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Fatigue Crack Growth Behavior and Life Prediction Analysis of Buried Pipelines with Circumferential Cracks under Vehicular Loads

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Abstract

With the increasing prevalence of urban roads intersecting with underground pipelines, fatigue failure of buried pipelines induced by vehicular loads has become increasingly prominent. To clarify the crack growth behavior, identify the most critical crack locations, and assess the remaining service life of buried pipelines containing circumferential cracks under cyclic vehicular loading, an ABAQUS-FRANC3D co-simulation approach was employed to investigate fatigue crack propagation. By comparing the effects of different crack positions (top/bottom/side surfaces, inner/outer surfaces), the study analyzed their influence on crack-tip stress intensity factors (K), crack propagation morphology, and pipeline life. Key conclusions are: For circumferential cracks, regardless of location, propagation initially occurs primarily along the circumferential direction before extending axially. Cracks located at the inner side surfaces exhibit higher propagation risk and are more prone to failure. Inner surface cracks generally endure fewer load cycles before failure compared to outer surface cracks.

Keywords

Buried Pipeline; Fatigue Crack; Vehicle Load; Stress Intensity Factor; Numerical Simulation.

1. Introduction

In recent years, with the acceleration of China's urbanization process, the level of road construction has continuously improved, and the number of municipal pipelines has also increased significantly. Many pipelines were buried during the initial construction phase. However, with prolonged service time, safety issues in their operation have gradually emerged. The *National Statistical Analysis Report on Underground Pipeline Accidents* shows that failures caused by structural problems inherent in the buried pipelines themselves account for the highest number of incidents, with cracks being the most common type[1].

Numerous researchers have investigated cracked pipelines. In 2019, Zhang Baolong et al. [2] developed a specialized finite element model for settlement simulation tests. This model adopted fracture toughness as the failure criterion, effectively computing and simulating the ultimate bending moment capacity of pipelines containing circumferential surface cracks. In 2020, Allan Okodi et al. [3] employed the extended finite element method (XFEM) to study crack propagation and burst pressure in pipelines with constrained and unconstrained concentric dent-crack defects. While results indicated that dent-crack defects posed relatively low integrity risks to pipelines under monotonically increasing pressure, the study only considered two crack depths without comprehensively examining dent-crack effects on pipeline integrity. In the same year, the author [4] further applied XFEM to investigate crack growth and rupture pressure in longitudinally cracked pipelines. Also in 2020, Atika Hossain Akhi et al. [5] calculated stress intensity factors (SIF) for buried cast iron pipes affected by external corrosion and cracks. Their study incorporated pipeline geometry, corrosion pit dimensions/shapes, and crack location/orientation, combining finite element analysis with analytical methods to solve SIF under diverse operating conditions. In 2021, Yang Qian [6] conducted an in-depth analysis of crack propagation characteristics in X80 long-distance pipelines based on actual engineering cases. Additionally, the research examined how variables (e.g., crack arrestor length, thickness, and material grade) influenced crack arrest behavior in X80 gas transmission pipelines. In 2022, Zhu Renchi et al. [7] investigated the effects of single/double point defects on pipelines with spiral weld flaws and associated crack propagation. Their methodology integrated finite element simulations with wide-plate tensile experiments. In 2023, Xiong Haiyin [8] focused on calculating plastic limit loads for large-diameter thin-walled pipelines with lack-of-penetration defects under combined internal pressure and bending moments. The research also established computational models and safety assessment curves for such defective pipelines. Also in 2023, Duan Yuhang et al. [9] modeled a river-crossing gas pipeline suspension span containing crack defects. Their finite element analysis examined complex stress, strain distributions and crack driving forces characterized by the J-integral. In 2024, Mingjiang Xie et al. [10] developed a multilayer perceptron-based model for predicting fatigue crack propagation in buried pipelines subjected to rockfall impact loads. However, the limited sample size may constrain practical applicability, as real-world rockfall impacts exhibit complex variability that could reduce prediction scope and accuracy.

