Response Mechanism of Metro Tunnel Structure under Local Collapse in Loess Stratum

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Abstract: Due to the frequent occurrence of large-scale water inrush accidents in metro tunnels under the condition of local collapse of loess stratum, there are few reports on the response mechanism of loess metro tunnel under the condition of local collapse. Based on the actual project of tunnel water gushing in a certain section of Xi'an Metro Line 4, the research method of combining theoretical derivation with numerical simulation is adopted, the expressions of internal force and deformation of loess metro tunnel structure under different collapsibility conditions are derived and verified by finite difference method. The results show that the development of water transport channels and the law of collapsibility morphology of loess under local collapsibility are analyzed. Based on the elastic foundation beam model, the structural response model and analytical solutions of internal force and deformation of metro tunnel under different collapsibility conditions (upper collapsibility, side collapsibility and bottom collapsibility) are derived. Combined with the actual data of water inrush accident, the calculation case of the supporting project under the upper collapsible condition is analyzed. When the water head height is 7.5 m, the internal force and deformation of the tunnel structure only occur at about 20 m of the collapsible center. The internal force and deformation of the segment in the main influence range show an obvious non-linear trend, and the strong, weak and no influence zones are defined. Moreover, the numerical simulation results are consistent with the theoretical results under the supporting conditions, which verifies that the theoretical results can effectively predict the influence range of metro tunnel structure under local collapsibility of loess stratum. This research can provide new ideas for the construction, operation and disaster prevention of metro tunnels under the condition of local collapsibility in loess stratum.

key words: Metro tunnel; Loess stratum; Local collapsibility; Theoretical derivation; Example analysis; Finite difference method

Introduction

Loess is widely distributed in the world, especially in China (Yao et al. 2012; Wang et al. 2018; Gao and Shao 2012; Luo et al. 2018), the loess extends widely all over the country with accounting for about 6.6% of the total land area (Li and Li 2017; Qiu et al. 2017; Qiu et al. 2020). Water flow has a significant response to loess scouring and seepage collapsibility, which is a serious disaster causing factor for loess. After being soaked by water, it will have a significant collapsible deformation and structural loss (Shi et al. 2016; Peng et al. 2015; Peng et al. 2017a; Xu et al. 2014; Wang et al. 2020), which can induce lining structure cracking, ground collapse and interrupt traffic (Wang et al. 2020; Zhang et al. 2018; Zhang et al. 2019). Many previous studies have analyzed the response

characteristics of loess tunnel structure under water environment by in-situ immersion test. Guo et al constructed the model of seepage channel development and seepage field evolution after water gushing in tunnel (Guo et al. 2020). By simplifying the leakage channel into a pressure pipe, the expression of water inflow prediction equation was derived based on the assumption of internal constant flow. Based on the in-situ immersion test results of Xinzhuangling tunnel, according to Darcy's law and one-dimensional seepage theory, Lai et al derived the empirical relationship between the influence range and time of saturated collapsible loess and obtained the characteristics of crack development and lining stress distribution under different water immersion conditions by finite element model (Lai et al. 2017). Liu et al put forward four kinds of failure models of shallow buried loess tunnel under different excavation methods, and based on the artificial neural network method, the Duncan Chang model is redeveloped (Liu et al. 2017). Wang et al studied the temporal and spatial distribution of water infiltration characteristics under the condition of loess immersion, and revealed the relationship between water movement and free surface through excavation of pilot tunnel (Wang et al. 2020). Weng et al carried out the centrifugal model test of metro tunnel structure by self-made immersion test platform, and found that the radial stress of lining structure is approximately proportional to the lateral earth pressure coefficient of the point, which indicates that the pressure arch effect of tunnel surrounding rock is weakened after loess is soaked by water, which changes the lining structure load in the collapsible area and causes the redistribution of tunnel structural stress (Weng et al. 2019). Wang et al conducted a large-scale field water immersion test of collapsible loess, divided the infiltration stage characteristics of collapsible loess and analyzed the influence of free surface on soil water migration behavior and its response (Wang et al. 2017). The previous research on structural response of loess highway tunnel is based on the field large-scale immersion test results, however, the influence of loess collapsibility on metro tunnel structure is obviously different from highway tunnel structure, compared with the large-scale collapsible deformation of loess, for example, such as the leakage of municipal pipelines and the infiltration of water near the foundation pit, there are few studies on the collapsible behavior of local soil around the metro tunnel (Qiu et al. 2020; Qiu et al. 2020), the deformation characteristics of tunnel structure affected by the surrounding soil collapse, and the interaction mechanism between the collapsible soil and the tunnel structure, therefore, water inrush induced by pipeline damage and leakage has become a common disease in the construction, operation and maintenance of loess metro tunnel (Guo et al. 2019; Luo et al. 2017; Wang et al. 2019; Qiu et al. 2018; Luo et al. 2018; Zhang et al. 2018; Zhang et al. 2018).

