Local buckling evolution mechanism of a buried steel pipe under fault movements

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Abstract
Pipe is the main transportation way for oil and natural gas. Fault movement mainly caused by earthquake, which will induce pipe bending, tension and compression. Then oil or gas leakage appear. Based on the moving mechanism of strike-slip fault and reverse fault, a numerical simulation model was employed to study the buckling evolution mechanism of the buried steel pipe under fault movements. The evolution processes of buried pipe under the fault moving action were analyzed, and the effects of pipe internal pressure, fault displacement, and pipe diameter-to-thickness ratio on the pipe buckling were discussed. The results demonstrate that there are three mechanical evolution stages on the pipe in the process of fault movement. High stress appears on the bending regions of pipe wall, and axial strain always fluctuates along the axial length. When the fault displacement is large, pipe collapsing and wrinkling patterns occur, which can be reflected by a sharp fluctuation of axial strain. The high-pressure pipe under the action of reverse fault is prone to failure than the low-pressure pipe. The pipe with a large D/t in the hanging wall is easier to be buckled than that with a small D/t in the footwall. The results obtained can be used for the design and evaluation of buried oil and gas pipes.

Keywords
buried pipe, collapse, fault movement, numerical simulation, wrinkling

1 | Introduction

Pipe is the most important and economical way for oil and natural gas transportation. Fault movements, a phenomenon of ground deformation caused mainly by earthquakes, seriously threaten the safe and stable operation of pipes¹ and endanger the security of national life and property.

Pipe deformations caused by fault make pipes failure. The earthquakes in Turkey and Chi-Chi in 1999,² ³ the Tangshan earthquake in 1976, and the Wenchuan earthquake in 2008⁴ ⁵ caused faults, resulting in the destruction of pipes. Since the San Fernando earthquake occurred in 1971, the seismic safety of buried pipes gradually became a hot topic for scholars. In terms of simplified and theoretical hypotheses, the stress-strain trilinear model of pipe was firstly put forward by Newmark and Hall.⁶ Subsequently, Kennedy⁷ improved the Newmark’s method by replacing the shape of the pipe section near the fault with an arc. The theory of beam on elastic foundation was first applied by Wang and Yeh⁸ to study the fault pipes in 1985. Considering pipe in the transition zone as a cantilever beam, further precise analyses were carried out by Wang.⁹ After that, the influence of fault dip angle was studied by Zhang et al.¹⁰ In recent years, equilibrium equations and compatibility of displacement have been used by Karamitos

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et al\textsuperscript{11} to obtain the axial force and moment of pipe. Dezhkam et al\textsuperscript{12} made a dynamic analysis of pipe subjected to far-fault motions by using cylindrical shell model and the theory of shear deformation. However, due to the thin-walled structure of the pipe, the mechanical properties of pipe buckling are complex, so the analytical accuracy of the simplified models mentioned above is insufficient.

Many scholars have also conducted experimental research. A full-scale experiment on the \( \phi \)114.3 mm and \( \phi \)168.3 mm pipes was completed by Jalali et al\textsuperscript{13}, and the buckling deformation of pipe in different buried depths was analyzed. And they put forward some reasonable buried schemes for pipe through experimental conclusions. Feng et al\textsuperscript{14} scaled down the experimental model and carried out the seismic static and dynamic experiments on buried steel and aluminum pipes. In addition, some centrifuge-scale models\textsuperscript{15,16} and small full-scale experiment studies\textsuperscript{17,18} have also been carried out. Still, due to the limitations of experimental devices, it is difficult to simulate a true full-scale experiment in a real environment.

Zhang et al\textsuperscript{19} simulated the interaction relationship between pipe and soil. A finite element model using three-dimensional beam element was established by Joshi et al\textsuperscript{20} to study the influence of parameters on pipe. The shell element was adopted by Vazouras\textsuperscript{21} to analyze the mechanical properties of the X65 and X80 pipes affected by soil and pipe parameters. Under different conditions of dip angle, pipe internal pressure, diameter-thickness ratio, the buckling variation of pipe was investigated by Zhang et al\textsuperscript{22} Besides, a beam-shell coupling finite element method was proposed by Xu et al\textsuperscript{23} to analyze several yielding judgment parameters of pipe. In order to reduce pipe failure under the fault, Melissianos et al\textsuperscript{24} proposed the flexible joints introduced in the pipe near the faults and evaluated their effectiveness through finite element model. In recent years, Gawande et al\textsuperscript{25} carried out pipe model to study the response of pipe buckling and discussed the buckling patterns and the mechanical parameters. Halabian et al\textsuperscript{26} proposed a new approach by reducing the degrees of freedom for the pipe-soil system considering the nonlinearity of soil, pipe geometric, and pipe material by regarding the pipe section far away from the fault as elastic beam elements. Shi et al\textsuperscript{27} proposed a simplified method to predict pipe curvature or bending strain of pipe directly.

