Deformation Control Standard of Utility Tunnel Based on Crack Control Standard

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Abstract. The construction of underground utility tunnel is being carried out on a large scale in China, however there is no corresponding control standard for the structural deformation of utility tunnel, so it is very necessary to establish the deformation standard of utility tunnel. In this paper, the maximum longitudinal bending moment of utility tunnel and the maximum stress of reinforcement controlled by cracks were used to establish the longitudinal deformation standard of utility tunnel structure. In addition, numerical simulation was used to analyze the deformation characteristics of underground composite utility tunnel under different section sizes and soils. And simulation results indicate that the crack reached its maximum of 0.2mm when maximum deformation curvature of utility tunnel was 2.12025*10⁻⁵.

1. Introduction

With the continuous development of urbanization, the demands of modern cities for municipal pipelines are increasing. However, the current layout mode makes many cities frequently appear the phenomenon of “road chain pulling” [1].

The construction of underground comprehensive utility tunnel has a long history in foreign countries and many achievements have been made. Takada zhiro et al. [2] began to analyze the instability mechanism of underground integrated utility tunnel caused by soil liquefaction in the 1970s, and summarized corresponding treatment measures [3]. Petrukhin et al. [4] proposed a method to determine the range of ground deformation caused by underground comprehensive utility tunnel construction. Nishioka T and Unjoh S [5] presented a concise analysis model of seismic performance of rectangular section utility tunnel.

Although the research on underground comprehensive utility tunnel started late in China, with the vigorous development, related researches develop rapidly and have made some achievements. Li’s research group of tongji university [6-8] used the layered sandbox based on variable stiffness method to analyze the seismic response law. Tan et al. [9] used fuzzy theory to evaluate the safety of the comprehensive utility tunnel. Wang et al. [10] used finite element software to analyze the main structure of the utility tunnel and proposed reinforcement measures.

In conclusion, the researches on underground comprehensive utility tunnel by domestic and foreign scholars mainly focus on seismic analysis and reinforcement, planning, construction methods, etc, but there are few researches on the deformation of utility tunnel and no deformation standards have been given. Therefore, based on the calculation of maximum crack width and maximum bending moment of
underground composite utility tunnel, the longitudinal deformation standard of underground composite utility tunnel structure is preliminarily established in this paper.

### 2. Provision of maximum crack width in utility tunnels

Referring to Urban Comprehensive Utility Tunnel Engineering Specification (GB50838-2015) [11], the crack control level of utility tunnel should be level 3, the maximum crack width shall be less than or equal to 0.2mm. Therefore, \( \omega_{\text{lim}} = 0.2 \text{mm} \).

When calculating the maximum bending moment of the utility tunnel, related contents of crack checking in the code for design of concrete structures should be involved. According to the Code for Design of Concrete Structures (GB 50010-2010), the maximum crack width of reinforced concrete members can be calculated with the effect of quasi-permanent load combination and long-term effect. The maximum crack width shall meet the following requirements:

\[
\omega_{\text{max}} \leq \omega_{\text{lim}}
\]

(1)

In the meantime, according to standard load combination or quasi permanent combination and considering the long-term effect, the maximum crack width can be calculated by the following formulas when it comes to reinforced concrete in tension, bending and eccentric compression member and axis of prestressed concrete in the tensile and flexural members of rectangle, T, Inverted T and I shaped cross section:

\[
\omega_{\text{max}} = \alpha_{c} \Psi \frac{\sigma_{s}}{E_{s}} (1.9 c + 0.08 \frac{d_{c}}{\rho_{c}})
\]

(2)

\[
\Psi = 1.1 - 0.65 \frac{f_{\text{tk}}}{\rho_{se} \sigma_{s}}
\]

(3)

\[
d_{eq} = \frac{\sum n_{i} d_{i}^{2}}{\sum n_{i} d_{i}}
\]

(4)

\[
\rho_{se} = \frac{A_{s}}{A_{c}}
\]

(5)

Where \( \sigma_{s} \) is longitudinal tensile reinforcement stress and calculated in equation (9); \( \alpha_{c} \) is Characteristic coefficient of member stress, and \( \alpha_{c} = 0.7 \); \( d_{eq} \) is equivalent diameter of reinforcement; \( \Psi \) is Stress nonuniformity coefficient of reinforcement; \( \rho_{se} \) is effective reinforcement ratio of section; \( c \) is concrete cover, \( f_{\text{tk}} \) is standard value of axial tensile strength.

