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Safety Length Simulation of Natural Gas Pipeline Subjected to Transverse Landslide

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Abstract

The safety of natural gas pipeline is often severely threatened by the transverse landslide. At home and abroad, it is the first time to study the safe length of the pipeline when affected by landslide, and take the safe length of the pipeline as an engineering practical index. Therefore, it is of great significance to study the influence of transverse landslide affecting the safety of natural gas pipeline when a certain length of pipeline is thrusted, and to establish practical index and simulation method for prediction and prevention of the landslide hazards to gas pipeline. Based on the current research results, this study could be divided into three steps: First of all, with the help of ANSYS finite element software, the model of transverse landslide acting on the gas pipeline can be set up, then the length value of gas pipeline safely withstanding transverse landslide can be calculated; Secondly, using the strength reduction method, which is commonly used in the research of landslide stability, can establish three-dimensional model of the landslide and pipes in the ABAQUS finite element software, next, under the same landslide pushed length, the calculation results will be obtained; Finally, to draw reliable conclusions, all calculated results of the former two methods will be linked to synthetically and comparatively analyze, then the length value of common X80 gas pipeline safely bearing transverse landslide can be got. All results can provide some references for engineering and design.

Keywords

Transverse Landslide, Gas Pipeline, Finite Elements Simulation, Strength Reduction Method

1. Introduction

Natural gas pipeline is a kind of important energy transportation facilities. Therefore, to avoid it suffering natural or man-made damage has very important practical significance. However, this kind of pipeline has the long linear engineering characteristic that lets it often subjected to landslide damage [1] [2] [3]. This damage may cause pipeline large deformation, fracture, or explosion, etc. and it can lead to the natural gas leakage, pipeline transportation interruption, even casualties. How to prevent and control the loss caused by landslide disaster has been becoming a problem which needs to be studied continuously by engineers and researchers.

Currently, the number of the research findings [4]-[10] about the transverse landslide [11] (**Figure 1**) acting on the natural gas and petroleum pipeline has been increasing abundantly. But most of them aim to find out the mechanical behavior, the weak position, the influence factors, etc. of the pipe under landslide. And they are all more theoretical rather than practical, moreover, the practical indicators of pipeline about prediction and prevention damaged by landslide disaster are not proposed. Engineering practice shows that before the landslide is happening, the ground surface tends to present some certain characteristics, such as cracks, deformations, sliding, etc., and experienced engineers can determine the landslide scale roughly according to these characteristics. However, it is still necessary to observe and even calculate the damage degree of the landslide to the pipeline. If a kind of direct index can be offered for engineering practice, then contrasting it with the scale of landslide. Through that, whether the natural gas pipeline will be destroyed or not can be more accurately evaluated. Moreover, it can become a kind of reliable basis for engineering rescuing, and according to that, emergency workers can take measures in time to prevent the expansion of damage. So such index is of great significance for practice.

At home and abroad, it is the first time to study the length of the pipeline affected by landslide, and take the length of the pipeline safety as engineering practical index. Thus, in this paper, the length of the pipeline is studied as the research object. Through finite element simulation, this study calculated the length of general natural gas pipeline X80 in different depth safely withstanding the action of transverse landslide. The results with admirable available property can provide a direct and reliable practical indicator for prevention and controlling hazards to the pipe when landslide happens.

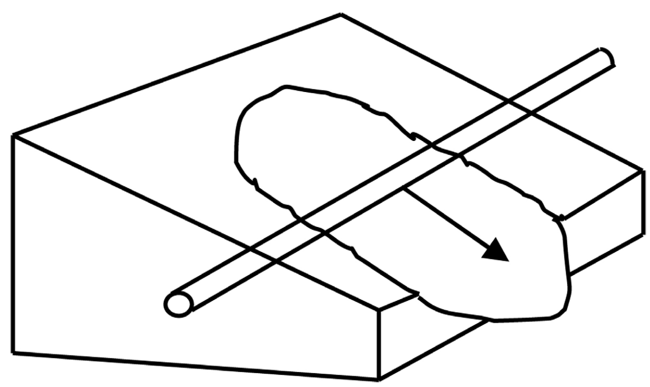

Figure 1. Transverse landslide schematic diagram.

2. Methodology

In order to make the research conclusion accurate and reliable, this study divided into three steps: First of all, in consideration of the landslide-thrust distribution on the natural gas pipe [12] and pipe-soil interaction research methods and findings [13]-[19], in the landslide area, the function of the landslide loaded on the natural gas pipe is simplified to thrust form, but outside the landslide area, the contact relationship is established. After that, with the help of ANSYS finite element software, the model of transverse landslide acting on the natural gas pipeline can be set up, and the length of the natural gas pipeline safely withstanding transverse landslide can be calculated. Secondly, using the strength reduction method, which is commonly used in the research of landslide stability, can establish three-dimensional model of the landslide and pipe in the ABAQUS finite element software, next, under the same landslide loaded length, the calculation results will be obtained. Finally, to draw reliable conclusions, all calculation results of the former two methods will be linked to synthetically and comparatively analyze, then the length value of common X80 gas pipeline safely bearing transverse landslide can be got. All results can provide some references for engineering and design.

