Impact of Deep Excavations on Adjacent Buried Pipelines

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Abstract

Construction of skyscrapers in China encouraged the development of deep excavation designs (e.g., the excavation of Shanghai Jin-mao Tower is 19.5m in depth). Deep excavations usually lie among the dense areas of buildings, roads, and underground pipelines, all of which can be greatly affected by the deep excavations. In severe cases, deep excavations have caused the tilting and cracking of buildings, the settlement of roads, and dramatic deformation and damage of adjacent buried pipelines, thus greatly affected people's daily life. These possible impacts of deep excavations on the adjacent infrastructures remain the key issue in designing deep excavations. The reason is that the strength of earth-retaining structures has been emphasized, while the protection of the surrounding structures was ignored. Deep excavations and the surrounding environment should be considered together as a whole system, and the strength of earth-retaining structures and the protection of adjacent structures should be equally treated in design.

In this paper, a 3-D finite element method (FEM) was developed to analyze the interaction among earth-retaining structures, soil, and adjacent buried pipelines. Based on this method, the displacement and the stress of nearby buried pipelines due to excavation were calculated. This paper analyzed the effect of soil improvement on reducing the displacement of buried pipelines. Through analysis of different soil improvement methods, the best protection plan for pipelines was derived. This paper also compared the behavior of buried pipelines with ductile joints with the pipelines with rigid joints. Conclusions drawn in this paper may assist in the design and construction of deep excavations.

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Numerical Simulation of the Protection Methods of Buried Pipelines

Simulation of Excavation
Calculation of the excavation load is the key to the FEM simulation of the excavation process. The equivalent excavation load is the interaction force between the excavated soil and the undisturbed soil. The excavation load, under the no-drainage condition as used in this paper, was determined by Brown (1985) and may be written as:

\[ \{f\} = \int [B]^T \{\sigma\}dv - \int [N]^T \{\gamma\}dv \]  

where \( \{f\} \) = equivalent excavation load vector, \( \{f\} \) is related to the stress condition and self-weight of the excavated soil

\( [B] \) = strain matrix

\( \{\sigma\} \) = soil stress vector

\( [N] \) = shape function matrix

\( \{\gamma\} \) = unit soil self-weight vector

\( v \) = excavation zone.

Simulation of the Interface Between Soil and a Retaining Structure
The contact of an earth-retaining structure with soil is of particular interest due to the difference of the deformation modulus between reinforced concrete and soil. In the earlier studies of the interaction between soil and retaining structures, two extreme hypotheses were used: (1) the contact interface is so abrasive that there is no relative movement between the soil and the retaining structure; and (2) the contact interface is so smooth that there is no shear stress to withstand the relative movement between the soil and the retaining structure. Apparently, the two hypotheses are idealized and cannot adequately address the real situation where both relative movement and shear stress between the soil and the retaining structure exist. To consider the movement between soil and a retaining structure, the widely used Goodman’s interface element (1968) was adopted in this paper.

Simulation of Buried Pipelines
Buried pipelines can be simulated by the elastic shell theory. There are two FEM approaches to analyze the elastic shell. One approach is to substitute the shell with a hinged plate system, which is made up of thin elements to obtain the stress condition of the shell by considering the plane stress condition and the annular stress condition; the second approach is to derive the elemental stiffness matrix using the shell theory by directly using circular plate elements. The latter method was adopted in this paper.

Case Study
Data from a project (Jinchao Building in Hangzhou, China) were taken to evaluate the FEM method developed in this paper. Figure 1 depicts a cantilever excavation pit. The excavation depth is 5m, the width of the retaining structure is 0.6m, and the burial depth is 10m. The impacted zone of the excavation, which is the soil zone beyond the excavation pit but still affected by the excavation, was analyzed using the
FEM method. Due to the symmetry of excavation, only half of the excavation pit is analyzed (Figure 1). According to construction experience and FEM calculation, the width and the depth of the impacted zone are at least 4 times of the excavation depth. In this study, in order to consider a broader calculation range, the width (45m) and the depth (30m) of the impacted zone take 9 and 6 times of the excavation depth (5m), respectively. Therefore, the study area is 60.6m x 121.2m x 35m (W x L x D, Figure 1). Figure 2 is the cross-sectional illustration of the excavation pit, three soil layers, and a pipeline near the excavation pit. Two scenarios were investigated in this case study.

![Figure 1. Plane layout of the excavation pit, pipeline and impacted zone](image)

**Impact of Soil Treatment on Buried Pipelines**

Soil treatment is a common method to control the displacement of retained structures. Ou (1996) proposed three typical patterns of treated soil used in excavation – block type, column type, and wall type. The block type is more effective in treatment than the other two, although it is more costly. This paper utilized the block type to analyze the treated soil, which is shown in Figure 2 as the shaded area with the width (B2) and depth (H2) equal to 6m and 10m, respectively. The soil was treated using cement mixing piles.

