Research Article

Lithological Interface Detection Using an Impact Source

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Early detection of abnormal geological targets during drilling can enhance the safety of petroleum drilling. An impact source equipped with the advantage of long detection distances can recognize lithological interfaces. However, coda waves in the vibration waveform are significant to reflected waves, which are difficult to recognize in the time domain. This paper presents the design of an impact source that includes a hammer, impacted metal, Teflon, and a metal base. With the length and diameter of Teflon kept constant, the effect of the hammer, impacted metal, and metal base on coda waves was experimentally investigated. According to the preferred metal materials, the effect of the length and diameter of Teflon on coda waves was also experimentally studied. A distance measurement experiment was implemented on 1.2 m sandstone on the basis of the preferred impact source design. The experimental results show that the coda waves are significantly attenuated by the preferred impact source. Moreover, the reflected waves are clearly identified in the time domain. Therefore, the preferred impact source can be used effectively in lithological interface detection.

1. Introduction

The geological structures encountered in petroleum drilling are complicated. Many abnormal geological structures are encountered by the drill bit, such as fault zones, faults, and caves. Prediction of abnormal geological structures ahead of the drill bit can offer important a priori information to improve drilling safety [1, 2]. Techniques for detection in advance mainly involve ground-penetrating radars, the ultrasonic pulse-echo technique, seismic wave detection technology, and the impact-echo technique [3–6].

Ground-penetrating radar uses electromagnetic waves to forecast geological targets and includes surface and borehole ground-penetrating radar [7]. Surface ground-penetrating radar is applied to detect shallow formation information, such as soil-water content [8]. Borehole ground-penetrating radar uses a radar antenna deployed in the borehole to detect deep stratum information, such as tunnel geological prediction [9]. In the drilling of deep and extradeep wells, a low-frequency radar antenna is inserted in the rotary steerable drilling assembly [10], and three receivers are fixed in the drill string. The frequency range of the radar antennas is between 10 MHz and 10 GHz. Although high-resolution detection can be obtained via high-frequency electromagnetic waves, the detection distance in petroleum drilling is limited.

The ultrasonic pulse-echo technique with sound waves is generally used to detect defects inside the structure. Ultrasonic waves, unlike electromagnetic waves, can travel through metal. Therefore, the ultrasonic pulse-echo technique has been applied to delamination detection in concrete bridges and deviation analysis of metal pipelines [11, 12], as well as quality control of multilayered plastic materials [5]. When ultrasonic waves are used for rock thickness detection, high-frequency sound waves are significantly attenuated by rocks. As a result, the ultrasonic pulse-echo technique is not suitable for detecting rock information ahead of the drill bit.

Tunnel seismic wave detection technology consists of tunnel seismic prediction, tunnel seismic tomography, and small-offset seismic wave detection. Tunnel seismic prediction uses a linear geophone array on the ground to receive seismic waves [13–15]. Digital filtering technology is applied to improve the signal-to-noise ratio of the seismic waves.
This detection method is suitable for large-scale anomalous geological targets. It is ideal for detecting discontinuous interfaces that are approximately perpendicular to the axis of the tunnel. However, it cannot accurately detect geological targets ahead of the tunnel face. Tunnel seismic tomography uses geophones on the tunnel surface to receive seismic waves [18, 19]. This detection method has been applied to detect geological targets ahead of the tunnel face; however, a long time is required to arrange the excite source and receiver on the face and the side walls of the tunnel. Orthogonal geophones are connected on the tunnel face in small-offset seismic wave detection [20]. The distance between the excite source and the geophone is small, which is suitable for detecting small- and medium-sized caves ahead of the tunnel face. The detection distance of tunnel seismic wave detection technology is within 120 m. However, a large number of geophones are fixed on the ground or the tunnel face; in this case, the geophones can be easily restricted by the downhole environment. Therefore, the tunnel seismic detection technology cannot be applied to petroleum drilling.

A controllable seismic source on the ground has been used to excite seismic waves in petroleum drilling. The geophone near the drill bit is used to receive reflected waves [1, 3]. When seismic waves propagate from the ground to near the drill bit, high frequencies are significantly attenuated. As a result, seismic wave detection technology has low resolution in petroleum drilling.

