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Research Article

Numerical Analysis of Pipelines Settlement Induced by Tunneling

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Three-dimensional finite element method analysis on the tunnel-soil-underground pipeline was carried out based on the ABAQUS program. PSI element was applied to simulate the interaction between the pipelines and soil. Parameters such as an elastic modulus of soil, stress release rate, at-rest lateral pressure coefficients, an elastic modulus of pipelines, and buried depths of tunnels were analyzed. The effects of tunnel excavation on the displacement of existing pipelines were investigated, and the settlement relationships were obtained. The relationship between each parameter and surface settlement was determined by the grey relational analysis method to analyze each parameter's sensitivity to the settlement of the pipeline, which can provide a reference for emphasis and methods of shield tunneling support. Finally, a formula of the settlement relationship between the maximum surface settlement and pipelines deformation was proposed for different pipe-soil relative stiffness. The formula was applied in the practical case. Compared with the field monitoring results and FEM computer results, it has been found that the proposed normalized formula is consistent with the measured results and numerical simulation of the pipeline settlement.

1. Introduction

The underground space in urban areas is frequently congested with utilities, including pipelines and conduits, which are affected by underground construction. However, with the growth of the cities, the necessity to harness the underground space, the tunneling technology has development taking into consideration the economic and technical efficiency. It is for that reason the construction of the tunnels is becoming more popular [1, 2].

It is still inevitable to disturb the surrounding soil and affect the deformation of the soil during the construction process. Nevertheless, many constitutive models are available nowadays to predict soil-structure interaction problems. It is sometimes not very easy for engineers to select a suitable soil model to carry out their design analyses regarding complexity versus accuracy [3]. Pipelines would be destroyed when the additional stress or deformation induced by shield tunneling exceeds its bearing capacity. Therefore, it is essential to analyze the deformation of pipelines during the excavation process correctly.

The effect of tunneling on existing pipelines is a problem that practicing engineers may need to face when designing new tunnels [4]. The problem of soil-pipe-tunnel interaction is relatively complex, as it involves features of the three systems. Tunneling-induced ground movements cause pipeline deformation that may disrupt the conveyance of essential services and resources (e.g., water, gas, electric power, and telecommunications) and threaten the safety and security of urban inhabitants (e.g., flooding and leakage of combustible gas from ruptured or leaking mains). The interaction between underground utility pipelines and the surrounding soil has attracted growing research attention recently; there has been substantial work performed on the impact of tunneling construction on the adjacent underground pipelines [1–3]. Due to the unavailability of analytical methods, three-dimensional numerical modeling was adopted to evaluate the influence of the pipe jacking

construction on the adjacent parallel underground and to simulate the dynamic response of pipeline during tunnel construction, by using the three-dimensional finite element method [5]. The centrifugal model experiment, numerical simulation analysis, and field measurement data were compared and analyzed to verify the reliability of numerical analysis results. Moreover, the main factors influencing the displacement of an underground pipeline and the displacement model were analyzed [6].

Through the application of ABAQUS program, a three-dimensional finite element model of the tunnel-soil-underground pipeline was developed in this study to research the laws governing pipeline settlement under different influencing factors and the sensitivity of different influencing factor to pipeline settlement. The results of this research gave a relationship graph of the pipeline settlement S_p and the maximum sedimentation S_{max} under different pipe stiffness. Numerical simulation analysis and the measured data of field test were compared to verify the rationality of the normalized model.

In recent decades, there are many types of research have been carried out to study the tunneling-pipeline interaction. Most of this work is based on local ground conditions, local tunneling techniques, and commonly used pipelines. The purpose of the paper is to supply a practical tool for civil engineers so that they can evaluate the behaviors of pipelines induced by tunneling. Based on our work described in this paper, engineers would be able to predict the settlement of the pipeline with the fundamental parameters of soil, tunneling, and pipes. This paper does not focus on theoretical computer methods but instead, on practical application. Engineers would be able to predict the settlement of the pipeline with the fundamental parameters of soil, tunneling, and pipes. One of the challenging tasks engineers need to confront when dealing with the construction of new tunnels in urban areas is the evaluation of the disturbance to existing structures. Nomograms for relatively simple structures, such as buried pipelines [7, 8] or beam, like structures can be used for a first estimation of the effects of tunneling [9].

2. Three-Dimensional Finite Element Method Analysis of Shield Crossing Underground Pipeline

The tunnel excavation generates soil settlement around the pipe, deforming it. Hence, the pipe suffers additional bending moment. The magnitude of pipe deformation and the changes in bending moment depend on the distribution of soil settlement due to tunneling at the pipeline level and the relative stiffness between the pipe and the surrounding soil [10]. Therefore, one of the tasks facing engineers in the 21st century is the operation and maintenance of aging infrastructure such as pipelines.

