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Research Article

Failure Mode and the Prevention and Control Technology of Buried PE Pipeline in Service: State of the Art and Perspectives

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Material defects and external environmental factors increase the engineering safety risks of buried PE pipelines in service. This paper mainly reviews the failure mode and the prevention and control technology of buried PE pipelines in service, as well as comparative failure characteristics between the buried PE and steel pipelines. The main failure factors of buried PE pipelines can be divided into four levels: the first level is third-party damage; the second level includes three failure factors, i.e., surface subsidence, joint failure, and aging failure; the third level consists of pipe piercing, crack development, and pipeline defect; the fourth level is a corrosion failure. Besides, steel and PE pipelines have various physical and mechanical properties, which lead to a significant difference in the service performance and degradation mechanism in practice. For instance, corrosion and welded joint leakage are the two common problems in steel pipelines during the service period, while PE pipelines have excellent corrosion resistance. Additionally, in order to ensure and maintain the long-term operations of PE pipelines, it is of great significance to develop and promote nonexcavation technologies of construction, renewal, and repair for natural gas-buried PE pipelines. Furthermore, based on the above studies, some further research studies on buried PE pipelines in service are suggested and discussed, e.g., (a) the service performance and degradation mechanism of buried PE pipelines in complicated environmental conditions, (b) the interaction mechanism among the engineering structure, PE pipelines, and geological environment, as well as PE pipeline geological soils coupled in multiple physical fields, and (c) the combinations of the traditional engineering risk assessment method and the numerical analysis method considering the interaction between the PE pipeline and geological environment. The results could be helpful for a better understanding of the operation conditions of buried PE pipelines, and it is also hoped that this study could provide guidance for the safe operation, maintenance, and integrity management of buried PE pipelines.

1. Introduction

Actions to deal with climate change have gradually become the consensus of all countries all over the world. In September 2020, China announced to achieve "carbon peak" by 2030 and "carbon neutral" by 2060. The whole country has made great efforts to adjust the industrial structure under the "double carbon target," especially the energy industry. Natural gas, as a typical representative of clean energy, has been widely used in urban and rural regions. Being the gas transmission and distribution system, it is significant to ensure the safe operation of natural gas pipelines.

Recently, under the expected background of increasing natural fossil energy supply, pipelines have become the best way to transport oil and gas with many advantages, such as continuous efficiency, stability, reliability, and high environmentally friendly and low energy consumption. By the end of 2016, the total mileage of oil and gas pipelines reached

110,000 km in China. According to the Medium- and Long-term Oil and Gas Pipeline Network Plan issued by the National Development and Reform Commission and the Energy Administration of China in 2017, the scale of the long distance oil and gas pipeline network reached 169,000 km by 2020, among which the length of natural gas pipelines reached 104,000 km. It is also stated that a natural gas basic network with "trunk pipelines being interconnected and regional pipelines being managed into the network" will be formed by 2025. Then, the total mileage of the long-distance oil and gas transportation will reach 250,000~300,000 km by 2030, indicating that a modern oil and gas pipeline network system will be basically constructed [1]. Besides, on May 7, 2022, the Development and Reform Commission and the Energy Bureau of Sichuan Province legislated a government document named the "14th Five-Year" Renewable Energy Development Plan of Sichuan Province, in which it is stated that the plan would vigorously promote the construction of the oil and gas infrastructure. It will also speed up the construction of oil and gas transmission pipelines in accordance with the principle of moderate lead. Additionally, it is also pointed that centering on major gas-producing and consumption regions, it will overall optimize the pipeline network layout and build a stable supply, efficient operation, safe and reliable transmission, and distribution of the natural gas pipelines system. From the above analysis, it is shown that being a "lifeline project," it is significant to ensure the safe operation and maintenance of the natural gas pipeline network.

Pipelines, as widely used transportation, are designed to transport liquids, gases, and powdery solid materials over long distances. According to the main making material, pipelines can be divided into metal pipelines, plastic pipelines, and reinforced-concrete pipelines, among which PE (polyethylene) pipelines occupy an important position due to their good performance, e.g., good impact resistance, flexibility, chemical corrosion resistance, fusible, and easy molding processing. However, PE pipelines are not widely used in practice, especially in urban natural gas transmission and distribution systems. Therefore, in this paper, we mainly overview the failure modes of buried PE pipelines in service and investigate comparative failure characteristics between buried PE pipelines and steel pipelines, as well as some crucial prevention and control technologies for buried PE pipelines at present. The results could be helpful for a better understanding of the operation conditions of buried PE pipelines, and it is also hoped that this study could provide guidance for the construction, renewal, and repair of natural gas PE pipelines to ensure the safety of buried PE pipelines [2, 3].

2. Service Status of Buried PE Pipelines

PE pipes are a linear polymer made of ethylene monomers after certain extrusion polymerization. Buried PE pipes have the advantages of long service life, excellent corrosion resistance, good impact resistance, and reliable connection performance and construction performance. In recent years, steel pipe and cast iron pipe are gradually replaced with PE pipes, and PE pipelines are widely used in natural gas transmission and distribution. Generally, based on the standards of the density and long-term hydrostatic strength (MARS), the classification of PE pipes is shown in Figure 1.

