Numerical Analysis of Buried Pipes Subjected by Tunnel Excavation

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***Abstract*—Tunnel excavation is one of the most important projects that threaten the safe operations of buried pipe. The numerical analysis of buried pipe after tunnel excavation were studied by using the finite element method in this paper. The results show that the high-stress region is concentrated in the middle of the pipe, and the maximum von Mises stress occurs on the upper surface of the pipe after excavation. During the excavation process, as the excavation length increases, the stress in the pipe increases, the horizontal displacement of the pipe decreases, and the vertical displacement of the pipeline increases. The maximum von Mises stress and deformation of pipe increase with the increasing of the radius-thickness ratio and buried depth, but decrease with the increasing of the internal pressure.**

Keywords—Buried pipe; Tunnel excavation; Numerical simulation; Von Mises stress

I. Introduction

In recent years, significant progress has been made in the exploration and development of oil and gas resources. As the main transportation method for oil and gas resources, pipes have received widespread attention for their structural safety and operational reliability [1]. Due to the direct contact between buried pipes and strata, they are significantly affected by geological conditions. The complex and ever-changing geological environment can easily cause large deformation or even failure of pipes, leading to accidents, not only causing serious economic losses, but also causing damage to the ecological environment. Among them, the geological subsidence and collapse caused by tunnel excavation are one of the main geological disasters that threaten and damage pipes. Due to human activities such as tunnel excavation, goafs are formed below the formation, which can cause damage to the rock and soil of the formation, potentially causing significant deformation, suspension, and breakage of oil and gas pipes. Therefore, conducting research on the mechanical behavior of buried pipes during tunnel excavation is of great significance and engineering value for the design of buried pipes, the improvement of pipe safety evaluation system, the improvement of pipe deformation resistance, and the development and application of pipe detection and protection devices.

In recent years, many scholars have studied the effect of tunnel excavation on buried pipe. Liu [2] conducted a study on the effects of tunnel construction on adjacent pipes using a two-dimensional finite element method. Zhang [3] proposed a continuous elastic method to evaluate the impacts of neighboring tunnels on existing pipes in multiple layers of soil. Klar [4] analyzed the effects of tunnels on existing pipes by employing two different theories, namely the Euler-Bernoulli simply supported beam theory and shell element theory to represent the pipe. Zhang [5] proposed a simplified displacement-controlled two-stage method and stress-controlled two-stage method, using the Winkler soil model to determine the mechanical behavior of buried pipes induced by underground excavations in soft clay. Bi [6] established a three-dimensional simulation model of tunnel excavation's impact on underground pipes using the finite element software, considering different burial depths, material characteristics, and stiffness of the underlying layer. These studies provide important theoretical and numerical simulation methods for evaluating the impacts of tunnel construction on adjacent pipes.

However, during tunnel excavation, the deformation pattern of the pipes is often neglected, which is different from real projects. Additionally, pipes are thin-walled structures, and residual stress and stress concentration phenomena may occur during excavation. Therefore, a finite element model is more suitable than an analytical model. To address this, a pipe-soil coupled finite element model was established to investigate the effects of tunnel excavation on the mechanical performance of buried pipes. Moreover, the influence of pipe parameters was also discussed. The research findings provide reliable references for buried pipelines and tunnels.

II. Numerical Simulation Model

In order to analyze the mechanical properties of the buried pipe, a soil-pipe coupling model was established based on finite element model. The model consists of tunnel, pipe, lining and surrounding soil.

Advanced nonlinear finite element software is used to establish a buried pipe model that accurately represents the actual model. The numerical computation model consists of the soil and pipe. To save computational costs and improve efficiency, the entire model is simplified to a certain extent by assuming a rectangular, where the overall model size is 50m × 20m × 30m to eliminate the influence of boundaries on the results. The tunnel section is circular with a diameter of D = 7m, and the tunnel axis is located 15m below the ground surface. The pipe has a diameter of d = 660mm, a thickness of t = 8mm, and a burial depth of H = 4m. The pipeline is perpendicular to the excavation direction of the tunnel. The lining thickness is r = 0.2m. Eight-node reduced-integration elements are used for modelling the soil [11], and the pipe uses shell elements [8]. The areas near the buried pipe have to be refined. The model is shown in Fig.1. The interface between the pipe and the soil are simulated with the friction coefficient 0.3 [7]. The whole model is the normal constraint except the top surface [10].