The estimation of the maximum bending moment for continuous or rigidly jointed pipelines affected by tunnel-induced ground movement, it is essential regarding the pipeline settlement. The estimation can be made based on the knowledge of tunnel and pipeline geometries, the stiffness of soil and pipeline, and tunnel-induced ground deformation at the pipeline level [11]. As can be deduced from case studies on small diameter pipelines affected by nearby tunneling [12, 13], it is evident that the problem of soil-pipeline-tunnel interaction is relatively complex.

2.1. Basic Assumptions. In this study, a three-dimensional finite element model is conducted to analyze the influence of tunneling on the deformation of the pipeline by using the software package ABAQUS [6]. The use of ABAQUS, a finite element package, and selection of the appropriate model to simulate soil elastoplastic behavior, has confirmed the importance, significance, and sensitivity of the soil material properties on the numerical simulation accuracy when compared with experimental data [14, 15]. Having as a consideration that the soil is elastoplastic, the analysis validated the output finite element models using a Mohr–Coulomb Plasticity model and the stratification of soil and considered the impact of the segment joint, and the staggered joint on the overall stiffness of the lining is not considered. Moreover, the deformation and stress produced by the weight of the soil have been completed before the excavation.

The primary purpose of the paper is to propose an effective formula, which is applicable for engineering application, which could help to estimate the settlement of pipeline used in China, the formula may be different from area to area, because of different local geology conditions. The engineers would be able to give some judgment based on the proposed formula in this paper with some fundamental parameters from soil and tunneling.

At the beginning of the calculation, different structure parameters of tunneling itself were applied; it was found that there would be a small effect for these parameters usually kept stable. There are numerous possible effects in the interaction of soil tunneling pipeline, which cannot be taken into consideration when is giving the formula. Therefore, only some effects that affect the results mostly and keep other effects unchanged were taken. Based on FEM analysis, the grey correlation method was applied in this study, obtaining rely coefficients significantly on the constitutive model which was applied.

2.2. Finite Element Method Model. According to the tunneling construction scheme, the 3D finite element model size was set to 100 m ∗ 40 m ∗ 60 m. The length of the pipeline perpendicular to the tunnel was 100 m and located at the half width of the model. When one of the parameters was changed, the other parameter values remained unchanged. The meshing is shown in Figure 1. The whole model had a total of 209098 elements and 220107 nodes. The parallel computing platform of high performance at the computing center of Hohai University was used to carry out the 3D finite element program, improving the efficiency of the calculation.

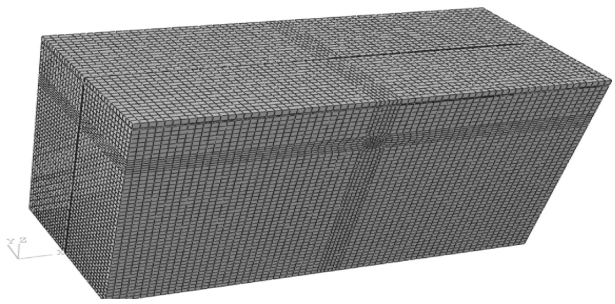

Figure 1: 3D finite element mesh for the calculation.

2.3. Calculation Analysis. The constitutive model frequently used during the numerical simulation of underground excavation work is linear-elastic perfectly plastic with a Mohr–Coulomb (MC) failure criterion [16, 17]. Several decades of scientific work took place on the influence of the constitutive model on the simulation of tunneling [18, 19]. Using sophisticated constitutive models, including nonlinearity, prefailure, and high stiffness, under minimal strain considerably improves the prediction of displacements. With the consideration that pipe usually is covered with a mixture of sandy gravel, the elastoplastic cap model [20–22] is used to simulate the material behavior of gravel, during the FEM analysis on gravel-pipe interaction [23]. The cap model applied is a more sophisticated constitutive model, which includes nonlinearity prefailure and high stiffness under minimal strain considerably, requires nine parameters of the soil, which improves the prediction of displacements. For the current research during the field testing, only five physical parameters were taken. Therefore, the constitutive soil model carried out in the present paper is the Mohr–Columb model [24].

It is necessary to use adapted constitutive models for the design of underground works; this leads to shallower and broader surface settlement troughs than those observed experimentally [16, 17, 25]. The critical exponents are demonstrated to be universal regardless of the randomness in various constitutive properties and their random noise levels; therefore, the Mohr–Coulomb model is suitable because of simplicity and accuracy [15].

The segment and grouting material were linear elastic. The C3D8R solid element was used to simulate the soil and grouting material. S4R shell element was used to simulate the segment. Pipe-soil interaction element was used to simulate the interaction between the pipelines and soil. Model boundary condition: A fixed boundary limited the vertical displacement of the bottom; horizontal displacement fixed left and right boundaries; the model only considered the role of the gravity model. To simulate the change of pipeline settlement during excavation, the length of two segments was unit excavation footage. It took six steps to excavate the tunnel; there were two kinds of construction operation per step, which was shield machine excavation and segment lining on the excavated soil layer (Figure 2).

