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Numerical simulation of mechanical behavior of buried pipeline impacted by perilous rock

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1. Introduction

Long distance oil and gas pipelines cross the vast and complex areas. There will be a major security risk when pipeline under poor geological conditions or areas where geologic calamities happen frequently. Collapse is one of the most serious geological disasters that threats to pipeline security. As shown in Fig. 1, the main hazard of collapse is the perilous rock that falls off from the mountain or slope. Impact load of perilous rock may lead to deformation or fracture of buried pipeline. Such as Zhong-Wu gas pipeline, which is an important part of China West-east Gas Engineering. According to incomplete statistics, there are 100 pieces of perilous rock in Zhangjigou-Shuanghe section (pipeline length is 6 km), and the volume range is 10~3000 m^3. In 2005, concrete cover plate of the pipeline was punctured by a perilous rock with 350 m^3 in Shunxi. A dent that is about 30 cm in diameter appeared in the pipeline [1]. Since Lan-Cheng-Yu Pipeline's operation in 2002, a number of perilous rock impact pipeline events have occurred [2], which have threatened the safe operation of oil and gas pipeline seriously.

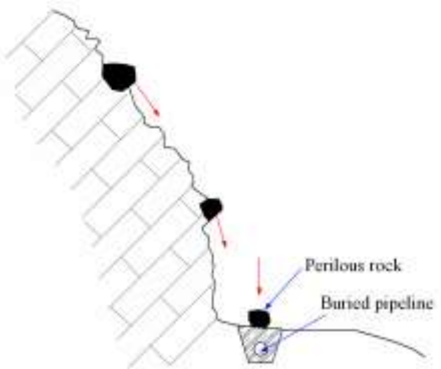

Fig. 1 Schematic diagram of buried pipeline impacted by perilous rock

Researches on damage features and prevention countermeasures of oil and gas pipeline impacted by perilous rocks are imperative. Li et al. [3] analyzed the stress and strain of buried pipeline from impact load. Wang et al. [4] simulated the perilous rock movement by rock-fall software, and impact load was evaluated with two methods. Deng et al. [5] simulated the dynamic response of buried pipeline induced by rock-fall impaction by 3DEC software. Xiong et al [6] studied the influence law of certain factors on the safety of buried pipeline by the explicit dynamic analysis software LS-DYNA. These researches are mainly focused on the stress and strain of buried pipeline when the impact load is very small, but not considering the buckling behavior. Zhang et al. [7] studied the deformation and plastic strain of ground pipeline impacted by rock, not considering buried pipeline. Mechanical behaviors of buried pipeline and ground pipeline are different. A study of impact assessment of the traffic-induce vibration on a buried natural gas pipeline was presented by Bajcar et al. [8]. But impact loads induced by perilous rock and traffic are also different. Fatigue failure is the main reason of pipeline failure under traffic load. For perilous rock impact condition, if the pipeline deformation is too large, it will influence the pigging, or may lead to pipeline rupture.

In this paper, mechanical behavior of buried pipeline impacted by perilous rock was simulated. Stress and plastic strain of buried pipeline in soil and rock stratum were compared. Effects of pipeline parameters and perilous rock parameters on stress and strain of buried pipeline were discussed. That will provide a basis of pipeline laying and protection engineering in bad geological region.

2. Finite element model

If buckling appears on the pipeline after impacted by perilous rock, it is different to calculate deformation by the theoretical formula. Soil-pipeline interaction is an important factor for the buckling behavior. In addition, pipeline is a thin shell structure, superposition principle can't be used for the interaction of stress and strain [9]. Finite element method is more suitable to analyze the mechanical behavior of buried pipeline impacted by perilous rock.

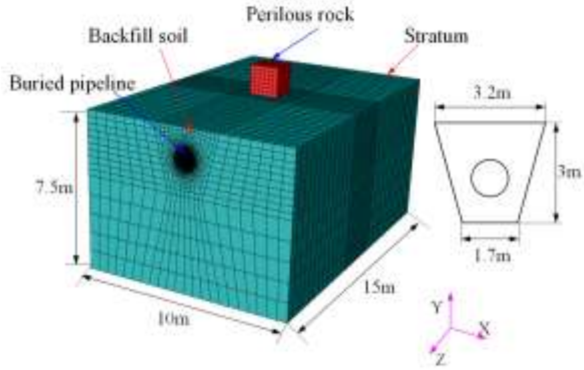

Fig. 2 Finite element models of pipeline, perilous rock and stratum

This paper assumes the shape of perilous rock as a cube. Numerical simulation of buried pipeline impacted by perilous rock is investigated in ABAQUS. Fig. 2 shows the finite element models of the buried pipeline, perilous rock and stratum. The pipeline is embedded in and elongated soil prism along Z axis. Shell element S4R is employed to mesh pipeline, and hexahedral element C3D8R is used to simulate the backfill soil and stratum. Diameter of the pipeline is 813 mm, wall thickness of the pipeline is 8 mm, side length of the perilous rock is 1.4 m. In order to eliminate the edge effect, size of the stratum is 10 m × 7.5 m × 15 m. Thickness of the overlying soil is 1 m, other parameters of the trench are shown in Fig. 2.