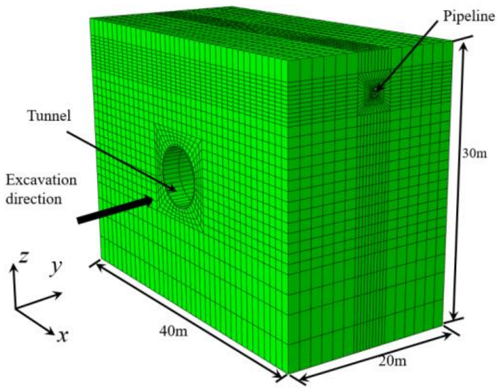


Fig.1 *Finite element model*

Take X65 pipe as an example to analyze. The density of pipe is 7800kg/m3, the elastic modulus of steel material E=210GPa, the Poisson's ratio is 0.3, and the yield strength is 448MPa [1]. The mechanical behavior of the soil material chosen by elastic-perfectly plastic Mohr-Coulomb constitutive model in this paper. The physical parameters of the soil are shown in Table 1.

Table 1: Physical parameters of the soil [9].

ρ (kg/m^3)	E (MPa)	μ	C (kPa)	ϕ (°)	Thick (m)
1860	15	0.35	12	15	6
1930	25	0.3	20	22	18
2060	60	0.24	40	26	6

III. RESULTS AND ANALYSIS

When the burial depth of the pipeline is 2m and the wall thickness is 8mm, the von Mises stress distribution of the pipeline during tunnel excavation is shown in Fig.2. During the excavation process, the maximum von Mises stress occurs on the upper surface of the pipeline. The high-stress region during the deformation of the pipeline is mainly concentrated in the middle of the pipeline, at the position of x=20m. At the same time, there are higher stress regions on both sides of the pipeline. The maximum von Mises stress increases with the increase in excavation length. When the excavation length reaches 16m and 20m, the stress in the pipeline remains basically unchanged, indicating that the deformation of the pipeline has already been completed.

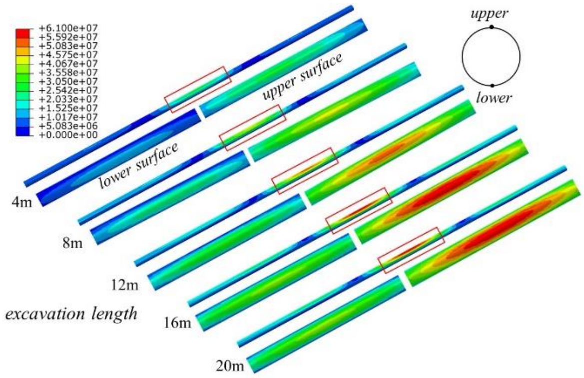


Fig.2 *Von Mises stress distribution of pipe after tunnel excavation*

Fig.3 shows the displacement of pipe with different excavation lengths. The pipe has horizontal displacement and vertical displacement during excavation, and the vertical displacement is much larger than the horizontal displacement. When the excavation length is 4m, the pipe has produced horizontal and vertical displacement. With the increasing of the excavation length, the horizontal displacement decreases, but the vertical displacement increases, both are approximately linearly changed. When the excavation length is greater than 16m, the pipe is basically no longer deformed.

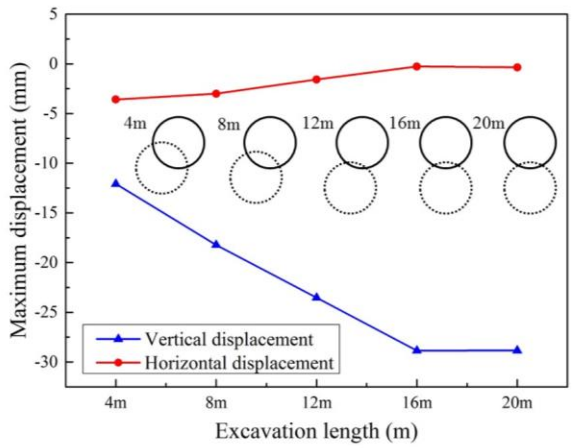


Fig.3 *Displacement of pipe after tunnel excavation*

IV. EFFECT OF PIPE PARAMETERS

A. *Radius-thickness Ratio*

The radius-thickness ratio of pipe has a great effect on the stiffness of pipe. When the diameter of pipe is 660mm, the von Mises stress in the cross section of the middle of pipe with different radius-thickness ratios is shown in Fig4. With the increasing of the radius-thickness ratio, the stress of upper surface of pipe increases, but the stress of lower surface of pipe decreases. And the stress area extends along the pipe's axial direction. The change of stress on the upper surface of the pipe is about 20 MPa, which is much bigger than lower surface of the pipe.