2.3.1. The Elastic Modulus of Soil. The elastic modulus of soil is an important parameter that shows the ability of soil resistance to deformation. During the excavation of the tunneling, the various elastic moduli of the soil would lead to the different mutual stiffness between the pipe and the soil, which affected the deformation of the pipeline. In order to verify the effect of soil elastic modulus on the settlement of pipeline, the model was calculated by taking the different elastic modulus of soil.

(1) With the increase of soil elastic modulus, the capability of the soil to resist deformation gradually increased and the transverse settlement of the pipeline gradually decreased. Figure 3 shows that when the elastic modulus of soil was 5 MPa, 10 MPa, 20 MPa, 40 MPa, and 80 MPa, respectively, conversely, the maximum settlement value of pipeline in the tunnel center area was 8.86 cm, 4.65 cm, 2.40 cm, 1.22 cm, and 0.62 cm.

(2) When the soil elastic modulus was constant, the deformation of the pipeline decreased gradually with the increase of the distance from the central area of the tunnel. When the distance was more than 40 m and the soil elastic modulus was 5 MPa, the lateral settlement deformation of the pipeline was very small at 0.31 cm, which is 3.45% of the maximum sedimentation value.

2.3.2. The Stress Release Rate. Tunnel driving disturbed the surrounding soil and caused the redistribution of the stress field. The process of unloading the initial stress was called stress release [26]. Supporting structure, shield rate, shield tail void, tail void grouting, and other factors were complex and difficult to quantify. In order to simplify the model, the stress release rate was considered. In the model, the stress release rate was simulated by reducing the elastic modulus of the soil in the tunnel. The release rate was 60%, 80%, 90%, and 95%, respectively.

Figure 4 provides the settlement rules of the surface and pipeline variation with the stress release rate, where S_0 was the surface settlement above the pipeline and S_p was the pipeline settlement.

(1) With the increase of stress release rate, surface and pipeline settlement gradually increased, while the degree of deformation gradually increased. Taking the pipeline settlement as an example, when the stress release rate was 0.6, 0.8, 0.9, and 0.95, respectively, conversely, the maximum settlement value of pipeline was 2.50 cm, 4.65 cm, 7.27 cm, and 10.42 cm. When the stress release rate increased from 0.8 to 0.9, thus increasing by 0.1, the settlement value increased by 2.61 cm. When the stress release rate increased from 0.9 to 0.95, thus increasing by 0.05, the settlement value increased by 3.16 cm.

(2) With the increase of stress release rate, the settlement difference between the surface and the pipeline was getting bigger and bigger. Compared with the surface settlement, when the stress release rate was 0.6, the settlement difference was 2.4%. When the stress release rate was 0.8, the settlement difference was

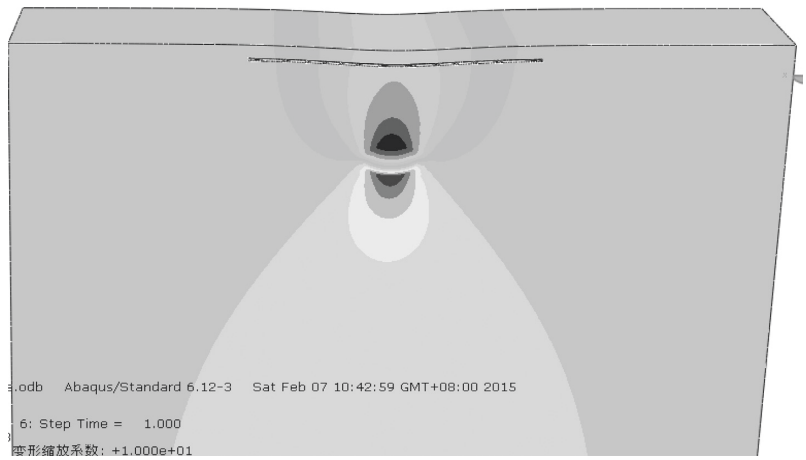

Figure 2: Vertical displacement of the pipeline at the face of tunneling.

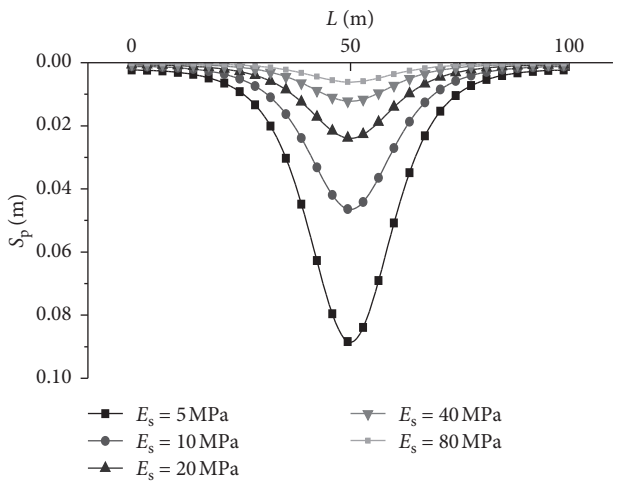

Figure 3: Transverse subsidence of pipeline in different soil compression moduli.

