

Article

Development and Preliminary Acoustic Calibration of an Experimental Platform for Evaluating the Cement–Formation Interface

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Abstract

In cementing operation, the “cement—rock” interface bonding ability is an important factor affecting the long-term sealing ability of cement sheath, and the evolution mechanism of the interface sealing ability needs to be further studied. However, due to the particularity of the interface transition area, it is difficult to comprehensively analyze the macroscopic acoustic properties, mechanical properties and sealing evolution ability of the interface due to the lack of precise quantitative testing equipment. To solve the above problems, a cement-sheath cementing-interface sealing capability evolution evaluation device was developed, and a laboratory acoustic response accuracy experiment was carried out to form a quantitative evaluation method of cement–formation interface capability. The developed apparatus withstood pressures up to 30 MPa and temperatures up to 150 °C during basic performance testing. The ultrasonic probes were calibrated using standard cylindrical steel specimens, with P- and S-wave measurement accuracies exceeding 95%. Preliminary cement stone–sandstone acoustic calibration was subsequently performed at 17 °C and 9.8 MPa for 9 days, corresponding to the conditions of the selected field interval. Comparison of the normalized laboratory acoustic response with representative field VDL data showed an agreement of approximately 86.8%. These results provide preliminary validation of the basic operational and acoustic measurement capabilities of the developed platform; however, cement stone–rock interfacial behavior under a broader range of temperature and pressure conditions remains to be systematically validated.

Keywords: cementing; interface; acoustic response; test device; evaluation method

Academic Editor: Blaž Likozar

Received: 18 August 2026

Revised: 7 October 2026

Accepted: 12 October 2026

Published: 17 October 2026

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1. Introduction

In the petroleum industry, cementing operations are performed on the open-hole rock intervals generated during drilling to reinforce the wellbore and isolate oil, gas, and water zones through measures such as cement slurry injection, thereby effectively ensuring the long-term, safe, and highly efficient development of oil and gas wells. With the ongoing advancement of exploration and production in unconventional and ultra-deep hydrocarbon reservoirs, the interlayer sealing capability of the wellbore under complex lithological conditions has increasingly become a critical focus in cementing operations [1,2]. This inter-layer sealing capability is primarily governed by the annular isolation system, which consists of the casing–cement sheath interface, the cement sheath stone, and the

cement–formation interface. Given that the cement sheath itself exhibits high strength and low permeability, making it less susceptible to the formation of flow channels, the overall sealing performance of the system is largely determined by the integrity of the cementing interfaces—especially the cement–rock bonding interface, which is subject to complex environmental conditions and variable lithology.

For the evaluation of cement–rock bonding quality, field practices primarily rely on acoustic variable density logging, gamma density logging, and natural gamma ray logging techniques to assess the interfacial sealing capability. By analyzing casing waves, formation waves, and annular density distributions, the bonding condition at the cement–formation interface can be comprehensively evaluated [3–6]. However, these macroscopic measurement methods are incapable of accurately reflecting the evolution of interfacial bonding performance under the complex physicochemical reaction conditions that occur during cementing operations. In the field of experimental and evaluation methods for interfacial sealing capacity, research has mainly focused on the concept of the “interfacial transition zone of cement-based composite materials” as used in the construction industry, with the aim of characterizing the mechanical properties of the bonded interface—primarily including interfacial bond strength, interfacial stiffness, and fracture energy. A variety of interfacial test models have been developed, such as interfacial bond strength testers [7], cement sheath channeling test apparatuses [8–11], sealing capacity test devices capable of simulating cyclic wellbore stresses and fracturing conditions [12,13], interfacial test devices that simulate perforation [14], interfacial strain monitoring devices [15,16], and a scaled model well cluster for cement bond evaluation that can simulate four types of cement bonding states [17]. Using these apparatuses, substantial progress has been made in analyzing macroscopic properties—including shear strength at the cement–formation interface, stress–strain behavior, and overall sealing performance—under conditions of high temperature and high pressure, oil/water/gas channeling, cyclic wellbore loading, fracturing, and perforation. Nevertheless, owing to the particular nature of the interfacial transition zone, no existing test device can directly acquire both acoustic and mechanical parameters of the cement–formation interface, nor can it provide an integrated analysis of acoustic response characteristics, interfacial performance parameters, and the evolution of sealing capacity.

Compared with conventional cement sheath integrity testing systems that primarily focus on macroscopic mechanical integrity or fluid migration and often employ a steel outer boundary to represent the formation, the platform developed in this study is specifically configured for investigating the cement stone–rock, or cement–formation, interface. Its main feature is the integration of real rock cores, controllable formation–fluid exposure, acoustic response measurement, sealing–performance testing, and subsequent interface recovery for microstructural characterization within a common experimental framework. This configuration enables acoustic, sealing, and microstructural information to be obtained for the same type of cement–formation interface under controlled conditions. The objective of the present work is therefore to establish and preliminarily calibrate an integrated experimental platform rather than to present a fully validated predictive model.

2. Functional Design and Development of the Simulation Platform

2.1. Interfacial Sealing Capacity Testing Device with Field-Scale Casing Geometry Under Dynamic/Static Curing Conditions

Static curing refers to the condition in which the cement slurry is maintained in a closed environment without invasion or wetting by flowing water during the curing process. In contrast, dynamic curing involves the presence of flowing water that invades and wets the cement slurry, resulting in an open curing environment where the cement hydration

products undergo material exchange with the external surroundings. This dynamic condition more realistically simulates the actual downhole geological and operational scenarios encountered in well cementing. Therefore, it is necessary to design and develop a dedicated test apparatus for evaluating the sealing capacity at the cement–formation interface. It should be noted that the static and dynamic curing conditions described herein represent configurable operating modes of the developed apparatus. The present study focuses on apparatus development and acoustic-performance validation; a systematic comparison of interface evolution between the two curing modes is outside the scope of the present work.

