The Stress Analysis of Buried Nature Gas Pipeline in Abrupt Slopes

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Abstract. The landform of the buried long-distance pipeline is complex and variable, especially in case of mountainous areas, the forces acting on the pipeline is not uniform. We make a calculation on how the gravity of pipeline and fluid in pipeline affects the stress in the bend connected to the front end of the pipeline, and make an analysis of how pipeline parameters and soil parameters affects the stress. We make a stress calculation on the bend with the method of the elastic bending method, and make an analysis of how diameter, thickness of pipeline and angle of slope affect the result of the calculation.

Keywords: Buried Pipeline; Long-distance Pipeline; Climbing; Stress Analysis; Elastic Bending Method.

1. Introduction

Pipeline stress analysis and calculation is the basis of pipeline design, which can be used to evaluate the strength and safety of pipelines, and also provide a basis for economic analysis of pipelines. The stress of the pipe is mainly caused by the internal pressure and external load and thermal expansion of the pipe (1-4). The stress profile of the pipeline under these loads is complex. Carry out stress analysis and calculation, make safety evaluation of the pipeline, and meet the limitation of the pipeline thrust of the connected equipment, so that the pipeline design is economical and reasonable.

The stress analysis of the buried pipeline is quite different from that of the process pipeline. The buried pipeline is axially constrained. Therefore, large axial stress will be generated under the influence of pressure and temperature. The key to the analysis of buried pipeline stress is to simulate the interaction between pipeline and soil, which mainly includes two aspects: axial friction and lateral thrust of soil to pipeline. The former exists only when the pipe has an axial movement tendency, and the latter is the reaction force when the pipe produces a lateral displacement.

In the mountain section, long-distance pipelines are limited by topography (5, 6), and inevitably there are high-steep slopes with different lengths and slope angles of about 30° to 50°. In this case, the pipeline at the bottom of the slope is under severe stress. In addition to the pressure and constraints of the soil, the pipeline may also cause local stresses at the bends at the bottom (top) of the pipeline due...
to the weight of the pipeline and the weight of the medium in the pipeline. Therefore, it is necessary to analyze the stress at the elbow of the high-steep slope. Provide a safe basis for the design, construction and operation of pipelines.

The load is the main reason for the stress generated by the pipeline. According to the basic characteristics of the stress, the stress is divided into primary stress, secondary stress and comprehensive stress (7-9).

The primary stress is the normal stress or shear stress generated inside the pipeline by the external load. The characteristic is that the primary stress satisfies the equilibrium relationship of the applied load and increases with the increase of the applied load; and there is no self-limitation, when its value is exceed the yield limit of the material, the pipe will be plastically deformed and destroyed.

The secondary stress is a normal stress or shear stress caused by the deformation of the pipe, which is not directly balanced with the external force. The secondary stress in the pipeline is usually caused by the positional load (thermal expansion, vibration load, installation error); when local yielding and a small amount of plastic deformation occur, the secondary stress can be reduced by deformation coordination; the secondary stress is based on periodic and fatigue fracture modes, not depending on the stress level of a period, but on the number of cycles and stress range of the alternating.

The highest stress value caused by local stress concentration of load and structural shape is called comprehensive stress. The characteristic of comprehensive stress is that the whole structure does not produce any significant deformation, which is the possible source of fatigue failure and brittle fracture (10-12).

2. Methods
Stress analysis was carried out on the slope pipe and the elbows at both ends, and the influence of factors such as pipe diameter and slope angle on stress concentration was worked.

1) Perform force analysis on the slope section pipeline and analyze the influence of primary stress (gravity) on the slope bottom bend;
2) Stress analysis and check of the elbow by elastic bending resistance method, and find the influence law of pipe diameter, slope angle and pipe thickness on elbow stress.

