Detection of formation shear wave in a slow formation using monopole acoustic LWD

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Summary

Acoustic logging-while-drilling (LWD) is a technology that is used to measure the formation elastic properties during drilling. When the formation shear slowness is smaller than the borehole fluid slowness (i.e., fast formation), monopole logging can be used to obtain both formation compressional and shear slownesses by measuring the corresponding refracted waves. In a slow formation where the shear slowness is larger than the borehole fluid slowness, other logging methods, such as quadrupole LWD, is used instead for shear slowness measurement due to the missing of fully refracted shear wave. Through modeling analysis, we find that the transmitted shear wave generated by a monopole LWD tool in a slow formation can be detected and used to measure the formation shear slowness. This phenomenon can be explained by Huygens' Principle, which states that every point on a wave front can be considered as a secondary source that induces particle motion. It is hard to discern the transmitted shear wave in monopole wireline data because it strongly interferes with the Stoneley mode in wireline logging. However, the transmitted shear wave decouples from the Stoneley in the LWD environment because the drill collar slows down the low frequency part of the Stoneley mode. The non-dispersive nature of the transmitted shear wave makes it suitable for shear slowness extraction using time semblance analysis, but sophisticated signal pre-processing might be needed as this wave is generally weak compared to the Stoneley wave. Moreover, this study helps better understand how the Stoneley mode behaves and interferes with other modes in a slow formation under the LWD conditions.

Introduction

Depending on the type of source used to excite acoustic energy in a borehole, conventional acoustic LWD can be divided into three major categories: monopole, dipole and quadrupole (Tang and Cheng, 2004; Zhu et al., 2008). Using a monopole LWD tool, both the compressional and shear slownesses can be measured from the corresponding compressional and shear waves refracted along the wellbore when the formation shear slowness is less than the borehole fluid slowness (called fast formation). However, the shear slowness cannot be directly measured from monopole logging in a slow formation where the formation shear slowness is larger than the borehole fluid slowness because there is no refracted shear wave (Tang et al., 2004; Wang et al., 2015). Because of the need for measuring shear slowness in slow formations, dipole and quadrupole tools were developed. Historically, due to the success of dipole tools in wireline logging, the dipole LWD tool was first developed and tested for shear measurements (Varsamis et al., 1999). However, the application of a dipole source under the LWD conditions was found to have two serious drawbacks caused by the drill collar: (1) strong tool mode contamination; (2) large slowness difference between formation shear and dipole flexural waves (Tang et al., 2002). In order to overcome the problems associated with the dipole LWD tool, the quadrupole tool was developed as a substitute for the dipole tool in LWD logging (Tang et al., 2002; Wang and Tang, 2003b). The advantage of using the quadrupole wave is that the collar mode exists only above the cut-off frequency (>10 kHz), so it doesn't affect the low frequency formation quadrupole wave, which is used for determining shear slowness (Tang et al., 2002).

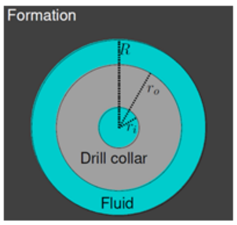
The quadrupole wave is dispersive and its slowness is equal to the formation shear slowness only near the cut-off frequencies (Chen, 1989; Tang and Cheng, 2004; Jørgensen and Burns, 2013). Thus evaluation of formation shear slowness using quadrupole data requires a model-based inversion approach that takes into account the dispersion of quadrupole modes (Zhang et al., 2010; Su et al., 2013). However, the inversion is not necessary to give the true answer in some situations as the dispersion behavior of quadrupole waves may not be reliable due to hardware limitations.

We discover that the transmitted shear wave generated by a monopole LWD tool is detectable in the borehole and may be used for shear slowness measurement in a slow formation. This can provide a data-based approach to determine slow formation shear slowness using monopole LWD, which complements the quadrupole method in LWD analysis.

