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Review

Analytical Perspectives on Cement Sheath Integrity: A Comprehensive Review of Theoretical Research

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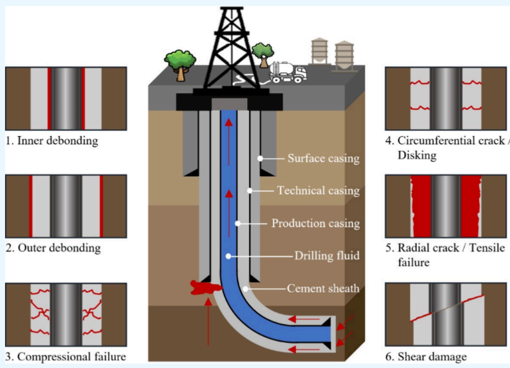
ABSTRACT: The cement sheath, serving as the primary element of well barriers, plays a crucial role in maintaining zonal isolation, protecting the casing from corrosion, and providing mechanical support. As the petroleum industry shifts from conventional to deep unconventional resources, the service environment for cement sheaths has become increasingly complex. High temperatures, high pressures, cyclic loading, and thermal stresses in downhole conditions have significantly increased the risk of cement sheath failure. A growing trend toward theoretical analysis of stress distribution, failure modes, and control mechanisms within the casing-cement sheath-formation system is evident. This paper comprehensively reviews theoretical research on cement sheath integrity from four key perspectives: (1) the concept of cement sheath integrity failure, (2) cement sheath constitutive models, (3) analytical models of the cement sheath-casing-formation system, and (4) numerical simulations of the cement sheath-casing-formation system. Through these discussions, this review provides profound insights into cement sheath integrity failure and offers valuable guidance for future research and practices.



1. INTRODUCTION

The petroleum industry is facing progressively scarce conventional resources, necessitating deeper drilling and operation in increasingly challenging conditions. The exploitation of deep and unconventional oil and gas resources presents complex working conditions, including high temperatures, pressures, strong alternating loads, and high temperature differential stress induced by hydraulic fracturing, staged fracturing, and large-scale production. Consequently, ensuring long-term well integrity throughout its lifecycle becomes even more crucial. The most widely accepted definition of well integrity is provided by NORSOK D-010,[1] which states that it involves the application of technical, operational, and organizational solutions to reduce the risk of uncontrolled release of formation fluids throughout the lifecycle of a well.

To control downhole fluids, appropriate barrier isolation must be established. The cement sheath, used in oil and gas wells since 1903,[2] can be considered the primary barrier to well integrity. After completing a stage of drilling and casing installation, cement slurry is injected into the annular space between the wellbore and casing, where it solidifies, forming a continuous and robust cement sheath. Failure to perform proper well cementing practices can lead to several problems, such as casing damage,[3] sustained casing pressure,[4] harmful gas and liquid leakage,[5,6] and wellhead lift.[7] These issues can severely impact well integrity and productivity.

The cement sheath plays an important role in maintaining zonal isolation, protecting the casing from corrosion, and providing mechanical support, all of which are crucial for well integrity. Preserving cement sheath integrity is indispensable for the secure and productive operation of oil and gas wells. Researchers and experts have been diligently studying the interaction of the casing-cement sheath-formation system in the downhole temperature and pressure environment, analyzing the failure mechanisms and dominant factors of cement sheath integrity, to find improvement measures and control methods. Important earlier summaries and compilations of cement sheath integrity can be found in refs 8−14.

This paper reviews the main developments in the field of cement sheath integrity, along with their implications and key findings. The paper is divided into four main sections: (1) concept of cement sheath integrity failure, (2) cement sheath constitutive model, (3) analytical model of cement sheath-casing-formation system, and (4) numerical simulation of cement sheath-casing-formation system. This review specifi-

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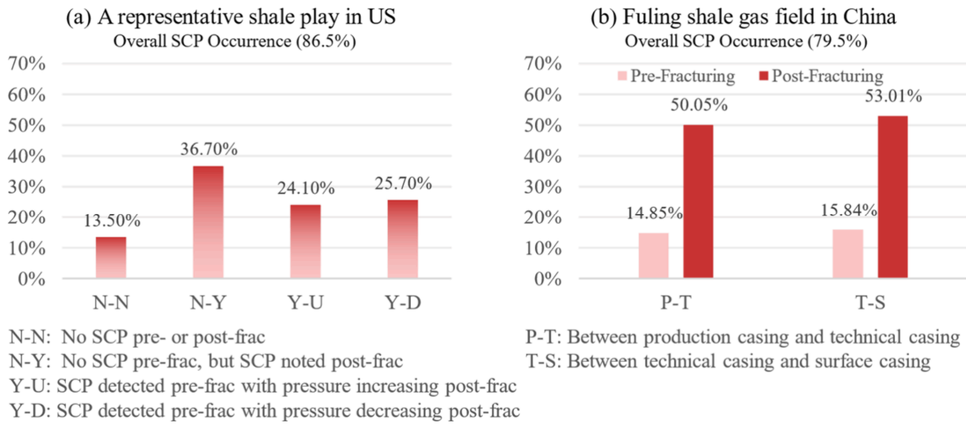

Figure 1. Overall occurrence of SCP in two shale plays in different regions.

cally addresses oil and gas well cement sheath integrity, providing practitioners with a comprehensive understanding of the latest research developments.

2. CONCEPT OF CEMENT SHEATH INTEGRITY FAILURE

2.1. Major Issues Related to Cement Sheath Failure.

Numerous significant incidents of oil and gas well blowouts or severe leaks worldwide have been linked to cement sheath integrity failures. On August 21, 2009, workers on the Montara wellhead platform off the northern coast of Western Australia observed a blowout of fluid coming from the H1 Well. The blowout caused the worst oil spill in Australia's offshore petroleum industry history.[15] The defective installation of a cemented shoe in the $9^5/_8$ inch casing of the H1 Well on March 7, 2009, was a direct and proximate cause of the blowout, resulting in a lack of integrity in the cemented shoe as a barrier.[16]

The most extensively publicized event is the Deepwater Horizon oil spill (also referred to as the "BP oil spill"), which began on April 20, 2010, off the coast of the United States in the Gulf of Mexico on the BP-operated Macondo Prospect.[17] It is recognized as the largest marine oil spill in the history of the petroleum industry. The main culprit was a poor cement job, which failed to prevent gas from escaping through the marine riser to the rig floor, where it subsequently ignited and exploded.[18]

On March 25, 2012, Well G4 on the Elgin wellhead platform in the U.K. Sector of the North Sea suffered an uncontrolled release of hydrocarbons into the atmosphere, estimated to be approximately 200 000 m^3 per day of natural gas.[19] While the failure of the production casing below its design pressure was the main cause of the accident, the failure of the cement sheath integrity also contributed to the worsening of the accident. A small crack exists in the cement sheath at the bottom of the B-annulus, allowing gas to migrate from the Chalk into the B-annulus itself.[20]

A natural gas well (ST A-3) blew out and caught fire on July 23, 2013, in the Gulf of Mexico. The report concluded that the ST A-3 well encountered higher-than-expected temperatures, which affected the completion fluid's density. As a result, the completion fluid did not effectively maintain the pressure balance in the well, which resulted in the flow of hydrocarbons into the well.[21]

The Aliso Canyon gas leak[22] in the United States was a massive natural gas leak discovered on October 23, 2015, potentially having a larger carbon footprint than the Deepwater Horizon oil spill. The primary cause of the spill was that well SS-25 was cemented only from the bottom up to a depth of 6600 feet, whereas modern wells are cemented from the surface to the reservoir. The rest—more than a mile of steel pipe—was left exposed to the rock formation. Gas was leaking through a hole in the 7-in. casing at 470 feet down to the bottom of the outer casing at 990 feet, and out through the rock to the surface.[23]

2.2. Investigation of Cement Sheath Integrity Failure.

One classic sign of cement sheath integrity failure is Sustained Casing Pressure (SCP), which can rebuild when bled down and manifest itself at the wellhead as irreducible casing pressure. A 2001 survey by the US Minerals Management Service (MMS) reported that 11 498 casing strings in 8122 Gulf of Mexico wells exhibited SCP. According to the MMS report in 2004, approximately 6650 wells had SCP, with 33% of them linked to leaking cement.[24] Data from offshore wells in the GOM[25] indicated that SCP issues increased with the age of the well. Wells older than 15 years had a barrier failure rate of 50% or higher.

As shown in Figure 1, data from shale plays in the U.S. and China were collected using different statistical methods. Combs et al.[26] collected and analyzed historical data on cementing, completion, and production operations that caused SCP in a representative shale area in the U.S. The analysis indicated that 86.5% of drilled wells manifested SCP to some degree. More than 30% of wells exhibited no SCP prefracturing but experienced SCP postfracturing. Xi et al.[27] indicated that the proportion of wells with SCP in the Fuling shale gas field in China is close to 80%. SCP issues significantly increased after multistage fracturing, reaching over 50%. There is no doubt that the integrity failure of the cement sheath is a serious issue.