2.1. Basic model
The basic model consists of a section of the slope section and two sections of straight sections at both ends. As shown in Fig.1:

![Fig.1 Basic model](image)

The basic parameters of the model:
(1) The diameter of the steel pipe is DN1016, and the pipe thickness is 30mm;
(2) The radius of curvature of the hot-bend elbow at the bottom and top of the slope is \( R = 1.5D \), and the angle between the slopes is 60°;
(3) The material of the steel pipe is X65, and the minimum yield strength is 450MPa;
(4) The buried depth of the pipeline is 1.2m;
(5) The length of the slope surface and the length of the straight pipe sections at both ends are both 200 m;
(6) The soil covered the pipeline is made of silt soil, and the relevant parameters(6) are as follows:

| Types   | Density(kg/m³) | Coefficient of friction(COF) | Friction angle(°) | Compaction factor |
|---------|----------------|-----------------------------|-------------------|------------------|
| Sediment | 1300           | 0.4                         | 37                | 5                |

2.2. Primary stress analysis

The influence of primary stress on the internal force of the pipeline is analyzed. The calculation method of internal force is usually obtained by the cross-section method. As shown in Fig.2-2, In order to find the internal force on a certain section m-m, it is possible to use a section to cut the rod at a distance of m-m, and divide it into two sections, and take one of them as a research object. If the left segment is taken, the left segment should be balanced. There must be a force \( F_N \) in the cross section. It is the force of the right segment to the left segment, that is, an internal force. Due to the continuity of the object, the internal force is actually distributed over the entire cross section, where the internal force refers to the resultant force of the internal force. Similarly, if the right segment is selected as the research object, the effect of the left segment on the right segment can be replaced by the force \( F'_N \). \( F_N \) and \( F'_N \) are the forces and reaction forces in the cross section of the left and right parts, both of which are equal in magnitude and opposite in direction.

![Fig.2 Schematic diagram of the cross-section method](image)

The cross-section method is used for analysis, and the section is set at the junction of the elbow and the slope section. The slope section is taken as the research object, and the effect of the elbow on the slope section is replaced by the internal force \( F_N \), and the slope section is subjected to the force. We can find the size of the internal force \( F_N \).

According to the principle of the cross-section method, the two internal forces \( F_{N1} \) and \( F_{N2} \) generated by the elbows on the slope are affected by the friction of the soil and the self-weight of the pipeline and the weight of the medium in the tube, as shown in Fig.3 shows:
Fig. 3 Schematic diagram of the stress on the slope

From the balance of force, the combined force of internal forces $F_{N1}$ and $F_{N2}$ is equal to the combined force of gravity and soil friction, and the direction is opposite.

1. The gravity of the pipe and the medium in the pipe can be obtained by the formula (1):

$$G = G_g + G_j = \pi \rho_g D l \delta + \frac{\pi}{4} \rho_j D^2 l$$  \hspace{1cm} (1)

- $\rho_g$ - the density of the pipe, kg/m$^3$;
- $D$ - the inner diameter of the pipe, m;
- $l$ - the length of the slope, m;
- $\delta$ - the thickness of the pipe, m;
- $\rho_j$ - Density of the medium in the pipe, kg/m$^3$.

2. Soil friction on the pipeline

The friction of the soil on the pipeline acts on the entire surface of the pipeline. When calculating the friction of the soil against the pipeline, the width of the plane is the outer diameter of the pipeline, and the maximum static friction of the soil to the pipeline is set. If the force is equal to the sliding friction, the maximum static friction of the soil to the pipe can be obtained according to formula (2):

$$f_{\text{max}} = f_c = \mu (G + 2DH\rho_s) \cos \theta$$  \hspace{1cm} (2)

- $f_{\text{max}}$ - the maximum static friction between the pipe and the soil; N;
- $f_c$ - the sliding friction between the pipe and the soil, N;
- $\mu$ - the coefficient of friction between the pipe and the soil;

When the axial component of gravity $G \sin \theta < f_{\text{max}}$, the gravity of the liquid in the pipe and the pipe is balance with the friction at this time, and the resultant force is 0, then the internal force is 0. At this time, the gravity of the slope pipe does not affect the internal force at the elbow. According to this, the critical angles under different pipe diameters and different buried soil types can be obtained.
It can be seen from Fig. 4 that the critical angles under different pipe diameters and different buried types are above 50°, and it can be concluded that when the angle between the slope and the horizontal plane is less than 50°, the gravity of the surface pipe is balanced with the soil friction and has no effect on the elbow at the bottom of the slope.