Modeling analysis

Our analysis focuses on investigating the characteristics of the borehole transmitted shear wave generated by a monopole acoustic source in a slow formation. Figure 1 shows the model geometry and material parameters. For comparison, we also study the corresponding wireline case, in which the model is an open fluid-filled borehole. As model properties are azimuthally invariant, a 2D staggered-grid finite-difference method (Wang and Tang, 2003a) can be used to simulate the borehole wave propagation in the *r*-*z* cylindrical coordinates. In all of the following simulations, the grid size is 3 mm and the time sampling is 0.25 us. Validation of the finite-difference program is presented in

Fang et al. (2014). The first receiver is 2 m away from the source and an additional 33 receivers with 3 cm spacing are positioned at distances between 2 and 3 m. To avoid aliasing in the analysis, the receiver array used in the simulation is much denser than that in a real sonic tool. The monopole source is modeled as a ring source mounted on the tool surface. The source wavelet is a Ricker wavelet. A receiver array extending along the borehole axis direction is also placed on the surface of the tool.



r_i=2.7 cm, r_o=8.4 cm, R=11.7 cm

Formation
S_P=139 us/ft, S_S=272 us/ft, ρ=2.2 g/cm^3
Drill collar
S_{TP}=52 us/ft, S_T=95 us/ft, ρ_T=7.85 g/cm^3
Fluid
S_f=207 us/ft, ρ_f=1 g/cm^3

Figure 1: Configuration of the LWD model. Borehole radius is R. The inner and outer radii of the tool are respectively r_i and r_o.

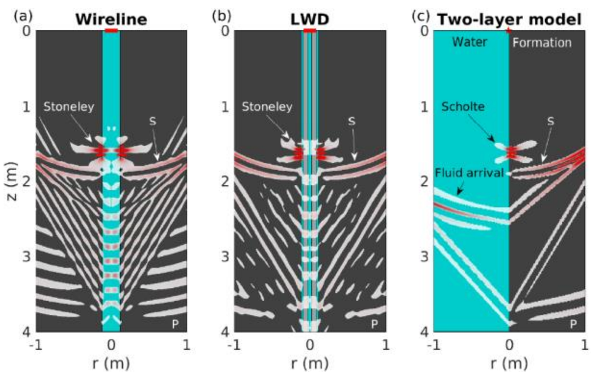


Figure 2: (a) and (b) Snapshots of the radial velocity component at 1.7 ms in the wireline and LWD models. P and S respectively denote the compressional and transmitted shear waves. The monopole source is located at z=0 m. (c) A two-layer model for comparison. A point explosive source (star) is placed in the fluid 1 cm away from the fluid-solid boundary.

Figure 2 shows snapshots of the wavefield (radial velocity component) at 1.7 ms in the wireline (2a) and LWD (2b) models together with a two-layer model (2c) for comparison. Source center frequency is 8 kHz. The only difference between the models in Figures 2a and 2b is the presence of the tool in the LWD model. In Figure 2c, the properties of the fluid and solid layers are the same as those of the borehole fluid and formation in the other two models. In the two-layer model, the transmitted shear wave (S) is very strong inside the formation. It is also detectable in the fluid near the interface because a portion of the shear energy leaks into the fluid. The strong interface wave arriving after the transmitted shear wave is the Scholte wave that propagates slower than all body waves. By comparing Figures 2a, 2b and 2c, it can be seen that the formation transmitted shear wave exists and remains strong in both the wireline and LWD models and the Scholte wave becomes the Stoneley wave in a borehole. The presence of the LWD tool has a strong impact on the formation compressional wave (P) but doesn't affect the transmitted shear wave very much.

