Mechanical Responses Analysis Of Curved Pipeline Crossing Mining Subsidence Area

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The deformation of the curved pipeline in the mining subsidence area may be different from the ordinary straight pipeline. Curved pipeline is prone to large deformation in the mining subsidence area, which may cause pipeline accidents. Thus, it is of great importance to investigate the mechanical properties of the curved pipeline in the mining subsidence area. The numerical simulation model of pipeline-soil coupling was established by the nonlinear numerical simulation method in this study. The mechanical responses of the curved pipeline under the stratum settlement, collapse, and suspension are investigated. The results show that when the settlement area is located below the curved section of the pipeline, the maximum stress is in the middle of the curved section, there will be more high stress areas when the curved angle larger. When the settlement area is located below the half curved part and half straight part of the pipeline, the high stress area of the pipeline is located at the end of the curved section. The stress and displacement increase with the increase of angle in both cases, but the maximum stress in pipeline is not reached the yield strength. Whether the collapse interface is located in the middle of the curved section or at both ends of the curved section, the high stress area occurs near the collapse interface, the large curved angle of the pipeline is prone to generate large high stress area and produce large plastic strain, and the cross section of the pipeline has a tendency to squeeze to one side. For the suspended curved pipeline, the stress, plastic strain and displacement of the suspended curved pipeline increase with the increase of suspended length and curved angle.

Keywords: Curved pipeline; Numerical Simulation; Mining subsidence area; Stress; Strain

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1. Introduction

The effect of geological disasters on China is enormous, with over 200 people injured to varying degrees and nearly 400 deaths in past decades. Moreover, it has caused huge losses of 3.17 billion RMB to the Chinese economy. Not only are these geological disasters, but some studies have also pointed out that the problem of subsidence in China is very severe, with a cumulative settlement of 20 centimeters in an area of 75000 square miles [1]. Buried pipelines are vulnerable to various ground movements. It might cause large deformations and fractures of the pipelines, resulting in leakage of oil and gas resources, pollution of the surrounding environment, and oil and gas resource stop [2]. Among them, subsidence and ground collapse caused by underground mining is one of the geological disasters that threaten and destroy pipelines.

Secondary geological disasters such as stratum settlement and ground collapse caused by mining subsidence areas are likely to cause large deformation, suspension, and breakage of oil and gas pipelines. If the excavation process of the mining area is considered at the same time, when the pipeline moves discontinuously through the subsidence basin, the pipeline is mainly bent and deformed. In the mining subsidence area, the pipeline has large deformation and even buckling failure of the pipeline's section, which greatly affects the safe operation of the pipeline [3]. Therefore, research on the mechanical behavior of buried pipeline in mining subsidence areas is of great significance and engineering value for the design of buried pipelines, improvement of pipeline safety evaluation systems.

At present, many scholars and scientific research teams at home and abroad have conducted in-depth research on the deformation of buried pipelines caused by underground mining, and have achieved considerable results. Xu [4] studied the interaction mechanism of pipe soil in mining subsidence areas based on the analytical model and numerical model and revealed the synergistic deformation relationship of pipe-soil and the characteristics of pipe's stress distribution during strata subsidence. Sarvanis and Karamanos [5] proposed an analytical method for pipeline strain analysis subjected to permanent ground actions in geological disaster areas, and the pipeline's displacement and strain were compared very well with numerical results. Zheng et al. [6] established a 3D nonlinear pipe-soil coupling model to investigate the failure characteristics of X80 steel pipe under the ground settlement, and the local inner corrosion defects are considered to evaluate the integrity and safety of pipeline. The mechanical behavior of buried PE pipeline under ground subsidence was studied using numerical simulation by Wu et al. [7], and the variation history and the variation behavior of maximum equivalent stress of PE pipeline caused by multiple variables with settlement were analyzed in detail. A fully-instrumented model tests were investigated by Li et al. [8] to estimate the effect of ground subsidence on buried pipelines, and a simplified analytical model was proposed to derive deflection profiles of the pipe-soil system in terms of axial strain measurements. Xu et al. [9] analyzed the surface subsidence characteristics of pipelines along the pipeline during the mining process based on probability integral method, and derives the influence of mining subsidence. Chen et al. [10] provided both calculation formulas for the earth pressure of the pipe-soil separation and contact sections, and compatibility of deformation is innovatively used to compute the settlement of the foundation and internal forces on the pipeline. Demirci et al. [11] developed a new experimental setup for physical modeling of buried pipeline crossing reverse fault and investigated the pipeline response according to finite element analysis by using ABAQUS. However, the existing researches are focused on the mechanical analysis of long-distance straight pipelines. Due to the influence of the underground mining area, the deformation law of the curved pipeline under the action of the stratum is different with the ordinary straight pipeline. Therefore, this will cause local buckling or pipeline failure, which is different from an ordinary straight pipeline. Once an accident occurs to the curved pipeline, not only the conveying capacity and service life will be greatly reduced, but also serious damage and economic loss will be easily caused.

