Numerical Analysis of Buried Pipeline under Land Subsidence Action

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Abstract

Buried pipelines operate in complex environments, where factors such as non-uniform soil settlement and corrosion from surrounding substances can alter their stress state, potentially leading to pipeline failure and subsequent accidents. To tackle these challenges, a finite element model was developed using ABAQUS to simulate the coupled pipe-soil interaction under ground subsidence conditions. With emphasis on the settlement behavior of an intact pipeline, numerical investigations were conducted to identify the threshold of pipe-soil coordinated deformation and to characterize the evolution of Mises stress distributions throughout the final settlement phase. Based on this, the Mises stress variations in the pipeline were compared at soil settlements of 0.22 m and 0.5 m. The findings reveal that the maximum Mises stress occurs in the vicinity of the settlement interface and moves progressively farther from this boundary as the degree of settlement increases, accompanied by an overall elevation in pipeline stress. On the left side of the interface, tensile stresses develop at the pipe crown, whereas on the right side, tension is observed at the pipe invert; in both cases, the tensile-side stresses remain consistently higher than their compressive counterparts. These findings can provide a basis for the protection of buried pipelines.

Keywords

Buried Pipeline; Corrosion Defects; Nonuniform Settlement; Loca Stress.

1. Introduction

In response to the carbon peaking and carbon neutrality targets, the demand for clean energy has been experiencing continuous growth. Natural gas, characterized by its clean and environmentally friendly nature and high energy efficiency, is currently the preferred choice for the low-carbon clean energy transition. However, a spatial mismatch exists between natural gas production areas and consumption regions in China [1], necessitating long-distance pipeline transmission. Due to China's complex and varied topography, long-distance pipeline transport inevitably crosses land subsidence areas. Additionally, the decline of urban groundwater levels and the utilization of underground space have resulted in varying degrees of land subsidence.

Current research on non-uniform settlement of pipe-soil systems primarily employs methods such as theoretical analysis, experimentation, and finite element analysis. In theoretical investigations, the elastic foundation beam model is frequently adopted, with the classical Winkler foundation beam model [2] being the most representative. Subsequent scholars have developed different theoretical models based on this foundation. Karamitros et al. [3], building upon the elastic foundation beam theory, proposed an analytical method for the nonlinear stress-strain response of pipelines subjected to permanent ground deformation. To overcome the limitations of the Winkler model, scholars such as Zhang Tuqiao [4] and Shen Wenming [5] introduced the Pasternak two-parameter foundation model to examine the longitudinal mechanical behavior of buried pipelines subjected to differential foundation settlement. Gao Huiying [6] employed a cubic curve equation to represent the large geometric deformation of pipelines in settlement areas, deriving equations for pipeline displacement and internal forces based on the boundary conditions at the settlement interface. Xu Ping [7] designed and developed an experimental system to study pipe-soil interaction during soil subsidence, measuring the critical point for coordinated pipe-soil deformation and the changes in earth pressure around the pipeline. Wang Le [8] experimentally simulated the failure process of seamless steel pipes under conditions of uneven settlement, fault movement, and their coupled effects, obtaining strain values and deformation curves of the pipes. Finite element analysis is capable of fully considering the nonlinear problems associated with the pipeline, soil, and pipe-soil contact, including geometric nonlinearity, material nonlinearity, and state nonlinearity. Liu Wei [9] established settlement models for pipelines made of four different materials using the ABAQUS finite element analysis software, comparing their resistance to settlement and the influence of different settlement modes on the maximum pipeline stress.

In summary, this paper conducts a numerical simulation analysis of buried pipelines subjected to non-uniform settlement.

2. Finite Element Analysis

2.1 Pipe and Soil Constitutive Model

The soil is characterized by an ideal elastic-plastic constitutive model, specifically the Mohr-Coulomb model [10], with the corresponding soil parameters detailed in Table 1. Here, μrepresents Poisson's ratio; E denotes the elastic modulus of the soil, in MPa; C is the cohesion, in MPa; and φ is the internal friction angle.

Table 1. Soil parameters

Name	μ	E/MPa	C/MPa	φ/(°)
Soil	0.42	33	20	11.4

The pipeline material is L415-grade steel, possessing a yield strength of 415 MPa. Given that ground settlement leads to large deformations, the numerical simulation necessitates the inclusion of elastic-plastic material behavior to ensure fidelity. Consequently, the Ramberg-Osgood constitutive model is adopted for the pipe material. The corresponding parameters are presented in Table 2. Here, P represents the internal pressure, in MPa; and D denotes the pipe diameter, in mm.

