

THE STRAIN-BASED DESIGN OF BURIED PIPELINE SUBJECTED TO LANDSLIDES

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Keywords: Pipeline; strain-based design; strain limit; landslide.

Abstract. *In recent years, a number of projects have been funded in China to quantitatively evaluate the tensile and compressive strain limits of pipes and apply these limits to buried pipelines subjected to landslides. This paper covers the technical basis of strain-based design for pipelines subjected to landslides. First, finite element analyses (FEA) were conducted for a total of 594 cases covering a wide range of materials, ratios of pipe diameter to wall thickness, D/t and various internal pressures. By using the calculated data, parametric equations for strain limits of pipelines were developed. FEA analyses were also conducted for 8 cases of buried pipelines subjected to landslides. An approach for design of buried pipelines subjected to landslides using strain-based design was also proposed. It is believed that the above applications may lay the initial base of using the strain-based design method for buried pipeline subjected to landslides for pipelines in China.*

1 INTRODUCTION

With the rapid development of oil and gas pipeline industry, new trend is showing on pipelines for long-distance, large-diameter and high-operating-pressure. This requires the corresponding pipeline design guidelines and criteria to be adapted to these new situations. In the design step, not only the safety and reliability of pipeline but also its economic and efficient operation should be ensured. Most of the existing pipeline design codes are based on limiting stress criteria, which is considered acceptable for steel with a well defined yield point and a well defined ductility and strength. But the stress in pipelines may exceed the limit under some situations, such as earthquakes, landslides, and some displacement-controlled loading, such as that in laying of the submarine pipelines. In these situations, the strength design criteria based on stress is no longer valid.

Stress-based design criteria are based on the minimum yield stress for the pipeline, while strain-based design criteria are based on limit state design in displacement-controlled loading. If the safe operation can be ensured under displacement-controlled loading, the pipeline strain is allowed to exceed the specified yield strain. Although some plastic deformations occur in the pipeline, the pipeline is able to meet the operation requirements with higher operating capacity. Using stress-based design method supplemented with strain-based design method, the deformation capability of pipelines can be fully applied in security and economic design.

Limit state is a state beyond which the structure no longer satisfies the design requirements. Both Det Norske Veritas (DNV, 2000) and Canadian Standards Association (CSA, 2007) use limit state method for pipeline design. There is slightly difference in state limit classification between these codes. In DNV-OSF101 (2000), four kinds of state limits are recognized. They are serviceability limit state, ultimate limit state, fatigue limit state and accidental limit state. When limit state method is applied to the pipeline design, appropriate design criteria are presented in order to make less conservative and more flexibility for the designers.

There are many different classifications on loadings for the pipelines. Displacement-controlled loading can be defined specifically as a loading that can be reduced to zero by a change in the shape of the part of interest. On contrary, a load-control loading cannot be reduced to zero by a simple change in shape. Bigger strain may be allowed to displacement-controlled loading. The loading on a pipeline may generally be a combination of load and displacement controlled. The pressure loading is load controlled, while the soil motion around a pipeline usually causes displacement-controlled moments.

A number of natural gas and petroleum pipelines have been or will be constructed across ancient and currently active landslides in China. The pipelines studied in this paper cross numerous areas of active or potential active landslides that pose a threat to pipeline integrity. The interaction of the moving soil with the pipeline redistributes the axial force along the pipe, increasing tension in some locations and compression in others. It can also increase pipeline curvature, which induces tensile strain in half of the pipe cross-section, and compressive strain in the other half. If unmitigated, excessive tensile strain can lead to pipeline rupture. Large compressive strain may cause buckling, usually accompanied by formation of wrinkles that can rupture due to material fatigue or severe yielding.

The general framework for the application of strain-based design has been the subject of considerable researches during the past twenty years. This work has been achieved through the publication of limit state design rules for submarine pipelines. Det Norske Veritas in 1982 proposed the use of combined stress-based design criteria and strain-based design criteria. In 1996 Det Norske Veritas published a subsea pipelines limit state design criteria with many analytical methods based on a variety of load conditions. In the same year, the Canadian

Standards Association (CSA) published CSA Z662-96 (1996), which comprises strain-based design criteria for submarine pipeline design and the limit state design.

Several codes have provisions that apply of strain-based design to pipelines, including DNV-OS-F101, CSA-Z662, API RP 1111-1999, ASCE, ASME B31.8., API 1104 and ABS 2001. These codes can be placed in three general categories: those that provide a comprehensive overall pipeline standard that includes requirements both for stress-and strain-based design (DNV 2000, CSA Z662-2007), those that specifically allow strain-based design but do not provide extensive provisions related to strain-based design (B31.8, API 1104), and those provide information on strain-based design related to a specific subgroup of pipelines (ABS 2001, API RP 1111). Several organizations have current research projects that will be released to the public domain after their completion in areas that directly or indirectly impact strain-based design of pipelines. The Minerals Management Service (MMS) and the Office of Pipeline Safety (OPS) of USA co-funded EWI (2003) to provide a general guidance on strain-based design for pipelines both for the on- and off-shore environments. DNV and other organizations (Wang, Rudland and Denys, 2002; Wang and Chen, 2004; Dinovitzer and Brian, 1996; Brian and Dinovitzer, 1993; Liu, Liu and Zhang, 2007) also have some research projects about it.

