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An Analytical Calculation Method and Mechanical Response Laws of Buried Pipelines Subjected to the Impact of Transverse Landslides

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Abstract. When the buried gathering and transportation pipelines cross the landslide area transversally, the migration of the landslide mass can cause the pipelines to be subjected to lateral thrust, which can seriously affect the safe operation of the buried pipelines. In order to study the mechanical response laws of the buried pipelines under the impact of transverse landslides, based on the elastic-plastic foundation beam theory, the mechanical models of buried pipelines are established for three situations, and the analytical solution of pipeline displacement is obtained by genetic algorithm. The influences of landslide thrust, landslide width, soil resistance coefficient, the pipe outer diameter and wall thickness on pipeline peak displacement and peak stress are also investigated. The results show that under the impact of the transverse landslide, with the increase of landslide thrust, the maximum displacement and maximum tensile stress of pipeline increase exponentially, and the failure risk of pipe increases. Secondly, with the increase of landslide width, the maximum displacement of pipeline increases in the beginning and then decreases to be constant, and the maximum tensile stress decreases sharply to be constant. Thirdly, with the increase of soil resistance coefficient, the maximum displacement and maximum tensile stress of pipeline decrease in a negative power trend, and the pipeline is safer. Fourthly, when the pipe outer diameter increases to a certain value, the maximum displacement and maximum tensile stress of the pipeline change very little, hence, pipe outer diameter can be optimized when designing pipe structure. Fifthly, the smaller the pipe wall thickness is, the greater the maximum tensile stress of the pipe is, therefore, pipe corrosion protection should be paid attention to. Sixthly, when the landslide thrust is large, the landslide width is small, or the pipeline outer diameter is small, the maximum tensile stress of the pipeline is located at the centre of the landslide, otherwise, it is located at $0.56L \sim 0.7L$ away from the landslide centre. In order to ensure the safe operation of the pipeline, the stress state of these two positions should be focused on. It is concluded that the study can provide the basis for the evaluation of pipeline safety status and has practical significance for ensuring the safe operation of buried pipelines.

Keywords. Transverse Landslides, Buried Pipeline, Analytical Method, Mechanical Responses, Influence Factors

1. Introduction

Buried pipelines are considered as one of the most practical and economical transportation means for liquid and gas energy resources, which form a key lifeline project for human life support and energy distribution [1-3]. In practice, buried pipelines will inevitably pass through potential geological hazard areas such as onshore or offshore landslides due to technically or financially considerations, which can result in severe destruction to the pipeline infrastructures [4-5]. As a serious geological disaster, the transverse landslide may lead to pipeline rupture mainly in the mode of tension or bulking. Hence, mechanical analysis for buried pipeline under the impact of the transverse landslides is of great engineering significance to guarantee the safe operation of the buried pipelines.

Up to present, many scholars have done lots of remarkable research related to the mechanical characteristics of buried pipelines under the action of transverse landslides. Chan et al. [6] simulated the pipe-soil interaction by setting springs between the pipe and soil and obtained the strain distribution of the pipelines. Cocchetti et al. [7] considered buried pipelines as beams, and gave the critical pressure and failure bending moment through nonlinear contact theory. Zhang et al. [8] established a new finite element model to predict the displacement and strain of pipelines subjected to the transverse landslide, which depicting the interaction between the pipeline and the soil outside the numerical model by equivalent boundary springs. Liu et al. [2] employed the arc-length algorithm and non-linear stabilization algorithm to respectively solve the nonlinear problem involved in the finite element method, assuming a parabolic displacement form within the middle zone of the buried pipeline. Vasseghi et al. [9] analyzed the rupture causes of the buried pipeline impacted by a field-measured displacement load of an actual landslide through the finite element method. Although the finite element method can present rigorous results for the deformation of the pipelines under the action of the transverse landslides, the analysis procedure needs high professional skills because of the convergence difficulties. From the perspective of the convenience and the basic role, the analytical or semi-analytical method still has practical value for preliminary research and can also facilitate the development of the more advanced finite element method. Rajani et al. [10] obtained the mechanical response of pipelines using an analytical method. Yuan et al. [11-12] proposed an analytical model dividing the pipeline into four segments and performed a parametric investigation with various loading conditions and soil properties. Moreover, Yuan et al. [13] improved the above analytical approach by introducing a non-constant axial tension with constant horizontal component. Zhang et al. [14] adopted the calculation formula of the drag force proposed by Hao et al. [15], and established the displacement differential equations which were solved through the finite difference method, particularly, the pipeline was partitioned into three segments in the model. Furthermore, Zhang et al. [16] investigated the mechanical behavior of buried pipelines under the impact of the landslides considering the inner pressure and the temperature difference. Chatzidakis et al. [17] investigated the response of an offshore steel natural gas pipeline taking the combined effect of the lateral and axial drag forces into account. In addition, Chatzidakis et al. [18] improved the analytical model of Yuan et al. [13] by assuming trilinear soil resistance and non-constant axial tension. Chaudhuri et al. [19] proposed a simplified analytical solution of the pipeline, assuming that the ground landslide-induced displacement satisfied a quartic polynomial function. Dong et al. [20] investigated the impact forces of submarine slides on partially-buried pipes using the material point method.

It can be seen that the research on buried pipelines under the action of transverse landslides has been very sufficient, but as far as the analytical method is concerned, the current research still needs further improvement. According to previous analytical and semi-analytical methods, the constitutive relation of the pipe-soil normal interaction adopted in the articles will change from elastic to plastic with the increasement of normal resistance between the pipe and soil. Considering this constitutive relation, three analytical mechanical models are established to overall describe the deformation of the buried pipelines during the process of landslide migration, including the whole elastic model (WEM) in which the pipe-soil interaction along the pipeline is elastic, the small plastic zone model (SPM) and the large plastic zone model (LPM) in which the plastic pipe-soil interaction zone is respectively within and beyond the landslide width range.

Genetic algorithm is adopted to obtain the solutions corresponding to the three mechanical models. Besides, a parametric study is performed to investigate the influence of landslide thrust, the pipe-soil interaction parameter and the pipe size on the mechanical peak response of buried pipelines. Through this study, it is hoped to provide the basis for the evaluation of pipeline status and the reference for the pipeline designation.