To fill this gap, mechanical responses of curved pipeline in mining subsidence area were studied in this paper, and the numerical model was established. Furthermore, the interaction between pipeline and soil was considered accurately. Based on the numerical model, the stress, plastic strain, and displacement of curved pipeline under the stratum settlement, collapse, and suspended is investigated, and the curved angle was also considered. It provides a reference to the engineering application of the pipeline.

2. Numerical model

2.1. Materials and methods

Previous studies have shown that it is very difficult to analyze pipelines using cable models or beam models [12]. When a large deformation occurs in the cross section of the pipe, the superposition principle cannot be used for the interaction of the longitudinal strain and the bending strain of the pipe. There may be residual stress and stress concentration in the pipeline, so the common theoretical analysis method is difficult to solve the mechanical response problem of the pipeline [13]. In contrast, the finite element method has its unique advantages to solve this problem more accurately. So, the mechanical behavior of the curved pipeline in the subsidence area is examined numerically. Through the nonlinear material behavior of the pipeline and the surrounding soil, the interaction between the buried pipeline and the deformation of the surrounding soil is accurately simulated, and the deformation behavior of the pipeline is evaluated with high precision.

In this paper, the X65 steel material is used to analysis the buried pipeline in the mining subsidence area, a linear isotropic strain hardening model is used for plasticity model of steel pipeline material. The yield strength is 448.5 MPa, the density is 7800 kg/m^3, the elastic modulus is 210 GPa, and the Poisson's ratio is 0.3 [14]. The outer diameter of the pipeline is D = 660 mm, the wall thickness of the pipeline is t = 8 mm. The buried depth of pipeline is 4 m, and the distance from the pipeline edge to the boundaries is more than 5 times of pipeline diameter [15]. Buried pipelines mainly bear the self-weight of backfill, and pulling force caused by pipeline pressure and stratum settlement under the action of stratum subsidence. The type of soil is clay, and the soil is simulated by 3D constitutive element in this paper. The soil materials are described by the elastic-perfectly Mohr-Coulomb constitutive model in general finite-element software, because it can avoid the convergence problem induced by the discontinuity caused the hexagon shape yield surface, and reflects the shear strength of the soil by selecting the friction angle and cohesion. The soil is assumed an isotropic material and free of impurities and groundwater, its parameters related to the experimental results after consolidation undrained test. The density of soil is 1950 kg/m^3, cohesion is 30 kPa, friction angle is 22.5°, elastic modulus is 50 MPa, Poisson's ratio is 0.3 [16].

For soil-pipeline interaction, the contact condition is a special discontinuous constraint that allows force to be transferred from one part of model to another part of the model. The constraint occurs when the two surfaces are in contact, and the constraint disappears when there is no contact. In the non-linear contact finite element calculation process, it is continuously judged whether the contact pair of two surfaces are in contact, and the constraint conditions are modified. Based on the contact theory, the contact penalty function is used to define the contact algorithm between the pipeline and the soil. According to the relevant research results, the friction coefficient of the contact surface between the pipeline and soil is 0.3 [17]. The buried pipeline is modeled by four-node shell element, with a total of 40 shell elements around the cylinder circumference of the pipeline, and the eight-node reduced-integration elements are used to simulate the surrounding soil [18]. In this paper, mining subsidence is divided into three stages in chronological order: settlement, collapse, and pipeline suspension. Among them, settlement refers to the incomplete collapse of the mining subsidence area, collapse refers to the situation where collapse pits have already been generated in the mining subsidence area, and pipeline suspension refers to the situation where the pipeline is exposed after the collapse of the mining subsidence area. A detailed description is provided in the section 3, followed by an analysis of the three conditions.

2.2. Model validation

The experimental model of buried PVC pipe in stratum settlement area was established by Xu [4], and valuable test results were obtained with system test. The same model established by FEM to verify the model in this paper. The material properties are the same with the experiment, and detailed parameter information has been published in Xu [4] and will not be repeated here. The displacements of the buried pipe in settlement area compared with the finite element method and experiment. The deformation curves have similar trends, and the error between the finite element model and the experimental results in the max displacement is less than 6%, as shown in Fig. 1. It demonstrates that the finite element model and mesh size of the buried pipe under stratum subsidence is reliable.

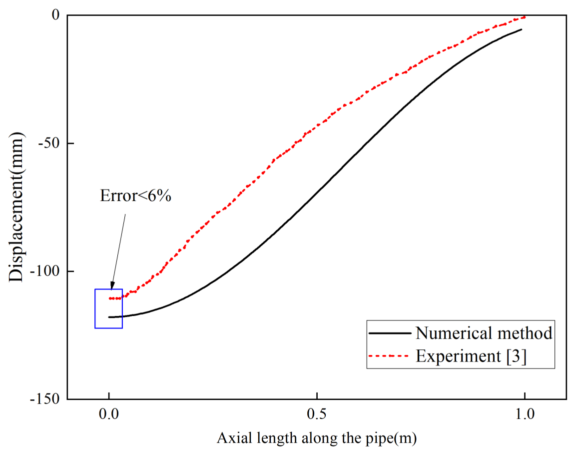
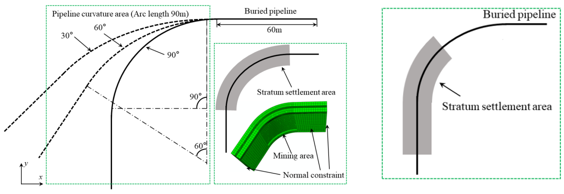


