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Strain-based design for buried pipelines subjected to landslides

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Abstract: Landslides are one of the key problems for stability analysis of pipelines in the western region of China where the geological conditions are extremely complicated. In order to offer a theoretical basis for the pipe-soil interaction, the general finite element program ABAQUS is used to analyze the distribution of pipe strain caused by landslide through which the pipeline passes. In this paper the Ramberg-Osgood constitutive equation is used to study the strain-based mechanical characteristics of pipelines. Different calculation schemas are designed by considering the change of spatial relationship between pipeline and landslide, and the change of D/t, diameter-thickness ratio of pipeline. The results indicate that the pipeline is primarily subjected to tension stress when the landslide crosses the pipeline perpendicularly, the pipe strain is a maximum along the central axis of the landslide, and reverse bending occurs on pipeline at both edges of the landslide. The pipeline is primarily subjected to friction force caused by the downward movement of the landslide, and the friction force is relatively small when the landslide is parallel to the pipeline. The pipe strain is in proportional to D/t, and this means decreasing D/t can help to improve security of pipelines subjected to the landslide.

Key words: Landslide, pipeline, strain-based design, numerical simulation, failure mode

1 Introduction

Buried pipelines can traverse hundreds of kilometers of terrain with varied environmental and geotechnical conditions. Along specific route corridors, the pipeline may experience long term, large scale ground movement due to accumulated soil deformation such as subsidence, frost heave and landslide movement (Zhao et al, 2006; Barbas and Weir, 2007; Yun et al, 2007; Tarek et al, 2009). Under these large ground movements, pipelines may yield and deform excessively, thus causing local buckling or wrinkles (Scheiner et al, 2006; Mahdavi et al, 2008; Shuai et al, 2008; Zhang et al, 2008). For the analysis of mechanical behavior of pipelines subjected to large geological hazard, traditional stress-based methods use the minimum yield strength as a load limit (Challamela and Buhan, 2003; Tian et al, 2010), which is based on consideration of limiting the stress of pipeline wall. This ideas lean towards conservative and security. When pipelines need to adapt to change of ground curvature, the latter will decide the pipeline strain, which expressed as pipeline curvature, not the values from the calculated stress. In this case, the strain-based methods will be more appropriate, it is based on a limit state and displacement controlled load (Limura, 2004; Hawlader et al, 2006; Yun et al, 2007; Liu et al, 2008; Hyde et al, 2009; Shantanu et al, 2011). If the safe operation can be assured under displacement-controlled load, the pipeline strain can be allowed to be more than the specified yield strain. Although some plastic deformation occurred in the pipeline, the pipeline has been able to meet the operation requirements (Li et al, 2007). In this paper, the mechanical behavior of pipelines subjected to landslides and the pipe-soil interaction are studied by numerical simulation, and the deformation characteristics of pipelines based on strain are also presented.

2 Calculation models and parameters

2.1 Calculation models

Assuming that the landslide is semi-infinite in space and the pipeline is infinite in the axial direction, and as a result the calculation model is established by intercepting one part of the landslide and pipeline in a certain proportion as the analytical object. On the basis of characteristics of the

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typical landslide, we build a calculation model as follows: the mountain model is 1,200 m long along the *y*-direction, the front range and back range of the mountain model are 175 and 320 m high respectively, the distance between them is 750 m, the slope angle of the model is 30 degrees, and the buried depth of the pipeline is 1.5 m. The model is defined in a three-dimensional space by its Cartesian coordinates *x*, *y* and *z*, and the bottom face of the model is in the *xy* plane and the side faces of the model (right and left sides) are normal to the *xy* plane. The calculation models are presented in Fig. 1. In the calculation process, 8-node 3-dimentional solid elements are adopted for the FEM models of pipeline and soil, which have good curve boundary adaptability. Using gradient gridding to generate the mesh, it is dense in the section of the pipeline passing through a landslide and relatively sparse in both ends of the model. The below nodes of elements are shared with the elements of the pipeline, the above nodes of elements are far-field ground surface points, and the moving boundary conditions of the landslide movement at the ground surface are applied on these nodes.

