Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 5, No. 2, 2023

Research on Improvement Measures of Cementing Acoustic Amplitude Logging

Jian Li[1], Zhidi Liu[1, 2]

[1] School of Earth Science and Engineering, Xi'an Shiyou University, Xi'an 710065, China
[2] Shaanxi Key Laboratory of Petroleum Accumulation Geology, Xi'an Shiyou University, Xi'an 710065, China

Abstract: Cementing is one of the important aspects in the exploration and development of oil and gas fields, and the quality of cementing has a great impact on the life, production capacity and overall efficiency of a well. Due to the limitations of the evaluation technology and the complexity of the influencing factors, the conventional method of cementing quality evaluation currently used in China often leads to misjudgment of the quality of the cemented wells and can no longer meet the requirements of high accuracy research. By analyzing the factors affecting the solids quality testing and the advantages and disadvantages of several common solids quality evaluation methods, and organically combining them according to the measurement principles and their usage correlations, a system of evaluation methods applicable to different requirements is formed, and the intelligent evaluation of solids quality is further explored to provide a concrete and practical basis for solids quality evaluation in the development and production of oil fields.

Keywords: Cementing quality, Logging, Influencing factors.

1. Introduction

Cementing quality evaluation is an important part of oil and gas development and production, and acoustic logging methods are usually used to evaluate the cement cementing degree of cased wells. The sonic method of cementing quality logging currently includes sound amplitude-variable density logging, sector cement cementing logging, etc. How to improve the quality of cementing has been the subject of exploration and research by experts in the field of cementing research at home and abroad[1]. H.O. Brown (1970) and others suggested that the minimum seal length of cement ring is related to cement cementing index and casing type, and the minimum effective interlayer seal length of cement ring increases with the increase of casing outer diameter[2]. The Drilling Manual developed by China National Petroleum Corporation (1990) stipulates that the evaluation index for casing with an outside diameter of 7in and a wall thickness of 0.408in is: relative sound amplitude less than or equal to 15% is evaluated as excellent cementing, relative sound amplitude between 15% and 30% is evaluated as qualified cementing, and relative sound amplitude greater than 30% is evaluated as poor cementing[3]. S. Talaba-ni (1993) established a fluid flow model and proposed effective measures to prevent gas fouling[4], which marked the generalized application of cementing theory research. Ding Shidong, Huang Bozong et al. proposed a new technique of pulse vibration cementing, which combined corrosion and gas fouling prevention, and developed DC200 latex cement slurry system with corrosion and gas fouling prevention, and proposed a new method of pre-side of circumferential air fouling[5]. In 2012, Hou Qingkong et al. studied the acoustic properties and strength properties of cement stone through simulation tests, and concluded that the evaluation criteria corresponding to different densities are not exactly the same[6].

At present, the quality testing methods used in China are still mainly the "old three" (sound amplitude, gamma, magnetic positioning), which can no longer meet the requirements of the oilfield for quality testing of cemented wells. With the promotion of VDL, CBL/VDL, SBT, PET, CAST-V, MAK-II, and SGDT logging technologies, the use of different types of logging methods in combination with each other has emerged, and significant breakthroughs have been made in the analysis of factors influencing the quality of cementing logging and the intelligent interpretation of logging data.

2. Basic Principle of Cementing Quality Logging Instrumentation

2.1. Cement cemented logging

The acoustic amplitude logging instrument consists of an acoustic system with a source distance of 1 m and an electronic circuit. The acoustic pulse from the transmitter T, which is incident at the mud-casing interface at a critical angle, produces a casing wave that propagates along the mud-casing interface through refraction. The propagation path is shown in Figure 1. In a cased well, there are three propagation paths for the acoustic wave from the acoustic transmitter to the receiver reception, which are the mud wave propagating in the drilling fluid (path T-R in Fig. 1), the casing wave propagating along the casing and drilling fluid interface (path R-C-B-A-T in Fig. 1), and the formation wave propagating along the cement ring and formation interface (path R-G-H-T in Fig. 1).