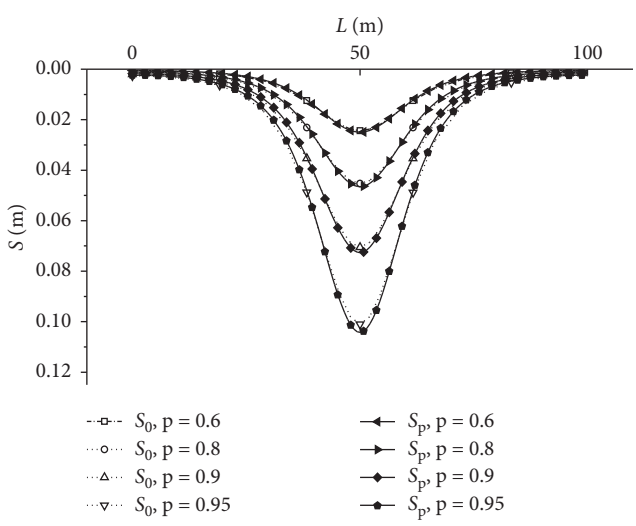

Figure 4: Transverse subsidence of ground surface and pipeline in different stress release rates.

2.7%. When the stress release rate was 0.9, the settlement difference was 2.9%. When the stress release rate was 0.95, the settlement difference was 3.2%. So, when the formation conditions or retaining structure was weak, it would cause aggravation of settlement difference between the surface and the pipeline.

2.3.3. Lateral Pressure Coefficient. As shown in Figure 5, the at-rest lateral pressure coefficient was an essential parameter in the soil, which represented the initial stress state and the stress history of the soil, when the at-rest lateral pressure coefficient was 0.3, 0.4, 0.5, and 0.6, respectively, conversely, the maximum settlement value of pipeline was 1.84 cm, 1.73 cm, 1.65 cm, and 1.49 cm. With the increase of at-rest lateral pressure coefficient, the transverse settlement of the pipeline gradually decreased. However, the width of trough unchanged.

2.3.4. The Elastic Modulus of Pipelines. The elastic modulus of pipelines was an important parameter which indicated the ability of pipelines to resist deformation. During the excavation of the shield, the various elastic moduli of pipelines would lead to the different mutual stiffness between the pipe and the soil, which in turn affected the deformation of the pipeline. In order to verify the effect of the elastic modulus of pipelines on the settlement, the model was calculated by taking the different elastic modulus of pipelines.

With the increase of the elastic modulus of pipelines, the transverse settlement of pipeline gradually decreased. It could be seen from Figure 6 that the curve of pipeline settlement was similar in different elastic modulus of pipelines. The smaller the elastic modulus of pipelines, the greater the settlement of pipeline, and when the elastic modulus of pipelines increased from 2.5 Gpa to 20 Gpa, the maximum lateral settlement value of pipeline decreased by 57.74%. When the elastic modulus of pipelines was constant, the deformation of the pipeline decreased gradually with the

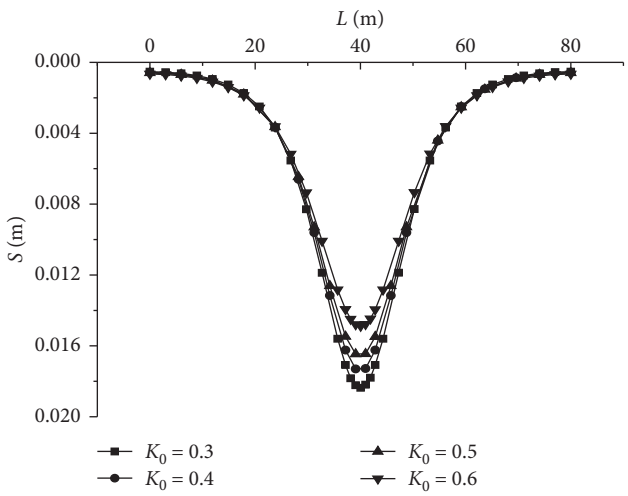

Figure 5: Transverse subsidence of pipeline in different static lateral pressure coefficients.

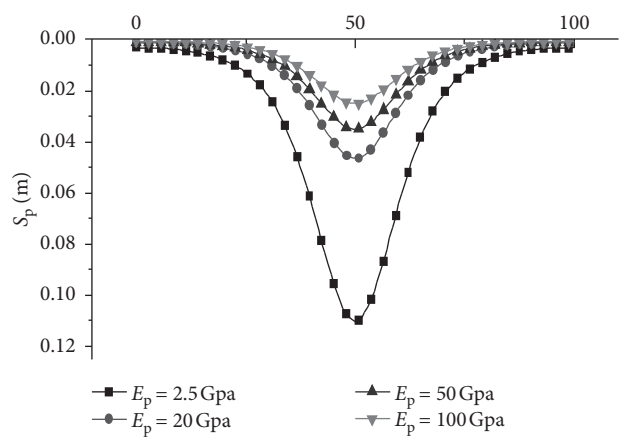

Figure 6: Transverse subsidence of pipeline in different pipeline compression moduli.

increase of the distance from the central area of the tunnel. The settlement curve was a normal distribution.