According to the planning of operating metro in Xi'an City, geological survey shows that most of the soil layer of tunnel site is new loess (Li et al. 2019; Wang et al. 2019; Luo et al. 2017; Wang et al. 2019; Yu et al. 2018; Yan et al. 2018; Yan et al. 2019), a large number of ground fissures are distributed in Xi'an city, the activity of ground fissures is a potential hazard to the urban network distribution of underground pipelines, it is easy to cause urban pipeline rupture and water leakage (Peng et al. 2017b; Liu et al. 2017; Wang et al. 2016; Liu et al. 2018). According to statistics, the ground fissure activities in Xi'an will cause more than 10 water supply and sewage pipeline damage every year (Fan et al. 2020; Zhang et al. 2020; Peng et al. 2013; Peng et al. 2016), the leakage water of pipeline will produce large-scale local collapsible deformation area (Qiu et al. 2019), and the normal management of metro tunnels under construction and operation will be disturbed, it has caused huge economic losses and high attention of relevant construction departments (Qu et al. 2014; Lai et al. 2018; Qiu et al. 2017; Xu et al. 2017). The previous studies mainly focus on the response mechanism of metro tunnel structure in soft soil and sandy soil under water rich conditions (Li and Li 2020; Zhang et al. 2020; Zhang et al. 2015), the experimental means and basic theory are relatively mature and the research results are relatively rich, however, there are few reports on the response mechanism of metro tunnel structure under local collapse, therefore, it is necessary to study the response mechanism of metro tunnel structure when water pipeline leakage occurs in loess area. The relevant research results can provide theoretical support and safety guidance for the safety construction and maintenance

of metro under the influence of water environment. The framework of the paper is as follows: in the second chapter, the collapsible form of loess is analyzed in the process of local water immersion, based on the assumption of Winkler elastic foundation beam, the internal force expressions of lining structure under different collapsible conditions (upper collapse, lateral collapse and bottom collapse) are derived; in the third chapter, based on the general situation of water gushing from the supporting project, an example of tunnel lining structure under the condition of upper collapse is analyzed, and the internal force and deformation value of lining structure along the length are obtained; in the fourth chapter, the numerical simulation model of "loess-water-lining structure" is established by using the finite difference software FLAC 3D, and the internal force distribution relationship of tunnel structure with immersion time is obtained, and the correctness of the theoretical derivation is verified by comparing with the theoretical derivation results.

Calculation model of metro tunnel structural response under local collapse

Different from the influence of water pressure in rock tunnels, when the loess metro tunnel is partially flooded and collapsed due to the dislocation of the water pipe, it will not form the outburst prevention layer and water-proof rock slab similar to the rock tunnel, and will play a role in the seepage flow. Under the circumstances, the loess will collapse and soften, so that the load will directly act on the tunnel structure, resulting in longitudinal uneven deformation under the combined effect of the local collapsibility of the loess surrounding rock and the unevenness of the soil properties after encountering water. Therefore, based on the theory of elastic foundation beams [54,55](Ansari R et al. 2021; Campione G et al. 2021), by revealing the mechanism of the permeability and collapse behavior of the loess under local collapse conditions, the internal force calculation model of metro tunnel structures under local collapse conditions can be further constructed.