A large-strain plasticity model with isotropic hardening is employed for the steel pipeline material. Numerical results are obtained for X65 steel pipeline. Fig. 3 shows the stress-strain curve of X65. Yield stress is 448.5 MPa, Young's modulus of steel material is 206 GPa, Poisson's ratio is 0.3, density is 7800 kg/m^3. Mechanical behaviors of stratum and rock material are described through an elastic-perfectly plastic Mohr-Coulomb constitutive model. For the soil stratum, materials of backfill soil and stratum are the same. The soil's cohesion is 15 kPa, friction angle is 15°, elastic modulus is 20 MPa, density is 1840 kg/m^3, and Poisson's ratio is 0.3. The perilous rock is limestone, its cohesion is 6.72 MPa, friction angle is 42°, elastic modulus is 28.5 GPa, density is 2090 kg/m^3, and Poisson's ratio is 0.29. The dilation angle of soil and rock is assumed equal to zero for cases considered in this paper.

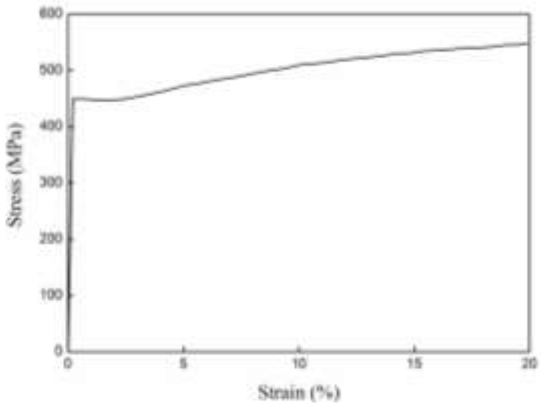

Fig. 3 Stress-strain curve of X65

The interface between outer surface of the pipeline and the surrounding soil is simulated with a contact algorithm, which allows the separation of the pipeline and soil, and through an appropriate friction coefficient is 0.5. Bottom surface of stratum is fixed. Gravity loading is applied to the whole model and internal pressure is loaded on the inner wall of the pipeline firstly. Initial impact velocity is applied to perilous rock.

3. Results in soil and rock stratum

3.1. Model validation

The experiment of rammer impacting roadbed was done by Guo [10] in 2007. Radius of the rammer is 1 m, height is 0.5 m, and its quality is 12000 kg. The roadbed's cohesion is 18 kPa, friction angle is 30°, elastic modulus is 14.4 MPa, density is 1960 kg/m^3, and Poisson's ratio is 0.2. The impact energy is 1200 kN·m. When the depth is 1 m, 2 m, 3 m and 4 m, the displacement of the soil is 0.131 m, 0.082 m, 0.048 m and 0.028 m, respectively.

In order to verify the reliability of the finite element model. The corresponding finite element model was established. The simulation results show that the displacement of the soil under different depth is 0.135 m, 0.084 m, 0.051 m and 0.027 m, respectively. The errors are 3%, 2.4%, 6.25% and 3.6%. Therefore, the established finite element is reasonable.

3.2. Simulation results

Fig. 4 shows the deformations of buried pipeline and backfill soil. Under the impact of perilous rock, the backfill soil is compressed. Impact energy is passed on to the buried pipeline by backfill soil. The upper part of the pipeline is compressed sharply. Then unstability of the cross section occurs and the impact dent appears.

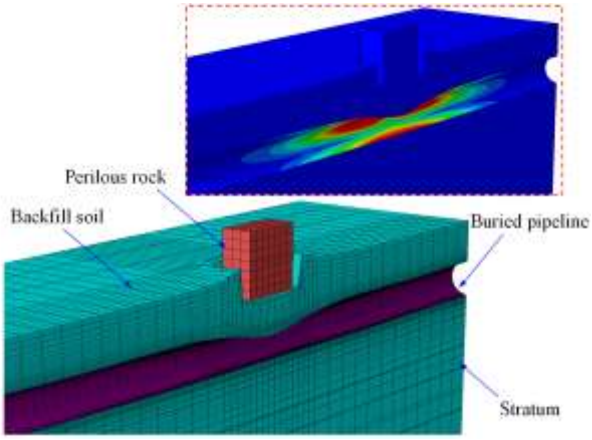

Fig. 4 Deformations of the buried pipeline and backfill soil

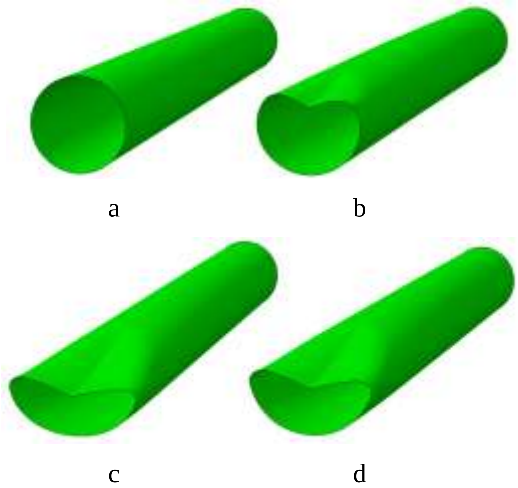

Fig. 5 Deformation process of the buried pipeline: a - No deformation; b - Initial deformation; c - Maximum deformation; d - Final deformation

Fig. 5 shows the deformation process of buried pipeline impacted by perilous rock. The impacting process can be divided into four stages. The first stage is no deformation, cross section of the pipeline is approximate circular (as shown in Fig. 5, a, the impact load doesn't pass on to the buried pipeline. The second stage is initial deformation, perilous rock intrudes into backfill soil and the soil is compressed. Then a dent appears on the pipeline under the action of backfill soil. The third stage is the maximum deformation, velocity of perilous rock becomes zero under the backfill soil resistance. The pipeline is compressed to limit state. The fourth stage is final deformation, impact load disappears in this stage. Elastic deformation caused by impact load will return, but the plastic deformation will not be restored. Elastic deformations caused by gravity of backfill soil and perilous rock are still existing.