Table 2. Pipeline parameters

Name	μ	E/MPa	P/MPa	D/(mm)
3	0.3	208	3	325

2.2 Model Establishment

A finite element model was established using ABAQUS, comprising both the soil and the pipeline, both discretized using solid elements (C3D8R). The soil domain is a rectangular prism with dimensions of 20 m × 5 m × 5 m. The lengths of both the settled and non-settled zones are 10 m. Settlement is simulated by applying displacement-controlled loading. Liu Wei [9] compared two methods of applying displacement load-specifically, whether or not to set constraints at the bottom of the settlement zone-and found that the settlement mode of the soil has virtually no effect on pipeline deformation. Therefore, for the sake of computational convenience, no constraints are applied at the bottom of the settlement zone in this study. The pipeline is 20 m in length, buried at a depth of 1.5 m, and subjected to an internal pressure of 3 MPa. Furthermore, a refined mesh zone, 1.5 m in length, is configured around the pipeline to enhance computational accuracy in the pipe-soil interaction region. The pipe-soil interaction is modeled using a nonlinear contact formulation. Given that tangential stresses play a dominant role in the pipe-soil interaction, a "penalty friction formulation" is employed to simulate this interaction, with a friction coefficient of 0.5. The normal contact behavior, which primarily transmits compressive normal stress, is simulated using a "hard contact" relationship. The final applied soil settlement at the bottom of the settled zone is 0.5 m.

The end of the non-settled zone is designated as the coordinate origin, with the soil extending 20 m along the Z-axis. Regarding the boundary conditions, the top surface of the soil domain remains free of all constraints. Lateral boundaries perpendicular to the X-axis are fixed against displacement in the X-direction, while those perpendicular to the Z-axis are constrained in the Z-direction. Consistent with the soil end conditions, both extremities of the buried pipeline are also restricted from longitudinal movement in the Z-direction. At the bottom of the soil, constraints in the Y-direction are applied to both the non-settled and settled zones; however, when displacement loading is imposed on the settled zone, the Y-direction constraints in that zone are removed. The displacement load is applied to the top surface of the soil in the settled zone.The settlement model is shown in Fig. 1.