The impact-echo technique is based on the use of transient stress waves for nondestructive detection of flaws in concrete structures [6, 21, 22]. The stress waves are produced by an impact device. A piezoelectric transducer detects surface displacements caused by reflected waves. A simple formula related to the reflected wave frequency and P-wave velocity is used to calculate the depth of the defect. The detection range of the impact-echo technique is within 1.5 m.

In these detection techniques, the large frequency values of the electromagnetic waves and ultrasonic waves limit the detection distance. The detection range of impact-echo technology is too close to be useful for petroleum drilling. Seismic wave detection technology can achieve long-range detection, but its resolution is low.

To improve the resolution of seismic wave detection technology in petroleum drilling, an impact source was designed in this paper. The impact source consists of a hammer, impacted metal, Teflon, and a metal base. The preferred metal material was determined according to the impact experiment results. On the basis of the preferred metal materials, the effect of Teflon length and diameter on coda waves was experimentally investigated. The preferred impact source was then used for measurement of rock thickness.

2. Detection Principle of the Impact Source

The white cylinder shown in Figure 1(b) is composed of Teflon. The metal above the Teflon is called the impacted metal, and the metal below the Teflon is called the metal base. Vibration waves are received by the acceleration sensor on the metal base shown in Figure 1. When the impacted metal is struck by the hammer as shown in Figure 1(a), vibrations are detected with the time-domain waveform and frequency spectrum shown in Figures 2(a) and 2(b). Coda waves in the vibration waves are more significant because the damping of the metal is small [23]. It is difficult to identify reflected waves in the time domain when reflected waves overlap the vibration waves. When the impacted metal is struck by a hammer as shown in Figure 1(b), vibrations are detected with the time-domain waveform and spectrum shown in Figures 2(c) and 2(d). As shown in Figure 2(c), the first wave in the vibration waveform is a Ricker wavelet that is generated by the impact. Coda waves in the vibration waveform are significantly attenuated because the attenuation coefficient of the Teflon is quite large [24]. When vibration waves propagate from the impacted metal to the metal base, the amplitude of the vibration waves is significantly attenuated by the Teflon. Moreover, viscous damping in Teflon and sandstone is much larger than that of the metal base. When the metal base is more tightly coupled with the Teflon and sandstone, the free vibration in the metal base is attenuated [25]. Therefore, coda waves in the vibration waveform are significantly attenuated. The first wave in the vibration waveform can be used for lithological interface detection.

2.1. Preference Experiments of the Metal Materials. To achieve better attenuation of coda waves, the effect of the hammer, the impacted metal, and the metal base on coda waves was experimentally investigated. The preferred material for each metal component was determined according to the impact experiment results. The metals considered included high-carbon steel, stainless steel 316, stainless steel 304, and aluminum, and these were processed using a milling cutter [26, 27]. High-carbon steel was selected to strike the metal in the impact experiment because high-carbon steel has higher hardness and better abrasion resistance. The downhole environment has stringent requirements for metal materials in petroleum drilling. Stainless steel 304 and stainless steel 316 exhibit good corrosion resistance and high temperature resistance. Furthermore, stainless steel 316 does not have the phenomenon of thermal expansion and contraction. Therefore, stainless steel 304 and stainless steel 316 were selected for consideration as the impacted metal and the metal base, respectively. For comparison with stainless steel, aluminum was also selected for consideration as the impacted metal and the metal base.

2.2. Preference Experiment of the Impacted Metal and Metal Base. The impacted metals made of aluminum, stainless steel 304, and stainless steel 316 are shown in Figure 3(a), and the impact source is shown in Figure 3(b). The high-carbon steel ball was applied to strike the different metals from the same height. The vibration waveforms generated by the impact source for aluminum, stainless steel 304, and stainless steel 316 are shown in Figures 4(a), 4(c), and 4(e), respectively. The respective frequency spectra are shown in
The experimental results show that the coda waves in Figure 4(e) and high frequencies in Figure 4(f) are significantly attenuated because the mass of stainless steel 316 is greater than that of stainless steel 304. The metal base is more tightly coupled with the sandstone and the Teflon, and free vibration in the metal base is...
attenuated. Therefore, stainless steel 316 was selected as the impacted metal.

