PAPER I

A NUMERICAL STUDY OF SINGLE BOREHOLE PROFILING

Youli Quan and Jerry Harris

ABSTRACT

Single borehole profiling is a relatively new seismic measurement. In single borehole profiling, the source and receiver(s) are in the same borehole. It can be viewed as sonic logging with low frequency source (~1 KHz) and large source-receiver offsets (~100 m). Single borehole profiling attempts to fill the frequency gap between conventional VSP (~0.1 KHz) and sonic logging (~10 KHz). The low frequency and large offset allow the wave to penetrate the invaded zones and casing. This makes it possible to measure the velocity and attenuation for undisturbed formation. Single borehole profiling may also detect the reflection from a fault or a salt dome near the borehole. We present two numerical examples to investigate the near borehole reflection and deeper penetration features of the single borehole profiling. The simulation is done by the generalized R/T coefficients method, and a salt flank is highly simplified as a large outer-cylinder. Although the model is simplified, the solution is exact. This simulation is useful for understanding the relative amplitudes of tube waves and reflections.

INTRODUCTION

Typical borehole related seismic measurements include conventional sonic logging, VSP, crosswell profiling, and single borehole profiling illustrated in Figure 1. Among these techniques, the single borehole profiling is relatively new. Chen (1993) and Chen et al. (1994) developed a single borehole profiling tool and collected some field data. Cameron and Chen (1995) presented a synthetic example for single borehole seismic imaging of a salt flank. Their synthetic data were calculated using the finite difference method. In general, the finite difference technique can deal with media with complex structures. Though tube waves are a major problem with single borehole profiling, the finite difference method is difficult to precisely include a fluid-filled borehole, because a very small borehole diameter and a very large formation extension will cause numerical problems: very fine grids and huge computation.

