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Research Article

Theoretical Solutions for Forecasting the Response of the Existing Pipeline Induce by Tunneling underneath

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In order to accurately and efficiently assess the impact of tunnel excavation on overlying existing pipeline, an analytical method is proposed to solve this problem. First, the vertical free displacement of the surrounding soil due to tunnel excavation can be derived by the Loganathan formula. Next, the overlying existing pipeline can be treated as a Timoshenko beam resting on the Vlasov foundation model, and the influence of the surrounding soil on the both sides of the existing pipeline is taken into consideration. Finally, an analytical solution for the longitudinal deformation of the existing pipeline can be obtained by using the integral method. Case analysis results demonstrate that the calculated results of this method closely in line with measured data. Compared to the degenerate analytical solution given by this method, the result from this method is more consistent with the measured data. Further parameter studies show that the volume loss rate, diameter of new tunnel, skew angle, and vertical distance between tunnel and pipeline are significant factors affecting the existing pipeline response due to tunneling underlying.

1. Introduction

In recent years, with the flourishing development of urban rail transit, the pressure on urban surface transportation has been significantly alleviated, making the development of urban subways a consensus among urban planners [1–9]. However, in the process of underground space development, existing subway lines and pipeline are inevitably threatened by nearby excavations, which can affect their safety and comfort, potentially leading to issues like tunnel or pipeline lining cracking, water seepage, and even structural damage. In many cases, shield tunnels crossing adjacent existing pipelines can pose challenges to ensuring the stability and safety of nearby pipelines, making it a hot topic in the field of geotechnical engineering. This issue has garnered increasing interest from scholars.

Compared to the labor-intensive and time-consuming methods of finite element analysis [10–13] and model testing [14–16], analytical methods [17–28] can be served as a fast and lower cost means to estimate the underlying excavation-triggered pipeline deformation. Especially those based on the two-stage approach, offer a quicker and more accurate means of assessing the impact of tunnel excavations on existing tunnels or pipelines. These analytical methods have two stages: the first stage relies on classical formulas, often based on the work of Loganathan and others, to estimate the influence of tunnel excavations on surrounding soil. The second stage involves applying soil displacements in reverse to the existing tunnel structure, based on various beam and foundation models, to obtain the stress and deformation responses of the existing tunnel due to nearby tunnel excavations [24–30].

However, Winkler foundation models [31], only consider the elastic behavior of the soil, and their calculated data often deviates significantly from field monitoring data. To address this limitation, scholars have proposed dual-parameter Pasternak [32] and Vlasov and Leontev [33] and three-parameters Kerr foundation models [4, 5, 34–36] that consider soil shear deformations. However, the control equation of tunnel responses is complicated by the multiplicity of parameters in the Kerr foundation model. Its inherent complexity in

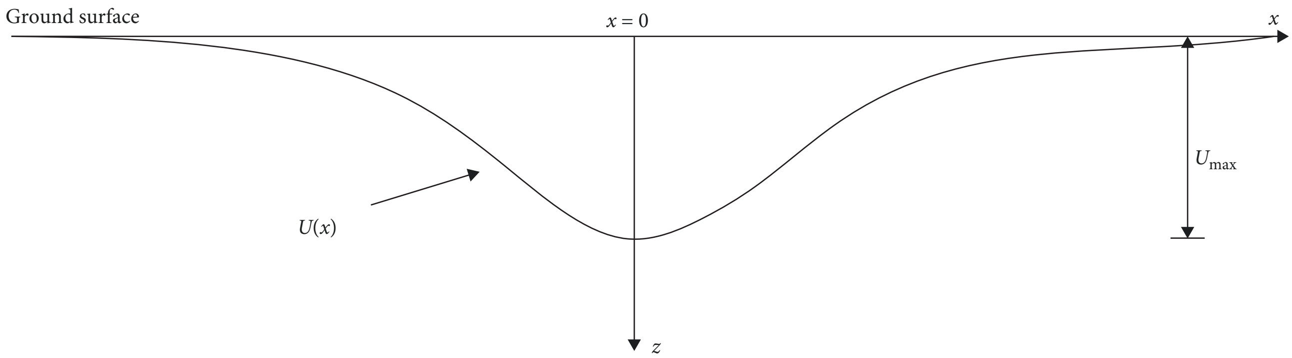


FIGURE 1: The free displacement induced by tunneling underneath.

parameter determination and it cannot be applied in actually engineering projects. At the same time, the Pasternak foundation model does not always offer an accurate calculation of subgrade parameters. It may often overlook disturbances induced by tunneling in the surrounding soil. Determining the shear modulus from the Pasternak and Kerr foundation models in real-world scenarios remains challenging. Consequently, many researchers have sought alternative means to equivalently substitute the second parameter, avoiding the difficulty of accurate determination. Instead, the Vlasov foundation model can be used to overcome many of these limitations [37]. Meanwhile, the metro tunnel and pipeline in soft areas are usually constructed by shield tunneling, and the tunnel is lined with prefabricated concrete segment linked by bolted joint. The Euler–Bernoulli beam, without taking the shear behavior into consideration, is not appropriate to estimate the mechanical of tunnel and pipeline response. To overcome this shortcoming, Timoshenko [38] beam was proposed and applied in an amount of investigations [28, 29].

In this paper, a Vlasov foundation model is selected with explicit parameters, which is less commonly used in practical engineering. Additionally, the lateral soil effects on pipeline structural deformation are taken into consideration, which always been overlooked. Then, the existing pipeline is treated as a Timoshenko beam placed on the Vlasov foundation model, accounting for the influence of lateral soil forces on the pipeline structure. By utilizing an integral method, an analytical solution is derived for the stress and deformation of the existing pipeline caused by tunnel excavations and a field verification is taking into discussion. Finally, an exhaustive parameter analysis, including volume loss rate, diameter of new tunnel, skew angle, and vertical distance between tunnel and pipeline, is conducted.

2. Analysis Method

To evaluate the interaction between tunnel excavation underneath, soil, and pipeline, the two-stage method is introduced here in this section. Some basic assumptions are as follows:

(1) The soil movement along the existing pipeline can be computed by using the Loganathan and Poulos [39] equation.