In the present work the control factors of tensile and compressive strain limits of pipelines were examined first. Based on the available experiment data of full scale pipe tests under the axial tensile strain and internal pressure loading, a valid finite element model was found. Finite element analyses were conducted for a total of 711 cases covering a wide range of material, girth weld mismatch and various internal pressures. Some parametric equations were developed based on FEA. The safety factors and appropriate limits for the parametric equations have been determined based on extensive experimental data. FEA was then carried out for 8 cases of buried pipeline subjected to landslides. These examples were used to verify the method used for strain-based design of pipelines. An approach for design of buried pipelines subjected to landslides using strain-based design was also proposed. It is believed that the above applications may lay the initial base of using the strain-based design method for buried pipeline subjected to landslides for pipelines.

2 TENSILE STRAIN LIMIT

The design of pipelines using strain-based approach must count both for resistance to tension and compression along the axial direction of the pipeline. In tension, the issues relate to the failure modes of plastic collapse or fracture. Among those, ductile fracture is often found in pipelines. At its initiation, ductile fracture is not a reasonable limit state to pipeline design within the standard wall thickness regime. The crack initiation in the pipe wall does not cause leaking of product from the pipeline. However, as the fracture expands, it may reach one of these limit states.

The capacity of tensile axial strain of the pipe is affected by a large number of factors: D/t ratio, Y/T ratio, internal pressure, girth weld effect, defect size and location. More details can be found from Liu (2008) and Liu and Zhang (2008).

Wide plate test is widely used as one of the closest representations of pipeline girth weld stress state under construction and service loading conditions. Much of the test development work was done by Denys (1990). Those tests originally focused on achieving plastic collapse of the girth welds, defined as achieving a measured failure strain of 0.5% or above. In recent years, wide plate test is being increasingly used to determine failure strains beyond yield, i.e., greater than 0.5% (Wang, Chen, 2006). The wide plate tests have been designed to obtain the tensile strain limits. The more details can be found from Liu (2008), Liu and Zhang (2008).

2.1 FINITE ELEMENT ANALYSES

Finite element techniques have been widely used for shell analysis. Nowadays FEA is able to provide numerical solutions for issues with many nonlinear effects that some classical techniques cannot deal with effectively. These effects exist in the ductile fracture behavior of pipes.

In the present study, FEA analyses were conducted on quarter length specimens or pipes due to symmetry conditions. Symmetric boundary conditions were imposed on the symmetry planes. Uniform remote axial displacement was applied as the primary loading. All the analyses used a large displacement formulation implemented in ABAQUS version 6.5 (SIMULIA, 2005).

The following assumptions were made to reduce the analysis matrix to a manageable level.

Zero weld cap height was assumed. The weld cap can provide some reinforcing effects to the weld. However, the weld cap height varies around the circumference of a pipe and is process dependent. Assuming zero weld cap height leads to conservative results.

The weld bevel geometry is omitted and the weld joint is assumed to have uniform properties.

The crack-tip opening displacement (CTOD) fracture criterion is one of the fracture criteria applied to fracture of metallic materials with cracks. The failure of the pipe in this paper is defined in CTOD. The crack driving force measured in CTOD is a fundamental parameter representing the magnitude of the driving force imparted on the defect. The failure of a girth weld is assumed when the CTOD driving force reaches material's resistance measured in apparent CTOD toughness (Wang, Horsley and Cheng, 2004).

The defect is located in weld metal, not in HAZ, though it has influence on crack driving force. In this paper the weld joint is assumed to have uniform tensile properties.

Generally speaking, the higher the pipe grade, the lower the strain hardening rate and uniform strain. In this paper using the API 5L minimum yield and tensile requirements as the baseline, generic relations among pipe grade, Y/T ratio, and uniform strain are established. The stress strain curve is assumed to obey the CSA Z662 relation,

$$\varepsilon = \frac{\sigma}{E_s} + \left(0.005 - \frac{F_y}{E_s} \right) \left(\frac{\sigma}{F_y} \right)^n \quad (1)$$

Where σ and ε are the stress and strain respectively. And E_s is elastic modulus, F_y is effective specified minimum yield strength, and n is the strain hardening exponent. This stress strain relation has a continuous yield (no Luders extension).

It is recognized that the actual Y/T ratio of a pipe material can be different from that computed using the API 5L minimum requirements. For each pipe grade, an upper bound and a middle level Y/T ratio are also included in the analysis matrix. The lower bound Y/T ratio is computed from API 5L minimum yield and tensile requirements. The upper bound Y/T ratio is taken as the average of the lower bound Y/T ratio and unity. The middle level Y/T ratio is the averaged value of lower bound and upper bound Y/T ratios. The stress-strain curve of X60 from the API 5L as an example is given in Figure 1.

The stress-strain curves of welds used for finite element analysis are got from standard testing from X60 to X80. The yield strength values are 497MPa, 585MPa, and 662Mpa, respectively to X60, X70 and X80.