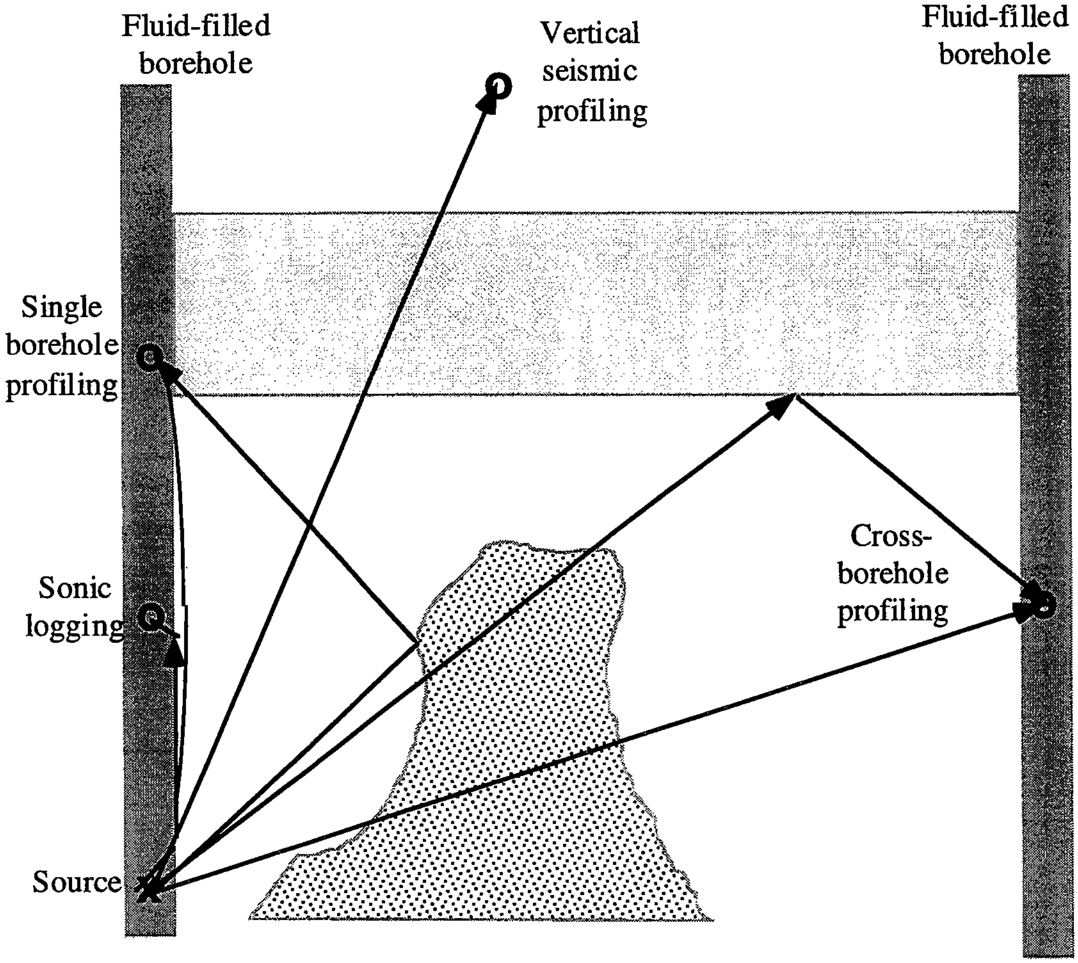


Figure 1. Borehole related seismic measurements.

In this numerical study, we investigate the single borehole profiling from another view: simplify the model and use accurate modeling method to precisely include the borehole. Chen, Quan and Harris (1996) proposed an analytical method to calculate complete elastic wave fields in radially layered media. In this method, the normalization or rescale technique is introduced in the formulation, and therefore can handle high frequency problems and thick layers. In the simulation, the salt flank is modeled as a large outer cylinder. The objectives of this simulation is to investigate (1) what events are expected in the profiling? (2) what are their relative amplitudes? To correct the reflection amplitude from cylindrical surface to a plane, we derive a formula for this correction.

REFLECTIONS DUE TO AN LARGE OUTER-CYLINDRICAL STRUCTURE

Let us first consider a scattering problem due to an outer-cylindrical formation. The physical configuration of this model is shown in Figure 2a in which a simple open borehole is surrounded by a two-cylindrical-layer composite formation. Receivers are clamped to the borehole wall, and the source-receiver offset ranges from 10m to 150m. Other model parameters are listed in Table 1. This model is useful in the study of single borehole imaging, i.e., reflection imaging of reflectors near a borehole. From this simulation, we can understand what and where reflections would appear on a seismogram, what are the relative amplitudes of these reflections, and how much the tube wave energy has to be attenuated in order to make the reflections show up.

The calculated seismograms are shown in Figure 2b which are the displacement component in r-direction. To more clearly indicate the scattering phases (i.e., reflections from the interface between formation I and formation II), we normalized each trace by using its maximum value rather than a global scale for all traces. We can see from Figure 2b that phases show up as expected. It should be emphasized that we set an extremely low Q-value ($Q_f = 3$) for the fluid in the borehole to reduce the tube wave energy. If Q_f is not low enough, we can only see tube waves on the seismograms. Therefore, to attenuate tube waves is one of the key problems for single borehole profiling.

In this calculation, the peak frequency of the Ricker wavelet is 800 Hz, thus the corresponding characteristic wave-length is about 2m to 3.5m. The thickness of formation I is about 100m and is much greater than the characteristic wavelength. Therefore, this is a typical high-frequency scattering problem. As mentioned earlier, the use of the normalized Hankel functions makes the algorithm numerically stable even for very high-frequency model. We also tried this model with ordinary Hankel functions, but the calculation failed because of the arithmetic overflow. This is a good example showing why we need the normalized formulation.

Table 1 Parameters of a scattering model

Layer	r (m)	α (km/s)	β (km/s)	Q_P	Q_S	ρ (g/cm^3)
Fluid	0.11	1.6	–	3	–	1.0
Formation I	100	3.0	1.85	200	120	2.1
Formation II	∞	1.9	1.4	50	40	1.8