At present, in some European countries, such as the United Kingdom, Denmark, and France, more than 90% of urban gas pipelines are used as PE pipelines. The use of plastic pipes in the United States has occupied approximately 55% of the total pipelines, of which 97%~98% of the plastic pipes are PE pipes. In 1982, the PE pipe was first used as an urban gas transmission pipeline in Shanghai, and then, various research studies and explorations have been conducted on raw material, fitting processing, engineering application standard specification of PE gas pipelines, etc. Besides, under the increasing demands for urban gas and the tendency of "replacing steel with plastic," some theoretical technical research studies achieved rapid development [6]. For example, great progress has been made in pipeline design, manufacture, construction and assembly, transportation technology, automation control, pipeline management, and operation. Furthermore, researches and applications of all kinds of new equipment and technologies have laid a strong foundation for the applications of the PE gas pipeline network in the future, and it also provides a guarantee for the safe, stable, and efficient operation of the natural gas pipeline. However, compared with the advanced technologies of PE pipelines in other countries, the development and application level of PE pipelines in China is low. Therefore, in order to promote the extensive use of PE pipes in China, it is one of the most important issues to evaluate their essential safety performance and long-term stable operation [7, 8].

The topology diagram of disaster evolution for natural gas pipeline leaks is shown in Figure 2. In order to reduce ultraviolet aging and human damage, PE pipelines are generally underground installed, and most of them are located at underground places with concentrated buildings and dense population. However, PE pipelines have high-risk and dangerous medium, and there are many factors that might cause disasters and significantly affect their safe operations, e.g., traffic barring, explosion, fire disaster, toxic gas diffusion, gas supply pressure drop, and gas interruption. Thus, some serious consequences might occur under the actions of certain factors, e.g., traffic jam, ground collapse, destruction of adjacent pipelines, loss of life and personal injury, and living in difficulty. Figures 3 and 4 show the statistics for the causes of outdoor gas accidents in 2021 and the causes of gas leakage in the first quarter of 2022, respectively. It can be seen that most of gas pipeline accidents are related to violent construction, external force damage, geological settlement, pipeline aging, and rapid cracking.

3. Failure Mode of Buried PE Pipelines

The walls of PE pipes can easily be damaged due to the nonstandard backfill and sharp bumps during the buried process. The interaction relationship and action mechanism between the PE pipelines and backfill soil (or base soil) are

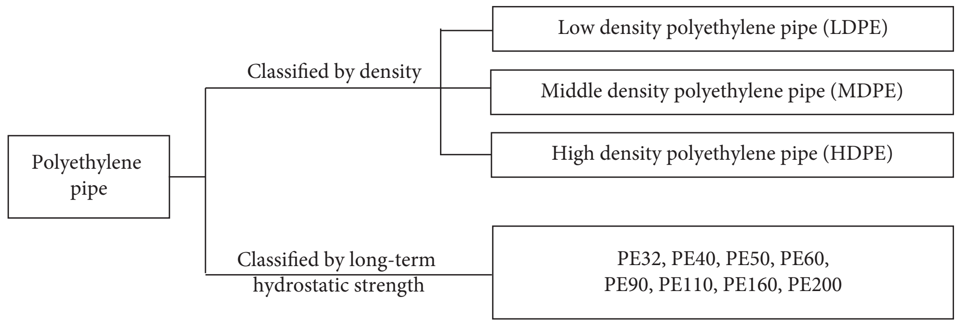

Figure 1: Classifications of PE pipes [4, 5].

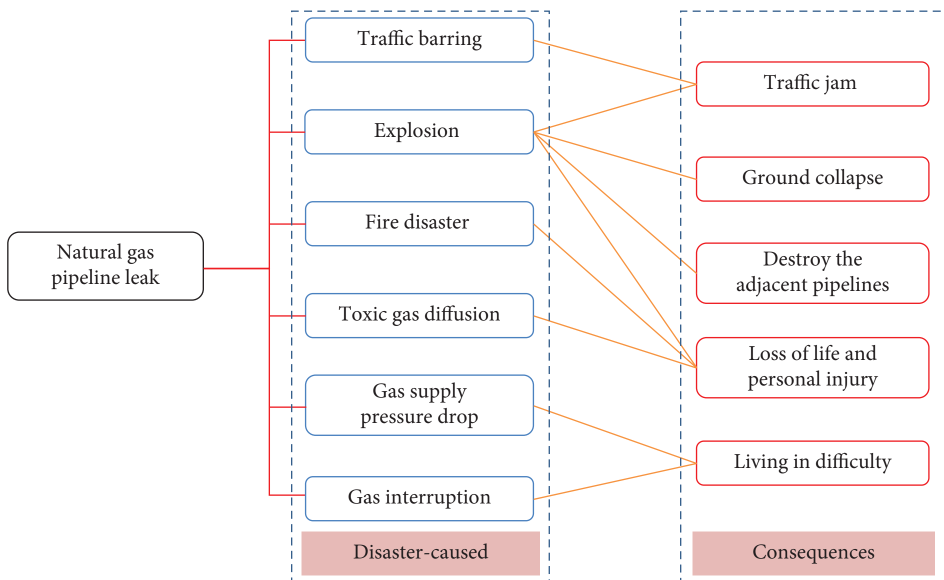

Figure 2: Topology diagram of disaster evolution for natural gas pipeline leaks [9].

complicated (Figure 5). The PE pipeline will be subjected to the external pressure (e.g., overlying soil pressure), and generally, the pressure on the pipeline is from all directions, including the inner wall pressure due to fluid. The inner wall pressure P_i and the external soil pressure P_o are distributed in each part of the pipeline (Figure 5). Besides, the performances of buried PE pipelines in service are significantly affected by various factors, e.g., surface subsidence, third-party damage, joint failure, pipe piercing, crack development, high temperature aging, corrosion failure, and pipeline defect (Figure 6). The above failure factors increase safety risks during the operation and maintenance of buried PE pipelines in service, and thus put forward high requirements for the integrity management of buried PE pipelines.

