Numerical Calculation of Pipe-soil interaction Subjected to Unstable Slope

Bing Han a, Qiang Fu b, *
China National Institute of Standardization, Beijing 100191, China.

Abstract. The integrity of oil and gas pipelines is seriously impacted by unstable slopes in tough terrain in western China. The quantitative evaluation technology is an effective method for pipelines risk management under the threat of geohazard. In order to establish the pipeline vulnerability evaluation indexes under effect of unstable slope, the finite element method is adopted to simulate unstable slope movement, pipeline mechanical behavior and pipe-soil interaction by changing geometrical sizes and mechanical characteristics of them, such as the material composition of unstable slope, movement type of unstable slope, diameter and wall thickness pipelines. The regularity for change of stresses and deformations of pipeline subjected to unstable slope can be obtained by means of numerical calculation.

Key words: Pipe-soil interaction; soil movement; Evaluation Indexes; Unstable Slope; Numerical Calculation.

1. Introduction
Risks are often inseparable from disasters. Pipeline risk is often associated with geological hazards. The geological environment and natural geographical conditions along some pipelines are complex and diverse, geological hazards are one of the main risk sources of oil and gas pipelines, especially for pipelines laid in mountainous areas with complex geological and geomorphological conditions, geological hazards have even become the number one risk affecting the safe operation of pipelines. Compared with other risk sources, pipeline damage caused by geological hazards often leads to more leakage of transport media and long-term disruption of operation, and the high cost of repair will bring greater economic losses and serious social adverse effects [1-3]. The huge risk of pipeline geological hazards has attracted great attention of pipeline operators at home and abroad, and some active protective measures have been taken to reduce the losses caused by geological hazards [4-6]. Because of the randomness and unpredictability of geological hazard events, pipeline geological hazard risk management has gradually become the mainstream means of pipeline geological hazard prevention and control. In order to ensure the safety of the buried pipelines which passing through active or potential landslides and unstable slope, we should pay attention to studying the stress state and deformation discipline of pipelines while strengthen the deformation monitoring for pipelines, these will help us improve and enhance the theoretical level of deformation monitoring and preventing failure of pipelines[7]. For reason given above the determination method of vulnerability evaluation indexes of pipeline subjected to unstable slope, we have studied the influence regularity of the axial stress and...
deformation of pipeline with the material composition of unstable slope, movement type of landslide, diameter and wall thickness of pipelines by means of numerical calculation, and this provided the theory basis for determination of the weights and scores of vulnerability evaluation indexes of pipeline subjected to unstable slope.

2. Calculation conditions and schemes

2.1. Calculation model and parameters

The calculation model can be established by applying generalizability theory to typical unstable slope characteristics. The mountain model is 100 meters long along axial direction of pipeline, the foreside and tail of mountain model are 15 meters and 28 meters high respectively, the distance between them is 80m, the slope angle of model is 30 degree, the buried depth of pipeline is 1.5 meters. The bottom face of model is fixed in the x, y, z-directions, and the side faces are fixed in normal direction. The geometrical sizes and mechanical parameters of slip mass and pipeline are different with calculation conditions. The geometrical model and mesh generation diagram of finite element are presented in Fig.1. The elastoplastic model and Mohr-Coulomb yield criterion are adopted in the study [8].

![Geometrical and Mesh Generation Models](image)

(a) geometrical model   (b) mesh generation model

**Figure 1.** Calculation model of pipe-slope interaction.

The mechanical parameters for geotechnical materials and pipe are given based on borehole sample data in situ, laboratory test on rock and soil mass and some interrelated specifications and manuals, and they are listed in Table 1.

| Parameters     | Sorts      | E (GPa) | μ   | γ (kN/m³) |
|----------------|------------|---------|-----|-----------|
| bed rock       |            | 35      | 0.28| 3200      |
| slip mass      |            | 2       | 0.33| 2070      |
| slip surface   |            | 0.08    | 0.41| 1520      |
| pipeline       |            | 210     | 0.30| 7800      |

Where \(E\) is the elastic modulus, \(μ\) is the passion’ ratio, \(γ\) is the unit weight.

2.2. Calculation schemes

In this paper, the numerical simulation focuses on the vulnerability evaluation indexes of pipeline subjected to unstable slope, and there are four kinds of calculation schemes designed by changing geometrical sizes and mechanical characteristics of slope and pipeline, including the material composition and movement type of unstable slope, diameter and wall thickness of pipeline. Every kind of scheme includes different calculation conditions for each index, and they are all listed in the Table 2~4.
Table 2. The calculation conditions for different geometrical sizes of pipeline.

| No. | D (mm) | Wt (mm) |
|-----|--------|---------|
| 1   | 325    | 5       |
| 2   | 377    | 6       |
| 3   | 426    | 7       |
| 4   | 508    | 8       |
| 5   | 610    | 9       |
| 6   | 720    | 10      |
| 7   | 1219   | 12      |

Where $D$ is the diameter of pipeline, $W_t$ is the wall thickness of pipeline.

