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Mechanical response analysis of the buried pipeline due to adjacent foundation pit excavation

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ABSTRACT

Foundation pit is one of the most factors that threaten the safe operations of buried pipeline. In order to study the effect of foundation pit excavation on the buried pipeline, a three-dimensional model of pipeline and foundation pit was established, and the variation regulations of pipeline's deformation under the foundation pit excavation were investigated. Effects of pipeline parameters, foundation pit parameters, soil parameters and underground continuous wall on the stress, strain and deformation of the pipeline were studied. The results show that the underground continuous wall can effectively reduce the pipeline deformation. After the foundation pit excavation, the upper surface of the pipeline's middle section is pressed, and the lower surface is pulled, but the strain distribution of the pipeline at the edge of the pit is opposite. Horizontal and vertical displacements occurs on the pipeline, horizontal displacement moves to the inside of the pit, and vertical displacement moves to the bottom of the pit. The pipeline deformation decreases with the increasing of pipeline's radius-thickness ratio, but it increases with the increasing of the distance between the pipeline and foundation pit. The internal pressure has a small effect on the pipeline deformation. Pipeline deformation increases with increasing of the foundation pit's width and depth. However, the length of the foundation pit has no effect on the pipeline. The pipeline deformation increases with the soil's Poisson's ratio increases, and it decreases with the increasing of soil's cohesion and elastic modulus. With the increasing of thickness and elastic modulus of the underground continuous wall, the pipeline deformation decreases. Those results can be used for pipeline laying, construction, maintenance and safety evaluation.

1. Introduction

Compared to roads, rail transport, pipelines are the safest and most economical way to transport flammable substances. With the increasing of infrastructure construction, buried pipelines may be affected by other projects, such as various urban underground constructions, which may cause pipeline failure and leakage (Shen and Xu, 2011). The foundation pit excavation will change the initial stress state of the soil, thus resulting in the surrounding soil deformation. That mainly includes the uplift at the bottom of the foundation pit, the displacement of the underground continuous wall and the soil settlement after the wall. The soil deformation will lead to segment leakage or local damage of the pipelines. Longitudinal distortion is a fatal threat to the structural safety and normal operations of buried pipelines. Therefore, mechanical behavior analysis of buried pipelines affected by foundation pit excavation is very important for its safety evaluation.

In recent years, many researches on the pipeline deformation caused by the foundation pit excavation were carried out. Zhang et al. (2012) provides a continuous elastic analysis to simulate the responses of the pipelines subjected to tunnel-induced soil movement in multi-layered soils. Klar and Marshall (2007) analyzed the effect of tunneling on the pipeline by using Euler-Bernoulli simple beam theory and shell element theory. Zhang et al. (2015) presented a simplified method to determ the mechanical behavior of buried pipeline induced by foundation pit excavation by using Winkler foundation model. Li et al. (1999) used Winker theory to establish the vertical displacement and horizontal displacement equations of the pipeline affected by the foundation pit excavation. Jiang (2014) derived the deformation and internal force of the pipeline by the elastic foundation beam. Yang et al. (2011) studied the pipeline response by the finite element model. In addition, Shi et al. (2016) study the effects of the lateral unloading caused by foundation pit excavation on the existing shield tunnels based on nonlinear contact theory. Chen et al. (2016) studied the influence of a nearby large excavation on existing twin tunnels in soft soils by FEM. However, they did not pay attention to the effect of foundation pit excavation on buried pipelines. Li et al. (2016) presents an analytical solution for the

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Nomenclature

$u(x)$	ground settlement
u_{max}	the maximum ground settlement
x	horizontal distance from the foundation pit axis
i	width coefficient of the ground settlement
K_0	the subgrade modulus
D	outer diameter of the buried pipeline
E	elasticity modulus
I	inertia moment of the pipeline section
y	displacement of the pipeline
a, b, c	constant
δ	the maximum ground settlement
L	deformation length of the pipeline
y_0	displacement of the pipeline at O point
θ_0	rotation of the pipeline at O point
M_0	bending moment of the pipeline at O point
Q_0	shear force of the pipeline at O point
$\phi(\beta x)$	Krylov's function
$\beta = \sqrt[4]{\frac{K}{4EI}}$	–
V	pit length
W	pit width
H	excavation depth
t	wall thickness
ρ	density
μ	Poisson's ratio
σ_y	yield stress
$P_{\max}$	the maximum operating pressure
l	distance between pipeline and foundation pit

deflection and the internal forces of an existing tunnel. Li et al. (2014) carried out a centrifuge model test to investigate the effect of new shield tunnelling on an existing underlying large-diameter tunnel. Despite the contributions of these researches are inordinately valuable, but most researches assumed that the pipeline is in close contact with the soil when it is deformed, and analyzed the pipeline as a beam. In real working condition, the buried pipeline and surrounding soil affect each other, the pipelines and soil will not contact with each other along the axial direction. In this paper, a pipeline-soil interaction model was established to analyze mechanical behavior of the buried pipeline under the influence of foundation pit excavation, which can provide a reference for the design, laying and maintenance of the buried pipeline.