Analysis of loess infiltration and collapsibility under local collapsible condition

The following basic assumptions should be made for statistical analysis of a large number of loess immersion tests: (1) The loess surrounding rock is homogeneous; (2) The advancing front of the collapsible area is approximately symmetrical ellipse, and the axial ratio of the upper and lower ellipses is constant. When the collapsible loess stratum is partially immersed due to water pipeline leakage, if the pressure is greater than the infiltration capacity of soil, there will be water storage near the water source, when the infiltration time is fixed, according to the soil saturation or water content distribution, the soil layer along the vertical section is divided into four areas: moist cavity area, soaking saturation area, soaking unsaturated area and water content invariant unsaturated area.

In view of the existence of macropores and vertical tubular pores in loess, the infiltration of local water causes the change of seepage field in loess stratum, the permeability of loess is higher in the vertical direction than in the horizontal direction, and the seepage movement occurs in the active area, at the same time, a small-scale collapsible cavity area is formed, which results in the compaction of soil and the increase of soil moisture content, a buoyancy force is formed on the softened soil, which weakens the self weight effect of the soil and water contact part, which leads to erosion and destruction of the soil in this range and forms a dominant water migration channel. And the passive zone is located in the upper part and around the seepage spreading area, which maintains the natural water content, for the soil layer with higher water content, the passive zone plays a role of loading, causing the passive soil layer to sink accordingly, the subsidence extends to a certain angle and forms a collapsible deformation area. The collapsible phenomenon of loess in the process of local water injection in laboratory multi group model tests is summarized, it can be simplified as an isosceles right triangle with a certain angle on the plane, and the optimal

water transport channel extends and develops along the two waists. Above the dominant migration channel, the collapsible fractures are distributed horizontally or parallel, and parallel strike along the dominant channel and collapsible area, while under the dominant migration channel, the collapsible fractures are inclined. So the spatial pattern of water migration path in loess stratum under the condition of local collapsibility is proposed, as shown in Fig. 2, local water source, collapsible cavity area, dominant migration channel, transverse fracture and oblique main fracture are indicated by serial number ①, ②, ③ and ④, respectively.

Stress model of beam on elastic foundation

When the loess does not collapse, the metro tunnel structure can be regarded as an infinite beam on the foundation. The self weight of overlying soil acts on the upper part of infinite beam as distributed load while the lower part bears a certain foundation reaction. Its stress model is shown in Fig. 3.

Upper water source conditions

According to the model of water flow passage under the condition of local collapsibility of loess stratum, the stress on the upper part of the tunnel structure can be simplified as the calculation model shown in Fig. 4, at this time, the external load acting on the infinite simply supported beam is the superposition of the self weight load of collapsible loess softening and the water pressure load, the external load distribution is approximately isosceles triangle distribution, and the collapse center point is set as the coordinate origin, taking the axis of beam on elastic foundation as *X* axis, the whole rectangular coordinate system *xoy* is established, there is a triangular distributed load at any position of tunnel structure from a to b(the maximum value is *q*), the self weight of segment is q_1, and a micro segment *dx* is taken at any position *x* for analysis.

Because of the infinitesimal segment *dx* is very short, the linear load can be simplified as a concentrated load acting on *x*, and its value is:

$$dF = qdx \tag{1}$$

The deflection curve differential equation of elastic foundation beam under concentrated load is as follows:

$$\omega = \frac{F\lambda}{2k} e^{-\lambda x} \left(\cos \lambda x + \sin \lambda x\right) \tag{2}$$

Where, F is the concentrated load, k is the subgrade coefficient of elastic foundation, d is the beam section width, $\lambda = \sqrt[4]{\frac{kd}{4EI}}$.

