Aspects of the Science Behind the PS Logger®

The science involved in acoustic wave propagation in boreholes is surprisingly complex and has been subject to considerable theoretical and experimental analysis over many years. This is especially true when considering shear waves and in particular the flexural mode resulting from dipole probes such as the PS Logger®.

Overview

The velocities of compressional waves (V_p) and shear waves (V_s), derived from sonic logging, are inherent material properties of formations, important in determining strength within the elastic limit. The theoretical basis behind borehole based methods for sonic logging has been widely described in important papers through the 1970's and 1980's and work continues to this day. The PS Logger®, operating in a single borehole, uses the "suspension method" whereby the source and receivers are suspended in the borehole fluid, connected only by a flexible tube. A cylindrical dipole source is employed that creates pressure waves in the borehole fluid which in turn excite the formation at the borehole wall in different modes. Energy is transmitted along the borehole wall to two receivers, each comprising a hydrophone (for P waves) and a geophone, aligned to the source, (for S waves).

Wave Propagation

The velocities at which waves propagate in a geological formation are inherent material properties, independent of the tool used for measurement. These velocities are a complex function of several factors, including density, porosity and mineralogy. Sonic logs measure velocities by activating a source in the borehole with a specific frequency spectrum (S_f) which excites waves in the surrounding formation at wavelength λ with frequency f travelling at velocity V. Two main forms of waves exist, body waves which travel through the formation itself and surface waves which travel along an interface between two media. The equation $V = f\ \lambda$ applies to both types. Body waves may be generally described as compressional (P waves), where particle motion is in the direction of propagation, or shear (S waves) where particle motion is perpendicular to the direction of propagation and may be horizontally (SH) or vertically (SV) polarised. Surface waves may exhibit more complex particle motion and for sonic logging are assumed to exist only at the borehole fluid/borehole wall interface.

Frequency Spectra

When a bell is struck with a hammer, it is distorted and subsequently vibrates in a highly complex manner, which can be described in terms of a linear combination of many normal modes of vibration as in *Figure 1*. The frequency spectrum of the bell is the summation of these modes.

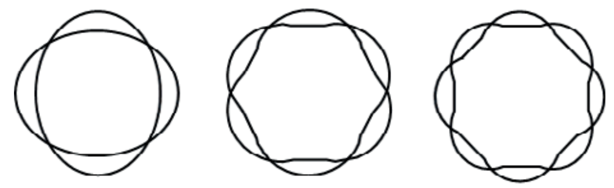


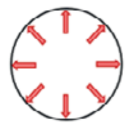
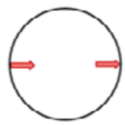
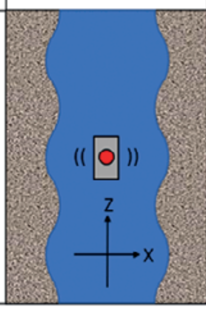
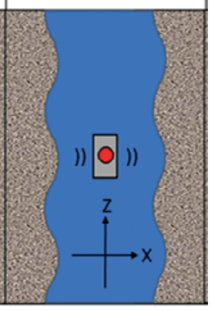
Figure 1: Bell - First Three Modes of Vibration.

Any acoustic source has an associated frequency spectrum which, when activated in the ground, causes the surrounding formation to vibrate within that frequency spectrum. The response of the ground to the signal from the source is dependent on the ground material properties and manifests itself in terms of a varying amplitude of vibration at the frequencies within the excited spectrum. Modes of propagation may also be dispersive in that different frequency components may travel at different velocities. The frequency spectra pertaining to the PS Logger® is of particular importance due to the mechanism by which shear wave velocities are derived.

Monopole and Dipole Tools

The fundamental modes shown in *Figure 2*. describe the lowest-order surface modes of monopole and dipole transducers in a borehole, exciting the Stoneley mode for a monopole and the flexural mode for a dipole.

Figure 2: Monopole and Dipole Wave Modes.

Configuration	●	●○
Transducer-type	Monopole	Dipole
Borehole force (cross-sectional view)		
Wave mode	Stoneley	Flexural
Borehole movement (axial view)		

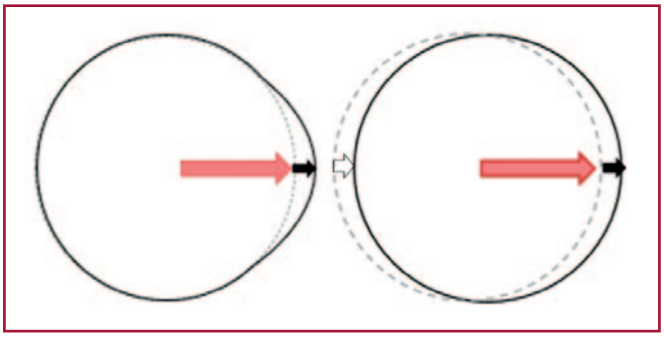


Figure 3: PS Logger® Source - Stoneley Mode (left) and Flexural Mode (right).

