

Vibration Signal Characteristics of Fractured Freezing Pipes with Different Diameter-to-Thickness Ratios Based on Similarity Model Tests

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Abstract

Sudden rupture of freezing pipes frequently occurs in artificial ground freezing engineering. Owing to complex field environments, it is difficult to clarify the single-factor evolutionary laws of vibration signals induced by pipe fracture through field monitoring. Four groups of model freezing pipes with diameter-to-thickness ratios ranging from 20 to 26 were fabricated through geometric scaling based on engineering prototype pipes of $\Phi 140 \times (5-7)$ and $\Phi 159 \times (6-8)$. A low-temperature brine medium at -30°C was circulated inside the pipes to simulate actual in situ refrigeration conditions. A series of tensile rupture tests were performed to explore the vibration response characteristics of freezing pipes with different specifications. The test results indicate that the ultimate rupture load is positively correlated with signal energy. Within the diameter-to-thickness ratio range of 20–26, the signal amplitude decreases approximately linearly ($R^2 = 0.99$), while the progress count and signal energy increase gradually, and the dominant frequency of rupture vibration signals decreases continuously. In other words, the dominant frequency gradually declines as the diameter-to-thickness ratio rises. Unlike conventional acoustic emission characteristics of bare steel fracture, which are typically characterized by high-amplitude, high-energy bursts with prominent central frequencies, the vibration signals of freezing pipes surrounded by frozen soil exhibit significantly lower dominant frequencies (3–30 kHz), rapid attenuation due to pipe–soil energy radiation, and a frequency shift that is structurally governed by the diameter-to-thickness ratio rather than by material properties alone. The quantitatively established frequency bands and parameter evolution patterns can serve as reference criteria for field monitoring and early warning of freezing pipe fracture in artificial ground freezing engineering.



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1. Introduction

With the increase in excavation depth during mineral mining, surrounding rock masses featuring substantial deformation and extreme instability are frequently encountered [1]. Coupled with high in situ stress and high water pressure, such geological conditions severely restrict the progress of underground engineering construction [2]. Improper

support measures can readily trigger catastrophic hazards including water inrush and collapse. Since the beginning of the 21st century, as shaft construction depths continue to increase, freezing pipe rupture accidents persist [3,4], and a comprehensive solution to such failures has not yet been achieved in China [5].

From the 1970s to the 1980s, the Soviet Union deployed artificial ground freezing technology for the construction of subways, mine shafts and various other industrial structures, with over 200 completed projects in total. In China, the AGF technique was first applied to the excavation of the air shaft at Linxi Coal Mine in the Kailuan Mining Area in 1955, marking a development history spanning more than six decades. Nevertheless, numerous fractures of freezing pipes have occurred throughout this period [6]. A typical case involves the South Ventilation Shaft of Pan'er Coal Mine in the Huainan Mining Area, where 14 freezing pipes fractured in the 1970s.

Severe engineering disasters will have already occurred by the time massive thawing of the frozen wall and substantial brine leakage emerge, so merely monitoring parameters such as brine flow rate [7,8] fails to achieve reliable detection and early warning of freezing pipe rupture accidents.

Existing studies confirm that characteristic AE parameters, including signal energy, ring-down count and amplitude, can distinguish distinct deformation phases throughout the metallic failure process [9,10]. Fracture waveforms of metallic materials are characterized by high amplitude, high energy, low frequency and long duration, along with a prominent dominant central frequency [11–13]. In contrast, waveforms generated during crack propagation of freezing pipes exhibit low energy and rapid attenuation. These two types of AE sources show remarkable discrepancies in waveform morphology, frequency spectrum and time–frequency distribution.

Nevertheless, the above investigations only address fracture signals of bare metallic specimens. In practical engineering, freezing pipes are fully encapsulated by frozen soil, and their vibration responses are dominated by integral structural interaction, leading to substantial differences from pure material fracture signals. Other researchers have adopted AE technology to inspect buried pipelines [14–16], and systematically investigated how the propagation and attenuation of AE signals are affected by internal/external surrounding media, internal pipeline pressure, joint configuration and pipe geometric dimensions, so as to realize leakage identification of underground pipelines [17–19].

Nevertheless, limited research has focused specifically on the monitoring of freezing pipe rupture [20–22]. As an early representative study, Zhang et al. (1990) conducted laboratory tests on freezing pipe fracture signals and developed a microcomputer-based early-warning system [23]. Their experimental program included laboratory three-point bending tests without frozen soil confinement and in situ fracture tests on buried freezing pipes. The test results revealed that pipe rupture signals possessed distinct dominant frequencies: approximately 1970 Hz for laboratory specimens and 210 Hz for field pipes, showing a prominent discrepancy. Importantly, both dominant frequencies exceeded that of the strongest field interference signals. However, this study adopted oversimplified assumptions regarding external frozen soil confinement, pipe joint characteristics and fracture modes, failing to yield comprehensive and in-depth conclusions.

In 2018, Zhao systematically investigated the acoustic emission (AE) signal characteristics and signal propagation attenuation induced by freezing pipe fracture in deep mine physical models confined by geotechnical similar materials. The influences of various rupture modes on acoustic wave signatures, together with the corresponding ranges of dominant frequency, amplitude and other characteristic parameters, were quantified [24]. Hereafter, the terms “vibration signal” and “acoustic emission (AE) signal” are used interchangeably throughout this work unless otherwise specified, with both referring to

high-frequency elastic wave signals generated by freezing pipe fracture and captured via the AE acquisition system.

Despite these prior contributions [25,26], a systematically verified similarity model that explicitly reproduces pipe–soil interaction and enables single-factor investigation of pipe geometric effects on vibration signal characteristics has not been reported, and the quantitative influence of D/t (diameter-to-thickness ratio) on vibration signal characteristics remains unestablished.

Accordingly, this paper establishes a laboratory physical similarity model and performs single-factor analysis focusing only on freezing pipe specifications. The influence law of freezing pipe specifications on core characteristic parameters such as the dominant frequency of vibration signals induced by pipe rupture is systematically investigated.

This study targets three vital yet insufficiently investigated research gaps in the current literature concerning fracture monitoring of freezing pipes. First, previous experiments were performed either on unconfined bare metal pipe samples without considering pipe–soil interaction, or based on drastically simplified hypotheses regarding frozen soil restraint and pipe joint properties. Consequently, few systematically verified similarity models can accurately reproduce the complete structural behavior of freezing pipes buried in frozen strata. Second, the independent quantitative correlation between pipe geometric parameters (particularly the diameter-to-thickness ratio, D/t) and vibration signatures triggered by pipe fracture remains unclarified. Third, dominant frequency, a signal characteristic featuring strong anti-interference performance and stable intrinsic regularity, has not been thoroughly exploited as a credible monitoring indicator for field engineering. In particular, despite field evidence showing that the dominant frequency of buried pipe fracture is an order of magnitude lower than that of bare laboratory specimens, this frequency shift has not been quantitatively linked to pipe specifications.

To address the aforementioned research gaps, this study constructs a laboratory physical similarity test model and conducts single-factor analysis with freezing pipe dimensions as the sole controlled variable. It systematically elucidates the influence patterns of freezing pipe specifications on core characteristic indicators, including the dominant frequency of vibration signals induced by pipe rupture. The findings provide a theoretical reference for field monitoring of freezing pipe fracture and bear certain practical engineering significance.