The metal bases made of aluminum, stainless steel 316, and stainless steel 304 are shown in Figure 5. The stainless steel 316 impacted metal was placed on the Teflon and struck by the steel ball. For the metal bases of aluminum, stainless steel 316, and stainless steel 304, the vibration waveforms generated by the impact source are shown in Figures 6(a), 6(c), and 4(e), respectively. The respective frequency spectra are shown in Figures 6(b), 6(d), and 4(f). The experimental results show that the coda waves in Figure 4(e) and high frequencies in Figure 4(f) are significantly attenuated because the mass of stainless steel 304 is greater than that of stainless steel 316. Stainless steel 304 is more tightly coupled with sandstone, and free vibration in the metal base is also attenuated. Therefore, stainless steel 304 was selected as the metal base.

2.3. Preference Experiment of the Impact Hammer. The hammers shown in Figure 7 were designated as hammer No. 1, hammer No. 2, and hammer No. 3 from left to right. Each hammer was fabricated using high-carbon steel. The stainless steel 316 impacted metal was placed on the Teflon, and the stainless steel 304 base metal was placed on the sandstone. When the impacted metal was struck by each hammer, coda waves were significantly attenuated, as shown in Figures 8(a), 8(c), 8(e), and 8(g). These results show that the shape and mass of the hammer have a small effect on coda waves. The frequencies of the first wave are 469.5 Hz, 450.5 Hz, 450.5 Hz, and 446.4 Hz, as shown in Figures 8(b), 8(d), 8(f), and 8(h), respectively. With the increase in hammer mass, the frequency of the first wave slowly decreases. Although the frequency of the first wave changes within a small range, hammer No. 3, with a greater mass, was selected to improve the detection distance.

3. Effect of Teflon on Vibration Waves

3.1. Effect of Teflon Diameter on the Vibration Waves. With the preferred metal materials, the effect of the Teflon diameter on the vibration waves was experimentally studied. The stainless steel 316 impacted metal was placed on the Teflon, and the stainless steel 304 base metal was placed on the sandstone. The length of each Teflon sample shown in Figure 9 was 8 cm. The steel ball was used to strike the impacted metal from the same height for each Teflon sample with diameter D shown in Figure 10. The coda waves and high frequencies were significantly attenuated in Figures 10(e) and 10(f) because coda waves are significantly attenuated by the Teflon. Moreover, the metal base is more tightly coupled with sandstone and Teflon when the Teflon diameter is increased. Free vibration in the metal base is also attenuated. Therefore, coda waves are significantly attenuated by the Teflon with a diameter of 12 cm.

3.2. Effect of Teflon Length on the Vibration Waves. Considering the preferred Teflon diameter, the effect of Teflon length on the vibration waves was experimentally investigated. Teflon samples with different lengths are shown in Figure 11. The Teflon diameter was 12 cm. The steel ball was used to strike the impacted metal at different heights according to Teflon length L. The steel ball was dropped from a height of 30 cm above the impacted metal. With the increase in Teflon length, coda waves and high frequency are significantly attenuated in Figure 12 because coda waves are significantly attenuated by the Teflon. On
Figure 4: (a, c, e) Time-domain waveforms and (b, d, f) frequency spectra for different impacted metals.

Figure 5: Metal bases used in the experiment.
the contrary, as the Teflon length increases, the metal base is more tightly coupled with sandstone and Teflon. Free vibration in the metal base is also attenuated. The experimental results show that coda waves are significantly attenuated when the Teflon length is greater than 16.2 cm. Therefore, Teflon with a length greater than 16.2 cm was applied to the proposed impact source detection apparatus.

With the preferred Teflon diameter, the relationship between the impact height and the amplitude of the first wave, the frequency of the first wave, and the main frequency is shown in Figure 13, where \( L \) represents the Teflon length. The distance between the steel ball and the impacted metal is defined as the impact height. When the impact height is enhanced, the amplitude of the first wave increases, as shown in Figure 13(a). The frequency range of the first wave is between 250 and 500 Hz for different Teflon lengths as shown in Figure 13(b). When the Teflon length is greater than 16.2 cm, the frequency range of the
Figure 8: (a, c, e, g) Time-domain waveforms and (b, d, f, h) frequency spectra for different hammers.
Figure 9: Teflon samples with different diameters.