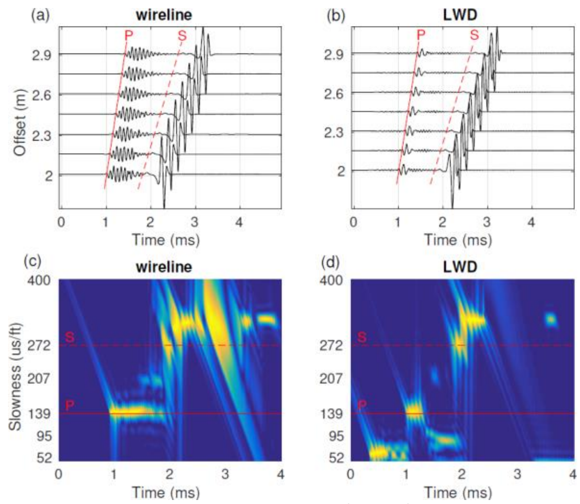


Figure 3: (a) and (b) Synthetic waveforms for the wireline and LWD models. Solid and dashed red lines respectively mark the compressional and shear arrival time. The source center frequency is 8 kHz. (c) and (d) STC calculated from the waveforms.

Figure 3 shows the recorded waveforms (pressure) at the receivers for the wireline and LWD models and the corresponding semblance of slowness-time-coherence (STC). The leaky P-wave appears as a long wave train in the wireline model while becomes a compact wave packet in the LWD model. The dashed red lines indicate the transmitted shear wave recorded in the borehole fluid. It lags a little bit behind the Stoneley wave. Although the transmitted shear wave looks relatively faint in the waveform data, it becomes prominent in STC after stacking because the signal is coherent and non-dispersive. The transmitted shear wave and the Stoneley wave can be easily recognized in the LWD STC, but the two modes are not separated very well in the wireline STC. At the first glance, the bright region corresponding to the transmitted shear wave in the wireline STC seems to belong to the Stoneley mode. LWD differs from wireline in STC analysis because of the change in Stoneley dispersion caused by the drill collar. Figure 4 shows the dispersion relations of the borehole modes calculated from the dispersion equations of the models (Rao and Vandiver, 1999). It can be seen that the slowness of the transmitted shear wave (denoted as S) is equal to the formation shear slowness (272 us/ft) in both models. The Stoneley dispersion curve for the wireline model bends downward toward the formation shear slowness at low frequencies, resulting in the interference of the Stoneley and transmitted shear waves at low frequencies. However, the Stoneley dispersion curve changes toward the opposite direction for the LWD model, as shown in Figure 4b, resulting in better separation of the Stoneley and transmitted shear waves in time. Thus the transmitted shear wave becomes easier to be distinguished in the LWD STC. In Figure 4b, the dispersive modes below 139 us/ft are the tool modes induced by the drill collar.

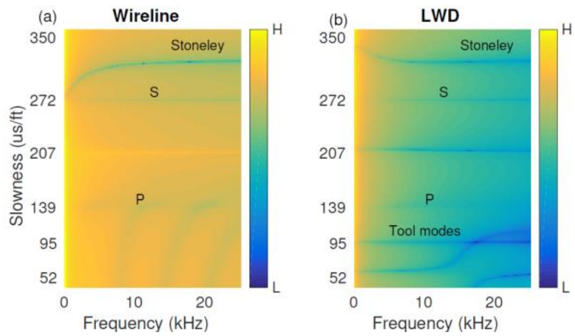


Figure 4: Dispersion relations calculated from the dispersion equation for the wireline (a) and LWD (b) models. Blue and yellow colors respectively indicate low and high values. The lines/curves with low values (in blue) indicate the modes excited in the borehole models. P and S indicate the compressional and transmitted shear waves, respectively.

In order to use the transmitted shear wave to measure slow formation shear slowness, it needs to be separate from other waves in STC so that its slowness can be easily extracted. The dispersion analysis shown in Figure 4 indicates that Stoneley is the most important mode affecting the transmitted shear wave. The amount of separation between the Stoneley and transmitted shear waves in slowness determines how well the transmitted shear wave separates from the Stoneley in STC. This can be studied by analyzing the Stoneley slowness in the low and high frequency limits.