2. Experimental Study on Freezing Pipe Size

2.1. Verification of Similarity Criteria

The derivation process of governing equations for the similarity model can be found in Ref. [27]. Based on the dimensional analysis method, a total of 32 parameters influencing the vibration signal characteristics of freezing pipe fracture were identified, including 5 dimensionless parameters and 4 independent dimensional parameters (length L , mass M , time T , and temperature θ), yielding 28 similarity criteria. A geometric scaling ratio of $C_L = 7$ was selected, corresponding to a prototype freezing pipe of $\Phi 140 \times 7$ mm and a model pipe of $\Phi 20 \times 1$ mm. Under the same-material simulation scheme (i.e., the model freezing pipe and frozen soil similar material share the same density and elastic modulus as the prototype, yielding $C_{\rho_p} = 1$ and $C_{E_p} = 1$), and neglecting gravity effects, the derived scaling ratios for key vibration parameters are as follows: when the geometric similarity scale factor is set to $C_L = 7$, the similarity ratio of signal velocity amplitude is 1, while the frequency similarity ratio is $1/7$.

The frozen soil similar material was prepared with mass ratios of 4.0 for the sand–binder ratio, 0.3 for the cement–gypsum ratio, 0.5 for the water–binder ratio, and 0.1 for the barite powder-to-aggregate ratio. A low-temperature circulating medium was applied inside the pipes, and circumferential grooves were fabricated at the mid-span position of

the steel pipes to simulate pipe joints. For the $\Phi 20 \times 1$ pipes, the test length was 50 cm, while for the $\Phi 40 \times 2$ pipes, the test length was 100 cm. For specimens with soil wrapping, the axial dimension was uniformly set to $30R_0$ (where R_0 is the outer diameter of the model freezing pipe). Four acoustic emission sensors (CH1–CH4) with frequency ranges of 0.5–10, 0.2–1.5, 0.3–12, and 0.5–6 kHz, respectively, were deployed along the pipe. Figure 1 shows the complete test configuration: the overall test model is illustrated in Figure 1a, the pipe plugs in Figure 1b, and the self-designed reaction frame in Figure 1c. Typical time-domain waveforms and frequency spectra of denoised pipe break signals for the two pipe specifications are shown in Figure 2.

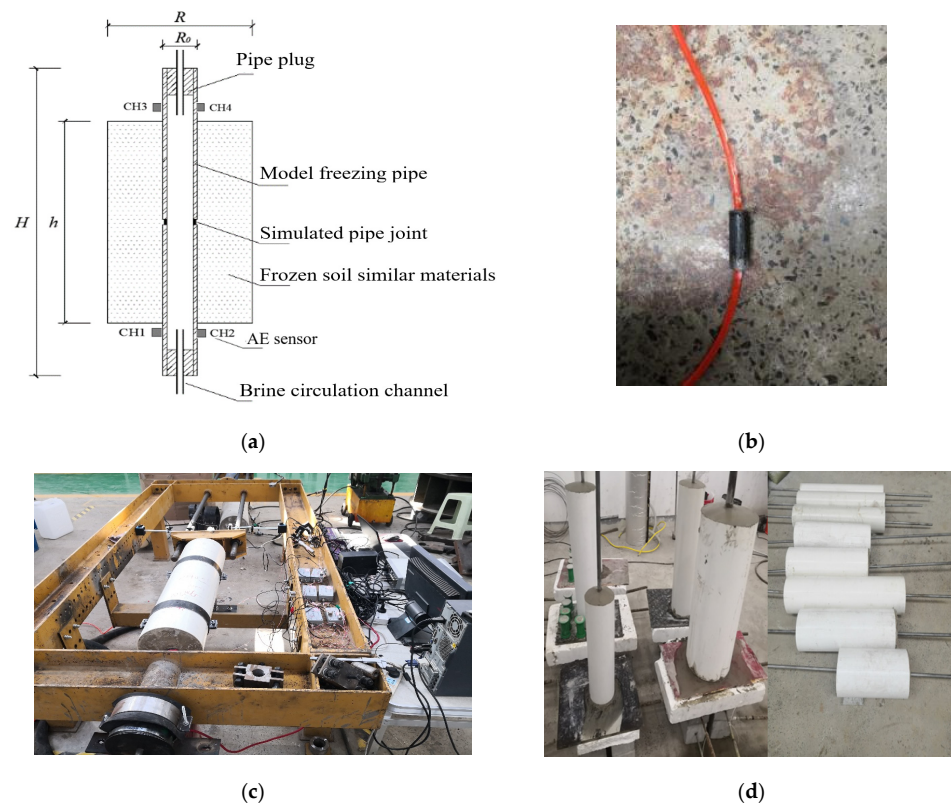


Figure 1. A schematic diagram of the model and test photographs. (a) A schematic diagram of the model. (b) A photograph of the pipe plugs. (c) The self-designed test platform. (d) The test specimens.

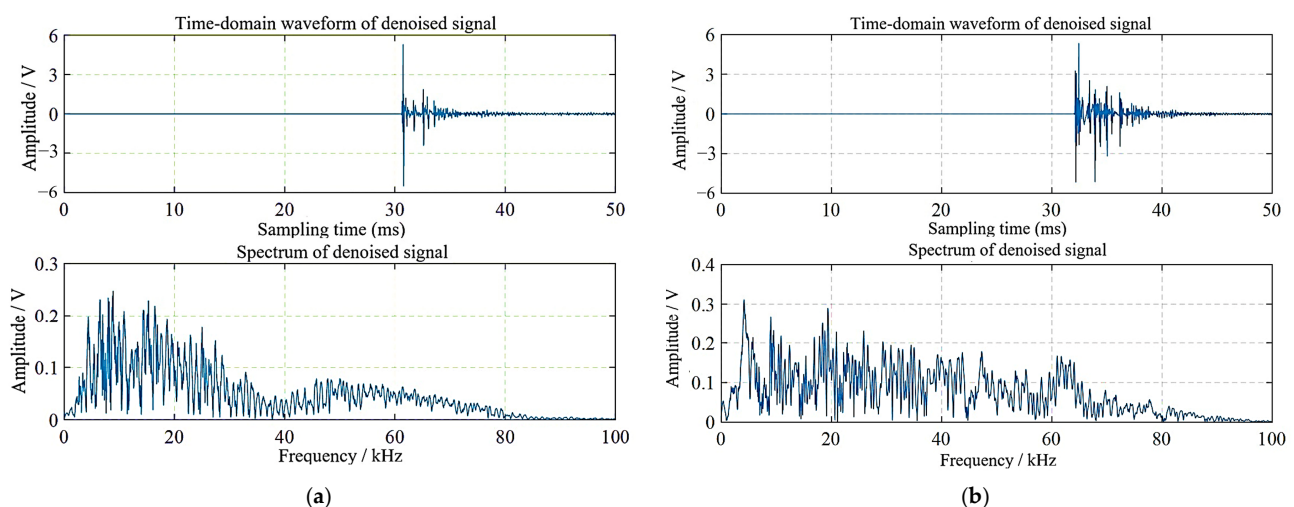


Figure 2. Waveform and frequency spectrum of denoised signal without soil wrapping. (a) $\Phi 20 \times 1$ steel pipe. (b) $\Phi 40 \times 2$ steel pipe.

These scaling ratios were experimentally verified through tensile tests on two model pipe specifications ($\Phi 20 \times 1$ and $\Phi 40 \times 2$) with a geometric similarity ratio of 2. For the case without external soil wrapping (data from Table 1), the measured signal velocity ratio was 0.971 (1.13% error) and the dominant frequency ratio was 0.465 (7% error), both agreeing well with the theoretical predictions. For the case with soil wrapping (data from Table 2), the measured velocity ratio was 0.938 (6.2% error) and the dominant frequency ratio was 0.478 (4.4% error). The small discrepancies are attributable to uncontrollable factors such as groove precision and loading rate variability. Overall, the vibration response of the scaled model has been properly reproduced in accordance with the similarity criteria.

Table 1. Characteristic value of pipe break signal without soil wrapping.

Steel Pipe Specification	Time-Domain Peak Value/V	Time-Domain Peak Value Ratio (b/a)	Dominant Frequency/kHz	Dominant Frequency Ratio (b/a)	Dominant Frequency Intensity/V
a: 20×1	5.393	0.971	8.873	0.465	0.2489
b: 40×2	5.332	(Theoretical value: 1)	4.125	(Theoretical value: 0.5)	0.3111

Table 2. Characteristic value of pipe break signal under soil wrapping condition.