2.1. Simplified Model

When pipeline is subjected to transverse landslide, it will produce large deformations, and the pipe-soil shall present complex nonlinear contact status. In order to simulate the corresponding behavior of pipeline, Shell181 element is took to simulate the natural gas pipe. Although soil consists of soil particles, but it often appears as entities in nature, so it can be regarded as one kind solid with elasticity and plasticity. In order to simulate the non-slip area soils more realistically, Solid185 element is used. Between the pipe and soil, the contact relationship is set up, which use TARGE170 unit and CONTA174 unit as the target surface element and contact surface element respectively.

Here, X80 pipe is used as the pipe modeling material, and the parameters are shown in **Table 1**. For the pipe stress-strain relationship curve, the ideal elastic-plastic bilinear kinematic hardening model is taken and shown in **Figure 2**. Outside the landslide zone, the soil parameters are adopted as follows: the density is 2000 kg/m^3, the elastic modulus is 32.5 MPa, the poisson's ratio is 0.35, the internal cohesion is 15 kPa, and the internal friction angle takes 10˚. It is worth noting that the weight of the natural gas is averaged distribution into the pipe body, so the natural gas pipeline equivalent density $\rho_{eq.}$ is 9197.7 kg/m^3.

The engineering practice shows that the soil mass in the non-slip area is basically in elastic state, so the soil can be regarded as an elastic material. The semi-symmetric finite element model (FEM model) is set up as **Figure 3**.

The length of the natural gas pipe is five times as long as the half-length pushed by the transverse landslide. The non-slip soil bulk width along the pipe transverse is 12 times long as the pipe diameter, but along the pipe axial direction

Table 1. Physical parameters of X80 Pipe.

D	δ	γ	P	ρ	σ_1	μ	E_1	E_2
1016	15.3	0.85	10	7850	555	0.3	207	6210

Notes: pipe diameter D (mm), pipe thickness δ (mm), natural gas density γ (kN/m^3), internal pressure P (MPa), pipe density ρ (kg/m^3), pipe material yield strength σ_1 (MPa), poisson's ratio μ, the elastic modulus E_1 (GPa), the tangent modulus E_2 (MPa).

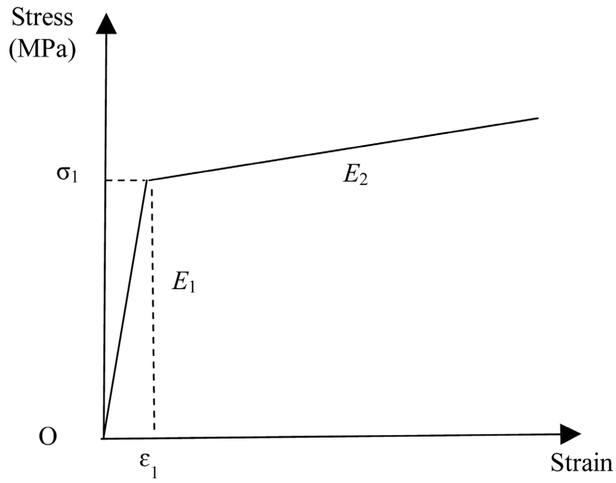

Figure 2. Pipe ideal stress-strain relationship model.

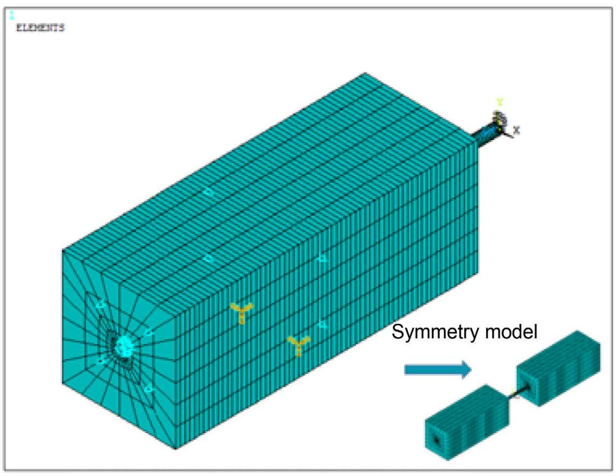

Figure 3. Simplified model of landslide and pipe.

is 4 times long as the half-length loaded by the transverse landslide. In the soil bulk, the upper surface and one end face near the landslide is free surface, but another end face far from the landslide is constrained along the pipe axis direction. The front and back plane of non-slip soil bulk are fixed up perpendicular to the corresponding surface. The soil base is fixed in all directions. On the natural gas pipe's two ends, one end away from landslide is constrained along the pipe axis, and the other end fixed as symmetry constraint.

The research [12] has shown that: under the action of transverse landslide, the pipe experiences different thrust force in different buried depth. Hereby, the thrust force on pipe in different buried depth is calculated and listed as follows (**Table 2**). About the distribution of thrust force along the pipe due to landslide, the study [20] have assumed it as uniform distribution, but in actual, the load distribution along the pipe is more closer to the parabolic distribution. Therefore, it will be assumed as a parabolic distribution in this article, and the parabolic vertex load is calculated as the study [12].

In order to get the limit length value of the natural gas pipeline safely bearing transverse landslide, the pipeline failure criteria is on the basis of that: the pipe Von Mises stress reach the pipe material yield strength. After a large number of trial, the final results is listed as follows (**Table 3**), and the relevant graphs are

Table 2. Thrust value of pipe buried in different depth.

