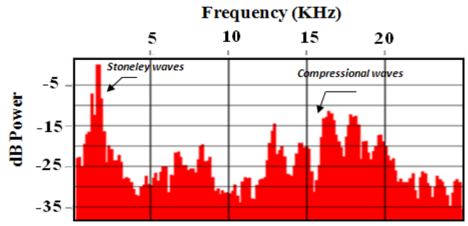

Figure 4: An example of power amplitudes for the source centred frequency at 1 KHz. Stoneley waves are present up to 5 KHz. The higher P-wave mode extends to 25 KHz.

Stoneley wave dispersion

Two techniques were used to determine Stoneley wave dispersion:

(A) Multi-filter analysis

Figure 5 shows the steps included in multi-filter analysis (MFA). First, in the time domain, we select two recoded signals (separated by known distance) and apply a muting window around the Stoneley wave wavelet. Then, a bandpass filter is applied every 0.05 KHz along the frequency axis. The bandwidth of the bandpass filter was centred over the peak of Stoneley wave energy in the frequency range of 1.1 to 2.8 kHz. The overlapping bandwidths help to produce a smooth and continuous dispersion curve. Subsequently, we cross-correlated the filtered data and combined them to generate cross-correlation gather. The maximum amplitude among the cross-correlation gathers was picked to obtain the travel time differences Δt at each frequency. The velocity of Stoneley wave is then obtained by known the distance between the input signals (e.g. 1ft between receiver 1 and 2) and Δt at each central frequency band. The results can be used to produce a partial dispersion curve over the selected bandwidth.

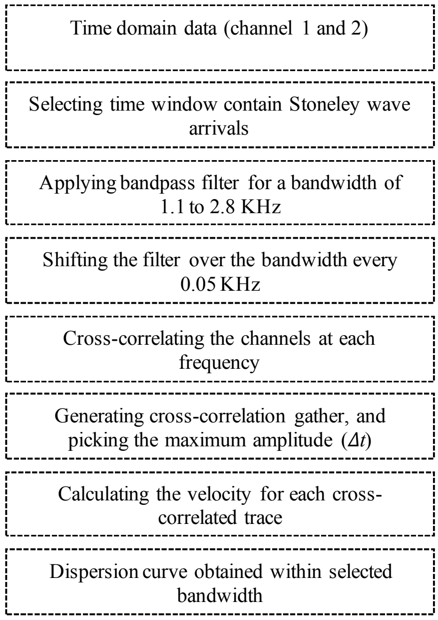

Figure 5. Flow chart of multi-filter analysis used to obtain dispersion curves at low frequencies.

Figure 6 shows an example of cross-correlation gather (bottom subfigure) for dispersion curve (top subfigures) obtained at three different positions (e.g. depths of 369.6, 369.7 and 369.8 m).

In MFA, the bandpass filter should be wide enough to cover most of the Stoneley wave energy at the low frequencies and should avoid the sharp slope of the cut-off filter frequencies. Movement of the filter window should be small enough comparing to the fundamental frequency of the signal. However, MFA has limitations at frequencies lower than 1 KHz. As shown in the upper subfigures of Figure 6, at all three depths, the low frequency band (1.25-1.45 KHz) produced a straight line, indicating no change in Stoneley wave velocity. To overcome this limitation in the lower frequency region, another technique is required.

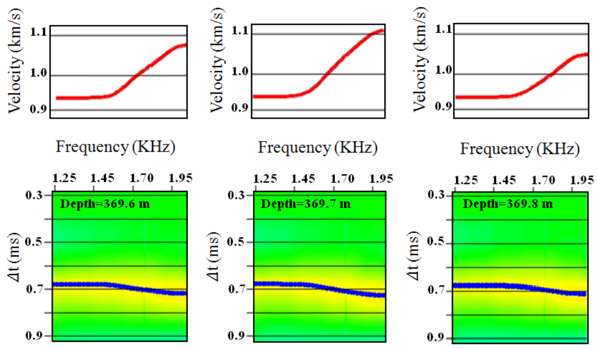

Figure 6. Examples of dispersion curves obtained by multi-filter analysis. The lower subfigures show cross-correlation gather values at three depths (369.6, 369.7 and 369.8m). The blue lines shows Δt values at each frequency. The upper subfigures show the associated velocity dispersion curves.

(B) Phase shift transform

A phase shift transformation technique was introduced by Park et al. (1998) for the analysis of the surface wave at low frequency of the seismic data. This technique was successfully used here (using four receivers) to obtain dispersion curves at low frequencies. The images obtained by applying phase shift transformation shown here as high-resolution dispersion curves starting from a frequency as low as 0.6 KHz (Figure 7). By applying this technique, dispersion curves in clays and sandstones can be observed. As shown in Figure 8, the dispersion curve for sandstone increases more sharply than that for clay and it shifted to a lower frequency.

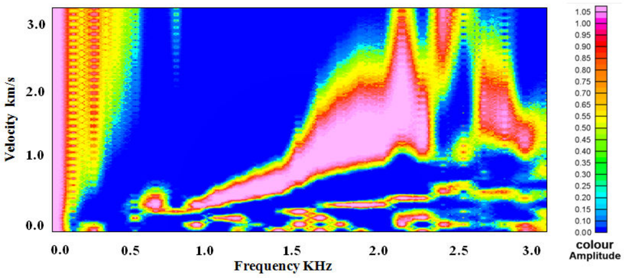

Figure 7. Dispersion curve obtained by applying phase shift transformation; red and blue colours indicate high and low amplitudes, respectively.