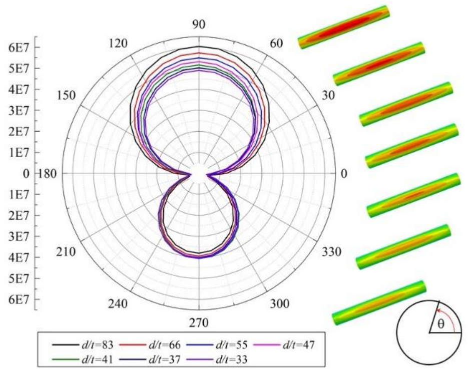
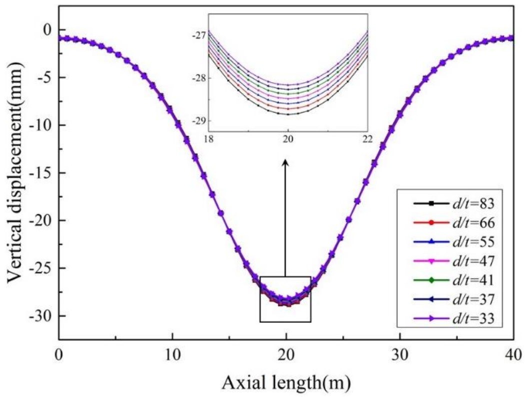
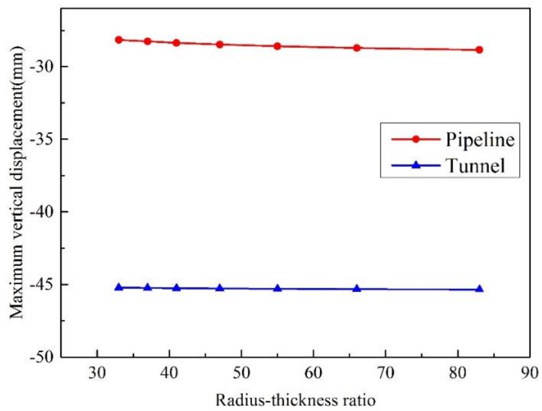


Fig.4 *Von Mises stress of pipe with different radius-thickness ratios*



(a) Vertical displacement



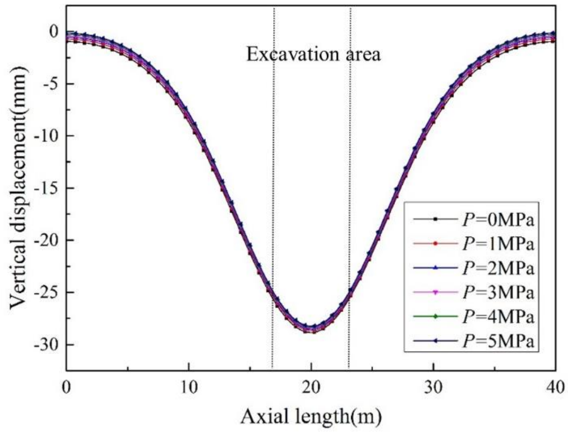
(b) Maximum vertical displacement

Fig.5 *Displacement of pipe with different radius-thickness ratios*

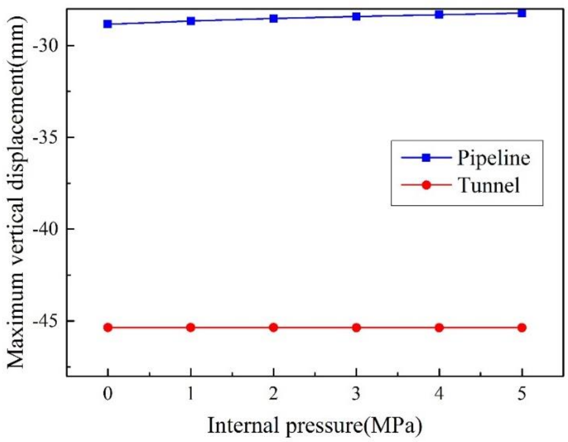
The displacement curves of pipe with different radius-thickness ratios are shown in Fig.5. In Fig.5(a), the displacement curves of pipe are basically coincident, and the curves are separated only at the maximum displacement in the middle of the pipe. The change is about 1mm. In Fig.5(b), the maximum vertical displacement of pipe increases with the increasing of radius-thickness ratio, and the change rate remains unchanged. The maximum vertical displacement of the tunnel vault which located below the pipe basically unchanged.

B. Internal Pressure

When the radius-thickness ratio is 83, the displacement curves of pipe with different internal pressures are shown in Fig.6. As shown in Fig.6(a), there is no significant difference in the displacement curves of the pipe. In Fig.6(b), the maximum vertical displacement decreases with the increasing of the internal pressure, but the displacement of tunnel vault does not change. This is because some of the earth pressure is offset by the pipe with large internal pressure, but the effect of internal pressure is very small. The change of displacement of pipe is less than 1mm, and the change rate is linear.



