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Stress Analysis of Buried Pipelines with Complex Defects based on ABAQUS

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Abstract

To investigate the influence of complex defects on the mechanical behavior of buried pipelines, a three-dimensional finite element model of buried pipelines was established based on ABAQUS software. Three typical defect models, including single corrosion defects, overlapping defects, and corrosion–crack coupled defects, were developed to analyze the stress response characteristics under different defect configurations. The control variable method was adopted to study the effects of defect length, width, and depth on the maximum equivalent stress of the pipelines. The results show that the maximum equivalent stress increases with the increase of defect length and defect depth, among which defect depth has the most significant influence on the stress response of pipelines. In contrast, the influence of defect width on stress variation is relatively negligible. Under the same geometric parameters, the corrosion–crack coupled defect model exhibits the highest equivalent stress, followed by the overlapping defect model, while the single defect model shows the lowest stress level. This finding indicates that complex defects can further aggravate local stress concentration and reduce the structural safety of buried pipelines. The research results can provide valuable references for the integrity assessment and safety evaluation of buried pipelines with complex defects.

Keywords

Buried Pipeline; Complex Defects; Finite Element Analysis; Corrosion Defect; Stress Analysis.

1. Introduction

Buried pipelines are widely used in oil and gas transportation and urban infrastructure systems.

Their safe operation is of great significance to energy supply and public safety[1]. During long-term service, pipelines are subjected to internal pressure, soil constraints, and external environmental factors, which may lead to corrosion, deformation, and crack defects. These defects can significantly change the local stress distribution of pipelines, thereby reducing their bearing capacity and service life[2].

In practical engineering applications, pipeline defects usually do not exist independently, but appear in the form of multiple interacting defects[3]. Local corrosion may reduce the wall thickness and further induce crack initiation in stress concentration regions. In addition, overlapping defects of different sizes and positions may result in more complex local stress behavior[4]. Therefore, investigating the mechanical behavior of buried pipelines containing complex defects is of considerable engineering significance.

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In recent years, many researchers have studied the influence of different defect types on the mechanical properties of buried pipelines. Yang et al.[5] established a finite element model of X100 pipelines with double corrosion defects and analyzed the influence of defect geometric parameters on failure pressure. Zhou et al.[6] investigated the interaction between multiple corrosion defects and their effects on the residual strength of pipelines. Mu[7] analyzed the residual strength variation of pipelines with internal and external coupled defects using the finite element method. Wang et al.[8] developed a finite element model of hydrogen pipelines containing overlapping corrosion defects and studied their failure pressure characteristics. Zhang et al.[9] conducted a numerical analysis of double corrosion defects and overlapping defects in X80 gas pipelines, investigating the effects of defect size on failure modes and failure pressure. Zhao et al.[10] employed the extended finite element method to study the influence of different crack parameters on the stress intensity factors at crack tips. Zhang et al.[11] examined the failure characteristics of coexisting crack and corrosion defects, analyzing the effect of crack depth on the failure pressure.

Although considerable studies have been conducted on single corrosion defects, research on overlapping defects and corrosion–crack coupled defects is still relatively limited. Therefore, this study establishes a three-dimensional finite element model of buried pipelines based on ABAQUS to investigate the stress distribution characteristics of single defects, overlapping defects, and corrosion–crack coupled defects. The effects of defect geometric parameters on pipeline stress response are analyzed to provide references for the integrity assessment and safety evaluation of buried pipelines.

2. Finite Element Model Development

To investigate the effect of complex defects on the stress behavior of buried pipelines, a three-dimensional finite element model of a buried pipeline was established using ABAQUS. Based on Saint-Venant's principle[7], when the pipeline length exceeds five times its outer diameter, the influence of boundary conditions can be neglected. Accordingly, a 4 m-long pipe segment was selected as the geometric model, and the defects were located at the mid-span of the pipeline.

The material parameters of the pipeline are listed in Table 1, while the soil parameters are given in Table 2. The pipeline material was modeled using an ideal elastoplastic constitutive model, whereas the soil was described using the Mohr–Coulomb constitutive model to realistically capture the mechanical behavior of the surrounding soil in a buried environment.