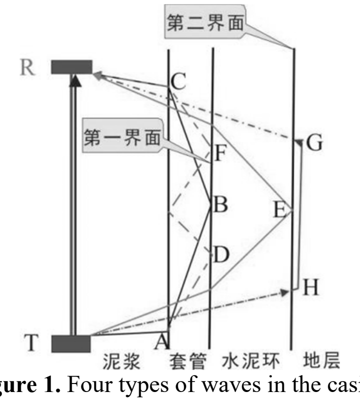

Figure 1. Four types of waves in the casing

In general, the casing wave reaches the receiver first, followed by the formation wave and finally the mud wave. If the casing and cement are well cemented, then the acoustic impedance difference between the casing and cement is small, the coupling is good, and most of the casing waves propagate outward, leading to a reduction in the acoustic waves received by R and a reduction in the cement cemented logging value. If the casing and cement are not well cemented, the mud will invade the cement ring, and because of the poor coupling of the mud casing, the receiver receives more casing waves and the cement cemented logging value is larger. When the casing and cement and cement and formation are well cemented, the acoustic energy signal propagates from the casing through the cement ring to the formation with the highest efficiency, and the amplitude of the sound amplitude curve is lower at this time (Figure 2).

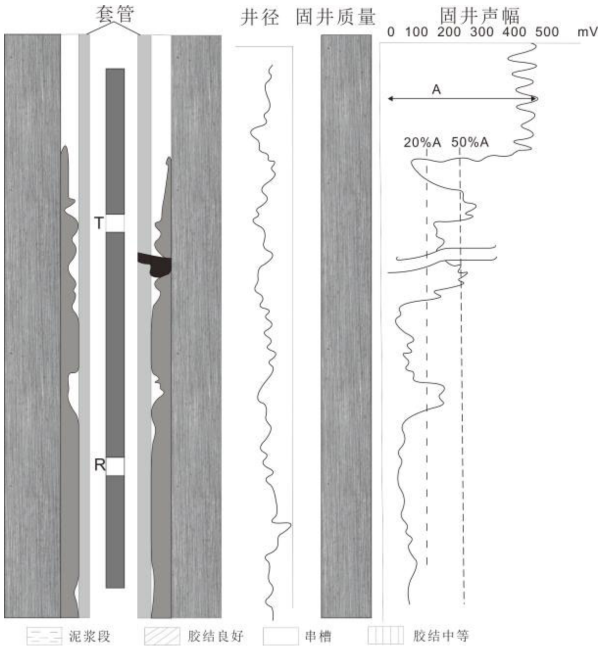

Figure 2. Schematic diagram of CBL logging curve and corresponding cementing quality

With the change of depth, the local formation lithology affects the amplitude of the sound amplitude curve to produce small-scale changes. In the study of sound amplitude variation, a quantitative interpretation method, namely the relative amplitude method[7], is generally used, and its evaluation criteria are shown in Table 1.

$$f = \frac{I}{I_p} \tag{1}$$

Where: f is the relative amplitude; I is the sound amplitude of the target layer section, mV; Ip is the sound amplitude of the free casing well section, mV.

Cement cementing logging can only effectively reflect the cementing of the cement ring and casing, and it has disadvantages such as low vertical resolution and no azimuthality. Since the strength increases with time during cement setting, which seriously affects the accuracy of the data, logging is usually performed after 48 hours of cementing. When the thickness of the cement ring is above 2 cm, the effect is not significant, and vice versa, it will have a more obvious effect, and then it is necessary to refer to the well diameter curve.

