Imaging of geological conditions ahead of drill bit using a drilling hole dipole source

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Abstract

To overcome shortcomings of current techniques in predicting geological conditions ahead of drill bit in real time, the capability of waves excited by a dipole source inside a fluid-filled drilling hole with surrounding and front formations in detecting geological reflectors is evaluated. Analysis on beam pattern show that SV and SH waves have large energy coverage and good reflection sensitivity, which have an advantage over P wave in detecting geological conditions ahead. Numerical results indicate that dipole acoustic sources have the capability of detecting geological conditions ahead of the drill bit.

Keywords: geological conditions; dipole source; drill bit; Finite Difference Time Domain method; SH wave; SV wave

1. Introduction

In drilling, it is important to control the direction of drilling in a desired direction, where the information about formations and other geological structures ahead of the drill bit must be obtained in advance. The more information gathered prior to actually encountering, the more effectively the drilling plan can be designed and modified. Some approaches, such as Drill-Bit Seismic (DBS) shown by Rector III and Hardage (1992), Seismic Measurements While Drilling (SMWD) investigated by Harrold et al. (2002), can detect some information ahead of the drill bit, which are useful in combination with well planning and while-drilling operations. These methods, however, have some limitations used in operational settings. The application effect and scope are restricted by a variety of factors such as long travel signal attenuation and noise aliasing during the propagation in many different strata. The purpose of the paper is to provide a method that can compensate deficiencies and give information about geological

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conditions ahead of the drill bit.

In recent years, lots of previous works such as those presented by Tang [3], Tang and Patterson[4], and Eidsvik and Hokstad[5], have focused on the detection of reflectors and fractures surrounding the borehole. Among them, Tang demonstrated that shear waves excited by dipole sources in a borehole have the capability of detecting reflectors surrounding the borehole. It is also pointed out that the merits of far-filed detection of shear waves excited by dipole sources may further be used in geosteering drilling. Thus, the objective of the paper is to demonstrate whether a dipole source can be used in imaging geological conditions ahead of the drill bit.

Based on numerical simulation, the radiation characteristics of different wave modes, including compressional (P) wave and two types of shear wave(i.e., SH and SV waves) at low frequencies are studied. Then, suppose that there are vertical and deviated reflectors ahead of the drill bit, the propagation of waves in different situations are investigated, respectively. Finally, conclusions are summarized.

2. Results and analysis

2.1. Beam Pattern of different waves

When activating a dipole source in the borehole, three kinds of waves are generated. That is compressional(P) wave and two types of shear wave(i.e., SH and SV waves). The beam pattern of each wave is analyzed in this section. Fig. 1(a) shows the schematic of the geophysical model when drilling. As is shown, the source is located on the string on the top of the drill bit, and the receivers which can gather information about the reflectors ahead of the drill bit are placed on the string with a distance \( d \) between each receiver. Formation 1 is the one that is drilling, while formation 2 is located ahead of the drill bit, forming a reflector perpendicular or intersect to the borehole, the distance between the drill bit and the reflector is \( H \).

In analyzing the beam pattern, numerical simulations on wave propagation in the model presented in Fig.1 is necessary. Fig.1(b) is the corresponding mathematical model described in Cartesian coordinate system, suppose that wave propagates along the direction \( r \), \( \theta \) is the angle between \( r \) and \( z \), \( \phi \) is the angle between the projection of \( r \) on \( xOy \) plane and \( y \). In case of the complexity and large scale of numerical calculations, a 3-dimentional staggered grid Finite Difference Time Domain (FDTD) method with a Convolution-Perfectly Matched Layer (CPML) absorbing boundary condition argued by many researchers such as Komatitsch and Martin[6], a parallel computation scheme based on Message Passing Interface(MPI) on computer cluster is proposed to simulate wave propagation in the geological models. The central frequency of the dipole source is 2.0kHz with the polarization direction in the \( x \)-axis.

Fig.2 present the directivity pattern of P wave and SV wave on \( xOz \) plane, SH wave on \( yOz \) plane and three
kinds of wave on the plane vertical to the borehole axis, respectively. Fig. 2(a) shows that the energy of P wave distribute symmetrically along $z$ axis on $xoz$ plane, and the energy distribution of SV wave is different from P wave, the main lobe reaches a peak value when $\theta = 0^\circ$, two side lobes reach the peak values at $\theta = 52^\circ$ and $\theta = -52^\circ$, respectively. It is shown that the beam pattern of SH wave in Fig. 2(b) have the same characteristics as those of SV wave except for the actual value at each incident angle. Seen from Fig. 2(c), it is clear that the total energy of SH wave is larger than P and SV waves.