δ		15.3	
H	1	2	3
β		q	
15	151.2	193	234.8
30	149	186.5	223.9
45	140.4	170.9	201.5
60	125.9	147.5	169.1
75	106.5	117.7	128.9

Notes: pipe thickness δ (mm), buried depth of pipeline H (m), angle between horizontal plane and soil sliding direction in place where pipe buried β (˚), uniform load q (kN/m).

Table 3. Calculation results of different pipe length subjected to transverse landslide.

H			**1**		**2**		**3**
L			30	24	27	24	24
β	15	σ_{max}	558	540	566	550	562
		U_{max}	0.5092	0.221	0.491	0.2897	0.3987
	30	σ_{max}	557	539	559	545	556
		U_{max}	0.5049	0.2199	0.4614	0.2807	0.3673
	45	σ_{max}	557	536	551	542	549
		U_{max}	0.4602	0.2093	0.3704	0.2566	0.3136
	60	σ_{max}	547	514	543	540	544
		U_{max}	0.3989	0.1901	0.3277	0.2211	0.251
	75	σ_{max}	539	489	538	497	519
		U_{max}	0.3341	0.178	0.2598	0.1794	0.1925

Notes: buried depth of pipeline H (m), pipe length pushed by landslide process L (m), angle between horizontal plane and soil sliding direction in place where pipe buried β (˚), the max Von Mises stress of pipe σ_{max} (MPa), the max displacement of pipe U_{max} (m).

drawn such as (**Figures 4-7**). At the same time, in order to observe the stress response characteristics of pipeline under the landslide, the finite element Mises stress contour plot of pipeline (it is buried in 2 m depth; the pipe length loaded by landslide process is 27 m; the angle between horizontal plane and soil sliding direction in place where pipe buried is 30˚) is taken as an example shown in **Figure 8**.

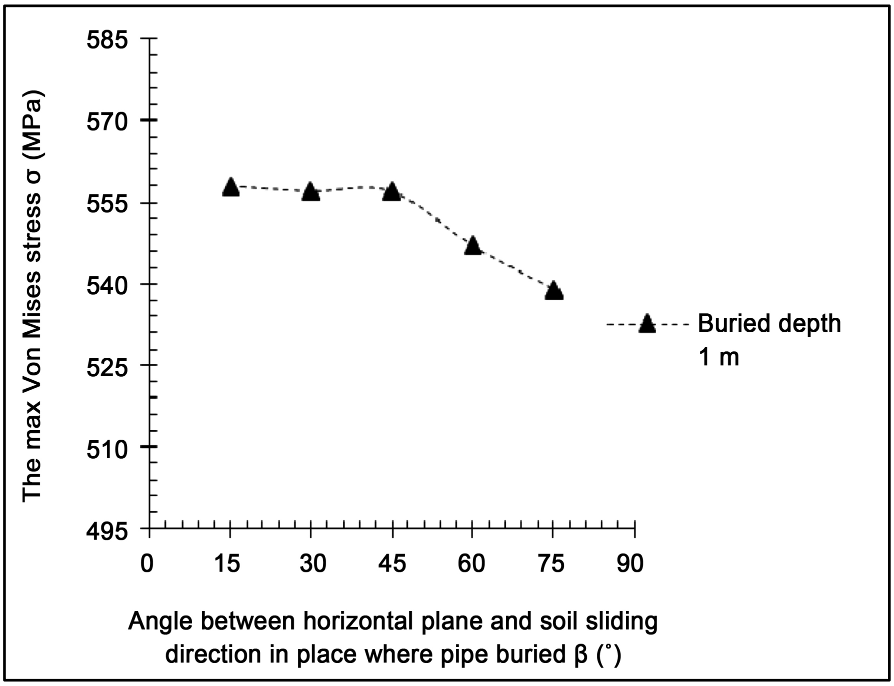

Figure 4. L = 30 m, the max Von Mises stress.

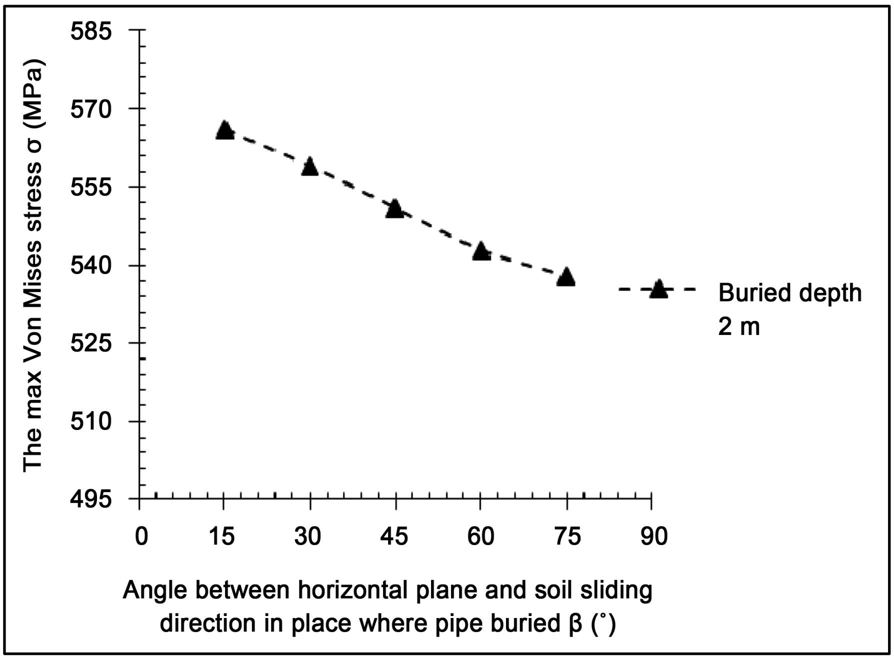

Figure 5. L = 27 m, the max Von Mises stress.