2. Mechanical Models

Figure 1 shows the diagram of a buried pipeline under the action of transverse landslide. When the landslide slides forward, the pipeline will generate deflection deformation due to the landslide thrust. In the pipeline cross section plane, the complex distributed load around the pipeline is simplified as two concentrated forces, namely the landslide thrust and the soil resistance. Therefore, all loads are represented by line loads along the pipeline. As shown in figure 2 (a) (b) (c), the xoy coordinate system is established with the pipe axis as the x-axis and the y-axis is perpendicular to the pipe axis, then three mechanical models are presented with detailed description later. q, L and p denote the landslide thrust, landslide width and the normal soil resistance respectively.

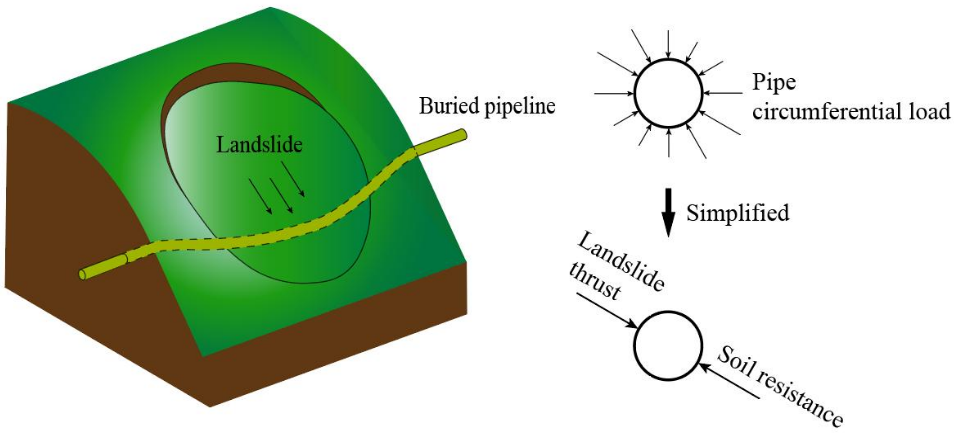

Figure 1. Schematic diagram and load simplification of a buried pipeline under transverse landslide.

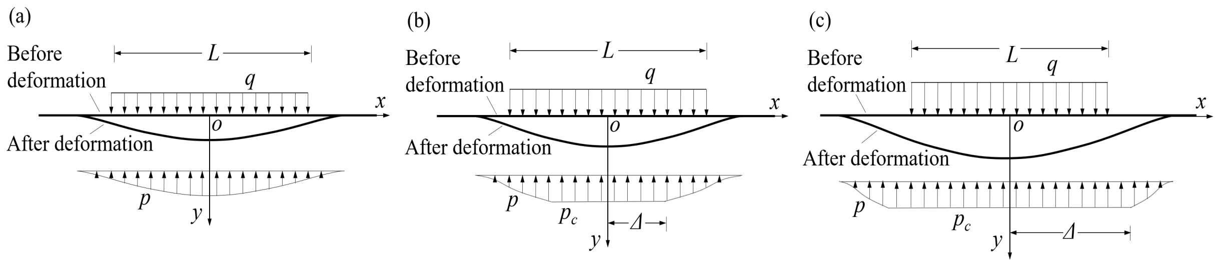

Figure 2. Three mechanical models of buried pipelines: (a) WEM, (b) SPM, (c) LPM

According to the elastic-plastic foundation beam theory, the ideal elastic-plastic constitutive relation can be adopted for describing the pipe-soil interaction. As shown in figure 3, when the normal displacement at any position of the pipe is smaller than the critical displacement w_c, there is a linear elastic relationship between the normal soil resistance p and the pipe displacement w for the position with a formula $p=kw$, where k is the soil resistance coefficient. Otherwise, when the displacement of the pipeline is larger than w_c, the soil resistance will keep as a constant value p_c, and the interaction between the pipeline and the soil is plastic. The critical displacement w_c is related to the pipe outer diameter D, namely $w_c=0.1D$ according to the research by [11-12].

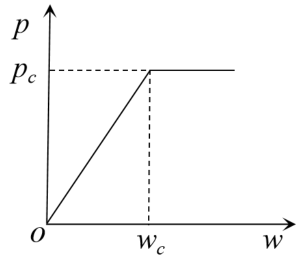

Figure 3. Constitutive relation diagram of pipe-soil interaction

In order to simplify the calculation of deformation of buried pipeline, some reasonable assumptions need to be made:

(1) The mechanical model of the pipeline is symmetrical about the landslide center.

(2) The dead weight, overburden pressure and internal pressure of the pipeline are ignored because of their much less effect on pipeline deformation compared to the landslide thrust.

(3) The landslide thrust is assumed to be uniformly distributed along the pipeline.

(4) The axial friction of the pipeline is also ignored due to its much less effect on pipeline deformation compared to the landslide thrust.

(5) The axial tension of the pipeline is considered as a constant to facilitate the solution of the governing equations.

3. Governing Equations and Definite Conditions

The zone where the plastic pipe-soil interaction arises is called the plastic zone, and the half width of the zone is denoted by Δ. Figure 2 (a) (b) (c) show three mechanical models of the WEM case, the SPM case and the LPM case with Δ=0, $\Delta \leqslant L/2$ and $\Delta > L/2$, respectively.