When the impact velocity is 35 m/s, considering the computation time is 0.300 s, change curves of impact dent depth along with time are shown in Fig. 6. The time range of the four stages are different in soil stratum and rock stratum. Time ranges of the first stage are 0 ~ 0.006 s in the two stratum, there are no deformation. In soil stratum, time ranges of the second stage, third stage and forth stage are 0.006 s ~ 0.129 s, 0.129 s ~ 0.237 s and 0.237 s ~ 0.300 s. In rock stratum, time ranges of the second stage, third stage and forth stage are 0.006 s ~ 0.054 s, 0.054 s ~ 0.081 s and 0.081 s ~ 0.300 s. In the second stage, when the time is smaller than 0.024 s, deformations of the two pipelines are the same. After 0.024 s, the change rate of dent depth in rock stratum is bigger than it in soil stratum. But the process lasts for a longer time in soil stratum. Meanwhile, duration of the third stage in soil stratum is longer than in rock stratum.

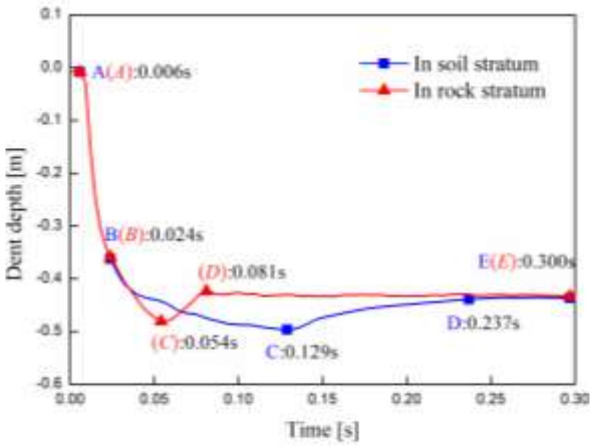

Fig. 6 Change curves of impact dent depth along with time

In order to study the effect of stratum on mechanical behavior of buried pipeline, take soil stratum and rock stratum for example. When impact velocity is 35 m/s, von Mises stress distributions of buried pipeline in soil and rock stratums are presented in Fig. 7. High stress areas of buried pipeline in the two stratums are more close to each other. In soil stratum, the maximum von Mises stress of pipeline, which mainly concentrated in the middle part, is bigger than in rock stratum. No matter in soil stratum or in rock stratum, there is a dent with ship form under perilous rock impact. The upper part of the pipeline becomes to M-shape, but the lower part is still round or oval.

Fig. 8 shows plastic strains of buried pipeline in soil and rock stratums. Plastic area of pipeline in rock stratum is bigger than in soil stratum. The maximum plastic strain is mainly concentrated in the bottom of the dent with ship form. Dent length in rock stratum is bigger than in soil stratum.

Cross section shapes of buried pipeline in the two stratums are presented in Fig. 9. Buried pipeline is compressed in Y direction, while the width increases in X direction. Stratum doesn't affect the deformation of the lower part of the buried pipeline. The biggest compression amount is in the middle part of the pipeline. For the most dangerous section, the biggest compression amount is 0.4283 m in soil stratum, but 0.4253 m in rock stratum. Buckling compression ratio is 52.9% and 52.5% respectively. So, maximum dent depth of pipeline in rock stratum is smaller than in soil stratum, but dent length is bigger (as shown in Fig. 8).

