Postprint of "Study on the Mechanical Behavior of River-Crossing Pipelines Based on the Element Birth-and-Death Technique"

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Abstract

To investigate the mechanical characteristics of the process in which a river-crossing pipeline transitions from being buried to having gradually reduced overburden until it becomes fully suspended, this study employs the ABAQUS finite element software and, based on the element birth–death technique, establishes a dynamic finite element model of an X80 gas transmission pipeline whose overlying soil is progressively removed, causing a continuous increase in the suspension length. The effects of flood flow velocity, scour angle, diameter-to-thickness ratio, operating internal pressure, and burial depth on the mechanical behavior of the river-crossing pipeline are analyzed. Through sensitivity analysis, the influence magnitude of each factor on the stress of the river-crossing pipeline is obtained and ranked. The results indicate that, under different parameter conditions, the maximum equivalent stress, displacement, and strain of the pipeline increase most rapidly when the suspension length is between 20–30 m. The flood flow velocity, pipe diameter, and operating internal pressure are positively correlated with the maximum equivalent stress, while the pipeline wall thickness is negatively correlated with the maximum equivalent stress. The scour angle is positively correlated with the maximum equivalent stress during the suspension process, but when the suspension length reaches a certain value, the scour angle and burial depth have little effect on the maximum equivalent stress. However, the scour angle is positively correlated with displacement, whereas burial depth is negatively correlated with displacement. The ranking of the influence magnitude of each factor on the maximum equivalent stress of the river-crossing pipeline is: pipeline wall thickness > flood flow velocity > operating internal pressure > burial depth > scour angle. The findings are intended to provide a basis for and improvements to pipeline planning and design requirements, thereby enhancing pipeline safety.

Full Text

Abstract

This study investigates the mechanical characteristics of river-crossing pipelines during the process from being fully buried to gradual overburden soil reduction until complete suspension. Using ABAQUS finite element software, a dynamic finite element model is established based on the element birth-death technique, where the suspended length of the gas pipeline gradually increases as the overlying soil decreases. The paper analyzes the influence of flood velocity, undercut angle, diameter-to-thickness ratio, operating internal pressure, and burial depth on the mechanical behavior of river-crossing pipelines. Sensitivity analysis is conducted to determine and rank the degree of influence of each factor on pipeline stress. Results show that under different parameters, the maximum equivalent stress, displacement, and strain of the pipeline increase fastest during the suspension period. Flood velocity, pipe diameter, and operating internal pressure are positively correlated with maximum equivalent stress, while pipe wall thickness is negatively correlated. The undercut angle is positively correlated with maximum equivalent stress during the suspension process, but when the suspended length reaches a certain value, both undercut angle and burial depth have little effect on maximum equivalent stress. However, the undercut angle is positively correlated with displacement, while burial depth is negatively correlated. The ranking of influencing factors on maximum equivalent stress is: pipe wall thickness > flood velocity > operating internal pressure > burial depth > undercut angle. These findings provide a basis for pipeline planning and design improvements to enhance safety.

Keywords: suspended pipeline; suspended length; mechanical principles; sensitivity analysis; numerical simulation

1. Mechanical Model of Suspended Pipeline Under Flood Action

When river-crossing pipelines are subjected to continuous flood impact, the overlying soil becomes soft and is washed away, causing partial pipeline exposure and suspension while both ends remain buried in intact soil. Based on the mechanical model for pipelines under flood action by Wang et al. [8], the simplified mechanical model of a suspended river-crossing pipeline segment under flood impact is shown in [FIGURE:2].

During flood scouring of river-crossing pipelines, the pipeline experiences transverse drag force F_D, vertical lift force F_L, inertial force F_I, as well as the self-weight of the pipeline and internal medium G and buoyancy F_B. The pipeline force analysis is illustrated in the cross-sectional diagram shown in [FIGURE:1].

The flood forces on the pipeline are calculated as follows: - $F_D = \frac{1}{2}C_D\rho_f v^2 D$ (drag force) - $F_L = \frac{1}{2}C_L\rho_f v^2 D$ (lift force)

- $F_I = C_M \rho_f \frac{\pi D^2}{4} \frac{dv}{dt}$ (inertial force)

where ρ_f is flood density, v is average flow velocity, D is pipe outer diameter, C_D is drag coefficient, C_L is lift coefficient, C_M is inertia coefficient, and dv/dt is horizontal water particle acceleration on the pipeline.

