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# Development of Subsea Pipeline Buckling, Corrosion and Leakage Monitoring

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**Abstract:** Oil and gas exploration is a sector which drives the global economy and currently contributes significantly to global economic development. The safety of subsea pipelines is deeply affected by factors such as pipeline buckling, corrosion and leakage. Once a subsea pipeline is seriously leaking or damaged, it will cause a lot of waste of resources at light level, and it will cause explosions in severe cases, resulting in heavy casualties and huge economic losses, and at the same time, seriously damaging the surrounding ecological environment. Therefore, it is necessary to pay attention to problems related to the buckling, corrosion and leakage of submarine pipelines. This paper consists of a literature review of the latest research about buckling, corrosion and leak detection.

**Keywords:** oil and gas; subsea pipeline; buckling; corrosion; leakage detection; protection

## 1. Introduction

The oil and gas exploration and production industry currently contributing a lot to the global economy. Subsea pipelines can connect subsea oil and gas resources with the entire onshore oil and gas production management system by the fastest, safest and most economical route, which is called the "lifeline" of offshore oil and gas engineering. With the development of oil and gas in deep water and even ultra-deep water, the design of subsea pipelines currently faces enormous challenges [1]. Dong et al. [2] assessed the fatigue strength of single-sided girth welds in offshore pipelines under these specific fatigue loads. The longitudinal stress range caused by the variation of the pipeline's internal pressure and temperature was calculated. The effective notch strain approach was used to assess the fatigue strength of welds. The results show that the plastic behavior of the weld root is only significant for severe local stress concentrations, which is mainly governed by the axial misalignment, weld root angle and the weld root bead width. Anwar et al. [3] presented a numerical analysis to investigate the impact of surface roughness on VIV in the crossflow direction of a circular cylinder. The methodology consisted of the categorization of sandwich pipeline collapse strength models based on interlayer adhesion conditions. Bhardwaj et al. [4] presented an approach for a probabilistic design and safety assessment of sandwich pipelines under external pressure. Bhardwaj et al. [5] assessed the structural reliability of a pipe-in-pipe system operating in deep waters under high internal pressure and high temperature. The high temperature and high pressure liquid or gas in the pipeline can cause buckling, and the occurrence of pipeline buckling often brings serious consequences. Most of the current subsea pipelines are made of steel materials. The pipelines are in seawater for a long time, and the environment inside the pipelines is often acidic. Therefore, corrosion is also prone to occur inside and outside the pipelines, causing the pipelines to fail. Once a subsea pipeline is seriously leaking or damaged, it will cause great economic losses. Therefore, it is necessary to pay attention to problems related to the buckling, corrosion and leakage of submarine pipelines. The influencing factors of lateral buckling in a pipe-in-pipe (PIP) structure containing initial imperfections and its

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critical force were investigated by conducting an experiment, a finite element analysis, and a theoretical derivation. [6] The change laws on the influence of initial imperfections of the PIP structure during thermal loading were revealed through an experimental study using imperfection amplitude and wavelength as parameters. Cai et al. [7] reviewed the research progress of the lateral buckling of submarine pipelines under high temperature and high pressure. Khakzad et al. [8] established a Bayesian network for predicting the corrosion rate distribution of petroleum pipelines using the point estimation generated by the empirical corrosion simulation model. Qasim et al. [9] reviewed the basic concepts of the formation and occurrence of hydrates and corrosion, and the research progress of hydrates and corrosion inhibitors in recent years. Zeng [10] conducted Systematic Computational Fluid Dynamics (CFD) simulations on incompressible water pipe flow with leakage. The aim was to provide an understanding of how different parameters, including the leakage pipe diameter, inlet mass flow rate, and main pipe length, affect the flow phenomena at the vicinity of the leakage location. The CFD data showed that the leakage pipe diameter has a dominant effect on the leak mass quantity, pressure change at the vicinity of the leak location, total pressure drop and pressure gradient along the main pipe. Ho et al. [11] reviewed the most commonly used underwater detection and monitoring techniques.

In summary, because the subsea pipeline buckling, corrosion and leakage will bring safety problems and economic losses, it is necessary to study the principle and prevention measures of buckling, corrosion and leakage in subsea pipelines to improve the reliability of submarine pipelines. This paper will introduce the latest research results of submarine pipeline buckling, corrosion, leak detection, and so on.