According to Urban comprehensive utility tunnel engineering specification GB50838-2015, the concrete strength grade of reinforced concrete structures shall not be lower than C30. The concrete strength grade of prestressed concrete structures shall not be lower than C40. Hence, the strength of concrete in this research is set at C30. Therefore, \( f_{\text{tk}} = 2.01 \text{ N/mm}^{2} \), and the minimum reinforcement ratio of the longitudinal reinforced concrete structure is \( \rho_{\text{min}} = 0.2\% \). Substituting equation (3):

\[
\Psi = 1.1 - 0.65 \frac{f_{\text{tk}}}{\rho_{se} \sigma_{s}} = 1.1 - 0.65 \frac{2.01}{0.01 \sigma_{s}} = 1.1 - \frac{130.65}{\sigma_{s}}
\]

(6)

According to Urban Comprehensive Utility Tunnel Engineering Specification (GB50838-2015) and Design Guide of Japanese Underground Comprehensive Utility Tunnel, the concrete cover in this paper is 65mm. The elastic modulus of steel reinforcement is \( 2.00 \times 10^{5} \text{N/mm}^{2} \), based on HRB335 and HRB400 which are commonly used in engineering practice. According to actual engineering experience, the diameter of steel bar is \( d = 12 \text{mm} \), and \( \psi = 0.7 \). And substituted into equation (4), it can be obtained:
Substituting equation (6) and equation (7) into equation (2):

\[ 0.2 = 0.7 \times (11 - \frac{130.65}{\sigma_s}) \times \frac{\sigma_s}{2.0 \times 10^4} \times (1.9 \times 65 + 0.08 \times \frac{17.14}{0.01}) \]

\[ \sigma_s = 318.10N \]

(9)

3. Calculation of the maximum bending moment of utility tunnels

According to the Code for Design of Concrete Structures (GB 50010-2010), under quasi-permanent load combination or standard combination, the stress of longitudinal ordinary reinforcement in the tensile zone of reinforced concrete members or the equivalent stress of longitudinal reinforcement in the tensile zone of prestressed concrete members can also be calculated with the following formula.

For bending members:

\[ \sigma_{sq} = \frac{M_q}{0.87h_o A_s} \]

(10)

Where: \( A_s \): longitudinal ordinary reinforcement in tension zone; \( M_q \): bending moment value calculated by quasi-permanent load combination; \( h_o \): effective height of section.

Take the ratio of reinforcement \( \rho = \rho_{\text{min}} = 0.2\% \), therefore \( A_s = 0.002bh \). And \( h_o \) is the effective height of the section. Since the concrete cover is smaller compared to the full height of the utility tunnels, hence \( h_o \approx h \).

Substitute the above parameters into equation (10):

\[ M_q = \sigma_{sq} \cdot 0.87h_o A_s = 0.00175bh^2 \sigma_{sq} \]

(11)

Substituting the results obtained in equation (9) into equation (11):

\[ M_q = 0.557bh^2 \]

(12)

Bending moment of unit width:

\[ M' = \frac{M_q}{b} = 0.00175h^2 \sigma_{sq} \approx 0.557h^2 \]

(13)

4. Analysis of ABAQUS numerical calculation results

Taking a typical section of two-cabin utility tunnels as an example (as shown in Figure 1 and Table 2), calculate allowable value of longitudinal radius of curvature of utility tunnels.

Figure 1. typical section of two-cabin utility tunnels

Design parameters: Cross-sectional width \( d = 6000\) mm; Cross-sectional height \( h = 3950\) mm; Coping thickness \( t_t = 350\) mm; Base plate thickness \( t_t = 400\) mm; Lateral thickness \( t_t = 350\) mm; Compartments thickness \( t_t = 300\) mm;

Elastic modulus of concrete \( E = 3.0 \times 10^7\) kN/m²; Longitudinal bending rigidity of structure \( EI = 5.148 \times 10^8\) kN/m²; Design strength of steel bar \( f_{py} = 300\) Mpa.
Table 1. soil parameters

| Parameter | Value   |
|-----------|---------|
| $\gamma$ | 19.09 kN/m$^3$ |
| $e$       | 0.849  |
| $w$       | 30.04% |
| $a_{1-2}$ | 0.34 MPa $^{-1}$ |
| $E_{1-2}$ | 6.44 MPa |
| $c$       | 7.7 kPa |
| $\phi$    | 25.72 MPa |
| $E$       | 19.32 MPa |
| $k$       | 21.252 Mpa/m |

The element mesh in the Concrete Damaged Plasticity model in ABAQUS is continuous and can’t show the crack development width. Therefore, this paper used the method of calculating the longitudinal deformation curvature of utility tunnels to determine the crack development width. And results are showed as follows using ABAQUS:

![Figure 2. Longitudinal distance of utility tunnels](image)

The longitudinal deformation of the unility tunnels calculated by the deflection angle is as follows,

$$q = \frac{\theta}{l}$$  \hspace{1cm} (14)

Where $q$ is longitudinal deformation curvature of utility tunnels; $\theta$ is longitudinal deflection angle; $l$ is the length of utility tunnels.