2.3.5. The Buried Depth of the Pipeline. The buried depth of pipeline refers to the vertical distance from the top of the pipe section to the natural surface. The pipeline was usually buried at 0.5 m below the surface. Parts of the pipelines were even buried at 5 m or 6 m below the surface.

As shown in Figure 7, the pipeline settlement law varies with the buried depth.

(1) With the increase of the buried depth and close to the tunnel excavation surface, the disturbance of pipelines was becoming more and more violent. As shown in Figure 7, when the buried depth of pipelines was 1.5 m, 3m, 4.5 m, and 6 m respectively, conversely, the maximum settlement value of pipeline in the tunnel center area was 4.65 cm; 4.79 cm, 4.95 cm, and 5.18 cm, when the buried depth increased from 1.5 m to 6 m, the maximum lateral settlement value of pipeline increased by 11.30%.

(2) With the increase of the distance from the center area of the tunnel, the settlement of the pipeline decreased gradually. When the distance from the tunnel axis was in the range of 10 m, the difference in sedimentation at the same depth was more noticeable. The maximum settlement difference was 11.30%. When the distance from the tunnel axis was out the range of 10 m, the difference in sedimentation at the same depth became more and more inconspicuous. The settlement difference was less than 1%.

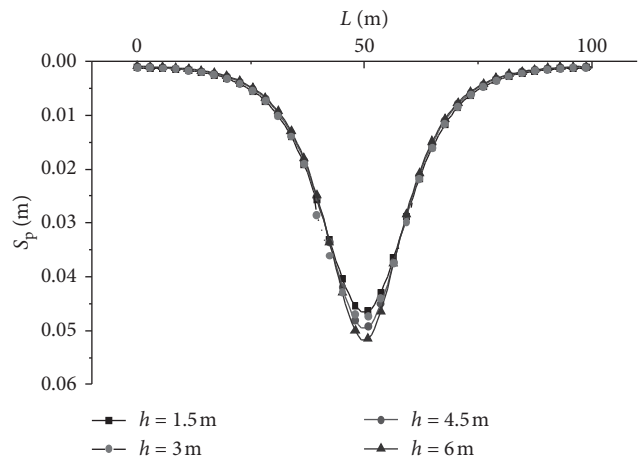

Figure 7: Transverse subsidence of pipeline in different embedment.

2.4. The Analysis of Parameter Sensitivity and Normalization. The finite element calculation showed the law of pipeline displacement due to tunneling construction under different conditions and that the pipeline can suppress settlement of the soil layer to a certain extent, and the insulating layer contributes to damage prevention of the underground pipelines [27]. The key to solving this problem is to predict the stress and the deformation of the pipelines precisely before construction [28], and then evaluate the impact degree of the construction on pipelines considering various factors comprehensively such as the function, the material, the size of the pipeline, and so on [29].

It was necessary to carry out the analysis of parameter sensitivity and normalization and to analyze the influence of different parameters and set up a calculation formula, which was convenient for engineering application. In this paper, the gray relational analysis method was used to analyze the parameter sensitivity.

For the interaction between the two systems, the degree of correlation with the change in time or different objects is called the degree of relevance. Grey relational analysis based on the sample data of each factor is used to describe the relationship among the factors. If the sample data series reflects the trend of two factors is the same, the degree of correlation between them is high. On the contrary, the degree of correlation between them is low [25]. The

following five steps show the methodology of the gray relational analysis:

(1) Establishing referring series and comparing series

The referring series is composed of the dependent variable. The comparing series is composed of the independent variable:

$$X_i = [x_i(1), x_i(2), \cdots x_i(n)], \tag{1}$$

$$Y_i = [y_i(1), y_i(2), \cdots y_i(n)]. \tag{2}$$

In the equation, n is the length of the series, m is the number of comparing series, $i = 1, 2, 3, ..., m$.

(2) Making the different series to be dimensionless

(3) Seeking the difference between the series

$$\begin{aligned} \Delta_{0i} &= |x_i'(k) - y_i'(k)|, \\ \Delta\max &= \max(\Delta_{0i}), \\ \Delta\min &= \min(\Delta_{0i}), \end{aligned} \tag{3}$$

where Δ_{0i} is the absolute value of the difference between the ith comparing series and the comparing series at the kth data point, respectively, and $\Delta\max$ and $\Delta\min$ are the maximum and minimum values.

(4) Solving the correlation coefficient

The meaning of the correlation coefficient is the degree of correlation between referring series and the ith comparing series at the kth data point. The formula is as follows:

$$r_{0i} = \frac{\Delta\min + p\Delta\max}{\Delta_{0i}(k) + p\Delta\max}. \tag{4}$$

The value of P which is the resolution coefficient is 0.1 to 0.5, generally taken 0.5. Its role is to improve the significance of the differences between the correlation coefficients.