Steel Pipe Specification	Time-Domain Peak Value/V	Time-Domain Peak Value Ratio (b/a)	Dominant Frequency/kHz	Dominant Frequency Ratio (b/a)	Dominant Frequency Intensity/V
a: 20×1	4.668	0.938	7.282	0.478	0.1588
b: 40×2	4.38	(Theoretical value: 1)	3.484	(Theoretical value: 0.5)	0.2084

2.2. Experimental Scheme

In this study, seamless low-carbon steel pipes (Grade 20) were adopted as model freezing pipes, with low-temperature brine circulation implemented to simulate the in situ refrigeration condition. Based on the engineering prototype consisting of frozen soil layers and freezing pipes with inner lining joints, a scaled physical model was established by simplifying and intercepting representative pipe segments. The refined model was composed of frozen soil similar materials and small-scale steel pipes with prefabricated simulated joints, as presented in Figures 3 and 4. To reproduce real engineering mechanical characteristics, circumferential grooves were fabricated at the preset fracture positions of model freezing pipes following the strength equivalence principle. The groove configuration was designed to guarantee that the joint strength reaches approximately 80% of the base pipe strength, realizing the accurate simulation of practical pipe joint structures.

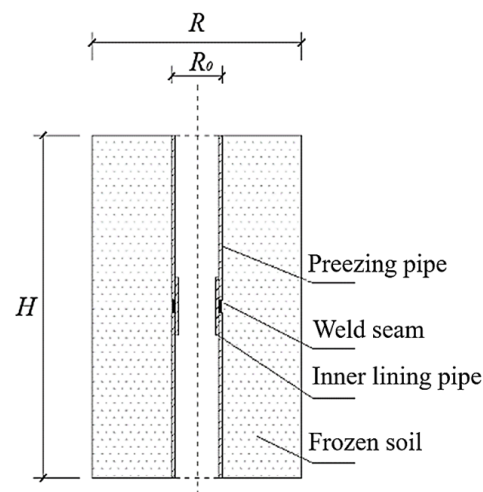


Figure 3. Model simplification diagram.



Figure 4. Simulated pipe joint.

During the test, both ends of the model freezing pipe were mounted on the clamps of the tensile testing machine, and steel plugs were fitted to avoid pipe-end deformation. To circulate brine into the pipe, a hole was drilled at the center of each steel plug for pipeline connection, and reliable sealing and waterproof treatments were applied to the pipe ends. The schematic diagram of the test model and the physical image of the steel plugs are shown in Figure 1a,b.

All tests were conducted on a self-developed tensile reaction frame, as shown in Figure 1c. The test specimen is displayed in Figure 1d.

Prior to the formal test campaign, the reliability of the self-developed tensile reaction frame and the associated measurement system was rigorously verified through preliminary calibration and validation testing. Specifically: (1) the load cell integrated with the reaction frame was calibrated against a standard reference load cell traceable to national metrology standards, confirming that the measured tensile force deviated by less than 1.0% across the full loading range; (2) the alignment of the loading axis was checked by performing multiple loading–unloading cycles on a standard steel specimen and confirming symmetric strain distributions on opposite sides, ensuring that eccentric loading effects were negligible; (3) the acoustic emission measurement chain, including the PAC PCI-2 acquisition system (sampling rate: 500 kHz, preamplifier gain: 20 dB) and the four AE sensors (CH1–CH4), was calibrated using the standard pencil lead break (Hsu–Nielsen source) method to verify sensor coupling quality and signal consistency; and (4) three repeated trial runs were conducted on identical specimen configurations, yielding consistent AE signal waveforms, dominant frequencies, and peak amplitudes with coefficients of variation below 5%. These preliminary tests confirmed that the self-developed reaction frame and the measurement system provide reliable and reproducible results suitable for the subsequent formal experiments.

2.3. Experimental Parameters

The commonly adopted dimensions of freezing pipes in practical engineering are listed in Table 3, and the specifications of geometrically scaled model freezing pipes are summarized in Table 4. Restricted by the available test conditions, four types of model freezing pipes with different specifications were selected for the subsequent analysis, as presented in Table 5.

Table 3. Common dimensions of prototype freezing pipe.

Outer Diameter/mm	Wall Thickness/mm	Maximum Diameter-to-Thickness Ratio	Minimum Diameter-to-Thickness Ratio
159	6–8	26.5	19.9
140	5–7	28	20

Table 4. Specification of model freezing pipe after geometric reduction.

Factor	Level					
Specification (Diameter-to-Thickness Ratio)	19.9	20	22.7	23.3	26.5	28

Table 5. Test parameters of similar materials in frozen soil.

Factor	Level			
Pipe specification/mm	$\Phi 20 \times 1$	$\Phi 22 \times 1$	$\Phi 24 \times 1$	$\Phi 26 \times 1$

The interior of the freezing pipe was refrigerated by a circulating low-temperature medium at $-30\text{ }^{\circ}\text{C}$. The frozen soil similar material surrounding the pipe was prepared with mass ratios of 3.5 for the sand–binder ratio, 0.5 for the cement–gypsum ratio, 0.5 for the water–binder ratio, and 0.1 for the barite powder-to-aggregate ratio. The axial dimension of the specimen was designed as $30R_0$, and a PVC pipe with a diameter of 200 mm was adopted for specimen casting, which can meet the radial dimension requirements for specimens with all freezing pipe specifications. After fabrication, all specimens were statically cured indoors for 24 h. Subsequently, the bottom wood supports were removed, and the specimens were continuously cured at room temperature for seven days. Five standard specimens were prepared and cured under the same conditions as the test specimens. Upon completion of curing, parameter tests were conducted. The arithmetic mean of three valid test results was taken as the representative mechanical parameter of the frozen soil similar material, and the corresponding test data are listed in Table 5.

A preamplifier gain of 20 dB was selected for all sensors. Vaseline was used as the coupling agent, and sensors were secured using mechanical clamps and adhesive tape. The acoustic emission acquisition system was configured with a sampling rate of 500 kHz, a peak definition time (PDT) of 300 μs , a hit definition time (HDT) of 600 μs , and a hit lockout time (HLT) of 800 μs . It should be noted that, due to the destructive nature of the tensile rupture tests, only one valid rupture event per specimen configuration was obtained for the AE signal analysis, and therefore error bars are not provided for the signal characteristic parameters. The standard deviations for the mechanical parameters of the frozen soil similar material are reported in Table 6.

Table 6. Test results of reserved samples.

Specimen No.	Density/ $\text{g}\cdot\text{cm}^{-3}$	Compressive Strength/MPa	Elastic Modulus/MPa
1	2.18	3.74	360.4
2	2.15	3.63	354.2
3	2.14	3.58	357.8
Mean $\pm$ SD	2.16 ± 0.02	3.65 ± 0.08	357.5 ± 3.1
CV/%	0.93	2.19	0.87

The tensile tests were conducted under displacement-control mode at a constant loading rate of 0.5 mm/min. Both ends of the pipe specimen were rigidly gripped by the reaction

frame, corresponding to fixed–fixed boundary conditions. Pipe rupture was identified as the event marked by an abrupt drop in the load–displacement curve accompanied by a sudden surge in all AE characteristic parameters (amplitude, ring-down count, and energy).

Five standard specimens were fabricated for each parameter, of which three were randomly selected for testing and the remaining two were kept as backups. All three measurement results, together with the calculated mean, standard deviation (SD), and coefficient of variation (CV), are presented in Table 6.