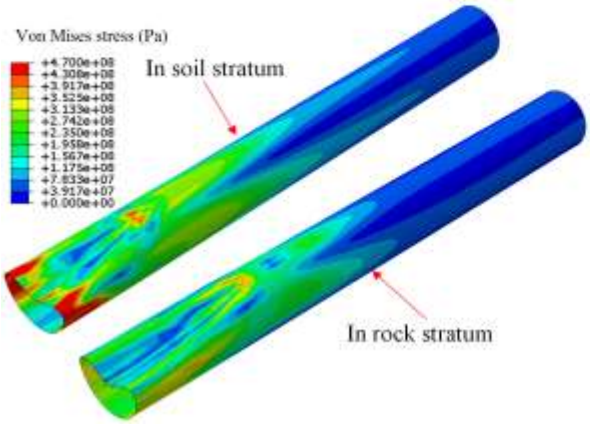

Fig. 7 Von Mises stress of the pipeline in the two stratums

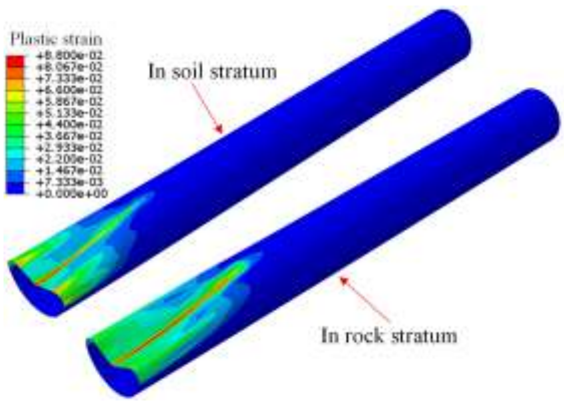

Fig. 8 Plastic strains of the pipeline in soil and rock stratum

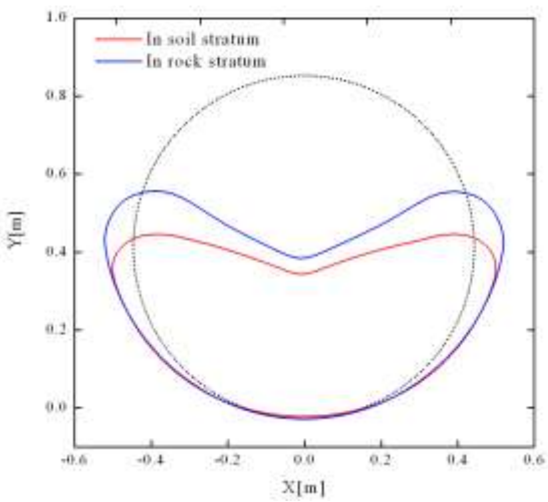

Fig. 9 Cross section shapes of the pipeline in soil and rock stratum

4. Sensitivity parameters of buried pipeline

4.1. Pipeline internal pressure

Fig. 10 shows von Mises stress distribution of the buried pipeline under different internal pressures. Stress distribution of pressure pipeline is different from the no-pressure pipeline. With the increasing of internal pressure, von Mises stress of both ends of the pipeline increases. When the internal pressure is higher than 2 MPa, the stress distribution of buried pipeline has a smaller change. There is a lower stress area in the upper part near the middle line. When the internal pressure is lower than 2 MPa, high stress area is in the upper part of the pipeline under the impact location.

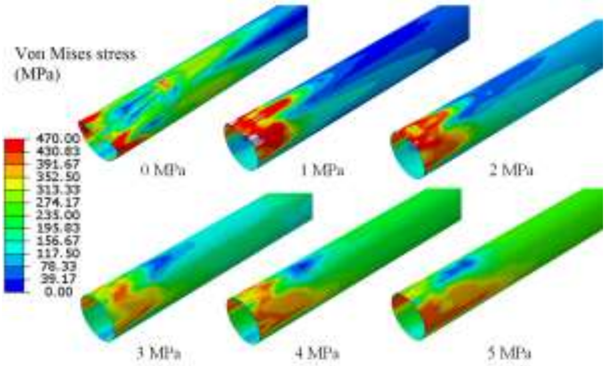

Fig. 10 Von Mises stress of the pipeline under different internal pressures

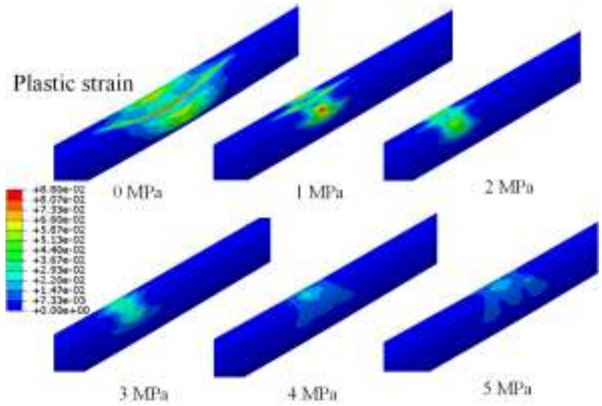

Fig. 11 Plastic strains of the pipeline with different internal pressures

Fig. 11 shows the plastic strains of the buried pipeline under different internal pressures. The plastic strain area of the pipeline decreases with the increasing of internal pressure. When internal pressure is lower than 2 MPa, the bigger plastic strain appears on the bottom and the two bulges of the dent. When internal pressure is higher than 2 MPa, the biggest plastic strain appears on the top of the pipeline.

Cross section deformations and the maximum dent depths of the buried pipeline under different internal pressures are shown in Figs. 12 and 13. Maximum dent depth of no-pressure pipeline is more than pressure pipeline, and the buckling mode is more serious. Therefore, no-pressure pipeline is more prone to failure after impacted by perilous rock. When internal pressure is higher than 2 MPa, change rate of the deformation decreases with the increasing of the internal pressure. Because the internal pressure can enhance stiffness of the pipeline to resistance the impact deformation. In the following text, no-pressure buried pipeline will be discussed.

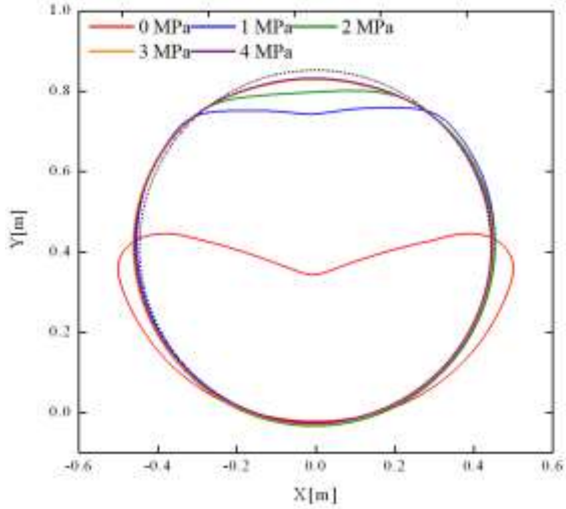

Fig. 12 Cross section deformations of the pipeline under different internal pressures