Table 1. I, II interface cementation evaluation index and its response characteristics

Relative magnitude value	Cementing condition	Stratigraphic wave characteristics	CBL curve characteristics
$f \leq 20\%$	Good	Significant stratigraphic waves	CBL range is relatively low
$20\% < f \leq 30\%$	Moderate	Stratigraphic wave characteristics are not clear, only part of the stratigraphic wave shows	CBL range medium
$f \geq 30\%$	Poor	Faint or missing stratigraphic waves	CBL range is relatively high

2.2. Acoustic amplitude-variable density logging principle

In the process of implementing measurements using solids amplitude, the transmitter emits an acoustic pulse that is refracted through the mud into the casing, generating the corresponding casing wave. According to Fermat's theorem, the casing wave follows the shortest path through the refraction into the mud, at which time the receiver receives the first wave of the longitudinal wave, part of which will receive positive peaks and part of which will receive negative waves, after which it is converted to the corresponding voltage value through the electronic circuit. Figure 3 shows the acoustic variable density logging diagram. The sound amplitude curve is mainly used in the evaluation of the quality of cementing at one interface[8]. A solidification sound amplitude curve is measured during the movement of the instrument along the well body, and in general a sound amplitude measurement curve with a source distance of 3 ft (1 ft = 304.8 mm) is applied. In particular, for variable density logging, a 5 ft variable density graph is generally applied in the logging evaluation; this is combined with the strength and weakness of the formation waves to evaluate the cementing quality at the diametral interface.

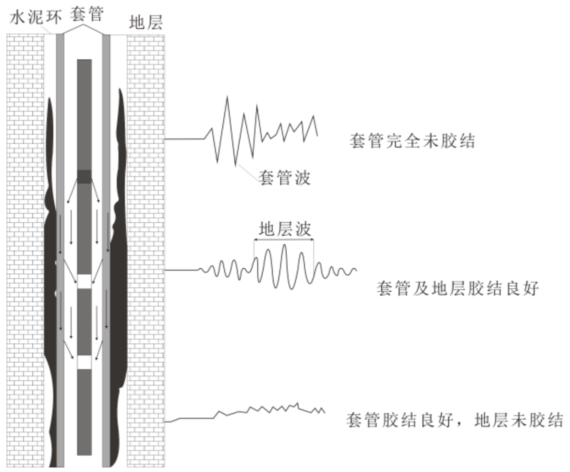

Figure 3. Acoustic variable density logging map

2.3. Principle of zoned cement cemented logging

The zonal cement cementation logging technique measures cementation quality in two different directions, lateral and vertical, along the casing circumference. The instrument uses twelve high frequency directional transducer acoustic systems mounted on six skids to perform specific measurements in six 60° blocks around the casing in a quantitative manner. This instrument is designed with short source distances in mind so that the fast stratigraphy does not overly influence the actual measurement results of compensated attenuation. The main advantages of SBT logging over variable density logging are the division of the equipment into six zones around the well perimeter to measure cement cementing conditions, the lesser influence of the formation, the acoustic volume directional format that highlights the cement-formation interface effects and minimizes casing effects, the ability to accommodate in-well logging of different fluids, including: heavy and gas-bearing muds, the ability to measure in horizontal wells, and other advantageous features.

2.4. Acoustic one-gamma density logging principle

This logging instrument can be divided into acoustic and gamma density logging instruments, which can measure the main parameters including the first wave propagation time recorded by the two receivers respectively, using these two parameters to calculate the acoustic time difference; it can also measure the attenuation of the first wave transmission to the first and second receivers, through these two parameters can be calculated for the acoustic variable density and attenuation coefficient.

For gamma density logging, a radioactive gamma ray source field is formed by a 250 mCi cesium 137 source, and the surrounding media are casing, formation, and well fluid, etc. A detector for measuring casing wall thickness is set at a source distance of 0.24 m, and six detectors for measuring cement thickness are set at a source distance of 0.4 m in different directions with uniform distribution, and a A natural gamma detector is also present to detect the secondary gamma ray counts from the inelastic collision of the casing, cement ring and mud medium, respectively, so that the actual thickness of the casing, the eccentricity of the casing and the average density of the cement ring can be calculated. SGDT logging is able to obtain several parameter curves, such as casing wall thickness count curves and natural gamma count curves. Based on these curves, the actual count rates of the thickness and density probes are converted to the actual casing wall thickness and the average density of the filling media, and the eccentricity of the casing is calculated using the SGDT gamma density evaluation system in conjunction with the formation density and bare borehole diameter information.

Evaluate the cementing quality, establish the return height of the free casing section to the cement, check for casing procedures and areas of damage, and establish the specific eccentricity of the casing in relation to the well wall, etc.