Table 1. Material parameters of pipeline

Name	Density /(kg/m^3)	Yield Strength /MPa	Young's Modulus/ MPa	Poisson's Ratio	Diameter/m	Wall Thickness/m
Pipe	7850	480	210	0.3	0.356	0.01

Table 2. Material parameters of soil

Name	Density /(kg/m^3)	Young's modulus /MPa	Poisson's ratio	Internal friction angle/ (°)	Cohesion /kPa
Soil	1800	30	0.35	25	30

As shown in Figure 1, three typical defect models were established, including a single corrosion defect model, an overlapping defect model, and a corrosion–crack coupled defect model.

To simulate the actual service conditions of buried pipelines, appropriate boundary conditions and loads were applied in the finite element model. A fully fixed constraint was imposed on the bottom of the soil domain, restricting displacement in all three directions, while normal displacement constraints were applied to the lateral boundaries to reduce boundary effects on the results.

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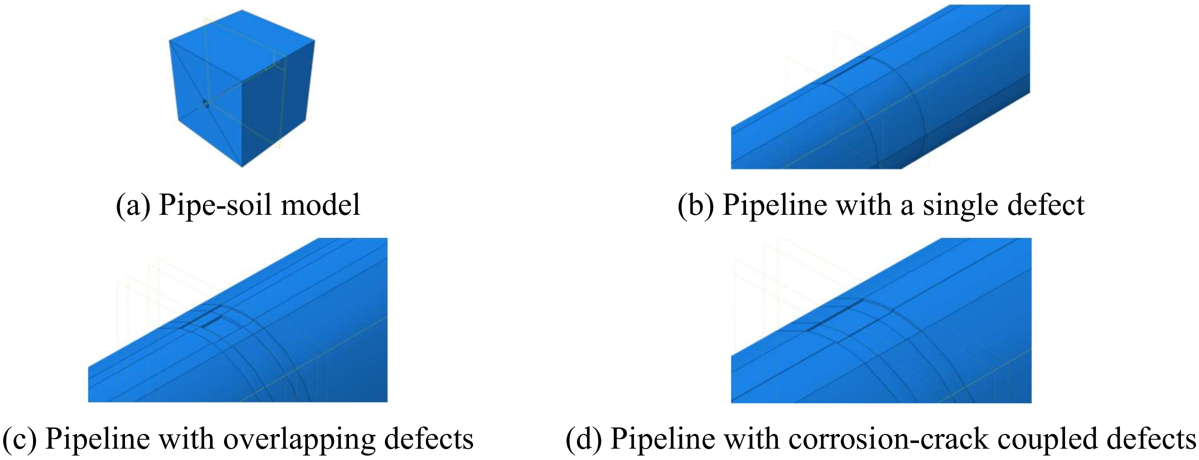

(a) Pipe-soil model (b) Pipeline with a single defect

(c) Pipeline with overlapping defects (d) Pipeline with corrosion-crack coupled defects

Figure 1. Schematic diagram of the finite element model of the defective pipeline

The interaction between the pipeline and soil was modeled using a nonlinear contact formulation. For the normal behavior, a hard contact formulation was adopted to prevent penetration between contact surfaces, while the tangential behavior was described using a penalty friction model with a friction coefficient of 0.5, reflecting the soil–pipe interaction under realistic buried conditions.

Regarding loading conditions, both the self-weight of the soil and the internal pressure of the pipeline were considered. A uniform internal pressure of 6MPa was applied to the inner wall of the pipeline to simulate the stress state under actual gas transmission conditions. To improve the computational accuracy in the regions of complex defects, a local mesh refinement was applied around the defect areas, while relatively coarser meshes were used in other regions to balance computational efficiency and accuracy. Both the pipeline and the soil were discretized using hexahedral solid elements. Due to the significant stress concentration in the defect regions, smaller mesh sizes were employed near the defects to enhance the accuracy of stress calculations. The finite element mesh model of the defective pipeline is shown in Figure 2.