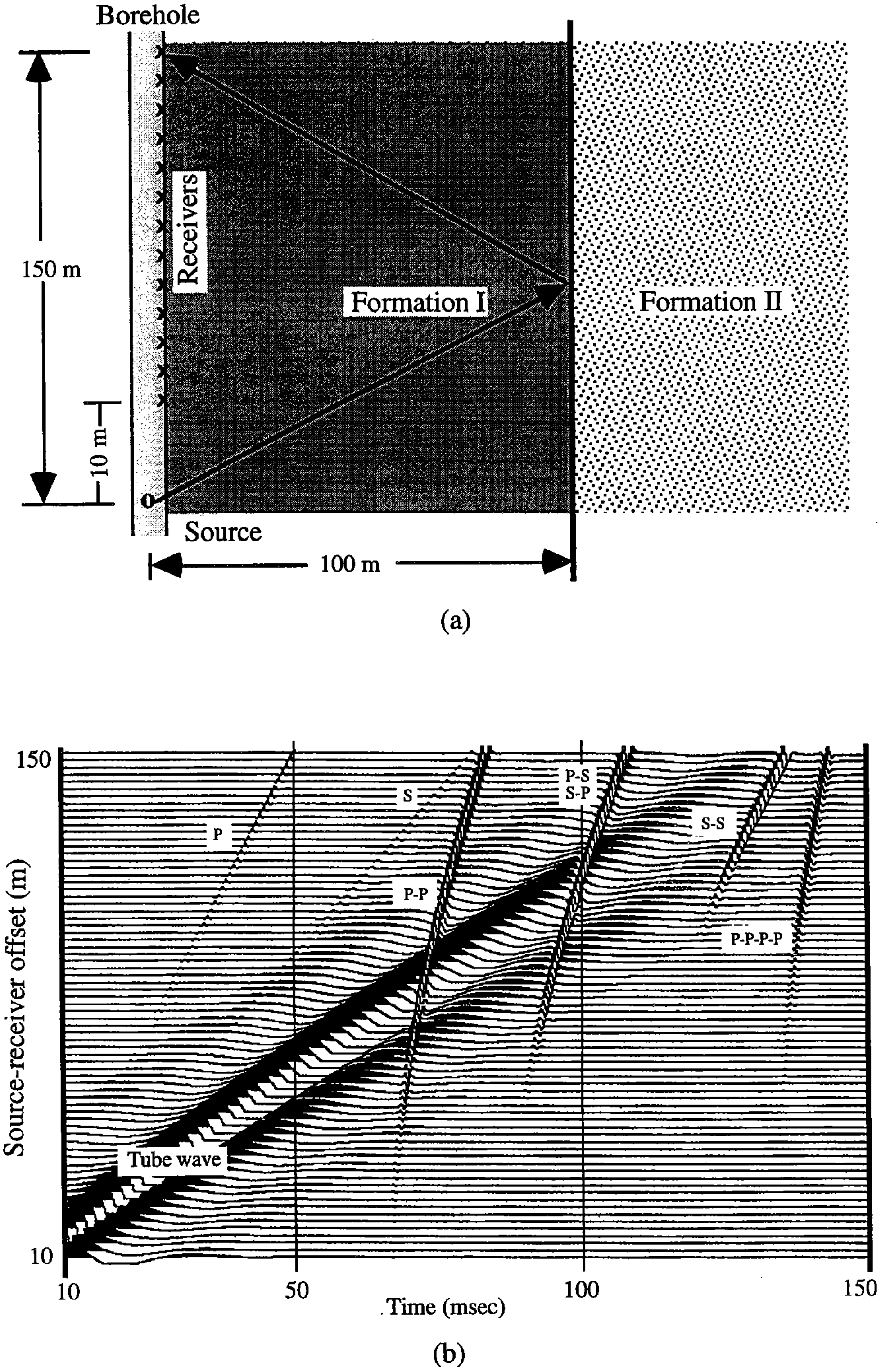


Figure 2. (a) Configuration of the model; (b) Seismograms of horizontal displacement *u*. Here, "P" indicates the direct *P* wave; "S" the direct *S* wave; "P-P, S-S, P-S and S-P" are primary reflections; "P-P-P-P" is a *P* wave multiple reflection.

The reflections in Figure 2b are from a cylindrical interface. In order to simulate the reflections from a plane interface, we need to correct the reflection amplitude. Let the energy from a point source be unit, and A be the amplitude. Based on the energy conservation, for the cylindrical interface reflection (Figure 3a), we have