Fig. 1. Model validation

3. Analysis of formation deformation

In the mining settlement area, there will be voids inside the stratum. Based on the release of the earth's pressure, the whole stratum will be displaced. Due to the cohesive force of the soil, the strata will not collapse and produce other large deformations. In this situation, the arc length of the pipe curved is 90 m, and the central angle of the pipe arc is 30°, 60°, and 90°, respectively. Fig. 2 shows the curved pipeline in the mining settlement area. The mining settlement area is located below the curved section of the pipeline as shown in Fig. 2a, and the mining settlement area is located below the half curved part and half straight part of the curved pipeline as shown in Fig. 2b. An initial gravity load is applied to the entire model first, then the mining area starts to be mined. The mining is divided into multi-step mining, and in the finite element program, each step of mining soil is deactivated (model change function) within the mining area until the entire mining area is completely deactivated to simulate the mining. Normal constraints are applied to each surface of the model, while the top surface is free.



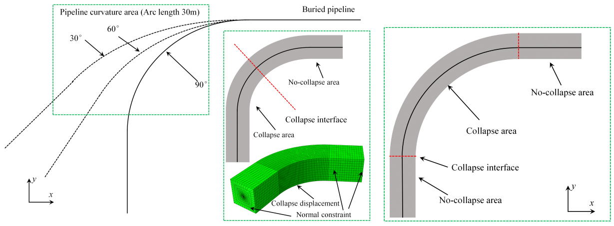
(a) Settlement area below the curved section

(b) Settlement area below the half curved section

Fig. 2. Schematic diagram of the curved pipeline in the settlement area

When the settlement of the stratum is too large, due to the limited stability of the surrounding soil, it is easy for the mining area to collapse under other actions. This causes the upper stratum to move downwards, resulting in an obvious collapse pit with surrounding high and middle low on the surface. Stratum collapse is easy to cause large buckling deformation of buried pipelines. Fig. 3 shows the schematic diagram of the curved pipeline in the collapse area. The deformation of the pipeline in the collapse area is divided into two parts: the collapse interface is located in the middle of the curved pipeline (Fig. 3a) and at both ends of the pipeline (Fig. 3b). It is assumed that the arc angles of the curved area are 30°, 60°, and 90°, respectively, the pipeline arc length is 65m, and the collapse displacement is 2 m, 4 m, and 6 m respectively. For this situation, an initial gravity load is applied to the entire model first, then the collapse displacement along z-direction is applied to the node of the bottom (x-y plane) of the collapse area. The node on the bottom planes of the no-collapse areas are remain fixed in z-direction. The normal constraint is applied on the side surface of model, and the top surface is free [19].

For shallow buried pipelines or pipelines with soft surrounding soil, after the deformation of the stratum, the curved pipeline may be suspended. At this time, the curved pipeline is prone to large deformation under the influence of its own gravity. Fig. 4 shows the schematic diagram of the suspended curved pipeline after the collapse. It is assumed the arc length of the curved section of the pipeline



(a) Collapse interface on the middle of the pipeline

(b) Collapse interface on the end of the pipeline

Fig. 3. Schematic diagram of the curved pipeline in the collapse area

is 50 m, 75 m, 100 m and 125 m, respectively, and the central angle of the arc of the pipeline is 30°, 60°, and 90°, respectively. In order to improve computational speed and efficiency, a 1/2 model is used for simulation. There is only one step in the analysis, the gravity load is applied to the entire model. The symmetrical constraint is applied to the surface of the symmetrical plane, the top surface of the soil is free, and normal constraints are applied to other surfaces.

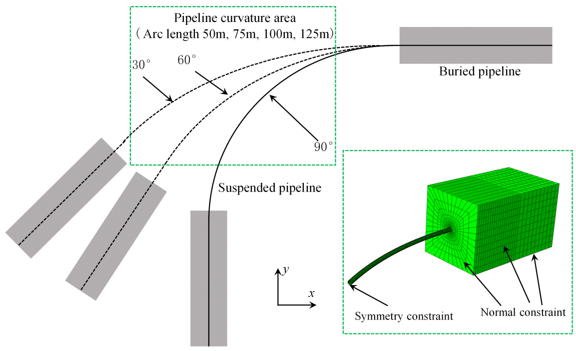


Fig. 4. Schematic diagram of the suspended curved pipeline

4. Curved pipeline under settlement

4.1. Effect of settlement area located below the curved part

After numerical simulation, the stress distribution of the curved pipeline in the settlement area is shown in Fig. 5. The high stress area of the pipeline is located in the middle of the curved pipeline. It is distributed in a stripe shape on the surface of the pipeline, the stress of the 90° pipeline is the largest, the maximum stress is 62 MPa, which is much less than the yield stress. The high stress area of the 30° pipeline and 60° pipeline is a narrowly shaped area, while the high stress area of the 90° pipeline presents two narrowly shaped areas. Uneven loads along the circumference of the 90° pipeline cause multiple high stress areas on the surface and the high stress area is located in the middle of the pipeline. Because the axial force sustained by the pipeline decreases as the pipeline angle increases in the mining settlement area, the pipeline is easy to bend deformation. No matter how the angle changes, the maximum stress is less than the yield strength.