(2) The existing pipeline is assumed to be an infinitely long Timoshenko beam resting on an elastic foundation model.

(3) The elastic foundation model employed is the Vlasov foundation model.

(4) Deformations of the pipeline and soil are assumed to be mutually consistent, and cases involving the separation of the pipeline from the soil are not considered.

(5) The spatial variability of soil properties and the effect of water pressure in this study are not taking into consideration.

2.1. Adjacent Tunnel Excavation-Triggered Unloading Stress. The free displacement of the surrounding soil due to tunnel excavation (as shown in Figure 1), as suggested by Loganathan and Poulos [39], is given by the following equation:

$$U(x) = \varepsilon R^2 \cdot e^{-\frac{1.38x^2}{(H+R)^2} - \frac{0.69z^2}{H^2}} \left[-\frac{z-H}{x^2+(z-H)^2} + (3-4\nu)\frac{z+H}{x^2+(z+H)^2} - \frac{2z(x^2-(z+H)^2)}{(x^2+(z+H)^2)^2} \right], \tag{1}$$

where R represents the excavation radius, H is the depth of the tunnel axis, x is the horizontal distance of the centerline between the new tunnel and existing pipeline, z is the vertical distance from the ground surface, ε is the equivalent ground loss ratio, and υ is the Poisson's ratio of the soil. Noted that when the new tunnel and existing pipeline have a nonzero inclination angle θ_0 in the horizontal plane, Equation (1) is replaced as follows:

$$U(x) = \varepsilon R^2 \cdot e^{-\frac{1.38(x\sin\theta_0)^2}{(H+R)^2} - \frac{0.69z^2}{H^2}} \left[-\frac{z-H}{(x\sin\theta_0)^2+(z-H)^2} + (3-4\nu)\frac{z+H}{(x\sin\theta_0)^2+(z+H)^2} - \frac{2z((x\sin\theta_0)^2-(z+H)^2)}{((x\sin\theta_0)^2+(z+H)^2)^2} \right]. \tag{2}$$

Consequently, the additional stress at the pipeline axis due to tunnel excavation is given by the following equation:

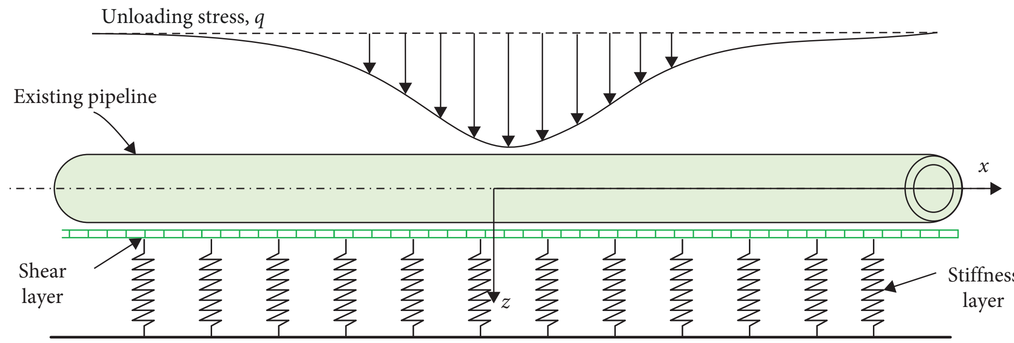


Figure 2: Vlasov foundation model.

$$q(x) = kU(x) - 2t\frac{\mathrm{d}^2U(x)}{\mathrm{d}x^2}. \quad (3)$$

Merging Equations (1)–(3), $q(x)$ can be easily solved.

2.2. Pipeline–Soil Interaction. According to the Valsov model (Figure 2), the foundation reaction beneath the pipeline $p(x)$ can be expressed as follows:

$$p(x) = kw(x) - 2t\frac{\mathrm{d}^2w(x)}{\mathrm{d}x^2}, \quad (4)$$

where $w(x)$ denotes the pipeline deformation, k is the spring stiffness of the soil, and $2t$ is the shear stiffness of the foundation layer. The values of k and $2t$ can be determined as follows:

$$\begin{cases} k = \dfrac{E_s(1+\nu)}{(1-2\nu)(1+\nu)}\displaystyle\int_0^{H_s}\left(\frac{\mathrm{d}h}{\mathrm{d}y}\right)^2\mathrm{d}y \\ 2t = \dfrac{E_s}{2(1+\nu)}\displaystyle\int_0^{H_s}h^2\mathrm{d}y \end{cases}, \quad (5)$$

where E_s is the elastic modulus of the soil, υ is the Poisson's ratio of the soil, $h = h(y)$ is a function varying in the y-direction, and H_s is taken as 2.5 times the diameter of the pipeline.

Most previous research has ignored the lateral soil effects on pipeline–soil interaction. Therefore, the paper introduces the lateral soil effects besides the pipeline. The equilibrium of the pipeline element under these lateral forces is analyzed, as shown in Figure 3. According to existing literature [40], the lateral forces from the soil on both sides of the pipeline satisfy the following equation:

$$T_1 = T_2 = \sqrt{2tk}w(x). \quad (6)$$

Based on Timoshenko's [38] beam, the equilibrium equation is as follows:

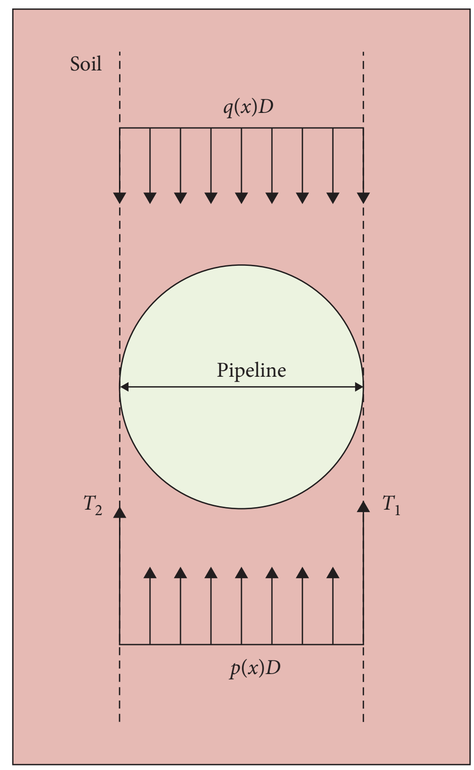


Figure 3: Force analysis of pipeline element.

$$\begin{cases} Q = (\kappa GA)\left[\dfrac{\mathrm{d}w(x)}{\mathrm{d}x} - \theta\right] \\ M = -EI\dfrac{\mathrm{d}\theta}{\mathrm{d}x} \end{cases}, \quad (7)$$

where κ is equivalent cross-section coefficient, pipeline is circular cross-section, which can be taken as 0.5, G is the tunnel shear modulus, A is the annular section area of the tunnel, and EI is the stiffness of the segmental rings.