2.3. Failure Modes of Cement Sheath Integrity.

The commercialization of hydraulic fracturing in the 1950s led to significant damage to the cement sheath due to fluctuations in wellbore pressure, prompting improvements in cementing practices.[28] Additionally, annular gas migration issues were recognized in the mid-1960s during cementing operations of gas wells.[29] Initial studies focused on gas migration during cement slurry displacement and curing, also known as gas channeling during cementing. At this stage, the main reasons for the failure of cement sheath integrity include:

(1) Drilling fluid retention due to poor displacement efficiency.[30]
(2) Poor cement bonding caused by mud cake.[31,32]

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Table 1. Possible Main Operations/Events during the Life of an Oil Well after Cement Placement[a]

operation/events	typical time of occurrence	typical duration	main affected property/load	range of variation/example value
cement hydration	start earlier	months	autogenous (bulk shrinkage)	volume reduction: 1−5%[49]
pressure testing	hours	hours	pressure	50 MPa in a 244 mm, 69.9 kg/m casing results in a strain in the casing-cement interface of 1.25 milli strains[50]
subsequent drilling	days	week	mechanical load (shock wave), pressure, temperature	drill string rotating at 100 rpm for 50 h pressure variation if the mud weight has been changed to drill the next section[51] temperature increases of the cased section when the mud, which has been heated by the formation being drilled, returns to the surface via the annulus[51]
well completion	weeks	weeks	pressure, temperature	pressure increase to values in excess of 40 MPa[51]
perforation	weeks	day	pressure, mechanical load (shock wave)	
hydraulic fracturing	years	day (*x* times)	pressure	differential pressure: (7−55) MPa[52,53] pressure increase is more damaging because the fluid injection lasts from minutes to hours[51]
hydrocarbon production	year	years	pressure, temperature	depends on production zone depth pressure and temperature fluctuation mainly concerns the near-surface casing sections[51]
fluid injection	years	months (*x* times)	pressure, temperature	steam injection: a temperature increase of 250 °C results in a strain in the cement sheath at the casing interface of 3.25 milli strains[50] injector well: max. P = 8 MPa; ΔT = 45 °C results in 420 pressure cycles from (0−8) MPa[54]
formation movement	decades	hours	mechanical load	dependent on formation creep-characteristics[55]

[a]Reproduced or adapted with permission from ref 48. Copyright 2017, Elsevier.

(3) Incomplete annular cementing job failing to reach the seal layer.[33]

(4) Interfacial microannulus caused by cement hydration shrinkage.[34]

(5) Channeling in the cement slurry.[35]

(6) Primary permeability in the cement sheath or cement plug.[36]

(7) Failure of the casing due to burst or collapse.[36]

The early gas channeling problem in cement slurry has been significantly mitigated through advancements in cementing technology, including dynamic cementing,[37] expanding cement,[38] self-healing cement,[39] etc. Significant improvements can be achieved in addressing the issue of strength retrogression in oil well cement due to high temperatures or corrosive environments by employing modified cement slurry systems. For example, Ahmed et al.[40,41] utilized nanoclay particles or olive waste to enhance the durability of the cement sheath in CO_2-rich environments. Subsequent study[42] also systematically evaluated the impact of silica content on the high-temperature mechanical properties of cement from slurry to set. Abdulmalek et al.[43] further explored the feasibility of using granite waste instead of silica in well cementing under high-temperature conditions.

Even after the cement sheath solidifies, its long-term integrity[44] can still be compromised during further drilling or production. Over the life of a well, changes in downhole conditions can generate stresses sufficient to compromise the integrity of the cement sheath.[45−47] Table 1 illustrates the typical working and stress conditions that the cement sheath may experience during its service.

Mechanical damage to the cement sheath results from significant increases in wellbore pressure (e.g., pressure testing, increased mud density, casing perforation, fracturing, production), elevated wellbore temperatures (e.g., geothermal production, water injection, HT/HP wells), or formation loading (e.g., creep, faulting, compaction). Major failure modes of cement sheath integrity, as shown in Figure 2, can be categorized as follows:

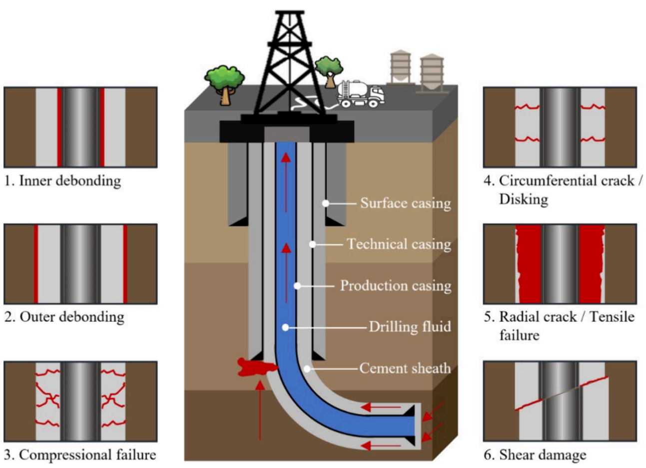

Figure 2. Major modes of cement sheath integrity failure.

(1) Inner debonding occurs due to casing contraction during heat/pressure cycling, causing the cement sheath to fail to follow casing deformations.

(2) Outer debonding occurs when the casing pulls inward, weakening the hydraulic bond between the cement sheath and the formation.

(3) Compression failure occurs when the cement matrix is crushed. The inner casing, under strong confinement from the formation or outer casing, pushes outward on the cement sheath, resulting in compressive stress exceeding the cement's compressive strength.

(4) Circumferential cracking or disking occurs due to axial contraction of the cement sheath when the effective vertical stress is lower than the cement's tensile strength.

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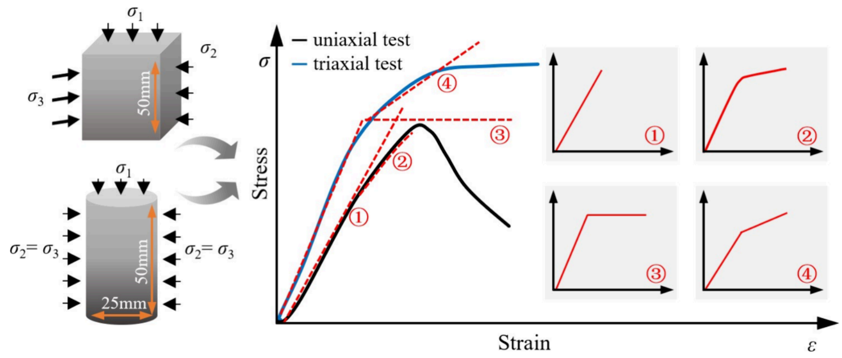

Figure 3. Cement stone compressive strength test and common constitutive model: ϕ, linear elasticity; κ, nonlinear elasticity; λ, ideal plasticity; and μ, strain hardening plasticity.

(5) Radial cracking or tensile failure results from high tensile stresses on the cement sheath due to the casing pushing outward with minimal confinement by the formation.

(6) Shear damage occurs when the cement sheath is subjected to a large deviatoric state of stress, often caused by casing damage or formation slips.

3. EVOLUTION OF THE CEMENT STONE CONSTITUTIVE MODEL

3.1. Stress−Strain Relationship of Cement Stone.

Research on cement sheath integrity after cementing begins with establishing a mechanical model. Mechanical models are essential tools for improving researchers' understanding of the fundamental aspects of the issue and the core problems to address. Analyzing critical factors, relationships between variables, and the interplay of various influencing factors provides profound insight into the problem's essence, offering a more precise purpose and direction for problem resolution.

On the basis of the cement constitutive model, the interaction between the cement sheath, casing, and formation rock is established, forming a mechanical model for the casing-cement sheath-formation system. The model considers downhole conditions and various operational scenarios, using mechanical calculations to assess the cement sheath's sealing performance. Thus, understanding the constitutive relationship of the cement sheath is fundamental to establishing a cement sheath integrity calculation model. Constitutive relationships depict the stress−strain relationship in the cement sheath, constructed based on its mechanical properties.

The stress−strain curves of uniaxial and triaxial tests for cement stone are depicted in the Figure 3. Cement stone specimens are either cubic with a side length of 50 mm or cylindrical with a height-to-diameter ratio ranging from 1.8 to 2.2.[56,57] Cement stone exhibits brittle behavior under unconfined conditions.[58,59] When stressed below the yield strength, approximately 0.7 times the compressive strength, cement stone undergoes elastic deformation, fully recovering after unloading, resulting in an approximately linear stress−strain curve. However, when stresses exceed the yield strength, the stress−strain curve deviates from linearity, exhibiting nonlinear characteristics. Thus, the linear elasticity model based on Hooke's law can describe the uniaxial behavior of cement stone, serving as the simplest constitutive model for it. In the linear elasticity model, cement stone is linearly elastic until it reaches its ultimate strength, beyond which it fails in a brittle manner. This simple linear elasticity model is effective under conditions of low stress and small deformation.

Cement stone is pressure-sensitive, and its overall strain response under loading is highly nonlinear and nonelastic, particularly under multiaxial stress conditions. The linear elasticity model is inadequate in such scenarios. To accurately describe the stress−strain relationship, a nonlinear elasticity constitutive model is required.[60] The primary difference between the linear elasticity and nonlinear elasticity models lies in the nonlinear stress−strain relationship observed within the elastic regime.

It is important to emphasize that cement stone experiences significantly increased ultimate strains and strengths when subjected to confinement in wellbore conditions. The stress−strain behavior of cement stone exhibits pronounced nonlinearity and ductility under these circumstances, which differs markedly from unconfined cement stone. Specifically, plastic deformation in cement stone induced by loading is not fully recoverable after unloading. An elastic stress−strain model cannot accurately capture the plastic behavior of cement stone. Plastic constitutive models are employed to represent the stress−strain relationship, explaining the presence of nonlinearity and irrecoverable strains in cement stone. A simplified constitutive model is the ideal plasticity model, which demonstrates that cement stone exhibits elastic behavior at stresses below the yield strength. Beyond the yield strength of cement stone, additional increases in strain do not result in further stress increments. Furthermore, to account for the phenomenon of increasing strength with increasing confinement, strain-hardening plasticity models are developed based on the ideal plasticity model.

Advancements in testing instruments have facilitated a deeper understanding of the stress−strain relationship of cement stone, resulting in a shift in constitutive models from linear elasticity to elastic-plasticity. As research has progressed, increasingly complex models have been proposed, such as viscoelastic-plastic models, continuum damage mechanics models, micromechanical models, and others. Using the constitutive models for cement stone, stress−strain computational models for the casing-cement sheath-formation system can be developed to analyze the integrity of the cement sheath. Such analysis can be conducted from both analytical and numerical perspectives.

