Study on Deformation of Shallow Buried Underground Pipe Gallery

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Abstract. The underground pipe gallery is a symbol of modernization and intensification of urban construction. Domestic research on the deformation of underground pipe gallery started late and has not yet formed a unified standard. Based on the deformation requirements and deformation control standard of the internal pipeline of the pipe gallery, the longitudinal deformation control standard of the integrated pipe gallery is preliminarily established. The main conclusions are as follows: Based on the deformation requirements of the underground pipe gallery, the equation for calculating the allowable value of the longitudinal radius of curvature of the pipe gallery is proposed. Comparing the safety standards of various types of inlet pipelines, the longitudinal deformation allowable value of the pipe gallery is given. At the same time, the influence of surface load on the deformation of pipeline gallery is analyzed by theoretical analysis and model test, and the theoretical and experimental results are compared. The results indicate that theoretical calculation features accuracy and practicality.

1. Introduction

The underground pipe gallery is a symbol of modernization and intensification of urban construction. China is promoting the construction of utility tunnels on a large scale. Nevertheless, the applicable deformation-controlled standard of tunnel structure has not been established. The development of the pipe gallery construction has been restricted by the lack of applicable standards. Therefore, the need of carrying out research on deformation-controlled standard of tunnel structure arises.

A series of related researches have been conducted to investigate the force and deformation characters of underground utility-tunnel. Petrukhin et al. [2] presented a calculating method of width of the zone of influence in underground utility-tunnel construction. Shamsabadi et al. [3-5] conducted research on interaction between soil and structure and Anti-Seismic and Reinforcement Measures in underground construction. Nishioka and Unjoh et al. [6] studied the seismic performance of five kinds of rectangular sections of pipe gallery and proposed a concise analysis method for the seismic performance of pipe gallery with rectangular section.

Domestic research on the deformation of underground pipe gallery is far from complete and lacks construction reference standard. Therefore, this paper conducts a theoretical study on the deformation characteristics and analyzes the influence of the orthogonal strip load on the deformation of the pipe gallery.
2. Study on the standards of deformation-controlled for pipe gallery

2.1. Standards of deformation-controlled for pipe gallery based on pipe structure

2.1.1. Moment of pipe gallery. The Based on the design code of concrete structure\(^\text{[7]}\), the stress of longitudinal bars in tensile area of reinforced concrete members or the equivalent stress of longitudinal bars in tensile area of prestressed concrete members can be calculated according to the following equation under quasi-permanent combination or characteristic combination of loading.

\[
\sigma_{eq} = \frac{M_s}{0.87h_b A_s} \tag{1}
\]

\(A_s\), area of longitudinal bars in tensile region, \(A_s = A p_{min}\); \(h_b\), the effective height of section, \(h_b \approx h\) (concrete cover thickness is small relative to the height of the pipe gallery).

Ratio of reinforcement \(\rho = \rho_{min} = 0.2\%\). Calculation of reinforcing bars of reinforced concrete box girder is reference to the research of Lixia Lin et al.\(^\text{[8]}\) as below. Figure 1 shows the parameters of reinforced concrete box girder.

\[
A_s = 0.002A = 0.02bh(1 + \gamma_1 + \gamma_2) \tag{2}
\]

\[
b = b_1 + b_2, \gamma_1 = \frac{(b_f - b)h_f}{bh}, \gamma_2 = \frac{(b_f' - b)h_f'}{bh} \tag{3}
\]

\[
M_s = 0.00175bh^2\sigma_{eq}(1 + \gamma_1 + \gamma_2) \tag{4}
\]

\(\sigma_{eq}\), equivalent stress of longitudinal bars in tensile area; \(\gamma_1\), \(\gamma_2\), section coefficient of box girder; \(h\), height of section; \(b\), width of section, \(b = b_1 + b_2\).

2.1.2. Radius of curvature of pipe gallery. Based on Design Code of Concrete Structure\(^\text{[7]}\), according to the relationship between the bending moment of the bending structure and the radius of curvature, The bending moment acting on the pipe can be calculated:

\[
M = BR^4 \tag{5}
\]

\(R\), radius of curvature.

\(B\), long-term rigidity of reinforced concrete structure, \(B = B_r \theta^4; B_s\), short-term rigidity of reinforced concrete structure, \(B_s = 0.85E; \theta\), influence coefficient which is 1.6 according to design code of concrete structure.

Substituting equation (3) to equation (4), longitudinal radius of curvature of the pipe gallery is calculated as:

\[
R = \frac{300EI}{bh^2\sigma_{eq}(1 + \gamma_1 + \gamma_2)} \tag{6}
\]

2.1.3. Analysis of examples. Taking a typical section of two-cabin pipe gallery as an example, calculate allowable value of longitudinal radius of curvature of pipe gallery.
Design parameters: Cross-sectional width \( d = 6000 \text{ mm} \); Cross-sectional height \( h = 3950 \text{ mm} \); Coping thickness \( t_c = 350 \text{ mm} \); Base plate thickness \( t_b = 400 \text{ mm} \); Lateral thickness \( t_l = 350 \text{ mm} \); Compartments thickness \( t_c = 300 \text{ mm} \).