At present, laboratory apparatuses for cement sheath integrity testing are predominantly based on the plane strain principle, in which a steel outer cylinder of a given thickness simulates the open hole formation and a steel inner cylinder of equal diameter and wall thickness simulates the casing. After the annulus is filled and the cement is cured, water channeling and gas channeling experiments are conducted at different stages to evaluate the long-term sealing capacity of the cement sheath. These apparatuses have essentially achieved the ability to perform integrity tests under temperature and pressure conditions comparable to those actually encountered in formations, and they can simulate fracture evolution at the casing–cement interface as well as the failure process of the cement stone. However, with respect to the cement–formation interface, the presence of the outer steel cylinder prevents these existing devices from adequately replicating the experimental conditions of real rock formations and formation fluid seepage. Directly using an authentic rock core as the outer cylinder, on the other hand, introduces a series of challenges, including difficulties in core sampling, high experimental costs, and a limited apparatus scale, which to some extent restrict research on cement sheath sealing performance under complex formation conditions. Therefore, further improvement and refinement of the sealing integrity test apparatus are required.

The newly designed experimental apparatus possesses the following features and functionalities:

- (1) The cement sheath seal testing device, capable of simulating realistic formation interface conditions, is primarily composed of a simulated wellbore system, a formation rock core simulation system, a formation fluid injection system, a channeling detection system, a heating and temperature control system, and an acoustic logging analysis system.
- (2) The simulated wellbore system mainly consists of inner and outer steel casings, an upper plug, and a lower base. The inner steel casing is used to simulate the actual casing used in cementing operations and can be directly sourced from drilling site casings, with a height of 100 mm. Its outer diameter and wall thickness conform to API standards, with optional outer diameters of 177.8 mm, 168.3 mm, 139.7 mm, and 127 mm, and corresponding wall thicknesses ranging from 5.21 to 16.13 mm. The outer steel sleeve is primarily intended to support the rock core holding device, also with a height of 100 mm; its optional inner diameters are 222.2 mm, 215.9 mm, 165.1 mm, and 155.5 mm, with corresponding wall thicknesses of 50–80 mm. The overall structure of the device is shown in Figure 1.
- (3) The external steel casing of the device is machined with four sets of flanges distributed at 90° intervals, with an inner diameter of 25.5 mm. The upper end cap is designed to connect with the influx detection system and the pressurization pump, while the lower base can be linked to the formation fluid injection pump and is equipped with a grounding wire. The simulated wellbore is sealed using a high-temperature resistant rubber ring, capable of withstanding temperatures up to 200 °C. The inner and outer layers of the steel casing, along with the base and upper end cap, collectively form a sealed annular space for the purpose of cement injection, as illustrated in Figure 2.

- (4) The stratigraphic core simulation system mainly consists of a core holder and a confining pressure pump. The core holder, featuring four modules with an inner diameter of 25.5 mm and a length of 80 mm, is attached to the outer steel casing of the simulated wellbore through flanges, arranged at 90° intervals. It accommodates various core samples, such as sandstone, mudstone, shale, and granite, to mimic real geological formations. The inner wall of the core holder is lined with a high-temperature-resistant rubber barrel, rated for up to 150 °C. The confining pressure pump connects to both the core holder's bottom and the upper cap of the simulated wellbore, allowing for fluid pressure adjustments. When linked to the core holder, it compresses the core to prevent fluid migration, while connection to the upper cap allows for cement slurry pressurization. The pump operates within a pressure range of 0–100 MPa. By removing the core holder, the cement-core interface products can be collected for mineral content analysis (XRD), chemical composition (XRF), particle size distribution, and specific surface area evaluation.
- (5) The formation fluid injection system primarily consists of a formation fluid injection pump and a high-pressure nitrogen cylinder, designed to simulate high-pressure water and gas reservoirs within geological formations. The formation fluid injection pump is connected to both the bottom of the cement ring in the simulated wellbore and the bottom of the core holder, with connections manageable through valves. When connected to the bottom of the cement ring, the system can detect fluid migration in the high-pressure water layer of the cement ring. Conversely, when connected to the core holder, it facilitates dynamic reservoir water curing at the cement–rock interface. The pressure range of the formation fluid injection pump is from 0 to 100 MPa, while the high-pressure nitrogen cylinder operates within a pressure range of 0 to 20 MPa.
- (6) The fluid migration detection system is primarily designed to monitor gas migration and water leakage flow rates that occur after the failure of the cement ring. It comprises components such as gas–liquid separators, a high-precision electronic balance, a dryer, and a micro gas flow meter. The high-precision electronic balance, specifically a Sartorius model with a capacity of 420 g, is utilized to measure the flow rate of fluid exiting during the cement core permeation process. The micro gas flow meter is employed for the precise measurement of low gas volumes, with a measurement range of 0 to 100 mL/min.
- (7) The heating and temperature control system consists of a silicone rubber heating jacket with an integral insulation jacket, a temperature controller, and temperature sensors. The temperature control range is 0–150 °C, and the temperature measurement probe employs a thermocouple. The temperature controller is an intelligent indicating controller with PID adjustment capability and a display accuracy of 0.1 °C. The desired control temperature can be arbitrarily set, and the PID regulation effectively compensates for thermal inertia.
- (8) The acoustic logging analysis system is primarily composed of a monopole acoustic transmitter, a main acoustic logging unit, and receivers. The excitation voltage ranges from 500 to 1000 V. With the aid of an electric servo device, the transmitter can be rotated 360° along the inner wall of the simulated wellbore, which is designed to simulate the field acoustic technique for evaluating cement bond quality. By analyzing casing waves, formation waves, and annular density distribution, the bonding quality at both the casing–cement interface and the cement–formation interface can be comprehensively determined.