3.2. Theoretical Model of Casing-Cement Sheath-Formation System.

Assuming a centered casing configuration, the stress model for the casing-cement-formation system can be treated as an axisymmetric problem. As illustrated in Figure 4(a), the hollow cylinder represents each ring of material: the casing, the cement sheath (second ring),

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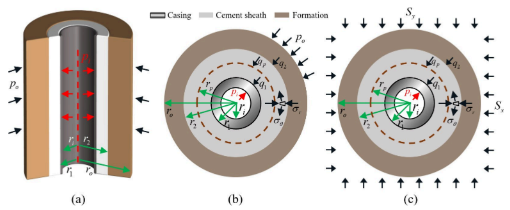

Figure 4. Schematic diagram of casing-cement sheath-formation system: (a) casing-cement sheath-formation system, (b) stress distribution for equal horizontal far-field in situ stress state, and (c) stress distribution for unequal horizontal far-field in situ stress state. (r_i, casing inner radius; r_1, cement sheath inner radius; r_2, cement sheath outer radius; r_o, formation outer radius; r_p, plastic yield radius of the cement sheath; P_i, internal pressure; P_o, external pressure; q_1 and q_2, radial stresses of the inner and outer walls of the cement sheath; q_p, force between the elastic-plastic interface of the cement sheath; and S_x and S_y: far-field in situ stress components).

and the outermost ring representing the formation with a larger radius. Under the conditions of radial displacement and radial stress continuity at the interfaces between the two materials, a complete analytical solution can be constructed. The inner ring representing the casing experiences a radial stress, denoted as P_i, induced by variations in wellbore pressure. The outer ring represents the formation and is subjected to a radial stress condition at its outer surface, denoted as the far-field stress P_o. Since the length of the wellbore is significantly greater than the cross-sectional dimensions, end effects are typically neglected in the development of the analytical model, resulting in a generalized plane strain state within the system.

In the simplest model, it is also assumed that both the formation and cement sheath are isotropic and pore-free. Furthermore, the formation stress is considered two-dimensional and time-independent, and in the horizontal plane, all directions are principal directions, with no shear stresses (Figure 4(b)).

For linear elastic isotropic materials, the stresses induced by wellbore pressure will be both radial and tangential. Radial stress acts outward perpendicular to the wellbore axis, while tangential stress acts perpendicular to the radial stress direction. Tangential stress is sometimes referred to as "circumferential stress". Radial stress is typically compressive, while tangential stress is usually tensile. However, in certain situations, radial stress can be tensile, and tangential stress can be compressive. Generally, in the casing-cement sheath-formation system subjected to increasing wellbore pressure, the highest radial and tangential stresses will occur at the casing-cement sheath interface.[61]

In reality, the isotropy of the cement sheath is not as perfect as that of the casing, due to mud channels, fluid flow damage zones, or other defects. The isotropy of the formation remains relatively poor, and horizontal stresses (displacements) may not be equal (Figure 4(c)). Further complicating the modeling is the presence of plastic zones in the cement sheath, which undergo plastic deformation once they yield. Typically, plastic deformation of the cement sheath is the primary consideration in modeling, with the casing and formation treated as elastic materials.

4. ANALYTICAL MODELS OF CASING-CEMENT SHEATH-FORMATION SYSTEM

4.1. Elasticity Model. As early as 1962, Zinkham and Goodwin[62] derived stress models for the casing-cement-formation system under both unconstrained and constrained conditions based on thin-walled and thick-walled cylinder theories. Their analytical models could calculate the displacements of the formation and cement sheath under wellbore pressure. Research demonstrated that when the casing and formation are well-bonded at the bottom of the well, the cement sheath can provide significant support to the wellbore.

In 1997, Thiercelin et al.[51] considered the integrity damage of the cement sheath as a function of downhole conditions and downhole geometry. Therefore, assuming that the casing, cement, and formation are homogeneous, isotropic, and linear elastic materials, they established an axisymmetric stress model for the casing-cement sheath-formation system, considering the effects of temperature. Three criteria were used to characterize cement sheath integrity failure: tensile failure, shear failure (Mohr-Coulomb criterion), and debonding.

Subsequently, numerous scholars, based on the principles of elasticity and thermal stress theory, continued to improve and enhance stress models for the casing-cement sheath-formation system, considering factors that better represent field operations. Most models are derived from wellbore parameters using Lame's equation based on thin-walled and thick-walled cylinder theories, but specific research focuses vary.

Mueller et al.[61] approximated the Young's modulus and Poisson's ratio of cement in tension using compression-derived values and corrected the bilinear elasticity model. A simple linear elasticity model was used to predict the magnitude of tensile or compressive forces resulting from changes in wellbore or reservoir conditions. The author discussed how nonuniform stress and material plasticity may affect the stress model of the casing-cement sheath-formation system, providing directions for further research.

Yin et al.[63] decomposed nonuniform stress into uniform stress and deviatoric stress components and solved them separately using elastic mechanics methods. The displacement field, stress field, and casing load under nonuniform stress conditions for the casing-formation system were obtained by superimposing these theoretical solutions.

Saint-Marc et al.[64] argued that the mechanical model of the casing-cement sheath-formation system should account for the effects of initial stresses. Effective stress initial conditions were shown to evolve over time due to cement hydration downhole, resulting in the final stress state being a combination of the initial state and additional stresses generated during operations.

Li Jing et al.[65] analyzed the radial distribution of thermal stress and thermal displacement of the casing-cement sheath-formation system based on the theory of elasticity and thermodynamics. The study found that the maximum Von Mises thermal stress occurs at the inner wall of the casing, the maximum radial compressive stress occurs at the outer wall of the casing, and the maximum radial thermal displacement occurs within the formation.

Teodoriu et al.[66] treated the casing as a thin-walled cylinder, the cement sheath and formation as thick-walled cylinders, and developed stress models for the integrity of three cement slurry systems under different wellbore and formation pressures. The research indicated that under static loads, ductile cement (with a low Young's modulus and high Poisson's ratio) exhibits lower

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tangential and radial stress values compared to brittle cement systems (characterized by high Young's modulus and low Poisson's ratio), highlighting the importance of cement properties.

Li et al.[67] comprehensively considered the influence of the nonuniform in situ stress field, temperature field, and pressure field in the casing, and analyzed the magnitude and distribution of the cement sheath stress under the nonuniform in situ stress, taking into account the pressure change in the casing. The study showed that nonuniform stress induces shear stress in the cement sheath, which gradually decreases away from the wellbore. Shear failure can occur when shear stress exceeds the cement sheath's capacity, but tensile failure does not.

Haider et al.[68] developed a stress model for the casing-cement sheath-formation system in CO_2 geological storage wells. The study emphasized that the stress state resulting from a decrease in wellbore pressure is more critical than that from an increase in pressure. Cement with a lower Young's modulus experiences lower tensile stresses, suggesting that ductile cement may be a general solution for initial well cementing.

Binh et al.[69] proposed a mathematical model to predict cement sheath failure in an anisotropic stress field. The model combined the effects of temperature, stress variations around the wellbore, internal pressure, and the integrity of the casing, cement sheath, and formation. The research showed that cement sheath failure is more severe in a highly anisotropic stress field than in an isotropic one.

Xu et al.[70] directly incorporated temperature load terms into the analytical model to analyze the impact of wellhead casing pressure (WHCP) on cement sheath integrity. The results indicated that as the WHCP increases, the safety factor decreases, and the influence of wellbore temperature variation becomes less significant. If the WHCP is less than 40 MPa, then the effect of wellbore temperature should not be ignored.

Li et al.[71] investigated the influence of cement sheath and formation stiffness on cement sheath sealing capacity based on anisotropic stress. The cement sheath/formation stiffness ratio was used to describe the impact of formation stiffness on cement sheath sealing. The assessment of cement sheath integrity in shale and sandstone formations involved in CO_2 injection wells suggested that cement sheaths placed in shale formations exhibit higher sealing capacity than those in sandstone formations.

Zhang et al.[72] studied the effect of annulus pressure on cement sheath bond interface stress and failure in high-temperature and high-pressure gas wells. Using elastic mechanics and the Mohr-Coulomb failure criterion, a stress and failure calculation model for the cement sheath was developed. The study indicated that annulus pressure-induced radial tensile stress in the cement sheath is a primary factor leading to cement sheath failure. Increasing wellbore temperature results in radial tensile stress and radial compressive stress, exacerbating the risk of cement sheath sealing failure.

Li et al.[73] improved the model established in 2015, considering the effects of the cement sheath-induced stress and formation pressure on the casing-cement sheath-formation system stress model. The research suggested that neglecting cement sheath-induced stress may underestimate maximum annulus injection pressure. The CO_2 injection pressure can be increased, but it should not exceed formation pressure significantly.

Zhang and Wang[74] developed a cement sheath safety factor calculation model that considered the influence of thermal expansion annulus pressure. The study found that increased thermal expansion annulus pressure could significantly reduce the safety factor of the cement sheath and expand the regions of cement sheath failure. When the thermal expansion coefficients of the casing, cement sheath, and formation are equal, the cement sheath's safety factor is maximized.

Liu et al.[75] developed an analytical model that considers the well completion steps to study the integrity of the cement sheath in double-string casing-cement sheath systems. The study suggested that tensile stresses generated by high fluid pressure inside the casing during hydraulic fracturing operations could be a primary cause of sustained casing pressure.

Liu et al.[76] further investigated the integrity of the cement sheath in different well types and developed a stress model for the casing-cement sheath-formation system under eccentric casing conditions using a bipolar coordinate system. The research indicated that casing eccentricity can lead to a significant increase in stress within the cement sheath, with circumferential stresses on the narrow side potentially being 2.5 times higher than on the thick side. Additionally, casing eccentricity has a minimal effect on radial stress within the cement sheath but significantly increases shear stress.

