Analysis on Mechanical Properties of the Buried Pipeline Considering Pipe-soil Interaction

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Abstract. Mechanical deformation of buried pipeline under vertical load is the result of pipe-soil interaction. In order to reveal the necessity of pipe-soil interaction while investigating mechanical properties of buried pipeline, the ANSYS commercial software is employed to construct pipe-soil interface and simulate pipe-soil coupling effect. With the newly developed model, mechanical properties of pipe under vertical static load are analyzed. Numerical solution is subsequently compared with analytical solution. The results reveal that (1) There is maximum Von Mises stress at internal surface of pipe side under overlying load, and minimum Von Mises stress appears in the pipe shoulder at angle of about 45° to x-axis; (2) The pipe-soil interaction has significant effect on analyzing the deformation and distribution of stress of buried pipeline; (3) Vertical displacement obtained from Marston model is larger than that obtained from newly constructed numerical model; (4) The deformation of pipe is obviously constrained by backfilled earth around the pipe. For a buried pipe, especially the elastic pipe, it is necessary to consider pipe-soil interaction while analyzing its mechanical properties.

1. Introduction

As the urbanization process accelerates and the demand for infrastructure construction increases, the demand for materials and energy continues to increase. In order to meet various requirements, the buried pipelines made of a wide variety of materials, are usually subject to increasingly complicated municipal engineering environment. At the same time, because buried pipelines are located below the ground, it is difficult to carry out inspection and maintenance. Rupture of the buried pipe can be catastrophic. A large number of incidents have been reported worldwide, with many resulting in substantial waste of resources and economic losses. The reasonable design, construction and maintenance of buried pipelines are essential to reduce the probability for occurrence of accidents.

Reasonable and effective analysis of the mechanical response of buried pipelines under overlying load is an important basis for its design, construction and maintenance work. The calculation of earth pressure applied to buried pipelines is key to the analysis of its mechanical properties. With respect to theoretical research, scholars have proposed a good deal of models for calculation of pipeline earth pressure. As a classical theory of earth pressure on buried structure, Marston's theory is a simple and practical tool for analysis of buried structures [1]. It assumes vertically downward sliding surface among soil columns and evenly distributed overlying loads along pipe diameter. The cohesion between the fills is not considered. However, the actual production shows that these assumptions are
too oversimplified to lead to large discrepancy between the theoretical calculation results and the actual stress state. The initial Marston’s equation has been extended by many researchers. Further, taking cohesion between the fills into account, Zeng [2] revises Marston's theoretical calculation model. By accounting the variation in the soil parameters and all possible forces acting on layer element of soil, Li et al. [3] propose a three-dimensional solution to the average vertical stress distribution. Based on the numerical studies reported by Li et al. [4], Li and Aubertin [5] introduce an analytical solution to predict the vertical stress by accounting the lateral variation of the vertical stress. The specification [6] also proposes a soil pressure calculation model based on the empirical soil pressure concentration factor. In general, these earth pressure calculation models neglect the deformation of buried pipelines under load. In other words they are only suitable for buried pipelines with high stiffness.

With the development of the level of engineering construction, material science and industry, the flexible pipes play an important role in current pipeline transportation due to their strong corrosion resistance, convenient construction and low cost. Different from the rigid pipe, the flexible pipe will squeeze the soil around the pipe after deformation under stress. Conversely, the squeezed soil around the pipe will have elastic resistance, as a result further deformation of the pipe will be restrained [7,8]. Spangler et al. [9] assumes that the vertical deformation of the buried pipeline is equal to the lateral deformation. A calculation model for the cross-section deformation of the flexible buried pipe is proposed. However, the shortcoming of this model is that pipe-soil interaction is roughly considered as well. Prevost et al. [10] emphasize the importance of pipe-soil interaction for the calculation and analysis of thin-walled steel pipes, and find that the pipe-soil interaction significantly affects the distribution of earth pressure. It is pointed out that the calculation model of earth pressure based on rigid pipes is no longer applicable. Zhou et al. [11, 12] uses ABAQUS commercial software to establish a finite element model of the oil pipeline considering the interaction between pipe and soil, and explains its influence on the soil pressure around the pipe.