Three-dimensional FE models simulating the curved wide plate (CWP) and pipe were generated. The C3D20R element of ABAQUS was used. This is a 20-node quadratic brick

element with reduced integration. The outline of a typical FE model and mesh is shown in Figure 2. The crack was meshed by Altair HyperMesh.7.0 (Altair Engineering, Inc, 2001).

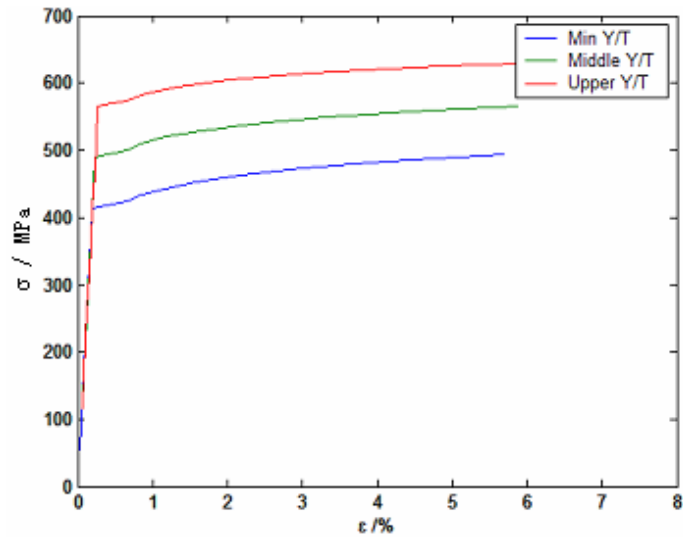
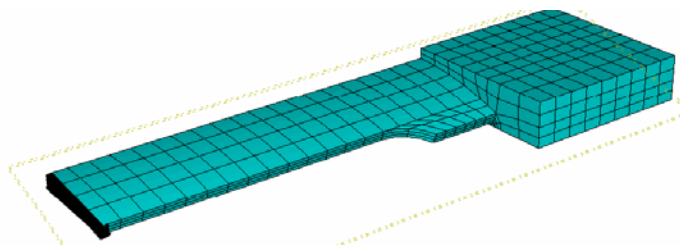
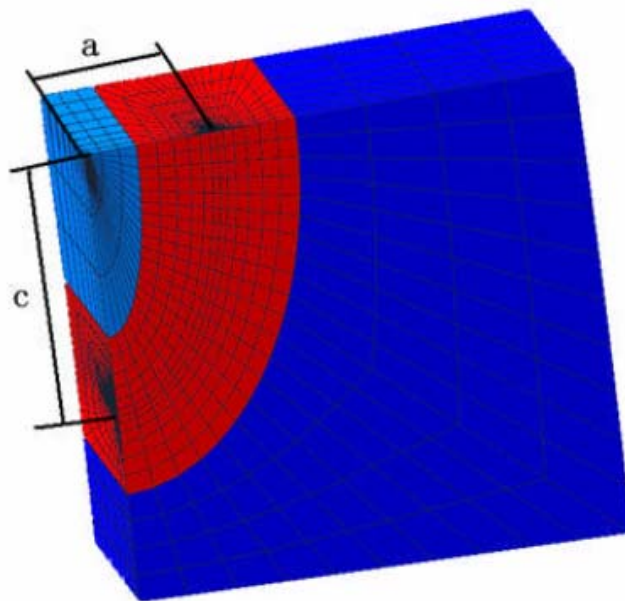


Figure 1 Stress-strain curve of X60 from the API 5L.



(a) The CWPs model.



(b) The mesh of Crack tip.

Figure 2 A typical FE model and mesh.

Internal pressure was considered in the FE analysis except that for CWPs. For straight pipe, the design pressure for a given design wall thickness or the design wall thickness for a given design pressure was determined by the following design formula in this paper,

$$P_0 = 0.72 \frac{2t}{D} \sigma_s \quad (2)$$

Where P_0 is the design pressure, σ_s is the specified minimum yield strength (SMYS), t is the design wall thickness, D is the outside diameter of pipe.

The finite element analyses for CWPs were corresponded with CWP tests. The matrix of the finite element analysis includes:

Pipe grade

The range of pipe grades analyzed is X60, X70, and X80. Only the middle level Y/T ratios were investigated in the analysis. So the Y/T ratio, $\lambda \in [0.850, 0.917]$.

Pipe diameter and thickness

The pipe diameter ranges from 30 in. (762 mm) to 48 in. (1219 mm). The pipe thickness ranges from 9.5 mm to 17.5 mm.

The internal pressure in pipe

Assuming $\gamma \equiv P_i/P_0$, where P_i is the applied internal pressure in pipe, and $\gamma \in [0,1]$.

The weld strength mismatch

The weld strength mismatch ($M = \sigma_s W / \sigma_s B$) ranges from 0 to 1.2. So The weld strength mismatch, $M \in [0, 1.2]$. When M is equal to zero, the result is corresponding to the plain pipe.

The defect size

The circumferential defect only is considered in this paper. Assuming $\xi \equiv 2c/t$, $\eta \equiv 2a/t$ (for buried defects, and a/t for surface defects), $\psi \equiv d/t$, so $\xi \in [1, 3]$, $\eta \in [0.2, 0.4]$, $\psi \in [0, 0.33]$, d is the depth of the defect.