Deng et al.[77] considered the impact of interface failure on casing stress under nonuniform stress and developed a mechanical model for the casing-cement sheath-formation system. The model accounted for failure interfaces with micro annulus using smooth contact boundary conditions and interfaces without micro annulus using ideal perfectly bonded boundary conditions. The study revealed highly nonuniform radial and shear stress distributions in the cement sheath under nonuniform stress, potentially leading to casing debonding and shear failure.

Meng et al.[78] treated the cement sheath as a porous elastic material, considering initial stress states and pore pressure. A transient thermal poroelasticity model for the casing-cement sheath-formation system was proposed. The research showed that temperature disturbances are more critical than pressure disturbances in inducing significant pore pressure changes. Slowing down the heating/cooling rate can prevent damage to the cement sheath.

Wu et al.[79] set the initial stress state of the cement sheath as hydrostatic pressure and developed a mechanical integrity analysis model for the casing-cement sheath-formation system. Using continuum mechanics theory, a statistical damage variable was introduced to describe the mechanical integrity failure of the cement sheath. The research indicated that the damage variable is highly correlated with wellbore pressure. Under the operational conditions faced by the oil well casing-cement sheath-formation system, the primary failure mode of the cement sheath is the development of micro annulus due to casing contraction.

Yu et al.[80] considering the formation stress as stress boundary and initial stress field conditions, and with fixed far-field displacement boundaries in the formation, derived stress correction solutions for the casing-cement sheath-formation system under directional well conditions using the method of undetermined coefficients. The research revealed that as the formation's elastic modulus decreases and the elastic modulus and Poisson's ratio of the cement sheath increase, the radial and circumferential compressive stresses on both the casing and the cement sheath increase, while the tensile stresses on the inner wall of the cement sheath decrease.

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However, when the internal pressure within the casing is relatively high, an increase in the elastic modulus of the cement sheath leads to higher tensile circumferential stresses at the cement sheath, resulting in an increased risk of tensile failure in the cement sheath.

4.2. Elastic-Plasticity Model. The stress models based on linear elasticity theory often overlook neglect the occurrence of plastic deformation in the cement sheath under continuous variations in casing pressure and temperature. In reality, fluctuations in temperature and pressure within the wellbore subject the cement sheath to continuous stress loading and unloading cycles. During loading, the cement sheath is susceptible to plastic deformation, while during unloading, it forms micro annulus at interfaces. Therefore, to accurately portray stress, displacement, and micro annulus in the cement sheath under continuous loading and unloading conditions, it is imperative to incorporate elastic-plasticity analysis into the stress model of the casing-cement sheath-formation system.

Li et al.[81] drawing upon the multilayer composite thick-walled cylinder theory, initially developed a stress model for the casing-cement sheath-formation system under elastic-plasticity conditions. The analysis encompassed various system states, ranging from linear elasticity to complete plasticity, which advocated for the cement sheath possessing high strength and low stiffness as ideal properties.

Chen and Cai[82] offered analytical solutions for displacement and stress distribution in the elastic-plastic region of a thick-walled cylinder under internal and external pressures. Focusing more on casing loads, the authors derived analytical expressions separately for cases where only the formation or only the casing enters plasticity.

Chu et al.[83] considered the cement sheath's plastic behavior and bonding strength at two interfaces, establishing a stress model to analyze micro annulus initiation and development (casing-cement sheath interface and cement sheath-formation interface). Their study suggested that loading processes could induce plastic deformation in the cement sheath. During unloading, the radial stress at the interfaces transitions to tensile stress. Micro annulus may appear at the two interfaces, especially at the casing-cement sheath interface if their bonding strengths are comparable and the tensile stress surpasses the bonding strength.

Zhang et al.[84] treated the casing as thermoelastic, the cement sheath as elastic-plastic, and the formation as porous elastic, developing a stress model for casing-cement sheath-formation interaction and micro annulus under continuous loading and unloading. The study suggested that during the unloading of casing pressure, if there is low far-field formation stress, then the radial contact stress can easily transition from compression to tension, leading to interface debonding.

In 2018, Zhang et al.[85] simplified their prior stress model by treating the cement sheath as elastic-plastic and the casing and formation as elastic materials, omitting temperature effects. Mechanical parameters and radial formation stress were identified as key factors affecting the stress and failure of the cement sheath. Cement sheath with high Young's modulus and low Poisson's ratio exhibited susceptibility to plastic deformation and micro annulus formation.

Zhao et al.[86] integrated drilling, cementing, and fracturing operations to evaluate the impact of initial wellbore stress states, cement sheath plastic deformation, and wellbore temperature changes. A phased stress model for the casing-cement sheath-formation system was established. The study suggested that tensile failure is more likely to occur on the inner surface of the cement sheath, and thicker cement sheath increase the risk of tensile failure. Extremely low elastic modulus and thermal conductivity of the cement sheath contribute to its integrity.

Bu et al.[87] compared the support provided by the cement sheath to tunnel rock support and applied the convergence-confinement theory commonly used in tunnel and support structure design to evaluate cement sheath integrity. Convergence-confinement curves and cement sheath integrity assessment methods were developed to determine shear failure, tensile failure, and the generation of micro annulus at the casing-cement sheath interface.

Su et al.[88] investigated the effects of differential temperature stresses on the debonding of cement sheath interfaces under acid-fracturing pressures and developed a novel elastic-plasticity mechanical model for the cement sheath. The study indicated that under acid-fracturing pressures, the casing-cement sheath interface is influenced by differential temperature stresses, which leads to interface debonding, but does not form micro annulus. After acid-fracturing, the interface between the casing and cement sheath is prone to form micro annulus, and the presence of differential temperature stresses may increase the risk of interface micro annulus.

Xu et al.[89] defined the stress state of the cement sheath formed by cement slurry solidification as the initial stress and established a mechanical model for the casing-cement sheath-formation system based on elastic-plasticity theory, considering the initial stress state of the cement sheath. A damage coefficient, defined as the ratio of the plastic zone area of the cement sheath to the total area, was used to describe the damage and failure characteristics of the cement sheath as the internal casing pressure increased. The study indicated that the smaller the internal casing pressure that induces plastic deformation in the cement sheath, the more likely the cement sheath is to be damaged. A smaller initial stress in the cement sheath results in earlier failure, with the damage factor increasing more rapidly.

Zhang et al.[90] developed an elastic-plasticity stress model for the casing-cement sheath-formation system and analyzed the safe load (critical load) of the cement sheath under cyclic loading using stability theory. The study revealed that the critical load is the smaller of the yield load during loading and the yield load during unloading. It also showed a linear relationship with external pressure. When the depth is considerable, the cement sheath often undergoes yielding during unloading.

Zhang et al.[91] further discussed the influence of nonuniform stress on the critical load of the cement sheath based on research on cyclic loading. They employed a trial method to find a stress function with certain accuracy, ensuring the satisfaction of the deformation compatibility equation. The study indicated that nonuniform stress has a significant impact on the load-bearing capacity of the cement sheath, and higher external pressures are favorable for reducing the adverse effects of nonuniform stress.

In summary, the analytical studies for the casing-cement sheath-formation system are organized by year in Table 2. These analytical models provide valuable insights into the behavior of casing-cement sheath-formation systems under various conditions. Elasticity models focus on stress distribution and integrity factors, while elastic-plasticity models consider plastic deformation and micro annulus. Both types

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Table 2. Analytical Model Studies for the Casing-Cement Sheath-Formation System Organized by Year

year	author	casing	cement sheath	formation	in-situ stress	temperature	focus	key findings
1962	Zinkham	elasticity	elasticity	elasticity	uniform	no	constraint pressure	Cement sheath can provide significant support to the wellbore when the casing and formation are well-bonded.
1997	Thiercelin	elasticity	elasticity	elasticity	uniform	yes	temperature and pressure increase and decrease	Cement debonding or cement cracking is a function of the nature of the downhole condition variations.
2004	Mueller Dan T.	elasticity	elasticity	elasticity	uniform	no	pressure increase and decrease	Stress modeling can be used to predict the magnitude and location of the maximum stress imposed on a cemented annulus due to postcementing well activities.
2005	Li Jun	elastic-plasticity	elastic-plasticity	elastic-plasticity	uniform	no	linear elastic and fully plastic states	The ideal properties of the cement sheath include high strength and low stiffness.
2006	Yin You-quan	elasticity	null	elasticity	nonuniform	no	nonuniform in situ stress	The long axis of the casing pressure figure directs to the minimum principal compression stress.
2008	Saint-Marc	elasticity	elasticity	elasticity	uniform	no	initial stress	The final state of stress is the consequence of the initial state plus additional stresses from operations.
2009	Li Jing	elasticity	elasticity	elasticity	uniform	yes	thermal stress and affecting factors	The radial displacement and stress first increase and then decrease with the radial distance increasing from casing center, and the maximum values are located on formation and casing external wall, respectively.
2009	Chen Chaowei	elastic-plasticity	null	elastic-plasticity	uniform	no	casing load calculation	When formation is in plasticity, casing load is larger than that of elastic solution.
2010	Teodoriu	elasticity	elasticity	elasticity	uniform	yes	static load calculation for three systems	Under static loads, ductile cement exhibits lower tangential and radial stress values compared to brittle cement systems. when casing is in plasticity, casing load is less than that of elastic solution.
2010	Li Yong	elasticity	elasticity	elasticity	nonuniform	yes	increase in internal pressure and temperature	Nonuniform stress induces shear stress in the cement sheath, which gradually decreases away from the wellbore.
2012	Haider	elasticity	elasticity	elasticity	uniform	yes	temperature and pressure increase and decrease	Cement with a lower Young's modulus experiences lower tensile stresses.
2013	Binh T. Bui	elasticity	elasticity	elasticity	nonuniform	yes	borehole inclination, azimuth and anisotropic stress field	Cement sheath failure depends strongly on the in situ stress field of the surrounding formation. With stronger uniform formation support, the casing and cement can withstand larger internal stress.
2015	Xu Honglin	elasticity	elasticity	elasticity	uniform	yes	wellhead casing pressure	As the wellhead casing pressure increases, the safety factor decreases, and the influence of wellbore temperature variation becomes less significant.
2015	Chu Wei	elasticity	elastic-plasticity	elasticity	uniform	no	micro annulus size	Loading processes could lead to plastic deformation in the cement sheath. The radial stress at the interfaces turns into tensile stress during the unloading process. Micro annulus could appear at both interfaces if the tensile stress exceeds the corresponding bonding strengths.
2015	Li Ben	elasticity	elasticity	elasticity	nonuniform	no	maximum allowable injection pressure for CO_2	Young's modulus of cement sheath is identified as a major factor that affects the sealing ability of cement sheath.
2016	Zhang Zhi	elasticity	elasticity	elasticity	uniform	yes	sustained casing pressure and temperature increases	Annulus pressure-induced radial tensile stress in the cement sheath is a primary factor leading to cement sheath failure.
2017	Zhang Hong	elasticity	elastic-plasticity	pore-elasticity	uniform	yes	casing pressure increase and decrease and micro annulus generation	When loading casing pressure, the radial contact stress on the bonding surfaces increases nonlinearly and cement sheath may deform plastically.
2017	Li Ben	elasticity	elasticity	elasticity	nonuniform	no	cement sheath induced stress and maximum annulus injection pressure	The CO_2 injection pressure can be increased, but it should not exceed formation pressure significantly.
2017	Zhang Zhi	elasticity	elasticity	elasticity	uniform	yes	thermal expansion annular pressure	Increased thermal expansion annulus pressure could significantly reduce the safety factor of the cement sheath and expand the regions of cement sheath failure.
2018	Liu Kui	elasticity	elasticity	elasticity	uniform	yes	double casing and completion steps	Tensile failure more likely occurs at the inner face of the cement sheath in the intermediate casing. The casing thickness is in favor of decreasing the tensile stress in the cement sheath.
2018	Zhang Hong	elasticity	elastic-plasticity	elasticity	uniform	no	casing pressure increase and decrease and micro annulus generation	When unloading casing pressure, if low far-field in situ stress exists, the radial contact stress may transform from compression to tension leading to the separation of bonding surfaces.
2018	Liu Kui	elasticity	elasticity	elasticity	uniform	no	casing eccentricity	Casing eccentricity can lead to a significant increase in stress within the cement sheath.
2019	Zhao Chao-jie	elasticity	elastic-plasticity	elasticity	uniform	yes	continuous operation	Tensile failure is more likely to occur on the inner surface of the cement sheath, and thicker cement sheath increase the risk of tensile failure.