In summary, existing research predominantly focuses on crack propagation under static loads or internal pressure, with insufficient investigation into how dynamic stress amplitudes induced by moving vehicular loads affect crack growth rates. Comparative studies on propagation characteristics of circumferential cracks at different pipeline locations remain limited. This study employs ABAQUS-FRANC3D co-simulation technology to simulate crack propagation in buried pipelines containing pre-existing micro-cracks under vehicular loading. The methodology comprises: Establishing a finite element model for buried pipelines under static loading and utilizing ABAQUS-FRANC3D co-simulation to determine crack-tip stress intensity factors (SIF), with validation against theoretical calculations; Simplifying vehicular loads as moving constant loads to simulate fatigue crack propagation under operational traffic conditions.

2. Theoretical Basis

2.1 Crack Types

Based on the location within a structural component, cracks can be classified as through-thickness cracks, surface cracks, or subsurface cracks. According to their mechanical characteristics, cracks are categorized as Mode I (opening mode), Mode II (sliding mode), or Mode III (tearing mode).In practical cracked bodies, cracks may not exist in these pure forms but rather as combinations of two or more fundamental types. Such cracks are termed mixed-mode cracks.Among the three fundamental crack types, Mode I (opening mode) cracks are the most prevalent, most hazardous, and most technically significant, constituting the primary focus of research[11].

2.2 Stress Intensity Factor Calculation

The SIF is a physical quantity characterizing the intensity of the elastic stress field at a crack tip and represents a crucial concept in fracture mechanics. Various methods exist for calculating stress intensity factors.

For semi-elliptical surface cracks in flat plates, Newman and Raju proposed a classical SIF formula in 1981[12].

$$K_{\mathrm{I}} = \sigma\sqrt{\pi\frac{a}{Q}}F \tag{1}$$

where:σ is the far-field stress (Pa),a is the crack depth (m),Q is the elliptical crack shape factor,F is the geometric correction factor. Expressions for Q and F in this formula can be found in reference [12].

Subsequent researchers introduced curvature corrections to study stress intensity factors at crack tips in buried pipelines based on this work[13,14,15].

$$f_R = 1 + C\left(\frac{a}{R}\right) \tag{2}$$

where:β is an empirical constant, typically ranging from 0.1 to 0.3,D is the mean diameter of the pipeline (m).

For circumferential cracks in buried pipelines, the dominant stress is the axial stress induced by internal pressure, which can be calculated using[16]:

$$\sigma = \frac{0.25pD}{t} \tag{3}$$

where:P is the design internal pressure of the pipeline (Pa),D is the pipeline diameter (m),t is the pipeline wall thickness (m).

3. Verification of Simulation Methodology

3.1 Finite Element Model

A three-dimensional solid model of the soil mass and pipeline was developed using ABAQUS/CAE. The soil dimensions (length × width × height) were 24 m × 10 m × 8 m. To accurately represent actual field conditions where road pavements exhibit layered characteristics, the soil was divided into four strata: pavement layer, base course, sub-base, and subgrade. Material parameters for each soil layer (Table 1) were determined based on synthesis of references [17, 18]. The pipeline material employed was X60 steel (Table 2).

Table 1. Material parameters of the soil body

Material	Thickness (m)	Density (kg/m³)	Elastic Modulus (MPa)	Poisson's Ratio
Pavement Layer (Asphalt Concrete)	0.18	2400	1200	0.3
Base Course (Cement-Stabilized Gravel)	0.6	2000	1000	0.25
Sub-base (Silty Clay)	0.1	1800	80	0.25
Subgrade (Soil Foundation)	7.12	1900	50	0.35

Table 2. Pipe dimensions and material parameters

Material	Outer Diameter (m)	Thickness (m)	Density (kg/m³)	Elastic Modulus (MPa)	Poisson's Ratio	Yield Strength (MPa)
Steel Pipe	1.016	0.012	7850	206000	0.3	415