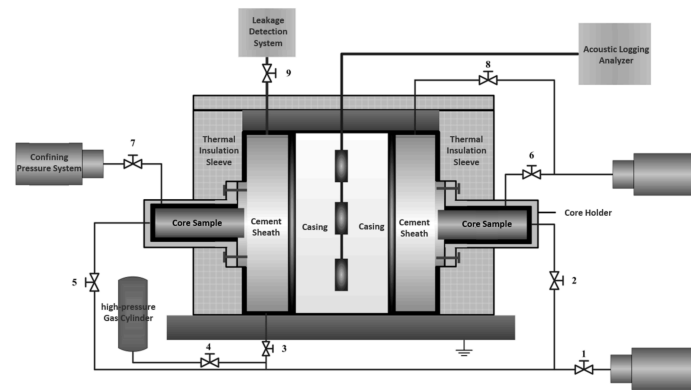


Figure 1. Schematic diagram of the interfacial sealing capacity testing apparatus with field-scale casing geometry. The main components include the inner casing, cement sheath, outer steel casing, rock core/core holder, upper plug, lower base, formation-fluid injection system, pressure-control system, heating system, and acoustic testing system. The arrows indicate the formation-fluid flow path.

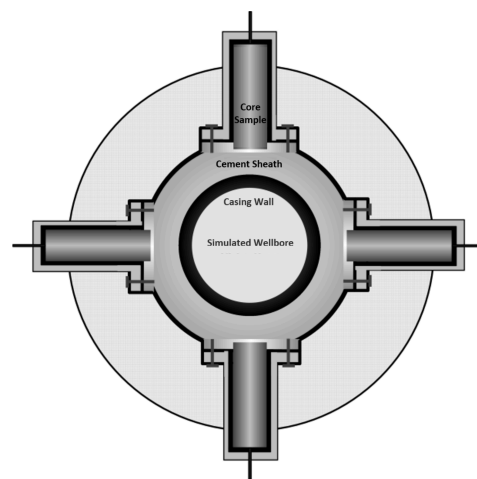


Figure 2. Core holder circumferential distribution diagram.

Compared with conventional cement sheath integrity apparatuses based primarily on steel-cylinder boundaries, the present design introduces detachable real-rock core holders around the simulated wellbore and integrates formation-fluid injection, acoustic testing, temperature/pressure control, and leakage detection. This design enables direct investigation and subsequent recovery of the cement–formation interface. Nevertheless, the apparatus remains a laboratory representation of the downhole system. Although field-scale casing dimensions and representative radial geometry can be adopted, the axial dimension and surrounding formation extent are reduced, and the complete in situ stress and acoustic propagation conditions cannot be reproduced. Therefore, the apparatus is intended for controlled comparative studies and preliminary calibration rather than direct reproduction of all field conditions.

2.2. Core Interface Sealing Capacity Testing Device Under Dynamic/Static Curing Conditions

The interfacial sealing capacity test apparatus with field-scale casing geometry retains the representative radial configuration of the casing–cement sheath–formation system and therefore provides a closer approximation of the geometric and operational conditions encountered in field cementing. However, due to its large experimental scale, it presents certain limitations for conducting extensive systematic experimental studies and is more suitable as a verification-oriented testing instrument. Therefore, it is necessary to develop

a small-scale interfacial sealing capacity test apparatus focusing on the cement stone–rock core interface, so as to enable interfacial sealing experiments under various curing conditions, different cement slurry systems, and different rock core types.

The design concept is to appropriately simplify the apparatus based on the field-scale interfacial sealing capacity test device while retaining its core functions. The overall structure of the apparatus is shown in Figure 3.

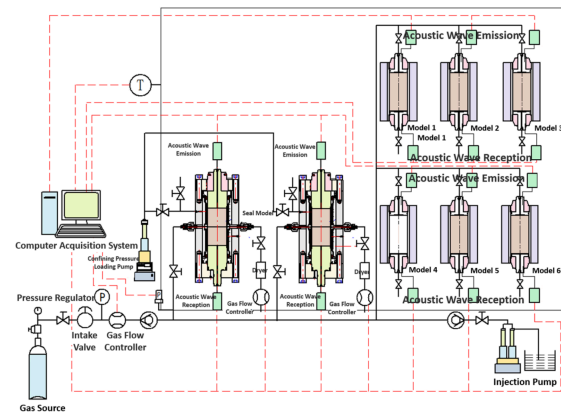


Figure 3. Schematic diagram of the cement stone–rock core interfacial sealing capacity test platform. The system mainly consists of the cement stone–rock core specimen and core holder, formation-fluid injection module, gas injection module, acoustic transmitter and receiver, pressure-control module, temperature-control module, and fluid inlet/outlet. The arrows indicate the direction of fluid flow through the experimental system.

In addition to the rock core holder assembly, the rock core interfacial sealing capacity test platform also comprises a formation fluid injection module, a gas injection module, an acoustic testing module, a formation temperature control module, and other components.

Among these, the primary apparatus of the formation fluid injection module is a liquid injection pump, specifically a HAS 200HSB dual-cylinder constant-speed and constant-pressure pump, which is used for quantitative displacement of the driving medium and serves as the power source for the experiment. The pump operates in a continuous, pulse-free circulation mode and is capable of constant-speed and constant-pressure operation. It features high metering accuracy and precision, with a maximum working pressure of 40 MPa and a flow rate range of 0.001–25 mL/min. It is equipped with pressure protection and upper/lower position limit protection. The pump head is made of 316 L stainless steel and provides functions such as suction, discharge, and pre-pressurization. The directional valve is pneumatically controlled by an electromagnetic actuator; the pump chamber has a small volume and a short dead time. The pump is also equipped with a communication port, allowing either computer-controlled or manual operation.