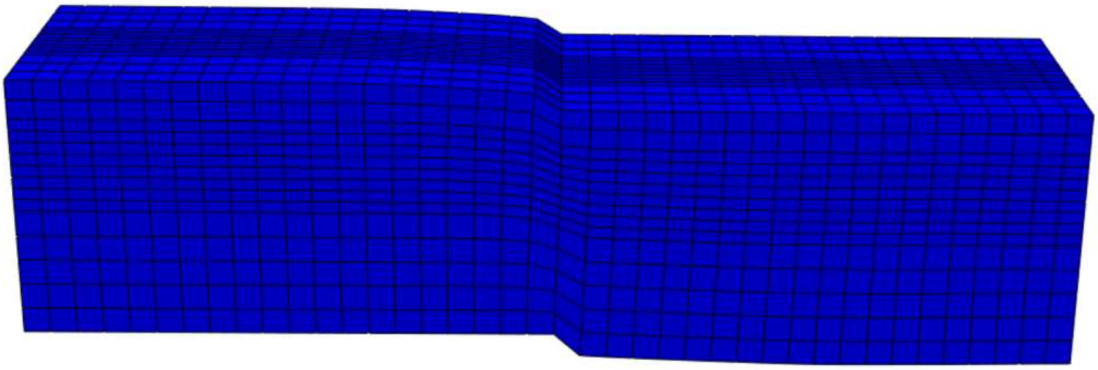

Fig. 1 Soil settlement model

2.3 Calculation Results and Analysis

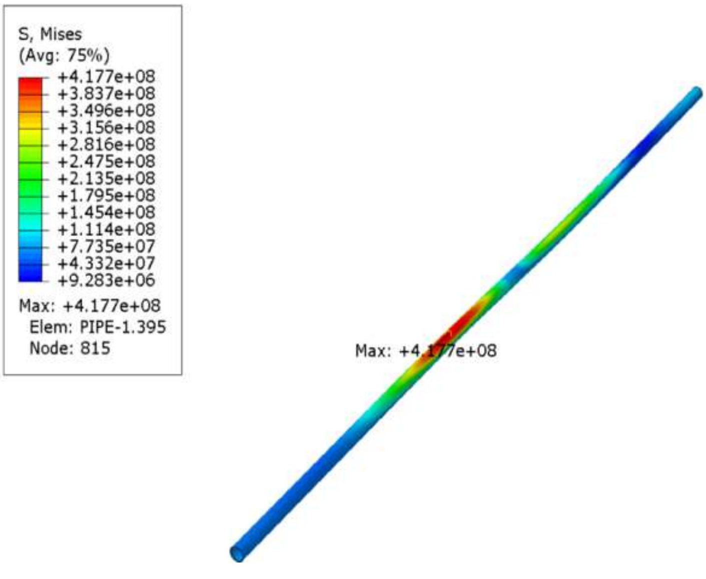

Fig. 2 Mises stress nephogram of the pipeline at a soil settlement of 0.22 m

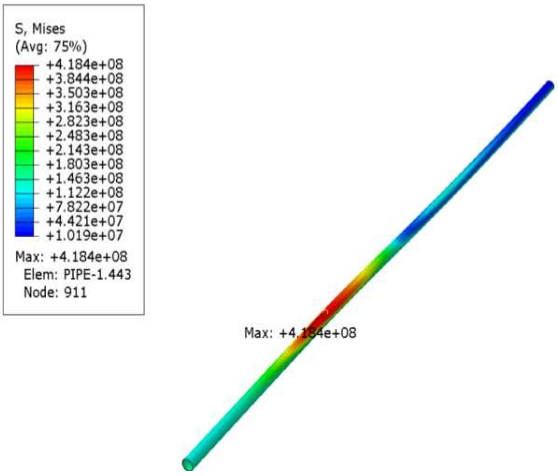

Fig. 3 Mises stress nephogram of the pipeline at a soil settlement of 0.50 m

Using the parameters outlined above, a finite element model was developed to simulate an intact pipeline. Fig.2 and Fig.3 illustrates the Mises stress nephograms corresponding to soil settlements of 0.22 m and 0.5 m. At a settlement of 0.22 m, the pipe-soil system reaches a critical threshold where coordinated deformation gives way to a non-coordinated regime. In this phase, the pipeline bottom in the settlement zone gradually separates from the soil, leading to a stress redistribution within the pipeline. The maximum Mises stress at the pipe crown within the settlement zone is highly dependent on the stage of pipe-soil interaction. In the coordinated deformation regime, this stress value exhibits a clear upward trend with progressive subsidence. Conversely, once the system transitions into the non-coordinated phase, further increases in settlement lead to a gradual reduction in stress. At a soil settlement of 0.22 m, the Mises stress at the pipe crown in the settlement zone reaches 328 MPa, which represents the maximum value attainable at the pipe crown throughout the entire settlement process. Thus, the settlement of 0.22 m is identified as the critical threshold for the transition from coordinated to non-coordinated pipe-soil deformation.

Analysis of the Mises stress distribution demonstrates that the pipeline's peak stress is consistently located within a zone adjacent to, rather than precisely at, the settlement interface. Subsequent increases in settlement drive a gradual outward migration of this peak location, concurrently elevating the overall stress state of the pipeline. Notably, the most significant stress variations are observed within the non-settled region.