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Table 2. continued

year	author	casing	cement sheath	formation	in-situ stress	temperature	focus	key findings
2020	Bu Yuhuan	elasticity	elastic-plasticity	elastic-plasticity	uniform	no	convergence-constraint curves	The tensile strength required to maintain the integrity of the cement sheath at the cement sheath-formation interface increases with increasing internal casing pressure.
2020	Deng Kuanhai	elasticity	elasticity	elasticity	nonuniform	no	influence of micro annulus on casing stresses	Under the action of nonuniform in situ stress, the radial and shear stress distribution of the cement sheath cross-section is extremely nonuniform.
2021	Meng Meng	elasticity	poroelastic	poroelasticity	uniform	yes	safe operating pressure and temperature	Slowing down the heating/cooling rate can prevent damage to the cement sheath.
2022	Su Dong-hua	elasticity	elastic-plasticity	elasticity	uniform	yes	cooling effects of the acid fracturing	Cement sheath-formation interface debonding and micro annulus occur only when the cement sheath is fully plasticized.
2022	Xu Feng	elasticity	elastic-plasticity	elasticity	uniform	no	initial stress and damage factor	The lower the initial stress in the cement sheath, the earlier the damage occurs and the faster the damage factor increases.
2022	Zhang Xiaoyu	elasticity	elastic-plasticity	elasticity	uniform	no	critical load under cyclic loading	The critical load is the smaller of the yield load during loading and the yield load during unloading.
2022	Zhang Xiaoyu	elasticity	elastic-plasticity	elasticity	nonuniform	no	asymmetrical stress	Higher external pressures are favorable for reducing the adverse effects of nonuniform stress.
2023	Wu Xuning	elasticity	elasticity	elasticity	uniform	no	statistical damage variable	The primary failure mode of the cement sheath is the development of micro annulus due to casing contraction.
2023	Yu Guimin	elasticity	elasticity	elasticity	nonuniform	no	stratigraphic far-field displacement perturbation	When the pressure inside the casing is high, the higher the elastic modulus of the cement sheath, the higher the tensile circumferential stress at the cement sheath.

of models emphasize the importance of material properties, temperature, pressure changes, and initial stresses in assessing cement sheath integrity. In general, the elasticity model explores the behavior of the casing-cement sheath-formation system under the assumption of linear elasticity. It began in the early 1960s and has evolved over the years with multiple scholars contributing to this field. Key findings include the importance of cement properties, effects of nonuniform stresses, and considerations of temperature on cement sheath integrity. The elastic-plasticity model builds upon the elasticity model but acknowledges the plastic deformation occurring in the cement sheath due to continuous pressure and temperature variations. It examines the occurrence of micro annulus during loading and unloading cycles. Researchers in this area have explored factors such as casing loads, plastic behavior of the cement sheath, and the initiation of micro annulus.

5. NUMERICAL SIMULATION OF CASING-CEMENT SHEATH-FORMATION SYSTEM

Excessive assumptions and simplifications in analytical models can lead to deviations from real-world conditions. For instance, two-dimensional models fail to capture failure modes in all directions, and it is challenging to address material or stress nonuniformity adequately. Numerical modeling offers significant advantages in many aspects, allowing consideration of material nonlinearity, complex geometric shapes, varying boundary conditions, and in situ stress conditions. With the widespread adoption of finite element numerical simulation techniques, scholars can integrate mathematical theories of solid mechanics, including elasticity, plasticity, poroelasticity, viscoelasticity, and complex constitutive models, along with failure theories of wellbore components.

Significant progress has been made in developing robust nonlinear finite element methods, especially in conducting finite element analyses of wells using phased approaches, enabling the examination of both short-term and long-term behaviors of the wellbore cement sheath. Phased modeling approaches mimic the construction of wells, following all or part of the development stages. Using finite element methods, the stress states for each stage are modeled, and damage metrics, plasticity, and other state variables, as well as loads and boundary conditions, are transferred to subsequent stage models. These models are primarily solved using software such as DIANA, ABAQUS, ANSYS, and FLAC 3D to analyze the integrity of cement sheath.

5.1. Casing Load and Thermal Stress.

Bosma[92] employed nonlinear mechanics to develop finite element models of the casing-cement sheath-formation system in DIANA software. Initially, he conducted drilling stability analysis to assess wellbore conditions, followed by an evaluation of cement sheath integrity during subsequent well operations. The study unveiled that with rising casing temperatures, circumferential stresses near the casing-cement sheath interface become compressive, while those near the cement sheath-formation interface turn tensile. Generally, if the Young's modulus of the sealing material surpasses that of the formation, then the sealing material is more prone to fail due to tensile cracking as casing pressure/temperature escalates.

Philippacopoulos and Berndt[93] examined the transient thermal-elasticity responses of various cements using finite element modeling to comprehend stress variations with time and location. The study found that radial stresses remain

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predominantly compressive and are minimally affected by the duration of temperature changes. However, circumferential stresses (mostly tensile) appear to be more influenced by the duration of exposure. Fiber reinforcement can improve tensile strength and modify thermal properties.

Alexandre et al.[94] developed a finite element model of the casing-cement sheath-formation system to assess the long-term integrity of carbon dioxide injection wells, and numerically investigated the effect of pores on stress distribution under mechanical or thermal loads in the near-wellbore region. The study suggested that isolated voids and channels could serve as nucleation points for fracture under sufficiently high concentrations of thermally or mechanically induced stress during thermal or mechanical loading processes.

Wu et al.[95] considering the characteristics of geothermal wellbores, established a two-dimensional finite element model in ANSYS to analyze the impact of differential temperature, thermal conductivity, and thermal expansion coefficients on the stress distribution in cement sheath. The study showed that a reverse situation of heat transfer from formations to casings was more detrimental to cement integrity. Radial and circumferential stresses in cement sheath were more sensitive to temperature changes than internal pressure loads.

Sohrab et al.[96] employed a modified discrete element method to consider cement sheath and rock formations as porous media, analyzing radial fractures, shear failures, and interface debonding during pressurization/depressurization operations. Results indicated that casing pressure reduction led to casing-cement sheath interface debonding, while pressure increase potentially induced progressive shear and tensile failures in the cement sheath. Further casing pressure increases did not extend these failures into the rock formation; instead, it increased the number of radial cracks in the cement sheath.

Li et al.[97] created a 3D thermo-hydro-mechanical coupled model for the formation-cement sheath-casing system to investigate the impact of initial stress and shale anisotropy on cement sheath integrity. The results showed that, compared to Poisson's ratio anisotropy, Young's modulus anisotropy had a greater influence on cement sheath integrity. Due to the high Young's modulus anisotropy of shale, debonding between the cement sheath and formation occurred more easily.

Guo et al.[98] developed a finite element model based on transient heat conduction theory and the concrete damage plasticity model in ABAQUS. The study analyzed the damage state of cement sheath during temperature variation processes. The study indicated that elevated wellbore temperatures could result in tensile or compressive failure of the cement sheath. Decreases in wellbore temperature could cause debonding at the casing-cement sheath interface, directly resulting in gas channeling. The degree of cement damage also increased with higher rates of temperature change.