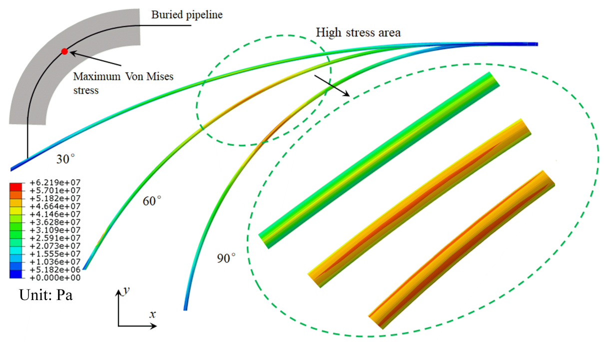


Fig. 5. Stress distribution of curved pipeline in settlement area

Fig. 6 shows the maximum vertical displacement of the curved pipeline in the settlement area. The maximum displacement is located in the middle of the pipeline. As the angle increases, the maximum vertical displacement gradually increases. The maximum vertical displacement of the pipeline at 90° increases by 9.4% compared with the 30° angle. Due to the effect of the curved, the pipeline with a large angle tends to produce greater deformation.

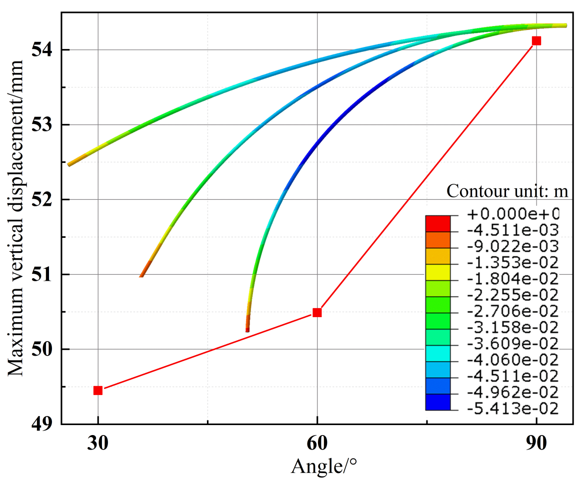


Fig. 6. Maximum vertical displacement of curved pipeline in settlement area

4.2. Effect of settlement area located below the half curved part

When the mining settlement area is located below the half curved part and half straight part of the curved pipeline, the stress distribution of the curved pipeline in the settlement area is shown in Fig. 7. The high stress area is located at the end of the curved section. The stress of the 90° pipeline is large, but the maximum stress is less than the yield strength. This position is where the straight pipeline connects with the curved pipeline, and the high stress area is easy to occur in the inner side of the pipeline with a large curved angle.

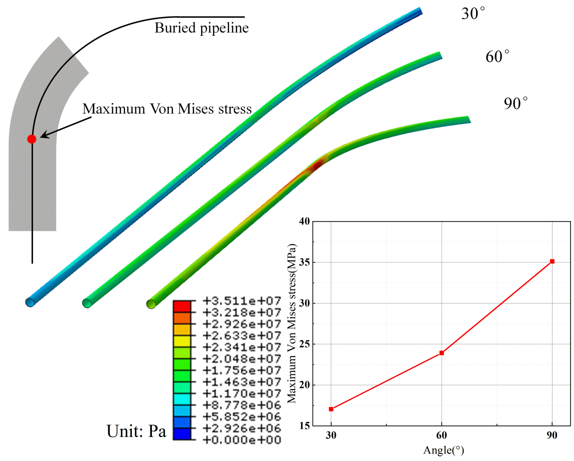


Fig. 7. Stress distribution of curved pipeline in settlement area

Fig. 8 shows the maximum vertical displacement of the curved pipeline in the settlement area. It shows that, with the increasing of curved angle, the pipeline has more deformation, and the change rate also increases. In general, the pipelines in the mining settlement area in the two cases are prone to bending deformation, but they are difficult to be failure.