Furthermore, when the concentrated load F acts on $X = C$, there are:

$$\omega = \frac{F\lambda}{2kb}\left[e^{-\lambda|x\text{-c}|}\left(\cos \lambda|x\text{-c}| + \sin \lambda|x\text{-c}|\right)\right] + \frac{q_1}{k} \quad \text{（Evenly distributed items in the whole length）} \tag{3}$$

$$\theta = -\frac{F\lambda^2}{kb} e^{-\lambda|x\text{-c}|} \sin\lambda\left(x\text{-c}\right) \tag{4}$$

$$M = \frac{F}{4\lambda}\left[e^{-\lambda|x\text{-c}|}\left(\cos\lambda|x\text{-c}| - \sin\lambda|x\text{-c}|\right)\right] \tag{5}$$

$$F_s = -\frac{F}{2} e^{-\lambda|x\text{-c}|} \cos\lambda |x\text{-c}| \tag{6}$$

For the right half beam, when $0<x<l$, the deflection of the beam under the triangle uniform load q between any a and b positions is as follows:

$$\begin{aligned}
\omega &= \int_{-l}^{l} \frac{q_c \lambda}{2kb} \left[e^{-\lambda|x\text{-}c|} \left(\cos\lambda |x\text{-}c| + \sin\lambda |x\text{-}c| \right) \right] dc + \frac{q_1}{k} \\
&= \frac{q\lambda}{2lkb} \left\{ \int_{-l}^{0} (l+c) \left[e^{-\lambda(x\text{-}c)} \left(\cos\lambda (x\text{-}c) + \sin\lambda (x\text{-}c) \right) \right] dc \right. \\
&\quad + \int_{0}^{x} (l-c) \left[e^{-\lambda(x\text{-}c)} \left(\cos\lambda (x\text{-}c) + \sin\lambda (x\text{-}c) \right) \right] dc \\
&\quad \left. + \int_{x}^{l} (l-c) \left[e^{\lambda(x\text{-}c)} \left(\cos\lambda (x\text{-}c) - \sin\lambda (x\text{-}c) \right) \right] dc \right\} + \frac{q_1}{k} \\
&= -\frac{q}{16lEI\lambda^5} \left(2\left(\cos\lambda x - \sin\lambda x \right) \boldsymbol{e}^{-\lambda x} - \left[\cos\lambda (x+l) - \sin\lambda (x+l) \right] \boldsymbol{e}^{-\lambda(x+l)} \right. \\
&\quad \left. - \left[\cos\lambda (x-l) + \sin\lambda (x-l) \right] \boldsymbol{e}^{\lambda(x-l)} \right) + \frac{q_1}{k}
\end{aligned} \tag{7}$$

By using the relation of deflection and rotation angle, the rotation angle of any position a to b under triangle load q is obtained as follows:

$$\begin{aligned}
\theta &= \int_{-l}^{l} -\frac{q_c \lambda^2}{kb} e^{-\lambda|x\text{-c}|} \sin\lambda (x\text{-c}) dc \\
&= -\frac{q\lambda^2}{lkb} \left\{ \int_{-l}^{0} (l+c) e^{-\lambda(x\text{-}c)} \sin\lambda (x\text{-}c) dc + \int_{0}^{x} (l-c) e^{-\lambda(x\text{-}c)} \sin\lambda (x\text{-}c) dc + \int_{x}^{l} (l-c) e^{\lambda(x\text{-}c)} \sin\lambda (x\text{-}c) dc \right\} \\
&= \frac{q}{8lEI\lambda^4} \left(2\cos\lambda x e^{\lambda x} - \cos\lambda (x+l) e^{-\lambda(x+l)} - \cos\lambda (x\text{-}l) \boldsymbol{e}^{\lambda(x\text{-}l)} \right)
\end{aligned} \tag{8}$$

By using the relation of deflection and bending moment, the bending moment of any position a to b under triangular load q is obtained as follows:

$$\begin{aligned}
M &= -EI \frac{d^2 w}{dx^2} = -EI \frac{d\theta}{dx} \\
&= \frac{q}{8l\lambda^3} \left\{ \begin{array}{c} 2\left(\cos\lambda x + \sin\lambda x \right) e^{-\lambda x} - \left[\cos\lambda (x+l) + \sin\lambda (x+l) \right] e^{-\lambda(x+l)} - \\ e^{\lambda(x\text{-}l)} \left[\cos\lambda (x\text{-}l) - \sin\lambda (x-l) \right] \end{array} \right\}
\end{aligned} \tag{9}$$