Apparent CTOD (Crack Tip Open Displace)

Assuming $\mu \equiv \delta a/t$, where δa is the apparent CTOD.

Finite element analyses for a total of 450 cases produced a lot of data for a wide range of material, girth weld mismatch, various defect sizes or locations, buried or surface defects, and various internal pressures. So the tensile strain limits can be developed from finite element analyses.

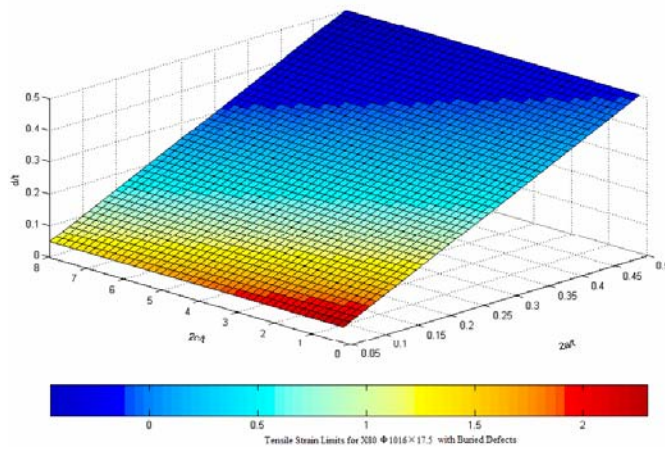
$$\varepsilon_{ct_FE} = \mu^{0.046+0.1858\xi^{0.061}-0.549\eta^{-0.516}+e^{0.3255(1-\psi)}} \cdot (1 + \lambda^{-7.44}) \cdot \text{Exp}[0.142(1-\gamma) - 0.879(1-M)] \quad (3)$$

Where when $M = 0$, the equation is for the pipe without weld, and when $M \neq 0$, the equation is for the pipe with weld, and $M = 1$ represents even match. And when $\psi = 0$, the equation is for the pipe with surface defect, and when $\psi \neq 0$, the equation is for the pipe with buried defect.

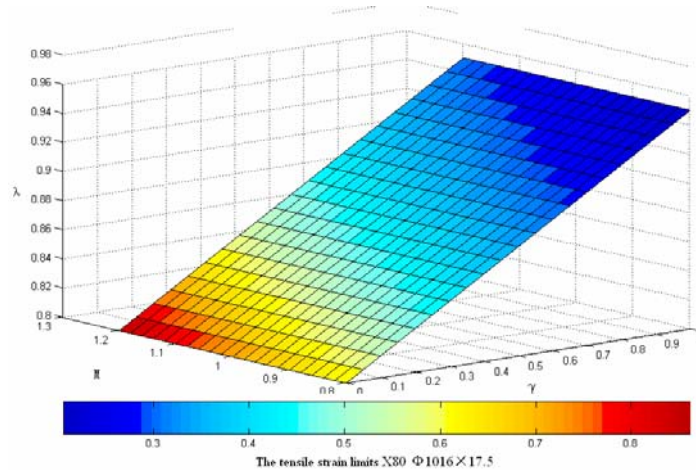
The equation was validated for $0.8 \leq \lambda \leq 0.95$, $0 \leq \gamma \leq 1$, $0 \leq M \leq 1.2$, $1 \leq \xi \leq 3$, $0.2 \leq \eta \leq 0.4$ and $0 \leq \psi \leq 0.3$. The strain limit is in percentage (%).

The coefficient of correlation of Eq. (3) is 0.921.

The relationship between the tensile strain limits with three defect-size factors predicted by Eq. (3) is shown in Figure 3 (a). From Figure 3 (a), it is seen that for the same type defect, the larger defect has less tensile strain capacity. For the same size defect, the surface defect is more dangerous than the buried defect.



(a) The relationship between the tensile strain limits with three defect-size factors.



(b) The relationship between the tensile strain limits with different Y/T, girth weld mismatch, and internal pressure ratio.

Figure 3 The tensile strain limits predicted by Eq.(3).

As the curved wide plate testing can not develop the relationship between the tensile strain limit and the internal pressure of pipe, the tensile strain limits of pressurized pipes were obtained from FEA. The comparison among the tensile strain limits with the different internal pressure is shown in Figure 3 (b). The figure indicates that the higher internal pressure and the Y/T ratio reduce the ability of deformation resistance of the pipe. However the girth weld over-match does help to the ability of the deformation resistance.

2.2 The Safety Factors for the Parametric Equations

Even though the safety factor is not provided in the parametric equation, it is recommended to decrease the strain limit by 25% for the fracture process. This factor can

decrease the failure probability to the unconditioned safety level in line with normal ULS checks.

3 COMPRESSION STRAIN LIMIT

In compression, the failure modes relate to varieties of buckling. Among those, local buckling is often found in pipelines. Local buckling is not, at its initiation, a reasonable limit state to pipeline design within the standard wall thickness regime. The beginning of a ripple in the pipe wall does not impede the flow of product through the pipeline. But as the buckling extends and expands, it may reach one of these limit states.

The capacity of compressive axial strain of the pipe is affected by a large number of factors: D/t ratio, Y/T ratio, internal pressure and girth weld effect. More details can be found from Liu (2008), and Liu and Zhang (2008).