In this paper, high-density polyethylene (PE pipe) is taken as the research object. The ANSYS commercial software is used to establish the pipe-soil contact to simulate the pipe-soil coupling effect, and the mechanical properties of the buried flexible pipe under static load are discussed. The numerical calculation results are compared with the theoretical calculation model to show the influence of pipe-soil interaction on the mechanical characteristics of flexible buried pipe below the roadway.

2. Theoretical calculation model

2.1. Earth pressure analysis

2.1.1. Marston earth pressure theory
The Marston earth pressure model is based on the theory of granular limit equilibrium, and mainly includes the vertical earth pressure model of the trench-buried and buried pipelines. The difference between them is the direction of friction resistance between the internal soil column and outer soil column. For the trench-buried pipeline, the settlement of the soil at the top of the pipe is larger than that of soil surrounding the pipe. The frictional resistance acting on the soil column at the top of the pipe is upward, resulting in that the vertical earth pressure acting on the pipeline is less than the weight of the soil column at the top of the pipe. For the buried pipeline, the settlement of the soil at the top of the pipe is less than that of soil surrounding the pipe, the frictional resistance of the soil column at the top of the pipe is downward, resulting in the vertical earth pressure of the pipe being greater than the weight of the soil column at the top of the pipe.

(1) Trench conduit

Fig. 1 shows the earth pressure model of a trench conduit. As shown in Fig. 1, the deformation of the pipe is neglected, assuming that the buried pipe is absolutely rigid. The change of vertical earth pressure along the pipe diameter is ignored, assuming that the vertical earth pressure is uniformly
distributed above the pipe. The pipe completely bears the vertical pressure of the upper fill. It is assumed that the fill is in a limit equilibrium state relative to the pits walls on both sides.

Vertical earth pressure stress on the top plane of the pipe is:

$$\sigma_h = \frac{1-e^{-2Kf\frac{H}{B}}}{2Kf} \cdot \gamma B$$

(1)

![Fig. 1 Stress analysis of the trench conduit](image1)

![Fig. 2 Stress analysis of the projecting conduit](image2)

The vertical earth pressure at the top of the pipe is:

$$G_g = B\sigma_h = k_g \gamma BH$$

(2)

Where $k_g$ is the concentration coefficient of vertical earth pressure on pipe top $k_g = \frac{1-e^{-2\mu\frac{H}{\pi}}}{2\mu\frac{H}{B}}$; $B$ is the width of the groove; $H$ is the calculation point to the depth of the soil surface; $\gamma$ is the bulk density of the backfill; $K$ is the ratio of lateral pressure to vertical pressure of backfill; $f$ is the friction coefficient between the backfill and the groove wall.

The horizontal earth pressure stress on the pipe side is calculated as Rankine active earth pressure:

$$q = \eta \gamma H$$

(3)

Where $\eta$ is the horizontal lateral pressure coefficient, $\eta = tan^2(45^0 - \phi / 2)$.

(2) Projecting conduit

The earth pressure model of projecting conduit is shown in Fig. 2. Different from the trench conduit calculation model, the settlement of the upper fill of the pipeline is smaller than that of its two sides due to the large rigidity of the buried pipeline. As a result, the direction of the shear force acting on soil column at the top of pipeline is downward.

The resultant vertical soil pressure on the top of the pipe is:

$$G_e = D \cdot \sigma_n = \frac{\gamma D^2}{2Kf}\left(e^{\frac{\pi n}{\mu} - 1}\right)$$

$$G_e = D \cdot \sigma_n = \frac{\gamma D^2}{2Kf}\left(e^{\frac{\pi n}{\mu} - 1}\right) + \gamma D(H - H_e) e^{\frac{\pi n}{\mu} - 1}\right).$$

(4)

Where $D$ is the diameter of the pipe; the other symbols are defined as above.
2.1.2 Correcting the Marston earth pressure model
Zeng [2] believes that the shear force acting on inner soil column by the outer soil column is actually the active lateral earth pressure, and the cohesion of the soil can not be ignored. The Marston earth pressure model is further modified.

\[
\begin{align*}
\gamma H + \gamma H^2 K_f / D + 2c (1 - 2 \sqrt{K_f}) & 
\begin{cases}
H / D, H \leq H_s \\
H / D, H > H_s
\end{cases}
\end{align*}
\]

Where the symbol has the same meaning as above.

