

A Review of Research on Buried Defective Gas Pipelines under Seismic Action

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Abstract

Seismic action causes severe damage to buried pipelines. During an earthquake, the surrounding soil exerts both resistance and support forces on the pipeline, leading to pipeline deformation. This deformation in turn acts back on the surrounding soil. This interaction effect determines the deformation and failure mode of the pipeline. Corrosion, as an unstable factor contributing to the failure of buried pipelines, significantly increases the probability of pipeline damage. Scholars both domestically and internationally have conducted extensive research on the stress and deformation characteristics of buried pipelines under geological hazards such as fault displacement and ground subsidence. The primary research methods encompass theoretical analysis, experimental studies, and finite element simulation. Research findings on the mechanical behavior of buried pipelines under seismic action are summarized as follows.

Keywords

Seismic Action; Buried Pipe; Corrosion Defect; Pipe Soil Interaction.

1. Introduction

In recent years, China's economy has maintained stable and progressive growth, achieving new milestones in high-quality development. This has been accompanied by a continuously increasing demand for energy. The proportion of urban natural gas pipelines in the total length of urban gas pipelines has risen from 37.6% in 2000 to 98.4% in 2020. In terms of growth rate, natural gas pipelines constitute the primary component of urban gas pipeline networks and represent the main type of pipeline being developed in China. Against the backdrop of increasingly stringent environmental policies and the deepening "coal-to-gas" transition in the heating sector, natural gas, as a high-quality, efficient, green, clean, and low-carbon energy source, is being actively promoted nationwide for broader adoption. Its share in the country's total energy consumption continues to rise. In 2023, China's apparent natural gas consumption reached approximately 394.53 billion cubic meters, a year-on-year increase of 7.6%, highlighting the particular importance of urban natural gas pipeline construction.

Given China's vast territory, the construction of buried gas pipelines inevitably traverses seismically active regions. In these areas, seismic actions can readily trigger geological hazards such as landslides, fault movements, and liquefaction-induced settlement. These hazards can subsequently cause structural damage or rupture to the pipelines, ultimately leading to secondary disasters like gas leaks, fires, or explosions. On the other hand, the soil environment surrounding buried gas pipelines is highly complex in composition, representing a specific corrosive environment. This leads to external corrosion damage on the pipelines, further increasing the probability of accidents.

2. Research on Soil-Pipeline Interaction Under Seismic Action

During an earthquake, the surrounding soil exerts both resistance and support forces on the pipeline, leading to pipeline deformation. This deformation, in turn, acts back on the surrounding soil. The interaction effect between the pipeline and soil determines the pipeline's deformation and failure mode. Corrosion, as an unstable factor contributing to pipeline failure, significantly increases the probability of pipeline damage. In terms of modeling approaches, pipeline models have evolved from beam models to shell models, while soil models have progressed from soil springs to elastoplastic and then to viscoelastic models. Scholars both domestically and internationally have conducted extensive research on the stress and deformation characteristics of buried pipelines under geological hazards such as fault displacement and ground subsidence. The primary research methods encompass theoretical analysis, experimental studies, and finite element simulation.

2.1 Theoretical Analysis

In 1967, Newmark^[1], based on his research on pipelines, proposed that the deformation of the pipeline and soil occurs synchronously, leading to an approximate calculation method for the response of buried pipelines. However, this method neglects the influence of pipeline inertia and is only suitable for scenarios involving minor deformations. Subsequently, research on soil-pipeline interaction developed rapidly. Pipeline models evolved from beam models to cable models, and finally to shell models. Soil models progressed from soil springs to elastoplastic models, and then to viscoelastic models. In 1977, Kennedy, Chow, et al.^[2] divided a deformed pipeline under seismic action into three segments: two straight sections on either side experiencing minor deformation and a central curved section experiencing major deformation. By neglecting the bending stiffness of the pipeline, they derived the pipeline strain. Although this method does not consider the pipeline's bending stiffness, its simple assumptions and ease of calculation have led to its adoption in the codes of multiple countries for estimating pipeline stress and strain.