Table 3. The calculation conditions for different material composition of unstable slope.

| Material  | Mechanical parameters of slip mass |
|-----------|-----------------------------------|
|           | $C$ (MPa) | $\alpha$ (degree) | $\sigma_t$ (MPa) |
| soft soil | 0.09       | 30                  | 0.01             |
| gravelly soil | 0.85       | 36                  | 0.05             |
| rock      | 2.20       | 42                  | 0.8              |

Where $C$ is the cohesion of slip mass, $\alpha$ is the internal friction angle of slip mass, $\sigma_t$ is the tension strength of slip mass.

Table 4. The calculation conditions for different movement types of unstable slope.

| Type      | Mechanical parameters of slip surface |
|-----------|--------------------------------------|
|           | $C$ (MPa) | $\alpha$ (degree) | $\sigma_t$ (MPa) | $\kappa$ | $\eta$ (MPa) |
| fast      | 0.03       | 21                   | 0                 | 0.05     | 0.8          |
| general   | 0.04       | 21                   | 0.05              | 0.1      | 1            |
| slow      | 0.06       | 25                   | 0.2               | 0.2      | 1.5          |

Where $\kappa$ is the friction modulus of slip surface, $\eta$ is the normal stiffness of slip surface.

3. Calculation results and analysis

In this paper, the finite element software ANSYS and finite difference software FLAC$^{3D}$ are adopted respectively for the numerical simulation of the geometrical sizes and mechanical characteristics of landslide and pipeline.

(1) changing the material composition of slope

The material composition of landslide has effect on the stress and deformation of pipeline, but it is not obvious. The Fig.2 shows the deformation contour map of pipeline for two different calculation conditions, the soil and rock landslide. The Fig.3 shows the comparison of axial stresses and maximum deformations of pipeline under the effect of three different landslides, the soil, gravel soil and rock landslide. As is shown in this figure, the stresses and deformations of pipeline both change with the material composition of landslide, but the variation extent is small and the stress and displacement are not rapid increasing, that is, the weight of this index may be a lower value.
Soil slope                         Rock slope

Figure 2. The deformation contour map of pipeline for different material composition of slope.

Figure 3. The comparison of axial stress and maximum displacement of pipeline under the effect of three different slopes.

(2) changing the movement type of slope

The movement type of landslide has less effect on the stresses and deformations of pipeline. The Fig.4 shows the deformation contour map of pipeline for two different calculation conditions, the fast landslide and slow landslide. The Fig.5 shows the comparison of axial stresses and maximum deformations of pipeline under the effect of three different landslides, the fast, general and slow landslide. As is shown in this figure, the stresses and deformations of pipeline both change with the movement velocity of landslide, but the variation extent is small and the stress and displacement are not rapid increasing, that is, the weight of this index may be a lower value.

Figure 4. The deformation contour map of pipeline for different movement types of slope.
(3) changing \( D \), the diameter of pipeline

The axial stress and maximum displacement of pipeline will change with \( D \), the diameter of pipeline. The Fig.6 shows the deformation contour map of pipeline for four different calculation conditions, which \( D \) is \( \Phi325 \text{mm} \), \( \Phi426 \text{mm} \), \( \Phi610 \text{mm} \), \( \Phi1219 \text{mm} \) respectively. The curves of axial stress and maximum displacement of pipeline with \( D \) are presented in Fig.7. The stresses and deformations of pipeline both gradually decrease with \( D \), and there are no obvious inflexion points appearing in the stress and deformation curves. That is, the scores of this index state should be given averagely.

![Figure 6. The deformation contour map of pipeline for different \( D \).](image)

![Figure 7. The curves of axial stress and maximum displacement of pipeline with \( D \).](image)

(4) changing \( W_t \), the wall thickness of pipeline

The \( W_t \) has less effect on the stresses and deformations of pipeline. The curves of axial stress and maximum displacement of pipeline with \( W_t \) are given in Fig.8. As is shown in this figure, the stresses and deformations of pipeline both increase with \( W_t \), but the variation extent is small and the stress and displacement are not rapid increasing, that is, the weight of this index may be a lower value.
Figure 8. The curves of axial stress and maximum displacement of pipeline with $W_t$.

In the end, the comparison diagrams of axial stresses and maximum deformations of pipeline for the seven indexes, including the length of pipeline in landslide, area, thickness, material composition and movement type of landslide, diameter and wall thickness of pipeline, are given in Fig.9.

Figure 9. The comparison diagram of axial stresses of pipeline for four indexes.

4. Conclusion
In this numerical simulation, the calculation conditions for the material composition of slope have not included all geotechnical characteristics, as a matter of fact, we know that the pipeline will more secure when it is subjected to soil slope than rock slope according to the actual cases and engineering experiences, so this index has a significant effect on the vulnerability evaluation of pipeline subjected to unstable slope. The loading time applied to pipeline subjected to unstable slope is different with the movement velocity of slope. If the movement velocity is slow, this will give us enough time to carry out risk mitigation, on the contrary, the fast slope will have disadvantage to risk mitigation, therefore this index has an indirect effect on the vulnerability evaluation of pipeline under effect of unstable slope. The pipeline diameter has some effect on the vulnerability evaluation, but the changing extent of this index is limited, the difference just is from $\Phi325$ to $\Phi1219$mm. The wall thickness of pipeline has less effect on the vulnerability evaluation in comparison with the indexes of geometrical sizes of slope, so these three indexes can all be ignored.

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