## 2. Research on Subsea Pipeline Buckling

Subsea pipelines are an important part of offshore oil and gas collection, transportation, and storage systems. When the submarine pipeline transports crude oil, in order to ensure the fluidity of crude oil and prevent paraffin deposition on the inner wall of the pipeline and the formation of hydrate, the medium transported by the pipeline needs to be kept above a minimum level. The pipeline expands under temperature, pressure and the Poisson effect, but is constrained by the foundation soil, and additional stress is generated in the pipe wall, and this additional stress on the pipeline continues to accumulate with the increase in the length of the pipeline. When the accumulated stress is greater than the critical buckling load of the pipe, the overall buckling of the pipe may lead to the structural failure of the pipe, such as fracture, fatigue or expansion buckling. When the pipeline is damaged and leakage occurs, it will not only cause economic losses but also may bring about safety problems, endangering the safety of people and the marine environment.

### *2.1. Theoretical Research of Subsea Pipeline Buckling*

The buckling of pipes has been extensively studied in the past few decades. Hobbs et al. [12] derived analytical solutions for the horizontal global buckling of ideal submarine pipelines on rigid foundations, and proposed five models. Hunt et al. [13] derived governing equations for the global buckling of elastic members with flexural stiffness on flexible foundations. The two theoretical solutions of Hobbs and Hunt have become the classics of theoretical research in this field, and the theoretical research on the overall buckling of submarine pipelines was based on this.

Taylor et al. [14] analyzed the lateral buckling caused by axial friction resistance when the initial defects of the submarine pipeline were in the shape of Mode 1 and Mode 2. They then plotted the buckling axial force of the pipeline with different initial defects, studied the influence of defects on the overall buckling of the pipeline, and found that the critical axial force of pipeline buckling increased with the decrease in defects, and when the defects were very small, there would be a “snap through” phenomenon. Hong et al. [15] analyzed the lateral buckling of Mode-3-shaped pipes with initial defects, on the basis of Taylor’s research. Karampour et al. [16] studied the lateral buckling of pipelines with dense defects buried on the uniform seabed with nonlinear soil pipe interaction. It was found that when the defect spacing was greater than half of the defect half wavelength, there was no interaction between the buck lobes. Wang et al. [17] compared the typical lateral buckling behavior caused by unstressed and stressed initial defects. The influence of the amplitude and wavelength of initial imperfections and the distance between adjacent initial imperfections on lateral buckling behavior were discussed. The results showed that reducing the distance between adjacent initial defects could reduce the displacement amplitude and maximum stress. Wang et al. [18] established a mathematical model for simulating the upward buckling of a submarine lined pipeline considering the difference in material properties between the lining and outer pipe. The axially compressive force distribution $\overline{P}(x)$ is shown in Formula (1). The concentrated axial soil resistance is denoted by $F_{At}$. The zone $-L \leq x \leq L$ is called the buckled region. Where $P$ is the axial compressive force within the buckled section in the post-buckling stage, $F_{At} = \mu_A F_t$ is the concentrated axial friction force induced by the vertical concentrated contact force $F_t = W_p L$ at $x = L$, $\mu_A$ is the axial friction coefficient between pipeline and seabed, $l_s$ is the half-length of the feed-in region, and $W_p$ is the submerged weight per unit length of the lined subsea pipeline.

$$\overline{P}(x) = \{^{P(0 \leq x < L)}_{P + F_{At} + \mu_A W_p (x-L)(L \leq x \leq l_s)} \tag{1}$$

The axial compressive force at the virtual anchor point $x = l_s$ is

$$\overline{P}(l_s) = N_T = P + F_{At} + \mu_A W_p (l_s - L) \tag{2}$$

The influence of Young's modulus and the thermal expansion coefficient of the liner on post-buckling response were analyzed. The results showed that the thermal expansion coefficient of the liner had a significant influence on the post-buckling performance of the liner and the outer tube. The displacement amplitude, axial compression force, maximum bending moment and maximum stress increased with the increase in the ratio of liner thickness to outer tube thickness.

### 2.2. Model Test and Numerical Simulation of Submarine Pipeline Buckling

Model test is an effective mean to study the overall buckling of submarine pipelines. Wang et al. [19] studied a pipe section with an outer diameter of 16 cm. The lateral movement model tests of pipe–soil interaction were carried out in sand. The large deformation behavior of the seabed and the change process of the berm were studied. Compared with the existing calculation methods, when the pipe section weight was greater than 0.1 kN/m, the lateral residual resistance was more significant in this study. However, when the pipe section weight was less than 0.05 kN/m, the existing calculation methods tended to exaggerate the lateral residual resistance.