When $G \sin \theta > f_{\text{max}}$, the internal force at the junction of the slope pipe and the elbow can be obtained according to the formula (3):

$$F = F_{N1} + F_{N2} = G \sin \theta - \mu (G + 2DHl \rho_s)$$  \hspace{1cm} (3)

where $F$ is the sum of the internal forces received by the slope section, $N$; $\theta$ is the angle between the slope and the horizontal plane, °.

According to the definition of stress, the stress at the junction of the slope pipe and the elbow can be obtained according to formula (4):

$$\sigma = \frac{F}{S} = \frac{4G \sin \theta - 4 \mu (G - 2DHl \rho_s)}{\pi (D + 2\delta)^2}$$  \hspace{1cm} (4)

Substituting the model parameters into equations (2) and (4) can find that the stress at the junction of the slope and the elbow is 0.825MPa.

If the slope angle is 80°, change the pipe diameter and soil type, then the stresses are as shown in Fig.5:
It can be seen from the Fig.5 that the junction stress under different pipe diameters and different buried soil types is less than 7.5MPa, which is far less than the allowable stress of the steel pipe, and it can be concluded that when the angle between the slope and the horizontal plane is greater than the critical angle, the influence of the gravity of the slope pipeline on the stress of the elbow at the bottom of the slope is small and negligible.

2.3. Secondary stress analysis
The buried pipeline is subjected to the continuous soil friction constraint. For the long straight pipeline, there is a natural anchoring phenomenon. The main failure mode is the axial instability and fatigue failure caused by the hot stress. For the climbing pipeline, the stress concentration point caused by the hot stress is located at the elbow at both ends of the slope. The stress analysis of the elbow at both ends of the slope is carried out, which is calculated by the elastic bending resistance method, and check it according to the specification.
As we can see from Fig.6:
(1) When the temperature rises, the pipe is heated and expanded, the top of the elbow is subjected to tensile stress, the bottom is subjected to compressive stress, and the elbow is deformed and displaced in the direction away from the center of curvature;
(2) When the temperature is lowered, the pipe is contracted by cold, the top of the elbow is subjected to compressive stress, the bottom is subjected to tensile stress, and the elbow is deformed and displaced toward the center of curvature.

The elbow is regarded as a special point, that is, elastic bending hinge. The pipe on both sides of the elbow is regarded as an elastic foundation beam. The static balance condition is considered, and the bending is considered in the force analysis. The flexibility coefficient of the head, the axial friction of the pipe and the axial force of the elbow are used to calculate the bending moment and the axial force of the elbow, and then the stress and strain of the elbow are analyzed.

It is conditional to use the elastic bending-stretching analytical method. Only when the arm length of the elbow meets the formula (5), the elbow can be simplified to the elastic bending-resistant strand for calculation:

\[
l_1(l_2) \geq \frac{2.3}{k}; \quad k = \frac{D_C C}{4EI_p \times 10^6}
\] (5)

\(l_1, l_2\)-the length of the arms on both sides of the elbow section, m;
\(k\)-parameters related to soil properties and pipe stiffness, 1/m;
\(C\)-the lateral compression reaction coefficient of the soil, N/m³;
\(E\)-the elastic modulus of the pipe, MPa.

The lateral compression reaction coefficient \(C\) of the soil should be determined according to local measurements or empirically. When the pipeline has horizontal displacement, the value of \(C\) is \(1 \times 10^6 \sim 10 \times 10^6\) N/m³; when the compaction degree of silty clay and sandy silt is 90%~95%, the value of \(C\) is \(3 \times 10^6 \sim 4 \times 10^6\) N/m³; when the pipe has a vertical downward displacement, the value of \(C\) is \(5 \times 10^6 \sim 100 \times 10^6\) N/m³.