3. The Main Factors Affecting the Quality of Cemented Wells

3.1. Cement

(1) Influence of cement setting time: High amplitude values of CBL curves can occur when logging in unset and well-sealed well sections, resulting in misclassification, so the wells are generally logged between 24 and 48 h after cementing.

(2) The effect of cement ring thickness: When the cement ring thickness is greater than 2 cm, the effect on the cement cementing logging curve is a fixed value; when it is less than 2 cm, the thinner the cement ring thickness, the higher the value of the cement cementing logging curve, and then it is necessary to refer to the well diameter curve for testing.

(3) The effect of cement density: Since the wave impedance value of high-density cement is greater than that of low-density cement, the acoustic coupling is worse than that of high-density cement in low-density cementing. In the case of the same degree of cementing, the wave amplitude of the casing cemented with low-density cement is much higher than that of the casing cemented with high-density cement[9].

(4) Cement micro-ring gaps: When cement sets, the volume shrinks, resulting in a reduction in its cementing strength at the two interfaces, forming micro-ring gaps that make the acoustic attenuation value smaller, at which point the stratigraphic waves cannot be accurately identified.

(5) Cement sector deficiency angle: As the cement sector deficiency angle decreases, the SBT attenuation value increases. When the missing angle of cement sector is less than a certain critical angle, the SBT attenuation value fluctuates and it is impossible to distinguish the cementing condition[10]. In addition, when there is mud and gas intrusion, a large attenuation of acoustic energy will occur, making low values in poorly cemented well sections and causing misclassification.

3.2. Stratigraphic lithology

(1) Fast stratigraphy: In fast stratigraphic casing wells, the time difference between the stratigraphic wave when the cementing is good and the casing wave when the cementing is poor at the I interface is small or even arrives at the receiver before the casing wave, resulting in the superposition and overlap of the stratigraphic and casing waves, thus mistaking the stratigraphic wave for the casing wave and causing a misjudgment of the cementing quality at the I interface. Therefore, when extracting the casing wave information, filtering can be performed first, and then evaluated by conventional interpretation methods.

(2) Slow stratum: Due to the low speed of sound propagation in the slow stratum, it makes the characteristics of the stratum wave at the interface of variable density not obvious. In the case of good cementation at interface I, the quality of cementation at interface II of the slow stratigraphic section is easily reduced.

(3) Formations with large differences in porosity permeability: For example, in mudstone formations, the hydration and condensation process of cement slurry is rapid and the temperature changes are large, and it is easy to form small gaps at the II interface; at the same time, the well diameter of these formations varies greatly, and the uneven thickness of the cement ring will make the sound field in the well change. In contrast, in highly porous and highly permeable formations, cement slurry can penetrate into the formation and is less likely to produce small gaps. When performing sound amplitude or variable density logging in sandy mudstone formations, it is common to encounter a good positive or negative correlation between GR and CBL, which is the effect of large differences in porosity permeability due to formation lithology variations[11].

3.3. Instruments

(1) Instrument eccentricity: When the instrument is eccentric, the casing waves from different directions do not reach the receiver at the same time, and the earliest arriving casing waves are only the result of the superposition of the first wave of the signal in the direction close to the instrument, which can easily misjudge the poorly cemented well section as well cemented, resulting in the logging value not correctly reflecting the cementing situation at the I interface.

(2) Instrument scale: Before CBL/VDL logging, it is necessary to select the same type of free casing as the target well section, and obtain the first wave opening time, gate width, and first wave amplitude value, respectively. The sound amplitude value of the log is only a value relative to the free casing, so the result of the scale is not only related to whether the first wave amplitude can be measured, but also affects the size of the relative value of the sound amplitude, which affects the final interpretation conclusion.

3.4. Casing

(1) Casing thickness and diameter: the size of the casing diameter will affect the magnitude of the sound amplitude curve, and the arrival time of the first wave of the variable density curve. The first wave (casing wave) of large casing diameter arrives late, and the first wave of small casing diameter arrives early[12].