Figure 10: (a, c, e) Time-domain waveforms and (b, d, f) frequency spectra for different Teflon diameters.
first wave is between 300 and 500 Hz at different impact heights. When the impact height is greater than 30 cm, the frequency range of the first wave is between 420 and 450 Hz, as shown in Figure 13(b). As the impact force increases, the frequency of the first wave changes within a small range. The main frequency range is between 200 and 700 Hz for different Teflon lengths, as shown in Figure 13(c). These results show that high frequencies in the vibration waves are significantly attenuated by the Teflon. Therefore, Teflon with a length greater than 16.2 cm was selected to attenuate coda waves.

4. Measurement Results

With the preferred metal materials and Teflon dimensions, a distance measurement experiment was performed on 1.2 m sandstone. The impact source consisted of hammer No. 3, stainless steel 316, 16.2 cm Teflon, and stainless steel 304, as shown in Figure 14. When the metal was struck by hammer No. 3, the metal base and rock surface could not be tightly coupled. To better receive reflected waves, the acceleration sensor was fixed on the rock surface. The first wave received by the acceleration sensor is a Ricker wavelet in Figure 15(a). In comparison with the Ricker wavelet, the time difference between the starting point and the abnormal change point was recorded as the arrival time of the reflected waves, as shown in Figure 15(b). The arrival time of the reflected waves was 680 μs. The longitudinal wave velocity of the sandstone was 3563 m/s, which was obtained by measuring the wave velocity of a sandstone core. The predicted rock thickness was 1.2114 m. The relative error between true rock thickness and predicted rock thickness was 0.95%. These experimental results show the measurement accuracy can meet the requirements of lithological interface detection. Coda waves in the vibration waveform were significantly attenuated by the preferred impact source. This detection method can thus improve the resolution of seismic wave detection technology.

5. Discussion

The impact source approach to interface detection has the advantage of long detection distance. However, it is difficult to recognize reflected waves in the time domain when reflected waves overlap coda waves. To better attenuate coda waves in vibration waves, the preferred metal material was determined according to the impact experiment results. Using the preferred metal materials, the effect of the Teflon length and diameter on the vibration waves was experimentally investigated. A distance measurement experiment was conducted on 1.2 m sandstone with the preferred metals and Teflon dimensions. There is currently no relevant research in this field, but the results of this study provide an experimental basis for attenuating the coda waves in vibration waveforms.

This work focused on the effect of Teflon diameter and length on coda waves in vibration waveforms because coda waves in vibration waveforms are significantly attenuated by the Teflon [24]. When the Teflon length is greater than 16.2 cm and the impact height is greater than 30 cm, the frequency range of the first wave is between 420 and 450 Hz in Figure 13(b). The preferred impact source improves the resolution of seismic wave detection technology.

The preferred metal material was determined according to the impact experiment results. The effect of metal materials on coda waves has not been studied in detail because of the limitations faced under the experimental conditions. From the impact experiment results, we found that stainless steel has a better attenuation effect on coda waves than aluminum. In addition, viscous damping in the Teflon and sandstone is much larger than that of the metal base. When the mass of the metal is increased, the metal base is more tightly coupled with sandstone and Teflon. The free vibration in the metal base is attenuated [25]. Therefore, a metal with greater mass is helpful for attenuating coda waves. We will carry out detailed research in this area in the future.

Prediction of rock information ahead of the drill bit during drilling can significantly improve drilling safety. The thickness of sandstone was accurately measured according to the preferred impact source materials. However, the downhole impact source has not been designed. The preferred impact source and an acceleration sensor will be fixed in a drill string in future research. More experiments will be performed to verify the proposed impact source can be used to forecast abnormal geologic targets ahead of drill bit in petroleum drilling.
Figure 12: Continued.
Figure 12: (a, c, e, g, i, k) Time-domain waveforms and (b, d, f, h, j, l) frequency spectra for different Teflon lengths.
Figure 13: Relationship between the impact height and (a) amplitude of the first wave, (b) frequency of the first wave, and (c) main frequency for Teflon of different lengths.