5.2. Cycling Temperature and Pressure. Zhou et al.[99] utilized ABAQUS software to simulate the elastic-plastic mechanical response of the casing-cement sheath-formation system, investigating the integrity of single or multilayer cement sheath under cyclic loading. The results suggested that in multistage hydraulic fracturing, shallow cement sheath was at risk of circumferential tensile failure, with the severity of tensile failure increasing with the number of fracturing stages. For deep formation cement sheath, there was a risk of plastic failure under compression, with cement sheath gradually entering a plastic yielding state with an increasing number of fracturing stages.

Yin et al.[100] introduced a fully coupled thermal stress model considering the cohesive behavior and thermal effects at the wellbore interfaces to predict the initiation and growth of micro annulus in the casing-cement sheath-formation system. The research indicated that, compared to pressure, temperature effects were the dominant factors influencing micro annulus occurrence and dimensions. The largest micro annulus occurred during the pressure drop after injection. Increasing tensile strength was not an effective method to prevent micro annulus. Properly distributing injection programs can eliminate micro annulus during injection/hydraulic fracturing operations.

Xi et al.[101] developed a numerical model for the combined wellbore with various segments in actual deep shale gas wells, calculating cumulative plastic strain patterns along the entire wellbore. The study revealed that, after a certain number of loading and unloading cycles, cumulative plastic strains increased with true vertical depth on vertical cross sections. On horizontal cross sections, cumulative plastic strains decreased with measurement depth.

Han et al.[102] proposed a thermal cycle plastic strain calculation model for cement sheath based on the residual strain theory and established a finite element model in ABAQUS to explore the occurrence of the cement sheath's plastic zone during high-temperature cycling processes. The research examined the interface debonding and micro annulus size induced by thermal stress cycling. Results indicated that tensile failure in cement sheath and micro annulus consistently occurred on the inner wall of the cement sheath, while the outer wall remained intact. The study established a method for matching injection steam temperature, cycle count, and cement sheath elastic modulus under different construction parameters.

Kao et al.[103] established a damage constitutive equation for cement sheath based on mechanical property tests and utilized FLAC 3D to simulate the damage characteristics of cement under reservoir conditions. The study revealed that cement sheath damage increased with the number of loading and unloading cycles, with most of the damage occurring in the first cycle. Reduction in pore pressure exacerbated the damage, especially at the boundaries between different formations.

Xi et al.[27] developed a nonlinear finite element model to analyze the plastic deformation characteristics of cement sheath under cyclic loading and unloading during multistage hydraulic fracturing. The research showed that with an increasing number of cycles, cumulative plastic deformation increased. Decreasing the elastic modulus, increasing the Poisson's ratio, cohesive strength, and internal friction angle were beneficial for protecting the integrity of the cement sheath.

He et al.[104] developed a theoretical model considering fatigue damage and plasticity to explore the failure mechanisms of wellbore cement sheath under the combined effects of plasticity and fatigue damage using ANSYS software. The study indicated that the coupling of plasticity and damage quickly led to interface failure in wellbore cement sheath. Under cyclic loading, fatigue damage, and plastic strain concentrated locally, primarily at the interface between the cement sheath and casing, making the inner bonding surface more susceptible to failure.

5.3. Cement Sheath Mechanical Performance. Restrepo et al.[105] utilized ANSYS to establish a plane strain

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model analyzing the impact of wellbore eccentricity on stress concentration in casings and cement. The study unveiled that poor concentricity could induce drilling fluid voids in cement, leading to casing failure during hydraulic fracturing operations. In a cement sheath with voids, the equivalent maximum stress in the casing and cement can increase three to four times compared to the concentric case.

Yang et al.[55] focused on cement sheath integrity in salt cavern gas storage and employed ABAQUS finite element software to simulate the influence of in situ stress and cement sheath elastic parameters under creep conditions. The study suggested that salt rock creep increased stresses acting on the cement sheath, leading to shear failure in the cement. A larger uniform horizontal in situ stress led to a shorter time period for shear failure of the cement sheath, larger equivalent plastic strain, and larger yield area. Lowering the elastic modulus of the cement sheath and increasing its Poisson's ratio reduced the risk of shear failure in salt rock formation.

Lian et al.[106] selected critical positions along the entire wellbore to focus on the cement sheath, constructing a stress and temperature coupled finite element model for the casing-cement sheath-formation system. The study investigated the stress state and integrity of B-annular cement sheath and analyzed the maximum production and wellhead pressure based on cement sheath integrity constraints. The research revealed that the greater the natural gas production, the greater the temperature fluctuations in cement sheath. Cement sheath close to the ground is at risk of tensile failure, potentially leading to circumferential tensile cracks. Cement sheath near the packer were susceptible to compressive failure, resulting in radial compressive cracks.

Elaheh et al.[107] investigated the mechanical failure of the cement sheath under casing eccentricity conditions using a concrete damage plasticity model. The interfaces between the cement sheath, casing, and rock formation were characterized using surface-based cohesive behavior. ABAQUS software was used to study the stress state, plastic deformation, and debonding within the cement sheath under different in situ stress directions and rock stiffness conditions. The results highlighted the dominant influence of eccentricity on stress distribution within the cement sheath, emphasizing the importance of centralizing the casing. Operating in a soft rock anisotropic in situ stress field posed a higher risk of fragmentation and cracking.

Gu et al.[108] constructed a finite element model to assess the integrity of cement interface seals throughout the well's lifecycle. Through comprehensive parameter analysis, the study investigated the effects of well trajectory, casing eccentricity, and cement sheath voids on cement sheath debonding. The research suggested that cement shrinkage was the primary factor leading to debonding at cement sheath interfaces. The size of micro annulus increased as casing internal pressure decreased. Greater casing eccentricity and larger cement sheath voids also resulted in larger micro annulus sizes.

5.4. Cement Sheath Interface Microannulus. Shahri et al.[109] investigated the cement sheath and casing interface bonding using finite element analysis to examine the stress distribution around and within the cement sheath under varying wellbore temperature and pressure conditions, aiming to predict cement sheath failure. The research suggested that temperature fluctuations could lead to unexpected behaviors in cement sheath, resulting in casing-cement sheath bond failures. In the case of eccentric casing, the cement sheath is more prone to radial fractures on the thicker side. Early cement failure may occur in high-temperature and high-pressure wells unless low-shrinkage cement is used.

Wu et al.[110] created a finite element model coupling stress and temperature effects for the casing-cement sheath-formation system in ANSYS. They investigated deformation and micro annulus occurrence mechanisms at wellbore interfaces during steam injection and shut-in stages. The research showed that significant thermal-mechanical coupling loads during steam injection led to wellbore elastic-plastic deformation, while micro annulus formed at wellbore interfaces during shut-in. Increasing the elastic modulus of casings, cement, and formations increased their plastic deformation during steam injection, subsequently enlarging micro annulus at the casing-cement sheath or cement sheath-formation interfaces.

Jarrett et al.[111] employed the softening traction-separation law to simulate debonding at the casing-cement sheath and cement sheath-formation interfaces. They modeled the pressure or temperature reductions necessary to initiate cement sheath debonding in ANSYS software, along with the resulting micro annulus width The results indicated the existence of a decreasing threshold at which micro annulus began to appear and enlarge. The size of the wellbore played a crucial role in micro annulus width.

Eissa et al.[112] developed a 3D numerical model in ABAQUS to investigate the impact of contact interface friction parameters and cement mechanical properties on cement sheath bonding. The study found that higher Young's modulus and lower Poisson's ratio, cohesive strength, and friction angle in the cement sheath resulted in larger plastic strains. An increase in frictional forces at the formation-cement sheath and cement sheath-casing contact surfaces was observed to reduce plastic strain of cement sheath.

Huan et al.[113] proposed a thermal-hydro-mechanical coupled model to examine effective stress accumulation and wellbore structural damage induced by cold water injection. The results indicated that changes in pore pressure and temperature during cold water injection gradually propagated effective stresses to the far field and compromised wellbore integrity. Radial tensile stresses concentrated at the casing-cement sheath interface, leading to cement sheath debonding.

He et al.[114] developed an anisotropic damage evolution model to characterize cement sheath failure in salt cavern gas storage wells. Using ANSYS software, the study analyzed cement sheath failure and predicted the occurrence of micro annulus and radial cracks in the wellbore. The research demonstrated that the anisotropic damage model improved the accuracy of predicting micro annulus and radial cracks by 50% compared to isotropic damage model.

5.5. Continuous Wellbore Loading and Different Operations. Ravi et al.[115] conducted finite element analysis to investigate how various operations affect the integrity of the cement sheath, formation, and casing. Simulated event sequences ranged from drilling and cement hydration to completion and production operations. The research indicated that the integrity of cement sheath is governed by its mechanical properties, formation characteristics, and well operation parameters. Volume changes during cement hydration should be evaluated under downhole conditions since this parameter affects cement sheath integrity over the well's life.