Actually, buried PE pipelines might suffer from more than one failure factor in service, and it is of great significance to clarify the failure mode and failure mechanism of buried PE pipelines under the action of a single factor for the safe operation, maintenance, and integrity management of buried PE pipelines. From the analysis of failure factors for a large number of buried PE pipelines in China, the main failure factors of buried PE pipelines can be divided into four levels (Figure 7). The first level of a failure factor is third-party damage, which is one of the crucial factors leading to the failure of buried PE pipelines, and more than half of the buried PE pipeline failures in China are caused by third-party damage, such as violent construction [12]. The second level includes three failure factors, i.e., surface subsidence, joint failure, and aging failure [13–15] (Figure 7). Surface subsidence includes the uneven deformation of pipes caused by the foundation of soil settlement, and the uneven settlement of ground is caused by vehicle loads, which in turn leads to the deformation and fracture of buried PE pipelines [16]. The joint is often the weak part of the buried PE pipe, and the joint failure often occurs due to the uneven deformation of buried PE pipelines. Besides, the failure risk of the buried PE pipe containing defective joints would sharply increase. The third level consists of pipe piercing, crack development, and pipeline defect (Figure 7) [17–19]. Three failure factors are often the secondary failure results caused by the above factors; for example, pipe piercing is often caused by third-party damage and pipeline defects are sources of scratches in pipeline installations and defective joints. Additionally, crack development is caused by the stress concentration points of buried PE pipelines, which are often induced by uneven deformation. The fourth level is corrosion failure (Figure 7), since many of the buried PE

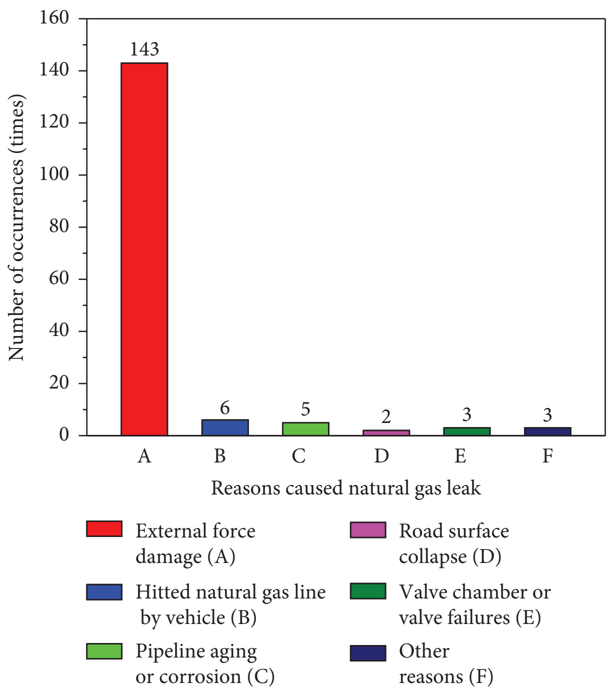

Figure 3: Statistics of causes of outdoor natural gas accidents in China in 2021 (source: the national gas explosion accidents in 2021 from the National Bureau of Statistics).

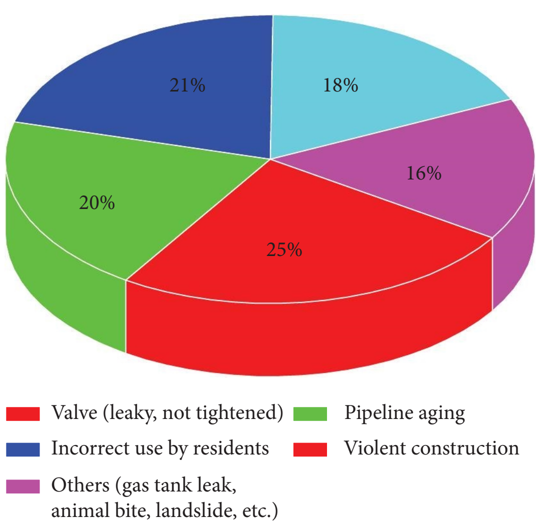

Figure 4: Statistical analysis of the causes of natural gas leakage in China in the first quarter of 2022 (source: the domestic gas explosion accidents in the first quarter of 2022 from the National Bureau of Statistics).

pipelines are made of polymer material, and therefore, corrosion failure has little effect on the performance of buried PE pipelines.

3.1. Third-Party Damage. Third-party damage refers to the accidental damage to natural gas pipelines due to behaviors of nongas pipeline employees in the construction process of road, foundation, pipe trench excavation, directional

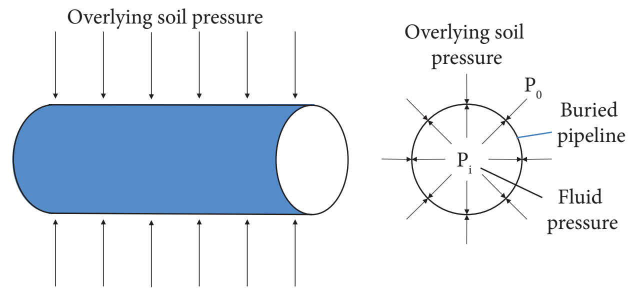

Figure 5: Schematic diagram of force at a cross section for buried PE pipelines [10].

drilling, cable laying, etc. Besides, damage or leakage of natural gas pipelines due to natural hazards (e.g., landslides, settlement destroy, and flood damage) and biological erosion (e.g., termite grazing) also belong to third-party damage [21]. There are two forms of third-party damage to natural gas pipelines: (a) the first form directly leads to the rupture of natural gas pipelines and causes gas leakage, which can easily cause accidents, such as explosion and fire, and can seriously threaten the safety of people's lives and property; (b) the second form refers to the damage of the external coating of the natural gas pipeline to a certain extent, including scraping and squeezing, which would leave a severe safety hazard for the pipelines. For the second form of third-party damage, if repair is not done in time, it would eventually lead to pipeline leakage due to external forces that cause pipeline fatigue, stress concentration, or pipeline corrosion [22].