3.1 FINITE ELEMENT ANALYSES

The following assumptions are made to reduce the analysis matrix to a manageable level.

- (1) The assumption for weld cap height is the same as that for FEA on tension.
- (2) The assumption on weld bevel geometry is the same as that for FEA on tension.
- (3) The failure of the pipe in this study is defined in limit state design, as a condition in which the structure ceases to adequately perform its function. The traditional criteria based upon ultimate strength are no longer relevant. The behaviors of the pipe in terms of the initiation and development of local deformation and wrinkling becomes a rational type of behavior upon which to base such limit state criteria.

Three-dimensional FE models simulating the pipe were generated. To focus the work on the post buckling behavior, the full length model was used. The C3D8R element in ABAQUS was used. This is an 8-node linear brick element with reduced integration in hourglass control. The meshes for CWPs are the same as used in FEA of tension. The outline of a typical FE model and mesh is shown in Figure 4.

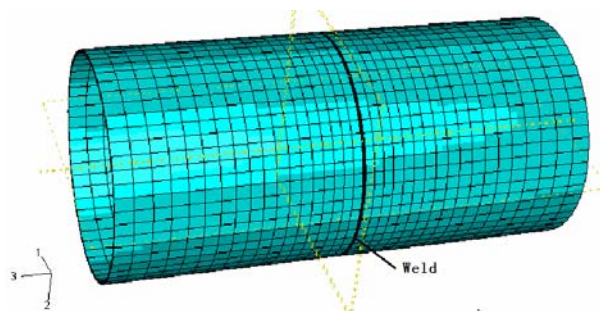


Figure 4 A typical FE model and mesh for a pipe

The finite element analysis of curved wide plate test was corresponded with testing. The analysis matrix of the additional finite element analysis as follows.

- (1) Pipe grade

The range of pipe grades analyzed is X60, X70, and X80. All level Y/T ratios, including the lower bound, the middle level and the upper bound Y/T ratios were investigated. So the Y/T ratio, $\lambda \in [0.800, 0.944]$.

(2) Pipe diameter to thickness ratio

The pipe diameter ranged from 30in. (762mm) to 48in. (1219.2mm). The pipe thickness ranged from 9.5mm to 25.4mm. So the diameter to thickness ratio, $\beta \in [43.5, 88.7]$.

(3) The internal pressure in pipe

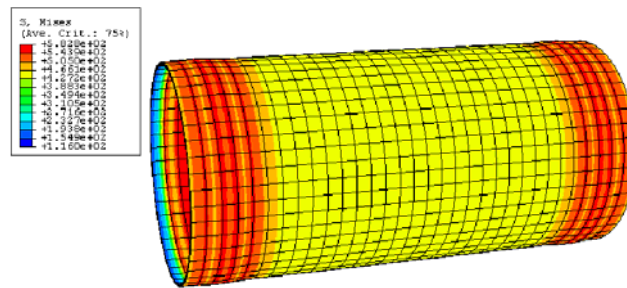
Assuming $\gamma \equiv P_i/P_0$, where P_i is the applied internal pressure in pipe, and $\gamma \in [0,1]$.

(4) The weld strength mismatch ratio

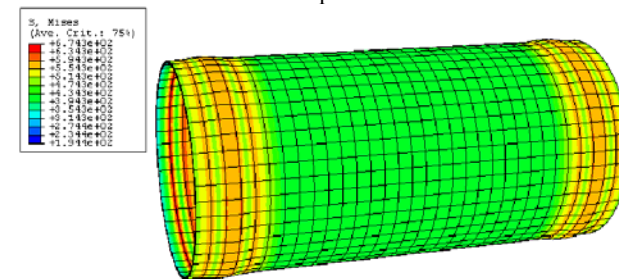
The weld strength mismatch ratio ($M = \sigma^W / \sigma^B$) ranges from 0.8 to 1.2. So The weld strength mismatch, $M \in [0, 1.2]$.

When M is equal to zero, the result is corresponding to the plain pipe.

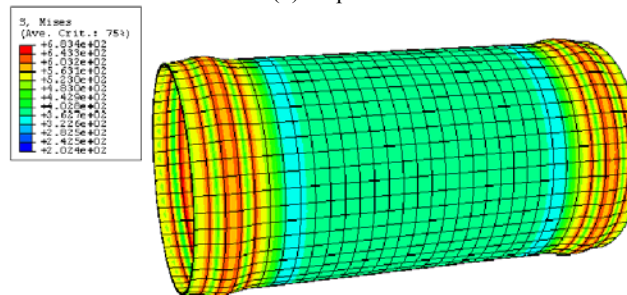
A typical pipe post-buckling behavior from FEA is shown in Figs 5 and 6. The criteria of compressive analysis are based on the beginning of a ripple.