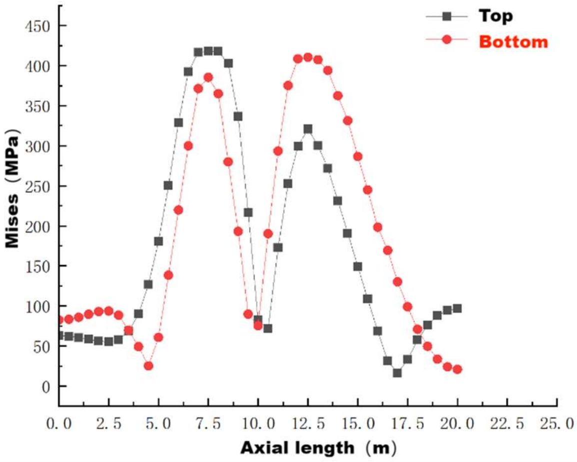

Fig. 4 Mises stress distribution along the pipeline at a settlement of 0.22 m

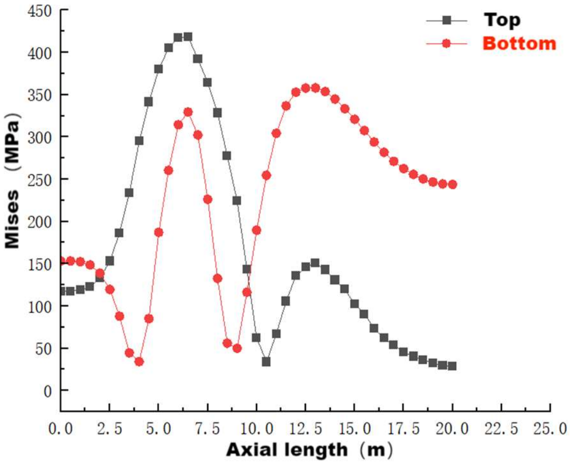

Fig. 5 Mises stress distribution along the pipeline at a settlement of 0.50 m

Fig. 4 and Fig. 5 present the Mises stress distribution along the pipeline at different settlement values. The x-axis represents the distance from the end of the non-settled zone to the end of the settled zone, spanning a total length of 20 m. The location x = 10 m corresponds to the interface between the non-settled and settled zones. A coordinated deformation state characterizes the pipe-soil interaction at a settlement of 0.22 m. Under this condition, the maximum Mises stress occurs on the pipe crown in the non-settled region, approximately 2.5 m away from the interface, attaining a value of 418.7 MPa. In contrast, the peak stress at the pipe crown in the settled zone measures 328 MPa, revealing a considerable difference between the two zones. The peak Mises stresses at the pipe invert in both the settled and non-settled zones are relatively similar, with the maximum value at the pipe invert in the settled zone exceeding that at the pipe crown in the same zone. During coordinated deformation, the pipeline segment to the left of the interface (non-settled zone) tends to move downward due to settlement, compressing the soil beneath the pipe. This configuration induces tensile stress at the pipe crown and compressive stress at the pipe invert, with the crown consistently experiencing higher stress levels. Across the interface to the right, within the settled zone, the pipeline subsides along with the soil, resulting in compression at the crown and tension at the invert. Hence, in this region, the stress at the pipe invert invariably exceeds that at the crown.

A significant transition in pipe-soil behavior occurs when subsidence reaches 0.5 m, marking the establishment of a non-coordinated deformation regime. While the locus of peak Mises stress persists on the pipe crown in the region unaffected by settlement, it undergoes a further outward displacement, stabilizing approximately 3 m from the geological interface. A comparative analysis reveals that the maximum stress recorded at the pipe crown within the subsidence zone diminishes by about 160 MPa relative to the threshold value observed at 0.22 m settlement. The underlying mechanism involves the progressive detachment of the pipe's basal surface from the underlying stratum within the subsidence zone. This detachment subjects the pipeline to the complete geostatic load, creating a distinct stress dichotomy: the pipe crown experiences compressive forces, whereas the pipe invert is subjected to tensile action. This phenomenon becomes increasingly pronounced at the central region of the subsidence zone (x = 20 m), where accentuated flexural curvature induces a precipitous increase in tensile stress at the pipe invert, coincident with a corresponding attenuation of stress at the pipe crown. On the left side of the interface (non-settled zone), the pipeline further compresses the underlying soil over a larger area. However, the pipe curvature in this region does not undergo significant changes, and the peak Mises stress remains relatively stable compared to that observed during the coordinated deformation stage.

3. Conclusion

(1) Numerical results reveal that the peak Mises stress in a buried pipeline subjected to non-uniform settlement is not situated exactly at the settlement interface, but rather within a localized zone adjacent to it. With progressive increases in settlement, this peak stress location migrates further away from the interface, accompanied by a general elevation of the overall stress magnitude within the pipeline. Upon exceeding a settlement threshold of 0.22 m, the pipe-soil system transitions into a non-coordinated deformation regime. Beyond this point, although the maximum Mises stress at the pipe crown within the non-settled region stabilizes without marked escalation, the adjacent pipeline section around this peak enters an elastic-plastic state. Concurrently, at the center of the settled zone, the full soil overburden pressure is exerted directly onto the pipeline, inducing compressive stresses at the pipe crown and tensile stresses at the pipe invert, with the latter demonstrating a continuously increasing trend.

(2) Throughout the subsidence process, distinct peak Mises stress points are observed at both the crown and invert across the settled and non-settled zones. Quantitatively, at a settlement of 0.22 m, the peak stress point is registered approximately 2.5 m from the interface; this distance extends to roughly 3.0 m when the settlement reaches 0.50 m. Mechanistically, on the left side of the interface, the descending soil compresses the underlying ground, causing the pipeline to bend-resulting in tension at the crown and compression at the invert, with the crown stress consistently predominating. In contrast, on the right side of the interface, the opposite mechanical response is observed: the pipe invert experiences tension while the crown undergoes compression, leading to higher stress values at the invert. Critically, regardless of the zone, the magnitude of tensile stress invariably surpasses that of compressive stress along the pipeline.

Acknowledgments

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