The low frequency Stoneley wave is also called the tube wave, whose slowness in the limit of zero frequency is given as (Norris, 1990),

$$S_{tube} = S_f \cdot \sqrt{1 + a_F \frac{\rho_f S_f^{-2}}{\rho S_S^{-2}} + a_T \frac{\rho_f S_f^{-2}}{\rho_T S_T^{-2}}} \quad (1)$$

with

$$a_F = \frac{1}{1-f} \quad (2)$$

$$a_T = \frac{f}{1-f} \cdot \frac{f_T + (1-\nu_T)/(1+\nu_T)}{1-f_T} \quad (3)$$

where ρ, ρ_f and ρ_T are respectively the density of formation, borehole fluid and drill collar, S_f is the fluid compressional slowness, S_S and S_T are respectively the formation and the tool shear slownesses, ν_T is the tool's Poisson's ratio, $f=(r_o/R)^2$ is the volume fraction of the tool in the borehole, $f_T=(r_i/r_o)^2$ is the volume fraction of the inner part of the tool. a_F and a_T are respectively the factors controlling the influence of the formation and the tool on the tube wave slowness.

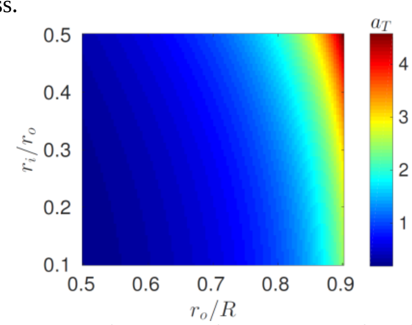


Figure 5: Variation of the value of a_T (equation 3) for different r_o/R and r_i/r_o ratios. R: borehole radius; r_i: tool inner radius; r_o: tool outer radius.

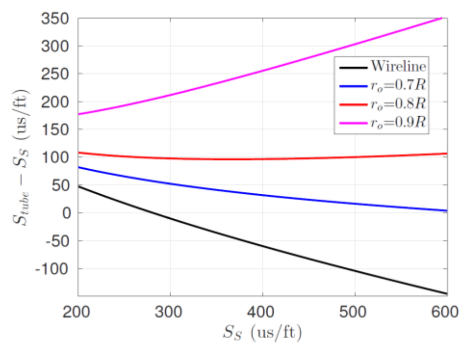


Figure 6: Difference between the tube wave slowness, S_{tube}, and the formation shear slowness, S_S, for different tool size when S_S varies from 200 to 600 us/ft. The value of the tool inner radius is fixed in the calculation. Blue, red and magenta curves respectively show the slowness difference for tools of different outer radii. Black curve shows the slowness difference for the wireline case.

According to Equation (1), the tube wave slowness is always larger than the borehole fluid slowness, but its relationship with the formation shear slowness depends on the formation properties and tool configuration. In Figure 5, the variation of the tool factor, a_T, indicates that the value of a_T is strongly influenced by the tool external radius, r_o, while it is less sensitive to the tool inner radius, r_i. A larger value of a_T means there is more tool effect. Thus the ratio of tool size and hole size is an important factor affecting the tube wave slowness. Figure 6 shows the slowness separation between the tube wave and formation shear wave for tools of different size when the formation shear slowness varies from 200 to 600 us/ft. The slowness difference, S_{tube}-S_S, increases with the tool size. For slow formations with S_S<300 us/ft, the slowness separation is 50~80 us/ft with a slim tool (r_o=0.7R) and can go beyond 150 us/ft with a large tool (r_o=0.9R). For very slow formations (S_S~600 us/ft), a moderate size tool (r_o=0.8R) can make the tube wave slowness separate from the formation shear slowness by about 100 us/ft. For the case of wireline (black curve), the slowness of the tube wave is very close to the formation shear slowness for small values of S_S. When S_S>280 us/ft, the tube wave slowness becomes less than the formation shear slowness, resulting in the intersection between the dispersion curves of the Stoneley and transmitted shear waves. Therefore, it is difficult to distinguish the transmitted shear wave at low frequencies in wireline data due to the Stoneley interference. However, it is possible to detect the transmitted shear wave in LWD data because the presence of drill collar can make the transmitted shear wave decoupled from the Stoneley wave.