Currently, commonly used failure criteria include strain-based and stress-based criteria. Strain-based criteria are suitable for problems involving large deformations, whereas the corroded defected pipelines studied in this work experience limited deformation at failure. Therefore, a stress-based failure criterion is adopted[12]. Specifically, the pipeline is considered to have failed when the maximum von Mises stress in the defected region reaches the material's ultimate tensile strength, and the corresponding internal pressure at this point is defined as the pipeline's failure pressure.

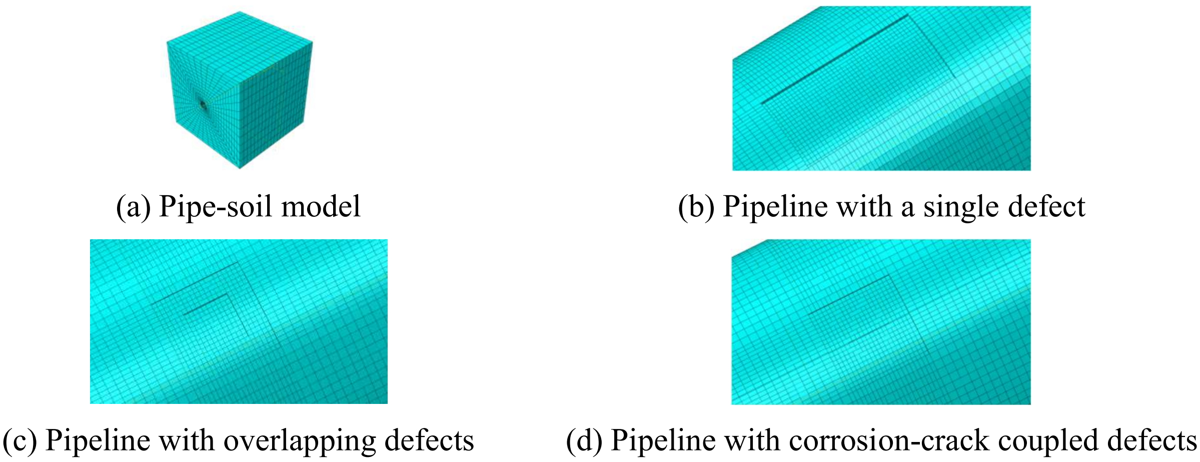

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Figure 2. Schematic diagram of the finite element mesh of the defective pipeline

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3. Results and Discussions

To verify the reliability of the ABAQUS finite element simulations, this study referenced corrosion defect burst test data from previous researchers[13] and compared the finite element simulation results with the experimental failure pressures, as well as the results calculated using the modified ASME B31G[14] and PCORRC[15] methods. The specific results are presented in Table 3.

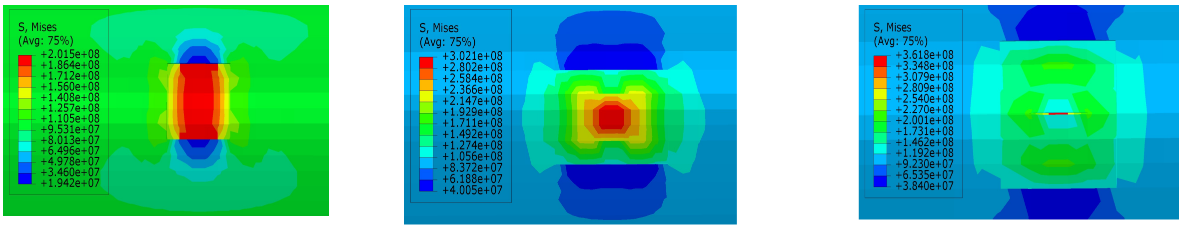
Table 3. Calculation Results

Pipe Number	Corrosion Depth /mm	Corrosion Length /mm	Corrosion Width /mm	Experimental Results /MPa	FEM /MPa	Modified B31G /MPa	PCORRC/MPa
1	4.4	200	50	24.11	24.20	20.99	24.06
2	8.8	200	50	21.76	21.83	17.59	20.87
3	13.1	200	50	17.15	17.31	13.10	15.77
4	8.8	100	50	24.30	24.85	20.41	23.26
5	8.8	300	50	19.80	19.85	16.26	19.01

The table shows that the errors between the finite element simulation results and the experimental data are all less than 5%. Compared with the modified B31G method and the PCORRC method, the finite element method can more accurately predict the failure pressure of pipelines under various corrosion depths and lengths. This indicates that the numerical model established in ABAQUS has good reliability, providing a solid foundation for subsequent numerical analysis of buried pipelines with complex defects.