(2) Casing eccentricity: When performing sound amplitude logging, casing eccentricity is equivalent to instrument eccentricity, which also results in low sound amplitude values and misclassifies poorly cemented well sections as well cemented. During SBT logging, the minimum attenuation value is significantly greater than the minimum attenuation value without centering, indicating a tendency for the SBT minimum attenuation value to decrease in the presence of casing eccentricity[13].

(3) Double casing: The effect in the free casing section is negligible; in the well cemented layer section, the effect of double casing is similar to that of fast stratigraphy, both of which increase the sound amplitude. In the variable density diagram, the outer casing almost shields the outer stratigraphic wave, and a flat casing wave appears.

3.5. Logging time

When performing cementing quality testing, testing too early or too late can affect the accuracy of cementing quality evaluation and lead to misjudgment. Insufficient cementing time after cementing will cause the cement ring to be weak and unstable, resulting in a low evaluation; if the cement takes too long to set, a high evaluation will occur, which will also lengthen the construction period of each well and affect the development efficiency of a single well. When choosing the logging time, the best logging time should be selected according to the density of the cement slurry used, whether or not retarders or other substances affecting cement cement cementation are added, and other different cement slurry properties, so as to obtain accurate logging data on the quality of the cemented wells and ensure the accuracy of the quality evaluation of the cemented wells.

4. Quality Improvement Measures for Cementing Wells

4.1. Cement slurry Selection

There are differences in the acoustic properties of cement paste systems with different densities. Due to the different density mitigants, the internal structure of the cement stone is different, and the acoustic properties show that at the same density, the denser the structure, the higher the sound velocity of the cement stone, so the response of the cementing quality evaluation logs will also differ, as the denser the structure, the lower the sound amplitude value, which is reflected in the cementing quality evaluation criteria. In addition, the applicable density range of the cementing quality evaluation criteria for each cement slurry system is different because there are certain restrictions on the addition of different mitigants, so there are certain restrictions on the density range of the cement slurry formulation.

Retarder is an important factor affecting the cementing quality evaluation criteria, and there are some differences in the cementing quality evaluation indexes of different retarders corresponding to the density cement slurry system, and the density range of each density cementing quality evaluation criteria should be limited due to the limitation of the amount of retarder itself. Retarder does not have much influence on the normal cementing quality evaluation, and the addition of retarder only has a greater impact on the logging response of the initial cementing quality evaluation, therefore, the influence of retarder can be ignored when the cementing quality evaluation criteria are improved.

4.2. Improving formation pressure-bearing capacity

In order to fully improve the pressure-bearing capacity of the formation, the staff needs to make a reasonable choice of plugging materials for cementing operations, using relatively reasonable diameter bridge plug particles as far as possible, from the entrance of the cement slurry, injecting this type of material into the more serious leakage problems of the formation for pressure-holding treatment, so that the particles can fully seal the pores in the formation. This type of particle can also enter the fracture and form a bridge plug structure to protect the formation by using mud cake. Field tests have shown that the formation pressure capacity can be maintained at 6.0 MPa with this type of material, and the quality of the cementing operation has been improved to some extent.

Control the density of the cement paste at 1.95 to 2.0 g/cm3 with a water loss of not more than 100 ml, avoiding as much as possible the influence of airborne moisture on the thickening of the cement ring. The cement paste properties are controlled by using suitable external materials for neutralization according to the cement paste properties. In order to improve the topping efficiency, the method of adding diphosphate should be used to reduce the shear force; the use of anticorrosive and impermeable cement slurry, which can reduce the degree of influence of the formation lithology on cement solidification and improve the interfacial viscosity.

4.3. Instrument centering

(1) Select the appropriate corrector to ensure that the instrument is reliably centered, and there should be strict requirements on the size of the corrector; the radius of the corrector is less than the radius of the inner wall of the casing mm should not be used. At present, the domestic

manufacturers of the ding-shaped corrector is not suitable for use in wells with large well slope, large casing in the well slope, three-claw corrector is not applicable, should be replaced by a new hard corrector; no corrector side sound amplitude cementing quality curve is not allowed.