(1)Calculation of bending moment

The bending moment generated at the elbow can be calculated. According to the displacement relationship and the geometric relationship of the direct deformation of the straight pipe section, the deflection equation of the straight pipe section and the static balance can be used to calculate the bending moment of the elbow:

\[
M = \frac{C_m [\alpha EA(l_1 - l_2) \times 10^6 - F_{\min} l_{ce} \tan \theta]}{2}
\]

\[
k + C_m \left(\frac{A \tan^2 \theta}{2} + \frac{2k^2 I_{p} l_{cm}}{2k^2 I_{p} l_{cm}}\right)
\]

\[
C_m = \frac{1}{1 + KkR_c \phi (l_p / l_b)}
\] (7)

\[
k = \frac{4D_C C}{4EI_p \times 10^6}
\] (8)
lcm—the average arm length, m
Fmin—the minimum unit length friction of the pipe, N/m
E—the modulus of elasticity of the steel, MPa
α—the coefficient of linear expansion of steel, m/m·℃
A—the cross-sectional area of the steel pipe, m²
K—the elastic flexibility factor
Ip—the moment of inertia of the cross section in the straight pipe, m⁴.

The frictional force of the pipe unit length along the axis can be obtained according to the formula (9):

\[ F = \pi \rho \mu \left( H + \frac{D_w}{2} \right) D_w + \mu G \]  

(9)

F—the frictional force of the pipe along the axis of the unit length, N/m
μ—the coefficient of friction between the outer surface of the pipe and the soil
ρ—soil density, kg/m³
H—the buried depth above the pipe roof, When H>1.5m, H=1.5m
Dw—the pipe outer diameter, m
G—the total mass of the pipe and medium per meter of prefabricated insulation pipe, kg/m.

To calculate the length of the horizontal corner section transition, which can be found according to equations (10) and (11):

\[ l_{r_{\text{max}}} = \sqrt{Z^2 + \left( \frac{2Z}{F_{\text{min}}} \right) N_s} - Z \]  

(10)

\[ Z = \frac{A \tan^2 \varphi}{2k^3 I_p(1 + C_m)} \]  

(11)

l_{r_{\text{max}}}-the length of the transition section of the horizontal corner pipe section under the design temperature and the installation temperature difference, m
φ—the angle between the slope and the water level, rad

To set l₁ and l₂ be the lengths of the two arms of the elbow, and lc₁ and lc₂ are the calculated arm lengths of the elbow, then the average calculated arm length lcm is calculated by the formula (12):

\[ l_{cm} = \frac{l_{c1} + l_{c2}}{2} \]  

(12)

When \( l_1 \geq l_2 \geq l_{\text{max}} \), \( l_{c1} = l_{c2} = l_{\text{max}} \)
When \( l_1 \geq l_{\text{max}} > l_2 \), \( l_{c1} = l_{\text{max}}, l_{c2} = l_2 \)
When \( l_{\text{max}} > l_1 \geq l_2 \), \( l_{c1} = l_1, l_{c2} = l_2 \)

(3)Hoop stress generated by bending moment
The maximum hoop stress under bending moment is calculated according to formula (13), formula (14), formula (15), and formula (16).
\[
\sigma_{bt} = \frac{\beta_b M}{I_b} \times 10^{-6} \tag{13}
\]

\[
\beta_b = 0.9 \frac{2}{\lambda^3} \tag{14}
\]

\[
\lambda = R_c \frac{\delta_b}{(\gamma_{bm})^2} \tag{15}
\]

\[
\gamma_{bm} = \gamma_{bo} - \frac{\delta_b}{2} \tag{16}
\]

\(\sigma_{bt}\) - the maximum hoop stress of the elbow under the bending moment, MPa