Then, considering the vertical equilibrium of the existing pipeline:

$$\begin{cases} p(x)D\mathrm{d}x + T_1 + T_2 - q(x)D\mathrm{d}x - \mathrm{d}Q = 0 \\ \dfrac{p(x)D}{2}\mathrm{d}x^2 + Q\mathrm{d}x - \dfrac{q(x)D}{2}\mathrm{d}x^2 - \mathrm{d}M = 0 \end{cases}. \quad (8)$$

Combing Equations (4)–(8), the vertical equilibrium of the existing pipeline can be expressed as follows:

$$\frac{d^4w(x)}{dx^4} - \gamma\frac{d^2w(x)}{dx^2} + \lambda^4 w(x) = \left[\frac{(\kappa GA)q(x)}{(\kappa GA) + 2tD} - \frac{EI}{(\kappa GA) + 2tD}\frac{d^2q(x)}{dx^2}\right]\frac{D}{EI}, \tag{9}$$

where

$$\begin{cases} \gamma = \dfrac{EIkD + 2tD(\kappa GA)}{((\kappa GA) + 2tD)EI} \\ \lambda = \sqrt[4]{\dfrac{\left(kD + 2\sqrt{2tk}\right)(\kappa GA)}{((\kappa GA) + 2tD)EI}} \end{cases}. \tag{10}$$

The homogeneous equation of Equation (9) is as follows:

$$\frac{d^4w(x)}{dx^4} - \gamma\frac{d^2w(x)}{dx^2} + \lambda^4 w(x) = 0. \tag{11}$$

Then, the solution of Equation (11) can be obtained as follows:

$$w(x) = e^{\alpha x}[C_1\cos(\beta x) + C_2\sin(\beta x)] + e^{-\alpha x}[C_3\cos(\beta x) + C_4\sin(\beta x)], \tag{12}$$

where C_1, C_2, C_3, and C_4 can be expressed as follows:

$$\begin{cases} \alpha = \sqrt{\lambda^2/2 + \gamma/4} \\ \beta = \sqrt{\lambda^2/2 - \gamma/4} \end{cases}. \tag{13}$$

Considering Equation (9), which is a fourth-order differential equation, the analytical solution is obtained using an approach that involves assuming an arbitrary force P acting at the $x = 0$ point of the infinitely long existing pipeline. The boundary of the pipeline in this case is defined as follows:

$$\begin{cases} w(\pm\infty) = 0 \\ \left.\frac{dw(x)}{dx}\right|_{x=0} = 0 \\ \left.EI\frac{d^3w(x)}{dx^3}\right|_{x=0} = PD/2 \end{cases}. \tag{14}$$

Substituting Equation (14) into Equation (12) yields the analytical solution for the deformation of the infinite existing pipeline under the action of any force P at $x = 0$:

$$w(x) = \frac{PD}{4E_pI_p\alpha\beta(\alpha^2 + \beta^2)}e^{-\alpha x}(\beta\cos(\beta x) + \alpha\sin(\beta x)). \tag{15}$$

Assuming that tunnel excavation underneath causes an additional stress $q(x)$ at any point on the axis of the existing pipeline, the additional stress acting on the existing pipeline at any pipeline point can be calculated from Equation (15). This additional stress causes vertical displacement dw (x) at any point on the pipeline axis:

$$dw(x) = \frac{q(\eta)D}{4E_pI_p\alpha\beta(\alpha^2 + \beta^2)}e^{-\alpha|x-\eta|}[\beta\cos(\beta|x-\eta|) + \alpha\sin(\beta|x-\eta|)]d\eta. \tag{16}$$

Integrating Equation (16) over the range of the distribution of the additional stress on the tunnel results in the longitudinal deformation of the existing pipeline caused by tunneling underlying:

$$w(x) = \int_{-\infty}^{+\infty} dw(x). \tag{17}$$

Additionally, the analytical solutions for the flexural moments and shear forces in the existing pipeline can be derived as follows:

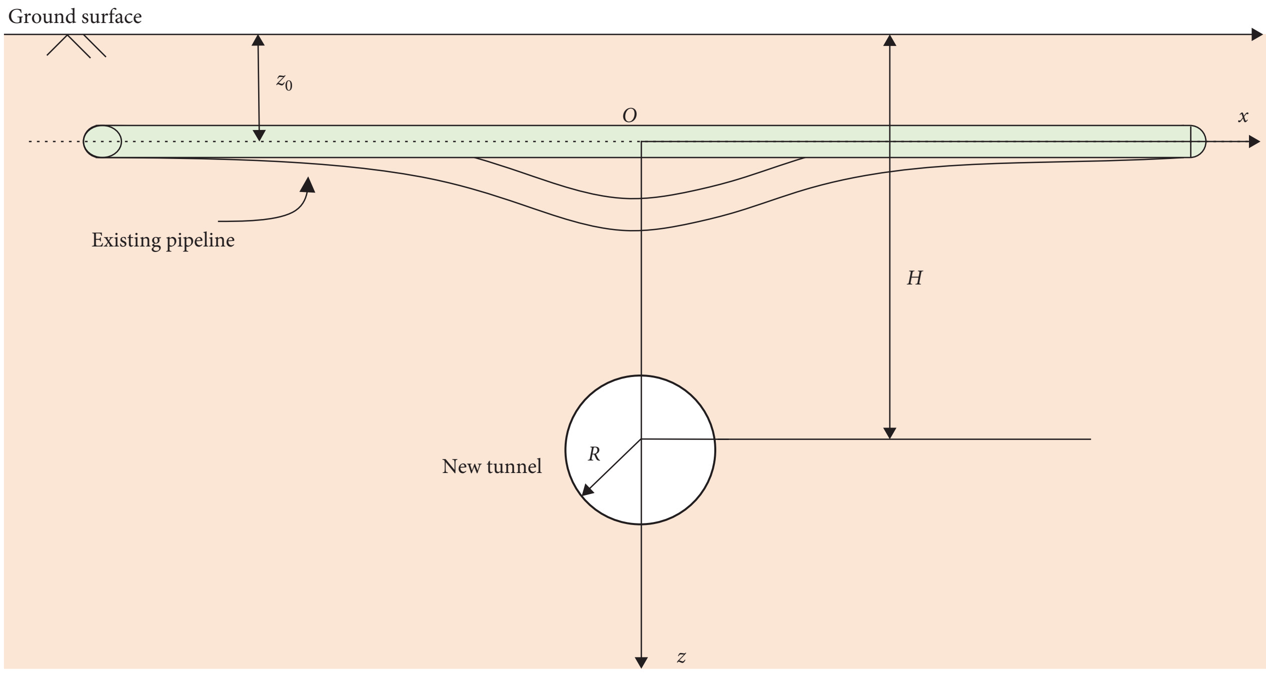
$$M = -EI\frac{d\theta}{dx}, \tag{18}$$

$$Q = (\kappa GA)\left[\frac{dw(x)}{dx} - \theta\right]. \tag{19}$$

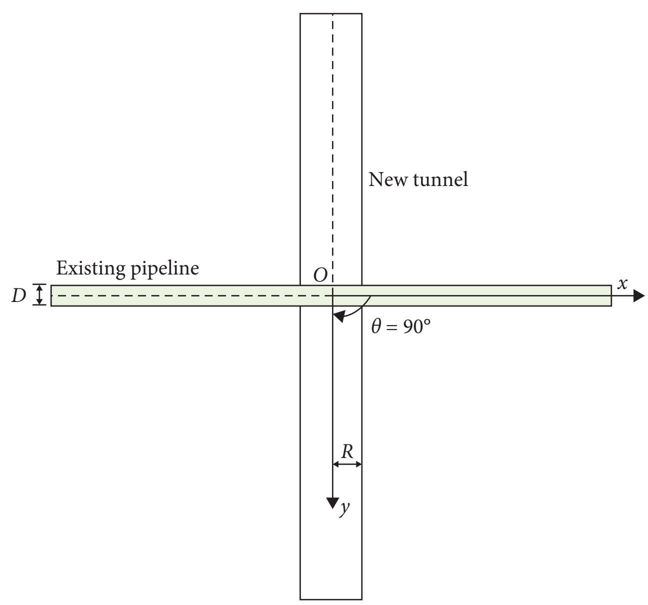
Therefore, the analytical solutions for the longitudinal deformation and internal forces of existing pipeline induced by tunneling underneath can be obtained. It is important to note that when there are no lateral soil effects on both sides ($T_1 = T_2 = 0$), the analytical results degenerate into the *T–V* model (in which the pipeline is treated as Timoshenko beam resting on Vlasov foundation model), and when the lateral soil effects and soil shear stiffness are not considered, the results degenerate into the *T–W* model (in which the pipeline is treated as Timoshenko beam resting on Winkler foundation model).

3. Verification

To validate the correctness of the methodology presented in this paper, the author collected measured data from Shenzhen metro and have a discussion between the results given by this study and its degenerate solutions. Therefore, a typical case, where the horizontal location between tunnel and pipeline is almost perpendicularity, is introduced here to verify the rationality of this study, as illustrated in Figure 4. The engineering parameters are as follows: the diameter and axis depth of existing pipeline are $D = 3.0$ and $z_0 = 8.7$ m, respectively. The diameter and axis depth of new tunnel are $2R = 6.0$ and $H = 14.4$ m, respectively. According to existing literature [41], the soil's elastic modulus and Poisson's ratio can be regarded as $E_s = 8.2$ MPa and $\nu = 0.3$, the compression stiffness and shear modulus of this model can be calculated as 2,873 and 14,741 kN/m^3, respectively. The excavation of the tunnel resulted in an average volume loss rate $\varepsilon = 0.84\%$,



(a)



(b)

Figure 4: Relative location between new tunnel and existing pipeline: (a) vertical location between tunnel and pipeline and (b) horizontal location between tunnel and pipeline.

and the existing pipeline's flexural stiffness and shearing stiffness can be treated as 5.87×10^7 kN·m^2 and 1.16×10^7 kN/m [42, 43].

In order to obtain a more accurate calculation result and eliminate influence of the size of length of existing pipeline, the calculated deformation of the pipeline is within 200 m from both sides of the neutral axis of the pipeline, and the calculation results of interception are within the range of 100 m in the middle. Therefore, the results obtained by using the proposed method are compared with engineering monitoring data in Figure 5, where the monitoring data are given by Zhang and Zhang [41]. Figure 5 indicates that the results obtained using our method and its degenerate solution are consistent with the trend of the measured data. The significant deformation of the existing pipeline is concentrated within a 30-m range on either side of the pipeline's central axis, while the measured data indicates deformations greater than 2 mm distributed within a 20-m range on either side of the neutral axis of the pipeline. The data obtained from this paper and its degenerate solution are in better agreement with the distribution of the measured data. By using our method, the maximum displacement of the pipeline is calculated to be 7.6 mm,

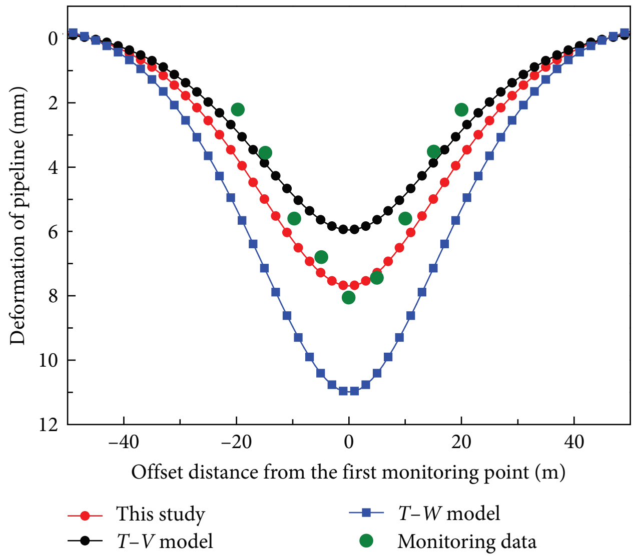


Figure 5: Prediction comparison between the proposed method and actual project.