The abovementioned investigations about the pipe mechanics under fault actions by numerical simulation are valuable. Nevertheless, those researches about pipe buckling and the buckling evolution mechanism under the fault actions are insufficient. The aim of this paper is to study the mechanics and buckling evolution mechanism of buried oil and gas pipe. Local collapsing and wrinkling of pipes under the strike-slip and reverse fault were analyzed particularly. In addition, effects of diameter-to-thickness ratio and fault displacement on the stress and strain of pipe were discussed.

2 | NUMERICAL SIMULATION MODEL

2.1 | Finite element model

The three-dimensional finite element model is shown in Figure 1. The crossing angle between the pipe and fault plane is \( \varphi \) = 45\(^\circ\), and the dip angle is \( \beta \) = 90\(^\circ\) for the reverse fault. The diameter of the pipe model is 813 mm. Referring to the reported papers\textsuperscript{22,28} the length of the soil model along the pipe axial direction (direction \( x \)) ensures 60 times the pipe diameter, and the height and width equal to 5 and 11 times pipe diameter, respectively. Furthermore, the buried depth of pipe is 2 times the pipe diameter, whereas the model dimension is 64 m \( \times \) 5 m \( \times \) 10 m eventually. The element type for pipe is four-node reduced-integration shell , while eight-node reduced-integration solid units are employed for surrounding soil.\textsuperscript{29}

The material of pipe is X80, its yield strength is 596 MPa, Young's modulus is 210 GPa, Poisson's ratio is 0.3, and the density is 7800 kg/m\(^3\). Considering a safety coefficient equal to 0.72, the maximum pressure of the pipe is\textsuperscript{21}:

\[
P_{max} = 0.72 \times \left( 2\sigma_s \frac{t}{D} \right)
\]  

In this paper, the minimum wall thickness of the pipe model is 8 mm, consequently, the maximum internal pressure that the pipe can withstand is calculated to be about 8.4 MPa.

The Mohr-Coulomb model is selected as the soil constitutive model. Choosing silty clay as the soil material, its density is 1840 kg/m\(^3\), elastic modulus is 20 MPa, Poisson's ratio is 0.3, internal friction angle is 15\(^\circ\), dilation angle is 0\(^\circ\), and the cohesion is 15 kPa.\textsuperscript{30}

As shown in Figure 2, mesh for pipe near the fault plane is refined to ensure the accuracy of analysis, while a larger mesh is used for the regions that far away from the fault plane so as to improve the calculation efficiency. There are 52 elements around the pipe circumference, and the element size in the refined region along the pipe axis is 0.05 m, whereas totally

\[\text{FIGURE 1 Numerical simulation model}\]
32,240 elements for the pipe are defined. For soil, the size of global element is 1.4 m and 33 elements are refined into the soil where contact with the pipe, resulting in 4,994 elements for each block of soil model.

Mesh density has a big influence on the calculation results, so the mesh sensitivity study is significant. Three groups of pipe mesh have been set up in Figure 3, which are named as Mesh1 (38,304 elements), Mesh2 (32,240 elements), and Mesh3 (21,996 elements). The extreme values of axial strain about Mesh1, Mesh2, and Mesh3 on the compression side are −0.225, −0.214, and −0.195, respectively, and the errors of Mesh2 and Mesh3 are 4.9%, 13.3% based on Mesh1, respectively. So, the Mesh2 with 32,240 elements can promise a better calculated precision.

Using a contact algorithm that takes into account surface friction, the outer surface of the pipe and the surrounding soil are adopted in a tangential behavior and a suitable friction coefficient is defined as 0.3. Since the contact surfaces about soil to soil are continuously changing when the soil blocks move, according to Cheng,31 so in this study, the friction coefficient of soil-soil is defined as 0.5.