Figure 14: Impact source on 1.2 m sandstone.

Figure 15: Time-domain waveforms received by the acceleration sensor on sandstone surface: (a) no reflected wave received; (b) reflected wave received.
6. Conclusions

The effect of metal materials and Teflon dimensions on coda waves in vibration waveforms was experimentally studied. A measurement experiment was carried out on 1.2 m sandstone according to the preferred impact source materials. The conclusions are as follows:

(1) The preferred impact source includes a high-carbon steel hammer, stainless steel 316, Teflon, and stainless steel 304. When the Teflon diameter is 12 cm and the Teflon length is greater than 16.2 cm, coda waves in vibration waveforms are significantly attenuated. The amplitude of the first wave increases when the impact force is increased. The frequency range of the first wave is between 420 and 450 Hz when the impact height is greater than 30 cm. As the impact force increases, the frequency of the first wave changes within a small range. Therefore, a hammer with greater mass improves the detection distance. In order to better attenuate coda waves in vibration waveforms, the metal base should be more tightly coupled with the rock and the Teflon.

(2) The preferred impact source was applied to measure 1.2 m sandstone. Reflected waves are clearly identified in the time domain. The relative error between true rock thickness and predicted rock thickness does not exceed 1%. This detection method has the advantages of long detection distance and high resolution and is not restricted by the downhole environment. However, the downhole impact source has not been designed. The downhole measurement experiment will be performed to predict abnormal geological targets in petroleum drilling in future research.

Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also form part of an ongoing study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] C. Esmersoy, W. Underhill, and A. Hawthorn, “Seismic measurement while drilling: conventional borehole seismic on LWD,” in Proceedings of the SPWLA 42nd Annual Logging Symposium, Houston, TX, USA, June 2001.
[2] E. Brückl, W. Chwatal, S. Mertl, and A. Radinger, “Exploration ahead of a tunnel face by TSWD-tunnel seismic while drilling,” Geomechanik und Tunnelbau, vol. 1, no. 5, pp. 460–465, 2010.
[3] A. Anchliya, “A review of Seismic-While-Drilling (SWD) techniques: a journey from 1986 to 2005,” in Proceedings of the SPE Europe/EAGE Annual Conference and Exhibition, Vienna, Austria, June 2006.
[4] S. Li, B. Liu, X. Xu et al., “An overview of ahead geological prospecting in tunneling,” Tunnelling and Underground Space Technology, vol. 63, pp. 69–94, 2017.
[5] R. Rašutis, R. Kazys, and L. Mažeika, “Application of the ultrasonic pulse-echo technique for quality control of the multi-layered plastic materials,” NDT & E International, vol. 41, no. 4, pp. 300–311, 2008.
[6] A. Sadri, “Application of impact-echo technique in diagnoses and repair of stone masonry structures,” NDT & E International, vol. 36, no. 4, pp. 195–202, 2003.
[7] E. Slob, M. Sato, and G. Olhoeft, “Surface and borehole ground-penetrating-radar developments,” Geophysics, vol. 75, no. 5, pp. 75A103–75A120, 2010.
[8] T. H. Ling, S. Zhang, and S. R. Li, “Hilbert-Huang transform method for detection signal of tunnel geological prediction using ground penetrating radar,” Chinese Journal of Rock Mechanics and Engineering, vol. 31, no. 7, pp. 1422–1428, 2012.
[9] X. Liu, J. Chen, X. Cui, Q. Liu, X. Cao, and X. Chen, “Measurement of soil water content using ground-penetrating radar: a review of current methods,” International Journal of Digital Earth, vol. 12, no. 1, pp. 95–118, 2019.
[10] M. V. Constable, F. Antonsen, S. O. Stalheim, P. A. Olsen, and O. Z. Fjell, “Looking ahead of the bit while drilling: from vision to reality,” Petrophysics, vol. 57, no. 5, pp. 1767–1775, 2016.
[11] J. Michal, P. Cikrle, J. Grošek, O. Anden, and J. Stryk, “Comparison of infrared thermography, ground-penetrating radar and ultrasonic pulse echo for detecting delaminations in concrete bridges,” Construction and Building Materials, vol. 225, pp. 1098–1111, 2019.
[12] B. S. Marció, P. Niemheysen, D. Habor, and R. C. C. Flesch, “Quality assessment and deviation analysis of three-dimensional geometrical characterization of a metal pipeline by pulse-echo ultrasonic and laser scanning techniques,” Measurement, vol. 145, pp. 30–37, 2019.
[13] A. Alimoradi, A. Moradzadeh, R. Naderi, M. Z. Salehi, and A. Etemadi, “Prediction of geological hazardous zones in front of a tunnel face using TSP-203 and artificial neural networks,” Tunnelling and Underground Space Technology, vol. 23, no. 6, pp. 711–717, 2008.
[14] Š.-S. Shi, S.-C. Li, L.-P. Li, Z.-Q. Zhou, and J. Wang, “Advance optimized classification and application of surrounding rock based on fuzzy analytic hierarchy process and Tunnel Seismic Prediction,” Automation in Construction, vol. 37, pp. 217–222, 2014.
[15] Y. Yue, T. Jiang, C. Han, J. Wang, Y. Chao, and Q. Zhou, “Suppression of periodic interference during tunnel seismic predictions via the Hankel-SVD-ICA method,” Journal of Applied Geophysics, vol. 168, pp. 107–117, 2019.
[16] B. Chen, Y. Li, X. Cao, W. Sun, and W. He, “Removal of power line interference from ECG signals using adaptive notch filters of sharp resolution,” IEEE Access, vol. 7, pp. 150667–150676, 2019.
[17] W. Sun and X. Cao, “Curvature enhanced bearing fault diagnosis method using 2D vibration signal,” *Journal of Mechanical Science and Technology*, vol. 34, no. 6, pp. 2257–2266, 2020.