The finite element analysis method is widely used in the study of the integral buckling of submarine pipelines. Yu et al. [20] used the finite element method to analyze the buckling failure of submarine pipelines under the action of reverse fault displacement, and studied the effects of soil properties, pressure loads, diameter thickness ratio and inclination on local buckling formation, tensile strain and section deformation. The results showed that the submarine pipeline had a large deformation capacity, and the bending curve was usually s-shaped. External pressure was more unfavorable than internal pressure, which increased the compression strain, but reduced the tensile strain. A small fault dip angle would cause serious axial pressure and lead to local collapse in the empty wait state. When the diameter thickness ratio or the pressure level was large, the external pressure caused the local collapse of the pipeline. Wang et al. [21] proposed a model integrating nonlinear pipe–soil interaction and initial defects to simulate the lateral buckling of submarine pipelines. The distribution of axial compressive force $\overline{P}(x)$ is written as:

$$\overline{P}(x) = P + f_A x (0 \leq x \leq l_s) \tag{3}$$

where $P$ is the axial compressive force at the center of buckle, $f_A = \mu_A W_{pipe}$ is the axial soil resistance, $\mu_A$ is the axial friction coefficient between the pipe and seabed, and $W_{pipe}$ is the submerged weight per unit length of the pipeline. The axial force balance is:

$$P_0 = P + f_A l_s \tag{4}$$

The analytical solution was obtained under the assumption of a rigid plastic pipe–soil interaction, and the numerical solution was obtained when considering the nonlinear pipe–soil interaction. Except for the negligible difference in the state before buckling, the analytical solution was basically consistent with the numerical solution. Zhang et al. [22] studied the lateral buckling critical force of a submarine pipe-in-pipe pipeline with one symmetrical initial imperfection on a soft foundation. Zhang et al. [23] also proposed a lateral soil resistance model to describe the lateral resistance force-displacement relation.

### 2.3. Protection of Submarine Pipeline Buckling

Buckling protection is key to the overall design stability of submarine pipelines. The protective measures against the overall buckling of submarine pipelines can be divided into two categories: one is to eliminate the overall buckling of pipelines completely by reducing the temperature and pressure loads, increasing the bending stiffness of pipelines or seabed binding force; the other one is to introduce buckling inducing factors at the predetermined position to control the overall bucking, which is called controlled buckling. Among them, buckling control is a relatively cost-effective buckling protection scheme applicable to deep-sea pipelines.

The installation of sleepers at specific locations along the pipeline route is a method to control buckling, as shown in Figure 1. Zhang et al. [24] analyzed the lateral buckling of the submarine pipeline caused by the sleeper with lateral restraint, considering the contact between the buckling pipeline and the lateral restraint. The results showed that the maximum deflection and maximum stress along the curved pipe were smaller than those without lateral restraint after the curved pipe contacted the lateral restraint. A soil berm may form around the pipeline, which makes the pipeline laterally subject to nonlinear forces. Wang et al. [25] established a mathematical model for the transverse buckling of submarine pipelines by considering the nonlinear interaction model of pipeline soil. After introducing the nonlinear pipe–soil interaction model, the deformation of the curved pipe decreased, and the minimum critical temperature difference and maximum stress of the curved pipe increased. However, with the increase in sleeper height, the influence of nonlinear pipe–soil interaction decreased.

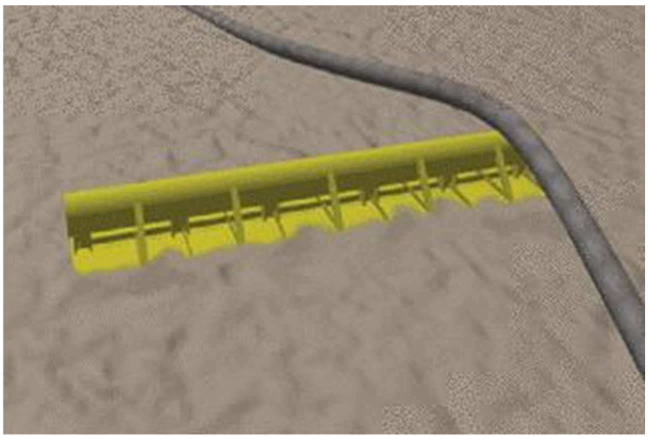

**Figure 1.** The installation of sleepers (yellow) to control buckling in the pipe structure (black). Reprinted with permission from Ref. [26]. 2018, Elsevier.