From statistical analysis, we concluded that there are many reasons that cause third-party damage to natural gas pipelines. For instance, distempered laws and statutes correlated with natural gas pipelines, insufficient communications between gas enterprises and third-party constructions, imperfection of pipeline network information, inadequate labeling, warning signs related to pipelines, and poorly enforced government intervention. Therefore, some measures could be effectively introduced to avoid third-party damage. First, when the pipeline is within the construction scope of other projects, an inspector must be dispatched to communicate and supervise with the project manager to ensure the safety of pipelines. Second, labeling piles are set up externally on pipelines, and eye-catching signs are set up on ground to avoid the subsequent damage to pipelines caused by improper digging or illegal constructions. Additionally, some other measures could also be taken, e.g., preventing third-party damage using a GIS system, aircraft patrol technology, and direct call system, spreading the significance of pipeline protection, and raising public awareness through news media [23, 24].

3.2. Surface Subsidence. Surface subsidence refers to the phenomenon and continuous process of surface elevation reduction and ground deformation in a large area (Figure 8), which is mainly affected by natural factors and human factors. From the perspective of natural factors, reasons causing surface subsidence could be divided into three aspects, i.e., stratum variation, geological tectonic process, and

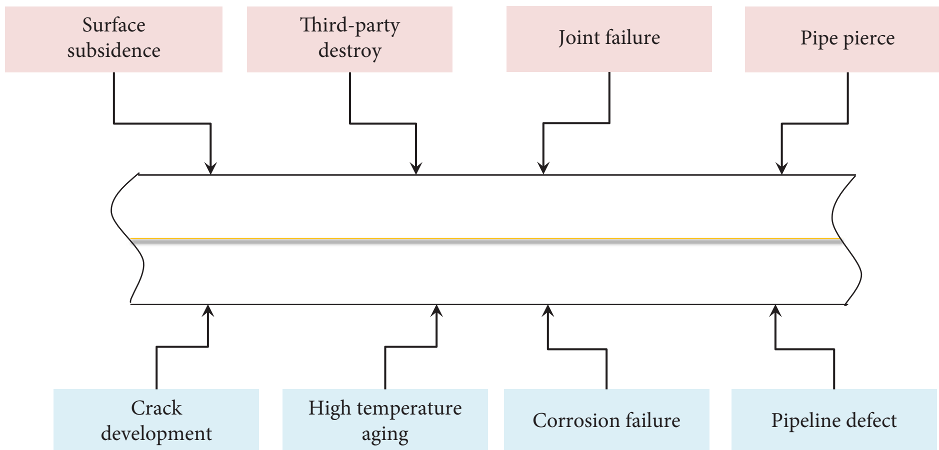

FIGURE 6: Main failure factors of buried natural gas pipelines in service [11].

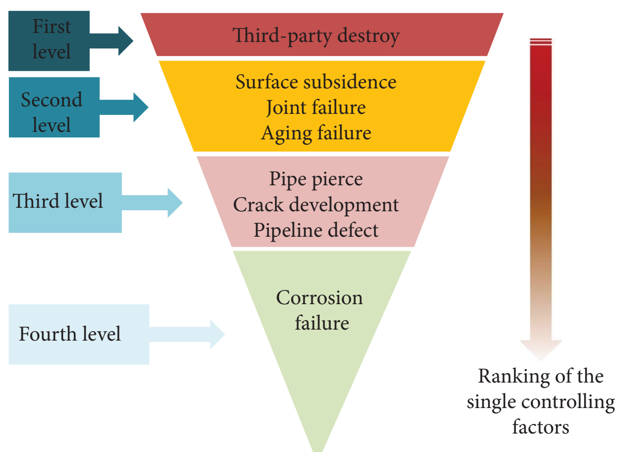

FIGURE 7: Rank of the main failure factors of buried PE pipelines [20].

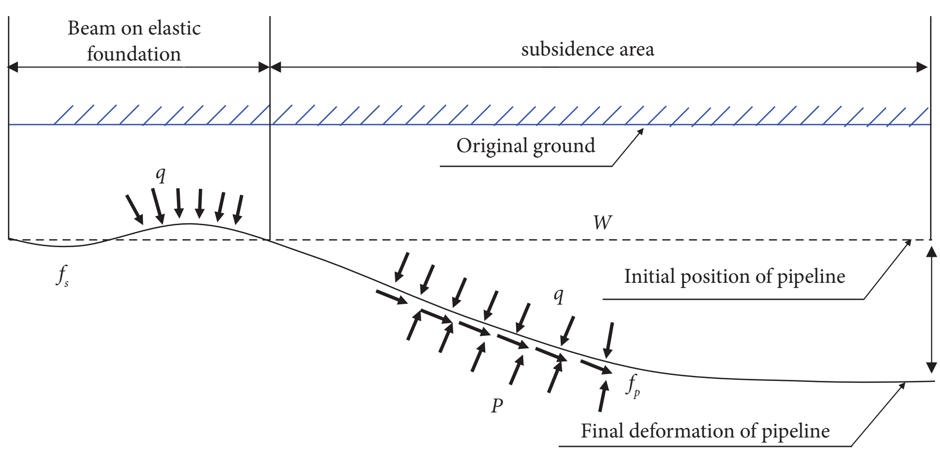

FIGURE 8: The deformation analysis model of buried pipelines under the action of surface subsidence [30].