The mixture design detailed above yields a physically similar material that faithfully replicates the core mechanical properties of frozen soil—including compressive strength, elastic modulus, and bulk density—at the target temperature of approximately $-10\text{ }^{\circ}\text{C}$, with all parameter deviations falling within an acceptable similarity tolerance. The material formulation adheres to the principle of equivalent strength and modulus ratios between the frozen soil simulant and the model pipe, which ensures that the stress field induced by pipe–soil interaction and the corresponding vibration response are reliably captured in the scaled physical model.

3. Analysis of Experimental Results on Freezing Pipe Dimensions

3.1. Analysis of Characteristic Parameters

In this study, three commonly used acoustic emission characteristic parameters, namely amplitude (A), ring-down count (N) and energy (E), were selected to investigate the signal features and their evolutionary laws during the tensile fracture process of steel pipes.

Three distinct amplitude-related parameters are adopted in this study:

- (1) Acoustic emission (AE) linear peak amplitude (A): A hit-based characteristic parameter extracted by the PAC PCI-2 acquisition system, defined as the maximum peak voltage of a single AE hit waveform, with a unit of millivolts (mV).
- (2) Dominant frequency amplitude (also termed “dominant frequency intensity” in Tables 1 and 2): The spectral amplitude corresponding to the peak frequency point of the fast Fourier transform (FFT) spectrum.
- (3) Time-domain peak value: The maximum absolute voltage of the entire denoised time-domain waveform, with a unit of volts (V). Unlike the AE amplitude—a hit-based parameter whose extraction depends on PDT/HDT/HLT threshold settings—the time-domain peak value is calculated from the full reconstructed signal after wavelet denoising, and characterizes the instantaneous intensity of fracture energy release, which is positively correlated with the total energy of the fracture event.

Specifically, the AE amplitude (A, mV) is a hit-based metric sensitive to structural stiffness, while the time-domain peak value (V) is positively correlated with the ultimate rupture load of the specimen.

The changing trends of these characteristic parameters are shown below.

As shown in Figure 5a–d, all characteristic parameters remained at low levels before the fracture of the steel pipe. These weak signals originated from the clamping friction between both ends of the steel pipe and the clamps, the friction between the soil and the steel pipe, as well as external background noise. Analytical characteristic parameter results for model freezing pipes of other specifications are provided in Figure A1 of Appendix A and Figure A3 of Appendix C.

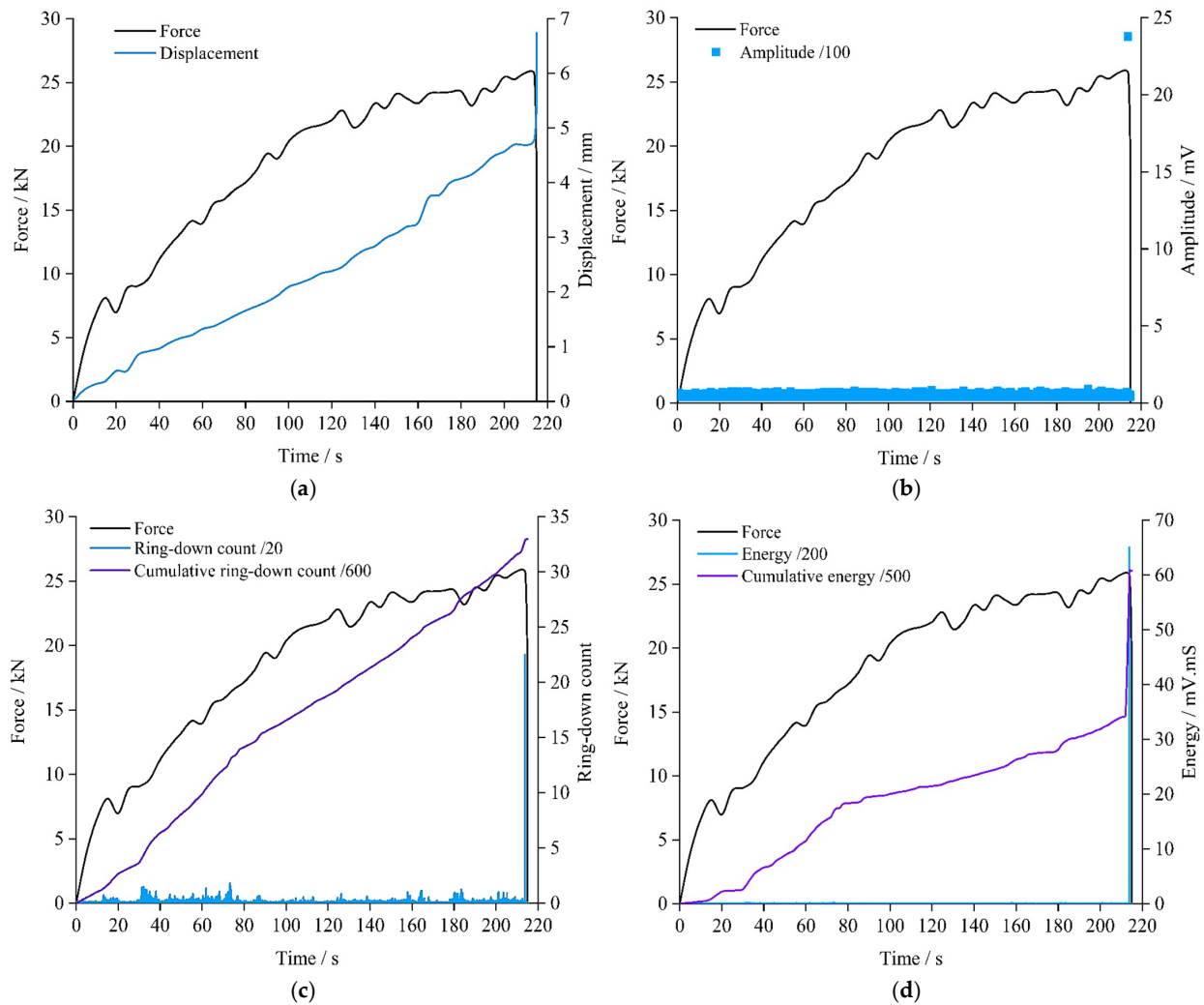


Figure 5. The load curves and characteristic parameter history of pipe breaking process under the condition of diameter-thickness ratio 20. (a) Force–displacement curves. (b) Amplitude history curves. (c) Ring-down count history curves. (d) Energy history curves.

The above characteristic parameters were extracted, and the variation curves of acoustic emission characteristic parameters under different diameter-to-thickness ratios were plotted, as shown in Figure 6.

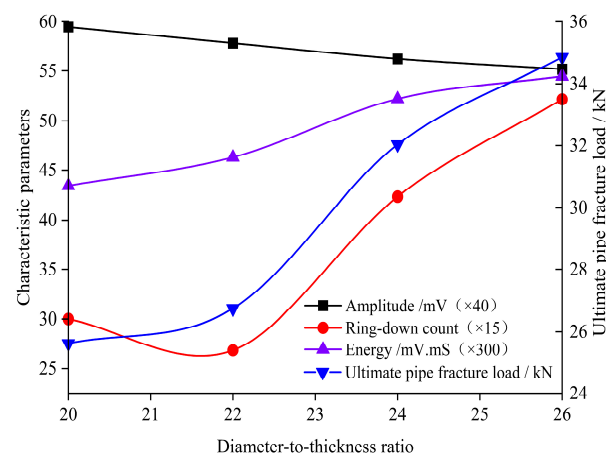


Figure 6. The variation curves of acoustic emission characteristic parameters at the moment of pipe rupture under different diameter-to-thickness ratios.