About the friction coefficient, referring to SY/T 0450-2004 standard,32 the friction coefficient is closely related to the type of anticorrosion coating on the surface of pipe and the soil type, which should be determined to the measured value.33-35 If there is no measured data, the value of silty clay can be taken from 0.25 to 0.55. Vazouras21 also obtained a similar conclusion. So, Cheng31 set it as 0.6 for pipe-soil behavior and Vazouras, Zhang, and Banushi21,22 assumed it equal to 0.3. Consequently, the friction coefficient is 0.3 in this model.

\[ \varepsilon_{ci} = \frac{\sigma_{ci}}{E} = \frac{4M_{ci}}{\pi D^2 t E} \]  

where the \( M_{ci} \) is given by Brazier36:

\[ M_{ci} = \frac{\sqrt{2}}{9} \frac{E \pi D t^2}{\sqrt{1-v^2}} \]

where \( \varepsilon_{ci} \) is critical buckling strain, \( \% \), \( \sigma_{ci} \) is critical buckling stress, MPa, \( t \) is wall thickness of the pipe, mm, \( D \) is pipe diameter, mm. \( E \) is the elastic modulus, MPa. \( v \) is Poisson’s ratio, \( v = 0.3 \).

Substituting Equation (3) into Equation (2), a simplified equation based on Brazier can be given as follows:

\[ \varepsilon_{ci} = 0.66 \frac{t}{D} \]

2.3 | Verification

In order to ensure the present numerical simulation results are rational, the critical buckling strain is compared with those of the theoretical equations come from Brazier, Li, and the CSA Z662 standard. Based on the equations performed by Brazier and Li, other formulas about critical buckling strain are obtained, as shown in Equations (2) - (6).

**FIGURE 2** Mesh details for soil and pipeline

**FIGURE 3** The results of axial strain in different mesh density

**FIGURE 4** Verification of numerical model by comparison the theoretical results
But Li obtained another modified critical static moment, $M_{c2}$:

$$M_{c2} = 0.388 \frac{Ert^2}{\sqrt{1-v^2}}$$  \hspace{1cm} (5)

where $r$ is pipe radius, mm. Substituting Equation (5) into Equation (2), a limit strain by Li ($\varepsilon_{c2}$) can be expressed in Equation (6):

$$\varepsilon_{c2} = 0.815 \frac{D}{L}$$  \hspace{1cm} (6)

About the formula is provided by the CSA Z662 as shown in Equation (7):

$$\varepsilon_{c3} = \begin{cases} 
0.5 \frac{D}{L} - 0.0025 + 3000 \left( \frac{(p_i-p_e)D}{2E} \right)^2, & \text{for } \frac{(p_i-p_e)D}{2\sigma_s} < 0.4 \\
0.5 \frac{D}{L} - 0.0025 + 3000 \left( \frac{0.4\sigma_s}{E} \right)^2, & \text{for } \frac{(p_i-p_e)D}{2\sigma_s} \geq 0.4 
\end{cases}$$  \hspace{1cm} (7)

where $\varepsilon_{c3}$ is the critical buckling strain by CSA Z662, $\%$. $p_i-p_e$ is internal pressure, MPa. $\sigma_s$ is the yield stress, MPa.

The strain values of no pressure pipe with different wall thicknesses in strike-slip fault are extracted, and the comparative results can be seen in Figure 4. The numerical solutions relatively agree with the results from the equations. Because the CSA standard is normally applied in the engineering problems, its results will be more secure. So, there is an error of strain between the proposed numerical solutions and the equations provided by CSA. Accordingly, the numerical model adopted in this paper is suitable for the buckling analysis of buried pipe under fault.

3 | BUCKLING BEHAVIOR UNDER STRIKE-SLIP FAULT

3.1 | Effect of internal pressure

Figure 5 depicts the deformed evolution of the buried pipe under the action of strike-slip fault. Moving in the $x$-$z$ plane, the stratum will impose bending moment to the pipe. As a result, one side of pipe wall is gradually separated from the soil, and another wall is in contact with it. Subsequently, with pipe gradually bending, one side of pipe wall is elongated, and another is compressed. Pipe would go through three deformation stages, “Elastic, Plastic, and Local buckling.” The geometry of pipes after deformation is an antisymmetric structure about the fault plane under the sustained fault movement, so a similar deformation process for pipe occurs on both sides of the fault plane.

When the displacement of strike-slip fault ($u$) is $1.5D$ and the internal pressure ($P$) is $0.2P_{\text{max}}$, the stress and strain distribution of pipe is shown in Figure 6. When the fault displacement is small, the maximum von Mises stress located in the compressive side is 437.7 MPa, where the maximum axial strain is $1.856 \times 10^{-3}$. There are four equally spaced strips with...
small-amplitude and “bamboo-shaped,” which are perpendicular to the pipe axis. They appear before the local buckling occurs.