By using the relationship of deflection and shear force, the shear force of any position a to b under triangle load q is obtained as follows:

$$\begin{aligned}
Q &= -EI \frac{d^3 w}{dx^3} = \frac{dM}{dx} \\
&= -\frac{q}{4l\lambda^2} \left\{ 2\sin\lambda x e^{-\lambda x} - \sin\lambda (x+l) e^{-\lambda(x+l)} - e^{\lambda(x\text{-}l)} \sin\lambda (x-l) \right\}
\end{aligned} \tag{10}$$

In the same way, for the right half beam, when $l<x$, we can get:

$$\omega=\int_{-l}^{l}\frac{q_c\lambda}{2kb}\left[e^{-\lambda|x-c|}\left(\cos\lambda|x-c|+\sin\lambda|x-c|\right)\right]dc+\frac{q_1}{k}$$
$$=\frac{q\lambda}{2lkb}\left\{\int_{-l}^{0}(l+c)\left[e^{-\lambda(x-c)}\left(\cos\lambda(x-c)+\sin\lambda(x-c)\right)\right]dc\right.$$
$$\left.+\int_{0}^{l}(l-c)\left[e^{-\lambda(x-c)}\left(\cos\lambda(x-c)+\sin\lambda(x-c)\right)\right]dc\right\}+\frac{q_1}{k} \tag{11}$$
$$=-\frac{q}{16lEI\lambda^5}\left\{2\left(\cos\lambda x-\sin\lambda x\right)\boldsymbol{e}^{-\lambda x}-\left[\cos\lambda(x+l)-\sin\lambda(x+l)\right]\boldsymbol{e}^{-\lambda(x+l)}\right.$$
$$\left.-\left[\cos\lambda(x-l)-\sin\lambda(x-l)\right]\boldsymbol{e}^{-\lambda(x-l)}\right\}+\frac{q_1}{k}$$

$$\theta=\int_{-l}^{l}-\frac{q_c\lambda^2}{kb}e^{-\lambda|x-c|}\sin\lambda|x-c|dc$$
$$=-\frac{q\lambda^2}{lkb}\left\{\int_{-l}^{0}(l+c)e^{-\lambda(x-c)}\sin\lambda(x-c)dc+\int_{0}^{l}(l-c)e^{-\lambda(x-c)}\sin\lambda(x-c)dc\right\} \tag{12}$$
$$=\frac{q}{8lEI\lambda^4}\left\{2\cos\lambda xe^{-\lambda x}-\cos\lambda(x+l)e^{-\lambda(x+l)}-\cos\lambda(x-l)e^{-\lambda(x-l)}\right\}$$

$$M=-EI\frac{d^2w}{dx^2}=-EI\frac{d\theta}{dx}$$
$$=-EI\frac{d}{dx}\left\{\frac{q}{2lkb}\left\{\frac{2\cos\lambda x}{e^{\lambda x}}-\frac{\cos\lambda(x+l)}{e^{\lambda(x+l)}}-\frac{\cos\lambda(x-l)}{e^{\lambda(x-l)}}\right\}\right\}$$
$$=\frac{q}{8l\lambda^3}\left\{2\left(\cos\lambda x+\sin\lambda x\right)e^{-\lambda x}-\left[\cos\lambda(x+l)+\sin\lambda(x+l)\right]e^{-\lambda(x+l)}-\left[\cos\lambda(x-l)+\sin\lambda(x-l)\right]e^{-\lambda(x-l)}\right\} \tag{13}$$

$$Q=-EI\frac{d^3w}{dx^3}=\frac{dM}{dx}$$
$$=\frac{q}{8l\lambda^3}\frac{d}{dx}\left\{\frac{2\left(\cos\lambda x+\sin\lambda x\right)}{e^{\lambda x}}-\frac{\cos\lambda(x+l)+\sin\lambda(x+l)}{e^{\lambda(x+l)}}-\frac{\cos\lambda(x-l)+\sin\lambda(x-l)}{e^{\lambda(x-l)}}\right\} \tag{14}$$
$$=-\frac{q}{4l\lambda^2}\left\{2\sin\lambda xe^{-\lambda x}-\sin\lambda(x+l)e^{-\lambda(x+l)}-\sin\lambda(x-l)e^{-\lambda(x-l)}\right\}$$