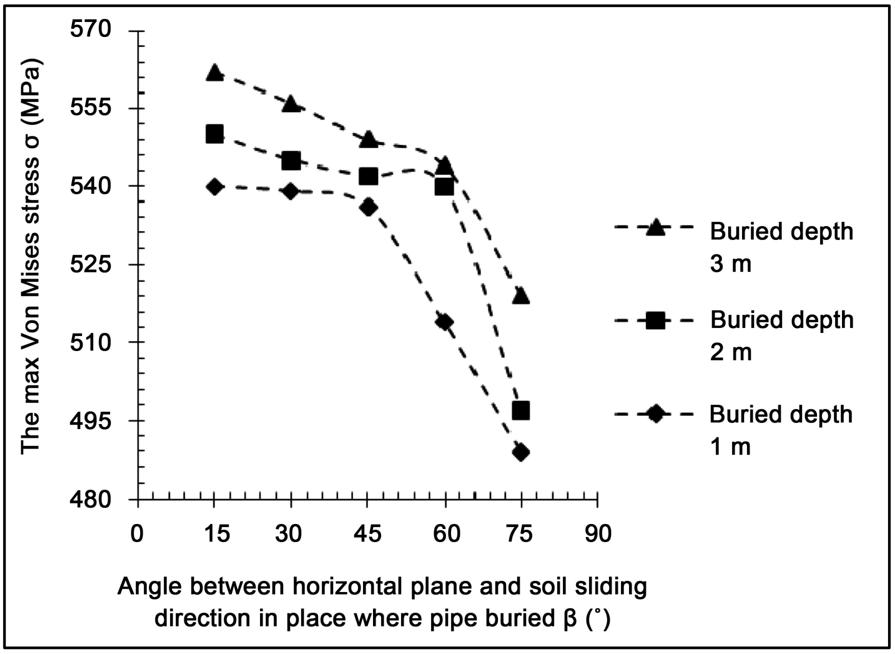

Figure 6. L = 24 m, the max Von Mises stress.

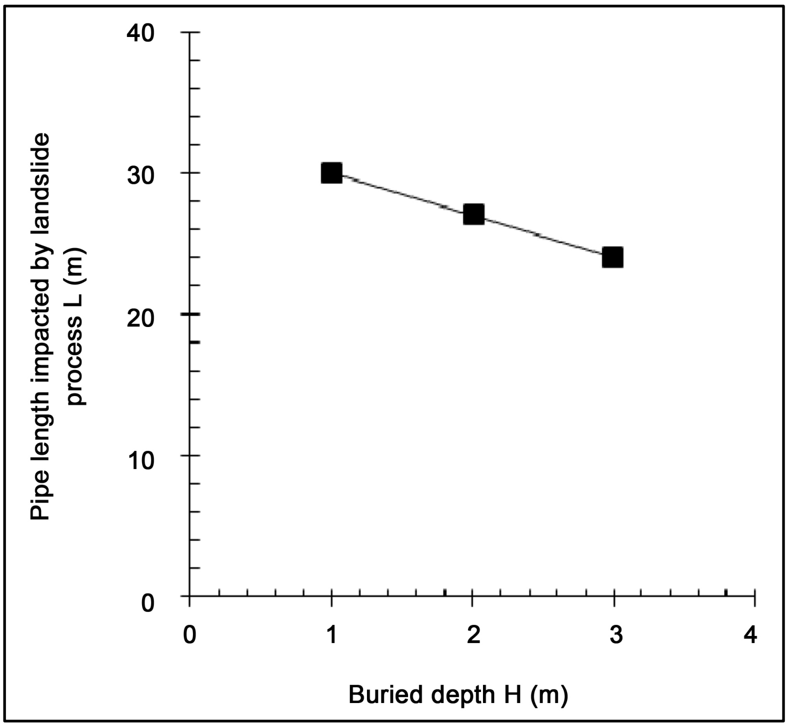

Figure 7. Limit length value of pipeline bearing landslide.

Observing **Figures 4-7**, it is easy to draw the following conclusions:

1) With the increase in β value, the σ_{max} value decreases gradually when the same L value is adopted.

2) With the increase in H value, the σ_{max} value increases gradually when the same L value is adopted.

