SPECIAL TOPIC — Acoustic

Generalized collar waves in acoustic logging while drilling*

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Tool waves, also named collar waves, propagating along the drill collars in acoustic logging while drilling (ALWD), strongly interfere with the needed P- and S-waves of a penetrated formation, which is a key issue in picking up formation P- and S-wave velocities. Previous studies on physical insulation for the collar waves designed on the collar between the source and the receiver sections did not bring to a satisfactory solution. In this paper, we investigate the propagation features of collar waves in different models. It is confirmed that there exists an indirect collar wave in the synthetic full waves due to the coupling between the drill collar and the borehole, even there is a perfect isolator between the source and the receiver. The direct collar waves propagating all along the tool and the indirect ones produced by echoes from the borehole wall are summarized as the generalized collar waves. Further analyses show that the indirect collar waves could be relatively strong in the full wave data. This is why the collar waves cannot be eliminated with satisfactory effect in many cases by designing the physical isolators carved on the tool.

Keywords: acoustic logging while drilling, borehole wave propagation, generalized collar waves, indirect collar waves

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1. Introduction

Acoustic logging while drilling (ALWD) is a newly proposed in-situ sonic measurement tool for oil/gas reservoir exploration. This technique could be widely applied to off-shore drilling platforms and highly deviated or horizontal wellbores. Moreover, it may be the only potential acoustic logging way for loose soils, high-pressure formations, and unconventional reservoirs in thin layers.[1–3] A good ALWD tool, however, is difficult to design because of the guided waves propagating along the drill collar. Those are the so-called collar waves. All the transducers, including sources and receivers, must be mounted on the steel-made collar, making the collar waves relatively strong and they are dominant in the full-wave arrays. Usually, the formation responses we need are covered by the collar waves and therefore can hardly be recognized. In past years, considerable research efforts have been made to suppress the collar waves in order to accurately pick up P- and S-wave velocities. Most of the previous studies focused on the designing of physical isolators, e.g., carving periodical grooves on the tool surfaces, between the source and receivers,[4–6] however, the accuracy of obtained formation velocities is not satisfactory in the real data. How to get rid of collar waves from formation waves is still a key problem for ALWD application.

In the recent numerical studies, we found that the collar wave signals still exist even if a perfect acoustic insulator is set to be between the source and the receiver sections.[7] Further investigation revealed that the collar waves actually contain two parts of propagation energy. One part of collar waves propagates through the tool from the source to the receiver arrays directly. This is the well-known direct collar wave. Another part of collar waves, however, has seldom been considered in previous studies. It is generated by the propagation of formation compressional waves on the borehole wall. When the compressional arrivals propagate along the side wall of the borehole, they will radiate onto the collars and then travel along the tools, which produce another kind of collar wave. These wave arrivals are categorized as the indirect-collar waves. Both waves on the collar and the borehole wall are totally coupled with each other during the propagation in the axial direction. Therefore, the isolators between the source and the receiver section cannot eliminate the indirect collar waves. We summarize both direct and indirect collar waves as generalized collar waves, to be distinguished from the traditional consumption of collar waves, which are thought to transmit only through the tool. Recently, some scholars engaged in the seismo-electric phenomenon[8] noticed that the sonic waves along logging tools can induce electric signals on the saturated poro-elastic formations. Zheng *et al.*[9,10] and Yang *et al.*[11] recognized that the induced-electric waves have the same velocities as collar waves. Actually, those electric signals propagating along the borehole walls are generated by the indirect waves we have mentioned above. But the properties of that kind of collar wave need to be studied. In the

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present paper, we will further investigate the generalized collar waves based on the numerical simulations and reveal the contributions of the indirect waves in the full waveforms.

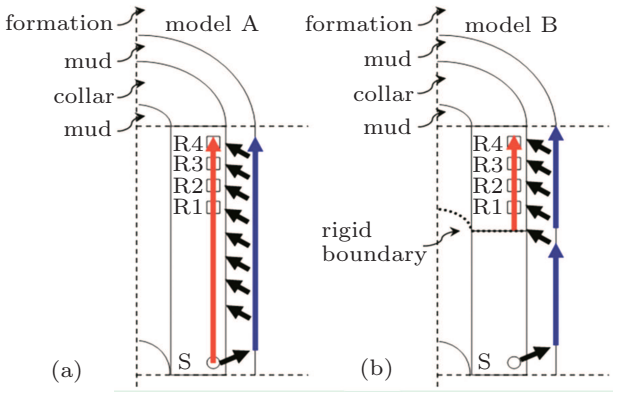


Fig. 1. (color online) Axisymmetric ALWD models used in the numerical simulations. (a) Model A: a common ALWD model with radial layering. (b) Model B: a rigid boundary is set to be between S and R1 in addition to model A, where S denotes the source; R1, R2, R3, and R4 represent the receivers.