earthquakes [25]. Usually, under the action of gravity, when the loose layer becomes dense, ground will settle due to the decrease in stratum thickness. The soil in the settlement area sinks or slips along the separation surface under the action of gravity, resulting in the corresponding vertical or tangential shear stress to pipelines, which might cause damage to pipelines (Figure 8). From the perspective of human factors, surface subsidence is closely related to human activities, which has become the dominant factor in recent years. Especially, with the rapid development of human society modernization, excessive exploitation of oil, natural gas, minerals, and groundwater resources directly leads to surface subsidence in many places. Besides, for the urban natural gas pipeline network, due to the overexploitation of groundwater, increasing number of high-rise buildings, and effect of transportation facilities such as railways, bridges, and transportation loads, surface loads and ground settlement acceleration drastically increase, leading to a large offset displacement of natural gas pipelines, which seriously endangers the safe operation of pipelines.

The deformation and failure process of buried natural gas pipelines caused by soil settlement and collapse could be studied by the combined methods of mathematical theory derivation, finite element software analysis, and indoor and outdoor geotechnical test simulations. For instance, first, the full-scale test of buried PE pipelines under vertical loads is used to obtain the change rule of the pipeline diameter change rate and soil surface settlement rate under parameter changes. The Mohr–Coulomb model is used to analyze parameters such as the load on the soil surface and the relative position of the load and pipeline, which provides a theoretical reference for practical engineering [26, 27]. Besides, combined analysis methods of the small-scale tests and numerical simulations were adopted to study the stress, strain, and their influence characteristics of the buried pipeline in settlement processes, so as to discover the cause of accidents. Additionally, some measures, such as casing pipes, soil replacement, flexible support, energy mitigation, support, and reinforcement, could be applied to alleviate or even eliminate the damage of surface settlement on buried pipelines [28, 29].

3.3. Joint Failure. At present, there are two most widely used connection methods between PE pipes, i.e., thermal fusion welding and electric fusion welding (Figure 9) [31, 32]. Besides, some other new polyethylene pipe welding methods have been introduced in engineering applications, such as ultrasonic welding, electromagnetic induction welding, laser welding, rotary welding, friction stir welding, and microwave welding [33]. For thermal fusion welding, the resistance wire, embedded in the inner wall of the fusion sleeve, is energized by using a fusion welding machine. Then, the contact interface between the sleeve and pipe is fused by the resistance heat. When the gap between the sleeve and pipe fitting is closed, the interpenetration entanglement of molecular chain segments occurs under the combined action of high temperature and expansion pressure. After natural cooling and crystallization, the welding strength between interfaces forms [34]. For electric fusion welding, two-welded pipe faces are closely attached to the heating plate until pipe faces are melted. Then, the two-fused pipe faces are connected together under the action of the welding pressure. It should be noted that in the cooling process, the welding pressure is always maintained for pipe faces. The International Pipeline Research Committee (ICRC) considers welded joints to be the most vulnerable part of pipelines because it is difficult to achieve the same materials between the welded joint and pipe material, and thus, welded joints and welded defects are regarded as "stable existing failure factors." Research studies on the failure modes of welded joints for PE pipes are mainly focused on the following aspects: the first is the joint tensile failure, including the fracture failure and fusion plane fracture failure, in which the fracture failure occurs from the outer edge root to the inner edge root. The second one is the fatigue failure of the thermal fusion-welded joint and the initial crack of the joint sprouted from the inner roll edge end and gradually extended to the middle of the outer coiling edge. Besides, the brittle fracture occurs in all failed joints. The third one is the failure of bending fatigue life, and the characteristics of the failure joint are as follows: the initial crack starts at the groove between the outer edge and the pipe, then, it spreads to the groove of the inner edge through the heat-affected zone, and after that, the fracture occurs. In addition, the rapid tensile test for the failure of bending fatigue life shows that the fracture appears in the thermal fusion zone, and this fracture belongs to a partial extension fatigue fracture [35].

Generally, ultrasonic testing and phased array ultrasonic nondestructive testing of welded joints are thought to be two effective measures to reduce the joint failure [36]. Ultrasonic testing is performed in accordance with the ultrasonic testing of electric fusion joints of polyethylene pipes (GB/T2961), nondestructive testing of polyethylene pipe weld (JB/T10662), and plastic weld nondestructive testing methods part 4: ultrasonic testing (JB/T12530.4). Phased array ultrasonic nondestructive testing can be referred to the phased array ultrasonic testing of welded joints of polyethylene (PE) pipeline for gas use (DB 31/T1058-2017).

3.4. Aging Failure. The high temperature aging of PE specimens aged by thermal oxygen means that the tensile strength of PE pipes gradually decreases with the increase in aging time and pressure. When temperature and pressure are low, the performance of the PE pipe slowly changes, while with the increase in temperature and pressure, the stability of PE pipes obviously deteriorates [37, 38]. There are many factors affecting the aging failure of PE pipes, which can be divided into internal and external factors [39]. The internal factor is the composition of PE pipes, including structure type, composition proportion, and material properties. The external factor includes working environmental conditions (e.g., temperature, pressure, humidity, acidity and alkalinity, and microbial erosion) and the heat radiation of surrounding heat pipes. Generally, the internal factor is the primary cause of the aging failure for PE pipes, while the external factor can significantly affect the internal factor and accelerate the aging failure of PE pipes. Aging will lead to irreversible changes in physical and chemical properties, thereby reducing their overall performance of PE pipes [40]. The commonly used aging detection methods include visual observation, hydrostatic test, tensile test, and thermal stability (oxidation induction time).