2.1.3 Empirical soil pressure concentration coefficient model
For the projecting rigid conduit, specification [6] propose that the vertical earth pressure on the pipe top is calculated according to the following formula:

\[ F_{sv, k} = 1.4 \gamma HD \] (6)

For the trench-buried rigid conduit, the vertical earth pressure on the pipe top is calculated according to the following formula:

\[ F_{sv, k} = 1.2 \gamma HD \] (7)

2.2 Analysis of cross-section deformation of buried pipeline
The analysis of cross-section deformation of buried pipeline mainly includes the elastic theoretical analysis method and the Iowa formula proposed by Spangler. Due to the limitation of space, this paper mainly introduces the Iowa formula. An detail introduction of the elastic theoretical analysis can be found in reference [7].

A schematic diagram of the Iowa formula calculation model proposed by Spangler et al. is shown in Fig. 3. It is assumed that the vertical earth pressure on the upper part of the buried pipeline is evenly distributed on the top of the pipe. Considering the deformation of the buried pipeline under the action of the surrounding soil, it is assumed that the same transverse and vertical deformation occurs, respectively, \( \Delta x / 2 \). Assuming that the pipe is elastically deformed, the deformation amount on the pipe side is proportional to the horizontal earth pressure on the pipe side, and the horizontal earth pressure is a parabola distribution along the vertical pipe diameter.

Fig. 3 Schematic of calculation model using Iowa formula
Fig. 4 Schematic of the plane model

The Iowa formula is:

\[ \Delta = \Delta x = \Delta y \] (8)

\[ \Delta = \frac{D_I K W r^3}{EI + 0.061r^4} \] (9)
Where $K$ is the foundation bed constant, $K = 0.083$; $D_L$ is the deflection extension coefficient, $D_L = 1.5$; $W_c$ is the Marston vertical earth pressure per unit length, kN/m; $E$ is the elastic modulus of the pipe, Pa; $r$ is the average radius of the pipe, m; $I$ is the unit length of the pipe wall section moment of inertia, m$^3$; $e$ is the resistance modulus of lateral fill.

3. Finite element model

3.1 Material parameters
To investigate the important influence of pipe-soil interaction on the mechanical properties of buried pipelines, a two-dimensional plane road model of buried pipeline is established, including asphalt concrete surface, cement gravel layer, filling soil around pipelines, hard rock foundation from top to bottom, as shown in Fig. 4.

High density polyethylene PE pipe is used as the pipe material, grade PE100, standard size ratio SDR = 17. The D-P constitutive model is used to simulate the filling around the pipe and the hard rock foundation. The viscoelastic Prony series mechanical model is selected as the constitutive model of high density polyethylene PE pipe. Because the thickness of asphalt concrete surface and cement stabilized gravel layer of pavement structure is low, the homogeneous linear elastic model is selected for them.

In the two-dimensional solid modeling, the Plane 82 planar unit is used to build the road model, and the Plane 183 unit is used to build the PE pipeline model. The diagram of the meshing is shown in Fig. 5.

![Fig. 5 Diagram of the meshing](image)

The values of the calculation parameters of each layer and pipeline of the road model are shown in Table 1.

| structure          | materials          | $E$ (MPa) | $\nu$ | $\rho$ (kg/m$^3$) | $c$ (kPa) | $\varphi$ (°) |
|-------------------|--------------------|-----------|-------|-------------------|-----------|---------------|
| rock foundation   | rock               | $8 \times 10^4$ | 0.25  | 2600              | 2100      | 45            |
| soil foundation   | compacted earth    | 8.5       | 0.35  | 1600              | 30        | 20            |
| basement layer    | cement gravel      | 1000      | 0.30  | 2000              | /         | /             |
| surface           | asphalt concrete   | 1200      | 0.30  | 2400              | /         | /             |
| pipeline          | polyethylene       | 900       | 0.38  | 953               | /         | /             |

3.2. Pipe-soil interaction
In practical work, there exists pipe-soil interaction between the buried pipeline and the surrounding soil. Under the load, the buried pipeline is deformed vertically and laterally due to compression. The soil around the pipe constrains the further deformation of pipe. Meanwhile, the deformed pipe forms a pressing action on the surrounding soil, and there is friction between the pipe and the surrounding soil to prevent relative slip. In this study, the coupling of pipe and soil is simulated by establishing a contact pair between the pipe and the surrounding soil. The pipe-soil contact is defined as face-to-face contact. The selected contact unit is contact 172, and the target unit is target 169. The contact pair is
defined as a flexible body-flexible body contact. The pipe serves as a contact surface (convex surface), and the soil serves as a target surface (concave surface). The friction coefficient between the pipe and soil is 0.18 [7, 12].