Figure 3 shows the calculated results of pipeline displacements before and after the soil treatments. As shown in Figure 3, the initial elastic modulus of the soil before the treatment, denoted as E_s, was 4MPa, and the elastic modulus of the soil after treatment, denoted as E_{ts}, was chosen to be 10, 20 and 40 times of E_s, respectively. Figure 3 indicates that when the elastic modulus of the treated soil is enhanced to 10 times of the original value, the horizontal displacement of the pipeline decreases by 56%, and the vertical displacement decreases by 57%. It can also be seen in Figure 3 that the soil treatment is greatly effective in decreasing the
displacement of the pipeline that directly faces the excavation pit \((45m \sim 60.6m\) in \(x\) coordinate, Figure 1), but almost has no effect on decreasing the displacement of pipeline that does not directly face the excavation pit \((0 \sim 45m\) in \(x\) coordinate, Figure 1). Figure 3 also shows the comparable impact of soil treatment on both vertical and horizontal displacements.

Figure 4 shows the relationship between the maximum displacement of the pipelines and the ratio of the soil treatment depth to width \((H/B_j\) where \(B_j\) is kept constant as 6m in this case, Figure 2). Both figures 4 (a) and 4 (b) generally show the decrement of the maximum displacement of pipeline with the increment of \(H/B_j\). When \(H/B_j\) is approximately 1.7 as indicated in Figure 4 (a), the maximum displacements showed almost no changes beyond this value, although this trend is not as prominent in Figure 4 (b) as it is in Figure 4 (a). In summary, Figure 4 reveals that given a soil treatment width, the treatment depth has a value for optimum treatment.

![Figure 2](attachment:image.png)

**Figure 2.** Cross section of the excavation

![Figure 3](attachment:image.png)

(a). Horizontal displacements  
(b). Vertical displacements

**Figure 3.** Pipeline displacements before and after soil treatments
(a) Relation of maximum horizontal displacement with $H_j/B_j$

(b) Relation of maximum vertical displacement with $H_j/B_j$

**Figure 4.** Maximum displacements of pipeline related to $H_j/B_j$

**Impact of Base Soil Treatment Under Pipeline on Pipeline Displacement**

Figure 5 illustrates another soil treatment plan, in which the treated soil (treated using cement mixing piles) is right beneath the pipeline. The pipeline displacements before and after soil treatment were calculated and are shown in Figure 6. Figure 6 (a) shows that the base soil treatment has no effect on horizontal pipeline displacement, while Figure 6 (b) shows great impact of base soil treatment on vertical pipeline displacement. When the treatment depth ($H_j$) was 3.5m, the maximum vertical displacement decreased by 18%; and when $H_j=11$m, the maximum vertical displacement decreased by 35%. Figure 6 (b) also indicates that vertical displacement does not always decrease as the treatment depth increases. In summary, there exists a critical treatment depth beyond which vertical displacement decreases very little. From Figure 6 (b), this depth can be taken as approximately 8.5m, because the vertical displacement when $H_j$ is equal to 11.0m shows little difference from the vertical displacement when $H_j$ is equal to 8.5m.

![Diagram of base soil treatment under the pipeline]

**Figure 5.** Base soil treatment under the pipeline
Investigation of Pipelines with Ductile Joints

There have not been many studies on pipelines with ductile joints. Although most pipeline manufactures conduct pipe-burst tests, experimental data of the strength of ductile joints are limited. This paper, based on Singhal's study (1984), developed the stiffness matrix of ductile joints and calculated the displacements of flexible pipelines and the stress of joints. The simulation of pipeline joints is stated in the following section.

Simulation of Ductile Joints

Ductile joints for pipelines are usually sealed by rubber gaskets, which provide skin friction between the inside wall of the joint and the gasket itself. The friction prevents the dislocation of joints when pipelines displace. The maximum pullout strength to dislocate a joint is determined by the pullout resistance test. Singhal
(1984) tested ductile iron pipes with diameters of 100mm, 150mm, 200mm, and 250mm, respectively, and derived formulas to calculate the axial pullout strength, bending moment, and torsional moment. These formulas are shown below.

**Axial Pullout Resistance**

The axial pullout resistance is expressed as:

\[ P_{\text{max}} = \frac{5}{24} \pi \mu E_i D \phi \left( \frac{D - I}{e - \phi} \right) \]

where \( \mu \) = friction coefficient between rubber gasket and pipeline, approximately 0.1
\( E_i \) = equivalent elastic modulus of rubber, approximately 255MPa
\( D \) = diameter of rubber gasket, mm
\( e, \phi \) = outside and inside diameters of pipeline joint, respectively, mm
\( I \) = joint fissure, it is calculated by \((e - \phi)/2\), mm.