The C3D20R element (20-node quadratic brick element with reduced integration) was selected for meshing both the soil mass and pipeline. Refined meshing was applied to the soil surrounding the pipeline and the crack region of the pipeline (Figure 1).The model incorporated the following loads: Gravity,Internal pipeline pressure (set at 10 MPa),Concentrated static load (simplified as tire contact area: 0.23 m × 0.156 m rectangle[19-20]).The pressure magnitude corresponded to that generated by a 100 kN single-axis standard axle load over this contact area.

The ABAQUS-generated .inp file was imported into Franc3D, where a semi-elliptical surface crack with semi-major axis = 0.01 m and semi-minor axis = 0.005 m was introduced. The computation was then submitted to determine the stress intensity factors at the crack tip.

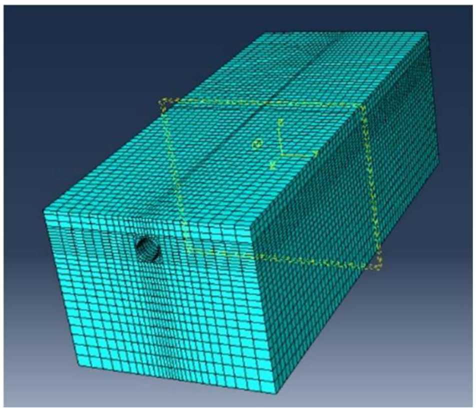


Fig. 1 Soil body mesh

3.2 Theoretical Results and Numerical Simulation Verification

The theoretical and simulated values of stress intensity factors (SIF) along the front of a circumferential inner-surface crack in a buried pipeline are presented in Table 3. According to the data:Simulated values exhibit a monotonic increase with growing crack angle.Theoretical values show a slight decrease between 0°–10°, followed by a gradual increase from 10°–90°. At the crack surface point (0°), the error reaches 57.7% (markedly anomalous). In shallow regions (10°–20°), errors rapidly decrease from 20.61% to 5.31%. In mid-to-deep regions (30°–90°), errors remain stable between 0.88% and 2.72%, demonstrating high agreement (consistently <3%).

Table 3. Comparison of theoretical vs. FEM-simulated SIF values for circumferential inner surface cracks

Crack Angle	Theoretical Value ($\times 10^7$ Pa√m)	Simulated Value ($\times 10^7$ Pa√m)	Error
0°(Surface)	2.1648	0.9143	57.7%
10°	2.1150	1.6792	20.61%
20°	2.1506	2.0364	5.31%
30°	2.2314	2.2555	1.08%
40°	2.3283	2.3916	2.72%
50°	2.4251	2.4866	2.54%
60°	2.5114	2.5639	2.09%
70°	2.5793	2.6077	1.1%
80°	2.6227	2.6460	0.88%
90°	2.6376	2.6953	2.19%

This divergence may arise because: The crack surface point (0°) lies at the free boundary, where the stress field is significantly influenced by pipeline curvature and loading conditions. While theoretical values derive from axial stress induced solely by internal pressure (Eq. 3), actual operational loads (gravity + internal pressure + concentrated static load) generate a complex non-uniform stress field, causing deviation from the idealized model. Notably, the variation trend and magnitude of simulated SIF align with computational results in references [21, 22]. This confirms the validity of the ABAQUS-FRANC3D interactive simulation technique for determining SIF at crack tips in buried pipelines.

4. Crack Propagation in Buried Pipelines under Moving Constant Loads

4.1 Finite Element Model

The finite element model employed for simulating crack propagation in buried pipelines under moving constant loads is fundamentally consistent with the validated model described previously, with only two modifications: Replacement of the static load with a moving constant load; Implementation of mesh refinement in the central pipeline section. Within ABAQUS: The moving constant load is applied via a DLOAD subroutine, translating along the pipeline's axial direction; Mesh refinement in the central pipeline region facilitates adaptive remeshing during crack propagation.