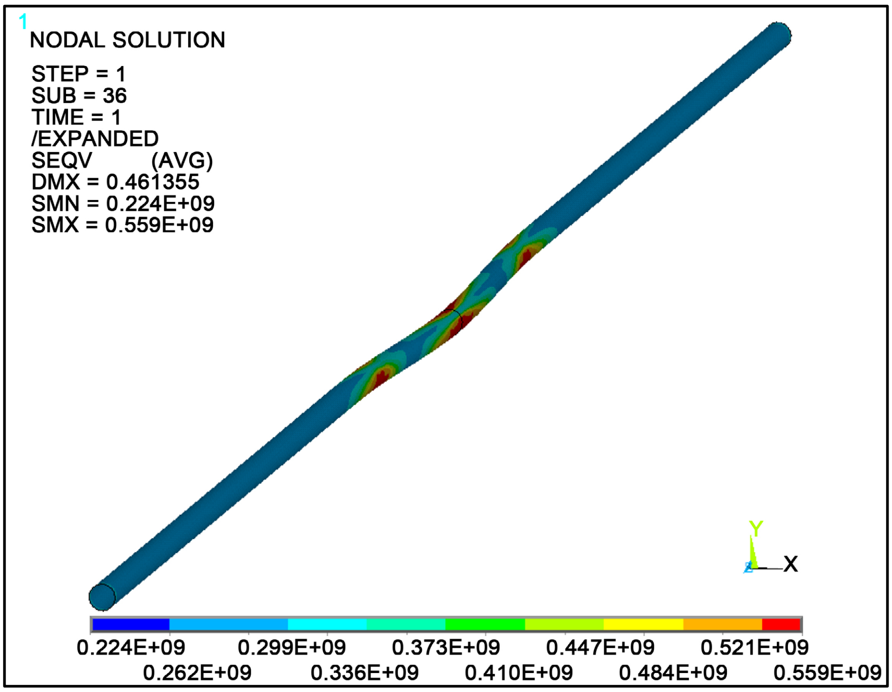

Figure 8. The finite element Mises stress contour plot of pipeline (H = 2 m, L = 27 m, β = 30˚).

3) With the increase of H value, the limit length of pipeline safely withstanding transverse landslide reduces gradually, and the curve presents a good linearity.

Figure 8 shows that: under the landslide thrust force, Mises stress in middle part of the pipeline and interface of soil slip zone and non-slip zone, is larger than the other positions. Such phenomena is in accordance with the practice discovery: the pipeline cracks or breaks from the middle part of pipeline and interface of soil slip zone and non-slip zone. Of course, this also indirectly indicates the feasibility of the above modeling.

2.2. Strength Reduction Method Model

To test and verify the reliability of above results, slope and pipe three-dimensional finite element model is set up using the ABAQUS finite element software (Figure 9).

The back of this Model is 70 m high; the front is 25 m high; the bottom is 100 m long, 100 m wide; the length of pipeline is 120 m. The bottom of the bedrock is fixed; two end faces, front and back end faces are constrained along the vertical direction of these end faces; the pipeline is embedded in soil. The stress-strain relationship of pipeline is the same as Figure 2. The buried depth of pipeline is 2 m, other parameters refer to Table 1. Mohr-Coulomb model is used to express the constitutive relationship of upper soil. The bedrock possessing 15 m thickness is regarded as an elastomer material. The bedrock and soil parameters all are shown in Table 4.

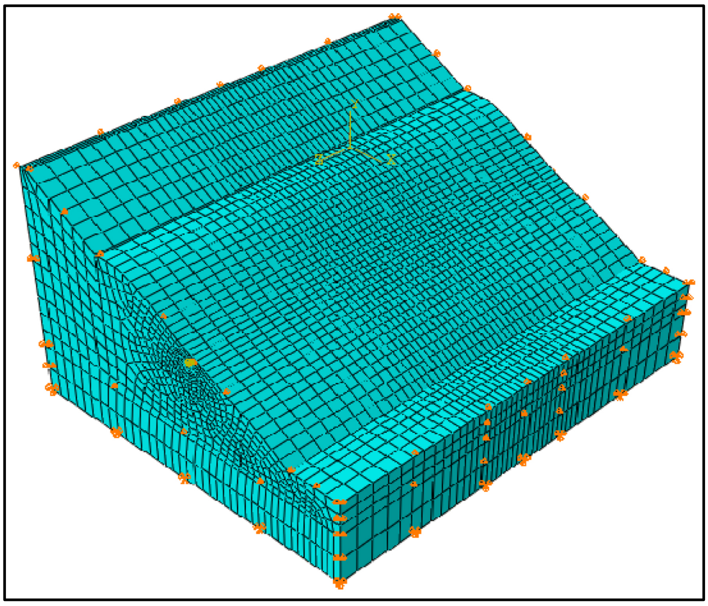

Figure 9. The slope and pipe three-dimensional model.

Table 4. The initial parameters of bedrock and soil.

The parameters	E	μ	γ	φ	c
Upper soil	32.5	0.35	20	25	20
Bedrock	100	0.3	25	-	-

Notes: the elastic modulus E (MPa), the poisson's ratio μ, density γ (kN/m^3), internal friction angle φ (˚), cohesion c (kPa).

The gravity and pipeline internal pressure is applied to the model, then the Strength Reduction Method [21] is utilized to the 27 m width zone in the model central area until the stability of slope reach to the state of limit equilibrium. With partial soil turning into plastic state, the failure surfaces under limit shear situation is produced gradually (Figure 10).