The acoustic testing module mainly consists of an acoustic signal transmitter and an ultrasonic wave velocity measurement system. Through the vibration of the excitation crystal in the acoustic signal transmitter, ultrasonic waves are generated and propagate through the test material; they are then received by the receiver, which converts the acoustic energy into weak electrical signals and sends them to the receiving system. After signal amplification, the waveforms are displayed on a screen, from which the amplitude and the first arrival time (t) can be read. With the known propagation distance (L) of the test material, the compressional wave velocity (V_p) in the material can be calculated as $V_p = L/t$. The ultrasonic velocity measurement system adopts the pulse transmission method to measure the travel time of compressional or shear waves along the length direction of the specimen and thereby calculates the compressional and shear wave velocities as well as the acoustic attenuation amplitude. On the raw data, waveform filtering, waveform

selection, band pass frequency selection (low/high), band rejection (dB), and conversion bandwidth (kHz) can be applied to obtain “filtered” waveforms, which greatly facilitates the processing of the “raw” waveforms. This ultrasonic system can simulate field shear wave conditions and includes both triaxial and true triaxial chambers; it can also be used for field testing. The system also incorporates a comprehensive data acquisition system to record other test parameters such as load and deformation, as shown in Figure 4.

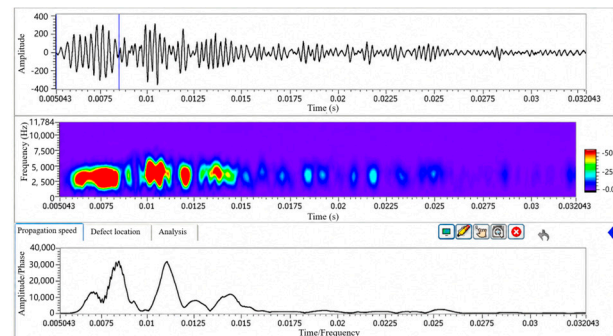


Figure 4. Calculation interface of acoustic wave velocity measurement system.

The primary apparatus of the formation temperature control module is a high-precision constant-temperature oven, which can simulate formation temperature conditions via an air bath. The maximum operating temperature is 150 °C, with a temperature control accuracy of ± 1 °C. The oven is equipped with a PID controller and supports programmed temperature ramping, and it can also perform corresponding coordinated adjustments of the temperature program automatically in response to pressure fluctuations.

Through the design and development described above, the field-scale interfacial sealing capacity test apparatus and the rock core interfacial sealing capacity test apparatus together enable systematic investigation of the sealing capacity at the cement–formation interface of the cement sheath under both dynamic and static curing conditions.

2.3. Development of Testing Equipment

Through the above-described design, the interfacial sealing capacity test apparatuses under both dynamic and static curing conditions have been successfully developed, with the various test platforms and functional components shown in Figures 5 and 6.

The assembled apparatus components were subjected to pressure testing, and the system withstood a pressure of up to 30 MPa, while the silicone rubber heating jacket endured temperatures exceeding 150 °C. With this apparatus, more than 30 sets of experiments were conducted, yielding over 5000 valid data records pertaining to interfacial acoustic responses, water channeling, and other relevant parameters. The instrument operated stably and meets the design requirements of the experimental setup.



Figure 5. Evolution evaluation device for sealing ability of the cement–formation interface of cement ring bonding.



Figure 6. Sealing acoustic test platform at the second cementing interface.

3. Testing and Validation of Acoustic Response Accuracy of the Device

Prior to conducting quantitative tests on the sealing capacity of the cement–formation interface in cementing operations, it is first necessary to evaluate the acoustic response accuracy of the experimental apparatus and compare the results with field measured logging data, so as to ensure the reliability of the experimental data.

3.1. Precision Testing of Ultrasonic Probe of the Device

The core testing component of the apparatus for evaluating the evolution of sealing capacity at the cement–formation interface of the cement sheath is the ultrasonic acoustic emission probe; therefore, the acoustic response accuracy of the probe is of critical importance. The main performance data of the acoustic probes are listed in Table 1.

Table 1. Performance of acoustic probe of cement–formation interface cementing evaluation device.

Acoustic Performance Parameter	P-Wave Crystal Frequency (MHz)	S-Wave Crystal Frequency (MHz)	Probe P-Wave Frequency (MHz)	Probe S-Wave Frequency (MHz)	Excitation Voltage (V)
Value	1.2	0.6	0.42	0.36	500

First, a direct probe-to-probe contact test was conducted to measure the actual travel time difference between the P-wave and S-wave of the probes. During the test, Vaseline was applied to the probe interfaces as a coupling agent, and an axial pressure of 15 MPa was applied. The P-wave and S-wave waveforms acquired from the probes are shown in Figures 7 and 8.

As can be seen from Figures 7 and 8, the P-wave and S-wave acoustic response curves of the two sets of probes exhibit certain differences, mainly reflected in the first arrival time data. For Probe #1, the first arrival times of the P-wave and S-wave are 6.00 μ s and 11.04 μ s, respectively; for Probe #2, the corresponding values are 7.72 μ s and 14.16 μ s. The primary reason for these differences is the deviation in the placement of the P-wave and S-wave crystals between the two probes. Under a fixed excitation frequency for both wave modes, the farther the crystals are from the probe end face, the longer the first arrival time. To improve measurement accuracy, during component testing it is necessary to subtract the travel time of the acoustic wave inside the probe (the first-arrival time obtained from the probe-to-probe contact test) from the measured arrival time, thereby yielding a more precise acoustic response.

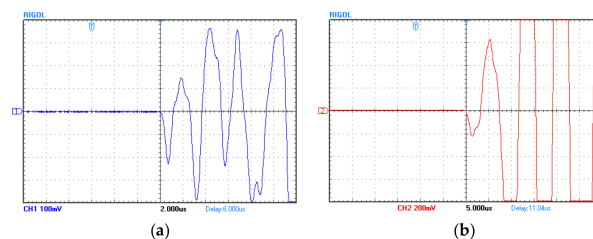


Figure 7. Response curve of 1# probe directly connected to P-wave acoustic wave. (a) P-wave curve; (b) S-wave curve.