Elastic modulus of concrete \( E = 3.0 \times 10^7 \text{kN/m}^2 \); Longitudinal bending rigidity of structure \( EI = 5.148 \times 10^8 \text{kN/m}^2 \); Design strength of steel bar \( f_{py} = 300 \text{ Mpa} \).

Moment of pipe gallery is calculated by equation (3):
\[
M_q = 0.00175bh^2\sigma_q(1+\gamma_1+\gamma_2) = 1.916 \times 10^4 \text{kN\cdotm}
\]  \( (6) \)

Allowable value of longitudinal radius of curvature of pipe gallery is calculated by equation (5).
\[
R = \frac{300EI}{bh^2\sigma_q(1+\gamma_1+\gamma_2)} = 15000 \text{ m}
\]  \( (7) \)

2.2. Deformation control standard of the internal pipeline of the pipe gallery

Based on the Design Code of Utility-Tunnel Construction, urban engineering pipelines such as water supply, rainwater, sewage, reclaimed water, natural gas, thermal, electricity, and communications pipeline can be brought into the underground pipe gallery. There are different kinds of internal pipelines in the gallery. These pipelines have different requirements for deformation control. The deformation of the pipe gallery should ensure the safety of all types of pipelines.

Settlement control is usually adopted to monitor the deformation of pipeline in civil engineering. The following introduces the settlement-control standards currently used in China, as shown in Table 1.

| Standard | Content |
|----------|---------|
| Technical Specification for Excavation Engineering Safety Monitoring (GB 50497—2009) | Rigid pipelines with pressure: accumulated value 10~30 mm, variation rate 1~3 mm/d; Rigid pipelines without pressure/ flexible pipelines: accumulated value 10~40 mm, variation rate 3~5 mm /d; |
| Engineer Handbook for Excavation (2009) | Gas pipelines: Settlement or horizontal displacement should not exceed 10 mm, and should not exceed 2 mm/d; Water pipelines: Settlement or horizontal displacement should not exceed 30 mm, and should not exceed 5 mm/d; |
| Beijing Technical Management System of Environmental Safety Risk for Rail Transit Engineering (2008) | Pressured pipelines: Displacement should not exceed 10 mm and inclination rate should not exceed 0.002. |
| Shanghai Designing Specification for Pipeline Structure in Water and Wastewater Engineering (GB50332-2002) | Gas pipelines: horizontal displacement should not exceed 10~15 mm; Water pipelines: horizontal displacement should not exceed 30~50 mm. |

Compared with those settlement-control standards, the pipelines in the gallery can be divided into rigid pipes and flexible pipes, in which the allowable value of deformation of rigid pressure pipes is strict, such as: the allowable value of settlement or horizontal displacement of gas pipelines is 10~15 mm, and the displacement rate should not more than 2 mm / d. The allowable deformation value of flexible pipeline is relatively large, for example, the water pipeline is 30~50 mm, and the displacement rate should not more than 5 mm / d.

In a word, Based on this example, the longitudinal deformation control standard of pipe gallery is as follows: ① Allowable value of longitudinal radius of curvature of pipe gallery is 15000m. ② Allowable value of settlement or horizontal displacement of gas pipelines is 10mm~15mm, displacement rate should not more than 2 mm / d.
3. Study on the effect of orthogonal strip load on deformation of pipe gallery

3.1. Nonuniform settlement caused by orthogonal strip load at the pipe gallery

This section uses two-phase method, based on the Pasternak bi-parameter elastic foundation infinite beam model, and uses the finite difference theory to give a solution to the deformation of the pipe gallery under strip loading.

3.1.1. Pasternak ground model. Equilibrium differential equation of pipe gallery in Pasternak ground model:

\[
(EI)\frac{d^4 w(x)}{dx^4} + kDw(x) - G_c D\frac{d^2 w(x)}{dx^2} = q(x)D
\]

(8)

\(D\), width of the pipe gallery; \(w\), vertical displacement of the pipe gallery; \(k\), modulus of foundation pressure; \(G_c\), rigidity of shearing layer.

Tanahashi \([9]\) suggested that rigidity of shearing layer can be defined as follows:

\[
G_c = 2t \frac{E_t}{6(1-V_t)}
\]

(9)

\(t\), influence depth of tunnel deformation in in Pasternak ground model.

3.1.2. Finite difference method. Use finite difference method to solve equilibrium differential equation of pipe gallery in Pasternak ground model. The pipe is discrete into several sections longitudinally, and the displacement values of the nodes are treated as unknowns. With the help of Matlab software, calculate the displacement of each node \([10-11]\).