5. Curved pipeline under collapse

5.1. Effect of collapse interface on the middle part

Fig. 9 shows the stress distribution of the curved pipeline in the mining collapse area when the collapse interface is in the middle of the curved pipeline. The large area of the pipeline has exceeded the yield strength and the local deformation is obvious. The high stress area of the pipeline is located on both sides of the collapse interface. With the increase of the collapse displacement, the stress of the pipeline with different curved angles gradually increases, and the range of the high stress area gradually expands along the axial direction. When the collapse displacement is 2 m, the difference in the maximum stress among differ-

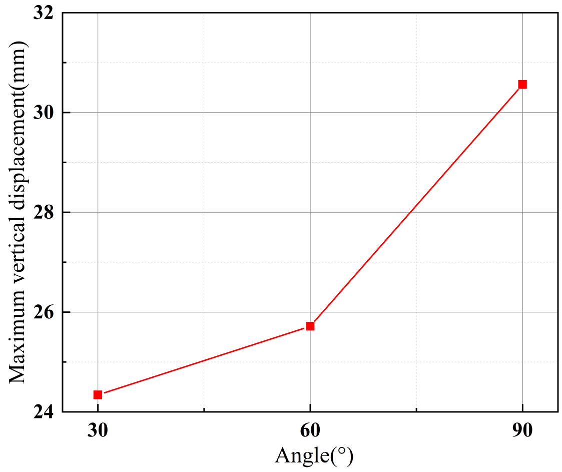


Fig. 8. Maximum vertical displacement of curved pipeline in settlement area

ent curved angles is small, but the high stress area with the bigger angle of the pipeline is larger. When the collapse displacement is 6 m, the high stress area of the pipeline with different angles covers the whole curved section. In addition, buckling occurs on the pipeline when collapse displacement and pipeline angle are large, the buckling position is located in the dangerous section shown. Therefore, the stress of the pipeline easily exceeds the yield strength in the collapse area, which is more likely to cause serious deformation of the pipeline.

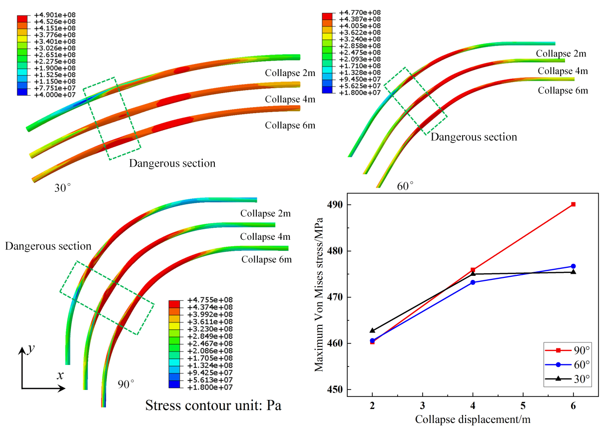


Fig. 9. Stress distribution of curved pipeline in collapse area

Fig. 10 shows the plastic strain of the curved pipeline in the collapse area. The plastic strain area is mainly concentrated on both sides of the collapse interface, and the high plastic strain area in the no-collapse area is larger, it is not evenly distributed along the circumference of the pipeline. The maximum plastic strain is located in the inner side of the no-collapse area. The curved angle and collapse displacement are bigger, the maximum plastic strain is larger.

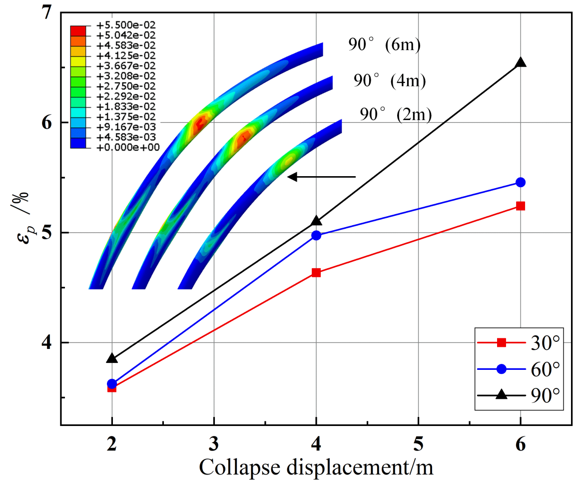
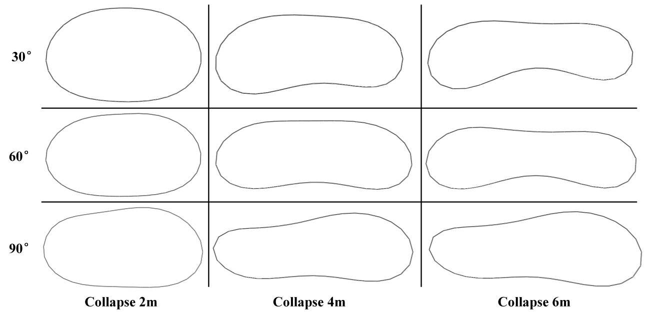


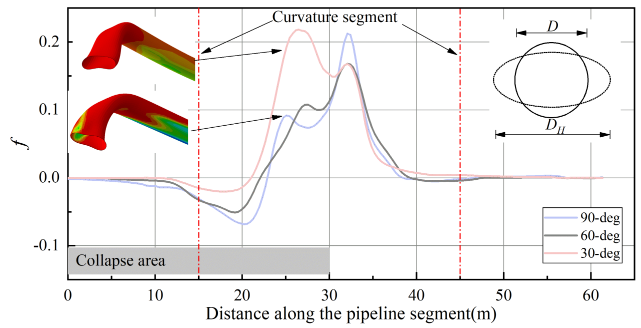
Fig. 10. Plastic strain of curved pipeline in collapse area

Fig. 11 shows the cross-section distortion of the curved pipeline in the collapse area. Fig. 11a shows the most dangerous cross-section of the buried pipeline. When the collapse displacement increases, the lower surface of the pipeline with different angles is deformed toward the inside of the pipeline, but the deformation of the upper surface is slightly different. The upper surface of the pipeline with 30° and 60° is gradually buckled with the increase of the collapse displacement, but the upper surface with 90° is squeezed to the inner side of the pipeline.