(2) reasonable choice of gate width and location, gate is too wide, the leading edge to the start time easy to cause the continuation to the wave into. Gate width is too narrow, when the first wave forward, easy to align the valley between the two peaks, resulting in a more unrealistic false amplitude output; a more reasonable approach is to use the back edge of the gate wave to align the centered first wave back edge, and the gate is adjusted to a wider (40 microseconds) or so, can make in a small amount of eccentricity caused by the first wave ahead, to obtain a more normal graph.

(3) Proper control of speed measurement.

(4) acceptance of sound amplitude data, due to the general randomness of the instrument eccentricity, the curve is bound to repeat badly, should emphasize the repeatability of the curve.

4.4. Improving topping efficiency and drilling fluid performance

For oil and gas wells, after the drilling operation is completed, the cementing operation should be carried out after the well penetration operation. In the actual operation process, the addition of diluent can effectively prevent the emergence of formation false cake problems, and at the same time, it can also effectively reduce the plastic viscosity. In general, the plastic viscosity should be controlled within 30 mPa-s, the dynamic shear force should be controlled between 5~7 Pa, and the static shear force should be controlled between 3~5 Pa. From the perspective of resistance and dynamics, the replacement efficiency of cement slurry can be improved by reducing the thixotropy, which is also a key measure to improve the quality of cementing operation.

Drilling fluids with low density, low water loss, low shear and low viscosity should be used for cementing operations. The drilling fluid density should be controlled to less than 1.20g/cm3 , the shear force to 0 Pa, the viscosity to less than 25 seconds, and the water loss to about 5 ml, which can help improve the quality rate of cementing. In addition, the use of less permeable drilling fluids can effectively reduce the influence of mud cake on the quality of cementing.

4.5. Intelligent Evaluation of Cementing Quality

Using the fuzzy mathematical theory - multi-level comprehensive evaluation method to evaluate the three major factors affecting the quality rate of cementing: borehole condition, drilling fluid performance and cementing parameters, compare the cementing well history data, and find out which specific type of factors play a dominant role, put forward some corresponding technical measures, countermeasures and suggestions for the cementing operation and how to reasonably regulate the construction It provides a theoretical basis for drilling and cementing parameters[14].

In the current well quality evaluation technique, acoustic amplitude logging is commonly used to evaluate the well quality by identifying the first wave amplitude of the formation echoes. This statistical method based on the statistical principle of relative amplitude is less fault tolerant, interference resistant and adaptive. BP wavelet neural network[15]. The wavelet transform is realized by adaptively adjusting the shape of wavelet bases through training, and it has strong self-learning, fault tolerance, interference resistance, and adaptiveness, which is superior to statistical pattern recognition. However, the traditional BP wavelet neural network tends to converge to local minima, and the network training time is long and the search success rate is low. In recent years, researchers at home and abroad have introduced the emerging stochastic global optimization technology-particle swarm (PSO) algorithm to train the weights of the neural network and perform intelligent interpretation of logging data based on intelligent information processing technology to achieve a higher degree of intelligence in logging interpretation and improve the accuracy and reliability of interpretation results, which has become a research hotspot and development direction in this field at home and abroad.

4.6. Optimal logging time determination

The theoretical analysis concluded that as long as the influence of waiting time on cementing quality evaluation criteria is not greater than 5%, the evaluation criteria can still accurately guide the evaluation of cementing quality. Within the optimal logging time, the evaluation criteria of cementing quality are influenced by the waiting time within 5%; temperature is an important factor affecting the optimal logging time. For the same retarder, the more retarder is added, the longer the optimal logging time. However, the relationship between the amount of retardant and the optimal logging time is not comparable among different retardants; moreover, the relationship between the thickening time, initial setting time, final setting time and sound velocity inflection time, which are affected by retardant, and the optimal logging time cannot be evaluated quantitatively.

5. Conclusion

In summary, cementing plays a very important role in the process of drilling and completion operations, but there are relatively many factors affecting the quality of cementing operations, and if these factors are not fully controlled, the quality of cementing operations will be seriously affected. Therefore, the staff needs to fully consider the factors affecting the quality of cementing operations and take reasonable measures to make the quality of cementing operations to be improved comprehensively.