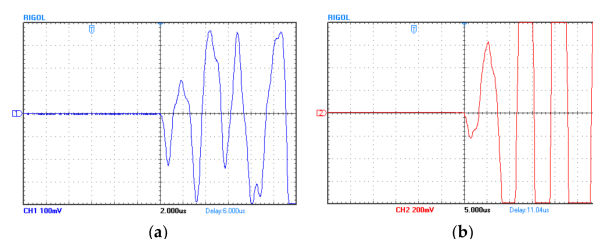


Figure 8. Response curve of 2# probe directly connected to P-wave acoustic wave. (a) P-wave curve; (b) S-wave curve.

This correction can be preset in the software of the ultrasonic velocity measurement system. On this basis, the probes were first used to test standard steel blocks of different specifications that simulate cylindrical rock samples, as shown in Figure 9.



Figure 9. Steel block simulated cylindrical rock sample test.

Using Probes #1 and #2, tests were conducted on cylindrical steel block specimens with dimensions of $\varnothing 50 \text{ mm} \times 30.00 \text{ mm}$, $\varnothing 50 \text{ mm} \times 50.00 \text{ mm}$, and $\varnothing 50 \text{ mm} \times 60.00 \text{ mm}$. The P-wave and S-wave velocities of the steel blocks were measured and compared with the calibrated values (P-wave: 5515.243 m/s; S-wave: 3005.330 m/s) to evaluate the acoustic response accuracy of the probes. The results are presented in Tables 2 and 3.

Table 2. Acoustic measurement accuracy of 1# probe.

Specimen	Specimen Dimensions (mm)	Measured Arrival Time (μs)		Corrected Actual Arrival Time (μs)		Acoustic Velocity of Specimen (m/s)		P-Wave Accuracy (%)	S-Wave Accuracy (%)
		Tp	Ts	Tp	Ts	Vp	Vs		
Contact	/	6.00	11.04	/	/	/	/	/	/
Steel block	$\varnothing 50 \times 30.00$	11.28	20.80	5.28	9.76	5681.81	3073.77	96.98	97.72
Steel block	$\varnothing 50 \times 50.00$	14.68	27.2	8.68	16.16	5760.36	3094.05	95.56	97.05
Steel block	$\varnothing 50 \times 60.00$	16.48	30.60	10.48	19.56	5725.19	3036.43	96.19	98.97

From the above table, it can be observed that although there is a certain deviation in the intrinsic arrival times between 1# Probe and 2# Probe, after eliminating the influence of the intrinsic arrival times through the software correction, the P-wave and S-wave velocities measured by the two probe sets on cylindrical specimens of different steel block

dimensions all achieved high accuracy, with the accuracy remaining above 95%. Therefore, the above experiments confirm that the measurement accuracy of the acoustic probes meets the requirements of the experimental study.

Table 3. Acoustic measurement accuracy of 2# probe.

Specimen	Specimen Dimensions (mm)	Measured Arrival Time (μs)		Corrected Actual Arrival Time (μs)		Acoustic Velocity of Specimen (m/s)		P-Wave Accuracy (%)	S-Wave Accuracy (%)
		Tp	Ts	Tp	Ts	Vp	Vs		
Contact	/	7.72	14.16	/	/	/	/	/	/
Steel block	φ50 × 30.00	12.92	23.76	5.2	9.60	5769.23	3125.00	95.39	96.02
Steel block	φ50 × 50.00	16.42	30.08	8.7	15.92	5747.12	3140.70	95.80	95.50
Steel block	φ50 × 60.00	18.20	33.28	10.48	19.12	5725.19	3138.07	96.19	95.58

3.2. On-Site Acoustic Wave Density Logging-Accuracy Verification

Having ensured the measurement accuracy of the ultrasonic probes, it is also necessary to compare the experimental results with field-measured logging data, so as to further verify the testing accuracy of the apparatus for evaluating the bonding quality at the cement stone–rock core interface.

To realistically reflect the cement bond quality at the wellbore interfaces, the industry developed the cement bond log (CBL)/variable density log (VDL) technique. In this approach, CBL is first used to acquire the casing wave amplitude, which evaluates the bonding condition at the casing–cement sheath interface between the casing and the cement sheath; then, VDL is employed to acquire full waveform sonic data to evaluate the bonding condition at the cement–formation interface between the cement sheath and the formation. Accordingly, this paper primarily compares the VDL variable-density-log amplitude values with the laboratory-measured data. The VDL tool records a full waveform sonic train at each depth point. In a cased well, the full waveform train consists, in order of arrival time, of the casing wave, the formation wave, and the Stoneley wave. On an actual VDL log display, the full waveforms can be presented as “full-energy wave” images arranged by depth. Two primary recording modes are commonly used:

- (1) Variable-intensity recording, in which variations in color intensity reflect the magnitude of acoustic energy. Darker colors indicate higher received acoustic amplitudes at the downhole receiver and greater acoustic impedance at the interface, which in turn implies poorer bonding quality at the corresponding depth interval. In field practice, the acoustic amplitude measured over the free casing section is typically taken as the reference calibration value, and the relative amplitude is used to evaluate cement bond quality, as expressed in Equation (1).
- (2) Variable-width recording, in which variations in the width of the phase lines (representing the same phase at different depths) reflect changes in both acoustic energy and phase.

$$U = \frac{A}{A_{FP}} \times 100\% \quad (1)$$

where U is the relative acoustic amplitude (%), A is the acoustic amplitude of the target interval (mV), and A_{FP} is the acoustic amplitude of the free casing section (mV). A_{FP} represents the acoustic amplitude received over the free casing section, which essentially accounts for nearly all of the energy emitted by the logging acoustic transmitter (approximately 95%). Owing to the presence of the free casing section, the cement does not effectively fill the annulus, resulting in a very high acoustic impedance at the casing–cement sheath interface. Consequently, the acoustic waves emitted within the casing cannot penetrate the formation and are completely reflected at the casing–cement sheath interface, where they

are then received by the logging receiver. Therefore, Equation (1) can also be transformed into Equation (2).

$$U = \frac{A}{A_{ITC} \times 0.95} \times 100\% \quad (2)$$

where U is the relative acoustic amplitude (%), A is the amplitude of the target interval (mV), and A_{ITC} is the total acoustic energy emitted by the logging tool (mV).