Table 3. Numerical Model Studies for the Casing-Cement Sheath-Formation System Organized by Year

year	researcher	sample structure and cement sheath size	dimension	constitutive theory	software	focus	key findings
1999	Bosma Martin	casing + cement sheath + formation ID: 178 mm OD: 216 mm	2D	nonlinear mechanics	DIANA	in-situ stress and multiple conditions	As casing temperatures increase, circumferential stresses near the casing-cement sheath interface are compressive, while those near the cement sheath-formation interface are tensile.
2002	Ravi K.	Casing + cement sheath + formation ID: 193.6 mm OD: 241.3 mm	2D	nonlinear elasticity	DIANA	multiple conditions	The integrity of cement sheath is governed by its mechanical properties, formation characteristics, and well operation parameters.
2002	Philippacopoulos A.J.	Casing + cement sheath + formation ID: 339.7 mm OD: 533.4 mm	2D	thermoelasticity	not mentioned	transient thermoelastic response of various cements	Radial stresses remain predominantly compressive and are minimally affected by the duration of temperature changes. Fiber reinforcement can enhance tensile strength and alter thermal properties.
2002	Pattillo P.D.	Casing + cement sheath + formation ID: 127 mm OD: 171.5 mm	2D	elasticity or ideal plasticity	ABAQUS	multiple phases of borehole drilling to production	A lack of effective cement sheath on a portion of the casing circumference accelerates stress concentrations within the casing.
2005	Shahri M.A.	Casing + cement sheath + formation ID: 127 mm OD: 152.4 mm	2D	elastic-plasticity	not mentioned	cement sheath-casing bonding and eccentric casing	Temperature fluctuations could lead to unexpected behaviors in cement sheath, resulting in casing-cement sheath bond failures. In the case of eccentric casing, the cement sheath is more prone to radial fractures on the thicker side.
2009	Gray K.E.	Casing + cement sheath + formation ID: 193.7 mm OD: 241.3 mm Height: 127 mm	3D	elastic-plasticity	ABAQUS	different material properties of rock formation	Interface micro annulus may or may not develop, depending on the extent of shrinkage.
2010	Jo H.	Casing + cement sheath + formation ID: 381 mm OD: 431.8 mmHeight: 127 mm	3D	poroelasticity	ABAQUS	inclined wellbore, temperature and pressure variations	As Young's modulus increases, the risk of shear failure decreases while the risk of tensile failure increases. Analytical models were consistently more conservative, reaching failure faster than numerical results.
2016	Andrade Jesus De	Casing + cement sheath + formation ID: 244.5 mm OD: 311.2 mm	2D	elasticity	ANSYS	temperature and pressure variations, casing centering	The key physical property influencing cement sheath failure mechanisms is the Young's modulus of both cement and the formation. Compared to heating conditions, cooling of the wellbore is more likely to lead to cement sheath damage.
2016	Alexandre Lavrov	Casing + cement sheath + formation ID: 340 mm OD: 380 mm	2D	elasticity	ABAQUS	voids under in situ stress or temperature variations	Isolated voids and channels could serve as nucleation points for fracture under sufficiently high concentrations of thermally or mechanically induced stress during thermal or mechanical loading processes.
2018	Fan Mingtao	Casing + cement sheath + formation ID: 139.7 mm OD: 215.9 mm	2D	elasticity	not mentioned	cyclic temperature and load	With increasing casing internal pressure, the circumferential tensile stresses in cement sheath exhibited an initial increase followed by a decrease.
2018	Elaheh Arjomand	Casing + cement sheath + formation ID: 193.7 mm OD: 215.9 mm Height: 127 mm	3D	plastic damage	ABAQUS	casing eccentricity, anisotropic in situ stress, rock stiffness	Casing centering facilitates cement sheath integrity. Cement sheath is at higher risk of mechanical failure in soft rock formations with anisotropic in situ stress fields.
2018	Kao Jiawei	Casing + cement sheath + formation ID: 250.8 mm OD: 311.2 mm Height: 10 m	3D	statistical damage	FLAC 3D	cyclic load, pore pressure	Cement sheath damage increased with the number of loading and unloading cycles, with most of the damage occurring in the first cycle.
2019	Zhou Shiming	Cement sheath ID: 139.7 mm OD: 227 mm	2D	elastic-plasticity	ABAQUS	multistage hydraulic fracturing	In multistage hydraulic fracturing, shallow cement sheath was at risk of circumferential tensile failure. For deep formation cement sheath, there was a risk of plastic failure under compression
2019	Yin Fei	Casing + cement sheath + formation ID: 139.7 mm OD: 215.9 mm	2D	linear elasticity traction-separation model	ABAQUS	micro annulus caused by casing pressure and temperature variations	Compared to pressure, temperature effects were the dominant factors influencing micro annulus occurrence and dimensions. The largest micro annulus occurred during the pressure drop after injection.
2020	Michael Mendez Restrepo	Casing + cement sheath + formation ID: 139.7 mm OD: 168.2 mm	2D	anisotropic elasticity	ANSYS	casing eccentricity, cement void	Poor concentricity could lead to the appearance of drilling fluid voids in cement, resulting in casing failure during hydraulic fracturing operations.
2020	Xi Yan	Casing + cement sheath + formation ID: 127 mm OD: 168.28 mm Height: 3 m	3D	elastic-plasticity	ABAQUS	cyclic loading in multistage fracturing	With an increasing number of cycles, cumulative plastic deformation increased. Decreasing the elastic modulus, increasing the Poisson's ratio, cohesive strength, and internal friction angle were beneficial for protecting the integrity of the cement sheath.
2020	Jarrett Wise a	Casing + cement sheath + formation ID: 244.5 mm OD: 311.2 mm Height: 50 mm	3D	thermal poroelasticity	ANSYS	micro annulus activation pressure or temperature drop	There is a decreasing threshold at which micro annulus begin to appear and grow. Wellbore size plays a key factor in micro annulus width.
2020	Wu Jiwei	Casing + cement sheath + formation ID: 244.5 mm OD: 311.2 mm	2D	elastic-plasticity	ANSYS	cement sheath failure during steam injection	Significant thermal-mechanical coupling loads during steam injection led to wellbore elastic-plastic deformation, while micro annulus formed at wellbore interfaces during shut-in.

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Table 3. continued

year	researcher	sample structure and cement sheath size	dimension	constitutive theory	software	focus	key findings
						and steam shutdown stages	
2021	Yang Heng	Casing + cement sheath + formation ID: 282.6 mm OD: 320 mm	2D	elastic-plasticity	ABAQUS	salt rock creep, cement sheath elastic parameters	A larger uniform horizontal in situ stress led to a shorter time period for shear failure of the cement sheath. Lowering the elastic modulus of the cement sheath and increasing its Poisson's ratio reduced the risk of shear failure in salt rock formation.
2021	Eissa Khodami	Casing + cement sheath + formation ID: 177.8 mm OD: 254 mm Height: 5 m	3D	elastic-plasticity	ABAQUS	contact surface friction parameters and cement mechanical properties	Higher Young's modulus and lower Poisson's ratio, cohesive strength, and friction angle in the cement sheath resulted in larger plastic strains.
2021	Wu Yuxing	Casing + cement sheath + formation ID: 177.8 mm OD: 222.3 mm	2D	thermal elasticity	ANSYS	temperature difference, thermal conductivity and coefficient of thermal expansion	Heat transfer from the formation to the casing is more detrimental to cement integrity than the opposite situation. Radial and circumferential stresses in cement sheath were more sensitive to temperature changes than internal pressure loads.
2021	Sohrab Gheibi	Casing + cement sheath + formation ID: 177.8 mm OD: 215.9 mm	2D	pore mechanics	not mentioned	failure of porous media cement sheath under casing pressure variations	Casing pressure reduction led to casing-cement sheath interface debonding, while pressure increase potentially induced progressive shear and tensile failures in the cement sheath.
2021	Huan Xiaolin	Casing + cement sheath + formation ID: 290 mm OD: 220 mm Height: 8 m	3D	thermal elasticity	not mentioned	geothermal well water injection and production	Changes in pore pressure and temperature during cold water injection gradually propagated effective stresses to the far field and compromised wellbore integrity. Radial tensile stresses concentrated at the casing-cement sheath interface, leading to cement sheath debonding.
2022	Xi Yan	Multilayer casing and cement structures in wellbores of different layers	2D	elastic-plasticity	ABAQUS	accumulated plastic strain under cyclic loading	After a certain number of loading and unloading cycles, cumulative plastic strains increased with true vertical depth on vertical cross sections. On horizontal cross sections, cumulative plastic strains decreased with measurement depth.
2022	Li Xiaorong	casing + cement sheath + formation ID: 114.3 mm OD: 154.3 mm Height: 0.1 m	3D	elastic-plasticity	ABAQUS	temperature/pressure variations, anisotropy of shale formation	Compared to Poisson's ratio anisotropy, Young's modulus anisotropy had a greater influence on cement sheath integrity. Due to the high Young's modulus anisotropy of shale, debonding between the cement sheath and formation occurred more easily.
2022	He Tao	Casing + cement sheath + formation ID: 88.9 mm OD: 120.9 mm Height: 0.5 m	3D	anisotropic damage	ANSYS	cement sheath damage under wellbore pressure	The anisotropic damage model improved the accuracy of predicting micro annulus and radial cracks by 50% compared to isotropic damage model.
2022	He Tao	Casing + cement sheath + formation ID: 122.3 mm OD: 155.6 mm Height: 0.5 m	3D	plastic damage	ANSYS	evolution of plastic strain and damage under cyclic internal pressure	Under cyclic loading, fatigue damage and plastic strain concentrated locally, primarily at the interface between the cement sheath and casing, making the inner bonding surface more susceptible to failure.
2022	Gu Chenwang	Casing + cement sheath + formation ID: 250.8 mm OD: 311.2 mm Height: 0.1 m	3D	elastic-plasticity	ABAQUS	casing eccentricity and cement sheath voids	Cement shrinkage was the primary factor leading to debonding at cement sheath interfaces. The size of micro annulus increased as casing internal pressure decreased. Greater casing eccentricity and larger cement sheath voids also resulted in larger micro annulus sizes.
2022	Guo Jialiang	Casing + cement sheath + formation ID: 177.8 mm OD: 215.9 mm Height: 0.5 m	3D	elastic-plasticity	ABAQUS	integrity damage from wellbore temperature changes	Elevated wellbore temperatures could lead to tensile or compressive failure of the cement sheath. Decreases in wellbore temperature could cause debonding at the casing-cement sheath interface, directly resulting in gas channeling.
2023	Han Xu	Casing + cement sheath + formation ID: 139.7 mm OD: 215.9 mm	2D	elastic-plasticity	ABAQUS	steam huff and puff thermal stress cycle in heavy oil thermal recovery wells	Tensile failure in cement sheath and micro annulus consistently occurred on the inner wall of the cement sheath, while the outer wall remained intact.
2023	Li Xiaorong	Casing + cement sheath + formation ID: 250.8 mm OD: 311.2 mm Height: 0.1 m	3D	elastic-plasticity	ABAQUS	THM coupling, staged modeling	Compared to cyclic pressure, the size of cement sheath debonding is more sensitive to temperature variations. Higher initial stress in the cement sheath can reduce the risk of interface debonding and mitigate plastic damage within the cement sheath.
2023	Lian Wei	Multilayer casing and cement structures in wellbores of different layers	2D	elastic-plasticity	ABAQUS	temperature, wellhead annulus pressure and production	The greater the natural gas production, the greater the temperature fluctuations in cement sheath. Cement sheath close to the ground is at risk of tensile failure, potentially leading to circumferential tensile cracks.