The equivalent stress contour plots of a single corrosion defect (with length and width both 100mm and depth 5mm), an overlapping defect (where the larger defect has the same parameters as the single corrosion defect, and the smaller defect has a length and width of 50 mm with a depth of 2mm), and a corrosion–crack coupled defect (where the larger defect has the same parameters as the single corrosion defect, and the crack has a length of 50mm and a depth of 2mm) are shown in Figure 3.

As shown in Figure 3, the maximum equivalent stress in all three models is primarily concentrated near the defect regions, indicating that defects significantly alter the local stress distribution of the pipeline. Among them, the corrosion–crack coupled defect model exhibits the most pronounced stress concentration and the highest maximum equivalent stress, followed by the overlapping defect model, while the single defect model shows relatively lower values. These results indicate that the interaction between multiple defects can further intensify local stress concentration, thereby reducing the overall safety of the pipeline.



(a) Pipeline with a single defect

(b) Pipeline with overlapping defects

(c) Pipeline with corrosion-crack coupled defects

Figure 3. Stress contour plots of pipelines with different types of defects

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The corrosion defect depth was kept constant at 5mm and the length at 100mm. For the overlapping defect, the smaller defect depth was set to 2mm, and its width was defined as 50% of the main defect width. For the corrosion–crack coupled defect, the crack depth was set to 2mm.

The corrosion defect length was varied as 20, 40, 60, 80, 100, and 120mm to analyze the stress response of buried pipelines under different defect configurations, as shown in Figure 4.

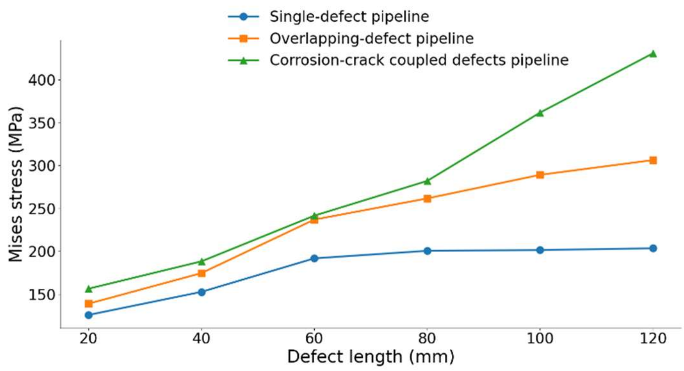

Figure 4. Stress variation curves of pipelines with different defect types under different defect lengths

With all other parameters kept constant, the maximum equivalent stress of all three defect models increases with increasing defect length. Compared with the single defect model, the overlapping defect model and the corrosion–crack coupled defect model exhibit a more pronounced increase. Among them, the corrosion–crack coupled defect model shows the fastest stress growth under larger defect lengths, indicating that complex defects further intensify local stress concentration in the pipeline.

The corrosion defect length and width were kept constant at 100 mm. For the overlapping defect, the length and width of the smaller defect were both set to 50 mm, and its depth was set to 2 mm. For the corrosion–crack coupled defect, the crack depth was set to 2 mm.

The corrosion defect width was varied as 20, 40, 60, 80, 100, and 120mm to analyze the stress response of buried pipelines under different defect configurations, as shown in Figure 5.