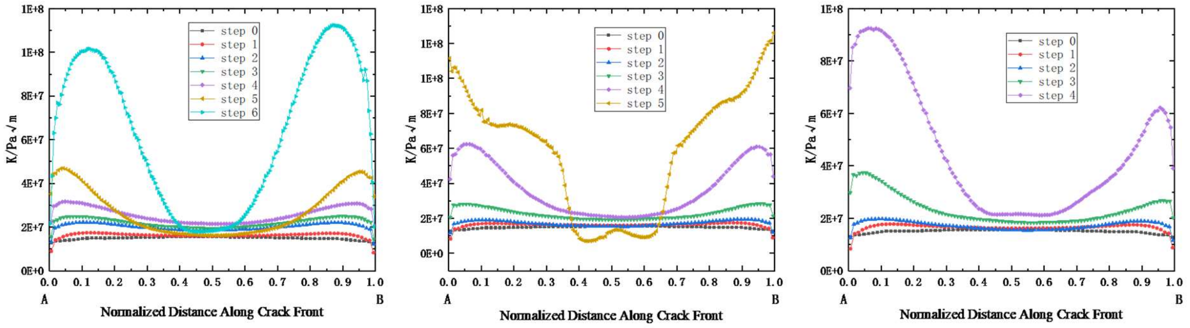
First, establish an intact (crack-free) global model in ABAQUS and define a submodel region via a *SET*. Subsequently, import the ABAQUS-generated .inp file into Franc3D, introduce an initial crack within the predefined submodel, and regenerate the mesh. Finally, merge the submodel with the global model to compute SIF at the crack tip. Franc3D then simulates the crack propagation process based on SIF results and fracture criteria (e.g., Paris' law), analyzing: Crack growth paths, Propagation rates, Final fracture morphology.

This study employs finite element software to simulate fatigue crack propagation in buried pipelines with circumferential cracks subjected to vehicular loading. By varying crack locations: Pipeline crown (top), Invert (bottom), Sidewalls, Inner surface, Outer surface. The research investigates their effects on: Crack-tip SIF, Crack propagation behavior, Pipeline fatigue life.

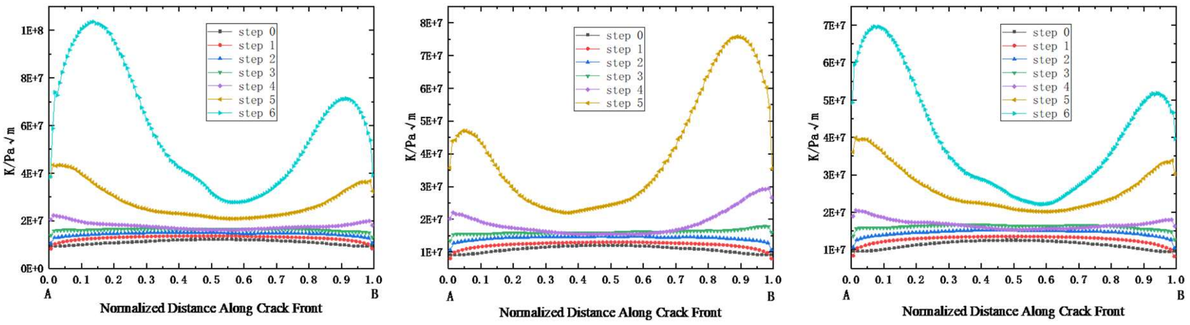
4.2 SIF

This study simulates crack propagation for circumferential cracks at various locations in buried pipelines under cyclic vehicular loading. Following crack initiation, unstable propagation occurs when the stress intensity factor $K \geq K_c$, characterized by rapid crack advancement without increased external load; conversely, when $K < K_c$, stable propagation (termed subcritical growth) proceeds only under increased loading. After a period of stable extension, cracks ultimately transition to instability, causing structural fracture. Consequently, the termination criterion requires $K_{\max} \geq K_c$. Computationally, a crack growth increment of 0.001 m is implemented—should termination remain unmet, the simulation proceeds with mesh updating until the criterion is satisfied.