Lab transmission tests (better bond, lower impedance, stronger signal) use Equation (3) to convert data to U_E , matching field log practice for comparison.

$$U_E = \left(1 - \frac{A_E}{A_{EITC} \times 0.95}\right) \times 100\% \quad (3)$$

where U_E is the relative amplitude (%), A_E is the experimental amplitude (mV), and A_{EITC} is the total energy emitted by the lab instrument (mV).

It should be noted that the laboratory ultrasonic test and field VDL measurement differ in measurement geometry, acoustic propagation path, excitation/receiving configuration, and boundary conditions. Therefore, their absolute acoustic amplitudes are not directly comparable. The absolute received amplitude is affected by multiple system-dependent factors, including excitation energy, transducer sensitivity, propagation distance, geometric spreading, coupling conditions, and system gain. To reduce the influence of these factors, the acoustic amplitudes obtained from both measurements are normalized by their respective reference responses and expressed as dimensionless relative acoustic amplitudes. Such normalization does not imply that the laboratory and field acoustic propagation processes are physically identical; rather, it provides a common parameter for evaluating the relative attenuation or transmission characteristics associated with interface bonding. Accordingly, the comparison in this study is intended to assess the consistency of the normalized acoustic response between laboratory and field measurements rather than to establish a direct equivalence between their absolute acoustic amplitudes.

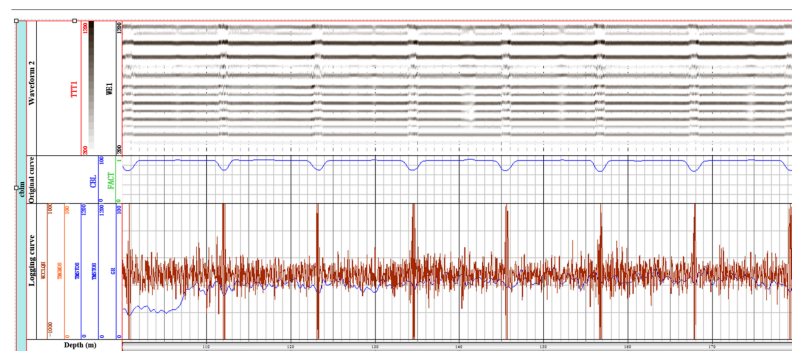
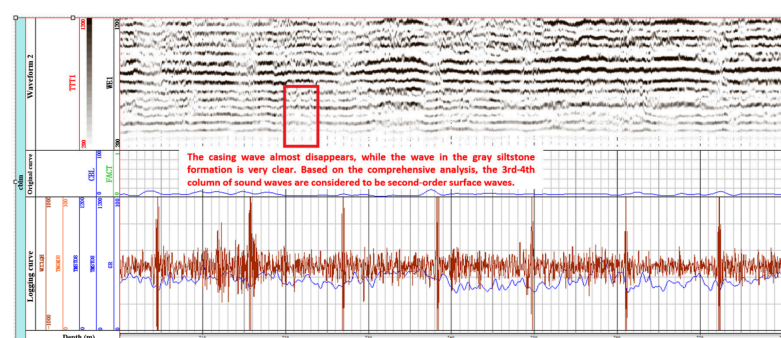
Thus, VDL logging evaluates both interfaces (Table 4). Relative amplitudes from typical VDL sections are read at selected depths, and lab data are converted and compared with field logs to verify the acoustic accuracy of the setup.

From the above table, it can be seen that in typical sandstone formations, the VDL signature of a well-bonded cement–formation interface is characterized by the near disappearance of casing waves (CBL amplitude < 10%), accompanied by clear formation waves that are in good synchronization with the AC log (open hole formation slowness). Under such conditions, the acoustic response at the cement–formation interface on VDL is most pronounced.

Following the above criteria, the VDL log from the sandstone interval of the double-stage cementing job in the $\Phi 193.7$ mm production casing of Well Bhattan X, operated by the Northwest Oilfield Branch Company, was selected for comparison with laboratory data. In this well, the interval from 0 to 694 m is the free casing section, and the interval from 694 to 3638 m is cemented with a high-temperature-resistant latex cement sheath. The open hole caliper log shows an average borehole diameter of 259.35 mm with an average enlargement rate of 3.4%; the maximum diameter of 358.6 mm occurs at a depth of 2025 m, and the minimum diameter of 250.52 mm occurs at a depth of 3000 m. CBL and VDL evaluations were conducted 9 days after the cementing operation. Based on the comprehensive acoustic log evaluation method for cement bond quality and the summary of the open hole caliper and lithology data of Well Bhattan X, VDL data from representative intervals (0–180 m and 720–725 m) of this well were selected for comparison with laboratory data, as shown in Figures 10 and 11.

Table 4. Comprehensive evaluation of cementing interface bonding quality based on VDL logging.