3.1. The WEM Case

For the WEM case, as seen from figure 2(a), the right half of the pipeline is divided into two segments, the governing differential equations of the two segments are respectively as follows:

$$\begin{cases} EI\omega_1'''' - T\omega_1'' + k\omega_1 = q & 0 < x \le L/2 \\ EI\omega_2'''' + k\omega_2 = 0 & x > L/2 \end{cases} \tag{1}$$

Where w_1 and w_2 denote the displacement of the two segments in y direction, E is the elastic modulus of the pipe, I is the moment of inertia of the cross section, T denotes the axial tension of the pipe, and is a constant. Solving these two fourth-order differential equations, the pipeline displacement expression can be written as:

$$\begin{cases} \omega_1 = \dfrac{q}{k} + e^{\alpha_1 x}\left[c_1\cos(\alpha_2 x) + c_2\sin(\alpha_2 x)\right] + e^{-\alpha_1 x}\left[c_3\cos(\alpha_2 x) + c_4\sin(\alpha_2 x)\right] & 0 < x \le L/2 \\ \omega_2 = e^{\beta x}\left[c_5\cos(\beta x) + c_6\sin(\beta x)\right] + e^{-\beta x}\left[c_7\cos(\beta x) + c_8\sin(\beta x)\right] & x > L/2 \end{cases} \tag{2}$$

Where $c_1 \sim c_8$ are the unknown constant coefficients, and

$$\alpha_1 = \frac{1}{2}\sqrt{2\sqrt{\frac{k}{EI}} + \frac{T}{EI}} \tag{3}$$

$$\alpha_2 = \frac{1}{2}\sqrt{2\sqrt{\frac{k}{EI}} - \frac{T}{EI}} \tag{4}$$

$$\beta = \sqrt[4]{\frac{k}{4EI}} \tag{5}$$

Considering the definite conditions, such as the continuity, symmetry and the boundary condition, eight equations related to the displacement, the inclination slope, the bending moment and the shearing force should be satisfied:

For x=0,

$$\begin{cases} \omega_1^{'}(x) = 0 \\ \omega_1^{'''}(x) = 0 \end{cases} \tag{6}$$

For x =L/2,

$$\begin{cases} \omega_1(x) = \omega_2(x) \\ \omega_1^{'}(x) = \omega_2^{'}(x) \\ \omega_1^{''}(x) = \omega_2^{''}(x) \\ \omega_1^{'''}(x) = \omega_2^{'''}(x) \end{cases} \tag{7}$$

For x =+∞,

$$\begin{cases} \omega_2^{'}(x) = 0 \\ \omega_2^{''}(x) = 0 \end{cases} \tag{8}$$

Besides, a supplementary equation can be obtained considering two different ways to calculate the elongation of the pipeline, the equation is written as:

$$\frac{TL'}{EA} = \int_0^{L/2} \sqrt{1+\omega_1^{'2}}\mathrm{d}x + \int_{L/2}^{L'} \sqrt{1+\omega_2^{'2}}\mathrm{d}x - L' \tag{9}$$

Where the left part of the equation denotes the elongation expressed by the axial tension T, L' is the original length and can be a very large value to ensure the accuracy of the elongation calculation, the right part is another way to calculate the elongation from the perspective of the arc length of the deflection curve, the first two items of the right part denote the pipe length after deformation.

Solving the nine equations above, the unknown constant coefficients of c_1~c_8 and the axial tension T can be obtained, and then displacement expression of the whole pipeline in the WEM case will also be obtained. Furthermore, the maximum axial tensile stress on the cross section of the pipeline is denoted by the following formula:

$$\begin{cases} M = EI\omega'' \\ \sigma_{\max} = \dfrac{T}{A} + \dfrac{|M|D}{2I} \end{cases} \tag{10}$$

Where M denotes the bending moment, A denotes the cross-section area of the pipeline, $\sigma_{\max}$ denotes the maximum axial tensile.

3.2. The SPM Case

For the SPM case, as seen from figure 2(b), the right half of the pipeline is divided into three segments which are different from the WEM case, and the governing differential equations of the three segments are respectively as follows:

$$\begin{cases} EI\omega_1^{''''} - T\omega_1^{''} = q - p_c & 0 < x \le \Delta \\ EI\omega_2^{''''} - T\omega_2^{''} + k\omega_2 = q & \Delta < x \le L/2 \\ EI\omega_3^{''''} + k\omega_3 = 0 & x > L/2 \end{cases} \tag{11}$$

Where w_1, w_2 and w_3 denote the displacement of the three segments in y direction, other terms in the equations are the same as WEM case except for the p_c and $\varDelta$ which are the plastic pipe-soil normal resistance and the half width of the plastic zone respectively. Solving these three fourth-order differential equations, the pipeline displacement expression can be written as:

$$\begin{cases} \omega_1 = \dfrac{p_c - q}{2T} x^2 + c_1 + c_2 x + c_3 e^{\gamma x} + c_4 e^{-\gamma x} & 0 < x \le \varDelta \\ \omega_2 = \dfrac{q}{k} + e^{\alpha_1 x}\left[c_5 \cos(\alpha_2 x) + c_6 \sin(\alpha_2 x)\right] + e^{-\alpha_1 x}\left[c_7 \cos(\alpha_2 x) + c_8 \sin(\alpha_2 x)\right] & \varDelta < x \le L/2 \\ \omega_3 = e^{\beta x}\left[c_9 \cos(\beta x) + c_{10} \sin(\beta x)\right] + e^{-\beta x}\left[c_{11} \cos(\beta x) + c_{12} \sin(\beta x)\right] & x > L/2 \end{cases} \tag{12}$$

Where $c_1 \sim c_{12}$ are the unknown constant coefficients, and

$$\gamma = \sqrt{\frac{T}{EI}} \tag{13}$$

Considering the definite conditions, such as the continuity, symmetry and the boundary condition, eight equations related to the displacement, the inclination slope, the bending moment and the shearing force should be satisfied:

For x=0,

$$\begin{cases} \omega_1'(x) = 0 \\ \omega_1'''(x) = 0 \end{cases} \tag{14}$$

For $x=\varDelta$,

$$\begin{cases} \omega_1(x) = \omega_2(x) \\ \omega_1'(x) = \omega_2'(x) \\ \omega_1''(x) = \omega_2''(x) \\ \omega_1'''(x) = \omega_2'''(x) \\ \omega_2(x) = 0.1D \end{cases} \tag{15}$$

For $x=L/2$,

$$\begin{cases} \omega_2(x) = \omega_3(x) \\ \omega_2'(x) = \omega_3'(x) \\ \omega_2''(x) = \omega_3''(x) \\ \omega_2'''(x) = \omega_3'''(x) \end{cases} \tag{16}$$

For $x=+\infty$,

$$\begin{cases} \omega_3'(x) = 0 \\ \omega_3''(x) = 0 \end{cases} \tag{17}$$

Besides, a supplementary equation can be obtained considering two different ways to calculate the elongation of the pipeline, the equation is written as:

$$\frac{TL'}{EA} = \int_0^{\varDelta} \sqrt{1+\omega_1'^2}\,\mathrm{d}x + \int_{\varDelta}^{L/2} \sqrt{1+\omega_2'^2}\,\mathrm{d}x + \int_{L/2}^{L'} \sqrt{1+\omega_3'^2}\,\mathrm{d}x - L' \tag{18}$$

Solving the fourteen equations above, the unknown constant coefficients of $c_1 \sim c_{12}$, the axial tension

T and the half plastic width $\triangle$ can be obtained, and then displacement expression and the maximum axial tensile stress on the cross section of the whole pipeline in the SPM case will also be obtained.