(5) Solving the correlation degree

The correlation coefficients are often discrete. The correlation degree uses the average of the correlation coefficients in the same series as its value:

$$w_{0i} = \frac{1}{n}\sum_{k=1}^{n} r_{0i}. \tag{5}$$

In the formula, the correlation degree is 0 to 1.

Many factors are influencing the settlement of the pipeline. Only several essential parameters were selected to analyze in the model. According to the basic principle and method of gray relational analysis, the gray correlation of different factors to the model calculation results was analyzed.

From the first to the fifth line, the factors are the elastic moduli of pipelines, the buried depth of pipelines, the elastic moduli of soil, the at-rest lateral pressure coefficient, and the stress release rate in order. The factor in the comparing series is the maximum settlement, which is the 5 ∗ 4 matrix.

$$\begin{aligned} X &= \begin{bmatrix} 2.5 & 20 & 50 & 100 \\ 1.5 & 3 & 4.5 & 6 \\ 5 & 10 & 20 & 40 \\ 0.3 & 0.4 & 0.5 & 0.6 \\ 0.6 & 0.8 & 0.9 & 0.95 \end{bmatrix}, \\ Y &= \begin{bmatrix} -0.1101 & -0.0465 & -0.0351 & -0.0249 \\ -0.0465 & -0.0479 & -0.0495 & -0.0518 \\ -0.0886 & -0.0465 & -0.0240 & -0.0122 \\ -0.0899 & -0.052 & -0.0465 & -0.0421 \\ -0.02495 & -0.052 & -0.0727 & -0.1042 \end{bmatrix}. \end{aligned} \tag{6}$$

Table 1 shows the results. The order of correlation is $E > P > H > K_0 > E_p$, that is to say, the elastic modulus of soil has the most significant influence on the settlement of pipelines, and the stress release rate takes second place. The elastic modulus of the pipeline has the least effect on the pipeline settlement. It indicates that the soil layer dramatically influences the pipeline settlement. Thus, it is a reasonable method by strengthening the soil to reduce pipeline settlement such as grouting.

3. The Predictive Method for Settlement of Underground Pipeline

Klar [30] proposed the normalized formula for pipe-soil relative stiffness. The settlement of pipelines can be calculated by monitoring the settlement of soil layers. However, the settlement of soil layers is not easy to monitor in the actual conditions. So, a chart of the settlement relationship between the largest surface settlement and pipelines deformation was derived from the proposed formula for pipe-soil relative stiffness in combination with the finite element model. It may provide a reference for pipeline monitoring:

$$R = \frac{E_p I_p}{E_s r i^3}, \tag{7}$$

where E_p is the elastic modulus of the pipeline, I_p is the polar moment of inertia of pipeline, "r" is the radius of the pipeline, and E_s is the compressive modulus of soil. The elastic modulus of soil is three times larger than E_s [30]. i is the coefficient of settling tank width. The formula is as follows:

$$i = \frac{Z_0}{\sqrt{2\pi}tg(45^\circ - (\varphi/2))}, \tag{8}$$

where Z_0 is the depth of the tunnel axis and φ is the friction angle of the soil.

Combining with the above-established finite element model, the relationship between S_p and S_{max} were researched at different pipe-soil relative stiffness by adjusting E and E_p gradually. Figure 8 shows the results.

When the pipe-soil relative stiffness is constant, the ratio between the settlement of pipeline and the maximum surface sedimentation is larger with the approach of the tunnel excavation surface, reaching the peak at the tunnel

Table 1: Correlation calculation table.

Influencing factors	The correlation coefficient	The correlation coefficient (removing the initial and end value)
The elastic modulus of soil E/Pa	$\omega_{01} = 1/4^* \sum_{j=1}^{4} \gamma_{1j} = 0.896$	$\omega_{01} = 1/2^* \sum_{j=1}^{2} \gamma_{1j} = 0.791$
The at-rest lateral pressure coefficient K_0	$\omega_{02} = 1/4^* \sum_{j=1}^{4} \gamma_{2j} = 0.743$	$\omega_{02} = 1/2^* \sum_{j=1}^{2} \gamma_{2j} = 0.487$
The elastic modulus of pipeline E_p/Pa	$\omega_{03} = 1/4^* \sum_{j=1}^{4} \gamma_{1j} = 0.701$	$\omega_{01} = 1/2^* \sum_{j=1}^{2} \gamma_{1j} = 0.401$
The buried depth of pipeline H/m	$\omega_{04} = 1/4^* \sum_{j=1}^{4} \gamma_{4j} = 0.716$	$\omega_{04} = 1/2^* \sum_{j=1}^{2} \gamma_{4j} = 0.434$
The stress release rate P	$\omega_{05} = 1/4^* \sum_{j=1}^{4} \gamma_{5j} = 0.767$	$\omega_{05} = 1/2^* \sum_{j=1}^{2} \gamma_{5j} = 0.533$