In 1979, the Japanese scholar Shinozuka et al.^[3] were the first to use soil-spring models to simulate the interaction between pipelines and soil. They simplified the buried pipeline, soil, and seismic waves as an elastic foundation beam, linear springs, and simple harmonic waves, respectively. The springs acted as a medium for wave transmission between the buried pipe and soil, transferring the soil's wave displacement to the pipeline. This method is known as the "response displacement method." It effectively simulates the displacement transfer process between pipeline and soil under seismic waves. In 1981, Wang^[4] first proposed a quasi-static analysis method for buried pipelines subjected to seismic body waves. This method is based on the understanding that because the mass of a buried pipeline is relatively small compared to the surrounding soil mass, and the soil's constraint on the pipeline is significant, the effects of damping and inertial forces on the pipeline can be neglected in the analysis. This method effectively calculates the axial deformation of buried pipelines under seismic body waves. It provides a simplified and effective analytical tool in earthquake engineering for assessing seismic impacts on buried pipeline structures. In 1982, Ye Yaoxian et al.^[5] conducted vibration tests on buried pipelines to investigate the co-deformation of pipelines and soil under dynamic loads. They proposed a computational model for assessing the stress in buried pipelines under seismic action. Zhang Tuqiao^[6] and Shen Wenming et al.^[7] respectively employed the Winkler elastic foundation beam model and the Pasternak two-parameter foundation model to establish longitudinal mechanical models for buried pipelines under differential ground settlement. These models aim to analyze the impact of differential settlement on the longitudinal mechanical behavior of buried pipelines. The Winkler model treats the soil as a series of independent springs, while the Pasternak model, building upon the Winkler model, adds soil continuity by considering shear effects through the introduction of a shear layer.

In 2004, Max A.N. Hendriks et al.^[8] compared the results from the elastic foundation beam model and the shell model, finding that the shell model was more accurate and aligned better with reality. However, the elastic foundation beam model is simpler and easier to calculate. In 2018, Zhao Yan, Jia Tian, Zhou Ruipeng et al.^[9], considering the non-stationary and coherence characteristics of seismic

loads, established a frequency-domain method for random vibration analysis of underground pipeline-soil coupled structures. They used Fourier-Stieltjes integrals to describe non-stationary random processes and characterized the time-varying properties of seismic load amplitude and frequency components via kernel functions. Fu Lingdi^[10] analyzed various complex factors affecting the axial compressive strain of pipelines crossing faults and, through MATLAB programming, derived a predictive formula for the maximum axial compressive strain in buried pipelines crossing reverse faults. In 2019, Zeng Xi^[11] simplified the small-deformation segment of the pipeline-soil system as a spring, considered the interaction between the pipeline and soil, and established the relationship between pipeline axial force and the relative displacement between pipeline and soil. In 2021, Wang Lijuan, Liu Xin, and Wang Jiahui et al.^[12] conducted an in-depth study on the forces acting on buried pipelines under seismic action using the elastic foundation beam model and wave theory. They simplified seismic waves as sinusoidal waveforms and simulated pipeline-soil interaction using spring connections. Based on this, they developed models for pipeline axial forces, transverse forces, torsional forces, and a combined forces model under combined deformation conditions. The establishment of these models particularly enhanced the analysis of torsional forces in buried pipelines and improved the accuracy of force analysis under combined deformation conditions. In 2022, Liu Jialin and Teng Zhenchao et al.^[13] established a COMSOL model for stress corrosion in pipelines. When tensile strain is applied to a pipeline containing corrosion defects, according to mechanical equilibrium principles, the resultant force across different longitudinal sections of the pipeline is constant. Since stress is inversely proportional to area, stress concentration occurs at the center of the defect. The stress level at different locations changes synchronously with the applied tensile strain. The non-uniform stress distribution at corrosion defects is primarily caused by the geometric shape of the defects themselves.