3.3. The LPM Case

For the LPM case, as seen from figure 2(c), the right half of the pipeline is divided into three segments, and the governing differential equations of the three segments are respectively as follows:

$$\begin{cases} EI\omega_1'''' - T\omega_1'' = q - p_c & 0 < x \le L/2 \\ EI\omega_2'''' - T\omega_2'' = -p_c & L/2 < x \le \varDelta \\ EI\omega_3'''' + k\omega_3 = 0 & x > \varDelta \end{cases} \tag{19}$$

Where w_1, w_2 and w_3 denote the displacement of the three segments in y direction, other terms in the equations are the same as SPM. Solving these three fourth-order differential equations, the pipeline displacement expression can be written as:

$$\begin{cases} \omega_1 = \dfrac{p_c - q}{2T}x^2 + c_1 + c_2 x + c_3 e^{\gamma x} + c_4 e^{-\gamma x} & 0 < x \le L/2 \\ \omega_2 = \dfrac{p_c}{2T}x^2 + c_5 + c_6 x + c_7 e^{\gamma x} + c_8 e^{-\gamma x} & L/2 < x \le \varDelta \\ \omega_3 = e^{\beta x}\left[c_9 \cos(\beta x) + c_{10}\sin(\beta x)\right] + e^{-\beta x}\left[c_{11}\cos(\beta x) + c_{12}\sin(\beta x)\right] & x > \varDelta \end{cases} \tag{20}$$

The definite conditions for the LPM case can be obtained if exchanging the terms of $\triangle$ and $L/2$ from the definite conditions in the SLM case. Solving the equations of the definite conditions, the final displacement expression and the maximum axial tensile stress on the cross section of the whole pipeline in the LPM case will also be obtained.

4. Genetic Algorithm for Solutions

In order to obtain the final displacement expressions of the buried pipeline in case of the three mechanical models, nonlinear equations of the definite conditions need to be solved. Genetic algorithm(GA) is adopted to solve the nonlinear equations in this paper. The unknown numbers to solve are the unknown constant coefficients c_1~c_8 and the axial tension T for WEM, or the unknown constant coefficients c_1~c_{12}, the axial tension T and the half width of the plastic zone $\triangle$ for SPM and LPM.

In GA, the objective function denoting the quality of the solution should be defined. The objective functions for the three mechanical models are defined respectively below.

For WEM, the objective function is written as:

$$f_T = \left| \int_0^{L/2}\sqrt{1+\omega_1'^2}\,\mathrm{d}x + \int_{L/2}^{L'}\sqrt{1+\omega_2'^2}\,\mathrm{d}x - L' - \frac{TL'}{EA} \right| \tag{21}$$

For SPM, the objective function is written as:

$$f_{T,\varDelta} = \left| \int_0^{\varDelta}\sqrt{1+\omega_1'^2}\,\mathrm{d}x + \int_{\varDelta}^{L/2}\sqrt{1+\omega_2'^2}\,\mathrm{d}x + \int_{L/2}^{L'}\sqrt{1+\omega_3'^2}\,\mathrm{d}x - L' - \frac{TL'}{EA} \right| + \left|\omega_2(\varDelta) - 0.1D\right| \tag{22}$$

For LPM, the objective function is written as:

$$f_{T,\varDelta} = \left| \int_0^{L/2}\sqrt{1+\omega_1'^2}\,\mathrm{d}x + \int_{L/2}^{\varDelta}\sqrt{1+\omega_2'^2}\,\mathrm{d}x + \int_{\varDelta}^{L'}\sqrt{1+\omega_3'^2}\,\mathrm{d}x - L' - \frac{TL'}{EA} \right| + \left|\omega_2(\varDelta) - 0.1D\right| \tag{23}$$

As investigated by Cui et al. [21], in GA, if the objective function value is smaller than a specified convergence threshold δ , then the calculation is over. It needs many generations of iterative calculation to obtain a solution meeting the required accuracy. Selection, crossover and mutation will be conducted per generation. GA procedure for solving the nonlinear equations in this paper is shown in figure 4. Firstly, an initial population for *T*(for WEM) or (T, $\triangle$) (for SPM or LPM) with *N* individuals will be produced randomly. Substituting each individual of *T* or (T, $\triangle$) into the equations of the definite conditions, the nonlinear equations become linear equations, and the remaining unknown numbers such as c_1~c_8 or c_1~c_{12} can be obtained by solving the linear equations. Furthermore, the pipe displacement *w* can be obtained. Then using the equation (21), (22) or (23), the objective function value for each individual can be calculated. If the objective function value of an individual is smaller than δ , then the calculation is over, the solution of this individual is the final solution. Otherwise, two individuals with larger objective function values may be selected by probability. The two selected individuals will be handled with the genetic operators of crossover and mutation and a new pair individuals are produced. The procedure of selection, crossover and mutation is repeated until *N* new individuals are produced. Thus, the G+1 population better than the current G population is obtained. The solution will be optimized with population renewal generation by generation. The GA terminates if the objective function value for an individual satisfies the convergence criteria and the final solution is obtained.