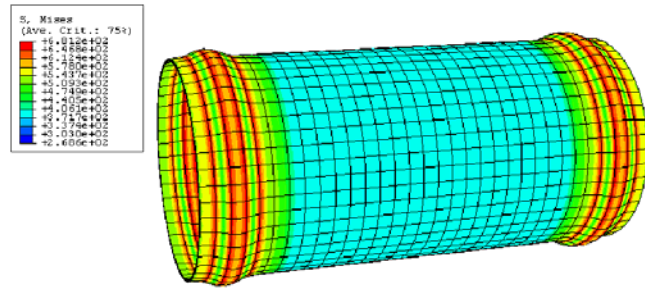
Step 1.



(b) Step 2.

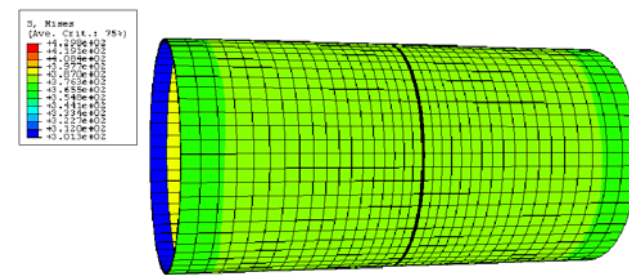


(c) Step 3.

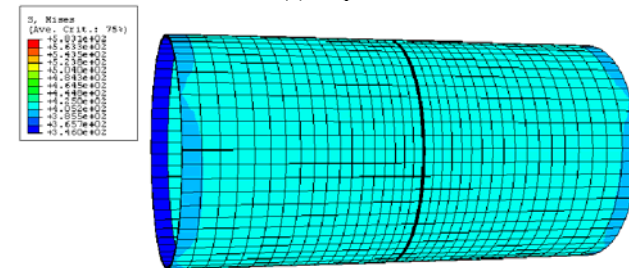


(d) Step 4.

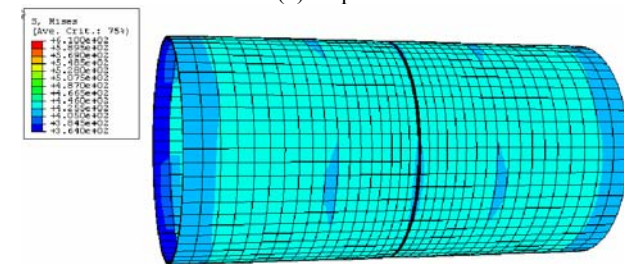
Figure 5 The post-buckling process of pressurized plain pipe.



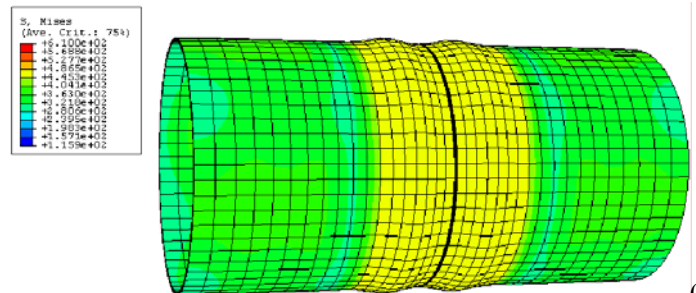
(a) Step 1



(b) Step 2.



(c) Step 3.



(d) Step 4.

Figure 6 The post-buckling process of pressurized weld pipe

Finite element analyses for a total of 144 cases produced data for a wide range of

material, D/t ratios, weld strength mismatch ratio and various internal pressures. By using these data, the following parametric equations were developed:

$$\varepsilon_{cc_FE} = \beta \left(7.219 \lambda^{-1.1787} \right) \left(3.305 \gamma^2 - 2.184 \gamma + 14.65 \right) \left(1.63 M^2 - 1.79 M - 0.905 \right) \quad (4)$$

Where when $M=0$, the equation is for the NO weld pipe, and when $M \neq 0$, the equation is for the weld pipe. The equation was validated for $50 \leq D/t \leq 90$, $0 \leq \gamma \leq 1$, and $0.80 \leq Y/T \leq 0.93$. The strain limit is in percentage (%).

The relationship between the compressive strain limits with three factors predicted by Eq. (4) is shown in Figure 7.

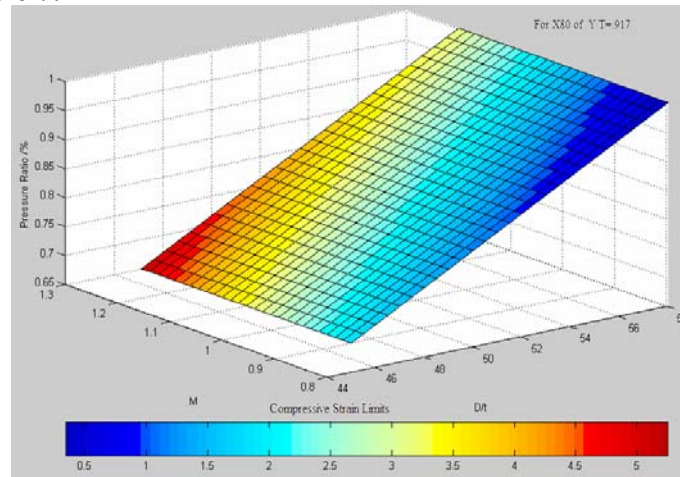


Figure 7 The relationship between the compressive strain limits with D/t, M, and the pressure ratio predicted

3.2 The Safety Factors for the Parametric Equations

Even though the safety factor is not provided in the parametric equation, it is recommended to decrease the strain limit by 25% for the post-buckling process. This factor can decrease the failure probability to the unconditioned safety level in line with normal ULS (Ultimate Limit State) checks.