Figure 6 demonstrates that, for steel pipes with a diameter-to-thickness ratio of 20–26, the vibration signal amplitude generated during pipe rupture decreases approximately linearly as the diameter-to-thickness ratio increases. A linear regression analysis yields the relationship $A = -0.72D/t + 73.81$ (where A is the scaled amplitude value plotted in Figure 5 and D/t is the diameter-to-thickness ratio), with a coefficient of determination $R^2 = 0.99$, confirming the approximate linearity of the amplitude decrease. Within the same ratio range, the ring-down count of fracture signals exhibits an obvious variation trend characterized by an initial decrease followed by a sharp increase, with the minimum value of 403 occurring at a ratio of 22 and the maximum value of 783 observed at a ratio of 26, which is about 1.94 times the minimum level.

3.2. Wavelet Analysis of Pipe Fracture Signals

Vibration signals generated by the fracture of the model freezing pipe were extracted and imported into MATLAB (Version 7.0, Itasca Consulting Group, Inc., Minneapolis, MN, USA) for wavelet analysis. The signal acquired by the CH1 sensor was selected as the analytical subject, and signal denoising was achieved through wavelet decomposition and reconstruction. The core determinants of wavelet analysis performance lie in the selection of the wavelet basis function and the determination of the decomposition level.

The decomposition level is determined by the following equation:

$$J \leq \log_2 \frac{f_s}{2f_{min}} \quad (1)$$

where J —denotes the signal decomposition level; f_s —sampling frequency/kHz; and f_{min} —minimum identifiable frequency/kHz.

The db6 wavelet was adopted for signal decomposition and reconstruction. Fast Fourier Transform (FFT) analysis of the freezing pipe fracture signal revealed that its dominant frequency band ranges from 5 kHz to 30 kHz; accordingly, the minimum identifiable frequency was set to 5 kHz. With an experimental sampling frequency of 0.5 MHz, substitution into the above equation yields a maximum decomposition level of less than 6, and a decomposition level of 5 was finally selected for this study.

The db6 wavelet function was used for five-scale decomposition and reconstruction of vibration signals captured upon the fracture of the $\Phi 20 \times 1$ model freezing pipe to achieve signal denoising, employing Stein's unbiased risk estimate (SURE) soft-thresholding rule for noise level estimation and threshold calculation. In this approach, the noise variance σ^2 is estimated from the finest-scale wavelet coefficients using the median absolute deviation (MAD) estimator: $\sigma = \text{median}(|D1|)/0.6745$, where $D1$ denotes the first-level detail coefficients. The SURE-based adaptive threshold λ is then computed for each decomposition level, and a soft-thresholding function is applied to suppress noise while preserving the abrupt characteristics of the transient fracture signal. The denoised signal is obtained by reconstructing the thresholded coefficients via inverse wavelet transform. The original signal is shown in Figure 7.

Wavelet analysis was performed on the original signal to eliminate the interference of background noise. The denoised reconstructed signal is shown in Figure 8.

Figure 8 demonstrates that wavelet denoising eliminates high-frequency noise within the range of 100–500 kHz. After denoising, the valid frequency band is narrowed to 0–100 kHz, with the primary frequency band concentrated at 5–25 kHz. Accordingly, time–frequency analysis is performed on the denoised fracture signal, and a time–frequency spectrogram is generated to intuitively characterize the time–frequency evolution features throughout the pipe rupture process, as presented in Figure 9.

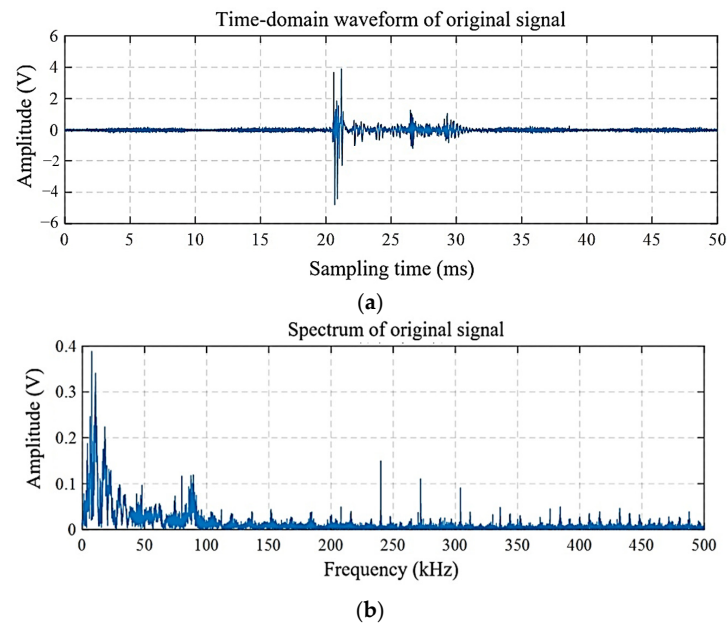


Figure 7. Waveform and frequency spectrum of original signal. (a) Original time–domain waveform of raw signal. (b) Original frequency–domain spectrum of raw signal.

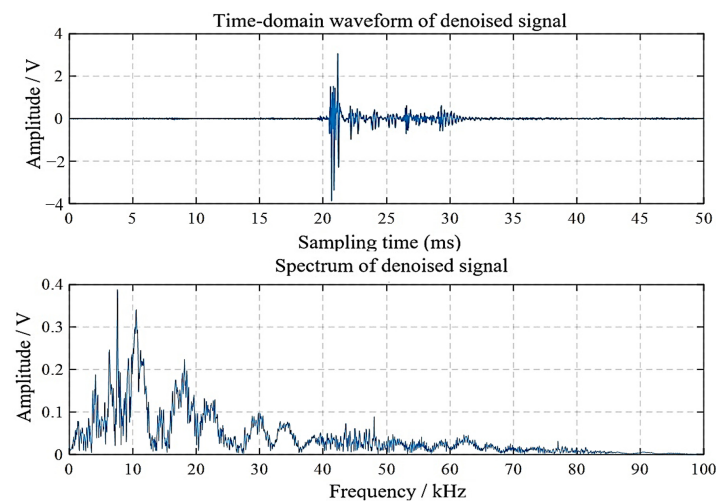


Figure 8. Signal waveform diagram and spectrum diagram of denoising reconstructed signal.

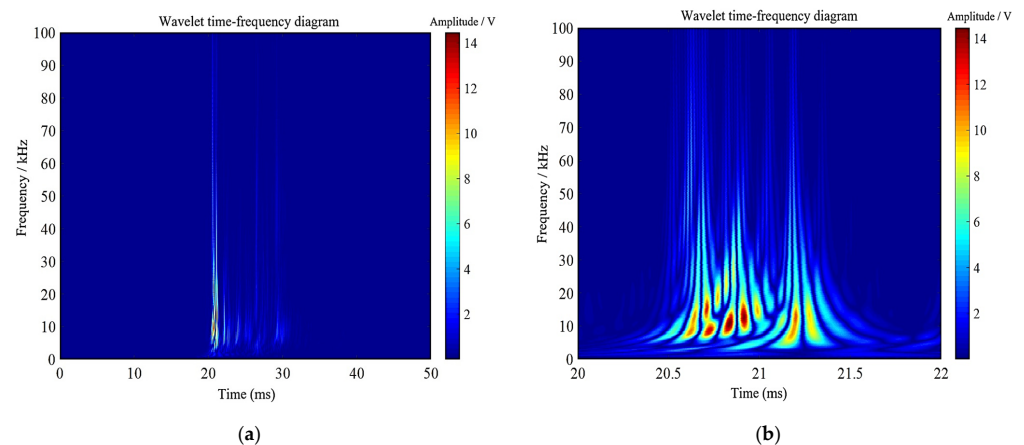


Figure 9. A time–frequency chromatogram of pipe broken vibration signal. (a) A time–frequency diagram of vibration signals during the whole pipe fracture process. (b) A time–frequency diagram of vibration signals at the moment of pipe fracture.

Figure 9 shows that the signal emerges at approximately 20 ms, gradually decays and lasts for about 10 ms before disappearing after 30 ms, which is consistent with the variation pattern reflected in the time-domain waveform: an obvious waveform with a large peak appears initially, followed by a gradual decline of subsequent peaks. Waveforms of fracture signals for model freezing pipes with other specifications are shown in Figure A2 of Appendix B.