A buoyancy block installed at a specific location of the pipeline route can reduce the buoyancy unit weight of the pipeline and reduce the soil-binding force on the pipeline to stimulate the overall buckling of the pipeline under the action of temperature and pressure. Wang et al. [27] studied the lateral buckling behavior of submarine pipelines caused by distributed buoyancy segments. They found that breakthrough resistance had a great influence on the minimum critical temperature difference. The influence of breakout resistance on buckling performance was far less than that of residual resistance. The optimum length of the distributed buoyancy segment should be equal to the length of the buckling segment. Therefore, in the design process, the maximum buckling section length should be estimated to determine the length of the best distributed buoyancy section. Wang et al. [28] established a model for lateral buckling caused by an imperfect buoyancy section in the submarine pipeline distribution. They found that the displacement amplitude increased with the increase in the initial defect amplitude, and first increased and then decreased with the increase in the initial defect wavelength. Compared with the pipeline without initial defects, the maximum stress would be amplified when the wavelength pairs of initial defects were small. Therefore, an initial defect of a large enough wavelength should be introduced. Seyfipour et al. [29] studied the interaction between walking and lateral buckling. A continuous serpentine deformation form was proposed, which could control walking. Lateral buckling could also be controlled by continuously deforming the pipe according to the specified radius and wavelength before or during installation [26].

## 3. Research on Corrosion of Submarine Pipeline

The pipeline may be subject to the internal and external corrosion of corrosive fluid and seawater in a harsh environment, which will also cause harm to the pipeline, as seen in Figure 2. Different microorganisms including bacteria, fungi and algae on the metal surface will accelerate the degradation of materials, so submarine pipelines are also affected by microbial corrosion. This chapter will introduce the latest research results of submarine pipeline corrosion and anti-corrosion from the perspective of submarine pipeline corrosion and anti-corrosion.

**Figure 2.** Schematics of some pipelines with corrosion defects. Reprinted with permission from Ref. [30]. 2021, Elsevier.

### *3.1. Research Progress of Submarine Pipeline Corrosion*

Chen et al. [31] estimated the collapse pressure of steel pipelines subjected to random non-uniform general corrosion and localized corrosion. The material of the pipes follows the J2 flow theory of plasticity and was assumed to be an elastic-plastic, finitely deforming solid that hardens isotropically. In finite element analysis, the Ramberg-Osgood (RO) model is used to define the constitutive relation of steel:

$$\varepsilon = \frac{\sigma}{E} + K\left(\frac{\sigma}{E}\right)^{\frac{1}{n}} = \frac{\sigma}{E}\left[1 + \alpha\left(\frac{\sigma}{\sigma_y}\right)^{n-1}\right] \tag{5}$$

where $\varepsilon$ is strain, $\sigma$ is stress, $E$ is Young's modulus, $K$, $n$ and $\alpha$ are constants that depend on the material being considered, and $\sigma_y$ is the yield stress of the material.

Bhardwaj et al. [32] proposed an approach to assess the structural reliability of corroded pipes with calibrated strength models. Mohammed et al. [33] studied the effect of calcium on the pitting corrosion of X65 carbon steel. They believed that calcium ions would affect general corrosion and pitting corrosion. Li et al. [34] established a prediction model for the maximum pitting depth of a submarine oil pipeline to support the development of submarine process system safety. The degradation of submarine pipelines under corrosive agents and cyclic loading may lead to the failure of these structures. Arzaghi et al. [35] established a comprehensive modeling of the pitting corrosion and corrosion fatigue degradation process of submarine pipeline using a dynamic Bayesian network (DBN), and used this method to estimate the remaining service life of high-strength steel pipes. Figure 3 illustrates a DBN in which the evolving process of the variable $Y_t$ is modelled. This variable in time slice $t$ is dependent on $Y_{t-1}$ as well as $X_t$. In order to establish a DBN, the conditional probability tables for evolving nodes should be completed; for instance, $P(Y_t|Y_{t-1},\ X_t)$ for variable $Y_t$ in the DBN presented in Figure 3. Feng et al. [36,37] studied the residual ultimate strength of pipes with uniform pitting under external pressure using a nonlinear finite element method. The results showed that the pitting strength and pitting depth had a significant effect on the ultimate strength, while the corrosion length had a relatively small effect. Zhang et al. [38] studied the sensitive area of stress corrosion cracking (SCC) of submarine pipelines. They found that the microenvironment at the bottom of the fracture showed obvious acidification. At the open position, due to the application of an overprotected cathodic protection potential, hydrogen atoms could enter the steel and induce a hydrogen embrittlement effect, resulting in the high sensitivity of steel to SCC.