[18] Y. Zhao, H. Jiang, and X. Zhao, “Tunnel seismic tomography method for geological prediction and its application,” *Applied Geophysics*, vol. 3, no. 2, pp. 69–74, 2006.

[19] S.-Y. Gong, J. Li, F. Ju, L.-M. Dou, J. He, and X.-Y. Tian, “Passive seismic tomography for rockburst risk identification based on adaptive-grid method,” *Tunnelling and Underground Space Technology*, vol. 86, pp. 198–208, 2019.

[20] S. H. Zhong, H. Z. Sun, S. C. Li, X. Li, and R. Wang, “Detection and forecasting for hidden danger of karst fissure water and other geological disasters during construction of tunnels and underground projects,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 31, pp. 3298–3327, 2012.

[21] A. Kumar, B. Rai, P. Kalyanasundaram, T. Jayakumar, and M. Thavasimuthu, “Structural integrity assessment of the containment structure of a pressurised heavy water nuclear reactor using impact echo technique,” *NDT and E International*, vol. 35, no. 4, pp. 213–220, 2002.

[22] F. Yao, G. Chen, and A. Abula, “Research on signal processing of segment-grout defect in tunnel based on impact-echo method,” *Construction and Building Materials*, vol. 187, pp. 280–289, 2018.

[23] M. Colakoglu and K. L. Jerina, “Damping behavior of cyclically deformed 304 stainless steel,” *Indian Journal of Engineering and Materials Sciences*, vol. 10, pp. 480–485, 2003.

[24] R. Khurana, P. C. Gautam, R. Rai, A. Kumar, A. C. Sharma, and M. Singh, “Studies on shock attenuation in plastic materials and applications in detonation wave shaping,” *Journal of Physics: Conference Series*, vol. 377, Article ID 012051, 2012.

[25] H. M. Faridani and A. Capsoni, “Investigation of the effects of viscous damping mechanisms on structural characteristics in coupled shear walls,” *Engineering Structures*, vol. 116, pp. 121–139, 2016.

[26] Y. Zhou and W. Xue, “A multisensor fusion method for tool condition monitoring in milling,” *Sensors*, vol. 18, no. 11, p. 3866, 2018.

[27] Y. Zhou and W. Xue, “Review of tool condition monitoring methods in milling processes,” *The International Journal of Advanced Manufacturing Technology*, vol. 96, no. 5–8, pp. 2509–2523, 2018.