2. Finite Element Model Establishment

2.1 Basic Assumptions

The following fundamental assumptions are made for numerical modeling [17]: 1. Material isotropy is assumed, with no consideration of temperature effects, pipe material randomness, or connection methods 2. Uniform soil type is used for buried sections 3. The suspended segment is completely exposed without any protective measures (e.g., weight coatings) 4. Overburden soil disappearance is modeled as regular reduction, approximated as hexahedral elements gradually removed

2.2 Material Parameters

With increasing oil/gas pipeline mileage, higher requirements for transportation efficiency and operational safety have led to adoption of X70 and X80 grade steel pipes in Southwest China (e.g., China-Myanmar gas pipeline). This study uses X70 steel parameters to establish the dynamic finite element model. Soil parameters follow the Mohr-Coulomb model, with detailed parameters listed in and pipeline parameters in .

2.3 Boundary Conditions

Based on actual pipeline constraints: - Soil top/bottom surfaces: displacement/rotation constrained in y-direction - Soil side surfaces: displacement/rotation constrained in x-direction
- Soil end face: displacement/rotation constrained in z-direction - Axisymmetric boundary conditions applied as symmetry constraints

The flood load direction is set along the positive x-axis (1,0,0), and vertical load along positive y-axis (0,1,0), both as surface tractions.

The failure criterion adopts elastic failure theory: when the equivalent stress in the suspended region reaches the material yield stress, pipeline failure is considered to occur. Equivalent stress is calculated using von Mises stress [18]:

$$\sigma_{\text{Mises}} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}$$

where σ_{Mises} must be less than yield stress σ_y.

The finite element model dimensions are determined based on field monitoring data: the affected buried zone on both sides of the work area is twice the

Figure 4

Figure 1: Figure 4

suspended length, so the soil model length is set to 2.5 times the suspended segment. Burial depth typically ranges 0.7-2.3 m, with 1.5 m used in this model. The soil cross-section is simplified to 5 m × 5 m, and a 1/2 symmetric three-dimensional model is established as shown in [FIGURE:3].

2.4 Contact Modeling

To accurately simulate the nonlinear contact behavior between pipe and soil, a 3D surface-to-surface contact model is employed. The pipe outer surface is designated as the master surface, and the soil inner surface as the slave surface. Contact properties define normal behavior (allowing separation after contact) and tangential behavior (friction coefficient of 0.3). The contact setting effects are shown in

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2.5 Element Birth-Death Technique

To realistically simulate the gradual disappearance of overburden soil causing increasing suspended length under flood action, ABAQUS element birth-death technology is applied. This technique simulates the lateral soil removal process and the resulting change in suspended length, as illustrated in [FIGURE:5] showing successive pipeline suspension stages.

3. Model Validation

To verify model reliability, theoretical methods and case studies from literature are used to analyze dynamic stresses in horizontally suspended oil pipelines and calculate forces in buried pipelines. The ABAQUS model with element birth-death technology is compared against published results. If errors remain within acceptable limits, the model is validated as reasonable and effective.

Validation is performed by applying alternating drag forces and lift forces on the suspended segment. With pipe wall thickness of 14.6 mm, elastic modulus of 12 MPa, and soil parameters from , maximum dynamic stresses are calculated for different suspended lengths. Comparison with literature results () shows reasonable agreement, confirming the finite element model’ s validity.

4. Mechanical Response Analysis of Suspended Pipeline Under Flood Action

Using the pipe-soil contact finite element model, the mechanical response of river-crossing pipelines is analyzed considering different flood velocities, under-

Figure 8

Figure 2: Figure 8

Figure 10

Figure 3: Figure 10

cut angles, diameter-to-thickness ratios, internal pressures, and burial depths for suspended lengths of 0-50 m. This enables precise calculation and detailed comparison of mechanical results to understand pipeline performance characteristics.