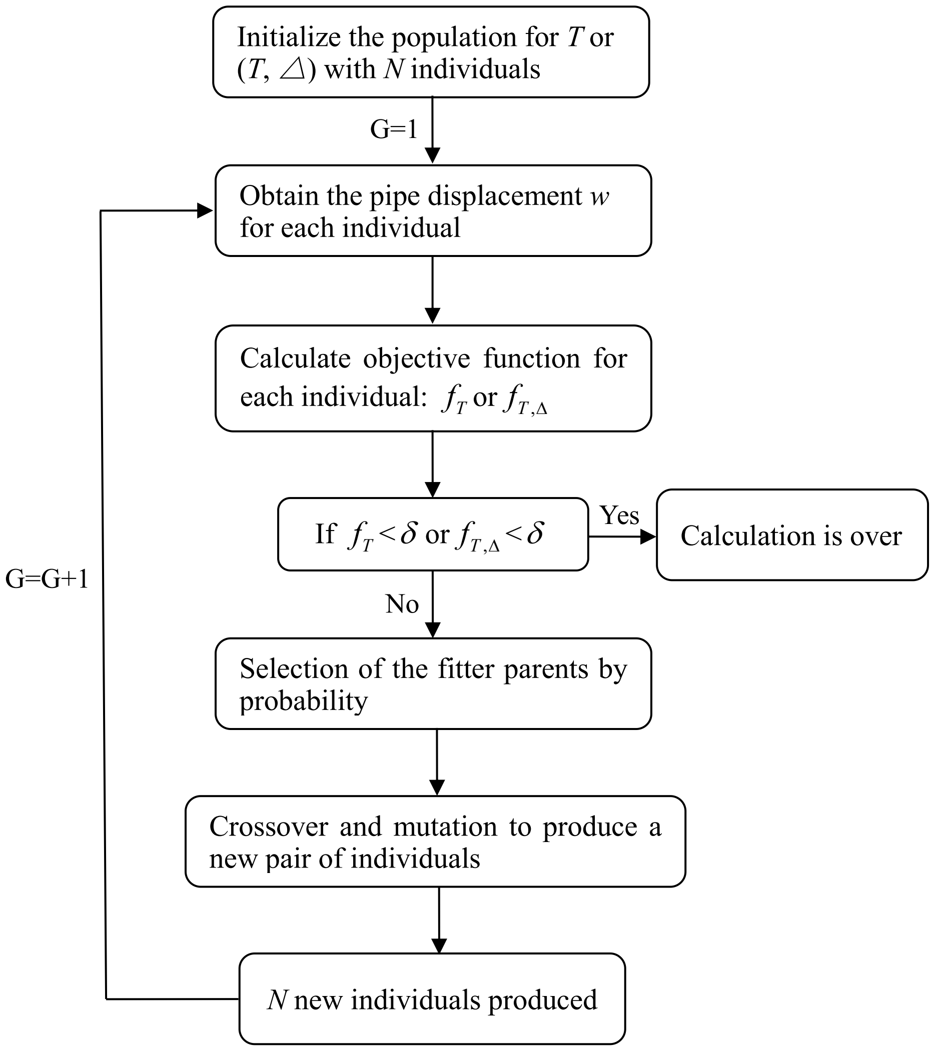

Figure 4. Solving procedure through genetic algorithm

5. Model Validation

The analytical method of the three mechanical models are compared with the corresponding finite element method (FEM). The considered pipeline is made of X70 steel. The material properties of the pipeline and the load conditions are presented in table 1 and table 2. For the finite element model, the Timoshenko beam element B21 is adopted for the pipeline, the PSI24 element is adopted for the pipe-soil interaction, and the mesh size is 0.5m. The fixed end constraints are applied at both ends of the pipeline.

The displacement solutions calculated by the analytical method and the finite element method are shown in figure 5. According to the critical displacement with the value of 0.1D and the specific landslide width, it can be seen from the displacement curve that when q is equal to 1400kN/m, 1600kN/m and 1800kN/m, the appropriate mechanical model is WEM, SPM and LPM respectively. For the latter two models, the half width of the plastic zone Δ is 7.13m and 10.41m. The analytical solutions of the pipeline displacement of the three mechanical models are very close to the finite element calculation results. The maximum displacement relative errors from the two methods are 0.25 %, 0.84 %, and 2.7%, which indicates that the three mechanical models proposed in this paper are reliable.

Table 1. Material properties of X70 steel.

Matrial	E(GPa)	μ	ρ(kg/m^3)	σ_s(MPa)	D(m)	t(m)
X70	210	0.3	7850	485	1.016	0.0175

Table 2. Load conditions and other parameters.

q(kN/m)	L(m)	k(N/m^2)	l(m)	L' (m)
1400/1600/1800	20	1.5× 10^7	600	300

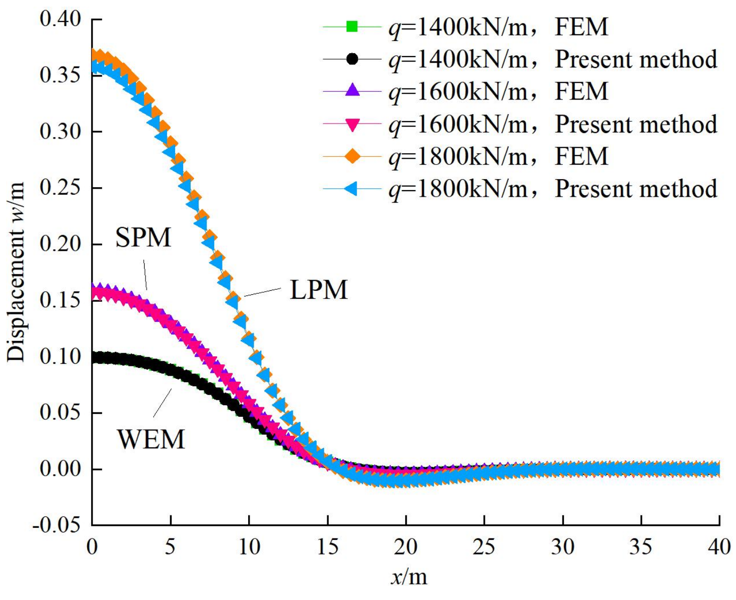

Figure 5. Comparison of analytical method and finite element calculation results

6 Parametric Study

6.1. Landslide Thrust

Landslide thrust is the active factor causing the deformation of buried pipeline. All the parameters are the same as those in the model validation except the landslide thrust. The peak responses of the buried pipeline under different landslide thrusts are shown in figure 6. In figure 6(a), the maximum displacement of the pipeline increases exponentially as the landslide thrust increases. The half width of the plastic zone also increases, but the increasing rate decreases. As shown in figure 6(b), the maximum tensile stress increases exponentially as the landslide thrust increases. Besides, when the landslide thrust is smaller than 1550kN/m, the maximum tensile stress position is located at x=0.650L~0.675L away from the landslide center, but when the landslide thrust exceeds 1550kN/m, the maximum tensile stress position is located at x=0, namely at the landslide center. The results show that the landslide thrust has a great influence on the displacement and stress of the buried pipeline.