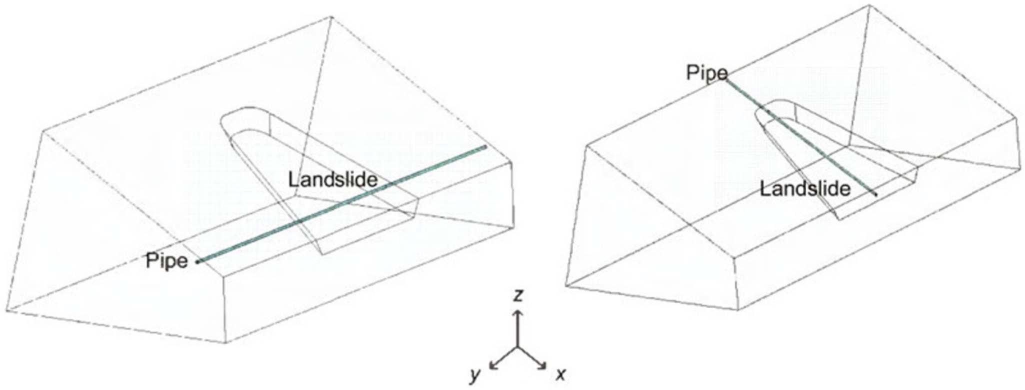


Fig. 1 Calculation models of the pipeline passing through the landslide

2.2 Model parameters

The mechanical parameters for geotechnical materials and pipelines are given based on borehole sample data in situ, laboratory tests on rock and soil mass and some interrelated specifications and manuals, and are listed in Tables 1 and 2.

Table 1 Pipeline parameters

Calculation schemes	Elasticity modulus MPa	Poisson's ratio	Density g/cm^3	Pipe diameter m	Wall thickness m	Internal pressure MPa
1	210000	0.24	7850	0.225	0.01	10
2	210000	0.24	7850	0.330	0.01	10
3	210000	0.24	7850	0.425	0.01	10
4	210000	0.24	7850	0.516	0.01	10
5	210000	0.24	7850	0.634	0.01	10
6	210000	0.24	7850	0.728	0.01	10

Table 2 Parameters of geotechnical materials

Material types	Elasticity modulus MPa	Poisson's ratio	Density g/cm^3	Friction angle degrees	Cohesion MPa
Bed rock	45650	0.23	2.92	43.85	22.75
Slip band	10	0.37	1.83	20.00	4.80
Slip mass	3250	0.40	2.01	22.50	0.35

2.3 Pipe-soil interaction

When landslides are in an unstable state, they will exert loads and displace buried pipelines. The pipelines will slow the landslide down. Two types of contact elements were used to simulate the pipe-soil interaction. For the constraint conditions of pipeline outside the landslide, the soil around the pipeline can be simplified as a number of equivalent elastoplastic springs as illustrated in Fig. 2, and the pipe-soil interaction can be represented by soil springs in the axial, horizontal and vertical directions which are connected to the nodes of pipe elements. The relationship curves between forces and displacements of the soil springs, in Fig. 3, can be described by only two parameters, the yield stress and the maximum elastic deformation value. In Fig. 3 P_u, T_u, and Q_u represent the yield stresses in the axial, horizontal, and vertical directions respectively; Δ_p, Δ_t, Δ_{qd}, and Δ_{qu} represent the maximum elastic deformation values in the three directions, respectively, and their calculation formulas can refer to the ASCE guidelines (ASCE, 2001).

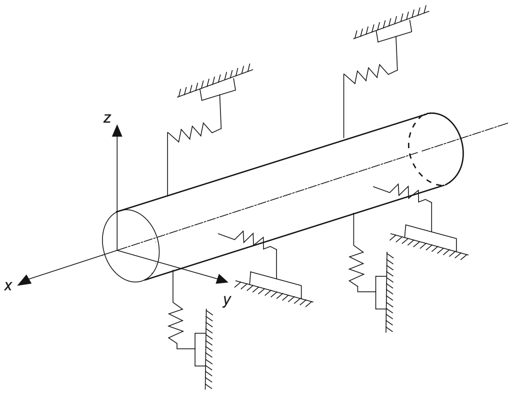
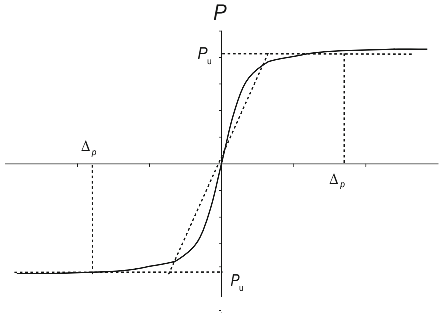
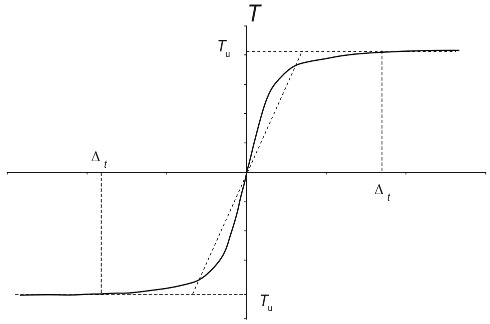