Characteristic values extracted from the above time-domain and frequency spectrum diagrams are summarized in Table 7.

Table 7. Characteristic value of broken pipe signal under different diameter-to-thickness ratio.

Pipe Specification	Dominant Frequency Range/kHz	Dominant Frequency/kHz	Dominant Frequency Amplitude/V	Dominant Frequency Amplitude/V	Ultimate Pipe Fracture Load/kN
$\Phi 20 \times 1$	3~25	7.588	0.3883	3.837	25.62
$\Phi 22 \times 1$	5~30	7.137	0.2785	4.095	26.73
$\Phi 24 \times 1$	5~30	6.099	0.5334	3.852	32.02
$\Phi 26 \times 1$	5~25	5.086	0.5113	4.266	34.84

Variation curves of characteristic values derived from the time-domain waveforms and frequency spectra of pipe fracture signals are plotted according to the data listed in the above table, as illustrated in Figure 10.

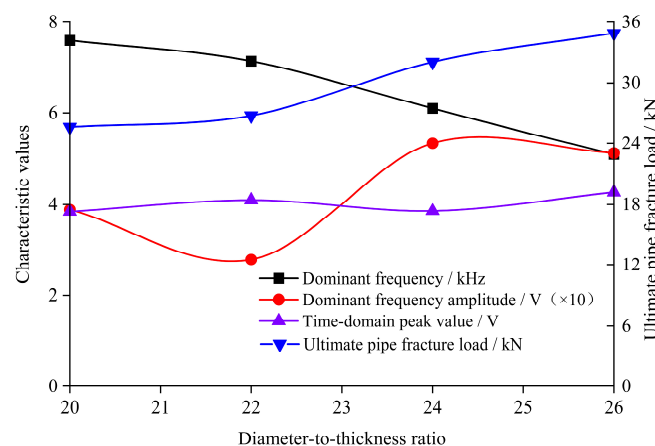


Figure 10. Characteristic value curve of pipe break signal under different diameter-to-thickness ratio.

As shown in the above charts, the vibration signals generated by pipe fracture under different diameter-to-thickness ratios all fall within the range of 0–100 kHz, with dominant frequencies mainly concentrated between 3 kHz and 30 kHz, which belong to low-frequency signals. When the diameter-thickness ratio ranges from 20 to 26, the time-domain peak value varies from 3.837 V to 4.266 V and generally exhibits an upward trend with increasing diameter-to-thickness ratio. This trend is basically consistent with that of the ultimate pipe fracture load, namely a larger fracture load corresponds to a higher time-domain peak of the signal.

4. Discussion

(1) Physical mechanism of the dominant frequency shift

The observed decrease in dominant frequency with increasing diameter-to-thickness ratio (D/t) can be interpreted from the perspective of structural vibration theory. For a cylindrical shell structure, the natural frequency is fundamentally governed by the wall thickness and diameter. A lower D/t ratio implies a relatively thicker wall, which provides higher structural stiffness and consequently yields higher natural vibration frequencies. Conversely, as the D/t ratio increases, the wall thickness decreases relative to the pipe diameter, leading to reduced structural stiffness and a lower dominant frequency of the vibration signals generated upon pipe fracture.

(2) Consistency with previous studies

This finding is consistent with prior research on the vibration characteristics of fluid-conveying pipes [28,29], which has demonstrated that the natural frequency of buried pipelines increases with wall thickness and decreases with increasing pipe length. Similarly, studies on acoustic emission signal propagation in pipes have shown that thin-wall components exhibit greater signal attenuation at higher frequencies, thereby preferentially preserving low-frequency components in the received signals.

(3) Frequency-dependent wave propagation and attenuation

The frequency range of the denoised fracture signals (0–100 kHz, with dominant frequencies concentrated at 3–30 kHz) falls within the low-frequency regime. This is consistent with the well-established observation that higher-frequency wave components attenuate more rapidly during propagation along steel pipes, and the remaining low-frequency components dominate the far-field signal. The observed frequency shift can therefore be attributed to the combined effects of: (a) reduced structural stiffness at larger D/t ratios, and (b) frequency-dependent attenuation during wave propagation along the pipe wall.

(4) Distinctions from conventional acoustic emission of bare steel fracture

It is critical to delineate the discrepancies between the vibration signal characteristics obtained in this study and conventional acoustic emission (AE) signatures of bare steel fracture. Prior investigations on bare metallic specimens (e.g., high-strength steel wires and pressure vessel steels) have consistently documented that fracture-induced AE signals exhibit high amplitude, elevated energy, long duration, and a well-defined central frequency, with dominant frequencies typically exceeding 100 kHz. In contrast, the freezing pipe fracture vibration signals measured in this work present distinctive features driven by the coupled pipe–frozen soil structural interaction:

(a) Markedly reduced dominant frequencies concentrated in the 3–30 kHz range, one order of magnitude lower than those of bare metallic fracture signals. This phenomenon is primarily attributed to two mechanisms: high-frequency energy dissipation by the surrounding frozen soil, and the global vibration of the pipe–soil system being governed by low-order natural frequencies.

(b) More prominent frequency-dependent attenuation behavior. The circumferential groove at pipe joints induces substantial amplitude attenuation but exerts negligible influence on the dominant frequency; such a structural discontinuity-driven attenuation pattern is absent in homogeneous bare specimens.

(c) A clear linear negative correlation between the dominant frequency and the pipe diameter-to-thickness ratio (D/t), i.e., the dominant frequency decreases linearly with increasing D/t . This trend reflects the global stiffness effect of the pipe–soil system, rather than the intrinsic fracture properties of the steel material itself.

These fundamental discrepancies verify that direct application of conventional metallic AE parameters and threshold criteria to freezing pipe fracture monitoring is methodologically inappropriate. The findings further underscore the necessity of the present similarity-model-based study, which establishes pipe fracture-specific signal benchmarks to provide solid theoretical support for field monitoring and early-warning engineering applications.

(5) Limitations and future work

It should be noted that the current study remains largely empirical in nature. To provide a more rigorous theoretical foundation for the observed trends, our team has conducted a complementary numerical simulation study on the characteristics and propagation attenuation of vibration signals induced by freezing pipe fracture [30].

(6) Mechanical interpretation of amplitude, ring-down count, and energy trends

The approximately linear decrease in amplitude with increasing D/t ($R^2 = 0.99$, Figure 6) may be attributed to the reduced structural stiffness at larger D/t , which could result in lower vibration intensity upon fracture despite the higher rupture load. As stated in the Abstract, the ultimate rupture load is positively correlated with signal energy; Table 7 further shows that the rupture load increases monotonically from 25.62 kN ($D/t = 20$) to 34.84 kN ($D/t = 26$), suggesting that greater stored elastic energy is released at fracture for pipes with larger D/t , which is consistent with the overall increasing trend of energy observed in Figure 6. The ring-down count exhibits a non-monotonic variation (initial decrease followed by a sharp increase, with the minimum at $D/t = 22$ and the maximum at $D/t = 26$), which may be attributed to the competing effects of higher rupture energy (tending to increase oscillation cycles) and altered vibration damping characteristics associated with different wall thicknesses. However, given that each data point represents a single rupture event, these mechanical interpretations should be considered as plausible explanations rather than definitive conclusions, and further repeated tests or numerical simulations would be needed to validate the proposed mechanisms.