Table 1: Related parameters of the project.

R (m)	H (m)	z (m)	ε (%)	E_s (MPa)	υ	D (m)	EI (N·m^2)
3.0	18.0	10.0	0.5	10	0.3	3.0	5.87×10^{10}

while the degenerate *T*–*V* model yields a smaller displacement with a peak of 5.9 mm. The *T*–*W* model produces significantly larger results with a maximum pipeline displacement of 10.9 mm. This phenomenon is because the *T*–*V* model neglects the influence of lateral soil on the pipeline–soil interaction, leading to an underestimation of the tunnel's impact on the existing pipeline. On the other hand, the Winkler foundation model does not consider the effect of soil shearing on soil–structure interaction, resulting in a significant deviation from the measured values. Compared to the degenerate solution of our method, the maximum pipeline deformation from the measured data [41] is 8.0 mm, indicating that the results obtained in this paper are more in line with the monitoring data.

4. Parameter Analysis

Herein, a series of parameter studies are conducted to examine influencing factors on the existing pipeline's response to tunneling underneath, including the volume loss rate, diameter of new tunnel, the skew angle, and vertical distance between tunnel and pipeline. The typical engineering parameters are assumed as in Table 1.

4.1. Volume Loss Rate. Figure 6 shows the calculated results of the existing pipeline response triggered by tunneling underneath by using our method with different volume loss rate. The volume loss rate can be regarded as 0.5%, 1.0%, 1.5%, 2.0%, and 2.5%.

As shown in Figure 6, the longitudinal displacement and bending moment of the existing pipeline are symmetrically distributed along the central axis of the pipeline, and the maximum longitudinal displacement and maximum bending moment values occur at the pipeline's central axis. Moreover, both the longitudinal displacement and bending moment of the existing pipeline linearly increase with an increase in volume loss rate. This is because the additional stress on the pipeline linearly increases with the volume loss rate, leading to linear variations in the longitudinal displacement at each position of the existing pipeline. Therefore, in practical engineering, it is advisable to minimize the volume loss rate caused by shield tunneling to reduce the adverse effects on nearby structures.

4.2. Diameter of New Tunnel. Figure 7 illustrates the existing pipeline's response to a new tunnel excavation underlying by using our method with different diameters of new tunnel. Here, the diameter of new tunnel can be assumed as 3.0, 3.5, 4.0, 4.5, and 5.0 m.

Figure 7 demonstrates that the longitudinal displacement and bending moment of the existing pipeline are symmetrically distributed along the central axis of the pipeline. Meanwhile, as the diameter of new tunnel increases from 3.0 to 5.0 m, the maximum longitudinal displacement of the existing pipeline gradually decreases from 4.4 to 12.7 mm, with an increase rate of up to 1.9 times, and the growth rate tends to increase gradually. Moreover, with an increase in the diameter of new tunnel, the maximum bending moment of the pipeline increases from 1.4 to 3.9 MN·m^2, with an increase rate of ~1.8 times. This indicates that increasing the diameter of new tunnel has a significant impact on the overlying existing pipeline, and the stress and strain peaks on the pipeline increase rapidly. Therefore, in practical engineering, efforts should be made to minimize the diameter of new tunnel to