\(\beta_b\) - elbow hoop stress reinforcement factor

\(M\) - the bending moment produced by the elbow, N·m

\(\gamma_{bo}\) - the outer radius of the elbow, m

\(I_b\) - the moment of inertia of the elbow cross section, m^4

\(\lambda\) - elbow size factor

\(R_c\) - the calculated radius of curvature of the elbow, m

\(\delta_b\) - elbow thickness, m

\(\gamma_{bm}\) - the average radius of the elbow cross section, m

The hoop stress at the top (bottom) of the elbow under internal pressure can be obtained according to formula (17):

\[
\sigma_{pt} = \frac{P_a D_{bi}}{2 \delta_b} \tag{17}
\]

\(D_{bi}\) - the inner diameter of elbow, m

\(\sigma_{pt}\) - the hoop stress at the top (bottom) of the elbow under internal pressure, MPa

3. Discussion

In the case of primary stress limit analysis, the stress level of the pipeline is required to not exceed the yield limit and the plastic flow of the pipeline is avoided. The internal pressure and the continuous external load work together, and the equivalent stress of the primary stress does not exceed the basic allowable stress of the steel at the calculated temperature. In engineering design, the limit analysis of primary stress is used to calculate the pipe thickness.

The primary stress and the secondary stress work together. According to the qualitative analysis, the pipeline can produce little plastic deformation. Under the action of primary stress and secondary stress, the equivalent stress variation range does not exceed twice the yield limit. The secondary stress generated by the thermal expansion and contraction, the displacement cannot be released, and the equivalent stress of the primary stress generated by the continuous external load of the internal pressure are not more than three times the basic allowable stress of the steel at the calculated temperature. Used for strength calculation of uncompensated straight pipe sections.

The calculation model of this subject belongs to the elbow calculation under the joint action of internal pressure and temperature difference. The combined stress calculation of the buried pipeline
elbow under the action of internal pressure and difference temperature should be according to formula (18).

\[
\sigma_e = \sigma_h + \sigma_{hmax} \leq \sigma_b
\]  

(18)

\(\sigma_e\) - the combined stress of the elbow under the action of internal pressure and temperature difference, MPa

\(\sigma_h\) - hoop stress generated by internal pressure, MPa

\(\sigma_{hmax}\) - the maximum hoop stress generated by the thermal expansion moment, MPa

\(\sigma_b\) - ultimate strength of material, MPa.

3.1. Model check

Calculated:

Average arm length \(l_{cm} = 99.19\) m;

The maximum bending moment of the elbow is \(M=712450\) N·m;

The maximum hoop stress generated by the thermal expansion bending moment \(\sigma_{hmax} = 36.29\) MPa;

Circumferential stress generated by internal pressure \(\sigma_h = 47.8\) MPa;

\(\sigma_e = 84.09\) MPa < \(\sigma_b = 450\) MPa

The combined stress of the elbow under the action of difference temperature and internal pressure can be seen, and the pipe under the model condition meets the strength requirement.

3.2. Influence of different working conditions

Based on this model, other conditions are unchanged, the pipe diameter, pipe thickness and slope angle are changed, and the combined stress of the elbow is calculated. The results are shown in Fig.7:

![Fig.7 Combined stress values when the pipe thickness is 25 mm](image)

It can be seen from the above Fig.7 that the combined stress of the elbow is between 50MPa and 120MPa.

(1) The combined stress of the elbow gradually decreases with the increase of the angle.

(2) Under the same pipe thickness, the combined stress increases with the increase of the pipe diameter. It can be seen that the reduction of the pipe diameter is advantageous for reducing the stress concentration at the elbow.
In order to more clearly express the influence of pipe thickness on the combined stress of the elbow, the pipe thickness is plotted as the abscissa, as shown in Fig.8:

![Fig.8 Trends of combined stress values with pipe thickness](image)

As can be seen from Fig.8:

1. The combined stress of the elbow gradually decreases with the increase of the pipe thickness.
2. With the increase of pipe thickness, the influence of the diameter of the pipe on the combined stress is gradually reduced.