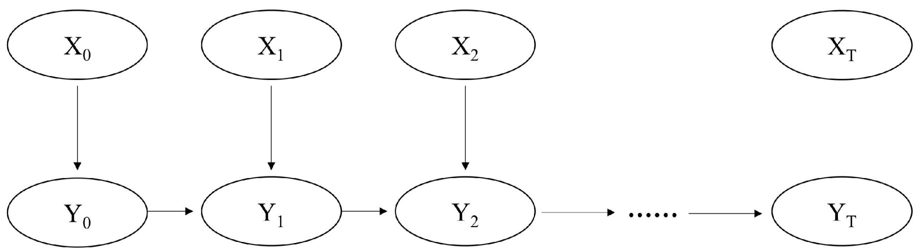


**Figure 3.** Dynamic Bayesian network. Reprinted with permission from Ref. [35]. 2018, Elsevier.

Yan et al. [39] analyzed the elastic collapse of asymmetric corrosion with internal and external corrosion under external pressure, and derived the control equations under the conditions of non-expandable and expandable membranes. The external pressure $p$ is exerted on the external surface of both the corroded region and the intact region, not on the middle surface. "Asymmetric" corrosion means that the middle axes of two regions may have different radii, i.e., $R_1$ is not necessarily equal to $R_2$. The governing equation is:

$$M_1(s) + \frac{p\left(4R_1^2 - t_1^2\right)}{8} - pR_1w_1(s) = M_2(s) + \frac{p\left(4R_2^2 - t_2^2\right)}{8} - pR_2w_2(s) = C \quad (6)$$

where $C$ is an unknown constant and $M_1(s)$ and $M_2(s)$ are cross-section resultant moments around the middle axis point in the corroded region and the intact region, respectively.

Wu et al. [40] conducted experiments on full-size pipes with longitudinal, circumferential and diagonal defects, respectively. A finite element model was established to simulate the experimental process; the influence of corrosion defect size on the interaction was analyzed, and the failure modes of pipelines under different defect forms were studied. The test found that the collapse mode of the pipeline with two external corrosion defects changed from U-type to $\infty$ type, while the collapse mode of the pipeline with internal and external corrosion defects or two internal corrosion defects was irregular, and the deformation was mainly concentrated in the corrosion defect area.

When microorganisms gather on the metal surface, the oxygen concentration on the metal surface decreases after the biofilm is covered, which plays the role of an anode. The covering part without the biofilm will show a higher oxygen concentration, which plays the role of a cathode. At this time, microorganisms promote the corrosion of metals [41]. Microbiologically influenced corrosion (MIC) is widely considered as an important reason for the release of dangerous hydrocarbons, which may lead to fire and explosion and have a significant impact on the economy and environment [42,43]. Yazdi et al. [44] used a continuous Bayesian network (CBN) and other technologies to monitor and manage MIC. The film formed by the corrosion inhibitor is shown in Figure 4. The lower part of the sandwich is the connection between the polar head of the molecule and the metal surface, and the protective function depends on the strength of this link. The middle part of the sandwich is the non-polar end of the molecules, and the degree of protection participation in the sector is dependent on the covering or wetting level of the surface by the molecules. The upper part of the protective sandwich is a hydrophobic layer of oil or hydrocarbon that is attached to the tails and the long carbon chain. This oil layer acts as an external protective film that, by covering the corrosion inhibitor film, acts as a barrier against the penetration of iron ions from the metal surface to the electrolyte, while also decreasing the diffusion to the internal parts and corrosive factors.