When the strength reduction factor surpasses 1.87, the slope is in unstable state, and it will change into landslide. In this state, the displacement of the slip soil is shown as Figure 11, and the pipe Mises stress contour plot is shown in Figure 12.

The Figure 11 shows that the maximal displacement of slope can be up to 0.5768 m. Meanwhile, the Figure 12 shows the maximal displacement of pipeline is 0.4937 m, and the maximum Von Mises stress of pipeline reach to 530 MPa. While landslide happens, the maximum stress and displacement of pipeline are greater than the ones above. The initial internal friction angle φ and cohesion c of soil are reduced to 14˚ and 10.695 kPa when the strength reduction factor reaches to 1.87. Through the Figure 13, β can be roughly determined as 30˚. The other parameters refer to Table 1 and Table 2. According to the formula in the literature [12], it can be calculated that the landslide thrust is 195.7 kN/m. The load distribution is taken as parabolic distribution and the parabolic

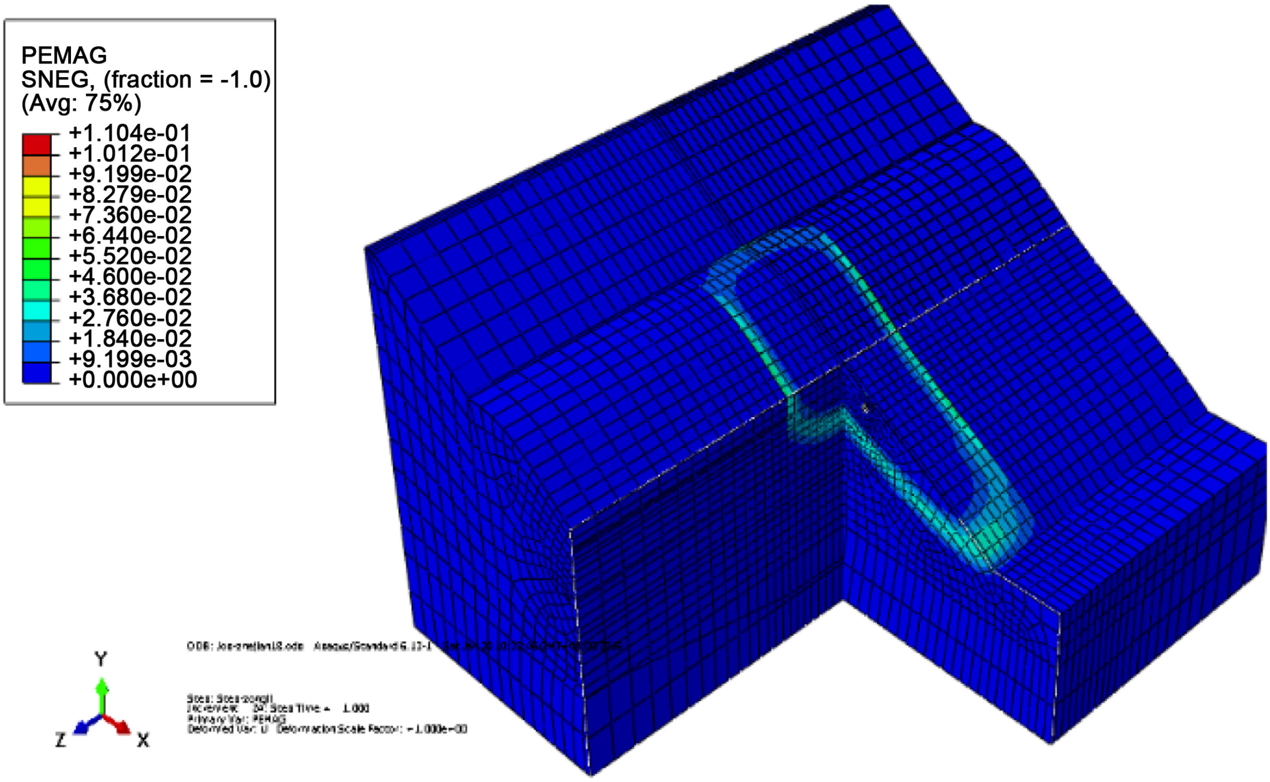

Figure 10. Plastic profile of slope in limit equilibrium state.