According to the symmetry, for the left half beam, when $-l<x<0$, we can get the following results:

$$\omega=-\frac{q}{16lEI\lambda^5}\left(2\left(\cos\lambda x+\sin\lambda x\right)\boldsymbol{e}^{-\lambda x}-\left[\cos\lambda(x+l)-\sin\lambda(x+l)\right]\boldsymbol{e}^{-\lambda(x+l)}\right.$$
$$\left.-\left[\cos\lambda(x-l)+\sin\lambda(x-l)\right]\boldsymbol{e}^{\lambda(x-l)}\right)+\frac{q_1}{k} \tag{15}$$

$$\theta=-\frac{q}{8lEI\lambda^4}\left(2\cos\lambda xe^{\lambda x}-\cos\lambda(x+l)e^{-\lambda(x+l)}-\cos\lambda(x-l)\boldsymbol{e}^{\lambda(x-l)}\right) \tag{16}$$

$$M=\frac{q}{8l\lambda^3}\left\{\ 2\left(\cos\lambda x+\sin\lambda x\right)e^{-\lambda x}-\left[\cos\lambda(x+l)+\sin\lambda(x+l)\right]e^{-\lambda(x+l)}\right.$$
$$\left.-e^{\lambda(x-l)}\left[\cos\lambda(x-l)-\sin\lambda(x-l)\right]\ \right\} \tag{17}$$

$$Q=-\frac{q}{4l\lambda^2}\left\{2\sin\lambda x e^{-\lambda x}-\sin\lambda\left(x+l\right)e^{-\lambda(x+l)}-e^{\lambda(x\text{-}l)}\sin\lambda\left(x-l\right)\right\} \tag{18}$$

For the left half beam, when $x<-l$, we can get:

$$\begin{aligned}\omega=-\frac{q}{16lEI\lambda^5}\Big\{&2\left(\cos\lambda x+\sin\lambda x\right)\boldsymbol{e}^{-\lambda x}-\left[\cos\lambda\left(x+l\right)+\sin\lambda\left(x+l\right)\right]\boldsymbol{e}^{-\lambda(x+l)}\\&-\left[\cos\lambda\left(x-l\right)+\sin\lambda\left(x-l\right)\right]\boldsymbol{e}^{-\lambda(x-l)}\Big\}+\frac{q_1}{k}\end{aligned} \tag{19}$$

$$\theta=\frac{q}{8lEI\lambda^4}\left\{2\cos\lambda x e^{-\lambda x}-\cos\lambda\left(x+l\right)e^{-\lambda(x+l)}-\cos\lambda\left(x\text{-}l\right)e^{-\lambda(x\text{-}l)}\right\} \tag{20}$$

$$M=\frac{q}{8l\lambda^3}\left\{\begin{aligned}&2\left(\cos\lambda x-\sin\lambda x\right)e^{-\lambda x}-\left[\cos\lambda\left(x+l\right)-\sin\lambda\left(x+l\right)\right]e^{-\lambda(x+l)}-\\&\left[\cos\lambda\left(x\text{-}l\right)-\sin\lambda\left(x-l\right)\right]e^{-\lambda(x\text{-}l)}\end{aligned}\right\} \tag{21}$$

$$Q=-\frac{q}{4l\lambda^2}\left\{2\sin\lambda x e^{-\lambda x}-\sin\lambda\left(x+l\right)e^{-\lambda(x+l)}-\sin\lambda\left(x-l\right)e^{-\lambda(x\text{-}l)}\right\} \tag{22}$$