(1) For blocks with more mature cementing process, CBL can be used directly for determination.

(2) When interpreting the low-density cemented section, the quality of the cemented well should be evaluated by combining the information measured by SGDT and acoustic amplitude logging.

(3) When evaluating the quality of cementing in large-slope wells, SBT cementing logs are required to eliminate the effect of instrument eccentricity. SBT logs are also generally used for cementing quality evaluation in heavy mud and gas-bearing wells to eliminate interference. SBTs are also used to find small fracture slots when high accuracy is required.

References

[1] Hamawi M, R. Masood, Z. Al-Kindi, and A. Elkadi. 2007. A pioneering ultrasonic technique that enhances light eight cement evaluation and allows A pioneering ultrasonic technique that enhances light eight cement evaluation and allows cement sheath thickness imaging [C]. The 1st Annual Middle East Regional SPWLA Symposium.

[2] Kimball C V, Marzetta T L. 1984. Semblance processing of borehole acoustic array data [J]. Geophysics, 49(3):274 -281.

[3] Morris C W, Sabbagh L, Wydrinski R, Hupp J, van Kuijk R, Froelich B. 2007. application of enhanced ultrasonic measurements for cement and casing evaluation [C]. SPE/IADC Drilling Conference, Society of Petroleum Engineers.

[4] V. Pistre, T. Kinoshita, M. Blyth, and E. Saenz . 2014. Attenuation-Based Quantitative Cement Bond Index with LWD Sonic: A Novel Approach Applicable to all Casing and Cement Cases. SPE 170886 -MS.

[5] W. Izuhara, H. Yamamoto, M. Blyth, and E. Saenz 2017. Full-Range Quantitative Cement Bond Evaluation with LWD Sonic: The Right Way of Approach Using a Hybrid of Amplitude and Attenuation. SPE-187438-MS.

[6] Yan Wei Feng, Nick Robinson, Wataru Izuhara and Hiroaki Yamamot o. 2016. Well Integrity Evaluation with LWD-Quantitative Full Range Cement Bond Index. the 22nd formation Evaluation Symposium of Japan, Sep 29 -30.

[7] Tang, H.. Quantitative well logging acoustics [M]. Beijing: Petroleum Industry Press.2004:54-56

[8] Wei T. Evaluation of oil and gas well cementing quality logging [M]. Beijing: Petroleum Industry Press, 2010:6-11.

[9] Xie R. H., Liu J. S., Li X. W. Development of solid well quality evaluation technology and its impact on oilfield development [J]. Logging Technology,2019,43(4):339-343.

[10] Zhang Xiumei. Study of sector cement cementation test (SBT) [D]. Qingdao:China University of Petroleum (East China). 2005

[11] FU Yongqiang, CHEN Jianbo, LIU Coco, WANG Tianyu, MA Chao, LIU Xiyan. Array acoustic logging to evaluate the quality of large-diameter casing cementing in gas storage reservoirs[J]. Logging Technology,2022,46(6):768-773.

[12] Wang Kunjian, Li Jin, Liu Pengfei, et al. Research and application of integrated technology of gyroscopic logging and solid well quality measurement[J]. Petroleum Machinery, 2020, 48(7): 51.

[13] Xu, G., Bai, Y. H.. Application of follow-on acoustic logging in the evaluation of large displacement well cementing-an example of Pinghu oil and gas field in the East China Sea [J]. Offshore Petroleum,2016,36(4):77.

[14] Zhang Wandong,Li Changcheng. Theoretical and numerical simulation study on the quality evaluation of cementing wells by follow-on acoustic logging[J]. Journal of Geophysics, 2020, 63(7):2763- 2769.

[15] Zhang Hongbing, Qin Zhenggui, Shang Zuoping, et al. Amplitude characteristics of stratigraphic waves in the full wave train of cased well acoustic waves. Advances in Geophysics,2009,24(3):1006- 1012.