Because of the slender shape and structural characteristic of the pipe, when the pipe buckles, the axial strain value changes drastically and obviously, so that comparing strain after pipe buckled is very meaningful. Thus, the axial strain was considered as an analytical parameter. When the internal pressure changes, the axial strains along the pipe axis are in Figure 7. The axial strain fluctuates along the axial length when the displacement is 1.5D. On the compressive side, the strain curve shows four “demarcation points,” corresponding to four strain extreme points, respectively. When pressure is 0.8P_{max}, the strain of one point drastically increases along with a sharp fluctuating. There is a plastic area as the axial strain is around −0.0025. With the internal pressure increasing, the compressive strain increases gradually, but the tension strain gradually decreases. When the pipe wall of the compression side is about to be buckling, small amplification stripes with plastic area will be formed to release the energy of other parts of pipe and then resulting in the stress reduced on the tension side. It is indicated that the high-pressure pipe is prone to buckling than the low-pressure pipe under fault displacement.

When fault displacement is 5D, Figure 8 describes the von Mises stress for different internal pressure pipes. When P < 0.6P_{max}, both the collapse and wrinkling failure modes occur, but the collapse is dominant. When P = 0.6P_{max}, the wrinkle becomes quite noticeable. As the internal pressure increasing, a second wrinkle appears in the buckling position. The maximum von Mises stress is 685.55 MPa. Accordingly, initial stress of the pipe caused by internal pressure will makes the pipe stress larger.

### 3.2 Buckling behavior of low-pressure pipe

When P = 0.2P_{max}, the von Mises stress of the pipe under different fault displacements is shown in Figure 9. When u < 4D,
there is no obvious buckling deformation in the pipe. Stress is concentrated on two positions of pipe. With the increasing of fault displacement, the pipe is gradually elongated along the axial direction. The distribution area of the high stress regions increases gradually. Also, there are slightly extruded stripes on the compression side. When \( u = 4D \), the pipe wall on the compression side is collapsed, which leads to high stress areas concentrated, and the stress in other parts of the pipe is released.

Figure 10 depicts the axial strain of low-pressure pipe \((0.2P_{\text{max}})\) along the pipe axial length. When \( u = 5D \), the fluctuation is most severe, and the maximum compressive and tensile strain in the compression side exceed \(-0.15\) and \(0.04\), respectively. While the maximum tensile strain does not exceed \(0.02\) in the tension side, which is less than the tensile strain limit of \(3\%\) given by IITK GSDMA-2007\(^3\)\(^9\) where there are no welding joints. So the pipe under this operation condition will hardly be cracked by stretching. The local collapse caused by compression is the main failure mode of pipe with low pressure under fault disasters.

When buckling and local wrinkling on the pipe wall appear, the strain would increase sharply, which resulting in a big jump and change of strain value from \(-0.15\) to \(0.04\) at around axial length of \(37.5\, \text{m}\). Smaller elements are used to calculate again, and the original model elements were \(32\,240\) (mesh-A), which increases to \(37\,520\) (mesh-B) after changing the mesh density, as shown in Figure 11. A deformation picture and local view obtained from the local buckled region indicate that the strain will increase rapidly along with a big jump phenomenon, and a finer mesh can only change the extreme of the strain.

### 3.3 Buckling behavior of high-pressure pipe

When \( P = 0.8P_{\text{max}} \), the von Mises stress of the high-pressure pipe under different displacements is shown in Figure 12. Compared with the low-pressure pipe, the buckling displacement for the high-pressure pipe is smaller. Due to the presence of internal pressure, the initial stress occurs on the pipe wall. When \( u = 3D \), the stripes begin to appear on the pipe wall, where indicated that the pipe is in the limit state of buckling, and the distribution area of the high stress on the compression side is significantly larger than that on the tension side. When \( u = 4D \), a “breaking” phenomenon occurs on the pipe compression side, accompanied with a “wrinkle.” Due to the additional bending moment of the soil and the high internal pressure, a premature buckling appears on the pipe wall.

The axial strain curve for the pipe with high internal pressure is shown in Figure 13. When \( u > 4D \), the strain on the compression side is almost negative, and the range of fluctuation is large. The maximum strain in the wrinkling regions is higher than \(-0.20\), which is much larger than that in the low-pressure pipe \((−0.15)\). Because there is a residual stress in the buckling pipe, the transportation pressure will redistribute the pipe stress.
to reduce the structural stiffness of the pipe that may cause cracking more seriously. So, those pipes should be replaced in time to prevent oil and gas leakage.