3.5. Crack Development. The crack failure of PE pipelines includes rapid crack propagation and slow crack growth. For rapid crack propagation (RCP), when the crack of PE pipelines occasionally happens, the crack rapidly grows at a large speed, which instantly causes the destruction of PE pipelines. Generally, the PE pipeline has great ductility and can absorb lots of mechanical energy before crack [41, 42]. However, the

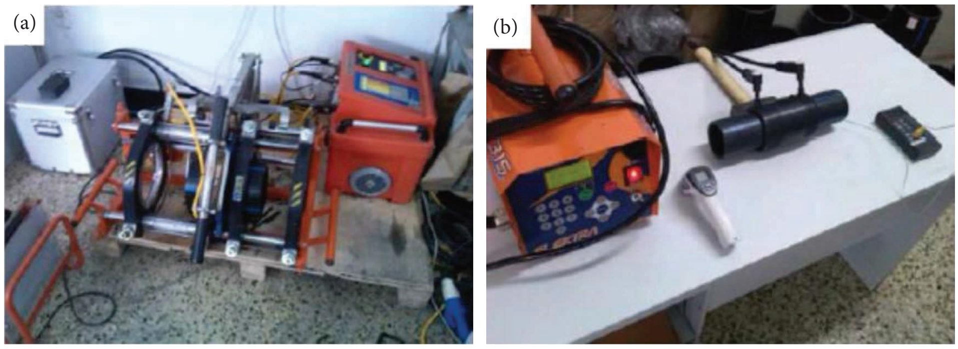

Figure 9: Connection methods between PE pipes: (a) thermal fusion welding and (b) electric fusion welding [31].

mechanical properties of polymer materials depend on the velocity and temperature of external force. If there is a defect in material or the loading speed is too large, the PE pipeline will not have enough time to undergo ductile deformation and then be damaged. For slow crack growth (SCG), the failure mechanism and the fracture mode of PE pipes occur under the action of a long time and low load [43, 44]. The slow crack growth of PE pipelines is essentially caused by creep and is usually a time-dependent fracture. Besides, slow crack growth is considered to be one of the most important hidden dangers that cause the failure of PE pipelines. Compared with rapid crack propagation, slow crack growth slowly occurs and is difficult to detect. Usually, failure of slow crack growth occurs before the usage time of PE pipelines reaches the expected service life, leading to more serious consequences. Currently, there are many kinds of experimental methods for slow crack growth, e.g., the curved strip method (ASTM D1693), notch constant band stress test (ASTM F2136), notch pipe test (ISO 13479), and single notch tensile test (ASTM F1473).

4. Comparisons of Failure Characteristics between Buried PE and Steel Pipelines

Steel and PE pipelines have various physical and mechanical properties, which lead to a significant difference in the service performance in practice. For example, compared with buried steel pipes, the density of PE pipes is only one-eighth of steel pipes, while inner wall roughness is one-tenth of steel pipes, and the service life is about 30 years longer than that of steel pipes. Table 1 lists the comparisons of main performances between steel and PE pipes. It can be seen that PE pipes have significant advantages in terms of mechanical properties, anticorrosion performance, and construction technology. However, corrosion and welded joint leakage are the two common problems in steel pipes during the service period, and PE pipes have excellent corrosion resistance and fissures, which can solve the above two problems of traditional pipes (i.e., corrosion and welded joint leakage) (Table 1).

Generally, the weak parts of steel pipes and PE pipes are various; that is, positions prone to leakage are different. It is significant to identify the weak parts or leakage positions of pipelines to ensure safe operations. Table 2 shows the distributions of main leakage points of steel and PE pipes, and it displays that the leakage points for steel and PE pipes mainly arise from three positions, i.e., joints, piercing points, and cracking points. Usually, for steel and PE pipes, most leakage points emerge from joints (Table 2).

The degradation mechanism of PE pipes is also significantly different from that of steel pipes. For steel pipes, corrosion is the main source to affect the service life of pipes. There are mainly four factors that cause the corrosion of steel pipes, namely, chemical corrosion, electrochemical corrosion, stray current corrosion, and microbial corrosion. Chemical corrosion is chemical contact reactions between metals and surrounding media, such as oxygen, hydrogen sulfide, and sulfur dioxide. Electrochemical corrosion occurs when metals contact with the electrolyte solution and forms a galvanic battery principle. Due to the leakage and grounding of various pieces of electrical equipment outside along metal pipelines, stray currents form in soil, and when the current flows through the natural gas pipe, it forms an electrolytic cell. Generally, stray currents can be divided into three forms, i.e., direct current (DC), alternating current (AC), and naturally existing ground current. Microbial corrosion refers to a corrosion process in which subsurface microorganisms participate. For instance, sulfate-reducing bacteria convert soluble sulfate into hydrogen sulfide via electrode reactions, which in turn chemically interact with metals and thus produce corrosion. However, the performance of PE pipes is affected by environmental factors, such as high temperature, humidity, and light, which will degrade its mechanical properties or even lose its service. Generally, we can judge whether the PE pipe suffers from aging from the following four aspects, appearance changes (e.g., color change, gloss, and crack), variation of physical properties (e.g., solubility, cold resistance, and heat resistance), variation of mechanical properties (e.g., tensile, bending, and shock resistance), and electrical properties changes (e.g., insulation).

Furthermore, the main load of buried PE pipelines is internal pressure, which may cause two failure modes, i.e., ductile failure and brittle failure [47]. The ductile failure, which belongs to the category of material mechanics, is damage caused by the creep of PE pipes over time, and the main reason for the ductile failure is the excessive pressure or load. Based on this failure mode, the current design criterion of the PE pipe is formed; that is, the service pressure of PE pipes is determined according to the relationship between the long-term life and long-term hydrostatic strength. The brittle failure belongs to the category of fracture mechanics, and when an episodic event causes a

Table 1: Comparisons of main performances between steel and PE pipes [45, 46].