3.2. Analysis of examples

Taking the analysis of the influence of the orthogonal stripe load on the existing pipe gallery in Shanghai as an example, the soil parameters of the site are shown in Table 2. Longitudinal bending rigidity of structure is \(EI=5.148\times 10^8\text{kN/m}^2\), Embedded depth is 2.5m. There is an orthogonal strip load at the surface over the pipe gallery. The width of load is 15m. The value of load is 20 kPa.

| Soil layer       | Thickness/m | Unit weight (KN/m$^3$) | Compression modulus /MPa |
|------------------|-------------|------------------------|--------------------------|
| ② silt clay      | 2.0         | 1.88                   | 4.83                     |
| ③ mucky silty clay | 6.0         | 1.78                   | 3.24                     |
| ④ silt clay      | 10.0        | 1.75                   | 2.3                      |
| ⑤ silt clay      | 10.0        | 1.83                   | 5.2                      |
| ⑥ silt clay      | 4.0         | 1.98                   | 7.47                     |
| ⑦ 1 sandy silt   | 16.0        | 1.89                   | 11.5                     |
| ⑦ 2 silt         | —           | 1.92                   | 15.3                     |

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Embedded depth of pipe gallery is 2.5m. Height of pipe gallery is 3.95m. The elastic modulus of the soil layer underneath the pipe gallery is about 4 times the compressive modulus, then \(E_s=3.2\times 4=12.8\text{MPa}\).

Coefficients of foundation bed:

\[
k = 0.65 \frac{E_s}{B(1-V_s)^2} \left( \frac{E_s D^4}{EI} \right)^{\frac{1}{2}} = 1.168 \times 10^4\text{kN/m}^3
\]

(10)

Rigidity of shearing layer:

\[
G_c = 2t \frac{E_s 2.5D}{6(1-V_s)} = 24.06\text{MN/m}
\]

(11)
The vertical displacement of pipe can be obtained by substituting the $k$, $G$, to finite difference method, as shown in Figure 2, which tells that the displacement of the pipe gallery caused by the additional stress is 5.5mm. The main area of deformation is -40m ~ 40m, which is about 6 times the width of the load (15m). Outside the range of 6 times the width, the pipe gallery has a reversal deformation, but the deformation is small.

![Figure 2. displacement of pipe gallery caused by strip load](image)

4. Analysis of the results

According to the theory in the previous section, by substituting the parameters of the model test into the calculation theory, the deformation and stress of the pipe gallery can be solved.

Parameters in the theoretical calculation: strip load width of 20cm, load value of 4kPa, length of pipe gallery 75cm, buried depth of pipe gallery 5cm, longitudinal bending stiffness $EI = 4.1\text{kN} \cdot\text{m}^2$, elastic modulus of soil $Es = 12.6\text{MPa}$. Deformation and stress of the pipe gallery can be solved by theoretical calculations.

In this paper, theoretical analysis is performed to compare the deformation and stress of the pipe gallery under the fourth-grade load (4kPa) in the model test. Figure 3 is a comparison between the model tests and theoretical calculations of the vertical displacement, the additional stress at the bottom, and the longitudinal moment of the pipe gallery under the fourth-grade load. It can be seen from the figure that the theoretical values of the displacement and additional stress are in good agreement with the model tests. There is a difference between the theoretical value and experimental value in longitudinal moment at both ends of the pipe gallery. It shows negative bending moments at both ends of the pipe gallery in model tests. But the theoretical calculations do not show that. This may happen because that the pipe gallery is considered as an infinite beam in the theoretical calculation, and the bending moment at both ends of the pipe are not considered. The longitudinal length of the pipe gallery is relatively small in theoretical calculation, which does not meet the assumption of an infinite. However, the overall difference between the two is not large, and the two are consistent in their changing trends.

Overall, the results indicate that theoretical calculation features accuracy and practicality.

![Figure 3. Comparison between the model tests and theoretical calculations](image)
5. Conclusion

Based on the deformation of pipe gallery and internal pipeline, the theoretical research on the longitudinal deformation control standards of the pipe gallery is carried out. Aiming at the effects of orthogonal strip loads on the deformation and stress of the pipe gallery, this paper studies the theoretical analysis and model tests, and compares the theoretical calculation and experimental results. The main research conclusions are as follows:

1. According to the deformation control requirements of the pipe gallery, the allowable value of the longitudinal bending moment of the pipe gallery is given. Based on the relationship between the bending moment of the bending member and the curvature radius, the allowable value of the longitudinal curvature radius is given.

2. The safety control standards of various pipelines are compared and analyzed, and the allowable values of settlement or horizontal displacement of pipelines such as gas pipelines and water pipelines are comprehensively considered. Compared with the calculation examples in this paper, the control standards for the deformation of the pipe gallery are: ① Allowable curvature radius of the pipe gallery $R = 24000m$; ② Allowable longitudinal displacement of pipe gallery is 10mm~15mm.

3. Based on two-phase method and the Pasternak model, using the finite difference theory, the solution of the deformation and stress of the pipe gallery under strip loading is given.

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