From figure 6(a), it can be also seen that when the landslide thrust equals to 1400kN/m, the peak responses of the buried pipeline under the action of the transverse landslide were calculated by the WEM because that the maximum displacement is smaller than the critical displacement 0.1D. When the landslide thrust is between 1450kN/m~1650kN/m, the half width of the plastic zone is 2.30m ~ 9.71m, the peak responses of the buried pipeline were calculated by the SPM. The maximum tensile stress is 167MPa~350MPa, which is also large compared to the yield strength σ_s=485Mpa, so that the WEM and the SPM should be also paid attention to.

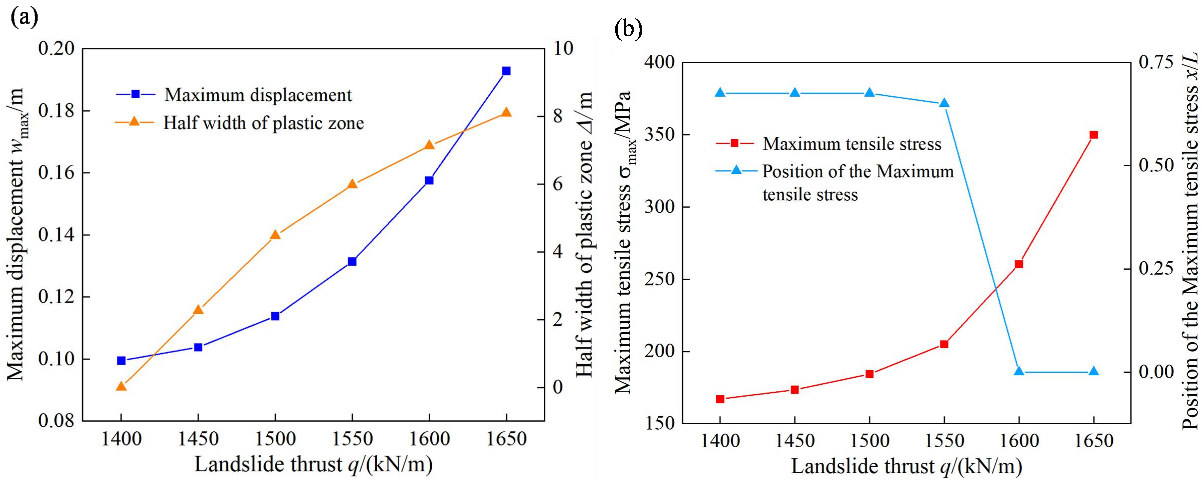

Figure 6. Peak responses of the pipeline under different landslide thrusts: (a) maximum displacement and half width of the plastic zone, (b) maximum tension stress and its position

6.2. Landslide Width

When landslide thrust is 1500kN/m, the peak responses of the buried pipeline under different landslide widths are shown in figure 7. From figure 7(a), it can be seen that as the landslide width increases, the curves of the maximum displacement of the pipeline w and the half width of the plastic zone $\triangle$ have the same variation trend, both of which increase firstly and then decrease to be basically a constant. At the beginning, when the landslide width is small, the landslide thrust has a stress concentration effect, resulting in the plastic pipe-soil interaction, and the local soil area near the landslide center loses the ability to resist the deformation of the pipeline. Hence the maximum displacement and the half width of the plastic zone increases gradually with the increase of the landslide width. On the other hand, when the landslide width is large, the stress concentration effect of the landslide thrust disappears because that the landslide thrust distributes on a wider area. So that the soil below the pipeline can resist the deformation of the pipeline and the mechanical model changes from SPM to WEM with the increase of the landslide width. The critical landslide width for the model transition is equal to 30m, and there is little influence when the landslide width is larger than 40m.

Figure 7(b) shows variation of the maximum tensile stress and its position under different landslide widths. It can be seen that the maximum tensile stress decreases sharply when the landslide width changes from 10m to 20m. at the same time, the position of the maximum tensile stress also changes from x=0 to x= 0.56L~0.65L away from the center of landslide. Unlike the displacement, the critical width for the maximum tensile stress is 20m, when the landslide width is larger than the critical width, the maximum tensile stress basically remains unchanged.

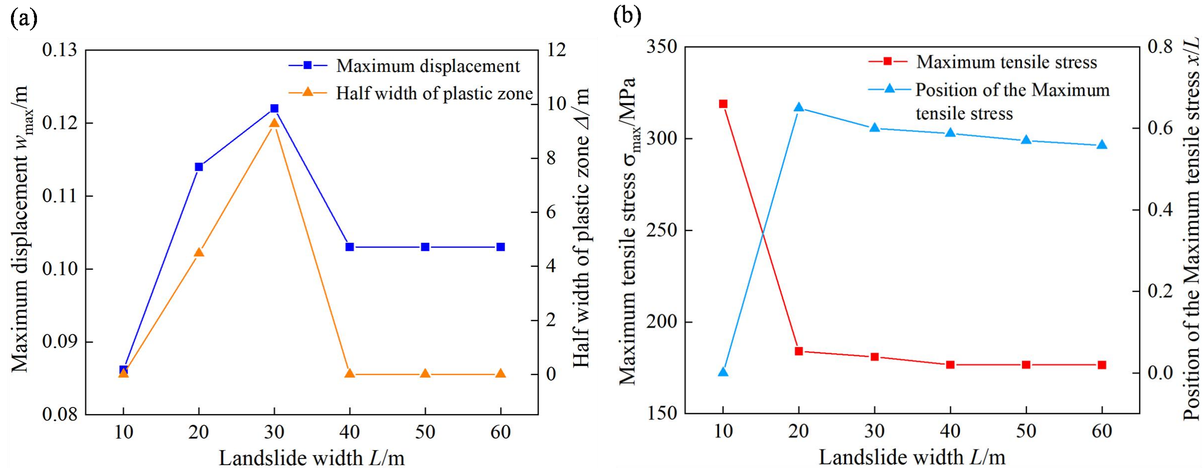

Figure 7. Peak responses of the pipeline under different landslide widths: (a) maximum displacement and half width of the plastic zone, (b) maximum tension stress and its position