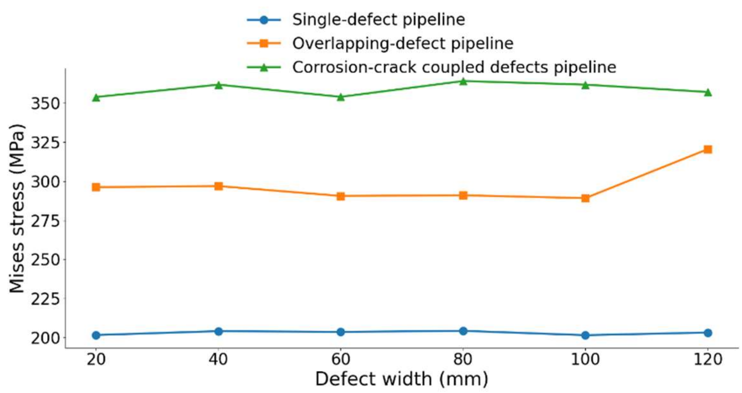

Figure 5. Stress variation curves of pipelines with different defect types under different defect widths

With all other parameters kept constant, the overall variation of the maximum equivalent stress with increasing defect width is relatively small for all three defect models, showing no obvious monotonic trend. This indicates that, within the current parameter range, defect width has a relatively limited effect on the local stress response of the pipeline. In comparison, the overlapping defect model and the corrosion–crack coupled defect model maintain higher overall stress levels than the single defect model.

The corrosion defect depth is kept at 5 mm and the length at 100 mm. In the overlapping defect model, the small defect depth is set to 2 mm, and its width is set to 50% of the main defect width; in the corrosion–crack coupled defect model, the crack depth is set to 2 mm.

The corrosion defect depth was varied as 1, 2, 3, 4, 5, and 6mm to analyze the stress response of buried pipelines under different defect configurations, as shown in Figure 6.

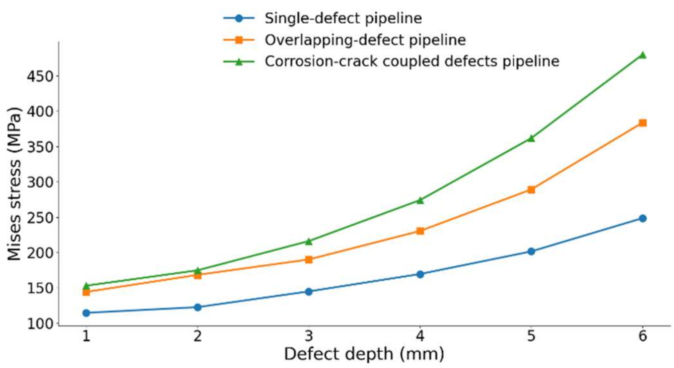

Figure 6. Stress variation curves of pipelines with different defect types under different defect depths

With increasing defect depth, the maximum equivalent stress of all three defect models increases significantly. Among them, the corrosion–crack coupled defect model exhibits the largest increase, followed by the overlapping defect model, while the single defect model shows the smallest increase. This is because an increase in defect depth reduces the remaining wall thickness of the pipeline, thereby intensifying local stress concentration. In addition, crack tips and interactions between defects further exacerbate the local stress concentration effect.

A comprehensive comparison of the influence of the three parameters indicates that defect depth has the most significant effect on the stress response of buried pipelines, followed by defect length, while defect width has a relatively minor influence.

4. Conclusion

In this study, a finite element model of a buried pipeline was established using ABAQUS. Numerical analyses were conducted for three typical conditions, including a single corrosion defect, an overlapping defect, and a corrosion–crack coupled defect. The effects of defect length, width, and depth on the stress response of the pipeline were investigated, and the following conclusions were obtained:

1) With increasing defect length and depth, the maximum equivalent stress of the pipeline generally shows an increasing trend. Among the parameters, defect depth has the most significant influence on the stress response, while defect width has a relatively minor effect.

2) Under identical geometric parameters, the corrosion–crack coupled defect model exhibits the highest maximum equivalent stress, followed by the overlapping defect model, and the single defect model shows the lowest values. This indicates that interactions between multiple defects further intensify local stress concentration.

3) Complex defects significantly reduce the structural safety of buried pipelines, with the crack tip effect having a particularly pronounced influence on local stress concentration. Therefore, in practical

engineering applications, greater attention should be paid to integrity assessment and safety monitoring in regions where corrosion and cracks coexist.

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