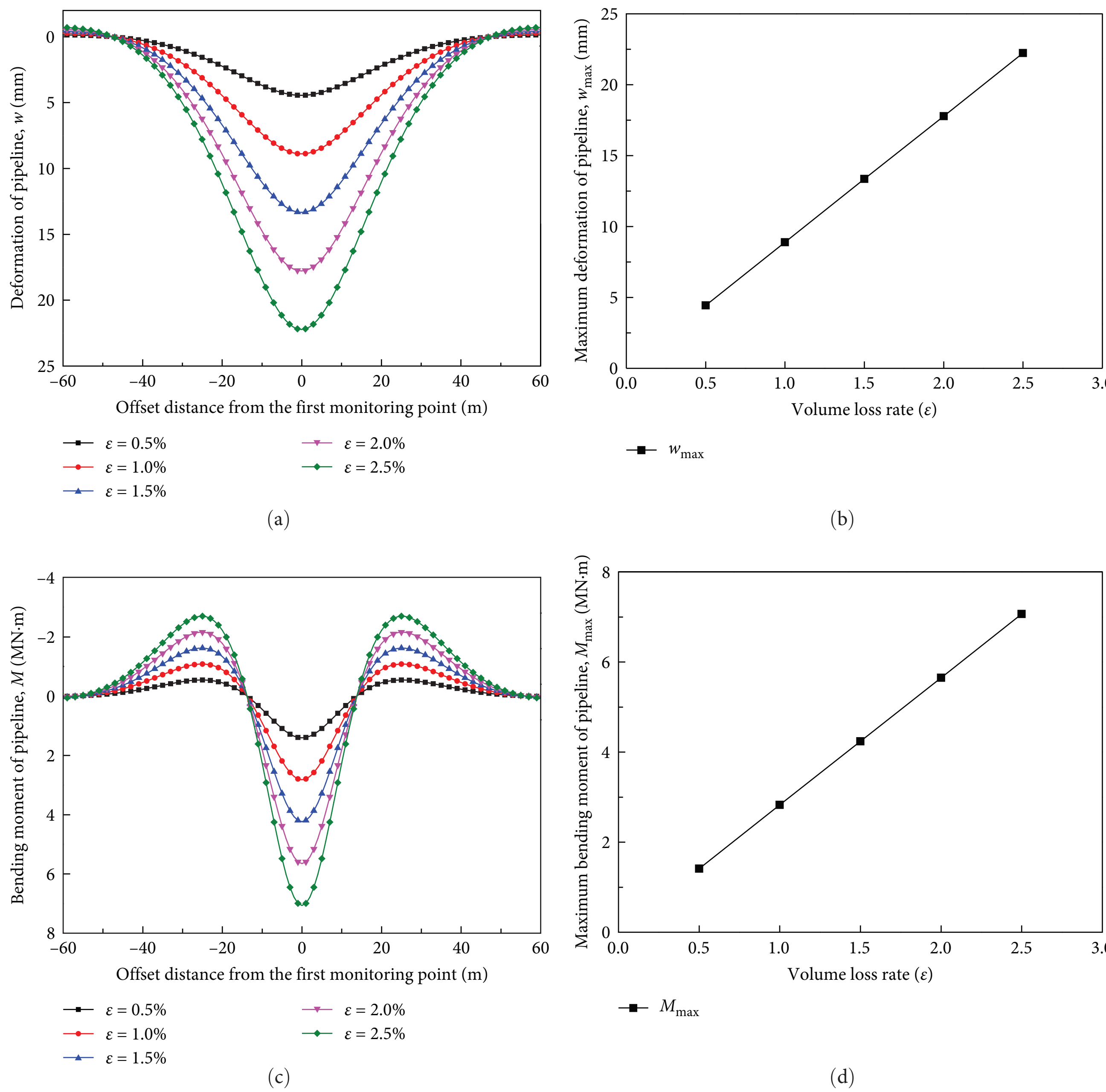


FIGURE 6: The response of pipeline with different volume loss rate: (a) pipeline deformation, (b) pipeline's maximum deformation, (c) pipeline's bending moment, and (d) pipeline's maximum bending moment.

reduce the impact of ground stress changes on the existing pipeline.

4.3. Skew Angle between Tunnel and Pipeline. Figure 8 shows the calculated results of deformations and internal forces given by the proposed method with different angles between tunnel and pipeline, which can be taken as $\theta = 15°$, $30°$, $45°$, $60°$, and $75°$.

Figure 8 indicates that the deformation and bending moment of the existing pipeline are symmetrically distributed along the central axis of the pipeline. Meanwhile, as the angle between the new tunnel and the existing pipeline increases from 15° to 75°, the maximum longitudinal displacement of the existing pipeline gradually decreases from 8.1 to 4.6 mm, a decrease of ~43%, and the rate of decrease becomes progressively smoother. However, it also shows that with an increase in the angle between the new tunnel and the existing pipeline, the maximum bending moment of the pipeline increases from 0.52 to 1.41 MN·m^2, an increase of ~1.7 times, and the growth rate becomes smoother as well. This is because, as the relative position of the new tunnel and the existing pipeline changes from a more "coincidental" state to a "vertical" state, the impact of ground settlement caused by the new tunnel on the existing pipeline axis decreases. Meanwhile, the additional stress on the existing pipeline changes from "uniform load" to "concentrated

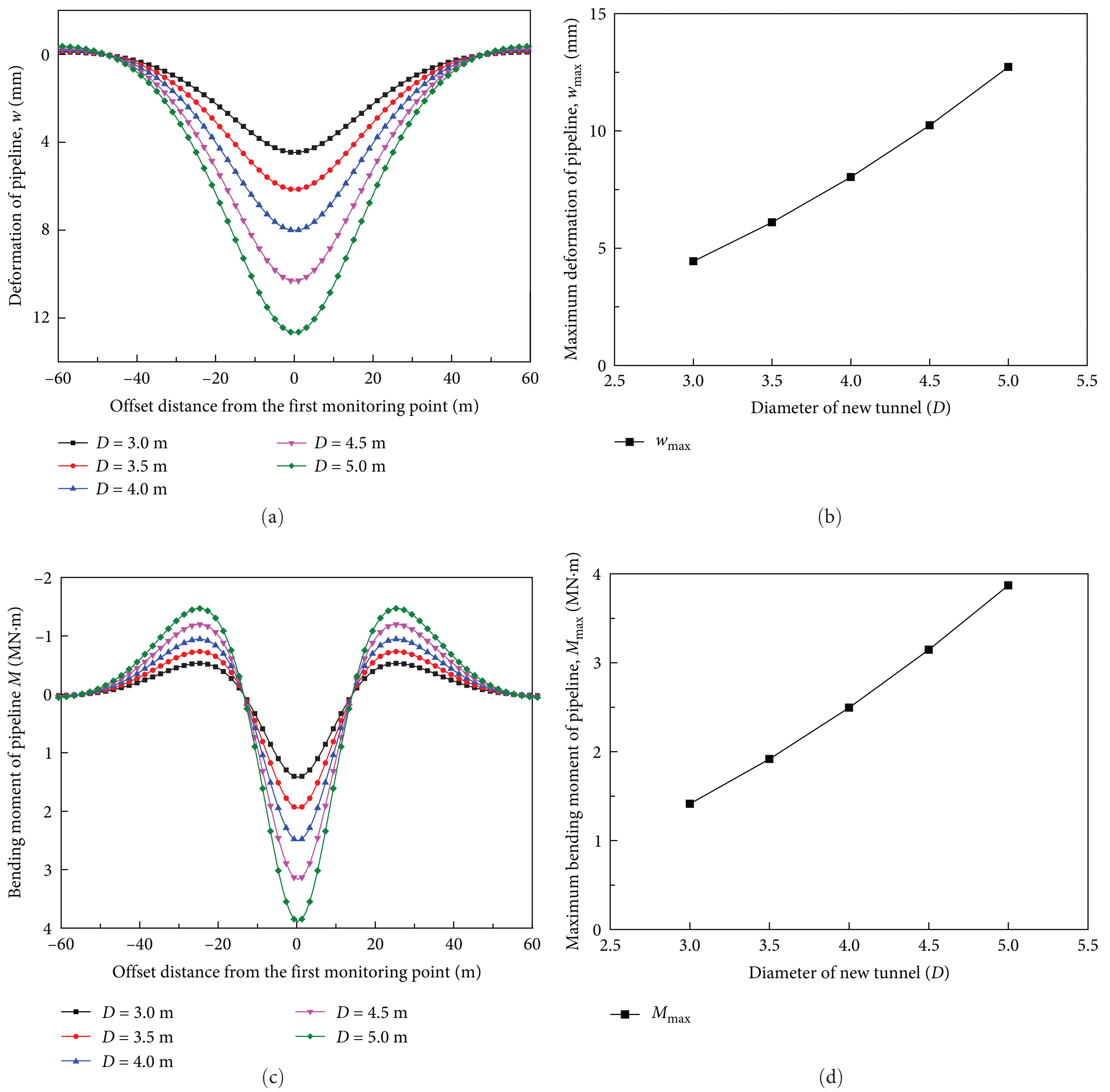


FIGURE 7: The response of pipeline with different diameter of new tunnel: (a) pipeline deformation, (b) pipeline's maximum deformation, (c) pipeline's bending moment, and (d) pipeline's maximum bending moment.