2. Numerical simulations of synthetic data

In order to validate the existence of indirect collar wave, we present some numerical simulation results based on physical models depicted in Fig. 1. Model A is a common ALWD model with radially layered structure, while model B contains a rigid boundary for the purpose of blocking all of the waves from propagating through the collar from the source to the receivers, directly. Assume that the formation P-wave velocity (V_p) is 4000 m/s.

Figure 2(a) shows the comparison of synthetic full wave between those two models. The simulations are numerically done by using the finite difference time domain.[12] The center frequency of the source impulse is set to be 12.5 kHz. Due to the rigid boundary that cuts the collar into two separate sections, the first arrival wave is remarkably suppressed compared with that through a collar without isolators. However, we cannot extract the right P wave slowness even perfect physical isolators are set to be between the source and receivers. From the slowness-time processing results,[13] the slowness of the first arrival in model B still equals that of the collar wave (190 μs/m), but not the P wave (250 μs/m). The so-called P-wave velocity of collar material, such as steel, obtained by the slowness time coherence (STC) method is a little lower than the given one. This is because the collar waves are frequency-related dispersive. The acoustic ray paths in Fig. 1(b) show the propagations of indirect collar waves in such an ideal case. Although the collar-wave paths are totally blocked on the collar, those guided waves can still be generated by the radiation of compressional sliding waves along the borehole wall, and then travel through the upper collar section, linking the receiver arrays. Since the slowness extraction is based on the difference in travel-time between wavelets recorded by the receiver arrays, we can surely obtain the collar wave slowness as long as the receivers are connected with the tool. And the result in Fig. 2(b) reflects that the indirect collar waves in model B are still strong enough to cover the P-wave signal. This is why we are unable to extract the P-wave velocity of the formation correctly from the synthetic data.

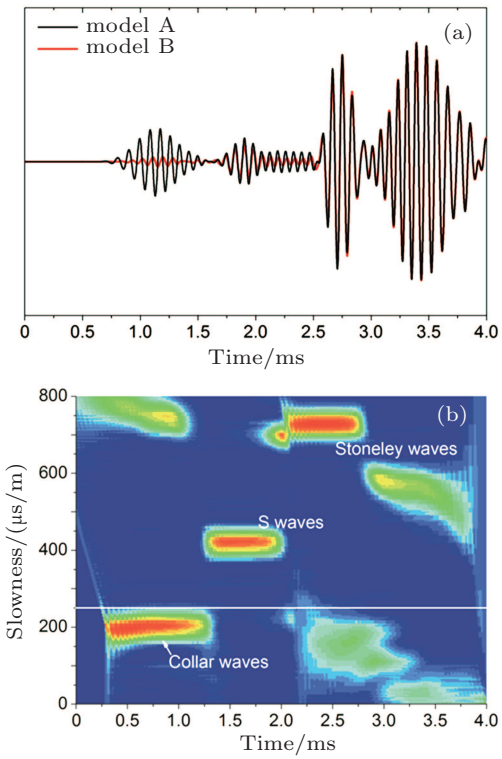


Fig. 2. (color online) (a) Comparison of synthetic full wave between model A and model B. The receiver-to-source distance is 3.6 m. (b) Slowness-time processing reveals that the slowness extracted from the first arrival in model B is consistent with that of the collar wave, not the P wave. The white line denotes the theoretical P slowness (250 μs/m).

3. Dispersion and excitation of collar waves

To investigate the properties of direct and indirect collar waves, we analyze both dispersion and excitation of those guided waves in infinite liquids, elastic boreholes and rigid boreholes, respectively. Assume that the collar is a homogeneous hollow pipe as that in model A. The transducers are fixed on its outer surface. The acoustic function in the frequency–wavenumber (f–k) domain for ALWD model can be derived by solving the elastic wave equations with suitable boundary conditions as indicated in Refs. [2] and [14]. Figure 3(a) shows the phase velocity dispersion curves of collar waves obtained from poles of the acoustic function in the f–k domain. Here we just focus on the lowest mode of collar wave because other modes are in a high frequency range far beyond the conventional source impulses. According to the analytical solutions of wave equations, the dispersion curves of collar waves in infinite liquids and within boreholes, no matter whether they are elastic or rigid ones, are almost the same. It