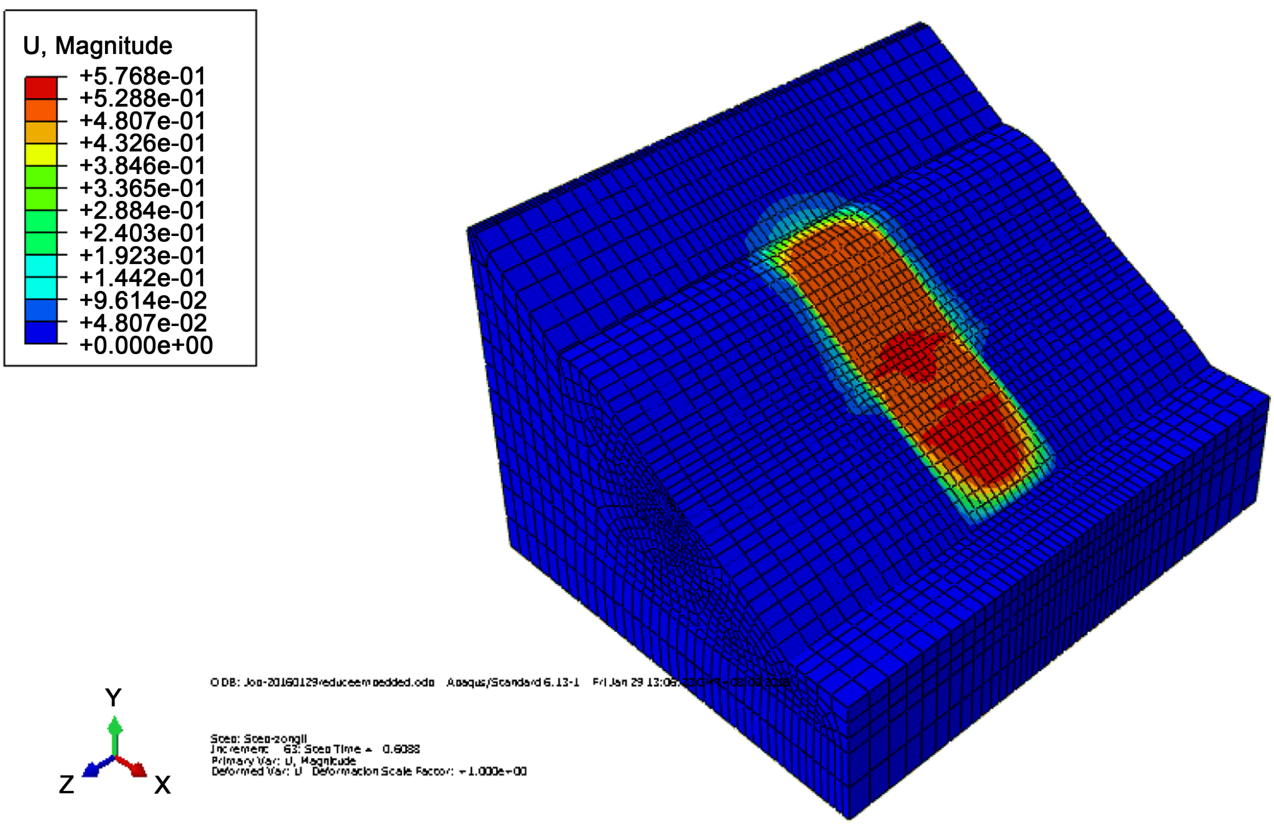

Figure 11. Displacement of slope in limit equilibrium state.

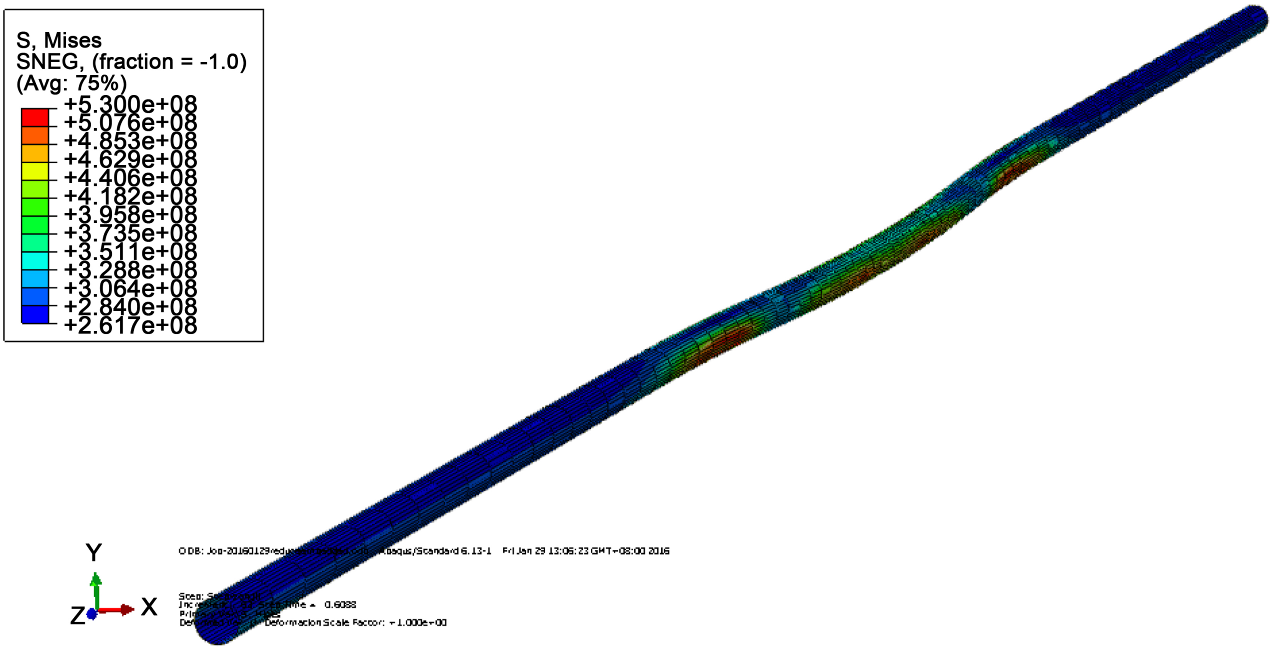

Figure 12. Von Mises stress contour plot of pipeline at the time of slope in limit equilibrium state.