load" mode, resulting in an increase in the maximum additional stress on the pipeline. This indicates that the angle between the new tunnel and the existing pipeline is a sensitive parameter affecting the deformation and internal forces of the overlying existing pipeline. In practical engineering, attention should be paid to the influence of changes in the skew angle between the new tunnel and the existing pipeline on the existing pipeline response.

4.4. Vertical Distance between Tunnel and Pipeline. Figure 9 shows the calculated results of the existing pipeline response triggered by tunneling underneath by using our method with different vertical distances between tunnel and pipeline. The relationship $d = nD$ is adhered to, where D represents the diameter of the pipeline. For this study, values of n such as 0.5, 1.0, 1.5, 2.0, and 2.5 are implemented.

As shown in Figure 9, the longitudinal displacement and bending moment of the existing pipeline are symmetrically distributed along the central axis of the pipeline, and the maximum longitudinal displacement and maximum bending moment values occur at the pipeline's central axis. Meanwhile, as the vertical distance between tunnel and pipeline increases from 0.5D meters to 2.5D, the maximum longitudinal displacement of the existing pipeline gradually decreases from 6.0 to 2.8 mm, and the rate of decrease becomes progressively smoother. Moreover, with an increase

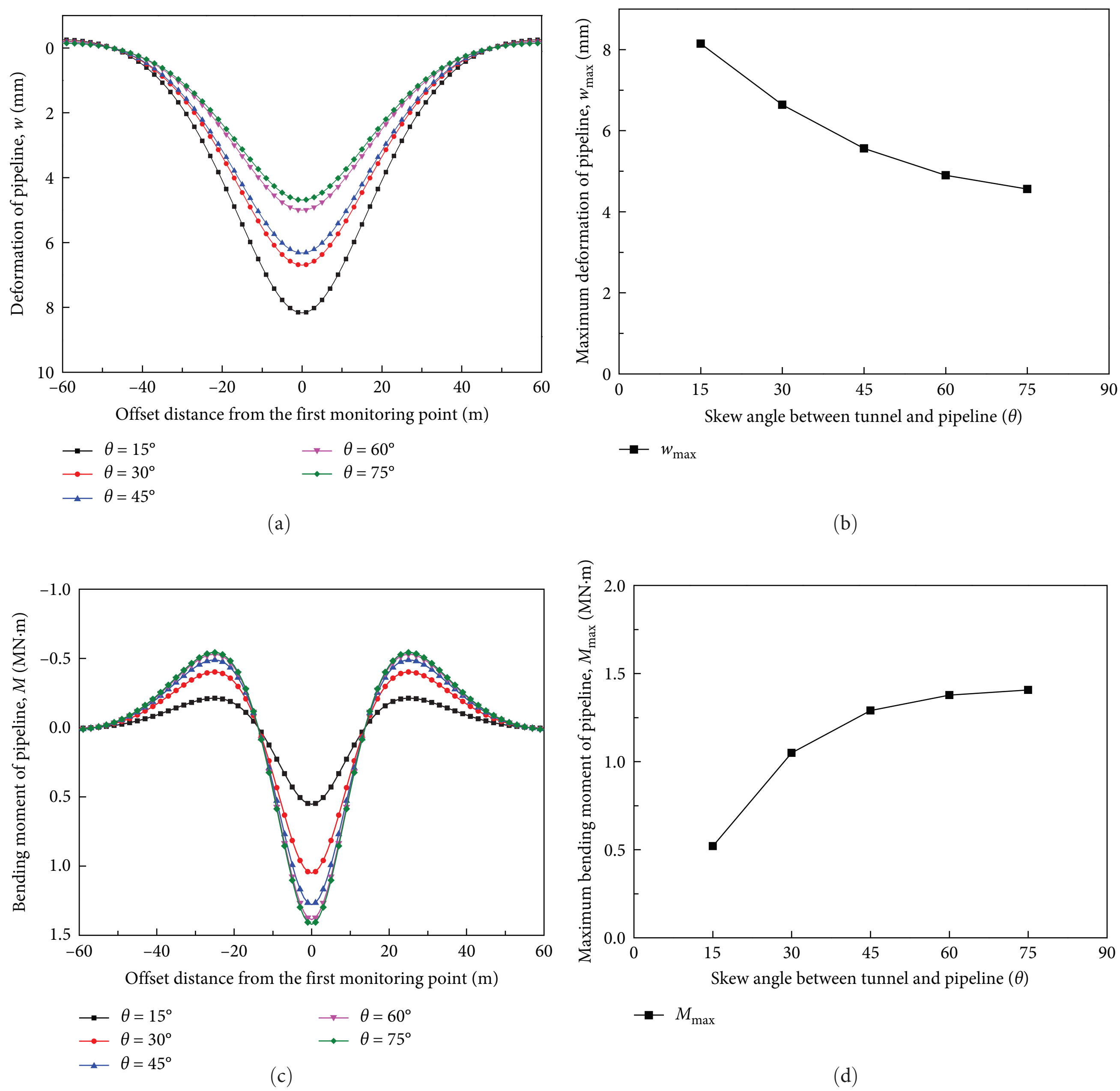


Figure 8: The response of pipeline with different skew angle between tunnel and pipeline: (a) pipeline deformation, (b) pipeline's maximum deformation, (c) pipeline's bending moment, and (d) pipeline's maximum bending moment.

in the vertical distance between tunnel and pipeline, the maximum bending moment of the pipeline decreases from 1.6 to 0.87 MN·m^2, with an decrease rate of ~46%. This indicates that increasing the vertical distance between tunnel and pipeline has a significant impact on the overlying existing pipeline, and it is useful for enlarging the vertical distance between tunnel and pipeline to ensure the existing pipeline safety.