The longitudinal curvature of the utility tunnels can be calculated as follows when the calculated length of utility tunnels is 10m:

$$q = \frac{\theta}{l} = \frac{2.119 \times 10^4}{10} = 2.119 \times 10^{-5}$$  \hspace{1cm} (15)

Therefore, when there is a mesh node with a curvature of $2.119 \times 10^{-5}$ in the model, it is considered that the model crack development width reaches 0.2mm. As can be seen from Fig. 1, the longitudinal maximum curvature of the utility tunnels is $2.12025 \times 10^{-5}$. Due to the accuracy of the ABAQUS calculation step, the maximum curvature can’t be guaranteed to be exactly $2.119 \times 10^{-5}$. Therefore, when its curvature is reached $(2.119 \pm 0.01) \times 10^{-5}$, it is considered that the utility tunnel has reached its maximum longitudinal deformation curvature and the crack development width has reached 0.2 mm.

5. Conclusion

According to the fact that there is no standard for controlling the longitudinal deformation of the structure of the underground integrated utility tunnels in actual engineering, this paper uses the relevant provisions on the width of the cracks in the concrete to develop the standard for the longitudinal deformation of utility tunnels.

(1) Using the relevant provisions of crack propagation width in the utility tunnel and concrete specifications, the maximum bending moment with unit width of utility tunnels and the maximum stress of the steel bar when the crack propagation width reaches the maximum value are derived
through some given assumptions.

(2) Established the longitudinal deformation control standard of the utility tunnel body structure.

(3) Based on ABQUAS, the longitudinal deformation curvature of utility tunnels is used to determine the crack development width. And the numerical results obtained basically corresponded to the theoretical results.

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References

[1] Wang HD. (2015) Revision Note for National Standard GB 50838-2015 Technical Code for Urban Utility Tunnel Engineering[J]. China Concrete and Cement Products, 08: 73-75.

[2] Takada Z, Luo WH. Seismic design of underground lifeline[J]. Modern Tunnelling Technology, 1991(07): 44-51.

[3] Shamsabadi A. (2001) Seismic Soil Tunnel Structure Interaction Analysis of the Posey Webster Street Tunnels[J]. US-JAPAN Soil-Structure-Interaction Workshop, 07(3): 499-502.

[4] Petrukhin V P, Isaev O N, Sharafutdinov R F. (2013) Determination of the Zone of Influence of Utility-Tunnel Construction[J]. Soil Mechanics and Foundation Engineering, 50(4): 164-170.

[5] Nishioka T, Unjoh S. (2003) A Simplified Evaluation Method for the Seismic Performance of Underground Common Utility Boxes[A]. Proceedings of the 2003 Pacific Conference on Earthquake Engineering[C]. Christ church, New Zealand, 13-15 February 2003, Paper No.005 (Published on CD-ROM).

[6] Shi XJ, Chen J, Li J. (2010) Shaking table test on utility tunnel under non-uniform seismic excitations (I): Experimental setup[J]. Earthquake Engineering and Engineering Dynamics, 30(1): 147-154.

[7] Chen J, Shi XJ, Li J. (2010) Shaking table test of utility tunnel under non-uniform seismic excitations (II): Experimental results[J]. Earthquake Engineering and Engineering Dynamics, 30(2): 123-130.

[8] Jiang L Z, Chen J, Li J. (2010) Shaking table test of utility tunnel under non-uniform seismic excitations (III): Numerical simulation[J]. Earthquake Engineering and Engineering Dynamics, 30(3): 147-154.

[9] Tan J, Wang J, Yang Z, et al. (2013) Study on the structural safety evaluation method of the municipal tunnel[C]. The international conference on pipelines and trenchless technology. 19-29.

[10] Wang LX, Cui YH, Wang XL. (2017) Mechanical Property Analysis for the Main Structure of A Utility Tunnel Using ABAQUS[J]. Structural Engineers, 33(5): 28-35.

[11] Department of Shanghai Urban and Rural Construction and Transportation Committee. (2012) Technical Specifications for Urban Comprehensive Pipe Gallery Projects[M]. China Planning Press.