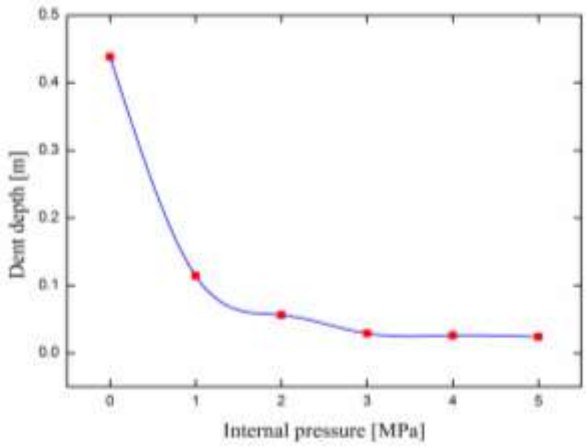

Fig. 13 Dent depth curve of the pipeline under different internal pressures

4.2. Wall thickness of pipeline

Wall thickness affects stiffness of the buried pipeline. When impact velocity is 35 m/s, von Mises stress and plastic strain of buried pipeline under different wall thicknesses are shown in Fig. 14. High stress area decreases with the increasing of wall thickness, and the maximum stress also decreases. Buckling mode of buried pipeline is more serious with the decreasing of wall thickness. And distribution shape of plastic strain turns from "M" shape to "I" shape, plastic strain also decreases.

Fig. 15 shows cross section deformations of the pipeline under different wall thicknesses. Cross-sectional area of buried pipeline increases with the increasing of wall thickness. Deformation of the upper part of the pipeline becomes smaller, curvature radius of the lower part decreases. As shown in Table 1, dent depth and its change rate gradually decrease with the increasing of wall thickness. Buried pipeline with thin wall is more prone to failure under perilous rock impact.

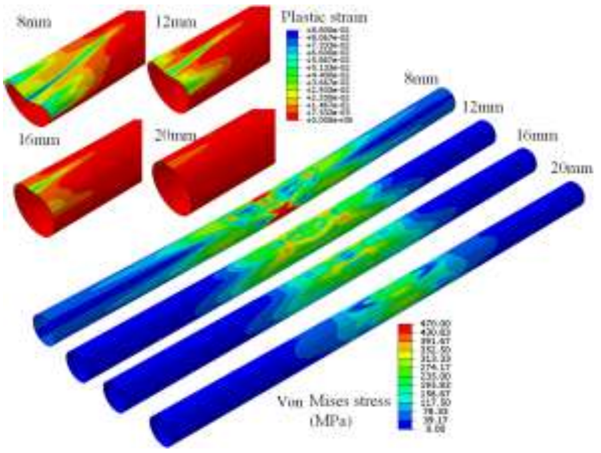

Fig. 14 Von Mises stress and plastic strain of the pipeline under different wall thicknesses

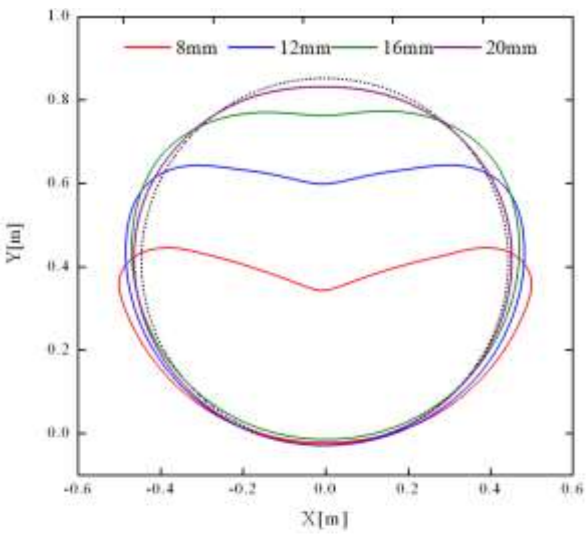

Fig. 15 Cross section deformations of the pipeline with different wall thicknesses

4.3. Diameter of pipeline

When impact velocity is 25 m/s, wall thickness is 8 mm, von Mises stress and plastic strain of the buried pipeline under different diameters are shown in Fig. 16. High stress area increases with the increasing of pipeline diameter. When the diameter is small, von Mises stress distribution is an elliptic spot. With the increasing of diameter, stress distribution becomes to elliptic ring, then becomes to four-point ring, and last becomes to two-point distribution. Plastic strain distribution turns from "I" shape to "M" shape with the increasing of diameter.

Fig. 17 shows cross section deformations of the buried pipeline under different diameters. When the diameter is 406 mm, cross section of pipeline is oval. With the increasing of diameter, cross section shape becomes to "D" shape. The upper part of the pipeline is squashed, and the lower part is still round. The dent appears when the diameter is bigger. As shown in Table 1, dent depth increases with the increasing of diameter. Therefore, buried pipeline with a smaller diameter is more safe in the collapse region.

Thickness of overlying soil (buried depth) has a great effect on the impact force from perilous rock. The lesser thickness of overlying soil, the bigger impact force is. When impact velocity is 30 m/s, wall thickness is 8 mm, von Mises stress and plastic strain of pipeline under different thicknesses of overlying soil are shown in Fig. 18. With the increasing of thicknesses of overlying soil, the maximum stress and high stress area decreases. When thickness of overlying soil is more than 1.5 m, stress and the plastic strain of the pipeline are all small.

