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Response of azimuthal acoustic logging to the fluid-filled strip channel behind a casing pipe

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ABSTRACT

One of the most important applications of acoustic well logging is to evaluate the cementation quality in the casing hole; such evaluation is in fact a physical question of detecting the position of the fluid-filled strip channel that is actually distributed in a limited azimuthal and axial zone behind the casing pipe. Currently, a common detection method is to measure the amplitude of the casing wave (ACW) in different azimuths and then reverse the position of the strip channel. Thus, in this paper, a 3D finite-difference algorithm is developed to study the azimuthal distribution of ACW caused by the strip channel. The simulation results show that ACW is affected by many parameters such as the radial position of azimuthal receivers and the azimuthal angle of the strip channel. More importantly, the product of the inner diameter of the casing pipe and the central frequency of the source will determine the azimuthal distribution of ACW: ACW reaches the maximum at the opposite azimuth of the strip channel when the product is below the threshold value, and it reaches the maximum at the central azimuth of the strip channel when the product is above the threshold value.

1. Introduction

As an important procedure during well completion, well cementation is defined as an engineering technology involving placement of the casing pipe into the borehole and pouring the cement slurry into the annulus between the casing pipe and the formation to provide zonal isolation. Given that the job is completed under a high-temperature and high-pressure environment as deep as thousands of meters, the cementation quality often encounters some problems. The most common problem is that one fluid-filled channel appears on the casing-cement boundary or the cement-formation boundary, which will damage the integrity of the cement sheath and provide a flow path for oil, gas, and water in different layers. As a result, the casing pipe becomes damaged, the oil and gas resources are wasted, and even the production plan fails. Thus, it is necessary to conduct the regular detection of the cementation quality after well completion.

Acoustic logging is the main method to evaluate the cementation quality because of its low price, damage-free implementation in the well, and accurate measurements (Biot, 1952; Chan and Tsang, 1983; Che etal., 2016; Chen etal., 1998; Dong etal., 2000; Guan etal., 2009; He etal., 2012). In early times, the monopole low-frequency source (20 kHz) is employed as the transmitter, and two monopole receivers with different spacing from the transmitter are used to record waveforms. The receiver with shorter spacing mainly acquires the casing wave, which arrives first and has long duration and similar velocity as the plate velocity of the steel (Leslie and Randall, 1992). ACW becomes very high when there is a fluid-filled or gas-filled channel on the casing-cement boundary. For waveforms acquired from the receiver with longer spacing, the ratio of the amplitude of the formation wave and ACW is sensitive to the channel on the cement-formation boundary (Liu etal., 1996). Thus, this method has the ability to recognize channels on two boundaries. Zhang etal. (Schmitt, 1989) proposed another method to detect the channel on the cement-formation boundary by using the amplitude and the travel time of the “casing-cement mode” wave, whose velocity is between the casing wave and the P-wave of the formations.

Subsequently, researchers found that, in most cases, the channel is no longer annular and exists only in a limited azimuthal range. As a result, both the depth of the channel and the azimuth of the channel must be determined. Thus, the monopole receivers are replaced by azimuthal receivers to detect the strip channel. Tang etal. (Schmitt, 1993) found that ACW will become larger with the increasing azimuthal

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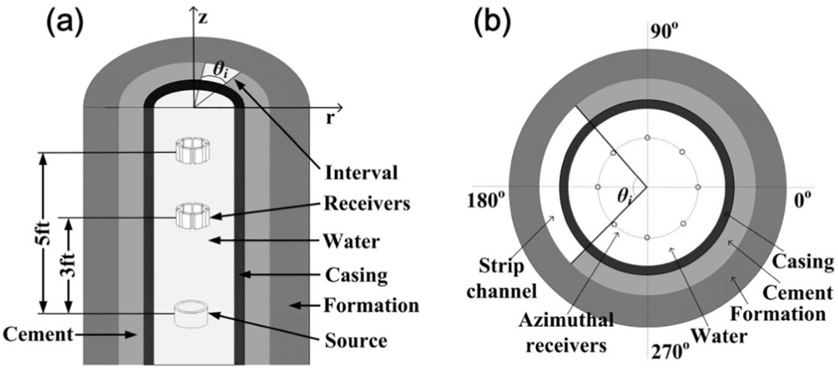

Fig. 1. The simulation model of a cased hole with a strip channel filled with water. (a)In the longitudinal section of the model, the borehole fluid, the casing pipe, the cement annulus, and the formation can be observed from the inside out. (b)In the cross section of the model, the central azimuth of the channel is 180° and invariable, and the azimuthal angle of the channel θ_i is a variable during the simulation.

angle of the strip channel in audio range; however, they used the monopole receiver that does not allow ACW to show the azimuthal difference.