The computational results for six distinct crack configurations, presenting SIF at each propagation increment, are summarized (Figure 2). Analysis of the data reveals that SIF values across all crack locations exhibit a consistent upward trajectory with increasing load cycles throughout the propagation process. This trend reflects progressively intensifying stress concentration at the crack tip, accompanied by increasingly severe SIF fluctuations and cumulative degradation of structural integrity. While specific SIF magnitudes and fluctuation patterns vary among crack positions, all cases demonstrate a unified mechanical response: as crack propagation advances, the amplitude of SIF variations escalates and peak values rise systematically. Critically, the location of maximum SIF within each propagation step gradually migrates from the deepest crack point (φ=90°) toward the crack surface.



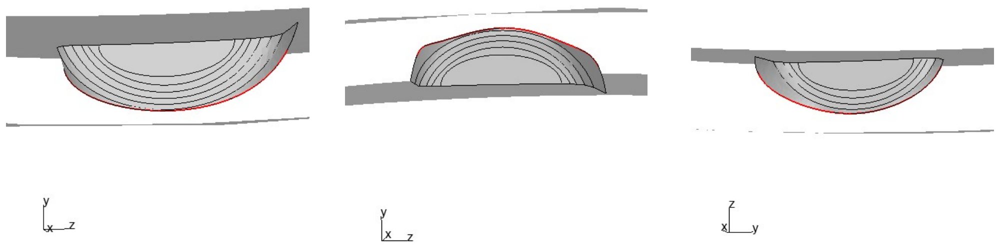
(a) Inner-Invert (b) Inner-Crown (c) Inner-Sidewalls



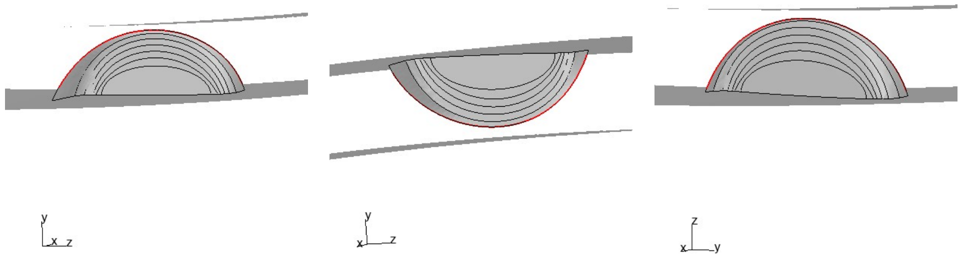
(d) Outer-Invert (e) Outer-Crown (f) Outer-Sidewalls

Fig. 2 SIF at each crack location for every propagation step

4.3 Crack Propagation Morphology



(a) Inner-Invert (b) Inner-Crown (c) Inner-Sidewalls



(d) Outer-Invert (e) Outer-Crown (f) Outer-Sidewalls

Fig. 3 Internal crack morphology

Analysis of crack propagation morphologies across six locations (Figure 3) reveals that during the initial 2-3 propagation increments, all cracks primarily extend circumferentially along the pipeline. Beyond these stages, cracks exhibit dual-directional growth: continuing circumferential extension while gradually deviating slightly inward toward the pipeline's central axis due to combined vertical loading from the pipeline's self-weight and vehicular loads, ultimately demonstrating axial propagation.

Furthermore, inner-surface cracks reach unstable fracture faster than outer-surface cracks under identical propagation increments, with this phenomenon being particularly pronounced at sidewall locations. This evidence indicates that: (1) inner-surface cracks pose greater hazards than external ones, and (2) circumferential cracks at sidewalls carry higher propagation risks than those at the crown or invert.