6.3. Soil Resistance Coefficient

Soil resistance coefficient is a passive factor affecting the deformation of buried pipeline. When the landslide thrust is 1500kN/m, the peak responses of the buried pipeline under different soil resistance coefficients are shown in figure 8. It can be seen from figure 8(a) that the maximum displacement of the pipeline decreases in a negative power trend as the soil resistance coefficient increases. For the variation of the half width of the plastic zone, except for k=1.5×10^{7}N/m^2, there is no plastic pipe-soil interaction zone. It indicates that the mechanical changes from SPM to WEM with the increasing of the soil resistance coefficient. Figure 8(b) shows the maximum tensile stress decreases in a negative power trend similar to the variation of maximum displacement, and the position of the maximum tensile stress is basically unchanged at x=0.625L~0.675L.

The peak responses of the buried pipeline indicate that large soil resistance coefficient can prevent the deformation of the buried pipeline, so it is favorable to select hard soil areas to lay the pipelines. However, too large soil resistance coefficient may lead to serious ovalization of the buried pipelines which is another interesting point to investigate.

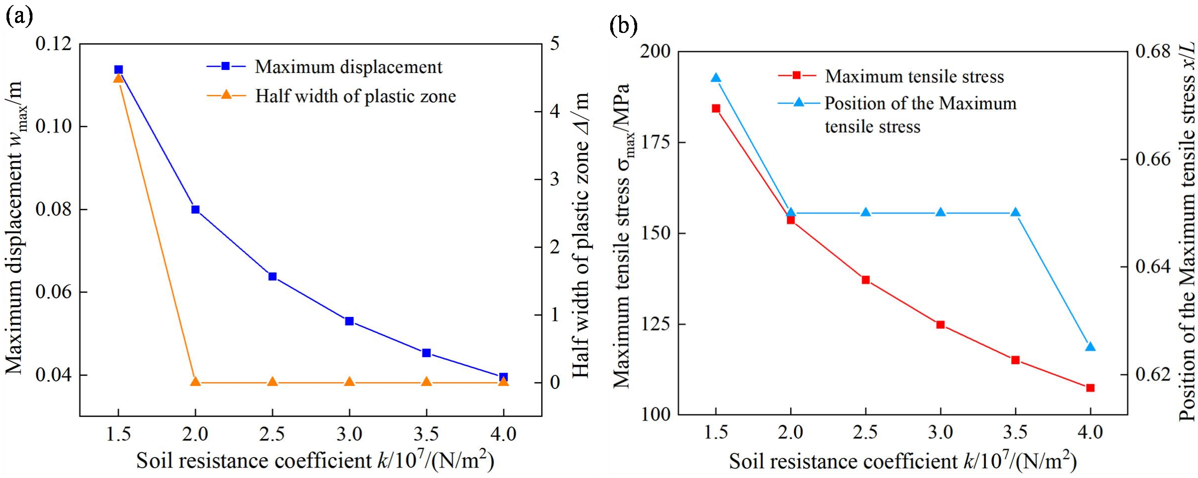

Figure 8. Peak responses of the pipeline under soil resistance coefficients: (a) maximum displacement and half width of the plastic zone, (b) maximum tension stress and its position

6.4. Pipe Outer Diameter

Pipe outer diameter is one of the geometric factors determining the anti-bending deformation ability. When the landslide thrust is 1500kN/m, the peak responses of the buried pipeline under different pipe outer diameters are shown in figure 9. In the figure 9(a), as the pipe outer diameter increases, the maximum displacement of the pipe decreases sharply and then remains basically unchanged. This indicates after the pipe outer diameter increases to a certain value, it has almost no effect on the pipe displacement. Therefore, the optimization of the pipe outer diameter can be considered for the design of pipe structure. The half width of the plastic zone decreases linearly and finally remains zero with the increasing of the pipe outer diameter, and the mechanical model changes from SPM to WEM.

It can be seen from figure 9(b) that the maximum tensile stress of the pipeline decreases sharply in the beginning and finally has little variation, which is the same as the variation trend of the maximum displacement. When the pipe outer diameter is smaller than 1.00m, the maximum tensile stress is located at the center of the landslide, on the contrary, the maximum tensile stress is located at x=0.65L~0.7L. The stress response also indicates there is little effect on the pipeline after the pipe outer diameter is larger than 1.0m when the landslide thrust is 1500kN/m.