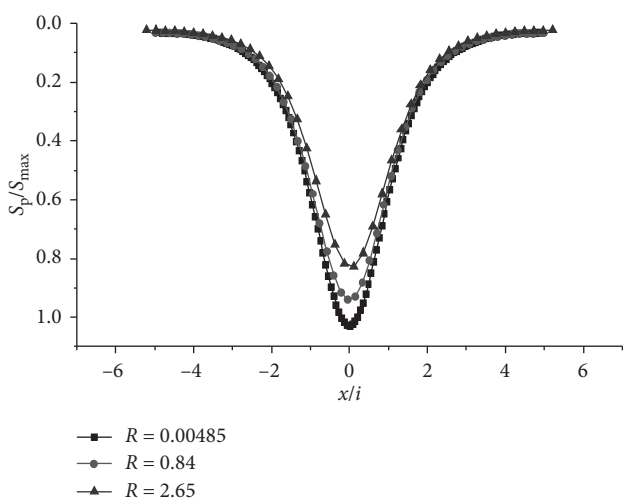

Figure 8: Numerical calculation of subsidence chart about the surface and pipeline.

excavation center. The ratio between the maximum settlement of pipeline $S_{p\ max}$ and the maximum sedimentation of surface S_{max} was set as K:

$$K = \frac{S_{p\,max}}{S_{max}}. \tag{9}$$

When $R = 0.0049$ approaching 0, $K = 1.026$. That is, the pipeline is flexible. The settlement of pipeline keeps steps to the surface. Surface subsidence can be regarded as pipeline subsidence at this time. When $R = 2.65$, $K = 0.827$. Pipeline subsidence is 82.7% less than surface subsidence. With the increase of R, K decreases gradually. Based on the safety considerations, K trends toward maximum value within the range of R.

$$\begin{aligned} R \le 0.00485 \approx 0, &\quad K = 1.026, \\ 0.00485 \le R \le 0.84, &\quad K = 0.94, \\ 0.84 \le R \le 2.65, &\quad K = 0.83. \end{aligned} \tag{10}$$

The maximum settlement of pipeline can be calculated by substitution of surface maximum sedimentation obtained from field monitoring. Through this method, the underground pipeline settlement can be predicted.

4. Example Analysis

4.1. The Field Tests. The overall length of Suzhou Metro Line 1 which was constructed by shield tunneling method is 25.739 km. The subway is divided into two lines. The spacing between the two lines was 15 m. The buried depth of the east line close to Xingtang Street was 12.6 m. The buried depth of the west line was 13.3 m. The external diameter of the shield machine and lining ring were 6.34 m and 6.2 m, respectively. One side of the Xingtang Street Station was selected as the field test area; the area was 36 m long and 32 m wide. A cast iron pipe which is perpendicular to the subway tunnel was buried above the tunnel. As shown in Figure 9, the distance from the ground surface was 1.5 m. Geological conditions were complex. The quaternary soil layer was more in-depth and was not stable enough. There is the presence of diving and microconfined water and widely distributed soft soil. Table 2 shows the physical-mechanical parameters of each soil layer.

4.2. The Calculation Results and Comparative Analysis. The pipeline is buried at 1.5 m from the surface as shown in Table 2, $E_s = 6.26$ MPa, $E_p = 14.1$ GPa. R can be calculated by the following formula:

$$R = \frac{E_p I_p}{E_s r i^3} = \frac{14.1 \times 10^7}{6.26 \times 10^6 \times 0.15 \times 8.3^3} = 0.26, \tag{11}$$

with $0.0485 \le R \le 0.84$, and K is equal to 0.94 calculated by formula (10).

Based on field monitoring, and S_{max} equal to 10.13 mm. $S_{p\ max}$ can be calculated by the following formula:

$$S_{p\ max} = K * S_{max} = 0.94 * 10.13 = 9.52 \text{ mm}. \tag{12}$$

Based on field monitoring, the actual is equal to 8.13 mm. The difference is equal to 1.39 mm.

The measured results, simulation results, and calculation results were plotted in a graph with the Gaussian distribution, as shown in Figure 10.

The obtained $S_{p\ max}$ from the measured calculations and simulated calculations by finite element were 8.13 mm and 9.81 mm, respectively, giving a difference between them of 1.68 mm, which can be seen clearly in the distribution from Figure 10. On the other hand, $S_{p\ max}$ calculated by formula was 9.52 mm, giving a smaller difference with the measured $S_{p\ max}$, which can be seen in the distribution from Figure 10. The results have shown that significance, consistency, and

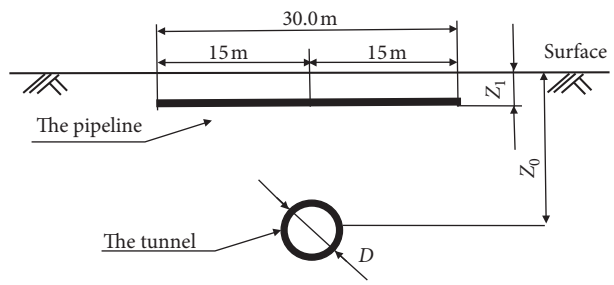

Figure 9: Spatial location of subway tunnel and pipeline.