4.4 Life Prediction

Figure 4 compares the relationship between propagation increments and load cycles for cracks at six locations. The data reveals an inverse correlation: as propagation increments increase, the number of load cycles decreases, indicating accelerated growth rates. Inner-surface cracks consistently exhibit fewer load cycles than external-surface cracks, with average values of approximately 430,000 cycles versus 920,000 cycles, respectively. Furthermore, regardless of being internal or external, cracks at pipeline sidewalls demonstrate the lowest cycle counts, followed by those at the invert and crown positions.

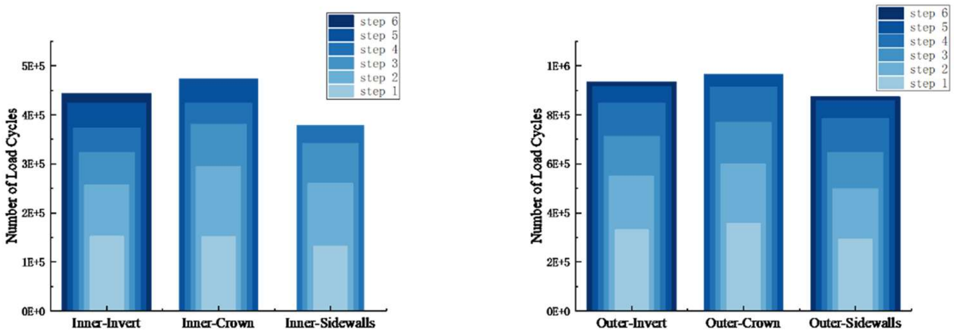


Fig. 4 Plot of crack location versus number of load cycles

5. Conclusion

This study simplifies vehicular loading as moving constant loads and employs ABAQUS-FRANC3D co-simulation technology to investigate fatigue crack propagation in buried pipelines containing pre-existing circumferential cracks. Key conclusions are:

1) As crack propagation progresses, the amplitude of stress intensity factor (SIF) variations increases and peak values rise systematically. Crucially, the location of maximum SIF within each propagation increment gradually migrates from the deepest crack point ($\varphi=90°$) toward the crack surface.

2) Regardless of crack location, circumferential cracks initially extend primarily along the pipe circumference before transitioning to axial progression.

3) Inner-surface sidewall cracks exhibit an average instability cycle count of 430,000 – 53.3% lower than outer-surface crown cracks (920,000 cycles) – confirming their substantially higher hazard potential.

4) For any given crack location, the crack growth rate accelerates with increasing propagation increments.

Engineering Recommendations:

For buried pipelines beneath urban roads, prioritize inspection of crack defects at inner-surface sidewall regions. Implement increased soil cover thickness or stress-buffering layers beneath high-traffic sections to reduce fatigue load amplitude.

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References

[1] M. Hagarová, G. Baranová, P. Peterka, et al.: Failure Analysis of a Gas Pipeline at the Kinked Dent Location with Crack Indications, Engineering Failure Analysis, Vol. (2023). DOI: 10.1016/j.engfailanal.2023.107579.

[2] B.L. Zhang, H. Yin, H.Q. Dong, W.Y. Wang, Z.Q. Cheng: Settlement Allowance of the Buried Pipeline with Circumferential Surface Cracks, Oil & Gas Storage and Transportation, Vol. 38 (2019) No.12 , p.1344-1349.

[3] A. Okodi, Y. Li, R. Cheng, et al.: Crack Propagation and Burst Pressure of Pipeline with Restrained and Unrestrained Concentric Dent-Crack Defects Using Extended Finite Element Method, Applied Sciences, Vol. 10 (2020) No.21.