2.2 Experimental Study

In 2000, Feng Qimin et al.^[14] employed a soil container with a fracture gap. A pipeline model was placed inside the container and buried with soil. One half of the container was then moved relative to the other to simulate the ground vibration and subsequent fracturing at weak zones during an earthquake. Due to practical constraints, the soil model could not be excessively heavy, limiting the size of both the soil container and the pipeline model. Under sinusoidal vertical loading, it was observed that as the fault displacement increased or decreased, the relative deformation of the pipeline at the fault plane was most severe. The axial deformation of the pipeline exhibited an antisymmetric shape. In 2008, Bai Wenbiao^[15], during dynamic testing, used an MTS pseudo-dynamic device to apply dynamic loading to the first container, simulating the reciprocating motion under seismic action. This experiment specifically considered the horizontal displacement of Container 2 and the vertical motion of Container 1 to simulate seismic force effects. The soil fill height within the container was set at 0.8 meters to simulate the displacement of a horizontal slip fault. The pipeline inside the container was oriented perpendicular to the fault plane. Strain gauges were symmetrically attached on both sides of the pipeline to measure strain during loading. After constructing the pipeline model and completing equipment calibration, soil was backfilled into the container in layers to simulate the soil deposition process. In the third set of specimen tests, sand was specifically used to study the influence of this soil type on pipeline stress characteristics. During the static test phase, a total of 15 loading cycles were conducted. The strain and displacement responses of the pipeline were monitored and recorded for each cycle, while the fault displacement magnitude was gradually increased to assess its impact on pipeline performance. In 2009, Kim J. et al.^[16] conducted detailed experiments on concrete pipelines using the Life-Line Testing Facility within the Network for Earthquake Engineering Simulation (NEES). They employed a large-scale model to thoroughly investigate the response of pipelines buried in loose granular soil under permanent ground deformation. This experiment involved connecting 13 segments of concrete pressure pipes and using strain gauges and sensors to accurately measure axial strain. A key finding was that the ends of the pipeline located at the crossing point of the seismic fault were most susceptible to fracture, exhibiting relatively poorer seismic performance.

In 2016, Liu Zhou^[17] set up three containers. An MTS system was used to apply vertical displacement to the middle test container, simulating fault action under seismic conditions. The pipeline model was buried parallel across all three containers, with the extending parts outside the middle container considered to represent infinity. The test results indicated that for pipelines located at the fault, the pipeline strain increased as the fault displacement increased. In 2019, Han Junyan et al.^[18] utilized a nine-shake-table array system to design and conduct, for the first time, a three-table-array shaking table test for buried pipelines under multi-support non-uniform excitation, studying the seismic response of soil layers under such conditions. Through the experiments, they analyzed the dynamic characteristics and acceleration responses of free-field and non-free-field soils. They investigated the seismic response characteristics and variation patterns of soil under different ground motions and intensities, with both uniform and non-uniform excitation. Comparisons were made regarding the acceleration amplification factors between free-field and non-free-field soils, as well as the acceleration time histories and Fourier spectra at the same measurement points. The experimental setups designed by Tian Jiangping^[19] and Lei Zhen^[20] consisted of two detachable containers, using a jack as the loading device to simulate fault displacement through stepwise loading. In 2021, researchers Dai Jianbo and Hu Chengtao et al.^[21], through in-depth analysis of the response of buried oil and gas pipelines under the traveling wave effect of earthquakes, developed a bi-directional laminar shear-type continuum model soil container. They designed a testing scheme and conducted shaking table tests to simulate seismic effects on buried oil and gas pipelines. The experiments compared the strain response, acceleration response characteristics, and their variation patterns of the pipelines and surrounding soil under transverse uniform seismic excitation versus excitation considering the traveling wave effect. Jiao Wenshuai et al.^[22] used an MTS system to drive the shaking table. The effects of ground friction were neglected during the test analysis and loading process. Zhu Jiang^[23] adopted a shaking table test scheme. For the model test, a soil container measuring 4 meters long, 0.84 meters wide, and 0.944 meters high was used. This container was designed as a three-segment structure, with the segments connected by hinged telescopic devices. The middle segment of the container's base was mounted on the shaking table via 12 ball bearings at each end. These bearings supported the container's weight and allowed necessary sliding. The left and right segments of the container were placed on two independent shaking tables, respectively. Gaps between layers were connected via ball bearings and grooves, ensuring mutual displacement between layers. On both sides of the container, limit plates were installed and secured via sliding grooves to prevent sliding between frame layers. The limit plates were bolted to the container frame, while limit cables in the middle tightly connected the frame layers. Testing confirmed that when seismic motions were input to the shaking tables, the soil container could effectively simulate the horizontal and vertical shear deformations experienced by the soil mass.