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Pattillo et al.[116] implemented a phased finite element model for a casing-cement sheath-formation system using ABAQUS software for horizontal wellbore integrity analysis. The model began from the original reservoir and considers depletion before drilling, wellbore drilling, casing installing, cement injection, and subsequent production. The study demonstrated that nonelasticity compaction of the reservoir before drilling significantly influences stress states and modeling complexity. A lack of effective cement sheath on a portion of the casing circumference accelerates stress concentrations within the casing.

De Andrade et al.[117] addressed the mechanical and thermal effects of different well loading events and changes in initial geometric defects, developing a numerical model to study cement sheath failure mechanisms. Finite element methods were employed to assess how changes in casing pressure, eccentricity, and temperature affect cement sheath integrity. The research suggested that the key physical property influencing cement sheath failure mechanisms is the Young's modulus of both cement and the formation. Compared to heating conditions, cooling of the wellbore is more likely to lead to cement sheath damage.

Fan et al.[118] used a phased approach to create a stress and temperature coupled finite element model for the casing-cement sheath-formation system. The study analyzed the influence of construction parameters and formation mechanical properties on the circumferential stress of cement sheath during multistage hydraulic fracturing. The research indicated that increasing fracturing fluid temperature could reduce circumferential stresses in cement sheath. Increasing casing internal pressure initially increased circumferential tensile stresses in the cement sheath, followed by a decrease.

In 2009, Gray et al.[119] emphasized the necessity of conducting nonlinear 3D analysis at all stages of wellbore life. A 3D model of the casing-cement sheath-formation system was established using ABAQUS finite element software to analyze the integrity of the cement sheath during drilling, cementing, curing, shrinkage, completion, hydraulic fracturing, and production stages. The study suggested that the development of interface micro annulus may vary depending on the extent of shrinkage.

Jo and Gray[120] developed a comprehensive three-dimensional spatial model using a porous elastic medium approach in ABAQUS to analyze stress distributions around deviated wellbores under all well conditions. The study demonstrated that as Young's modulus increases, the risk of shear failure decreases while the risk of tensile failure increases. The impact of wellbore pressure exhibited very similar behavior between analytical and numerical results. However, analytical models were consistently more conservative, reaching failure faster than numerical results.

Li et al.[121] considered the nonlinear interaction between the casing and formation, along with the loading history of the system, to establish a phased finite element model based on the thermal-hydro-mechanical coupled method for simulating the integrity of the cement sheath during the well life. The research indicates that cement sheath debonding is highly sensitive to cement shrinkage during curing, and subsequent casing pressure and temperature fluctuations exacerbate the debonding. Compared to cyclic pressure, the size of cement sheath debonding is more sensitive to temperature variations. Additionally, higher initial stress in the cement sheath can reduce the risk of interface debonding and mitigate plastic damage within the cement sheath.

In summary, the numerical model studies for the casing-cement sheath-formation system are organized by year in Table 3. Numerical simulations are crucial for comprehending the behavior of casing-cement sheath-formation systems. Such simulations overcome the limitations of analytical models by accounting for complex geometries, material nonlinearity, and diverse boundary conditions. The studies involve both two-dimensional and three-dimensional numerical simulations, covering thermal effects, mechanical properties, and the influence of construction parameters.

6. SUMMARY

This review offers a comprehensive overview of cement sheath integrity, focusing on failure concepts, the evolution of constitutive models, analytical approaches, and numerical simulations of the casing-cement sheath-formation system.

By introducing major issues and investigation reports related to cement sheath integrity failure, as well as cement sheath failure modes, the seriousness of cement sheath integrity failure and the need for improved cementing technology are emphasized.

Cement constitutive models are vital for comprehending the behavior of the cement sheath under multiaxial stresses. This review traces the evolution of constitutive models from linear elasticity to elastic-plasticity, elucidating the nonlinear, pressure-sensitive behavior of cement.

Analytical models provide valuable insights into the behavior of casing-cement sheath-formation systems under various conditions. Elasticity models focus on stress distribution and integrity factors, while elastic-plasticity models consider plastic deformation and micro annulus. Both types of models emphasize the importance of material properties, temperature, pressure changes, and initial stresses in assessing cement sheath integrity.

Numerical simulations are indispensable for assessing and enhancing the integrity of wellbore cement sheath. These simulations cover various stages of a well's lifecycle, including drilling, cementing, hydraulic fracturing, and production. These simulations aid in identifying potential failure mechanisms, guiding wellbore design, and informing operational decisions to ensure the long-term reliability of well systems.

7. RESEARCH GAP

The effective zonal isolation provided by cement sheath is crucial for the safe and efficient exploitation of oil and gas wells. The paper provides an in-depth review of theoretical studies concerning zonal isolation issues of cement sheath in wellbore conditions. Despite extensive scholarly research improving cement sheath integrity, several limitations persist:

7.1. Analytical Models Inadequately Consider the Anisotropy of Reservoir Mechanical Parameters. Cement sheath, integral to well cementing, is influenced by the surrounding formation's stress field. The difference in stress between isotropic and anisotropic reservoir wall rocks directly affects the stress and integrity of cement sheath. Traditional models for studying cement sheath integrity often assume isotropic formation, which may lead to errors in some cases. Therefore, for anisotropic formations, consideration should be given to the directional nature of reservoir mechanical

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parameters, such as the elastic modulus and Poisson's ratio of rocks, as well as the directional nature of stress fields. Hence, on the basis of anisotropic theory, combined with mechanical experimental methods to obtain anisotropic parameters, establishing a casing-cement sheath-formation system model considering different directions of formation parameters can more accurately assess the integrity of cement sheath and propose corresponding correction models.

7.2. Lack of Quantitative Analysis of Micro Annulus Generation and Evolution at the Cement Sheath Interface under Cyclic Loading. Cyclic loading can lead to the generation of micro annulus at the casing-cement sheath interface, which further results in sustained casing pressure. Certain studies have qualitatively examined micro annulus generation at the casing-cement sheath interface resulting from cement sheath plastic deformation. However, the generation and evolution of micro annulus at the cement sheath interface are influenced by various factors, such as the amplitude and frequency of cyclic loading, load history, formation properties, cement material properties, etc. It is crucial to provide a clear description and definition of the characteristics of micro annulus generation mechanisms, size distribution, and deformation behavior. Therefore, there is an urgent need to establish unified quantitative indicators for micro annulus at the cement sheath interface to lay the foundation for predicting the integrity of cement sheath.

7.3. Lack of Research on the Transient Temperature–Pressure Coupling Effect on Cement Sheath Integrity. The temperature–pressure coupling effect is a significant factor leading to sustained casing pressure. The study of the transient temperature–pressure coupling effect on cement sheath integrity is also an important and complex issue. Current research mainly focuses on engineering situations such as thermal recovery wells and high-temperature and high-pressure wells, often emphasizing the analysis of cement sheath integrity under static conditions. There is a lack of in-depth analysis of the effects of dynamic temperature and pressure changes on cement sheath integrity during casing running and continuous tubing processes. Therefore, more experiments and numerical simulation studies are needed, introducing more complex working conditions and situations to reveal the mechanism of the transient temperature–pressure coupling effect on cement sheath integrity.

7.4. Cement Slurry Design Methods That Consider Both the Mechanical Integrity of Cement Sheath and the Interface Sealing Requirements Are Scarce. The failure modes of cement sheath zonal isolation are diverse, and different failure modes have different design requirements for the mechanical properties of cement sheath, such as increasing the compressive strength of cement sheath to withstand higher casing loads or enhancing the deformability of cement sheath to improve strain recovery capability under cyclic loading. Yet, current designs often prioritize single failure modes. Performance indicators derived from traditional cement slurry system design methods face challenges in reconciling cement sheath's mechanical integrity with interface sealing requirements. Therefore, there is a need to establish comprehensive mechanical performance design methods for cement sheath to achieve the rational design of mechanical performance parameters based on multiple failure modes of cement sheath under wellbore conditions.

8. FUTURE PROSPECTS

The theoretical research presented has significantly advanced our understanding of casing-cement sheath-formation systems. Future research should focus on refining and validating these models, integrating multiphysics coupling, advanced material models (e.g., viscoelasticity, poroelasticity), and incorporating machine learning and data-driven approaches. Specific aspects include:

(1) Multi-Physics Coupling: Integrating various physical phenomena, including thermal, mechanical, and hydraulic effects, will enhance our understanding of cement sheath behavior. This can lead to improved predictive models and enhanced wellbore designs.

(2) Advanced Constitutive Models: Developing advanced constitutive models to capture the nonlinear behavior of cement under diverse loading conditions is crucial. These models should consider factors like creep, fatigue, and damage evolution for more accurate predictions.

(3) Machine Learning and Data-Driven Approaches: Integrating field data and real-world observations into theoretical research will validate and calibrate models, enhancing their reliability and applicability.

(4) Experimental Validation: While theoretical research provides valuable insights, experimental validation is essential. Future studies should continue to conduct laboratory and field experiments to validate the predictions made by these models.

(5) Expanding the Scope of Research: Against the backdrop of carbon neutrality and the hot research topics of CCUS, underground energy systems such as geothermal wells and gas storage facilities are receiving increasing attention, and the long-term integrity of cement sheath is crucial for the safe operation of these systems. Future research should address the unique environments and conditions of emerging underground energy systems and develop methodologies to assess the long-term integrity of cement sheath.

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Notes

The authors declare no competing financial interest.

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