4. Calculation results and analysis

4.1. Stress state of the pipeline

Fig. 6 shows the Mises stress map of a buried pipeline under earth pressure. Under the vertical static load, the internal force of pipeline section is symmetrically distributed, and stress concentration occurs. The maximum equivalent stress appears on the inner surface at the middle of the pipe. The maximum stress value is 0.79 MPa. The minimum equivalent stress appears on outer surface of pipeline section at an angle of about 45° to the x-axis. The minimum stress value is 0.05 MPa.

To further analyse the distribution of the equivalent stress along the pipe circumference in the section, the monitoring points are symmetrically arranged on the outer surface and the inner surface of the pipe along the pipe circumference. The specific arrangement is shown in Fig. 7.

![Fig. 6 Mises stress of pipe under the action of soil weight](image1)

![Fig. 7 Arrangement of observation points](image2)

Fig. 8(a) and 8(b) show the variation of the equivalent stress along the circumference of the outer surface and the inner surface, respectively. The equivalent stress of the inner and outer surfaces is symmetrically distributed. The maximum equivalent stress on outer surface is at the C and G, the minimum equivalent stress at waist F and H, followed by the equivalent stress at shoulder B and D. The equivalent stress at side E and A is less than that at top and bottom of the pipe. The stress at bottom of the pipe is slightly larger than that at top of the pipe. On the inner surface of the pipe, the equivalent stress at points E1 and A1 on the pipe side are the largest, while those at points B and D of the shoulder are the smallest, followed by points H and F of the waist. The equivalent stresses at points C, G are smaller than those at the middle of pipe.

Different from the calculation model proposed by Spangler, the results show that the parabolic distribution rule of the horizontal earth pressure on the pipe side can only be applied to area between shoulder of the pipe at the angle of 45° to the x-axis and the waist of the pipe at the angle of -45° to the x-axis. The earth pressure between the top and the shoulder changes monotonously, in which earth pressure at the top of the pipe is the largest, while reaches the minimum at the shoulder.

Different from the Marston earth pressure, the pipe-soil interaction significantly affects the distribution of soil pressure around the pipe. The calculation results show that the vertical earth pressure is roughly parabolic distributed along pipe diameter. While the Marston earth pressure theory assumes that the vertical earth pressure is evenly distributed along the horizontal diameter.

In fact, considering the interaction between the soil and the pipe, the boundary shape of the upper and lower semicircles (inverted arches) of the shoulder and the waist of the pipe significantly affects the vertical and horizontal earth pressure distribution of the fill soil acting on the pipeline. The vertical earth pressure is parabolic distribution centering on the top and bottom of the pipe, while the horizontal earth pressure is parabola distributed in the scope of pipe shoulder and pipe waist taking the pipe side as the center. The finite element analysis results are more realistic.
4.2. Pipe deformation state

Fig. 9 shows the displacement contour plot of the cross section of the buried pipeline under earth pressure. Under the squeezing action, the overall displacement is vertically downward. The displacement at the top of pipeline is the largest, of which maximum is 1.4 cm. The displacement at the bottom of the pipe is the smallest, of which the minimum is 1.27 cm, as a result the relative displacement between the top point and bottom point is 0.13 cm.

![Displacement Contour Plot](image)

**Fig. 9** Displacement of pipe under the action of soil weight

Different from the Spangler's assumption, the lateral and vertical displacements of the pipeline are not equal considering the pipe-soil interaction conditions. Because the soil around pipe constrains the deformation of pipelines, the top displacement of the pipe is the largest, and the bottom displacement is the smallest, and the lateral displacement of the pipeline side is lower than the vertical displacement.