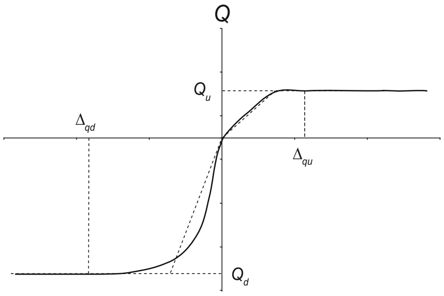
Fig. 2 Idealized representation of soil with discrete springs



(a) Soil spring in the horizontal direction



(b) Soil spring in the axial direction



(c) Soil spring in the vertical direction

Fig. 3 Relationship curves between forces and displacements of soil springs

For a pipeline inside a landslide, the pipe-soil interaction (PSI) can be simulated using the PSI elements which have only one degree-of-freedom of displacement on nodes. The one side of the PSI element has common nodes shared with the pipe element below, and the nodes on the other sides of the PSI element represent far-yield surface, so the boundary conditions of the ground movement are generally given on these nodes.

The deformation of the PSI elements is the relative displacement between pipeline and far-field soil surface. The positive strain is defined as (Shen, 2010):

$$\varepsilon_{ii} = \Delta u \cdot e_i \tag{1}$$

where $\Delta u = u^f - u^p$, u^f is the far-field displacement, m; u^p is the pipeline displacement, m; e_i is the local direction vector.

In Fig. 4, e_1 is the axial direction of the pipeline, and e_2 is the direction of pipeline pointing to far-field. When the PSI elements produce strains caused by relative displacement, the stresses will be applied to the nodes at the pipeline. The stress-strain behavior may be linearly elastic, or nonlinearly elastic-plastic, this depends on the constitutive model adopted by the PSI elements.

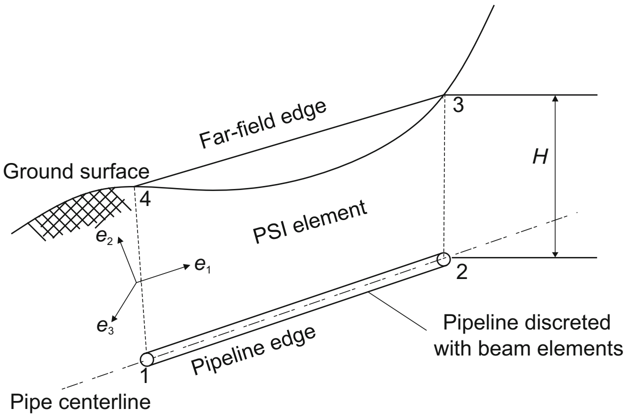


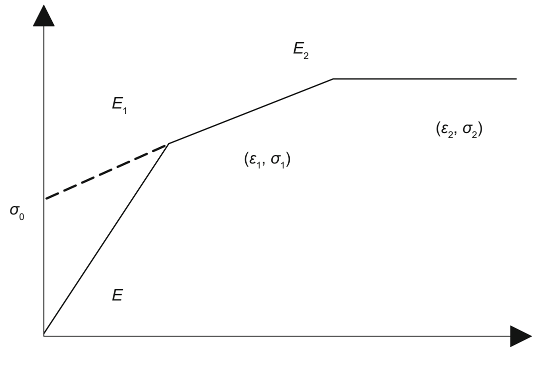
Fig. 4 Diagram of pipe-soil interaction element

The PSI elements are not real to mesh the soil around the pipeline, and the range of soil is reflected by the stiffness of PSI elements. The PSI elements do not include soil density, and the inertia effect of soil can be simulated with the concentrated mass applied to nodes of PSI elements in practical analysis. Based on experimental results, the calculation parameters of the constitutive relation of PSI elements can be determined as follows: the element stiffness in the axial, vertical, and horizontal directions are 730, 1,460 and 1,460 N/m, respectively, the stiffness index is 0.125, and the interface friction angle is 25°.