4 THE RESPONSE OF BURIED PIPELINE SUBJECTED TO LANDSLIDES

4.1 The FE Model

In designing pipeline layouts, potentially unstable slope areas are commonly by-passed. In fact, as landslides are sometimes instantaneous and unexpected, enormous costs are incurred by environmental damages caused by conduit or pipeline servicing failures. Nevertheless, either for cost reasons or unclear definition of the boundaries of the unstable areas, it is not always possible to operate this way, unstable areas are not avoidable. The analysis of the problem of the interaction between landslides and pipelines is therefore of some importance. So in this part, the response of buried pipeline subjected to landslides was analyzed for the Lan-cheng-yu pipeline of China National Petroleum Corporation (CNPC).

The Lan-cheng-yu pipeline of CNPC is one of important pipelines of CNPC. It has been designed long ago, and, particularly in Sichuan across the highly unstable region of the Erlang temple (See Figure 8), without much concern for the potential instability of the crossed slopes. As a consequence, failure is likely to occur. In the figure, the landslide is transverse across the pipeline with about 20° bevel.

To introduce the interaction model in a simple way, assume first that the free surface of the slope is planar and that its inclination with respect to the horizontal plane. The soil-pipe interaction model used in the present study is shown in Figure 9.

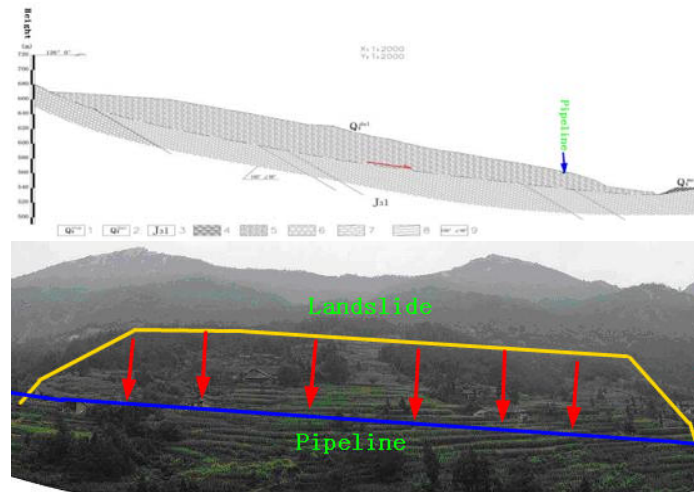


Figure 8 Er-lang temple landslide of the Lan-cheng-yu pipeline

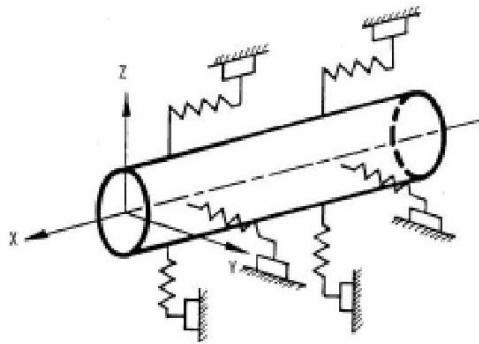


Figure 9 Simple soil-pipe interaction model used in the present study

Three-dimensional FE models simulating the CWP and pipe were generated. The PSI element was used. After FE analysis, the maximal tensile and compressive strains of the pipe were obtained as: $\varepsilon_t=3.2\%$ and $\varepsilon_c=2.4\%$. They are the same as that calculated from Eqs (3) and (4). Using these two values, the strain based design of buried pipelines subjected to landslides was conducted.

4.2 The FE Analysis Result

In order to find the relationship between the pipe and the soil, 8 finite element analyses were done as shown in Table 1. Four of shape of FE models are set as shown in figure 9, and the others are axial across the pipeline. The width of landslides is shown in Table 1. The soil spring stiffness is shown in Table 2.

No.	Direction	Width/m	Displacement of soil/m
V1	Transverse	50	10
V2	Transverse	100	20
V3	Transverse	150	40
V4	Transverse	200	40
A1	Axial	50	5

A2	Axial	100	5
A3	Axial	150	5
A4	Axial	200	5

Table 1. The analysis matrix of the landslides.

Direction	Stress/MPa	Strain/%
Axial	42000	0.005
	-76705	-0.018
Vertical	0	0
	1252448	0.12
	2000000	0.25
	-370638	-0.124
Horizontal	0	0
	370638	0.124

Table 2. The soil spring stiffness.

As shown in Figure 10, the tensile and compressive strain limits of pipelines decrease with the increase of the transverse landslide width when the landslide width is smaller than 125m, while increase with the transverse landslide width when the landslide width is larger than 125m.