2.3 Numerical Simulation

In 2013, Wang Lili et al.^[24] used the finite element method to establish numerical models for oil pipelines with and without crack defects. By combining solid modeling with automatic mesh generation, they completed the development of a finite element model for an oil pipeline containing a crack defect. Through numerical simulation analysis, they investigated pipeline behavior under various conditions, including the presence and depth of cracks, as well as stress and deformation under seismic loads. The results indicated that the presence of crack defects causes stress redistribution within the pipeline and reduces its seismic performance. In 2015, Md. Aftabur Rahman^[25] made the first attempt to combine the Discrete Element Method (DEM) with the Finite Element Method (FEM) in the field of buried pipelines. Discrete spherical particles were used to model the soil, and numerical simulations were conducted to obtain the pipeline's response under fault slip. The deformation, strain, and force responses induced by permanent ground displacement were discussed. The use of an assembly of spherical particles made the proposed model more realistic, and the pipeline in the model remained at a shallow burial depth. The pipeline deformed following particle movement upon rupture, correspondingly exhibiting incremental strain with fault slip. The movement of contacting particles was tracked, and based on this, the relative displacement between the pipeline

and particles was calculated. This relative displacement indicated the significant influence of particles on the pipeline near the fault crossing point. Particles near the crossing point reached yield values earlier than those farther from the fault. Mu Yuan et al.^[26] used ABAQUS to establish a three-dimensional model of a buried pipeline, including straight and bent pipe sections, considering the physical and mechanical properties of the pipeline. To simplify the model and ensure the reliability of calculation results, specific boundary conditions were adopted. The ends of straight pipe sections were connected to the ground using equivalent nonlinear springs to simulate soil-pipeline interaction. A detailed pipeline model including both straight and bent sections was established. For complex ground conditions, spring elements were used to simulate the soil and the interaction between the pipeline and soil. The model's calculation results showed that the buried pipeline underwent compressive plastic deformation under the action of a reverse fault but remained in a safe state. In 2017, Tahamouli Roudsari M^[27] modeled GRP pipes of different diameters in finite element software and calculated failure criteria based on maximum strain. Tests on GRP pipes of various diameters were conducted in different types of sand and clay under landslide and seismic wave propagation conditions. The results showed that for straight-buried GRP pipes of different diameters, failure is possible under the action of either average or strong seismic waves. Quan Kai and Zhou Qingsha^[28] used finite element analysis to study the mechanical response and potential buckling behavior of buried pipelines under fault displacement. A finite element model including the pipeline and soil was established, considering the nonlinear contact behavior at the pipeline-soil interface. The research results showed that as fault displacement increased, pipeline deformation also increased. Particularly at lower diameter-to-thickness ratios (i.e., smaller wall thickness), the pipeline was more prone to local buckling.

In 2018, Dong Feifei et al.^[29] used ABAQUS for simulation. They constructed a three-dimensional model including the pipeline and surrounding soil, where the pipeline used 4-node shell elements and the soil used 8-node reduced-integration solid elements. A nonlinear contact model was established between the pipeline and soil, considering both normal and tangential actions. By adjusting parameters such as fault displacement, pipeline crossing angle, and soil properties, they analyzed the specific impact of these factors on the pipeline's mechanical performance. The results indicated that an increase in fault displacement led to increased pipeline displacement and warping, with the final curve tending to stabilize. Chen Yanfei^[30] established a finite element model for an oil pipeline containing multiple corrosion defects. The study found interactions among the corrosion defects that affected the pipeline's remaining strength, and a formula for calculating its failure pressure was proposed. In 2019, N. Psyrras^[31] established a refined finite element model of a certain type of heterogeneous geological medium and the cylindrical shell pipeline traversing it. The model predicted the range and spatial distribution of longitudinal ground strain peaks developed along the pipeline under low and high-intensity seismic motions to highlight the most critical scenarios. The results showed that under specific conditions, a typical buried, large-diameter, high-pressure steel natural gas pipeline subjected to seismic wave propagation loading could exhibit non-axisymmetric shell wrinkling. With increasing load, this wrinkling gradually localized and led to collapse. Zhang Jie et al.^[32] used a coupled soil-pipeline numerical calculation model, taking a buried pipeline in loess stratum as the research object. Through numerical simulation, they analyzed the deformation and local instability behavior of the pipeline under reverse fault action. The study found that an increase in stratum dislocation led to stress concentration in the pipeline on both sides of the fault plane, which could gradually develop into local buckling.