4.1 Flood Velocity

Flood velocities of 1, 2, 3, 4, and 5 m/s are modeled. Variation curves of maximum Mises stress, displacement, and strain with suspended length under different velocities are shown in [FIGURE:7] and

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Maximum Equivalent Stress: Flood velocity is positively correlated with maximum equivalent stress. As velocity increases, maximum equivalent stress continuously increases, with the trend flattening after reaching yield strength. At 5 m/s, the pipeline reaches yield strength when suspended length reaches 39-50 m; at 4 m/s at 2-3 m; at 3 m/s at 10-30 m; and at 1-2 m/s at 4-3 m. The stress increases fastest during 10-30 m suspension, indicating that measures taken before this stage can significantly reduce failure probability.

Displacement and Strain: Flood velocity is positively correlated with both displacement and strain. As velocity increases, both displacement and strain increase continuously. Displacement growth rate is highest during 10-30 m suspension, then gradually slows. Strain shows similar positive correlation with flood velocity, with higher velocities producing faster growth rates.

The mechanism involves flood-borne sediment and rock fragments impacting and eroding the riverbed (overburden soil) [22-23]. As overlying soil is washed away, the undercut angle forms at the soil-pipeline interface. Higher velocities expose more pipeline surface area to flood loads, increasing stress accumulation.

4.2 Undercut Angle

Undercut angles of 30°, 45°, 60°, 75°, and 90° are analyzed. Variation curves are shown in [FIGURE:9] and

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Maximum Equivalent Stress: The undercut angle is positively correlated with maximum equivalent stress during suspension. As the angle increases,

Figure 15

Figure 4: Figure 15

maximum equivalent stress increases. However, when suspended length reaches a certain value, the undercut angle has minimal effect on maximum equivalent stress. At smaller angles (30°, 45°), each analysis step removes a relatively small soil region, resulting in smaller stress increases. At larger angles, each step exposes more pipeline area, causing greater stress growth.

Displacement and Strain: The undercut angle is positively correlated with both displacement and strain. Larger angles produce greater displacement and strain. The growth rates are highest during 10-30 m suspension, then gradually slow. Interestingly, strain growth rate is inversely related to undercut angle magnitude during early suspension stages because larger angles expose more surface area, distributing loads and reducing localized strain rates.

4.3 Diameter-to-Thickness Ratio

Two scenarios are analyzed: (1) fixed diameter with varying thickness, and (2) fixed thickness with varying diameter.

Fixed Diameter (1016 mm), Varying Thickness (12.8, 15.3, 18.4, 22.9, 26.4 mm): - Maximum equivalent stress is negatively correlated with wall thickness. As thickness increases, maximum equivalent stress decreases. At 12.8 mm thickness, yield strength is reached at 10-30 m suspension; at 15.3 mm at 20-6 m; while 18.4, 22.9, and 26.4 mm thicknesses do not reach yield strength within 50 m suspension. Increasing wall thickness significantly improves load-bearing capacity. - Displacement and strain are negatively correlated with wall thickness. Thicker pipes exhibit smaller displacement and strain. However, at 12.8 mm thickness, strain shows sudden increase when suspended length reaches 10-30 m due to approaching plastic stage.

Fixed Thickness (18.4 mm), Varying Diameter (1016, 1219, 1422 mm): - Maximum equivalent stress is positively correlated with diameter. As diameter increases, maximum equivalent stress increases, but the growth rate slows after initial suspension. The stress increments are 232.6, 193.7, and 155.5 MPa respectively. Larger diameters provide greater surface area to distribute flood loads, reducing stress 增幅. - Displacement and strain are negatively correlated with diameter. Larger diameter pipes show smaller displacement and strain because the increased surface area distributes external loads more effectively.

4.4 Operating Internal Pressure

Internal pressures of 6, 7, 8, 9, and 10 MPa are modeled. Variation curves are shown in and [FIGURE:16].

Maximum Equivalent Stress: Operating pressure is positively correlated with maximum equivalent stress. As pressure increases, maximum equivalent stress increases, but pressure does not significantly affect the stress growth trend. Pressure primarily affects the initial equivalent stress value before suspension. At 10 MPa, yield strength is reached at 20-30 m suspension, while 6-9 MPa pressures do not reach yield within 50 m. The stress 增幅 at 10 MPa is much greater than at lower pressures. Reducing operating pressure during flood seasons can effectively decrease maximum equivalent stress trends.

Displacement and Strain: Operating pressure is positively correlated with both displacement and strain, but the effect is relatively small compared to other factors. Displacement growth is highest during 20-30 m suspension. Strain increases with pressure, with higher pressures producing greater strain values.