2. Analytical model of the buried pipeline

In the current theoretical calculations, the pipeline is usually analyzed as an elastic foundation beam to solve the displacement after pit excavation (Shen et al., 2013). The load on the pipeline due to foundation pit excavation is determined by the ground settlement. The ground settlement curve can be expressed by the Peck formula (Peck, 1969):

$$u(x)=u_{\max}e^{-\frac{x^2}{2i^2}} \tag{1}$$

According to Winker assumptions, the load on the pipeline is:

$$q(x) = K\cdot u(x) \tag{2}$$

where $K = K_0D$.

Then the differential equation for the pipeline displacement induced by foundation pit excavation can be obtained:

$$EI\frac{d^4y}{dx^4} + Ky = q(x) \tag{3}$$

The solution of Eq. (3) consists of general solution and particular solution, but the particular solution is difficult to find out. Therefore, the ground settlement curve can be approximated as a quadratic function curve (Li et al., 1999). The pipeline under the load is shown in Fig. 1, the ground settlement curve is:

$$u(x) = ax^2 + bx + c \tag{4}$$

where a, b and c can be obtained by boundary conditions: $u(0) = 0$, $u(L) = 0$, $u\left(\frac{L}{2}\right) = \delta$. Then Eq. (4) can be written as follows:

$$u(x) = -\frac{4\delta}{L^2}x^2 + \frac{4\delta}{L}x \tag{5}$$

The general solution of Eq. (3) can be obtained by using the initial parameter method of short beam (Li et al., 1999); the general solution is:

$$y = y_0\phi_1(\beta x) + \frac{\theta_0}{\beta}\phi_2(\beta x) - \frac{M_0}{EI\beta^2}\phi_3(\beta x) - \frac{Q_0}{EI\beta^3}\phi_4(\beta x) \tag{6}$$

where $\phi_1(\beta x)$, $\phi_2(\beta x)$, $\phi_3(\beta x)$, $\phi_4(\beta x)$ is Krylov's function. Eq. (6) is differentiated to get the rotation equation as follows:

$$\theta = -4\beta y_0\phi_4(\beta x) + \theta_0\phi_1(\beta x) - \frac{M_0}{EI\beta}\phi_2(\beta x) - \frac{Q_0}{EI\beta^2}\phi_3(\beta x) \tag{7}$$

The particular solution of Eq. (3) can be obtained:

$$f = \frac{1}{EI\beta^3}\int_0^x Ku(z)\phi_4[\beta(x-z)]dz \tag{8}$$

And the particular solution of Eq. (3) is:

$$f = -\frac{4\delta}{L^2}x^2 + \frac{4\delta}{L}x - \frac{8\delta}{L^2\beta^2}\phi_3(\beta x) - \frac{4\delta}{L\beta}\phi_2(\beta x) \tag{9}$$

So, the vertical displacement equation of the pipeline can be obtained by initial parameter:

$$y = y_0\phi_1(\beta x) + \frac{\theta_0}{\beta}\phi_2(\beta x) - \frac{M_0}{EI\beta^2}\phi_3(\beta x) - \frac{Q_0}{EI\beta^3}\phi_4(\beta x) + f \tag{10}$$

The initial parameters are determined by the boundary conditions. At the O point, $y(0) = 0$. So, $y_0 = 0$, $\theta_0 = 0$. At the L point, $y(L) = 0$. So, M_0 and Q_0 can be obtained by displacement equation and rotation equation as follows:

$$\frac{M_0}{EI\beta^2}\phi_3(\beta L) + \frac{Q_0}{EI\beta^3}\phi_4(\beta L) + \frac{8\delta}{L^2\beta^2}\phi_3(\beta L) + \frac{4\delta}{L\beta}\phi_2(\beta L) = 0 \tag{11}$$

$$\frac{M_0}{EI\beta}\phi_2(\beta L) + \frac{Q_0}{EI\beta^2}\phi_3(\beta L) + \frac{8\delta}{L} - \frac{8\delta}{L^2\beta}\phi_2(\beta L) + \frac{4\delta}{L}\phi_1(\beta L) - \frac{4\delta}{L} = 0 \tag{12}$$

Then the vertical displacement equation can be expressed as follows:

$$y = -\frac{4\delta}{L\beta}\phi_2(\beta x) - \left[\frac{M_0}{EI\beta^2} + \frac{8\delta}{L^2\beta^2}\phi_3\right](\beta x) - \frac{Q_0}{EI\beta^3}\phi_4(\beta x) - \frac{4\delta}{L^2}x^2 + \frac{4\delta}{L}x \tag{13}$$

The horizontal displacement of the pipeline can be obtained by the

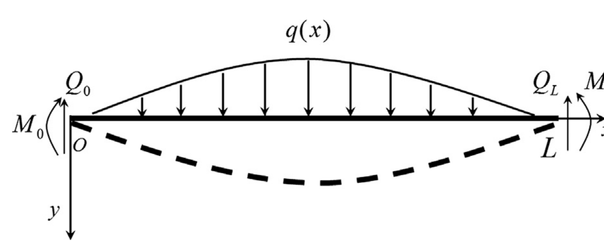

Fig. 1. Schematic diagram of a pipeline under the load.