5. Conclusions

- (1) The load history during pipe fracture is highly consistent with the variation trend of characteristic parameters. Before the fracture of the model freezing pipe, all characteristic parameters remain at low levels with slight fluctuations. These parameters surge instantaneously upon pipe rupture, presenting distinctive fracture signal characteristics. This indicates that the occurrence of freezing pipe fracture in practical engineering can be identified via the variation in these characteristic parameters.
- (2) The ultimate fracture load exhibits a consistent trend with signal energy: a larger fracture load corresponds to higher signal energy. When the diameter-to-thickness ratio of the model freezing pipe ranges from 20 to 26, the signal amplitude decreases approximately linearly ($R^2 = 0.99$) with the rising diameter-to-thickness ratio, while both ring-down count and signal energy show an overall increasing trend.
- (3) After wavelet denoising, fracture vibration signals for pipes with various diameter-to-thickness ratios fall within 0–100 kHz, with dominant frequencies concentrated at 3–30 kHz, classified as low-frequency signals. For diameter-to-thickness ratios of 20–26, the dominant frequency declines gradually as the ratio rises, with the maximum value 1.49 times the minimum. Dominant frequency amplitudes fluctuate between 0.2785 V and 0.5334 V without a clear trend. Meanwhile, time-domain peaks range from 3.837 V to 4.266 V and increase with the ratio, matching the trend of ultimate rupture load: greater rupture load yields a higher time-domain peak.
- (4) Based on the frequency similarity ratio of $1/C_L$ ($=1/7$), the model dominant frequency range of 5.086–7.588 kHz corresponds to approximately 0.73–1.08 kHz for prototype freezing pipes in engineering practice, providing a reference frequency band for field monitoring sensor configuration and signal identification.
- (5) It should be noted that the above conclusions are derived from single rupture events per pipe specification due to the destructive nature of the tensile tests, and are limited to the tested diameter-to-thickness ratio range of 20–26. Extrapolation beyond this range requires further experimental validation or numerical simulation.

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Appendix A

In all subplots of Appendix A, the left Y-axis represents the applied force (kN) and the X-axis represents time (s). For the force–displacement curves (a, e, i), the right Y-axis denotes displacement (mm) using raw values. For the amplitude history curves (b, f, j), the right Y-axis denotes acoustic emission amplitude (mV), with plotted values divided by 100. For the ring-down count curves (c, g, k), the right Y-axis denotes ring-down count, with instantaneous values divided by 20 ($D/t = 22, 24$) or 30 ($D/t = 26$), and cumulative values divided by 1400 ($D/t = 22$), 6000 ($D/t = 24$), or 1000 ($D/t = 26$). For the energy history curves (d, h, l), the right Y-axis denotes acoustic emission energy (mV·mS), with instantaneous values divided by 200 ($D/t = 22$) or 400 ($D/t = 24, 26$), and cumulative values divided by 1000 ($D/t = 22, 26$) or 4000 ($D/t = 24$).

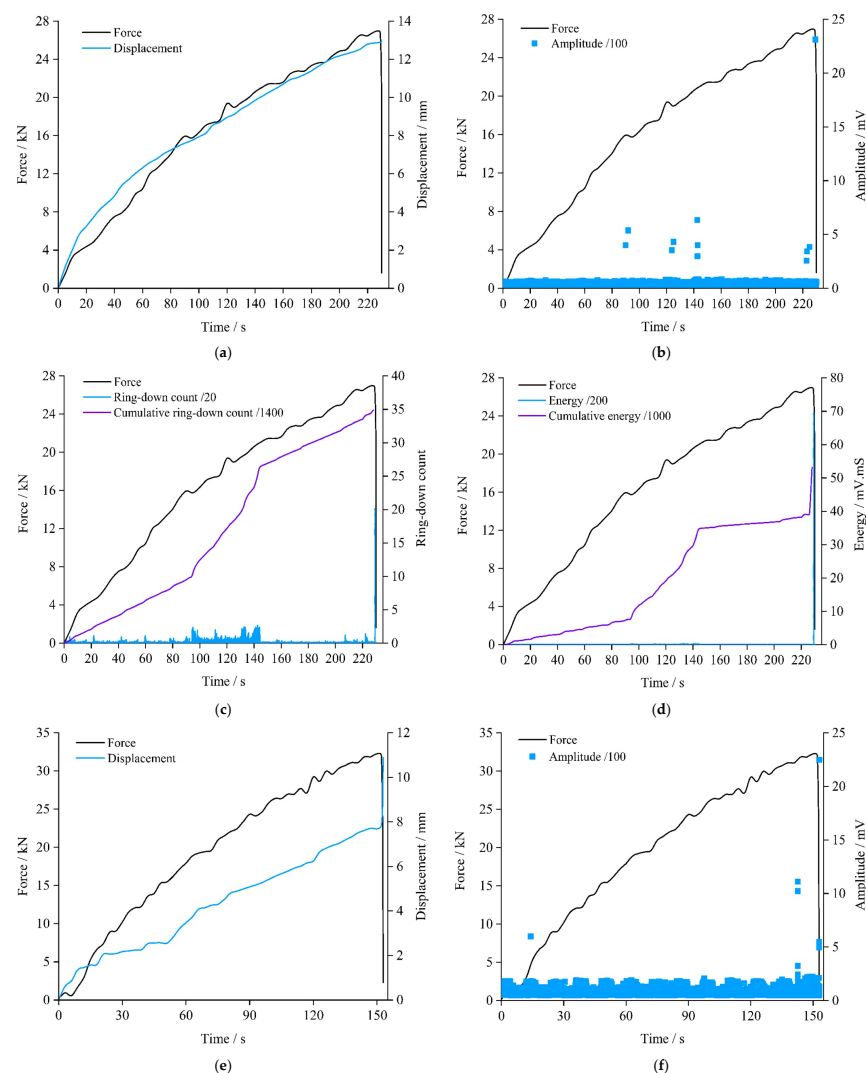


Figure A1. Cont.