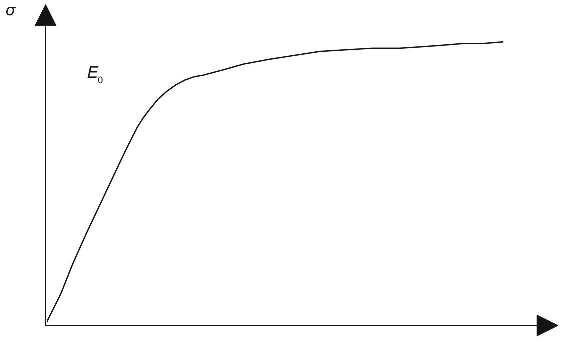
3 Constitutive equations for the pipe material and the pipeline failure modes

3.1 Constitutive equations

Simplified stress-strain curves of a pipeline are generally adapted to analyzing the forces applied on the pipeline. One is the trillinear model (as shown Fig. 5(a)), and the stress-strain curve of the pipeline can be divided into three stages in this model, i.e. elastic (E_1), elastic-plastic (E_2) and plastic stages. The failure will occur when the stress applied on the pipeline exceeds σ_0 or the strain of the pipeline exceeds ε_2.



(a) Trilinear model



(b) Ramberg-Osgood model

Fig. 5 Stress-strain curves of the pipeline

Another is the Ramberg-Osgood model (as shown Fig. 5(b)), the function suggested by Ramberg-Osgood can be used to describe stress-strain characteristics of the pipeline material in the post yield state (Liu and Sun, 2005):

$$E\varepsilon = \sigma + \alpha \left(\frac{|\sigma|}{\sigma_0} \right)^{n-1} \sigma \tag{2}$$

where E is the stiffness of the pipeline in the initial loading state, MPa; ε is the engineering strain; σ is the axial tension stress, MPa; σ_0 is the yield stress of the pipeline, which is generally defined as the stress at 0.5% strain, MPa; and n and α are the parameters of Ramberg-Osgood. The practical stress-strain curve of the pipe material can be simulated well with this model within 4% yield strain, and the model is also used to estimate the deformation mode of the pipeline.

ABAQUS /Standard provides a deformation theory, the Ramberg-Osgood plasticity model, for use in developing fully plastic solutions for fracture mechanics applications in ductile metals. The model is most commonly applied in static loading with small-displacement analysis for which the fully plastic solution must be developed in a part of the model.

3.2 Pipeline failure modes

The failure modes of pipelines subjected to landslides are connected with the patterns and angles which pipelines pass through landslides (Lin et al, 2010). If the landslide is perpendicular to the pipeline (as shown Fig. 6), the direction of sliding is perpendicular to the pipeline axis, the pipeline is mainly subjected to a pushing force from the landslide, and subjected to shearing forces at the lateral edges of the landslide. If the landslide is parallel to the pipeline (Fig. 7), the direction of sliding is parallel to the pipeline axis, and then the pipeline is mainly subjected to a friction force caused by the landslide, which could lead to local wrinkling or buckling of the pipe wall. And there are a compressive force and a tensional force applied on the pipeline at the leading and tailing edges of the landslide, respectively, which could lead to tensile failure. The force exerted on the pipeline can be split into vertical and horizontal components when the angle between the pipeline axial direction and the sliding direction is smaller than 90 degrees, and the effects of landslide movement on the pipeline include pushing force, tension force and shearing force.