is revealed that the propagation velocities of the generalized collar waves have little relation with the borehole or formation properties. The guided wave speed is just determined by the geometry and material properties of the collar itself. However, due to their coupling with the reflection and sliding waves on the borehole wall, the excitation intensities of generalized collar waves vary dramatically as shown in Fig. 3(b). For the collar placed in infinite liquids, only the direct collar waves exist as the indirect ones cannot be generated without reflection. When the collar is located in a borehole with a formation P-wave velocity of 2000 m/s, the amplitude of collar wave excitation is enhanced due to the indirect collar waves in addition to the direct ones. As the P-wave velocity of the formation increases ($V_{\rm p} = 4000$ m/s, 6000 m/s), the reflection from the borehole wall becomes stronger and therefore the whole amplitudes of generalized collar waves increase. Moreover, the peak value shifts toward higher frequencies as the resonant frequencies of compressional sliding waves also vary with formation property.[15] When the borehole wall is entirely rigid ($V_{\rm P} = \infty$), the generalized collar wave tends to a maximum amplitude compared with other cases because of the total

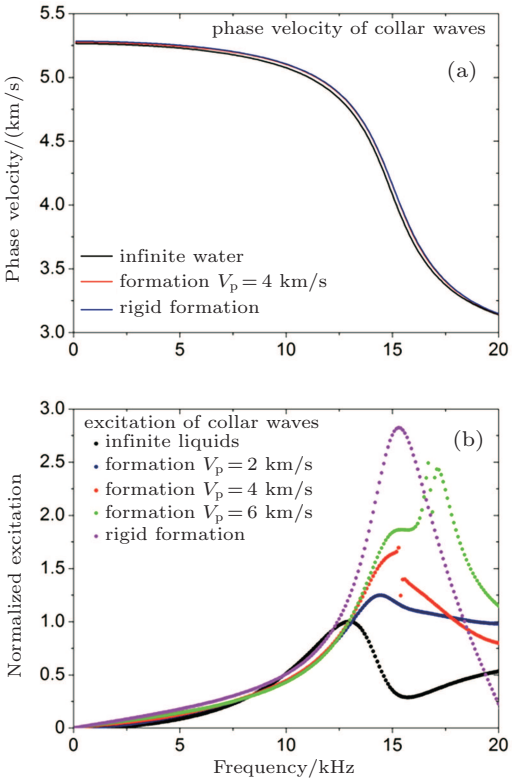


Fig. 3. (color online) (a) Velocity dispersion of collar waves in infinite liquids ($V_{\rm f} = 1500$ m/s), a borehole surrounded by an elastic formation ($V_{\rm p} = 4000$ m/s), and a rigid borehole, respectively. (b) Excitation intensities of collar waves in infinite liquids, borehole surrounded by elastic formations ($V_{\rm p} = 2000$ m/s, 4000 m/s, 6000 m/s), and a rigid borehole, respectively. The receiver-to-source distance is 3 m. The excitation amplitudes are normalized with respect to the maximum value for the case in infinite liquids.

reflection. The indirect collar wave can be simply evaluated by subtracting the direct collar waves from the whole ones. Therefore, from Fig. 3(b), it can be concluded that the indirect collar waves have amplitudes which are approximately equal to, or even stronger than, the direct waves.

4. Conclusions

Adopting the idea different from the widely acknowledged view that tool waves propagate only through the collar, in this work we confirm the existence of the collar wave propagating through another path, which is caused indirectly by the coupling effect between the steel collar and the borehole wall. Both the direct and indirect waves in the ALWD model are parts of the generalized collar guided modes. The indirect collar waves are also strong compared with the well-known direct ones. According to the conclusions summarized in this article, the indirect collar waves cannot be blocked by the physical isolators between the source and the receiver sections. The idea of carving well-designed grooves on the collar and hoping to eliminate the collar waves can only work for isolating direct collar waves. Setting extra isolators to be among all receivers to suppress the indirect collar waves through the receiver connection seems to be an intuitive but actually limited solution because of the very short distance from one receiver to another. Future research should focus more on digital signal processing to separate the collar waves from full wave data to compensate for the deficiency of physical insulation. Moreover, the optimization or new design of acoustic transducer, e.g., directional transmitter and receiver, is also a potential means to generate and catch fewer collar waves in the real data.

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