![Fig. 2. (a)P and SV waves in xoz plane; (b)SH wave in yoz plane; (c) P wave, SV and SH waves in the plane perpendicular to the borehole axis.](image)

2.2. Wave propagation mechanism

Suppose that the working principle of receivers configured get signals as those used in dipole acoustic tools, then waveforms gathered compose SV and SH wave mainly. If the direction of polarization of the source is $x$, signals gathered at $x$ and $y$ directions can be described as:

\[ xx = SV \sin^2 \varphi + SH \cos^2 \varphi \]  \hspace{1cm} (1)
\[ xy = (SV - SH) \sin \varphi \cos \varphi \]  \hspace{1cm} (2)

If the direction of polarization is $y$, signals gathered at $x$ and $y$ directions can be described as:

\[ yy = SV \cos^2 \varphi + SH \sin^2 \varphi \]  \hspace{1cm} (3)
\[ yx = (SV - SH) \sin \varphi \cos \varphi \]  \hspace{1cm} (4)

In the simulation, suppose that the angle between $z$ axis and normal line of formation 2 refers to dip angle $\theta$ of the reflector, while the azimuth of the reflector is defined as $\varphi$. In contrast, two reflectors are considered, the dip and azimuth of the first one are all zero, while $\theta = 75^\circ$, $\varphi = 0^\circ$ for the second one. The dipole source is placed 0.5
away from the drill bit, and the receivers are located along z axis with the spacing \( d = 0.8m \). The distance \( H = 15.0m \). Other acoustical parameters of the fluid in the drilling hole and the formations are listed in Table 1

| Fluid     | \( V_{p} \) (m/s) | \( V_{s} \) (m/s) | \( \text{Den} \) (kg/m\(^3\)) |
|-----------|-------------------|-------------------|-----------------------------|
| Fluid 1   | 1500              | /                 | 1000                        |
| Formation 1 | 3500            | 2000              | 2000                        |
| Formation 2 | 4500            | 2650              | 2400                        |

For the first case, the snapshots of particle velocity \( v_x \) in xoz plane with time is shown in Fig.3, (a)–(d) represents \( t = 4.0\mu s \), \( t = 8.0\mu s \), \( t = 12.0\mu s \) and \( t = 16.0\mu s \), respectively, where the polarization direction of the source is \( x \) axis. It is clear that a guided wave (flexural mode) is excited in the borehole, then propagates into the formation as a body wave, reflects from the interface formed by the reflector, and is converted back into the borehole as a guided wave. In the approach presented, the guided borehole waves generating from reflection of the body wave are used to imaging the reflectors ahead. For the case of a deviated formation 2, the characteristics of the snapshots of \( v_x \) are the same as those shown in Fig.3 except for the exact value at each location, specially, the amplitude of reflected waves from the reflector is smaller than that of a vertical reflector.

Full waveforms gathered by the receivers are given in Fig.4. First arrivals in waveforms include two parts, direct wave propagate from the source to the receiver and reflected waves from the interface at the drill bit. Second arrivals in Fig.4 are the main components from the reflector ahead of the drill bit. By using the first arrivals, shear wave velocity of formation 1 can be evaluated as \( V_{s1} = 1960m/s \) with the relative error 2%. Define that \( TT \) denotes the propagation time of the guided wave reflected from the drill bit, which can be expressed as

\[
TT = (TR + 2\times TB)/\nu.
\]

Where \( TR \) is the source-receiver spacing, \( TB \) is the distance between the source and the drill bit. By subtracting \( TT \), the variation of the travel time of reflected body waves \( T_{ss} \) in formation 1 with the source-receiver spacing can be reflected. Then after analyzing the relationship of \( T_{ss} \) with \( \theta \), \( H \) and other parameters, the tip angle and the distance \( H \) can be determined. For the vertical and deviated reflector, the evaluated tip angle \( \theta^* \) is 0° and 79°, respectively, and the evaluated \( H^* \) is 15.2m and 15.3m, respectively. The relative error between the evaluated and the corresponding actual parameters are within 2.0%.
3. Conclusions

The paper concentrates on the performance evaluation of a dipole source for the detection of geological conditions ahead of the drill bit. The analysis on beam patterns of different waves show that the radiated energy of SV and SH waves have large energy coverage and good reflection sensitivity, which have an advantage over P wave in detecting geological conditions ahead. In addition, the reflected SH wave is strong when the tip angle of the reflector is small. Signals gathered by receivers inside the borehole can be used to identify shear wave velocity of the surrounding formation, the dip angle, and the distance to the reflector ahead. The results indicate that dipole acoustic sources have the capability of imaging geological conditions ahead of the drill bit, which may provide reference for the better design of instruments in realizing a more accurate geologic steering drilling system.

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