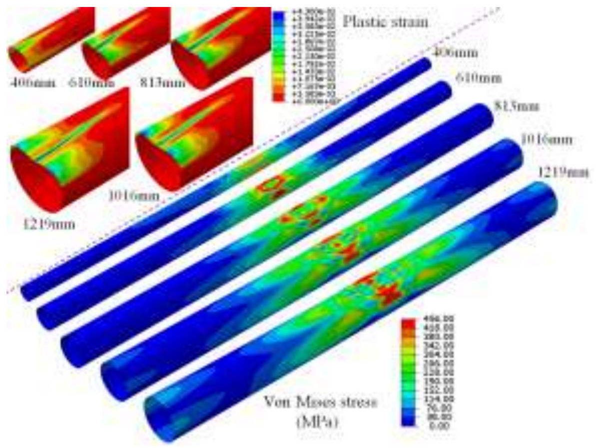

Fig. 16 Von Mises stress and plastic strain of the pipeline under different diameters

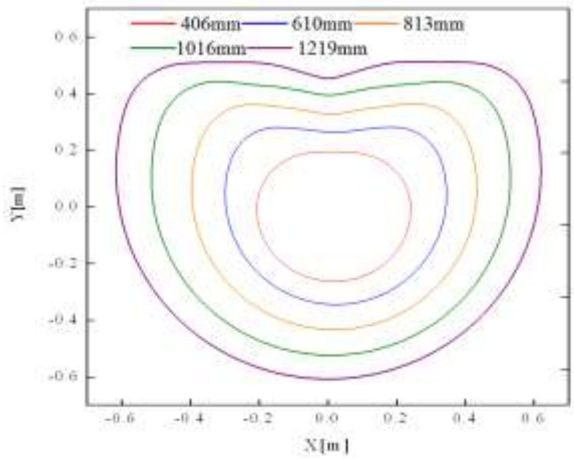

Fig. 17 Cross section deformations of the pipeline under different diameters

4.4. Thickness of overlying soil

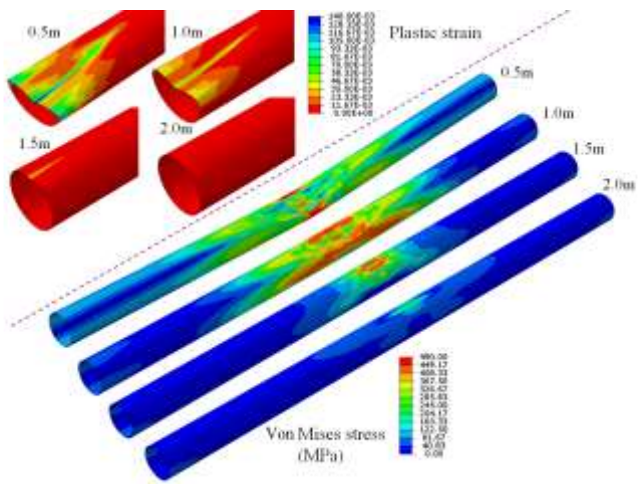

Fig. 18 Von Mises stress and plastic strain of the pipeline under different thicknesses of overlying soil

Fig. 19 shows cross section deformations of the buried pipeline under different thicknesses of overlying soil. The lesser thicknesses of overlying soil, the cross section is more flat. It means that buckling behavior is more serious with the decreasing of buried depth. When thickness of overlying soil is 2.0 m, the cross section is oval, and there is no buckling. As shown in Table 1, dent depth is smaller with the increasing of buried depth. Therefore, buried depth can be increased to avoid the premature failure when crossing the geological disaster area.

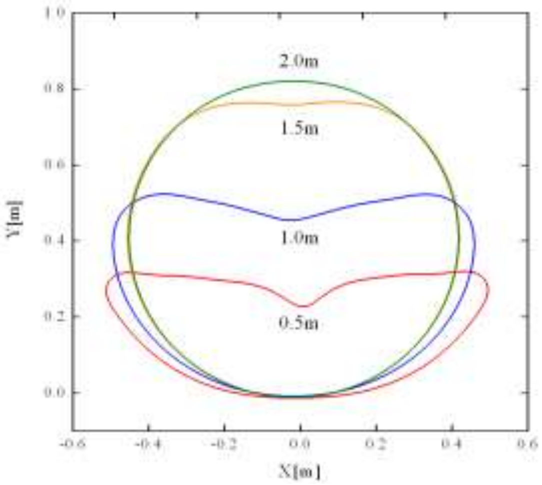

Fig. 19 Cross section deformations of the pipeline under different buried depths

Table 1

Dent depths under different buried pipeline parameters

δ	λ	D	λ	h	λ
8	0.4384	406	0.0473	0.5	0.5393
12	0.2315	610	0.1136	1	0.3365
16	0.1132	813	0.1684	1.5	0.0703
20	0.0452	1016	0.2341	2	0.0176
		1219	0.2929		

λ - the maximum dent depth, m; δ - wall thickness of pipeline, mm; h - thickness of the overlying soil, m; D - outer diameter, mm.

5. Sensitivity parameters of perilous rock

5.1. Impact velocity

Impact velocity of perilous rock determines impact momentum. The bigger impact velocity, the greater the kinetic energy is. Von Mises stress and plastic strain of the pipeline under different impact velocities are shown in Fig. 20. High stress area expands gradually to the two sides of the impact location with the increasing of impact velocity. High stress area increases from the upper part to the lower part. When impact velocity is less than 20 m/s, von Mises stress and plastic strain is very small, and there is no buckling for the buried pipeline. But with the increasing of impact velocity, dent length and maximum plastic strain increase gradually.

Fig. 21 shows cross section deformations of the buried pipeline under different impact velocities. Cross section deformation of buried pipeline increases with the increasing of impact velocity. The cross section shape is oval first, then is "D" shape, and last is "M+U" shape. As shown in Table 2, dent depth also increases, but its change rate increases first and then decreases. Impact velocity is determined by the height of perilous rock before fall off. So, dangerous rocks in high mountain and slope should be cleared and prevented.