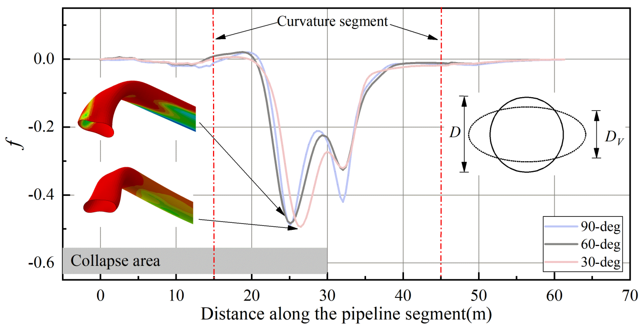
The cross-sectional distortion can be represented by the so-called "flattening parameter" f, which is defined as the ratio of the maximum change in pipeline diameter ΔD to the original pipeline diameter D ($f = \Delta D/D$) [20]. Fig. 11b and Fig. 11c show the f along axial direction of the pipeline when the collapse displacement is 6 m. The maximum f is in the collapse area and close to the collapse interface. The pipeline with 30° is easy to distort seriously in the horizontal direction. Because when the angle of pipeline is large, the axial tension of the pipeline is not on the same straight line, which makes the pipeline move towards the one side (the direction of the center of the curved pipeline), but the resistance of the soil is more serious, so the horizontal distortion is small, and the distortion of cross-section presents the form of Fig. 11a. The maximum f for vertical direction with different is close, this is because the pipeline resists the displacement of the soil above the pipeline, so the interaction between pipeline's lower surface and soil is weakened.



(a) Most dangerous cross-section



(b) *f* along axial direction of the pipeline for collapse displacement of 6 m; the change of ΔD is measured relative to the pipeline horizontal diameter ($\Delta D = D_H - D$)



(c) *f* along axial direction of the pipeline for collapse displacement of 6 m; the change of ΔD is measured relative to the pipeline vertical diameter ($\Delta D = D_V - D$)

Fig. 11. Cross-section distortion of curved pipeline in collapse area

5.2. Effect of collapse interface on both ends

When the collapse interface is located at both ends of the pipeline, Fig. 12 shows the stress distribution of the curved pipeline in the collapse area. There are two high stress areas, which are located in the middle and the end of the curved section of the pipeline, and stress of the curve's end is larger, this high stress area gradually expands along the axial direction with the collapse interface as the center. The high stress area of the 90° pipeline is larger than other angles, and the maximum stress is still located on the inner side of the pipeline. In addition, the buckling position is located at the collapse interface respectively. Therefore, regardless of the form of the pipeline in the collapsed area, a large curved angle of the pipeline in the collapse area maybe not allowed.

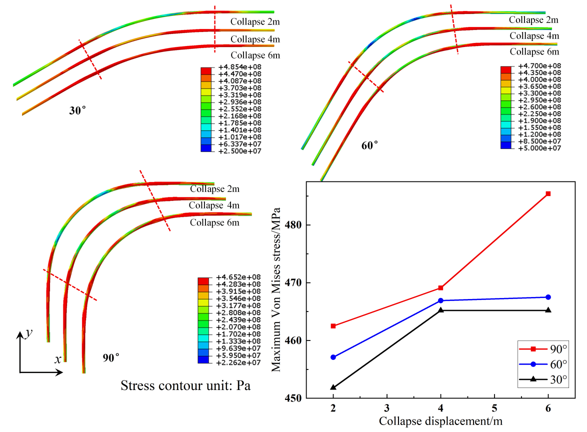


Fig. 12. Stress distribution of curved pipeline in collapse area

Fig. 13 shows the plastic strain of the curved pipeline in the collapse area. The plastic strain areas are mainly concentrated on both sides of the collapse interface and are not evenly distributed along the circumference of the pipeline. Maximum plastic strain curves are similar to the maximum stress curves.