Table 2: Physical-mechanical parameters of soil.

Level number	The depth of the bottom (m)	Slice thickness (m)	Elevation of the bottom (m)	The type of soil	Es (MPa)	c (kPa)	φ (°)	Poisson's ratio v
①$_2$	0.7	0.7	−2.24	Silt	6.64	61	11.4	
③$_1$	1.5	0.8	−3.04	Clay	6.26	48	10.9	0.32
③$_2$	6	4.5	−7.54	Silty clay	5.66	24	11.4	0.3
④$_3$	11	5	−12.5	Silty clay	5.78	28	11.3	0.31
⑤	19	8	−20.5	The silty clay layer contains a small amount of silt	5.58	62	10.2	0.32
⑥$_1$	21.5	2.5	−23	Clay	7.16	43	18.8	0.31
⑥$_2$	27.8	6.3	−29.3	Silty clay	8.08	24	23.1	0.31
⑥$_3$	30	2.2	−31.5					

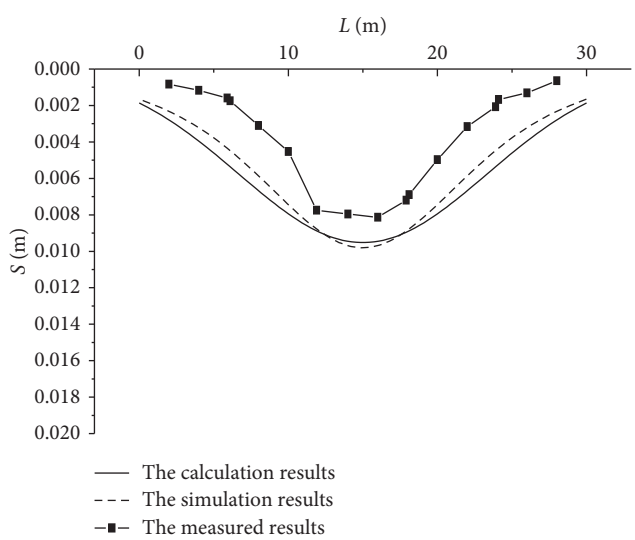

Figure 10: Comparison of measured settlement and finite element method and formula calculation.

sensitivity of the soil material properties on the finite element simulation accuracy when compared with experimental data, on the contrary with the results calculated with the formula.

The parameters in the formula are only related to Mohr–Column models, which makes the formula easier and simpler to apply. However, there are more sophisticated or advanced models which could simulate the soil-tunnel-pipeline interaction more reasonable. So, with better models, a formula that is more suitable may be obtained.

More practical engineering examples may be used to verify the formula because the model is only calibrated with one field testing. The formula in this paper has been verified to some extent with infield testing, and with more data from different fields, we can supply a more precise formula to predict the behaviors of the pipeline induced by tunneling. Moreover, the main aim of our work is to establish a design or prediction chart for engineering usage in related fields. Nevertheless, the formula suggested in this paper could be revised and modified, and for the difference of local geology conditions, the formula may be different from area to area. Moreover, the main aim of our work is to establish a design or prediction chart for engineering usage in related fields.

Besides, the formula was developed based on the FEM analysis on continuous pipelines. In practice, there are more pipelines with joints between each section, which would affect the results of the formula. Therefore, the soil's constitutive model, the verification example, and the pipelines are the three factors which could be taken into consideration for further studies.

5. Conclusions and Discussion

The research of the paper focused on the law of pipeline settlement under different influencing factors and the sensitivity of different influencing factors to pipeline settlement, through the application of the ABAQUS program. From the above work, the settlement relationship between pipeline and surface could be obtained by the formula for pipe-soil relative stiffness. Compared with the actual results of the field, it can be noted the following conclusions:

(1) The order of correlation is $E > P > H > K_0 > E_p$. So, the elastic modulus of soil is the most sensitive to the settlement of the pipeline and the stress release rate is

the second. The elastic modulus of the pipeline has the least effect on the settlement of pipeline.

(2) The proposed formula for pipe-soil relative stiffness in combination with the finite element model derived a chart of the settlement relationship between the maximum surface settlement and pipelines deformation. The value of maximum settlement calculated by the calculation chart agreed well with the measured results.

(3) Results obtained in this paper were based on Mohr–Coulomb model, which is convenient for its simplicity. More sophisticated models such as cap model need to be applied to do a further study once the required parameters could be determined.

(4) Based on FEM analysis, the grey correlation method was applied in this study, obtaining rely coefficients significantly on the constitutive model which was applied. The coefficients could be modified for future studies with other advanced constitutive models, but for engineering purpose, the simple the models are appropriate the few coefficients.

Data Availability

The data 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 conflicts of interest.

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