Performances	Steel pipes	PE pipes
Mechanical properties	Poor ductility, toughness and resistance to fast crack transmission, poor seismic performance	Good ductility, toughness and resistance to fast crack transmission ability, good seismic performance
Anticorrosion performance	Risks of the corrosion protection and joint weld treatment in the humid environment	Excellent performance
Service life	Depend on anticorrosion	Easy to creep deformation
Fire hazard	Low (nonflame retardant material)	High (combustion-supporting material)
Construction technologies	Slow welding, large smoke, difficult transportation and lifting	Thermal fusion welding or electric fusion welding, fast construction speed, light material, easy transportation and lifting
Hydraulic interference	Rigid interfaces are affected	Rigid interfaces are affected
Thermal expansion and cold contraction	Need to design expansion joints	Need to design expansion joints

Table 2: Distributions of main leakage points for steel and PE pipes.

Locations	Steel pipes	PE pipes
Joints	Welding interface, tee interface, elbow interface, all kinds of wiring points	Conversion joint between steel pipes and PE pipes
Piercing points	Corrosion perforation points	Thermal fusion welding points
Cracking points	Welding point cracking	Aging damage points
Other points	Underground gas facility interface	

penetrating crack in the pipe wall, the crack might rapidly grow at a speed of hundreds of meters, leading to large-scale destruction of pipes in a short time. Subsequently, combustion and explosion accidents might occur. The main reason of the brittle failure is defects or scratches that exist in the operation of the pipeline.

5. Prevention and Control Technology of Buried PE Pipelines

Currently, PE pipes have been widely used in service for a long time in China. However, with the increased service age, the safety problems of PE pipes have been constantly exposed due to their material defects and external environmental factors. Therefore, in order to ensure and maintain the long-term operations of PE pipelines, nonexcavation technologies of construction, renewal, and repair for natural gas PE pipelines have been proposed and developed (Figure 10). Nonexcavation technologies refer to a professional technology that implements the construction, renewal, and repair of pipelines without excavating the ground, and it is a significant technology revolution in construction, renewal, and repair for underground pipelines [48]. Considering characteristics of the natural gas PE pipelines, there are some types of nonexcavation technologies for natural gas PE pipelines, e.g., PE pipeline nonexcavation rehabilitation with the cured-in-place pipe, PE pipeline intercrossing method, PE pipeline heating shrinkable expansion lining method, and PE pipeline U-shaped lining method.

5.1. Cured-in-Place Pipe. The cured-in-place pipe (CIPP) is a PE pipeline nonexcavation rehabilitation technology, and this method soaks thermoset epoxy resin glue into a textile fiber hose with sealing coating (thermoplastic polyurethane elastomer). Then, the solidified part is used as a lining material for repaired pipelines. Subsequently, the hose is turned into a buried pipe by air pressure or water pressure, and the face of the hose is immersed in thermoset epoxy resin glue pastes with the inner wall of buried PE pipelines while maintaining a constant inside pressure of the PE pipeline to make the resin glue cure. Consequently, a composite structure composed of original PE pipelines, epoxy resin glue, textile fiber, and sealing coating was formed to withstand external and internal loads. Thus, the original PE pipeline was repaired, transmission and distribution capacity of the original pipeline was restored, and potential safety risks of the original pipeline were eliminated. For example, some subsidence and dislocations between pipelines occurred in Nantong, Jiangsu Province in China in 2016, CIPP-repaired technology was used to eliminate the safety risks of buried pipelines, and repaired engineering was evaluated as an excellent project. Generally, technology is widely used when the ground surrounding buried pipelines is not convenient or cannot be excavated.

5.2. PE Pipeline Intercrossing Method. The method involves inserting a new PE pipeline into the old pipeline and replacing the old pipeline for gas supply. In the replacement, the diameter of the new PE pipeline is smaller than that of the old pipeline [49]. Generally, the intercrossing method in repaired old metal pipes usually uses pipe-class high-density