VDL Characteristics		Comprehensive Evaluation of Cementing Quality	
Casing Wave Characteristics	Formation Wave Characteristics	First-Interface Bond Quality	Second-Interface Bond Quality
Very weak or absent	Formation waves clear, phase lines in good sync with AC log	Good	Good
Very weak or absent	Absent; AC reflects soft formation	Good	Good
Very weak or absent	Absent; AC reflects soft formation with enlarged borehole	Good	Poor
Very weak or absent	Relatively weak	Good	Poor
Relatively weak	Formation waves clear	Partial bond (or micro-annulus)	Partially bonded, good
Relatively weak	Absent or weak formation waves	Partial bond	Poor
Relatively weak	Formation waves unclear	Moderate	Poor
Relatively weak	Weak	Relatively poor	Partially bonded, good
Relatively weak	Absent	Poor	Indeterminate

**Figure 10.** VDL diagram of 0~180 m free casing section of well Bhattan X.**Figure 11.** VDL diagram of 720~725 m with a well-cemented interface of Well Bhattan X.

It should be noted that complete mineralogical and petrophysical characterization, including mineral composition, porosity, permeability, and saturation, was not available for either the selected field interval or the laboratory sandstone core used in this preliminary comparison. Therefore, petrophysical equivalence between the field formation and laboratory core cannot be established. The field interval was selected to provide representative field acoustic data, while the laboratory sandstone was used to construct a controlled cement–formation interface. Accordingly, the following comparison is intended only as a

preliminary field-referenced assessment of the normalized acoustic response and should not be interpreted as a direct laboratory reproduction of the field formation.

As shown in Figures 10 and 11, the interval from 0 to 180 m exhibits typical acoustic characteristics of a free casing section, which can therefore be used as the reference amplitude calibration. The interval from 720 to 725 m displays typical features of a well-bonded section, with a relative acoustic amplitude of 13.75% compared with that of the free casing section. Drilling and logging data indicate that this interval has a formation temperature of 17 °C and a confining pressure of 9.8 MPa.

Accordingly, these conditions (17 °C, 9.8 MPa) were adopted as the curing environment for laboratory interface tests. A high-temperature-resistant latex cement slurry (formulation: Class G cement + 6% silica fume + 3% fluid loss additive + 0.2% retarder + 8% latex + 0.3% latex defoamer + 36% water) was placed against a siltstone core and cured for 9 days, after which acoustic response data at the interface were acquired to determine the first arrival amplitude AE. Under the same curing conditions, additional tests were performed on a cement stone–sandstone interface incorporating an interfacial bonding agent (assumed to be fully bonded) to obtain the acoustic amplitude AEITC. The relative acoustic amplitude UE under laboratory conditions was then calculated using Equation (3).

Figure 12 presents the acoustic response curves of the latex cement stone–sandstone interface and the calibrated fully bonded interface under identical curing conditions, with the horizontal axis representing P-wave arrival time and the vertical axis representing P-wave amplitude.

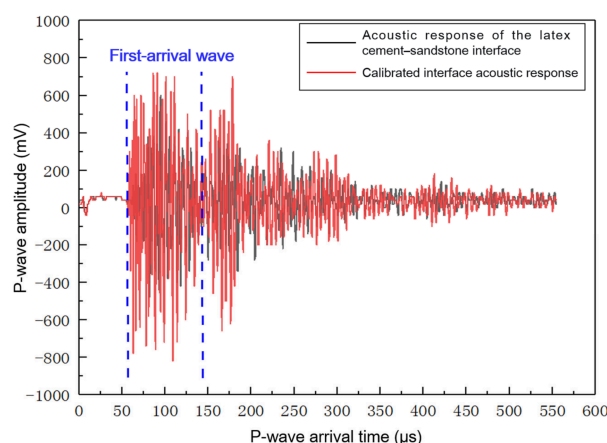


Figure 12. Acoustic response curve of the interface between latex cement stone and sandstone.

As shown in Figure 12, the acoustic amplitude curve of the latex cement stone–sandstone interface is lower than that of the calibrated fully bonded interface; the former is almost completely overlapped by the latter. However, the waveform shapes and arrival times of the two curves are nearly identical, with the first arrival times being 60 μs and 61 μs, respectively. After applying envelope processing to the first arrivals and calculating the integrated area of the first arrival waveform, the integrated amplitude of the first arrival for the latex cement stone–sandstone interface (AE) is obtained as 27,240 mV, and that for the calibrated fully bonded interface (AEITC) is 33,960 mV. Substituting these values into Equation (3) yields

$$U_E = \left(1 - \frac{A_E}{A_{EITC} \times 0.95} \right) \times 100\% = \left(1 - \frac{27240}{33960 \times 0.95} \right) \times 100\% = 15.56\% \quad (4)$$

For the selected field interval, the normalized laboratory acoustic response was compared with the relative acoustic amplitude of 13.75% obtained from the field VDL data.

The resulting agreement for this individual laboratory–field comparison was approximately 86.8%. It should be emphasized that this value represents the level of agreement for the investigated case and should not be interpreted as the measurement accuracy or overall validation accuracy of the developed system. Because only one representative laboratory–field comparison was performed, the present result is regarded as a preliminary field-referenced acoustic consistency check. Additional comparisons involving different formations, downhole conditions, and independent datasets are required to quantitatively evaluate the robustness and general applicability of the laboratory–field relationship.

4. Proposed Experimental Framework for Evaluating the Cement–Formation Interface

Based on the functional design and experimentally verified acoustic measurement capability of the developed apparatus, the following procedure is proposed as an experimental framework for future systematic evaluation of the cement–formation interface under static and dynamic curing conditions (Figure 13).

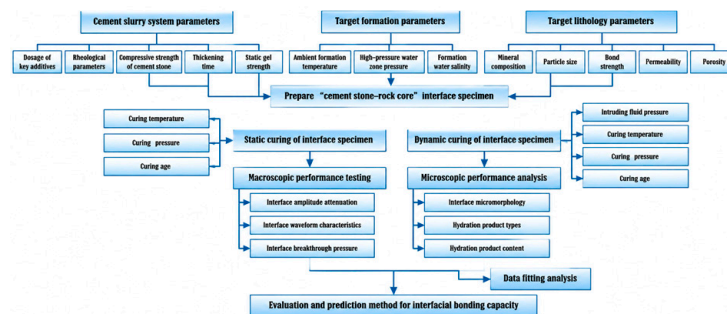


Figure 13. Technical route of evolution evaluation of interface cementation capability.