These modes are generated directly by the force applied to the borehole wall and are therefore present in both fast and slow formations, propagating away from the acoustic source, in both vertical directions. Traditional sonic probes use only a monopole source and therefore only excite the Stoneley mode. In fast formations, where the shear velocity is higher than the fluid velocity, a monopole tool can produce shear waves by mode conversion which are critically refracted along the borehole wall.

For the PS Logger® the source comprises a steel cylinder which is struck on the inside surface by a solenoid operated shuttle under operator control, with the direction of motion of the shuttle being reversible between shots. This source operates in both modes as shown in the planar view in *Figure 3*. The Stoneley mode occurs as an initial imbalance or bulge is produced in the cylinder which acts as a monopole source, exciting P and Stoneley waves. As the opposite side reacts, a pressure doublet is set up, such that a pressure increase in the fluid on one side of the cylinder is matched by a pressure decrease in the fluid on the other side exciting the flexural mode, generating dipole P waves and flexural waves. The PS logger is fitted with hydrophones and geophones, which are configured to measure P and Sf (flexural) wave velocities, respectively. Shear wave measurements are made in two horizontal directions (left and right), producing flexural modes 180 ̊ out of phase, a key indicator when identifying the flexural/shear wave components of recorded waveforms.

The Flexural Mode

The flexural mode excited by a dipole tool propagates along the borehole wall in both fast and slow formations causing it to bend. It is highly dispersive and is bound at the upper frequency limit by the Scholte wave velocity, and at the lower frequency limit by the formation shear wave velocity. The dispersive behaviour of flexural waves applies only to a specific frequency bandwidth (see *Figure 4*) where propagation velocity varies asymptotically with frequency. Below a critical frequency (the cutoff frequency), there is no dispersion and the flexural wave travels at the formation shear velocity. The PS Logger® is a low frequency tool which operates at a suitably low frequency bandwidth such that the flexural mode is non-dispersive and propagates at the formation shear velocity, precluding the need for dispersion correction. As the flexural mode exists only along the borehole wall, it is not a body wave mode, and therefore the flexural wave is technically separate from the shear wave, although it travels with the same velocity at low frequencies. The PS Logger® source centre frequency is typically 1.5kHz or below.

Applicability to the PS Logger®

The flexural mode of wave propagation in boreholes is perhaps the least understood aspect of the PS Logger® in the wider geotechnical community. An understanding of the basis of this mode, as described above, is useful when discussing the applicability of the PS Logger® across a wide variety of borehole conditions and formations. Robertson Geo have accumulated a repository of PS Logger® data from more than a thousand borehole runs over 15 years which clearly demonstrates how well it can work in practice.

P wave velocity determination is invariably straightforward as these are always the first arrivals and are characterised by a sharp peak in the waveform on the P channel (hydrophone). The S waves, or rather flexural waves, measured on the geophone channels, arrive somewhat later and tend to exhibit a slower rise time. These later arrivals may be superimposed on other waves, such as the decaying P waves making arrival time picking more difficult. As they are recorded twice (left and right shots) the characteristic 180° reversal between them is a key indicator for correct identification. In all cases velocities are derived from the time difference between the near and far channel arrivals which eliminates any difficult to quantify borehole effects.

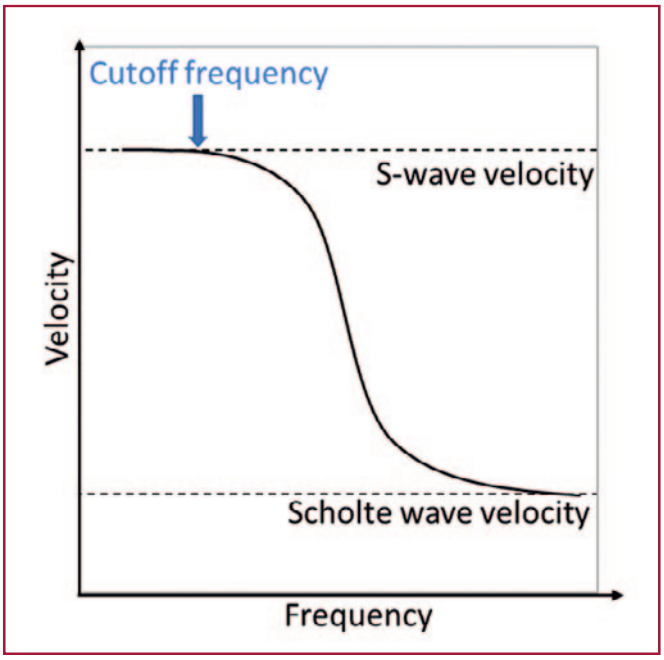


Figure 4: Flexural Wave Velocity Dispersion versus Frequency.

Conclusion

The theory behind the operation of the PS Logger® is important to understand as it needs to explain why the probe works so well across a spectrum of logging conditions. Excellent velocity data can be obtained in fast and slow formations, in borehole diameters from 75mm to 300mm and in open and cased boreholes. Robertson Geo have recently undertaken an exhaustive review of the theory supporting the probe to ensure the demonstrably good results routinely obtained in the real world are also put on a firm theoretical basis.