4. Conclusion

The primary stress analysis and secondary stress analysis were carried out on the long-distance buried slope climbing pipeline. It was found that the internal stress of the long-distance buried slope climbing pipeline is mainly caused by the secondary stress. The magnitude of the stress is closely related to the slope angle and the pipeline parameters:

1. There is a certain critical angle. When the angle between the slope pipe and the water level is less than the critical angle, the gravity of the slope pipe has no effect on the elbow at the bottom of the slope. The critical angles under different pipe diameters and different buried soil types are calculated. It is found that the critical angle is more than 50°.

2. After calculation, the combined stress($\sigma_e = 84.09$MPa < $\sigma_b = 450$MPa) of the elbow under the influence of temperature difference and internal pressure in the model indicates that the pipeline under the model condition meets the strength requirement.

3. The combined stress of the elbow is from 50MPa to 140MPa when the pipe thickness is 30 mm. The combined stress increases with the increase of the pipe diameter. It can be seen that the reduction of the pipe diameter is advantageous for reducing the stress concentration at the elbow.

4. Under different pipe thicknesses and different pipe diameters, the combined stress of the elbow gradually decreases with the increase of the angle.

Data Availability Statement
All data included in this study are available upon request by contact with the corresponding author.

References
[1] A. Kovacs, Z. Szabo, Stress analysis of buried pipelines due to seismic motions. *Zeitschrift Fur Angewandte Mathematik Und Mechanik* 80, S475-S476 (2000).
[2] C. Kalliontzis, E. Andrianis, K. Spyropoulos, S. Doikas, Nonlinear static stress analysis of submarine high pressure pipelines. *Comput Struct* 63, 397-411 (1997).
[3] D. S. Jeng, P. F. Postma, D. H. Cha, *Internal stresses of a buried pipeline due to wave loading: Finite element analysis*. S. Valliappan, N. Khalili, Eds., Computational Mechanics, Vols 1 and 2, Proceedings: New Frontiers for the New Millennium (2001), pp. 369-374.

[4] H. J. Zhou, S. W. Yan, W. Cui, Nonlinear static finite element stress analysis of pipe-in-pipe risers. *China Ocean Eng* 19, 155-166 (2005).

[5] R. Khademi-Zahedi, P. Alimouri, Finite Element Analysis to the Effect of Thermo-Mechanical Loads on Stress Distribution in Buried Polyethylene Gas Pipes Jointed by Electrofusion Sockets, Repaired by PE Patches. *Energies* 11, (2018).

[6] M. Y. Xia, H. Zhang, Stress and Deformation Analysis of Buried Gas Pipelines Subjected to Buoyancy in Liquefaction Zones. *Energies* 11, (2018).

[7] J. L. C. Diniz, R. D. Vieira, J. T. Castro, A. C. Benjamin, J. L. F. Freire, Stress and strain analysis of pipelines with localized metal loss. *Exp Mech* 46, 765-775 (2006).

[8] D. K. Karamitros, G. D. Bouckovalas, G. P. Kouretzis, Stress analysis of buried steel pipelines at strike-slip fault crossings. *Soil Dyn Earthq Eng* 27, 200-211 (2007).

[9] O. V. Trifonov, V. P. Cherniy, A semi-analytical approach to a nonlinear stress strain analysis of buried steel pipelines crossing active faults. *Soil Dyn Earthq Eng* 30, 1298-1308 (2010).

[10] B. Han et al., *ANALYSIS OF STRESSES ON BURIED PIPELINE SUBJECTED TO LANDSLIDE BASED ON NUMERICAL SIMULATION AND REGRESSION ANALYSIS*. Proceedings of the Asme International Pipeline Conference 2010, Vol 1 (2010), pp. 83-88.

[11] O. V. Trifonov, V. P. Cherniy, Elastoplastic stress-strain analysis of buried steel pipelines subjected to fault displacements with account for service loads. *Soil Dyn Earthq Eng* 33, 54-62 (2012).

[12] O. V. Trifonov, V. P. Cherniy, Analysis of Stress-Strain State in a Steel Pipe Strengthened With a Composite Wrap. *J Press Vess-T Asme* 136, (2014).