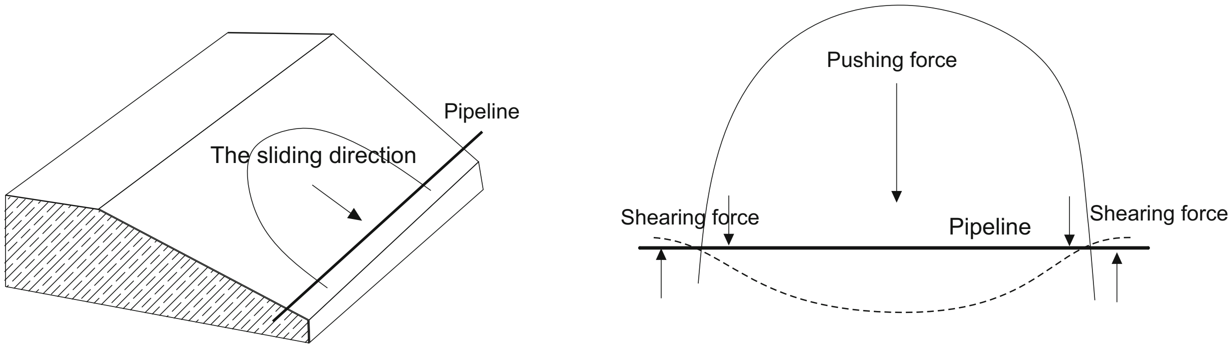


Fig. 6 Deformation of the pipeline passing perpendicularly through the landslide

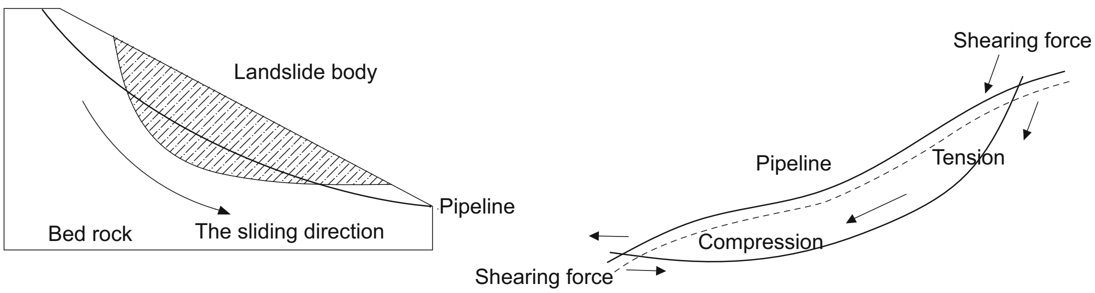


Fig. 7 Deformation of the pipeline oriented parallel to the landslide

3.3 Strain limit and allowable strain of the pipeline

3.3.1 Tension strain limit

The limit value of tension strain uses generally the methods combining elasticity with plasticity theory. DNV-OS-F101 dictates if the accumulated plastic strain exceeds 0.3%, an engineering critical assessment (ECA) is needed. If the accumulated plastic strain exceeds 2.0%, in addition to the ECA there are some extra requirements, for example in material quality. The tension strain design criterion is listed in Table 3 (ASME, 2007; DNV, 2007; CSA, 2007).

Table 3 Tension strain limit of the pipeline

Specification	Strain limit
CSA-Z662	2.5%
DNV-OS-F101	Accumulated plastic strain exceeds 2.0%
ASME	2.0%

3.3.2 Compressive strain limit

According to the specification CSA-Z662, the critical compressive strain of local buckling in the longitudinal direction can be estimated with the following formula:

$$\varepsilon_{\mathrm{c}}^{\mathrm{crit}} = 0.5\frac{t}{D} - 0.0025 + 3000\left[\frac{(p_{\mathrm{i}} - p_{\mathrm{e}})D}{2tE_{\mathrm{s}}}\right]^2 \tag{4}$$

where $\varepsilon_{\mathrm{c}}^{\mathrm{crit}}$ is the critical compressive strain of the pipeline; t is the wall thickness of the pipeline, m; D is the outside diameter of the pipeline, m; p_{i} is the maximum internal design pressure of the pipeline, MPa; p_{e} is the minimum hydrostatic pressure of the pipeline, MPa; E_{s} = 207000 MPa.

3.3.3 Allowable strain

Based on the strain limit values, the allowable strain of the pipeline can be obtained by taking into account a safety factor. When pipelines are in compressive state, the safety factor is set to 1.25; in tensile state, the safety factor is 1.25 if the hoop stress does not reach or exceed 40% of the yield strength, and the safety factor is 1.5 if it exceeds 40% of the yield strength. The strain design criterion can be established after the allowable strain is determined. The design requirements will be satisfied if the calculation value of design strain does not exceed allowable strain, otherwise, pipeline failure will then occur (Yu et al, 2010).