4.5 Burial Depth

Burial depths of 0.7, 1.1, 1.5, 1.9, and 2.3 m are analyzed. Variation curves are shown in [FIGURE:17] and [FIGURE:18].

Maximum Equivalent Stress: Burial depth has minimal effect on maximum equivalent stress. As suspended length increases, maximum equivalent stress shows linear upward growth regardless of burial depth, indicating suspended length has far greater influence than burial depth.

Displacement and Strain: Burial depth is negatively correlated with displacement. As burial depth decreases, displacement increment shows linear increase. Shallow burial depths result in less overlying soil weight to counteract flood-induced lift forces, leading to greater displacement. During 20-30 m suspension, displacement growth rate is highest. Strain is nearly unaffected by burial depth, with minimal strain increments across different depths.

5. Sensitivity Analysis

5.1 Orthogonal Numerical Experiments

To comprehensively evaluate parameter influence and improve result universality, orthogonal experimental design is adopted. Five factors are selected: flood velocity v, undercut angle θ, pipe wall thickness t, operating internal pressure P, and burial depth h, each with five levels. The $L_{25}(5^6)$ orthogonal array is used to design 25 test schemes. Factors and levels are listed in , with test schemes and results in .

5.2 Range Analysis

Based on orthogonal simulation results, range analysis is performed to determine each parameter’ s influence degree on maximum equivalent stress. The visualization analysis results are shown in . The ranking of influence on maximum equivalent stress is: pipe wall thickness (largest effect) > flood velocity > operating internal pressure > burial depth > undercut angle. This indicates that during flood action, pipeline maximum equivalent stress is primarily affected by material properties (wall thickness), followed by flood velocity, while undercut angle and burial depth have relatively minor influence.

5.3 Sensitivity Coefficient Analysis

Sensitivity coefficients are calculated using the formula:

$$f = \frac{\Delta\sigma/\sigma}{\Delta F/F}$$

where f represents the sensitivity coefficient of maximum equivalent stress σ to parameter F, $\Delta\sigma/\sigma$ is the ratio of stress change to baseline stress, and $\Delta F/F$ is the ratio of parameter value change to baseline value.

Positive f values indicate positive correlation (parameter increase raises stress), while negative values indicate inverse correlation. Larger absolute sensitivity coefficients indicate greater parameter influence. Using baseline values of flood velocity 1 m/s, undercut angle 30°, wall thickness 12.8 mm, internal pressure 6 MPa, and burial depth 0.7 m, sensitivity coefficients are calculated for each parameter. The relationship between sensitivity coefficients and parameter variation is shown in [FIGURE:19].

Key Findings: - Pipe wall thickness has the highest sensitivity coefficient (negative correlation), showing strong inverse relationship with maximum equivalent stress - Flood velocity sensitivity coefficient increases with parameter value, indicating growing influence at higher velocities - Operating internal pressure, undercut angle, and burial depth have relatively small sensitivity coefficients, showing linear relationships with stress - The absolute ranking of maximum sensitivity coefficients confirms: wall thickness > flood velocity > operating pressure > burial depth > undercut angle

6. Conclusions

1. Pipeline maximum equivalent stress and displacement increase fastest during 20-30 m suspension. Measures taken before this stage can significantly reduce failure probability.
2. Flood velocity, pipe diameter, and operating internal pressure are positively correlated with maximum equivalent stress. Pipe wall thickness is negatively correlated. Undercut angle is positively correlated during suspension but has minimal effect after certain suspended length. Burial depth has little effect on maximum equivalent stress but is negatively correlated with displacement.

3. Larger undercut angles essentially mean more suspended length, leading to greater maximum equivalent stress. As suspended length increases, maximum equivalent stress gradually shifts from the suspended segment middle toward the buried sections.
4. The influence degree ranking on maximum equivalent stress is: pipe wall thickness > flood velocity > operating internal pressure > burial depth > undercut angle.
5. For pipeline design, comprehensive consideration of safety and economy is needed to determine appropriate wall thickness. During operation, measures such as altering river flow, implementing stabilization measures, and reducing operating pressure can help prevent failure and extend service life.

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Figure 11

Figure 5: Figure 11

Figure 13

Figure 6: Figure 13

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