(a) Vertical displacement



(b) Maximum vertical displacement

Fig.6 *Displacement of pipe with different internal pressures*

C. Buried Depth

When the radius-thickness ratio is 83, the von Mises stress in the cross section of no-pressure pipe is shown in Fig.7. With the increasing of the buried depth of pipe, the stress of upper surface and lower surface of pipe increases. And the stress area extends along the pipe's axial direction. The change of stress on the upper surface of the pipe is about 38MPa, but it is less than the stress of lower surface of the pipe, which is about 65MPa. Therefore, the shallow buried pipe is more secure under the tunnel excavation.

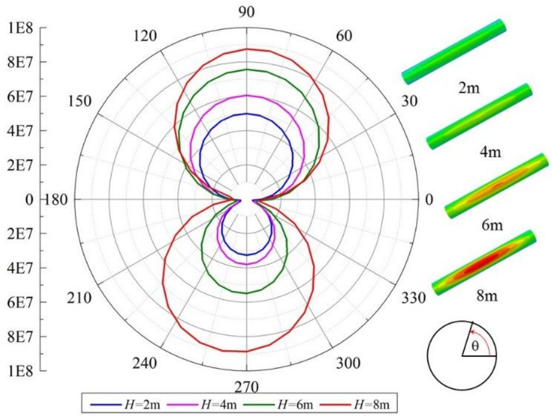
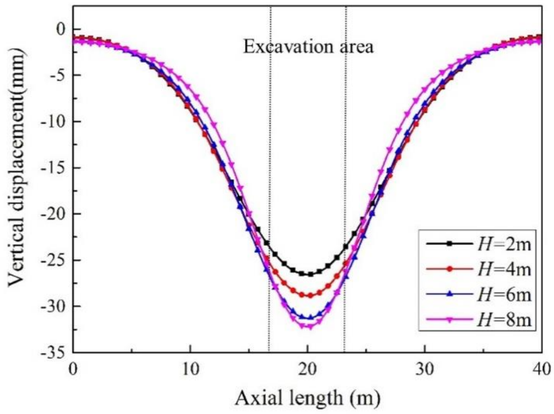
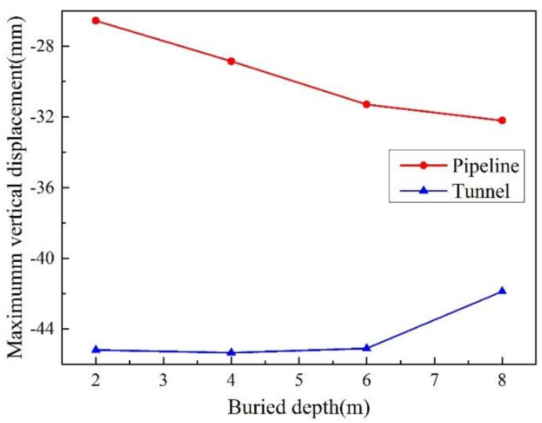


Fig.7 *Von Mises stress of pipe with different buried depths*

The displacement curves of pipe with different buried depths are shown in Fig.8. In Fig.8(a), with the increasing of the buried depth of pipe, the vertical displacement of pipe increases. But when the buried depth is 8m, the displacement width is significantly decreased, because the distance between the soil and the tunnel is closer, the displacement width is smaller. In Fig.8(b), with the increasing of the buried depth, the maximum vertical displacement of pipe increases, but the maximum vertical displacement of tunnel vault decreases. When the buried depth is 8m, the maximum vertical displacement of tunnel vault is 41.9mm, this is because the pipe can withstand more soil pressure which caused by excavation, so the soil pressure on the tunnel vault is small, and the vertical displacement is small.



(a) Vertical displacement



(b) Maximum vertical displacement

Fig.8 *Displacement of pipe with different buried depths*

V. CONCLUSIONS

Numerical analysis of buried pipe under tunnel excavation were investigated which led to the following conclusions:

(1) The high-stress region is concentrated in the middle of the pipe, and the maximum von Mises stress occurs on the upper surface of the pipe after excavation. During the excavation process, as the excavation length increases, the stress in the pipe increases, the horizontal displacement of the pipe decreases, and the vertical displacement of the pipeline increases.

(2) The maximum von Mises stress and deformation of the buried pipe increase with the increasing of the radius-thickness ratio and buried depth, while decreases with the increasing of the internal pressure.

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