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Numerical study of mode waves in a deviated borehole penetrating a transversely isotropic formation

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Abstract

A 2.5 dimensional method is developed to investigate the mode waves in a deviated borehole penetrating a transversely isotropic formation. The phase velocity dispersion curves of the fast and slow flexural mode waves excited by a dipole source are computed accurately at different deviation angles for both hard and soft formation. The sensitivity of flexural waves to all the five elastic constants are calculated. Numerical results show that for a soft formation, the fast flexural mode wave is dominated by C_{66} at high deviation angles and low frequencies, the slow flexural mode wave is dominated by C_{44} at the same condition. An inversion procedure is presented to prove the sensitivity analysis.

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Keywords: Deviated borehole; transverse isotropy; acoustic mode waves; dispersion curve; sensitivity analysis

1. Introduction

Acoustic wave propagation in boreholes is the theoretical basis for acoustic well logging. In a real situation, many of the sedimentary rocks with horizontal layers can be characterized as transversely isotropic (TI) when the wavelength of the elastic waves is much larger than the thickness of layers. For such a TI formation, the medium presents isotropy in the horizontal plane while the wave propagation along the vertical axis is different from that in the horizontal plane. When the borehole axis is parallel to the symmetrical axis of the TI formation, analytic methods such as the real axis integration (RAI) and the branch-cut integration can be used to investigate the borehole acoustic field. When the borehole axis is deviated, analytic solutions of the wave field can no longer be obtained [1]. A finite difference time domain (FDTD) method is widely used to study this problem by computing the waveforms [2]. Dispersion curves can be obtained from the results in time domain. The perturbation method is also used when the formation shows weak anisotropy [3].

In this paper, we present a 2.5-dimensional frequency wave-number method to investigate the mode wave characteristics in a deviated borehole. The mode distributions and their dispersion characteristics are observed and analyzed intuitively and accurately. The sensitivities of the mode waves to the elastic constants are obtained based on calculating the dispersion curves accurately. A simple inversion procedure is provided to support our results.

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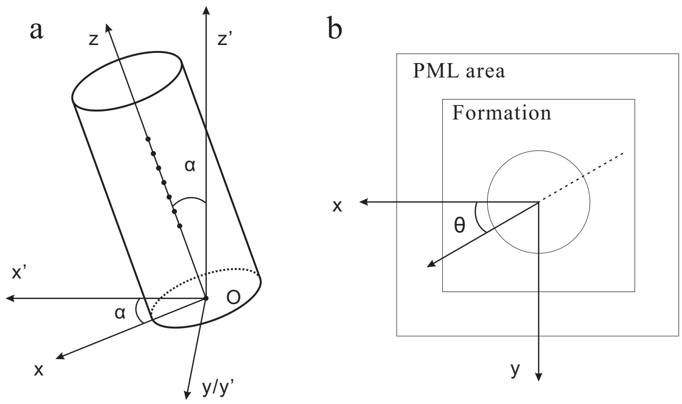

Fig. 1. (a) Model of a deviated borehole; (b) Model of the computation area.

2. Method and results

2.1. Method validation

Consider a fluid-filled cylindrical borehole embedded in an infinite TI formation. The vertical z' axis is the symmetrical axis of the formation while the borehole is deviated with deviation angle α, see Fig. 1(a). Because the formation exhibits isotropy in the horizontal plane, without loss of generality, we assume that y axis and y' axis coincide so that we can obtain the Cartesian coordinate $O - xyz$ from $O - x'y'z'$ when it rotates around y' axis with angle α. The acoustic source is located at the origin. The receivers are located at the borehole axis. For a dipole source, there exists an orientation angle θ, see Fig. 1(b).

When the borehole and surrounding formation are assumed invariant in the axial z direction. Using the separation of variables technique, the wave propagation in the z direction may be described by $\exp(ik_z z)$ where k_z is the wavenumber in the z direction. We have:

$$\phi(x, y, z, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \phi(x, y, \omega, k_z) e^{i(k_z z - \omega t)} d\omega dk_z, \tag{1}$$

where ϕ is the displacement potential which fulfills the wave equation. Thus, we can compute $\phi(x, y, \omega, k_z)$ for different ω and k_z instead of computing $\phi(x, y, z, t)$ directly, i.e. the 2.5-dimensional method. From the $\omega - k_z$ domain results, mode distribution can be seen clearly and dispersion can be obtained. The computation area is shown in Fig. 1(b). We use the PDE module of a commercial FEM software COMSOL to solve the equations. An artificial convolutional perfectly matched layer (PML) is realized to absorb the incident waves [4], [5]. The Bond Transform $C = MC_0M^T$ is used to obtain the elastic constants in the new coordinate [6], where C_0 is the elastic constants matrix expressed in the coordinate of TI formation and M is a matrix related with deviation angle α.

Firstly, we use a non-deviated borehole model to validate our method as the analytical solution exists for such a model. The acoustic velocity in the borehole fluid is $v_f = 1500m/s$ and the density is $\rho_f = 1000kg/m^3$. The borehole radius is $0.1m$. A dipole source is located at the origin. The parameters of TI formation are listed in Table 1.

Table 1. Parameters of the formations

	C_{11}(GPa)	C_{33}(GPa)	C_{13}(GPa)	C_{44}(GPa)	C_{66}(GPa)	$\rho_s(kg/m^3)$
Cotton Valley shale	74.7	58.8	25.3	22.0	30.0	2640
Austin Chalk	22.0	14.0	12.0	2.4	3.1	2200

Fig. 2(a) shows the phase velocity dispersion curves of flexural modes for both fast and slow formations. The solid lines are the analytic results while the points are the results obtained using our method. The comparison indicates that our results are in good agreement with those of the analytic method. These results give us a confidence that the mode