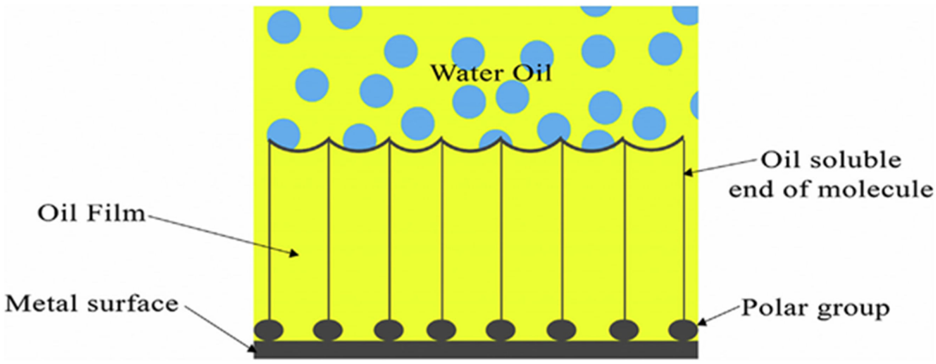


**Figure 4.** Schematic figure of the film formed by corrosion inhibitor. Reprinted with permission from Ref. [45]. 2018, Elsevier.

### *3.2. Measures to Prevent Corrosion of Submarine Pipelines*

#### 3.2.1. Corrosion Inhibitors Method

The use of corrosion inhibitors is the preferred method of protecting the inside of the pipe. A corrosion inhibitor can be chemically adsorbed to form a protective film with an inhibitory effect on the metal surface or to increase the metal surface potential, so that the metal can enter the passivation area and form a natural oxide film in the passivation area. A corrosion inhibitor can also react with the potential corrosion components existing in the water medium, so that it can become an anode or cathode by simply slowing down the active sites on the metal surface [46,47]. Di et al. [48] synthesized two kinds of fluorine-containing imidazoline Schiff-base derivatives. Singh et al. [49] studied the effect of plant extracts on reducing the corrosion of steel materials. Sun et al. [50] studied the feasibility of inhibiting the corrosion of X70 steel in a hydrochloric acid solution with Chinese cabbage extract (CAE) as an environmentally friendly corrosion inhibitor. The experimental results showed that CAE had a good protection performance for X70 steel in a HCl solution, and its corrosion inhibition efficiency could reach 95.37%.

#### 3.2.2. Methods to Reduce the Influence of Microorganisms on Submarine Pipeline Corrosion

At present, the methods for reducing microbial corrosion are limited [51,52]. The adhesion of a microbial membrane in offshore oil pipelines provides a complex microenvironment for microorganisms, and the changed electrochemical characteristics and physical and chemical properties provide the primary conditions for the growth of microorganisms. At the same time, organic sediment, corrosion sediment and accelerated metabolism sediment might easily block the pipeline. Chemical microbiological corrosion and electrochemical microbiological corrosion occur easily in petroleum pipelines. The corrosion mechanisms are acid generation corrosion and electron transfer corrosion of different electron acceptors. Common corrosion mechanisms include a metabolic product corrosion mechanism, electron transfer mechanism and stress process mechanism. The conditions for the two mechanisms are the concentration of the carbon source. The amount of metabolites of microorganisms in a high carbon source environment is rich. Copper in steel not only has the function of aging precipitation strengthening, but also has the function of sterilization, which has a special biological function for steel. Shi et al. [53] prepared two kinds of copper containing steel pipelines (1% Cu and 2% Cu) based on the chemical composition of a traditional X80 pipeline steel, which could reduce the impact of microorganisms on the corrosion of submarine pipelines.

#### 3.2.3. Study on Anticorrosive Coatings

Coating the original steel material surface can effectively improve the corrosion resistance of the pipeline. El-Din et al. [54] prepared three kinds of hydrophobic copolymer composite coating materials using batch emulsification polymerization technology to prevent the corrosion of the internal surface of oil pipelines. Dai et al. [55] prepared a nickel coating on an X70 pipeline steel using electroplating. Wang et al. [56] successfully prepared a duplex stainless steel coating on the surface of high-strength alloy steel using laser melting deposition which improved the corrosion resistance of pipes.

#### 3.2.4. Cathodic Protection Method

The cathodic protection mechanism limits corrosion by changing the metal into an electrochemical cell. This can be achieved in two ways: one is to apply current density with an external current source, the other one is to use more active materials as anodes. Marcasoli et al. [57] evaluated the integrity of submarine pipelines in combination with potential profile and electric field gradient. Sun et al. [58] studied the cathodic protection criteria of the theoretical and measured protection potentials of 10Ni5CrMoV low alloy steel in a simulated deep water environment (350 m).