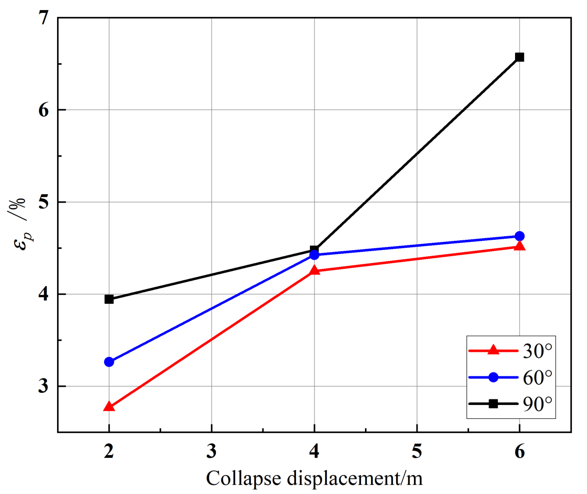
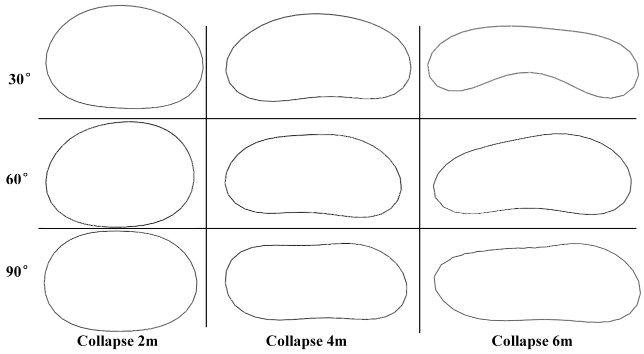
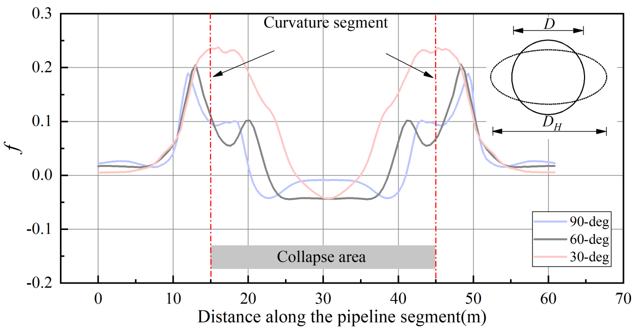


Fig. 13. Plastic strain of curved pipeline in collapse area

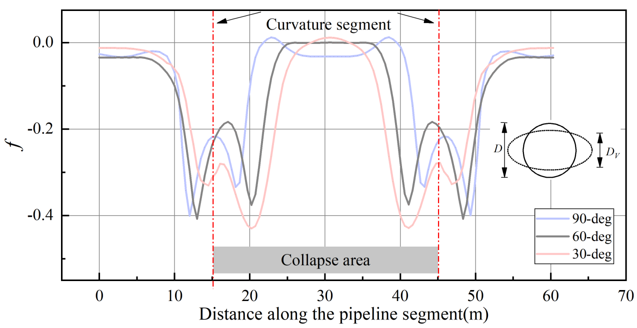
Fig. 14 shows the cross-section distortion of the curved pipeline in the collapse area. Fig. 14a shows the most dangerous cross-section of the buried pipeline. Fig. 14b and Fig. 14c show the *f* along axial direction of the pipeline when the collapse displacement is 6m. When collapse displacement is large, the lower surface of the 30° pipeline is



(a) Most dangerous cross-section



(b) f along axial direction of the pipeline for collapse displacement of 6 m; the change of ΔD is measured relative to the pipeline horizontal diameter ($\Delta D = D_H$ - D)



(c) f along axial direction of the pipeline for collapse displacement of 6 m; the change of ΔD is measured relative to the pipeline vertical diameter ($\Delta D = D_V$ - D)

Fig. 14. Cross-section distortion of curved pipeline in collapse area

more serious than other angles. And the upper surfaces with 60° and 90° pipelines are squeezed to the one side of the pipeline. Therefore, the cross section of the pipeline with small angle is easy to squash in the vertical direction when crossing the collapse area, and the large angle pipeline will deform in the horizontal direction. When the collapse interface on both ends of the curved pipeline, the restrictive effect of the intersection of the straight pipeline and curved pipeline in axial direction is more obvious. So, the deformation of the pipeline is slightly smaller compared to the case described in subsection 5.1.

6. Suspended curved pipe after subsidence

The stress distribution of the suspended curved pipeline is shown in Fig. 15. The high stress area of the pipeline is located at the end of the pipeline, which is in contact with the soil. The high stress area on the pipeline's upper surface is oval, but not in the middle. The stress increases as the suspended length increase. When the suspended length is less than 50 m or more than 125 m, the maximum stress of the pipeline with different angles is similar. Because when the suspended length is large, the stress of the pipeline with different angles already has reached the yield strength, and the stress increase is small as the suspended length increases. The stress of the 90° pipeline increases rapidly and first exceeds the yield strength. Therefore, large curved pipelines are prone to high stress zones and can lead to a large area of weakened strength, leading to accidents such as tensile cracking.