3.4 Effect of diameter-thickness ratio

When $P = 0.8P_{\text{max}}$ and $u = 5D$, Figure 14 shows the von Mises stress of the pipe with different $D/t$ under the fault action. With the decreasing of $D/t$, the wrinkling amplitude and the number of wrinkles gradually decrease. When $D/t = 68$, the wrinkles disappear, but a large area of stress concentration occurs in the past wrinkling regions with the maximum Mises stress is 684.63 MPa, where pipe becomes smooth. With the increasing of wall thickness, the...
pipe stiffness and the ability to resist external forces are enhanced.

Figure 15 is the axial strain curve of high-pressure pipe with different $D/t$ under the strike-slip fault. When $D/t \leq 68$, the change of axial strain is relatively gentle after slight fluctuations. When $D/t \geq 102$, the strain curve on the compression side begins to fluctuate drastically and the maximum axial strain exceeds $-0.20$. But the strain on the pipe tension side only transforms in a slight amplitude and the maximum axial strain is about 0.02. With the $D/t$ ratio continually increases, the buckling region is close to the fault plane.

4 | BUCKLING BEHAVIOR UNDER REVERSE FAULT

4.1 | Effect of internal pressure

Figure 16 is the evolution of the buckled shapes of pipe under reverse fault. Under the action of reverse fault, the soil blocks on the both sides of fault plane move in the vertical direction (along the direction $y$), which makes the pipe bended and gradually elongated. Still, the pipe goes through three deformation stages: Elastic, Plastic, and Local buckling. In this model, the bottom surface of hanging wall of the reverse fault is connected with dense strata, while the top surface of the footwall is ground. So, the movement space for the pipe in the footwall will be larger. Hence, the mechanical properties for the upper and lower sides of the pipe wall are different.

When $u = D$, $P = 0.2P_{\text{max}}$, the von Mises stress (upper side of the dashed line) and the axial strain (lower side of the dashed line) of the pipe under reverse fault are shown in Figure 17. Conformed to the effect of the strike-slip fault, the tensile side when pipe bends is also stretched under the fault action, and the tensile strain is dominated here. But the value of maximum stress (416.5 MPa) and maximum strain ($-1.772 \times 10^{-3}$) on the compression side is larger than that on the tension side. The “bamboo-shaped” stripes within small amplitude are also observed in the pipe wall at the compression position. The difference is that the stripes are not perpendicular to the pipe axis, but there is an angle with the axis. Comparing with the crossing angle $\phi$ between pipe and the fault plane, the two angles are close, which indicating that the buckling modes of pipe will be affected by the crossing angle.

The deformed evolutions on the top and bottom sides of the pipe wall are different in reverse fault. When $u = D$, strain curves on the two sides of pipe wall with various pressure are obtained as shown in Figure 18. The axial strain on the topline is shown in Figure 18A. There are demarcation points in the strain curve on the compression sidewall. When $P = 0.8P_{\text{max}}$, the strain value of the demarcation point increases rapidly with a plastic area appearing as the strain extreme value is at $-0.003$. But the greater internal pressure is, the smaller strain on the tension side will be, which illustrated that pipe stress is released due to the

\[\text{FIGURE 15} \quad \text{Axial strain of the buried pipe with different } D/t \text{ under strike-slip fault}\]

\[\text{FIGURE 16} \quad \text{Deformation process of the pipe under reverse fault}\]
plastic deformation. The curve of axial strain on the bottom side is shown in Figure 18B. There is no obvious plastic phenomenon at the compression side, which indicated that the deformed evolution process is different between the pipe in the hanging wall and footwall.

When $u = 4.2D$, the buckling modes of the pipe with different internal pressures under reverse fault are depicted in Figure 19. The pipe in the hanging wall is below the dashed line. When $P = 0.2P_{\text{max}}$, the pipe in hanging wall and footwall is already collapsed. When $P = 0.4P_{\text{max}}$, local wrinkling appears on the pipe in hanging wall, and the pipe in the footwall is in the critical state of collapsing and wrinkling. When the internal pressure rises to the maximum value, the pipe wall in the footwall is near to rupture, but a second wrinkle with a smaller amplitude appears on pipe located in the hanging wall. On the tension side of the pipe, new areas of stress concentration appear in the maximum pressure environment, which can further release the pipe stress.