4.3. Vertical earth pressure on pipe top at different buried depth

To further explain the necessity of considering the pipe-soil interaction for analyzing the mechanical properties of buried flexible pipeline under load, the finite element calculation results of vertical earth pressure at the top of the pipe at different buried depths are presented and compared with the theoretical model results, as shown in Fig. 10(a). The finite element calculation results of the vertical displacement of the pipe top at different buried depths are compared with the theoretical model results, as shown in Fig. 10(b).

By the comparative analysis diagram of vertical earth pressure on the top of the pipe at different buried depths, it is not difficult to find that the vertical earth pressure of the pipe top calculated based on three theoretical methods is greater than that calculated by the finite element model considering the pipe-soil interaction. Moreover, the vertical earth pressure on the pipe top calculated by Marston theoretical formula is the largest, followed by that calculated by model by Zeng, and is larger than that calculated by empirical concentration coefficient method recommended by the code. Compared with the finite element results, with the increase of the buried depth, the error of the Code [6] is relatively small. Therefore, for calculating the earth pressure of buried pipelines in the high-filled roadbed, it is more suitable to adopt the empirical formula recommended in Code [6].
By the comparison and analysis of vertical displacement on the pipe top at different buried depths, we can see that:

1. With the increase of buried depth, the vertical displacement of the pipe top increases gradually. The elastic theory solution is the largest, followed by the Spangler formula, and the finite element calculation result is the smallest. In addition, the first two calculation results show that the vertical deformation of the pipe top is linear with the buried depth, while the finite element calculation results reveal that the increase rate of vertical deformation of the pipe top gradually decreases with the increase of the buried depth, and that tends to be gentle eventually.

2. The horizontal deformation of the pipe side based on the finite element calculation increases gradually with the increase of buried depth, but the velocity gradually decreases, and finally tends to be stable, which is smaller than the pipe top deformation at different buried depths.

3. Since the elastic theory method does not consider the constraint of the soil around the pipe on the pipe deformation, the calculated vertical deformation of the pipe top is the largest. The Spangler calculation model assumes that the horizontal earth pressure is parabolic distribution in the vertical diameter height range, weakening the lateral deformation constraint of the horizontal earth pressure on the pipeline. The Marston theoretical vertical earth pressure has a large different from the vertical earth pressure of pipeline in actual work, so the calculated vertical deformation is still large. The finite element model established in this study considers the pipe-soil interaction and the influence on the earth pressure distribution, which is more consistent with the actual working conditions. The necessity of considering pipe-soil interaction in the design and construction of buried pipelines is confirmed.

5. Conclusions
The ANSYS software is used to establish the pipe-soil contact to simulate pipe-soil coupling effect for calculating the mechanical response of the buried flexible pipe. The stress distribution law and displacement distribution law of the buried pipe are discussed. The distribution law of soil pressure stress around the pipes is revealed, and the mechanical properties of flexible pipe under different buried depths are displayed. By comparing the calculation results with the theoretical model results, the following conclusions are obtained:

1. The maximum stress of the pipeline under earth pressure appears on the inner surface of the pipeline side. The minimum stress value appears at the shoulder of the pipe at an angle of $45^\circ$ to the x-axis, which is symmetrically distributed along the x-axis and y-axis. The change trend of stress on the inner and outer surface of the pipeline is opposite.

2. The pipe-soil interaction affects the distribution of soil pressure significantly. Vertical earth pressure and horizontal earth pressure are roughly distributed according to the parabola along the pipe diameter. The lateral and vertical displacements of the pipe are not equal. Due to the constraint of the pipe surrounding soil on the pipe deformation, the displacement of the pipe top is the largest, the
displacement of the pipe bottom is the smallest, and the lateral displacement on the pipe side is lower than the vertical displacement.

(3) Compared with finite element calculation results, Marston's theoretical formula has the largest soil pressure on the pipe top, followed by Zeng's formula, and the error of Code method is relatively small.

(4) The elastic theory does not consider the lateral pressure of the soil at pipe side, so the calculation results of vertical displacement on the pipe top is obviously larger. Whether the Iowa formula can effectively evaluate the deformation of the pipe depends on the determination of the reaction modulus. The finite element calculation results considering the interaction between the pipe and the soil are more realistic.

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