[4] A. Okodi, M. Lin, N. Yoosef-Ghodsi, et al.: Crack Propagation and Burst Pressure of Longitudinally Cracked Pipelines Using Extended Finite Element Method, International Journal of Pressure Vessels and Piping, Vol. 184 (2020).

[5] A.H. Akhi, A.S. Dhar: Stress Intensity Factors for External Corrosions and Cracking of Buried Cast Iron Pipes, Engineering Fracture Mechanics, Vol. 250 (2021).

[6] X. Yang: Research on Dynamic Crack Propagation and Crack Arrest of Buried Long Distance Gas Pipeline (Ph.D., Hunan University of Science and Technology, China 2021).

[7] R.C. Zhu, H.H. Zhu, H.L. Guo: Behavior Analysis on Strain and Crack Propagation of Buried Pipeline Containing Defects Under Tensile Stress, Journal of Fuzhou University (Natural Science Edition), Vol. 50 (2022) No.04, p.553-559.

[8] H.Y. Xiong: Research on the Ultimate Load Carrying Capacity of Steel Pipes with Ring Weld Defects (Master, Southwest University of Science and Technology, China 2023).

[9] Y.H. Duan, S.H. Dong, H.T. Wei, N. Yang: Safety Analysis on Girth Weld Crack Defect of River-Crossing Pipeline, China Petroleum Machinery, Vol. 51 (2023) No.06, p.143-150.

[10] M. Xie, Y. Wang, J. Zhao, X. Pei, T. Zhang: Prediction of Pipeline Fatigue Crack Propagation Under Rockfall Impact Based on Multilayer Perceptron, Reliability Engineering & System Safety, Vol. 242 (2024), p.109772. DOI: 10.1016/j.ress.2023.109772.

[11] H.M. Zhang: Fracture Mechanics (China University of Mining and Technology Press, China 2018), p.4-5.

[12] J.C. Newman, I.S. Raju: An Empirical Stress-Intensity Factor Equation for the Surface Crack, Engineering Fracture Mechanics, Vol. 15 (1981) No.1-2, p.185-192.

[13] I.S. Raju, J.C. Newman: Stress-Intensity Factors for Internal Surface Cracks in Cylindrical Pressure Vessels (NASA, USA 1982), p.TM-84596.

[14] A. Zahoor: Ductile Fracture Handbook: Section 5.2 (Electric Power Research Institute, USA 1991), p.NP-6301-D.

[15] American Petroleum Institute: Fitness-For-Service: Annex 9D: Curvature Correction for Cylindrical Shells (API Publishing Services, USA 2023).

[16] S.P. Xiang, M.X. Gao, J.H. Lu, Y.H. Yang, G. Chen: Analysis of Deformation Control Value of Urban Buried Gas Steel Pipe, Gas & Heat, Vol. 43 (2023) No.05, p.27-30.

[17] S.Y. Fu: Study on Mechanical Response and Protection Measures of Buried Pipelines Under Vehicle Load (Master, Southeast University, China 2021).

[18] L. Liang, W.J. Gou, D.L. Tian, X. Wang: Analysis on 3D Mechanical Characteristics of Buried Pipeline Under Traffic Loading, Journal of Xi'an University of Architecture & Technology (Natural Science Edition), Vol. 52 (2020) No.01, p.72-78.

[19] Beijing Municipal Engineering Design & Research Institute: Code for Design of Urban Roads: CJJ37-2012 (China Architecture & Building Press, China 2012).

[20] Ministry of Housing and Urban-Rural Development of PRC: Code for Design of Urban Road Surface: CJJ169-2011 (China Architecture & Building Press, China 2011).

[21] H. Xuan: Numerical Analysis of Crack in Submarine Suspended Span Pipeline Under Pipe-Soil Interaction (Master, Southwest Petroleum University, China 2018).

[22] Y.W. Lv: Study on Failure Law of Buried Pipe Line with Defects Under Non-Uniform Settlement of Soil (Master, Anhui University of Science and Technology, China 2021).