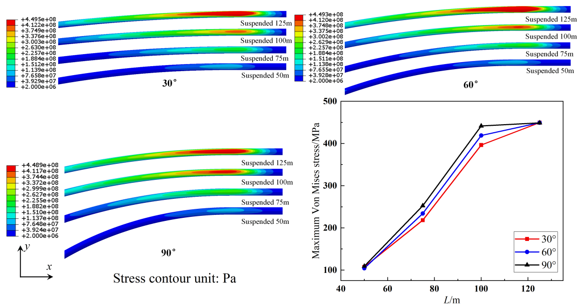


Fig. 15. Stress distribution of suspended curved pipeline

Fig. 16 shows the plastic strain of the suspended curved pipeline. The plastic strain area is concentrated on the suspended ends, the lower surface of the pipeline is larger. Because the interaction between the lower surface of the pipeline ends and the soil is stronger under gravity load, and the interaction between the upper surface of the pipeline ends and the soil is weaker. The max plastic strain has a small angle with the direction of gravity, this is because the curved pipeline has a tendency to rotate around the center of curved pipeline under gravity load. In addition, the plastic strain increases with the increase of curved angle. When considering the installation of pipeline protection devices, targeted attention could be paid to the side of suspended curved pipelines.

Fig. 17 shows the maximum displacement of the suspended curved pipeline. The maximum displacement locates in the middle of the suspended curved pipeline. The maximum displacement of the pipeline increases nonlinearly with the increase of the suspended length. In addition,

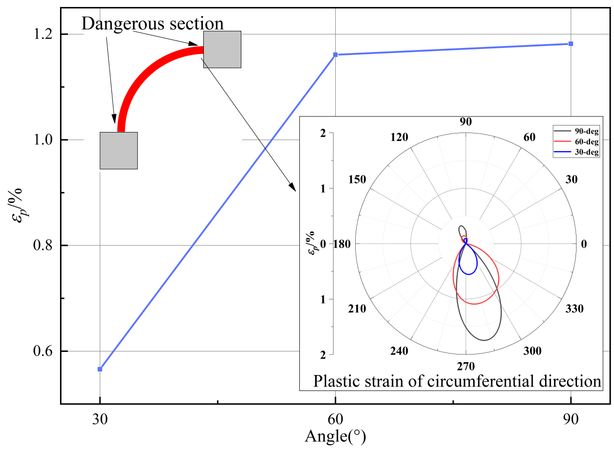


Fig. 16. Max plastic strain of suspended curved pipeline

the maximum displacement also increases slightly as the angle increases, and the difference of displacement is small when the suspended length is less than 50 m.

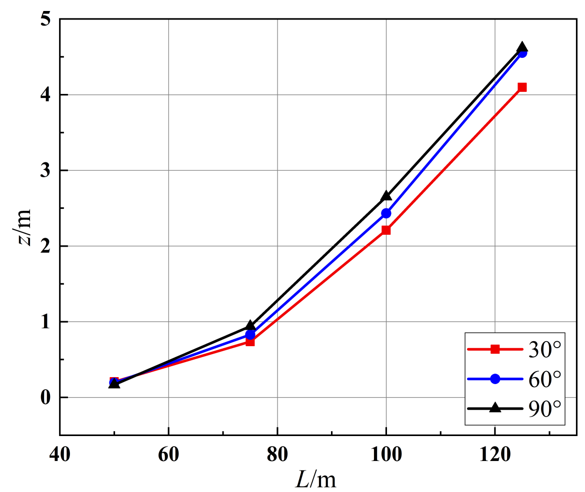


Fig. 17. Maximum displacement of suspended curved pipe

7. Conclusions

When the settlement area is located below the curved section of the pipeline, the maximum stress is in the middle of the curved section. There may be more high stress areas when the curved angle is larger. The high stress area of the pipeline is narrowly shaped area, it is easy to deform along the axial direction of the pipeline. When the settlement area is located below the half curved part and half straight part of the curved pipeline, the high stress area of the pipeline is located at the end of the curved section, and the high stress area is easy to occur in the inner side of the pipeline with large curved angle. This may cause local buckling of the pipeline, which should be given extra attention during design. The stress and displacement increase with the increase of angle in both cases.

When the collapse interface is located in the middle of the curved section of the pipeline, the high stress area of the pipeline is located on both sides of the collapse interface. When the collapse interface is located at both ends of the curved pipeline, there are two high stress areas, which are located in the middle and the end of the curved section of the pipeline, and the stress of the curve's end is larger. The large curved angle of the pipeline is prone to generate large high stress areas and plastic strain, and the cross section of the pipeline has a tendency to squeeze to one side in both cases. The pipeline in the collapsed area is the most prone to failure. Discontinuous high stress areas may cause additional wrinkles in the pipeline. The smaller the spacing between high stress areas, the more complex the degree of wrinkling. It is possible to consider adding longer protective devices to avoid potential threats. The cross-section deformation causes irregular dents in the pipeline, which affects its integrity and long-term performance. For example, cracking occurs under external forces, and significant wall thinning occurs during the oil transportation. The lateral reinforcement or monitoring should be considered in pipeline design.

The stress, plastic strain and displacement of the suspended curved pipeline increase with the increasing of suspended length and curved angle. The max plastic strain has a small angle with the direction of gravity. There is significant local strain in the suspended curved pipeline, and efforts need to be made to avoid the curved pipeline being suspended.

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9. Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

10. Data

Some or all data, models, or code generated or used during the study are available from the corresponding author by request (list items).

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