At high frequencies, the Stoneley dispersion curve asymptotically approaches the Scholte wave slowness, which satisfies the following equation (Zheng et al., 2013):

$$\frac{\rho_f}{4\rho} S_S^4 \sqrt{\frac{S_P^2 - S_{sch}^2}{S_f^2 - S_{sch}^2}} + \left(S_{sch}^2 - \frac{S_S^2}{2}\right)^2 + S_{sch}^2 \sqrt{\left(S_P^2 - S_{sch}^2\right)\left(S_S^2 - S_{sch}^2\right)} = 0 \qquad (4)$$

where S_{sch} is the Scholte wave slowness, S_P and S_S are respectively the formation compressional and shear slownesses, S_f is the fluid slowness.

The Scholte wave slowness is obtained by numerically solving equation (4). Scholte wave always exists for a fluid-solid interface and its slowness is larger than all body wave slownesses (Zheng et al., 2013). Thus the Stoneley wave slowness is always larger than the formation shear slowness at high frequencies. Figure 7 shows the slowness difference between the Scholte wave and the formation shear wave for formations with different S_S/S_P ratios when S_S varies from 200 to 600 us/ft. For a wide range of S_S and S_P values, the separation of the Scholte wave and formation shear wave in slowness is considerably large (>40 us/ft).

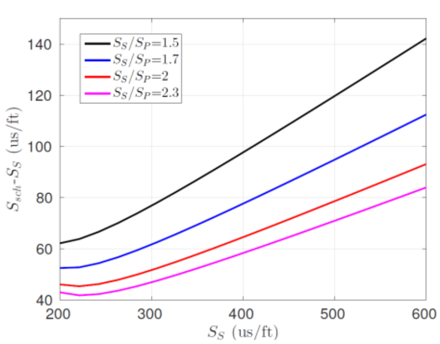


Figure 7: Difference between the Scholte wave slowness, S_{sch}, and the formation shear slowness, S_S, for different formation S_S/S_P ratios when S_S varies from 200 to 600 us/ft. The other parameters in equation (6) are fixed in the calculation of S_{sch}.

Based on the tube wave and Scholte wave analysis, we know that the transmitted shear wave can be decoupled from the LWD Stoneley wave and the amount of their separation in slowness mainly depends on the tool size and frequency. Figure 8 shows the dispersion relations for the wireline model (a) and three LWD models (b, c and d) with different tool outer radii. All parameters for the LWD models are the same as those listed in Table 1 except for the tool outer radius. The behavior of the Stoneley dispersion for these four models is consistent with the previous theoretical analysis. The amount of separation between the Stoneley and transmitted shear waves increases with the tool size at low frequencies while remains unchanged at high frequencies.

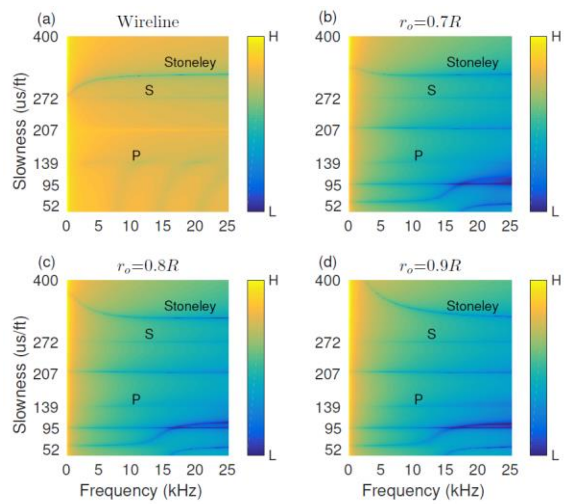


Figure 8: Dispersion relations for the wireline model (a) and three LWD models (b, c and d) of different tool outer radii. R is borehole radius.

Conclusions

Through numerical and theoretical analyses, we have shown that the transmitted shear wave generated by a monopole LWD tool can be detected in sonic data because the transmitted shear wave can be decoupled from the Stoneley wave in the LWD environment. This may provide a new means to measure slow formation shear slowness as the transmitted shear wave is non-dispersive and it propagates at the formation shear velocity. Moreover, this study brings new insight into the characteristic of borehole shear wave propagation under the LWD conditions.

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