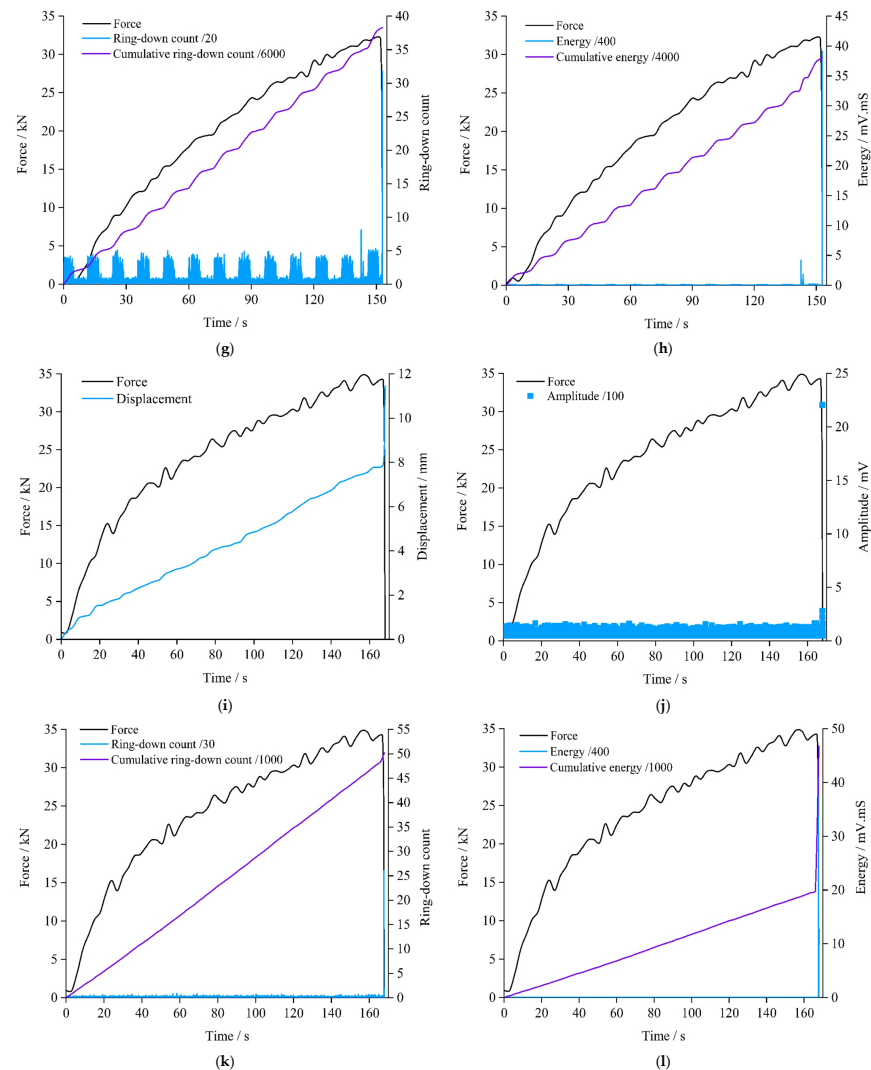


Figure A1. Load curve and characteristic parameter history of pipe breaking process under different diameter-to-thickness ratios. (a) Force–displacement curves under diameter-to-thickness ratio of 22. (b) Amplitude history curves under diameter-to-thickness ratio of 22. (c) Ring-down count history curves under diameter-to-thickness ratio of 22. (d) Energy history curves under diameter-to-thickness ratio of 22. (e) Force–displacement curves under diameter-to-thickness ratio of 24. (f) Amplitude history curves under diameter-to-thickness ratio of 24. (g) Ring-down count history curves under diameter-to-thickness ratio of 24. (h) Energy history curves under diameter-to-thickness ratio of 24. (i) Force–displacement curves under diameter-to-thickness ratio of 26. (j) Amplitude history curves under diameter-to-thickness ratio of 26. (k) Ring-down count history curves under diameter-to-thickness ratio of 26. (l) Energy history curves under diameter-to-thickness ratio of 26.

Appendix B

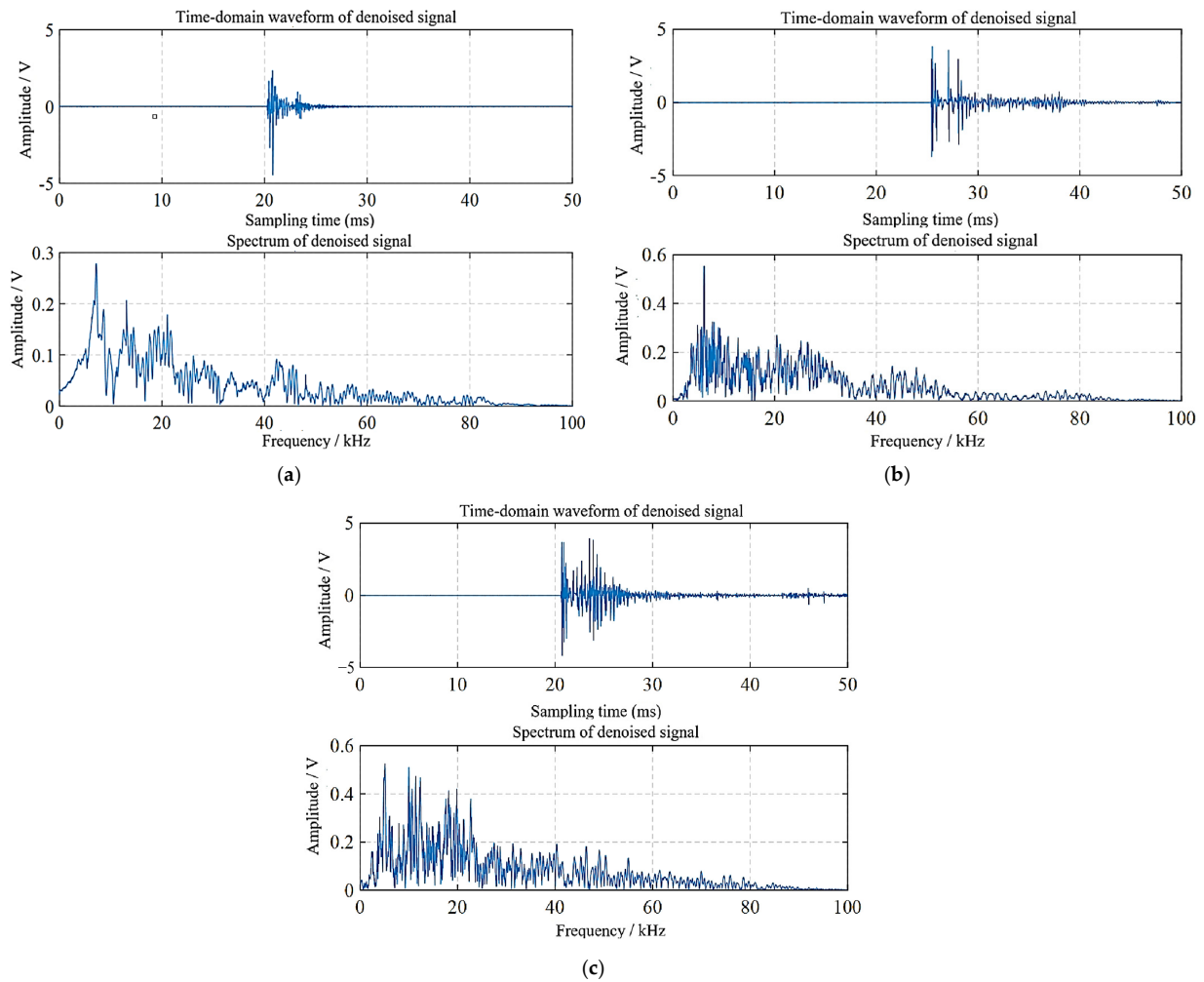


Figure A2. Fracture signals of model frozen pipe with different diameter-to-thickness ratio. (a) Diameter-to-thickness ratio of 22. (b) Diameter-to-thickness ratio of 24. (c) Diameter-to-thickness ratio of 26.

Appendix C

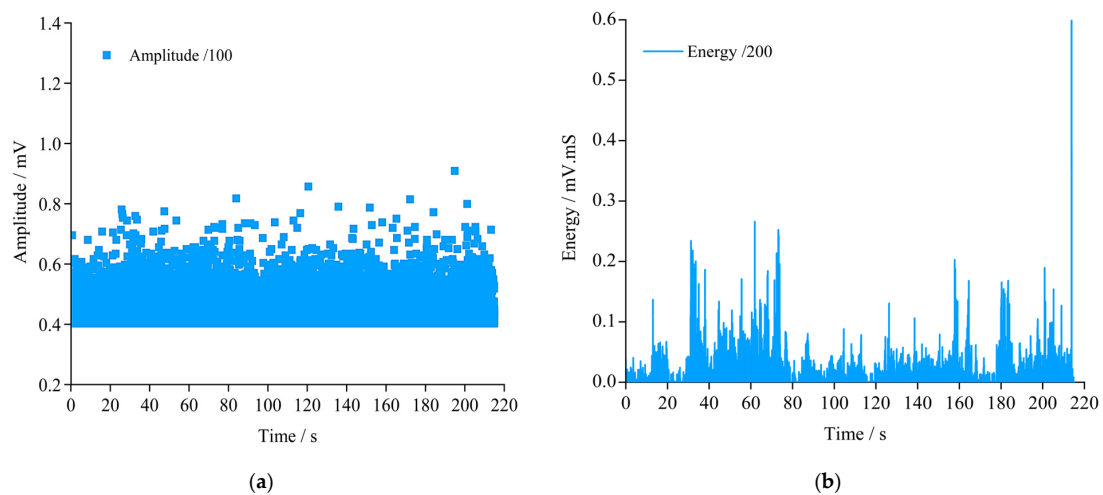


Figure A3. Amplitude history and energy history curves under diameter-to-thickness ratio of 22. (a) Amplitude history curve. (b) Energy history curve.

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