- (1) Obtain cementing operation parameters for various slurry systems, including slurry density, key additives, cement stone wave velocity, and compressive strength.
- (2) Obtain target lithology parameters, including mineral composition, bond strength, permeability, and porosity, and prepare natural or artificial rock cores.
- (3) Obtain formation parameters, including ambient formation temperature, high-pressure water zone pressure, formation water salinity, and in situ stress.
- (4) Assemble the static curing specimen mold using the interfacial sealing capacity test apparatus, seal the inlet and outlet ports, and prepare “cement stone–rock core” interface specimens under static curing conditions. The curing pressure is 21 MPa, and the curing temperature is set to the ambient temperature of the target formation. For subsequent systematic applications of the proposed framework, representative curing ages (e.g., 1, 2, 7, 15, and 30 days) may be selected according to the research objective. These curing ages were not systematically investigated in the preliminary calibration presented in this study.
- (5) Assemble the dynamic curing specimen mold using the interfacial sealing capacity test apparatus, and open the fluid inlet and outlet. During dynamic curing, the curing pressure is maintained at 21 MPa. Formation fluid is continuously supplied by the constant-speed/constant-pressure injection pump through the inlet at the bottom of the specimen assembly. The fluid flows upward along the cement–formation interface and is discharged through the upper outlet, forming a bottom-to-top flow path and maintaining continuous fluid exchange at the interface. The curing temperature is set according to the target formation temperature, and for subsequent systematic applications of the proposed framework, representative curing ages (e.g., 1, 2, 7, 15, and 30 days) may be selected according to the research objective. These curing

ages were not systematically investigated in the preliminary calibration presented in this study.

- (6) Upon reaching the designated curing age, close the inlet and outlet ports, activate the acoustic detection system, measure the acoustic amplitude attenuation through the specimen interface, analyze waveform variations, and obtain the macroscopic acoustic response of the specimen interface.
- (7) After acoustic testing is completed, open the inlet and outlet ports and gradually increase the inlet pressure until a sudden pressure drop occurs along with water breakthrough at the outlet, thereby obtaining the macroscopic breakthrough pressure of the specimen interface.
- (8) Disassemble the curing mold, extract the “cement stone–rock core” specimen, collect interfacial debris (5–10 mm), analyze the micromorphology of interfacial hydration products using scanning electron microscopy (SEM), identify typical hydration product types using energy-dispersive spectroscopy (EDS), determine the specific component contents of hydration products using thermo-gravimetric analysis (TG), and characterize interfacial porosity using mercury intrusion porosimetry (MIP), so as to investigate the evolution of the interfacial hydration products and microstructure.
- (9) Compile the experimental data, taking macroscopic performance parameters of the cement stone–rock core interface as objective functions and the experimental conditions and interfacial acoustic responses as independent variables. Based on big-data fitting methods, establish the correlation between macroscopic interfacial bonding performance and acoustic response evolution characteristics through multivariate linear or nonlinear regression, thereby developing a quantitative evaluation and prediction method for interfacial bonding capacity.

5. Conclusions

Scope and limitations. The present study focuses on the development and preliminary calibration of the experimental platform rather than a comprehensive parametric investigation of cement stone–rock interfacial behavior. The cement stone–sandstone acoustic calibration presented herein was conducted at 17 °C and 9.8 MPa after 9 days of curing. Therefore, the current results should not be extrapolated to other temperature, pressure, or curing-age conditions. Although the developed platform provides configurable static and dynamic curing modes and adjustable temperature and pressure conditions, their effects on interfacial evolution have not yet been systematically compared. Comprehensive experiments covering broader temperature and pressure ranges, multiple curing ages, and controlled static/dynamic conditions are required before generalized quantitative relationships can be established.

- (1) An experimental platform for investigating the cement–formation interface was developed by integrating real-rock core holders, pressure/temperature control, formation-fluid injection, acoustic measurement, and configurable curing modes. Basic performance tests were conducted to assess the operational capability of the apparatus.
- (2) The ultrasonic probes were calibrated using standard cylindrical steel specimens, with P- and S-wave measurement accuracies exceeding 95%. A preliminary field-referenced acoustic comparison was subsequently performed for a cement stone–sandstone interface cured at 17 °C and 9.8 MPa for 9 days. The result provides an initial consistency assessment of the normalized acoustic response for the investigated case, rather than comprehensive validation of the system.
- (3) Based on the functional capabilities of the developed apparatus, an experimental framework is proposed for the subsequent investigation of interfacial acoustic response, sealing performance, and microstructural evolution. Systematic experi-

ments covering broader temperature and pressure ranges, multiple curing ages, static/dynamic curing conditions, and independently characterized rock properties are required before generalized quantitative relationships or predictive models can be established.

Author Contributions: The authors confirm contribution to the paper as follows: study conception and design: C.C. and P.L.; investigation: S.D.; data collection: Y.L.; analysis and interpretation of results: C.L.; draft manuscript preparation: C.C.; writing–review and editing: C.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Oil & Gas Major Project “Engineering Technology and Equipment for Full-Lifecycle Well Integrity” (2025ZD1402200) and the National Natural Science Foundation of China’s Enterprise Innovation Joint Fund Project “Sealing Theory and Control Methods for Cement Casing throughout the Entire Life Cycle in Complex Environments” (U22B6003).

Data Availability Statement: Data are available on request from the authors.

Conflicts of Interest: Author Chao Chen was employed by the company Sinopec Northwest Petroleum Branch, Urumqi. Author Peiqing Lu was employed by the company Sinopec Research Institute of Petroleum Engineering, Beijing. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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