4 Results and discussion

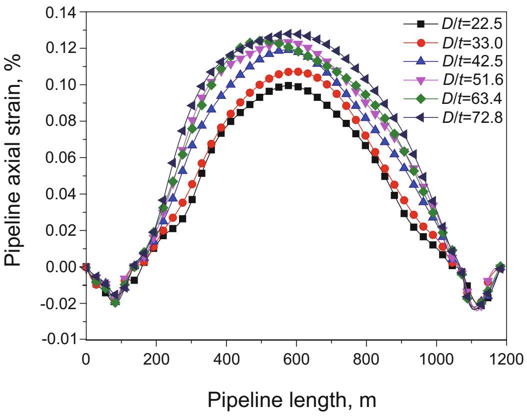
On the basis of the Ramberg-Osgood constitutive equation, the variations of strain versus length of the pipeline (with different *D*/*t*) in the landslide were obtained using the finite element program ABAQUS. The distribution of the axial strain in the pipeline crossing the landslide, are shown in Fig. 8. In the first case, the pipe body endures mainly tension stresses in the radial direction, and the maximum strain in the pipe body occurs in the principal direction of sliding. The strain decreases gradually towards both edges of the landslide, and then the strain distribution curves are characterized by a parabolic shape and they are basically symmetric with respect to the principal direction of sliding. There are particular peak values at both ends of the pipeline at the edges of the landslide due to constraint effect. In the second case, the pipe body endures mainly friction forces, and at the same time is subjected to a compressive force and a tension force at the leading and tailing edges of the landslide. The axial strain in the pipeline is mainly characterized by compressive strain, and the maximum axial strain in the pipe body occurs on the end of pipeline at the shear-outlet of landslide due to the constraint effect.

When the pipeline transversely passes through the landslide, the variation of the maximum axial strain caused by the pushing force is 0.09-0.12 (Fig. 8(a)); when the pipeline passes longitudinally through the landslide, the variation of the maximum axial strain caused by the friction force is –0.0017- –0.0038 (Fig. 8(b)). So presumably, the friction force has less effect on the pipeline compared with the pushing force. Fig. 8 shows that the axial strain of the pipeline increases with *D*/*t*, and this means decreasing *D*/*t* can help to improve security of a pipeline subjected to a landslide.

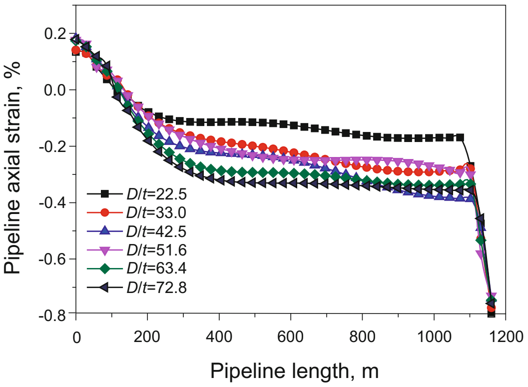
5 Conclusions

1) In this paper, the PSI element of ABAQUS/standard is used to simulate the pipe-soil interaction under the effect of the landslide with the Ramberg-Osgood equation, which is a strain-based model. The strain distributions of the pipelines with different lengths and *D*/*t* values are obtained when the pipelines pass through the landslide transversely and longitudinally respectively.

2) The axial strain in the pipeline is mainly characterized by tensile strain in the case of the pipeline perpendicularly passing through the landslide. There are particular peak values appearing at both ends of the pipeline at the edges of the landslide due to the constraint effect. The axial strain in



(a) Perpendicularly crossing



(b) Parallel crossing

Fig. 8 Strain distributions of pipelines subjected to the landslides

the pipeline is mainly characterized by compressive strain in the case of the pipeline parallel passing through the landslide, and the maximum axial strain appears at the end of the pipeline at the shear-outlet of the landslide due to constraint effect. The axial strain in the pipeline is in proportional to *D*/*t*.

3) The strain-based design idea allows pipeline strain to reach or even exceed the yield strain, which can sufficiently improve the bearing capacity of the pipeline. Compared with traditional stress-based idea, it takes advantage of security design of pipelines after improving the transport capacity of the pipeline. This will provide references for design, route selection, construction and operation of pipelines subjected to landslides.

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