$$\frac{A_{cyl}^2 4\pi R^2}{2\pi r} = 1, \tag{1a}$$

or rewrite it as

$$A_{cyl} = \sqrt{r}/(\sqrt{2}R); \tag{1b}$$

and for the plane interface reflection (Figure 3b), we have

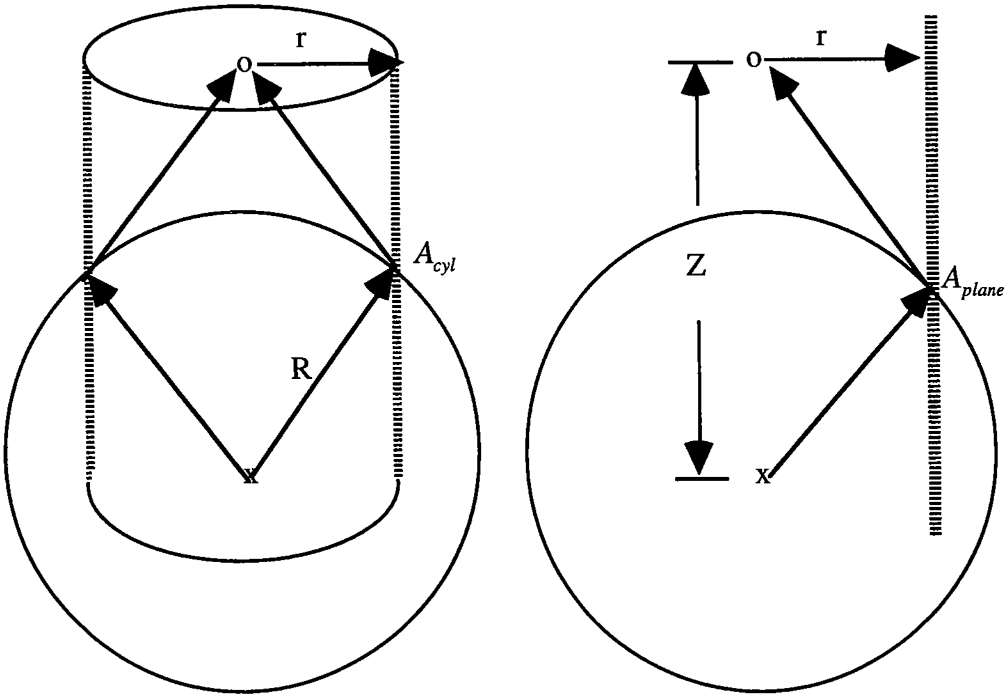
$$A_{plane}^2 4\pi R^2 = 1, \tag{2a}$$

or rewrite it as

$$A_{plane} = 1/(2\sqrt{\pi}R). \tag{2b}$$

From equations (1b) and (2b), we finally obtain the correction formula:

$$A_{plane} = A_{cyl}/\sqrt{2\pi r}. \tag{3}$$



(a) (b)

Figure 3. Amplitude correction from cylindrical interface reflection to plane interface reflection.

LOW FREQUENCY ACOUSTIC LOGGING

The rock property near a borehole wall is often altered during drilling, forming an invaded zone. The altered depth is usually 0.2 to 0.8 meters. Baker (1984) studied the effects of invaded zones on the conventional acoustic logging. For the conventional acoustic logging, the first arrival could only penetrate a few inches into the formation. Low frequency logging (or single borehole profiling) can penetrate deeper. In the low frequency logging, however, tube waves become very strong comparing with direct waves. We have to suppress tube waves to make the direct waves observable.

This section gives a numerical simulation on the low frequency acoustic logging. Table 2 lists the model parameters used. Figure 4a shows the model configuration. The source function is Ricker wavelet with peak frequency of 1 KHz. We set a very low Q-value for the fluid to significantly reduce the tube wave energy. Figure 4b displays the pressure seismograms in gray scale. Each trace is normalized to unit by using each trace's maximum value. The first arrival is direct P wave whose propagating velocity is 4 km/s. It can be seen from Table 2 that this velocity (4 km/s) is the formation velocity. Therefore, we can say that the frequency and source-receiver offset used in this test have the capability penetrating the invaded zone to measure the formation velocity. If the invaded zone becomes thicker, we may need larger source-receiver offsets and/or lower source frequency to have a deeper penetration.

For comparison with conventional acoustic logging, Figure 4c shows the seismograms with closer source-receiver offsets and higher source frequency (peak frequency = 10 KHz). The direct P wave in this case propagates with a velocity of 5 km/s, which is the velocity of the invaded zone.

Table 2 Model parameters for low frequency logging simulation

Layer	r (m)	Vp (km/s)	Vs (km/s)	Q_P	Q_S	ρ (g/cm^3)
Fluid	0.1	1.6	–	3	–	1.1
Invaded zone	0.3	5.0	3.0	300	150	2.7
Formation	∞	4.0	2.2	200	120	2.6