In 2023, Wu Ying et al.^[33] used the finite element analysis software ABAQUS to simulate and analyze the influence of factors such as corrosion depth, corrosion width, and corrosion length on the seismic dynamic response of pipelines. The dynamic response method was used for seismic response analysis of the pipeline, with seismic acceleration time history as the ground motion input. The von Mises equivalent plastic criterion was adopted to describe the soil constitutive model. The results showed that as corrosion defects increased, the maximum equivalent stress exhibited a linear upward trend, while internal pressure and laying angle affected the initial stress value of the corroded pipeline.

Cheng Xudong et al.^[34] established a model for pipelines under the combined action of internal corrosion and strike-slip fault, analyzed the stress and strain of the corroded pipeline, proposed a method for determining pipeline failure modes based on corrosion parameters, and defined the boundary between stress failure and strain failure. In 2024, Dong Ya and Wang Fei^[35] studied the mechanical response of buried pipelines using different numerical models such as beam-shell coupling models and PSI elements. They discussed the differences and applicability of stress-based and strain-based pipeline design and assessment criteria. It was pointed out that in areas prone to geological hazards, stress-based design criteria might be insufficient to meet strength requirements. Therefore, it was recommended that, in addition to stress-based design methods, strain-based design criteria should also be considered. Sun Bijun et al.^[36] established a finite element model and used system energy conservation and pseudo-static tests to validate the numerical model's effectiveness. The model validation results confirmed the accuracy and reliability of the finite element simulations, with an average error less than 5% and a maximum error of about 6.2%. The study found that pipeline wall thickness had the strongest influence. The greater the burial depth, the more significant the impact of fault displacement, and shallow burial could enhance the pipeline's ability to resist fault displacement. Xue Jinghong et al.^[37] employed finite element models with different boundary conditions (such as viscoelastic boundaries and artificial boundaries) to study pipeline responses under different seismic waves (P-waves and SV-waves). By varying corrosion width, depth, and insulation layer thickness, they investigated the influence of these factors on the stress response in the corroded area of the pipeline. The research results indicated that the growth rate of Mises stress in the corroded area under SV-waves was higher than under P-waves, which is significant for pipeline safety assessment.

3. Conclusion

In summary, the finite element modeling of buried pipelines traversing seismic hazard zones primarily employs beam models and shell models. In beam models, the pipeline is simplified into one or multiple beam elements, which possess significant height and limited width along one dimension while their length may vary along another. This approach is suitable for analyzing scenarios involving small displacements and strains. Shell models are applicable for examining large deformations and strains; however, they struggle to adequately handle complex geometric shapes and intricate loading conditions. Research on corroded pipelines predominantly relies on numerical simulations, with experimental studies being relatively scarce. Within the numerical simulation process, key challenges include establishing reasonable constitutive models and accurately characterizing the initiation and propagation processes of corrosion defects.

Current research on the mechanical response of buried pipelines mainly utilizes soil-container model tests. Due to experimental constraints, these tests represent a simplified version of full-scale experiments, i.e., scaled-down tests. Nevertheless, scaled tests also face limitations, such as difficulties in eliminating boundary condition constraints and ensuring consistent soil density across multiple trials. Although physical model tests can yield definitive conclusions, technical limitations prevent them from providing precise quantitative results. Therefore, a combined approach integrating experimental and numerical simulation methods is recommended to investigate the mechanical response of buried defective gas pipelines under seismic action.

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