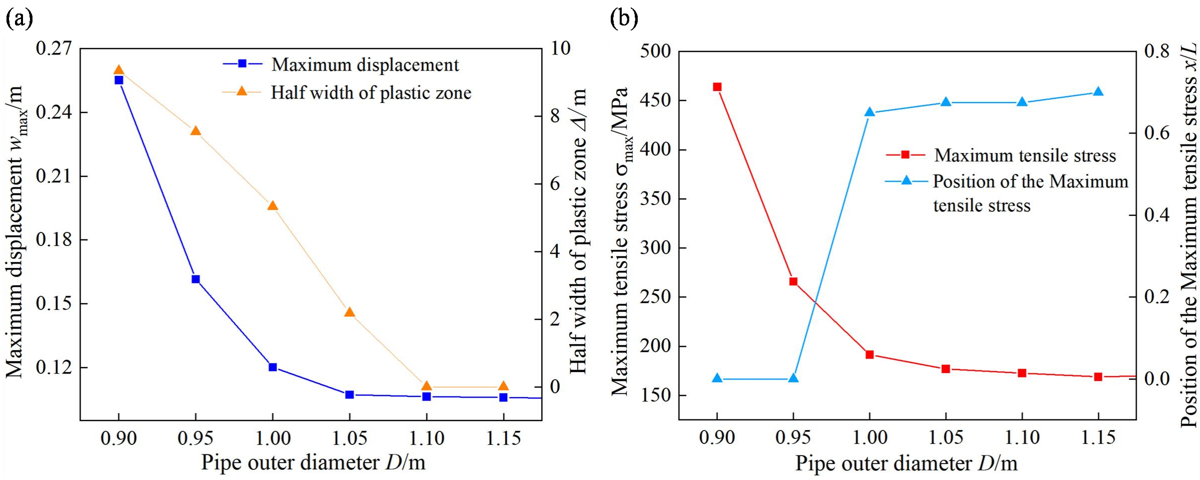

Figure 9. Peak responses of the pipeline under pipe outer diameter: (a) maximum displacement and half width of the plastic zone, (b) maximum tension stress and its position

6.5. Wall Thickness

Wall thickness is another geometric factor determining the anti-bending deformation ability. When landslide thrust is equal to 1500kN/m, the peak responses of the buried pipeline under different pipeline wall thickness are shown in figure 10. As seen in figure 10(a), when the wall thickness of the pipe increases from 0.005m to 0.030m, the maximum displacement decreases from 0.123m to 0.109m with only 0.014m reduction. The half width of the plastic zone only decreases by 2.42 m. The results show that the wall thickness of the pipeline has not too much effect on the displacement of the pipeline.

Figure 10(b) shows the maximum tensile stress of the pipeline decreases in a negative power trend with the increase of the wall thickness of the pipeline. When the wall thickness of the pipeline increases from 0.005m to 0.030m, the maximum tensile stress decreases from 336MPa to 143MPa, indicating that the wall thickness has a great influence on the stress of the pipeline. This is because as the wall thickness of the pipeline increases, the bending and tensile stiffness of the pipeline are enhanced resulting in the bigger resistance to the deformation of the pipeline. The change of pipe wall thickness almost does not affect the location of the maximum tensile stress, of which the coordinate is x=0.625L~0.7L.

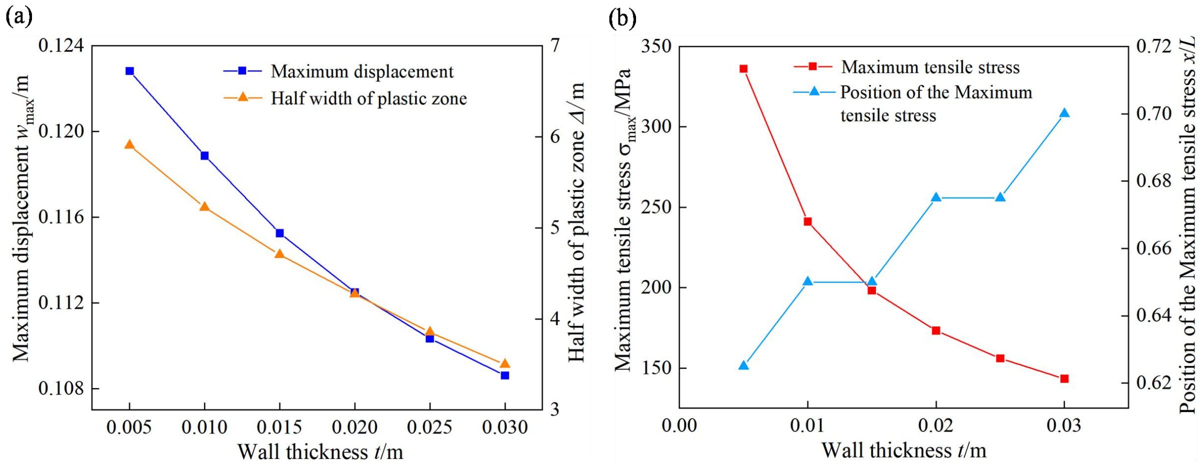

Figure 10. Peak responses of the pipeline under the wall thickness: (a) maximum displacement and half width of the plastic zone, (b) maximum tension stress and its position

7. Conclusions

(1) Three mechanical models of WEM, SPM and LPM are established for the buried pipelines subjected to the transverse landslide in this paper. The corresponding analytical solutions for the three models are obtained through genetic algorithm. The comparison with the finite element results shows that the analytical solutions are reliable. The three mechanical models can totally describe any situation of the buried pipelines when the transverse landslide is sliding continuously.

(2) With the increase of landslide thrust, the maximum displacement and maximum tensile stress of pipeline increase exponentially, and the half width of plastic zone of pipe-soil interaction also increases. With the increase of the landslide width, the maximum displacement of the pipeline increases in the beginning and then decreases to a constant value, but the maximum tensile stress of the pipeline decreases monotonically and finally remains almost unchanged. Besides, the mechanical model has a transition from SPM to WEM with the increase of the landslide width. As the soil resistance coefficient increases, the maximum displacement and maximum tensile stress of the pipeline decrease in a negative power trend. Therefore, in order to prevent the failure of the buried pipeline, an appropriate hard soil area can be considered to lay the pipelines.

(3) When the pipe outer width increases, the maximum displacement and maximum tensile stress of the pipe decrease rapidly for a small pipe outer width and then remain unchanged for a large pipe outer width. The wall thickness of the pipeline has little effect on the maximum displacement of

the pipeline, but the maximum tensile stress decreases in a negative power trend with the increase of the wall thickness of the pipeline. So that the pipe outer diameter and wall thickness can be optimized for the structure design of the buried pipelines.

(4) The maximum tensile stress of the pipeline is located at the center of the landslide for a larger landslide thrust, a smaller landslide width, or a smaller pipe outer diameter. Otherwise, it is located at 0.56*L*~0.7*L* away from the center of the transverse landslide. In order to ensure the safe operation of the buried pipeline, the stress monitoring sensor can be installed near the two locations along the pipeline route to evaluate the safety status of the buried pipelines.

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