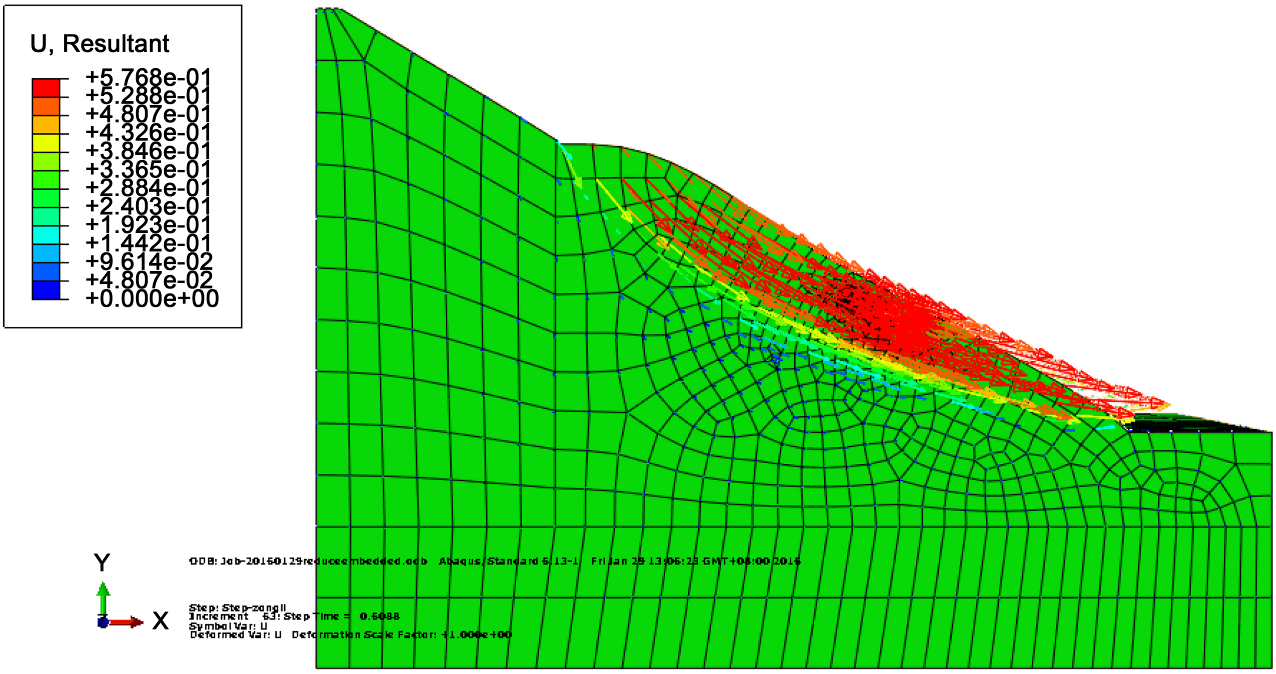

Figure 13. Symbols plot for displacements of slope in limit equilibrium state.

vertex load is adopted as the value we just calculate out. After that, we use the same simulation method as Section 2.1 to calculate. Results display that the maximum Von Mises stress of pipeline reach to 566 MPa, which exceeds the pipe material yield strength more than 2%, and the maximum displacement of pipeline is 0.5212 m. Due to these result values related to the pipeline are larger than those values when the slope is in limit equilibrium state. So these results

Table 5. The limit length of X80 pipe (D = 1.016 m, δ = 18.2 mm) safely withstanding transverse landslide.

δ		**18.2**	
H	1	2	3
L_0	32	29	26

Notes: pipe thickness δ (mm), buried depth of pipeline H (m), the limit length of pipeline safely withstanding transverse landslide L_0 (m).

Table 6. The limit length of X80 pipe safely withstanding transverse landslide.

δ		**15.3**			**18.2**	
H	1	2	3	1	2	3
L_0	30	27	24	32	29	26

Notes: pipe thickness δ (mm), buried depth of pipeline H (m), the limit length of pipeline safely withstanding transverse landslide L_0 (m).

can indirectly indicate the feasibility and correctness of the modeling in Section 2.1.

Similarly, the limit length of pipeline safely withstanding transverse landslide can be calculated out, when the X80 pipe (D = 1.016 m, δ = 18.2 mm) is buried in different depth. The results are shown in Table 5.

3. Conclusions

Through the above results, some conclusions can be got, such as: When the same L value is adopted, the σ_{max} value decreases gradually with the β value increase, and the σ_{max} value increases gradually with the H value increases. Moreover, as the H value increases, the limit length of pipeline safely withstanding transverse landslide reduces gradually, and the curve presents a good linearity. Besides that, Mises stress in middle part of the pipeline and interface of soil slip zone and non-slip zone, is larger than the other positions when pipeline is subjected to the landslide thrust force.

Of course, the most important and practical conclusion is that the practical indicators of pipeline about prediction and prevention damaged by landslide disaster can be proposed. The limit length L0 of X80 pipe safely withstanding transverse landslide is used to express this indicator. In order to provide some references for engineering and design, the indicator is concluded and listed in Table 6.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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