In this paper, a 3D finite-difference model is performed to simulate the case of a cased hole with a strip channel in which a monopole source emits acoustic waves and azimuthal receivers detect the casing waves from different directions. The effects of many factors on the azimuthal distribution of ACW are examined, such as the azimuthal angle, thickness, and axial position of the channel, the radial position of the azimuthal receivers, the inner parameter of the casing pipe, and the central frequency of the source.

2. Simulation model

Fig. 1(a) shows the simulation model of a cased hole with a channel filled with water. In the left longitudinal section of the model, the borehole fluid, the casing pipe, the cement annulus, and the formation can be observed from the inside out. During the simulation, the monopole source is a round tube with height of 0.05 m in the axial direction and thickness of 0.005 m in the radial direction. Two azimuthal receiver stations are positioned 3 ft. and 5 ft. from the source, each of which includes one dozen azimuthal receivers. The azimuthal receiver station has the same size as the monopole source in the axial and radial directions. The channel is between the casing pipe and the formation. The channel has the same axial length as that of the whole simulation model, except for Section3.5. We define the azimuthal angle of the channel as the distribution range of the strip channel in azimuth. As shown in Fig. 1(a), θ_i represents the azimuthal angle of the channel, which is a variable during the simulation. When θ_i reaches 360°, the cement will be replaced completely by the channel; this condition is usually called the free pipe situation. Fig. 1(b)shows the cross section of the model. It can be found that the central azimuth of the channel is 180° and invariable. The parameters used in the model are shown in Table 1. The Ricker wavelet is chosen as the source function; its central frequency is equal to 14 kHz during the simulation, unless specifically noted. The reason for selecting 14 kHz is that several acoustic well logging tools use this frequency as their main frequency of the source. It should be noted that during the simulation, there is not only 8 azimuthal receivers as shown in Fig. 1, but 180 azimuthal receivers, the number of nodes in azimuth direction.

Table 1
Initial parameters of the simulation model.

Material	P-wave velocity (m/s)	S-wave velocity (m/s)	Density (kg/m^3)	Diameter (m)
Borehole fluid	1500	–	1000	0.12
Casing pipe	6100	3300	7800	0.14
Cement	2800	1700	1900	0.22
Formation	4000	2300	2500	–
Channel	1500	–	1000	–

The finite difference method (Sun etal., 2004; Tang and Cheng, 2004; Tang etal., 2016; Tsang and Rader, 1979; Tubman etal., 1986) is typically used for calculating the acoustic field in a complex model. Given that the model in this paper is a non-axisymmetric cylinder with multiple layers in the radial direction, a 3D finite difference method in the cylindrical coordinate is performed (Wang and Fehler, 2018a). In consideration of acoustic waves propagating through the boundary between two materials with large difference of acoustic impedance, a second-order finite difference is used, which can reduce the effect of zero value of shear stress in the fluid layer on the calculation of the velocity field in the solid layer. To eliminate artificial reflections from the boundaries of the restricted computation region, a perfectly matched layer (PML) formulation is introduced. In this paper, we use a non-splittingPML method proposed by Wang and Tang (Wang and Fehler, 2018b). The node of finite difference is set to be 0.005 m in the radial direction, 0.01 m in the axial direction, and 2° in the circumferential direction. The whole model is 150 × 400 × 180 (0.75 m × 2 m × 360°), where the PML layer includes 10 nodes in axial and radial directions. In this paper, the normal stress in the radial direction is taken as waveforms and acoustic fields.

To validate the 3D finite difference algorithm, the simulation model is simplified to an axisymmetric cased hole, and the transmitter and receivers are replaced by point transducers on the borehole axis. Fig. 2 shows comparisons of the results calculated by the finite difference method (FD) and the real-axis integration (RAI) method (Wang and Tang, 2003; Zhang etal., 2011). Fig. 2(a)represents the case of no channel, Fig. 2(b)represents the case of one channel of 2 cm thickness in the radial direction on the casing-cement boundary, and Fig. 2(c)represents the free pipe situation. A comparison of the results shows that, whether there is a channel or not, the waveforms calculated from two methods match each other. Note that, for Fig. 2(b)and (c), the waves of FD and RAI diverge after 0.7 ms because of the numerical dispersion of the finite difference method itself. However, we mainly focus on the first arrival of the casing wave.

3. Simulation result and analysis

The initial values of some important parameters are given here. The channel has the same thickness of 4 cm as the cement annulus, and the azimuthal angle of the channel θ_i is 120°. The source and azimuthal receivers are in the borehole fluid and 4 cm away from the borehole axis in the radial direction. The other parameters are presented in Table 1. In the next section of 3.1, acoustic propagation in the model with initial parameters is simulated. In sections of 3.2–3.7, only one parameter is changed to examine its effect on the azimuthal distribution of ACW.