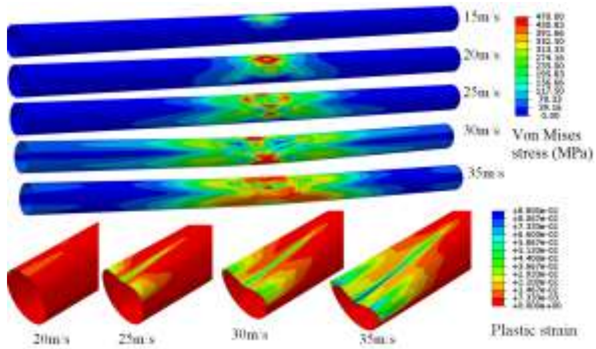

Fig. 20 Von Mises stress and plastic strain of the pipeline under different impact velocities

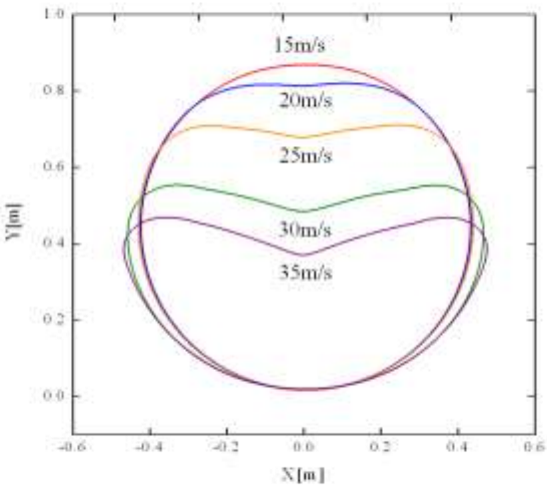

Fig. 21 Cross section deformations of the pipeline with different impact velocities

5.2. Impact location

If impact location of perilous rock is away from the buried pipeline, it will not affect mechanical behavior of the pipeline. Eccentricity distance is defined as the distance between the centers of buried pipeline and perilous rock. When impact velocity is 30 m/s, wall thickness is 8 mm, von Mises stress and plastic strain under different impact positions are shown in Fig. 22. With the increasing of eccentricity distance, high stress area decreases, and its location tends to the right side. When eccentricity distance is 1.5 m, von Mises stress is very small, and there is no plastic strain. When eccentricity distance is less than 1.0 m, plastic strain distribution is similar to the central impact ($w = 0$). Dent length decreases with the increasing of eccentricity distance.

Fig. 23 shows cross section deformations of the buried pipeline under different impact positions. With the increasing of eccentricity distance, impact dent turns along a clockwise direction, and dent depth decreases. As shown in Table 2, when eccentricity distance is 1.5 m, dent depth is only 9 mm. Therefore, if perilous rock is inevitable, some measures should be taken to change the impact location, then make it far form buried pipeline. Or the pipeline installation position should be changed to avoid the impact area.

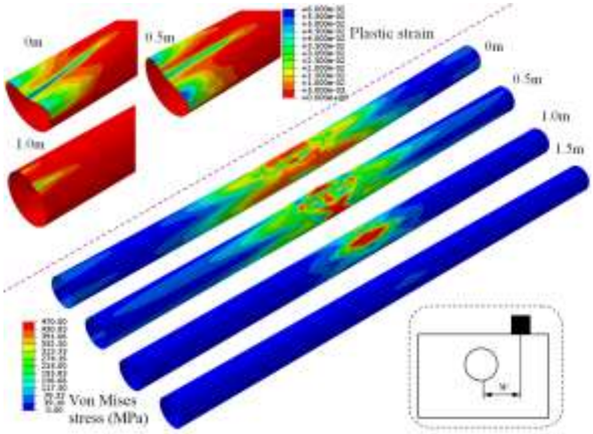

Fig. 22 Von Mises stress and plastic strain of the pipeline under different impact positions

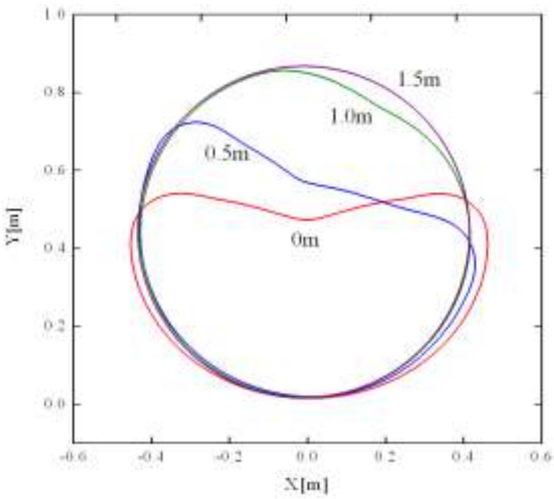

Fig. 23 Cross section deformations of the pipeline with different impact positions

5.3. Volume of perilous rock

Volume of perilous rock is another factor to determine impact momentum and kinetic energy. Volume ($V = l^3$) change of perilous rock can be done by changing of side length of the cube. When impact velocity is 30 m/s, von Mises stress and plastic strain of pipeline with different rock volumes can be seen in Fig. 24. High stress area increases with the increasing of rock's side length. And the buckling mode becomes from plan to bend. With the increasing of rock's side length, plastic strain area gradually increases, the maximum plastic strain and length of dent also increase.