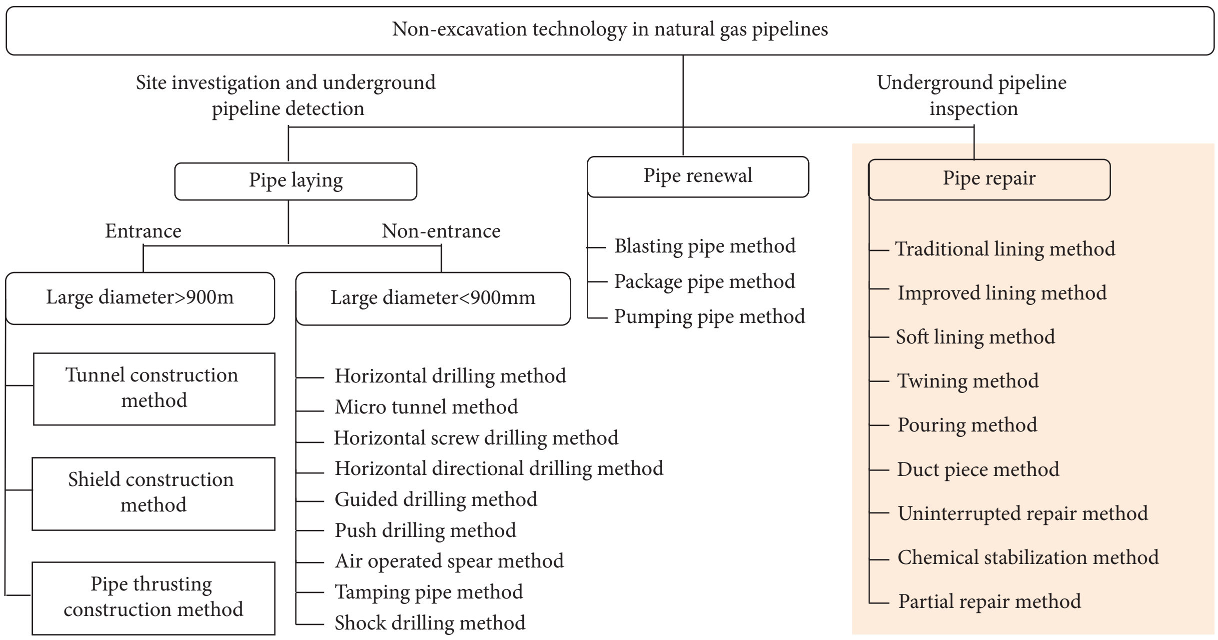

Figure 10: Nonexcavation technology of construction, renewal, and repair for natural gas pipelines.

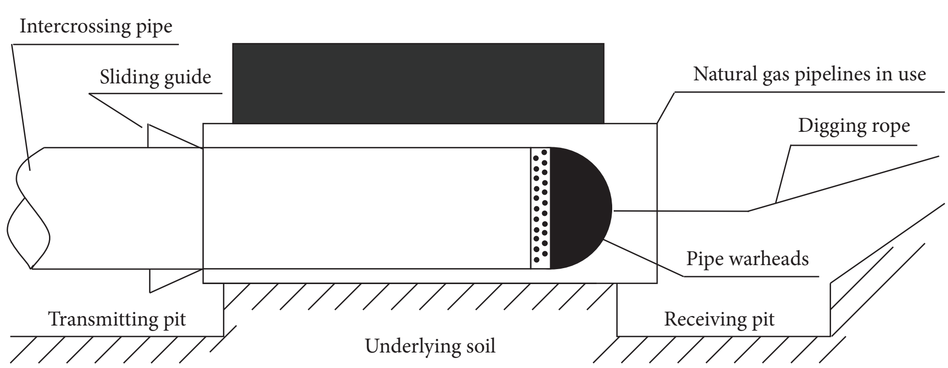

Figure 11: Construction technology processes of the intercrossing method in repairing buried PE pipelines [50].

polyethylene (HDPE) as lining plastic underlayer pipes. Figure 11 shows construction technology processes of the intercrossing method in repairing buried PE pipelines, and it can be seen that pipe warheads were used to drag the new pipeline through the old pipeline, one end is a PE pipe and the other end is a steel head with an iron ring, and the steel head was used to fix the rope. The gas transmission capacity of the repaired pipeline diminished under the same gas transmission pressure due to the reduction of the diameter of the inserted PE pipeline, and thus, the applications of this method are significantly limited to some extent. Therefore, some new technologies for repairing buried PE pipelines have been put forward, such as fiber-reinforced PE hose-repaired technology.

5.3. PE Pipeline Heating Shrinkable Expansion Lining Method and the U-Shaped Lining Method. The PE pipeline heating shrinkable expansion lining method and U-shaped lining method are almost the same. Taking the U-shaped lining method as an example, at the in situ site, the PE pipe is folded into a U-shaped and inserted into the existing natural gas PE pipe, and then, the U-shaped pipe restores its original circular shape though heated and pressurized steam. During construction, a pipe heating truck loaded with PE pipes and steam boilers is installed on the side of the starting vertical pit and a winch is installed on the other side of the final vertical pit. Because of the simple process and small construction land, this method is suitable for gas pipelines with complicated pipeline systems in the center of large cities where it is difficult to obtain work zones.

6. Conclusions and Discussion

Under the background of increasing natural fossil energy supply, PE pipelines have become one of the effective measures to transport oil and gas with many advantages, such as continuous efficiency, stability, reliability, and high environmentally friendly and low energy consumption in the transportation process. However, the engineering safety risks of buried PE pipelines in service increase due to material defects and external environmental factors. This paper mainly reviews the failure mode and the prevention and control technology of buried PE pipelines in service, as well as comparative failure characteristics between buried PE and steel pipelines. It can be concluded that the main failure factors of buried PE pipelines can be divided into four levels, the first level is third-party damage; the second level includes three failure factors, i.e., surface subsidence, joint failure, and aging failure; the third level consists of pipe piercing, crack development, and pipeline defect; the fourth level is the corrosion failure. Besides, steel and PE pipelines have various physical and mechanical properties, which lead to a significant difference of service performance and degradation mechanism in practice. Additionally, in order to ensure and maintain the long-term operations of PE pipelines, it is of great significance to develop and promote the non-excavation technologies of construction, renewal, and repair for natural gas-buried PE pipelines.

However, some further research studies on the failure mode and the prevention and control technology of buried PE pipelines are needed. (a) The service performance and degradation mechanism of buried PE pipelines in complicated environmental conditions are suggested to be studied, i.e., large deformation failure, joint failures between different materials, and combined actions of multiple single failure factors. (b) The interaction mechanism among the engineering structure, PE pipelines, and geological environment, as well as PE pipeline-geological soils coupled in multiple physical fields (e.g., hydro-thermal-mechanical) is also suggested to be further studied. (c) The combination of traditional engineering risk assessment and numerical analysis methods considering the interactions between the PE pipeline and geological environment is an effective way to improve the reliability of risk assessment for buried PE pipelines. (d) It is of significance to actively promote the construction of "intelligent monitoring" and "smart pipelines networks" to improve the operation level of PE pipe networks.

Data Availability

The data used to support this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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