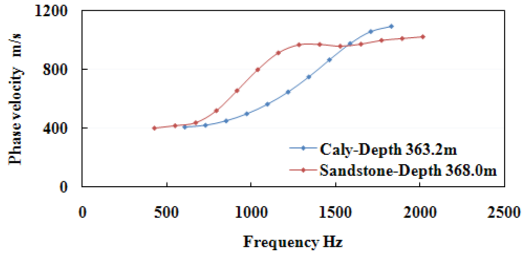

Figure 8. Dispersion curves obtained by using the phase shift transform method for clay (blue) and sandstone (red).

An important characteristic of dispersion curves is in their shape as a function of frequency. As indicated in Figure 9A, the dispersion curve at low velocity value of 0.7km/s remain nearly constant over the selected interval, except in high permeability zone where the dispersion curve tends to shift slightly backward to a lower frequency range with lower magnitude of the transformed amplitude.

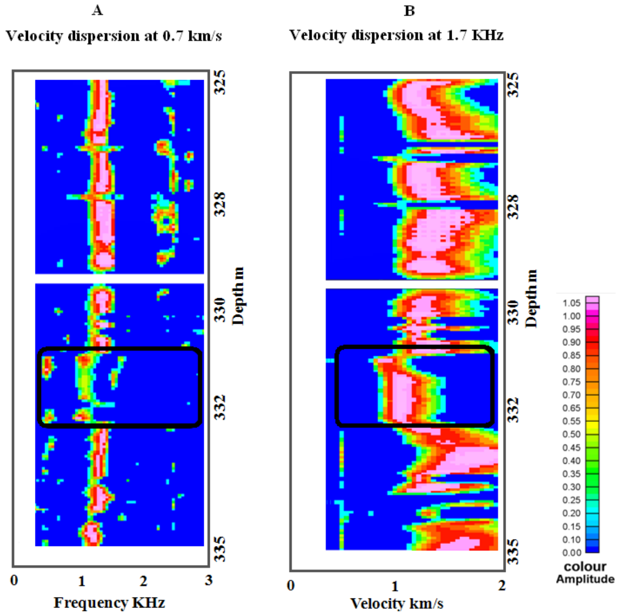

Figure 9. Phase-velocity dispersion of Stoneley wave, as function of depth, obtained by phase-shift method. The key depth interval is highlighted by the black boxes. A) Dispersion curve at a velocity of 0.7 km/s as a function of frequency. The dispersion shows a shift to a lower frequency, due to possible permeability effects. B) The dispersion curve at a frequency of 1.7 KHz as a function of velocity. The velocity decreased in the key permeable layer.

Figure 9B, the dispersion curve at a frequency of 1.7 KHz is plotted as function of velocity. As can be seen, the phase velocity variations are also an indicator for permeable sandstones zone. The figure shows that the velocity decreases significantly between 330 and 332m. These highly characteristic of dispersion curves mean that high permeability sandstone layers should be readily identified in FWF sonic data.

CONCLUSIONS

Acoustic data is successfully used to assess the velocity-frequency dependence of Stoneley wave in high permeability sandstone layers. It was found that the most permeable layers had highly characteristic dispersion curves. The highest permeability layers at the M345 site, could be readily identified by analysing Stoneley wave dispersion curves (e.g. the layer 330 to 333 at drill hole M345-109). More low frequency FWF sonic data will be needed before a robust imperial relationship could be used to directly map Stoneley wave dispersion to permeability in the sandstones of the Wanneroo formation.

REFERENCES

Bakulin, A., Alexander, S., Boris K. and Mikko, J., 2008, Acoustic surveillance of production impairment with real-time completion monitoring: SPE 112301, 2008 SPE International Symposium and Exhibition on Formation Damage Control, Lafayette, Louisiana.

Cheng, C, H., Zhang, J. Z. and Burns, D, R. 1987**.** Effects of in-situ permeability on the propagation of Stoneley (tube) waves in a borehole: Geophysics 52, 1297-1289.

Harris, B., Dupuis, C., Almalki, M., Li, Q., Martin, M. and Prommer, H.2010. Near well seismic methods for aquifer recharge projects: Perth Basin Western Australia. ISMAR7, Abu Dhabi, UAE.

Malajczuk, S., 2010, Time lapse thermal and induction logging in the near well environment, Perth Basin WA: BSc (Geophysics) Honours, Report GPH 15/10, Curtin University, November 2010.

Park, C. B., Miller, R. D., and Xia, J., 1998, Imaging dispersion curves of surface waves on multichannel records: 78th Annual International Meeting, SEG, Expanded Abstracts, 1377–1380.

Prommer, H., Descourvieres C.D., Handyside, M., Johnston, K., Harris, B., Li, Q., Fang, H., Costello, P., Seibert, S. and Martin, M., 2011, Interim Report – Aquifer storage and recovery of potable water in the Leederville Aquifer. CSIRO: Water for a Healthy Country National Research Flagship.

Rockwater Pty Ltd, 2009, Mirrabooka aquifer storage and recovery trial: bore completion and hydrogeological evaluation: Report no 236.20.4/09/01. Water Corporation.

Tang, X.M. and Cheng, A., 2004, Quantitative borehole acoustic method: Elsevier Science Publishing Company, first edition.

Williams, D.M., Zemanek, J., Angona, F.A., Dennis, C.L. and Caldwell, R.L, 1984, The long space acoustic logging tool: Paper T in the 25th Annual Logging Symposium Transaction: Society of Professional Well Log Analysts.

Winkler, K.W., Sinha, B.K. and Ploa, T.J., 1989, Permeability and borehole Stoneley waves: Comparison between experiment and theory: *Geophysics* 54: 66–75.

Zhao, X., Toksoz, M.N. and Cheng, C.H., 1993, Stoneley wave propagation in heterogeneous permeable porous formation: 63rd Annual. International. Meeting: Society of Ecploration geophysicists.,76-79.