### 4.2 Buckling behavior of low-pressure pipe

When $P = 0.2P_{\text{max}}$, Figure 20 shows the buckling evolution of buried pipe under different fault displacements. When $u = 2.5D$, stripes with “wave” pattern appear on the pipe wall in footwall, while wrinkles have formed in hanging wall. When $u = 3.2D$, the compression side of the pipe wall was totally collapsed. Then, the pipe is obviously divided into three sections: the hanging wall section, the fault transition section, and the footwall section.

Figure 21 shows the axial strain curves of low-pressure pipe under reverse fault. When $u = 3.2D$, three extreme points on the compressive side are formed. With the increasing of fault displacement continuously, the strain curve shape does not change, but the strain value increases again. The maximum axial tensile strain and compressive strain on the compression side is around 0.06 and $-0.20$ till $u = 4.2D$. When $u = 4.2D$, the peak of the strain curve on the tension side is
dented, which resulting in M-shape curve, which is regarded as the critical yield tensile strain of the pipe.

4.3 | Buckling behavior of high-pressure pipe

When $P = 0.8P_{\text{max}}$, Figure 22 shows the von Mises stress of the pipe with high internal pressure under different displacements. When $u = 1.7D$, the obvious “wave” stripes appear on the pipe surface in the footwall, which illustrates that the pipe is in a critical buckling state. Also, wrinkles on pipe have already emerged in the hanging wall. The buckling displacement of the reverse fault is smaller than that of the strike-slip fault, which indicates that the high-pressure pipe is more dangerous in the reverse fault than in strike-slip fault.
**FIGURE 21** Axial strain of the low-pressure pipe under reverse fault movement

**FIGURE 22** Stress distribution of the high-pressure pipe under reverse fault movement

**FIGURE 23** Axial strain of the high-pressure pipe under reverse fault movement
4.4 | Effect of diameter-thickness ratio

The stress variations of high-pressure pipe under different $D/t$ are shown in Figure 24. When $u = 4.2D$, with the decreasing of $D/t$ ratio, the buckling position is gradually far away from the fault plane. And the high stress region spreads along the axial direction from the buckling position. The pipe shape is gradually changed from a z-shaped curve to s-shaped curve during buckling. When $D/t = 68$, the pipe is in the critical buckling state with small plastic stripes on the pipe.

Figure 25 shows the axial strain curves of high-pressure pipe with different $D/t$ under reverse fault. When $D/t = 68$, the axial compressive strain about −0.05 appears on the compression side. And the maximum axial strain on the compression side is −0.30 and −0.25 when the $D/t = 102$ and $D/t = 136$, respectively. When $D/t = 136$, there is another small “wave” in strain curve with value of −0.03 near the maximum compressive strain point of −0.25. Other wrinkles appear for energy releasing, which leads to the reduction of the first wrinkling strain.

5 | CONCLUSIONS

1. Pipe goes through three deformed evolution stages including “Elastic, Plastic, and Local buckling” under the fault action. The deformed pipe is an antisymmetric structure for strike-slip fault, while the pipe deformed pattern in the hanging wall is different from that in the footwall. When the fault displacement is small, there are strips on the compressive side of pipe. When the fault displacement is large, the pipes with various pressures are buckled with collapsing and wrinkling modes.
2. For low-pressure pipe under strike-slip fault, there is no obvious buckling deformation in the pipe when $u < 4D$. When $u = 4D$, the pipe wall on the compression side is collapsed,
and the stress in other parts of the pipe is released. Under reverse fault, stripes with “wave” pattern appear on the pipe wall in footwall when \( u = 2.5D \), but wrinkles have formed in hanging wall. The strain curve shape does not change with the displacement continuously increasing. When \( u = 4.2D \), the tensile side is in the critical yield stage. The local collapse is the main failure forms for low-pressure pipe.

3. For high-pressure pipe strike-slip fault, the buckling displacement is smaller than that in the low-pressure pipe. The stripes appear on the pipe wall when \( u = 3D \). Pipe buckled with a wrinkle when \( u = 4D \). For reverse fault, the wrinkles have already emerged in the hanging wall but “wave” stripes appear in the footwall when \( u = 1.7D \). The local wrinkle is the main failure forms for high-pressure pipe.

4. With the diameter-thickness ratio decreasing, the wrinkling amplitude and the number of wrinkles gradually decrease, and the pipe pattern becomes smooth. At the same displacement, the pipe with high internal pressure is more prone to buckling failure. One more wrinkles would happen on pipe with high pressure under large fault displacement. The deformed evolution process of pipe is different in the hanging wall and footwall under reverse fault.

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