Fig. 25 shows cross section deformations of the pipeline under different rock volumes. Cross-sectional area decreases with the increasing of rock's side length, the buckling is more serious. Dent depth of buried pipeline increases with the decreasing of rock's side length. In geological disaster area, large perilous rock should be early cleaned. Because large perilous rock is difficult to be prevented. Especially when the earthquakes occur, the harm from perilous rock is very serious.

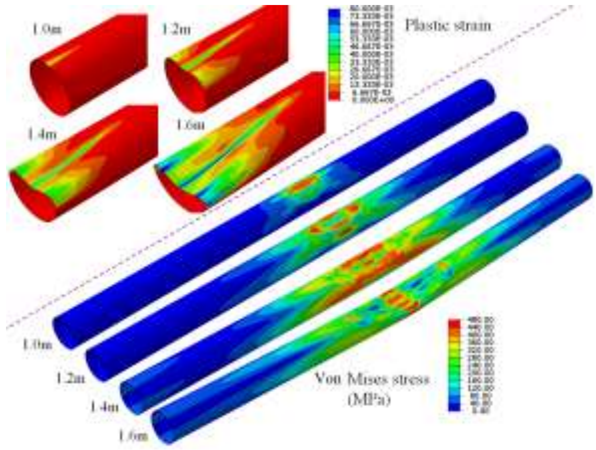

Fig. 24 Von Mises stress and plastic strain of the pipeline under different rock volumes

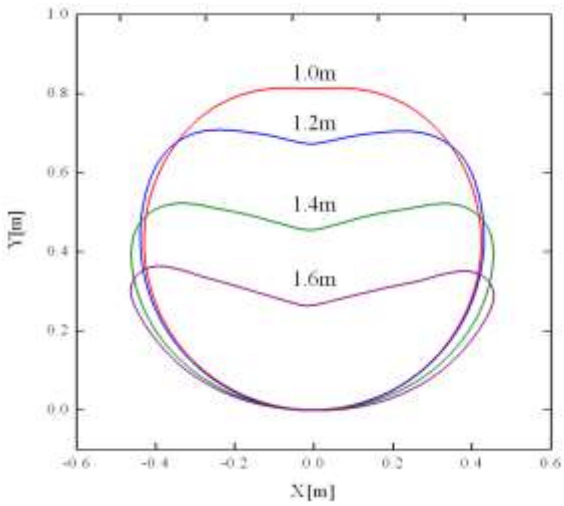

Fig. 25 Cross section deformations of the pipeline under different rock volumes

Table 2

Dent depths under different perilous rock parameters

v_0	λ	w	λ	l	λ
15	0.0156	0	0.3365	1.0	0.0384
20	0.0617	0.5	0.2630	1.2	0.1583
25	0.1684	1.0	0.0481	1.4	0.3365
30	0.3365	1.5	0.0090	1.6	0.5051
35	0.4386				

v_0 - impact velocity, m/s; w - eccentricity distance, m; l - rock side length, m.

6. Conclusions

1. Deformation process of buried pipeline impacted by perilous rock can be divided into four stages. The first stage is no deformation, cross section of the pipeline is approximate circular. The second stage is the initial deformation, a dent appears on the pipeline. The third stage is maximum deformation, buried pipeline is compressed to limit state. The fourth stage is final deformation, elastic deformation caused by impact load will return.

2. No matter in soil or rock stratum, there is a dent with ship form under perilous rock impact. The upper part

of the pipeline becomes to M-shape, but the lower part is still round or oval. Plastic strain area of pipeline in rock stratum is bigger than in soil stratum. Dent depth of the pipeline in rock stratum is smaller than it in soil stratum, but dent length is bigger.

3. Stress distribution of the pressure pipeline is different from no-pressure pipeline. Plastic strain area of the pipeline decreases with the increasing of internal pressure. Dent depth of no-pressure pipeline is more than the pressure pipeline. High stress area, maximum stress, plastic strain and dent depth decrease with the increasing of wall thickness and buried depth. Shape of plastic strain turns from "W" shape to "I" shape. High stress area, dent depth increases with the increasing of diameter.

4. With the increasing of impact velocity and rock's volume, maximum plastic strain, dent length and dent depth increase gradually. Cross section of the pipeline is oval first, then is "D" shape, and last is "W+U" shape. With the increasing of eccentricity distance, high stress area and dent depth decrease gradually, and high stress location tends to one side.

Acknowledgements

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NUMERICAL SIMULATION OF MECHANICAL BEHAVIOR OF BURIED PIPELINE IMPACTED BY PERILOUS ROCK

S u m m a r y

Mechanical behaviors of buried pipeline under perilous rock impact in soil stratum and rock stratum were investigated by finite element method. Effects of pipeline parameters and perilous rock parameters on stress and strain of buried pipeline were discussed. The results show that deformation process of buried pipeline impacted by perilous rock can be divided into four stages (no deformation, initial deformation, maximum deformation and final deformation). Plastic strain area of the pipeline in rock stratum is bigger than in soil stratum. High stress area, maximum stress, plastic strain and dent depth decrease with the increasing of internal pressure, wall thickness and buried depth, but increase with the increasing of diameter. With the increasing of impact velocity and rock's volume, plastic strain, dent length and dent depth increase gradually. With the increasing of eccentricity distance, high stress area and dent depth decrease gradually, and the stress location tends to one side.

Keywords: buried pipeline, perilous rock, finite element method, mechanical behavior, plastic strain.

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