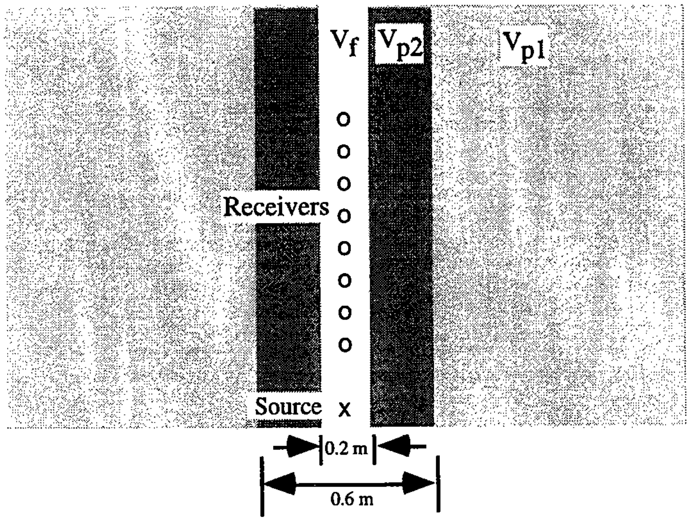


Figure 4a. An invaded zone model used for low frequency logging simulation. V_f, V_{p1} and V_{p2} are *P* wave velocities for borehole fluid, invaded zone and formation, respectively.

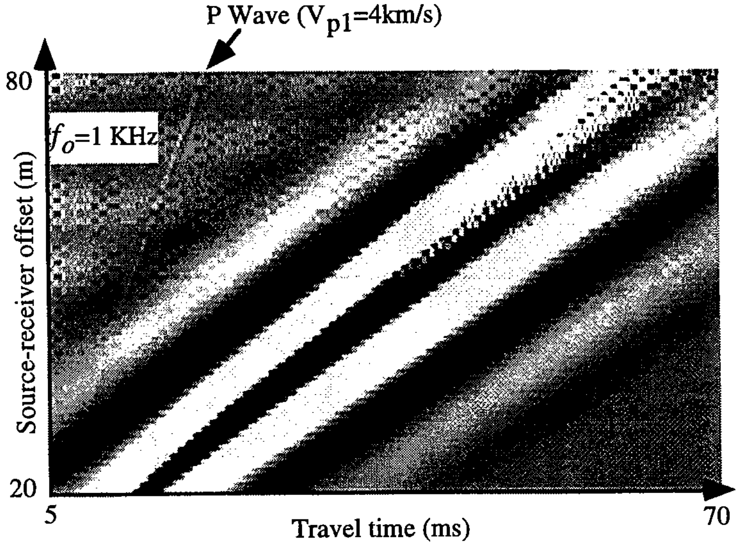


Figure 4b Low frequency acoustic logging with peak frequency of 1 KHz and large source-receiver offsets. The direct wave corresponds to the formation *P* wave velocity (4 km/s)

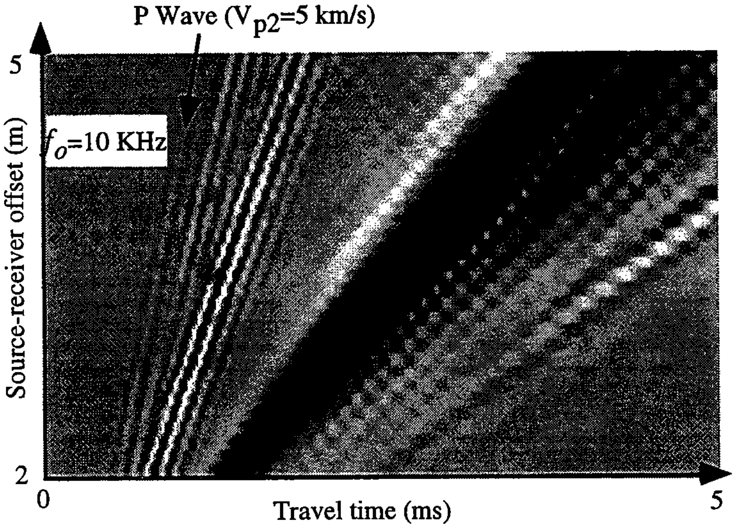


Figure 4c. Conventional acoustic simulation with peak frequency of 10 KHz and small source-receiver offsets. The direct wave corresponds to the *P* wave velocity (5 km/s) in the invaded zone.

CONCLUSIONS

Tube waves is a major problem in single borehole profiling. In the numerical simulation, we have to set a very low *Q*-value for the borehole fluid (Q_{fluid} = 3) to attenuation tube waves and make the reflections observable. Low frequency source and large source-receiver offset make the seismic penetrate deeper. This makes it possible to measure the undisturbed formation.

ACKNOWLEDGMENT

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