5. Conclusions

Based on a two-stage approach, this paper presents a theoretical method for predicting the deformation response of overlying existing pipelines when shield tunnels are constructed beneath them. The conclusions obtained are as follows:

(1) The pipeline is simplified as an infinitely long Timoshenko beam placed on Vlasov foundation model, and the influence of lateral soil on both sides of the pipeline is introduced. The integral method is used to analyze the stress and deformation response of the pipeline.

(2) Compared to measured data from a specific project (Shenzhen Project), the results obtained by using our method are in good agreement with the measured

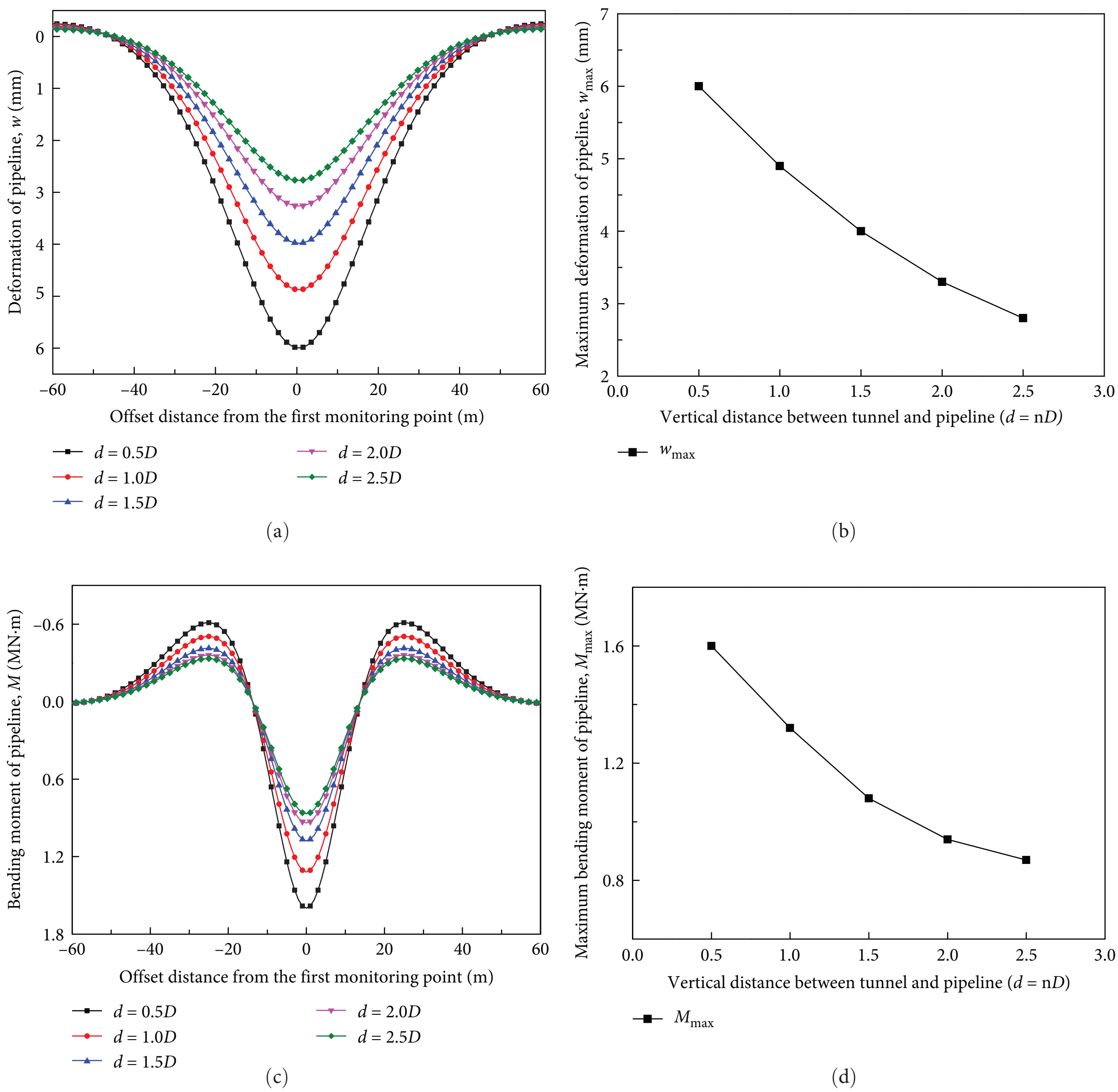


FIGURE 9: The response of pipeline with different vertical distance between tunnel and pipeline: (a) pipeline deformation, (b) pipeline's maximum deformation, (c) pipeline's bending moment, and (d) pipeline's maximum bending moment.

data. Compared with the degenerate solutions (*T–V* and *T–W* methods), the suggested method is more in line with monitoring data.

(3) Increasing the ground loss rate effectively increases the displacement and internal forces of the existing pipeline, but the displacement and internal forces of the existing pipeline decrease with the increase the vertical distance between tunnel and pipeline. The displacement and bending moment values of the pipeline gradually increase with an increase in the diameters of the tunnel passing beneath. Increasing the skew angle between the new tunnel and the existing pipeline leads to a reduction in the pipeline's displacement but an increase in its internal forces, with the rate of change becoming smoother. Therefore, the skew angle between tunnel and the existing pipeline is a sensitive parameter that should be carefully considered in practical engineering to assess the deformation and stress response of the existing pipeline.

(4) The suggested analytical solution is appropriate for beams that are supported by linear foundation soils. The absence of consideration for the nonlinearity of pipeline–ground interaction is evident in this context. Future investigations should pay closer attention to these deficiencies.

Data Availability

All data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' Contributions

Yao Rong contributed to methodology, formal analysis, writing–original draft, and software. Guohui Feng contributed to conceptualization, writing–review and editing, and funding acquisition. Yang Sun contributed to formal analysis and writing–review and editing. Yujie Li contributed to resources and data curation. Guanyu Chen contributed to writing–review and editing and visualization. Haibin Ding contributed to writing–review and editing. Changjie Xu contributed to supervision and funding acquisition.

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