## 4. Pipeline Leakage Detection Method

Severe buckling or corrosion of submarine pipelines may lead to pipeline damage. In case of serious leakage or damage to the submarine pipeline, it may cause a large waste of resources, or even an explosion, leading to heavy casualties and huge economic losses. In addition, offshore oil and gas fields would also be shut down, thus directly causing greater economic losses. Therefore, the development of new pipeline leakage detection methods is conducive to reducing losses as much as possible. Leakage detection of submarine pipelines is generally divided into two categories. The first is the direct detection method, that is, to determine whether a leakage has occurred by detecting external parameters of the pipeline, such as hydrocarbons or temperature changes. The second method is indirect detection, that is, sensors are used to detect the internal parameters of the pipeline, such as temperature, viscosity, pressure, flow, sound speed, etc., and data processing is used to determine whether a leakage has occurred.

Xie et al. [59] put forward a new method to detect pipeline leakage in a subsea production system based on an acoustic leakage signal collected by hydrophone. The acoustic radiation equation for fluid motion is:

$$\left(\frac{\partial^2}{\partial t^2} - c_0^2\nabla^2\right)\rho = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j} \tag{7}$$

where $T_{ij}$ is the stress tensor, namely the radiation of the quadrupole sound source, and $x_i$ and $x_j$, respectively, are the physical spaces. Through the pipeline leakage test, it was found that the radiated noise was a continuous medium and high-frequency noise spectrum. The increase in pipeline pressure and leakage hole diameter narrowed the spectral structure and shifted the spectral center to low frequency. The integrated empirical mode decomposition and Hilbert–Huang transform were used to process the acoustic signal to obtain the time-frequency image, which was input into the two-layer convolutional neural network (CNN) for leak detection. Zhang et al. [60] used an autonomous underwater vehicle (AUV) combined with a multi beam echo sounder and a forward looking sonar (FLS) to automatically detect the submarine pipeline. During the detection, the AUV maintained autonomous navigation along the preset pipeline route at a fixed height above the pipeline, and MBES collected water column images. After extracting bubble contour features and judging the leakage risk, the bubbles would rise to the sea surface and sent an alarm to the shore-based command center via satellite. Qu et al. [61] presented a SVM-based pipeline leakage detection and pre-warning system. In the system, an optical cable was laid in parallel with a pipeline in the same ditch and three single-mode optical fibers inside constituted the distributed vibration sensor. The sensor was based on a Mach–Zehnder optical fiber interferometer and could detect the vibration signals along a pipeline in real time. Then, the eigenvectors of the vibration signals were extracted using the “energy-pattern” method based on a wavelet packet decomposition. Subsequently, the vibration signals were recognized by the support vector machine (SVM) through the features so that it could judge whether any abnormal event was taking place. Zhou and Liu et al. [62,63] proposed a new distributed optical-fiber pipeline-leakage detection technology based on the principle of the Mach–Zehnder optical fiber interferometer. An optical cable should be laid along the pipeline when applying this technology to pipeline leakage detection. The distributed micro-vibrant measuring sensor was composed of three single-mode optical fibers in the optical cable. Oil leakage could be detected by the sensor in real-time by measuring leaked noise along the pipeline.

With the development of computer technology, artificial intelligence and other disciplines, pipeline leak detection methods based on software provide a platform for the application of various modern inspection/monitoring technologies, which will have good development prospects.

## 5. Conclusions

This paper summarizes the important achievements of some scholars in the research field of submarine pipeline buckling, corrosion and leakage detection. The complexity of submarine pipeline buckling, corrosion and other related issues and the characteristics of multidisciplinary intersection are revealed.

The theoretical research on the buckling of submarine pipelines has made some progress in recent years, but scholars cannot take into account the nonlinear pipe–soil interaction while obtaining the analytical solutions of the overall buckling amplitude and bending moment of pipelines, which is a direction that needs further research. Additionally, it is of great significance to establish a model pipeline with structural optimization similar to the actual engineered pipelines for future pipeline buckling test research.

It is meaningful to study new anti-corrosion materials, inhibitors and anti-corrosion methods for submarine pipelines. Microbes also have a great impact on pipeline corrosion, but there is a lack of targeted and efficient measures to prevent microorganism corrosion.

Leakage in a submarine pipeline will cause great harm, so it is necessary to develop more timely and accurate submarine pipeline leakage detection technology. The combination of computer technology and artificial intelligence algorithms will be one of the directions of developing submarine pipeline leak detection in the future.

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