**Bending**

The applied moment at the joint is balanced by the stress in the rubber gasket. Given the joint shape, the shape of the compressed gasket, and the elastic modulus of rubber, the value of maximum bending moment resistance for the joint can be calculated by the following equation:

\[ M = \frac{4\pi \phi^3}{9(e - c)} \theta \]

where \( \theta \) = joint rotation, in radians
\( f \) = the length of niche in which the gasket fits, mm
\( c \) = the inner lip of the bell in the joint, mm.

**Torsion**

During pipeline installation, the friction between the compressed rubber gasket and the wall of a pipeline joint produces the torsion moment resistance. Once the torsion moment resistance is reached, the joint will rotate freely and can no longer provide any resistance. The calculation of maximum torsional moment resistance is written as:

\[ T = \pi \mu \phi^2 E_i B \left( \frac{D - I}{2D} \right) \]

where \( B \) is the width of the rubber gasket, mm.

**Case Study**

A cantilever excavation pit is used to study the behavior of pipelines with ductile joints using the FEM method as discussed in this paper. Figure 7 illustrates the plane layout of the pit, and Figure 8 depicts the cross section of the excavation pit. The excavation pit is 30m in both length and width, the excavation depth is 5m, the retaining structure width is 0.6m, and the burial depth is 10m. According to the structural symmetry and field experience, one fourth of the actual excavation zone is considered in the calculation. The dimensions of the study area in the FEM method are 60m x 35m x 35m (L x W x D).
The layout of a buried pipeline is shown in Figure 9. The burial depth is 2m, the pipeline diameter is 1m, the length of joint is 0.1m, and the distance of the pipeline from the excavation pit boundary where the retaining structure is located, is 15m. The pipeline is laid out in a way that the joints #1, 2, 3, and 4 do not directly face the excavation pit, while the joints #5 and 6 directly face the excavation. According to the specification, the length of a pipe segment between two joints is 5m. The pipeline joint is simulated by a spatial beam element.

The displacements of the flexible and rigid pipes were calculated and are shown in Figure 10, and the stresses of the flexible and rigid pipes are shown in Figure 11. Figure 10 indicates that, in contrast to rigid joints, ductile joints deflect accordingly with the displacement of the pipeline. Under the same condition, flexible pipelines show more displacement than rigid pipelines do, but the stress of flexible pipelines is less than that of rigid pipelines, as shown in Figure 11. As it usually occurs in the field, when a rigid pipeline fails, a flexible pipeline with ductile joints still works.
properly under the same condition. This is because ductile joints deflect accordingly with the pipeline.

Figure 11 shows that both the flexible and the rigid pipeline segments that directly face the excavation pit are subjected to compression (negative value), while both pipeline segments that do not directly face the excavation pit are subjected to tension (positive value). This is because during excavation the soil outside of the excavation pit pushes inwards towards the soil within the excavation pit. Unfortunately, there is limited in-situ data of longitudinal displacement of buried pipelines.

Table 1 lists the values of the longitudinal displacements and axial stresses of the ductile joints. For stresses, positive value indicates tension and negative value indicates compression. In Table 1, the axial tension of joint #1 is 1.6kN, which is greater than \( P_{\text{max}} = 1.482 \text{kN} \) (calculated from Equation 2). This means that this joint
Table 1. Longitudinal Displacements and Axial Stresses of Joints of Ductile Joints

<table>
<thead>
<tr>
<th>Joints</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
<th>#6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal displacement (mm)</td>
<td>0.0473</td>
<td>0.045</td>
<td>0.03919</td>
<td>0.01285</td>
<td>-0.03526</td>
<td>-0.08885</td>
</tr>
<tr>
<td>Axial stress (kN)</td>
<td>1.6</td>
<td>1.4</td>
<td>1.2</td>
<td>0.3</td>
<td>-1.2</td>
<td>-2.7</td>
</tr>
</tbody>
</table>

fails. The tension of joints #2, #3 and #4 are less than P_{max}, therefore these joints continue to function. Joints #5 and #6 are subjected to compression, and generally are less likely to fail. Data in Table 1 also indicate that the failure of flexible pipeline is usually due to the joint pullout that occurs in the pipeline segment that does not directly face the excavation pit.

Conclusions

This paper studied the displacement of buried pipelines under, or adjacent to, an excavation. This paper also demonstrated that treating specific areas of soil is an effective method to protect existing pipelines. When the width of the treated soil is fixed, there exists a critical depth for optimum treatment. When the depth of the treatment exceeds this critical depth, the protection improves very little. It can also be concluded that flexible pipelines with ductile joints have more displacement flexibility than rigid pipelines. With the same displacement, when rigid pipelines fail, flexible pipelines can still function properly. The failure of flexible pipeline is usually due to the joint pullout.

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References