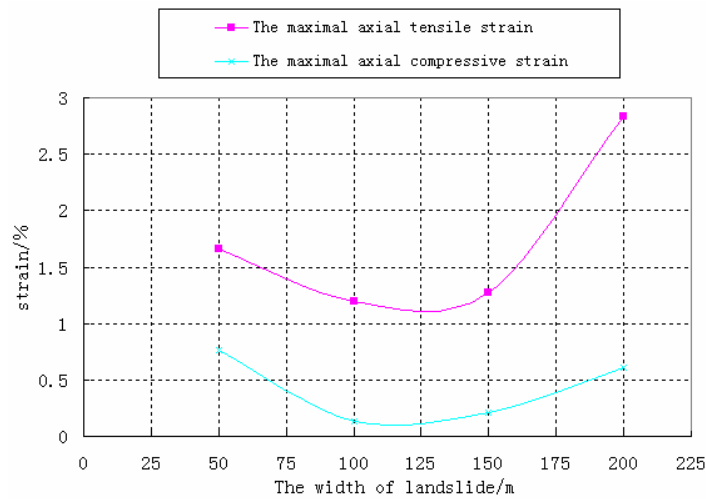


Figure 10 The relationship between the transverse landslide width and the strain of pipeline.

As shown in Figure 11, the tensile and compressive strain limits of pipelines increase with the increase of axial landslide width.

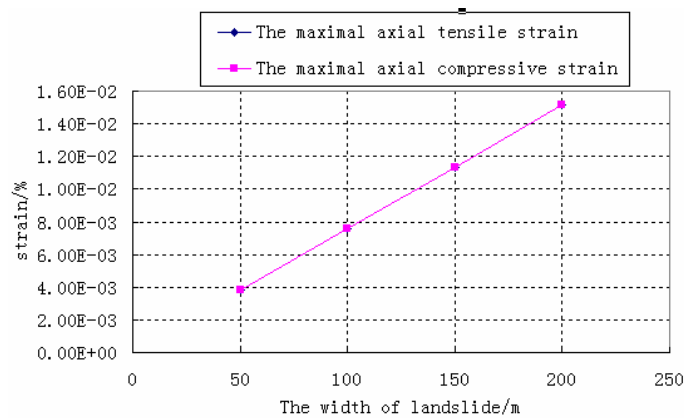


Figure 11 The relationship between the axial landslide width and the strain of pipeline.

4.3 The Strain Based Design Method of Buried Pipeline Subjected to Landslides

When the pipelines cross the area with big ground movement, the strain-based design should be considered. In the present study, the strain based-design method of buried pipeline subjected to landslides was developed. The steps of this method are listed as follows and shown in Figure 12.

Analysis steps for strain based-design of buried pipeline subjected to landslides:

- (1) Estimate the location, range and magnitude of ground displacement.
- (2) Estimate the strain limits.
- (3) Find the material, wall thickness and depth of pipelines.
- (4) Compute the soil-pipe interaction.
- (5) Compute the applied strain of pipelines.
- (6) Compare the strain limits and the applied strain of pipelines.
- (7) Finish

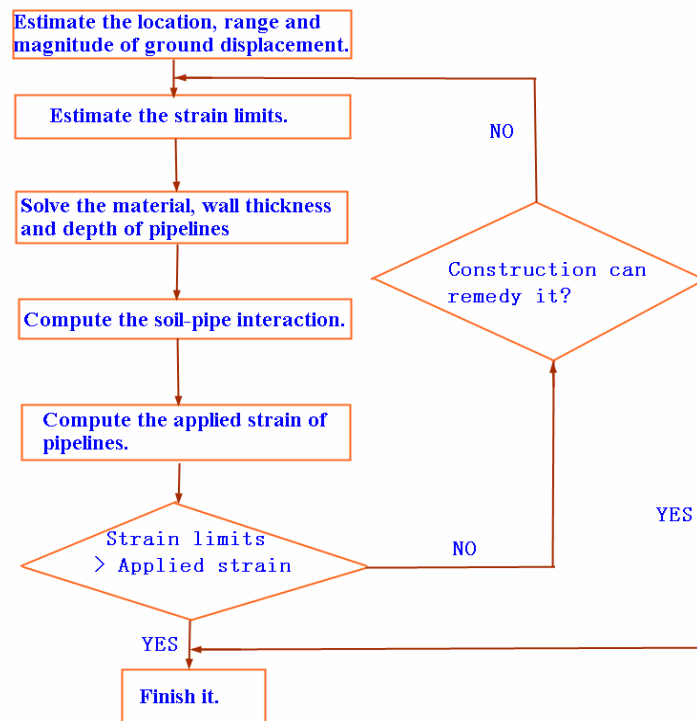


Figure 12 Strain-Based Design Method for Buried Pipeline Subjected to Landslides.

5 CONCLUSIONS

The parametric equations for the quantitative evaluation of tensile and compressive strain capacity of pipelines were proposed based on extensive FEA. The strain-based design method for buried pipeline subjected to landslides was developed. It is believed that the method presented in this paper may lay the initial basis for pipelines integrate assessment using strain-based design for pipelines in China.

6 ACKNOWLEDGEMENTS

This work was supported by China National Petroleum Corporation (CNPC). We would like thank Dr. Yong-Yi Wang, the President of Center for Reliable Energy Systems and all

colleagues from R&D Center of PetroChina Pipeline Company for discussion and advising of this work, especially Dr. Bing Han.

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