Under the condition of upper water source, the stress response model of tunnel structure can be integrateed into the following forms:

$$\begin{aligned}\omega=-\frac{q}{16lEI\lambda^5}\Big\{&2\left(\cos\lambda|x|\boldsymbol{e}^{-\lambda|x|}-\sin\lambda|x|\boldsymbol{e}^{-\lambda|x|}\right)-\left[\cos\lambda\left|\left(x+l\right)\right|-\sin\lambda\left|\left(x+l\right)\right|\right]\boldsymbol{e}^{-\lambda\left|\left(x+l\right)\right|}\\&-\left[\cos\lambda\left|\left(x-l\right)\right|-\sin\lambda\left|\left(x-l\right)\right|\right]\boldsymbol{e}^{-\lambda\left|\left(x-l\right)\right|}\Big\}+\frac{q_1}{k}\\\theta=\operatorname{sgn}(x)&\frac{q}{8lEI\lambda^4}\left(2\cos\lambda|x|\boldsymbol{e}^{-\lambda|x|}-\cos\lambda\left|\left(x+l\right)\right|e^{-\lambda\left|\left(x+l\right)\right|}-\cos\lambda\left|\left(x-l\right)\right|e^{-\lambda\left|\left(x-l\right)\right|}\right)\\M=\frac{q}{8l\lambda^3}&\left\{\begin{aligned}&2\left(\cos\lambda|x|+\sin\lambda|x|\right)e^{-\lambda|x|}-\left[\cos\lambda\left|\left(x+l\right)\right|+\sin\lambda\left|\left(x+l\right)\right|\right]e^{-\lambda\left|\left(x+l\right)\right|}\\&-\left[\cos\lambda\left|\left(x\text{-}l\right)\right|+\sin\lambda\left|\left(x-l\right)\right|\right]e^{-\lambda\left|\left(x\text{-}l\right)\right|}\end{aligned}\right\}\\Q=-\frac{q}{4l\lambda^2}&\left\{2\sin\lambda x e^{-\lambda|x|}-\sin\lambda\left(x+l\right)e^{-\lambda\left|\left(x+l\right)\right|}-\sin\lambda\left(x-l\right)e^{-\lambda\left|\left(x-l\right)\right|}\right\}\\\operatorname{sgn}(x)=&\begin{cases}1 & x\geq 0\\ \text{-}1 & x<0\end{cases}\end{aligned} \tag{23}$$

Side water source conditions

The water pressure produced by the side collapse is similar to that of the upper part, but the direction of action becomes horizontal. The calculation model is shown in Fig. 5. At this time, only the bending deformation caused by the full-length distribution of surrounding rock pressure and the self weight of the structure is superimposed, which is the total deformation of the structure:

$$\omega = \mathrm{sqrt}\left\{\left(\frac{q}{16lEI\lambda_1^5}\right)^2 \left\{2\left(\cos\lambda_1|x| - \sin\lambda_1|x|\right)\boldsymbol{e}^{-\lambda_1|x|}\right.\right.$$

$$\left.\left. -\left[\cos\lambda_1\left|(x+l)\right| - \sin\lambda_1\left|(x+l)\right|\right]\boldsymbol{e}^{-\lambda_1|(x+l)|} - \left[\cos\lambda_1\left|(x-l)\right| - \sin\lambda_1\left|(x-l)\right|\right]\boldsymbol{e}^{-\lambda_1|(x-l)|}\right\}^2 + \left(\frac{q_1}{k}\right)^2\right\}$$

$$\theta = \mathrm{sgn}(x)\frac{q}{8lEI\lambda_1^4}\left(2\cos\lambda_1|x|\boldsymbol{e}^{-\lambda_1|x|} - \cos\lambda_1\left|(x+l)\right|e^{-\lambda_1|(x+l)|} - \cos\lambda_1\left|(x-l)\right|\boldsymbol{e}^{-\lambda_1|(x-l)|}\right) \tag{24}$$

$$M = \frac{q}{8l\lambda_1^3}\left\{\begin{array}{l} 2\left(\cos\lambda_1|x| + \sin\lambda_1|x|\right)e^{-\lambda_1|x|} - \left[\cos\lambda_1\left|(x+l)\right| + \sin\lambda_1\left|(x+l)\right|\right]e^{-\lambda_1|(x+l)|} \\ -\left[\cos\lambda_1\left|(x\text{-}l)\right| + \sin\lambda_1\left|(x-l)\right|\right]e^{-\lambda_1|(x\text{-}1)|} \end{array}\right\}$$

$$Q = -\frac{q}{4l\lambda_1^2}\left\{2\sin\lambda_1 x e^{-\lambda_1|x|} - \sin\lambda_1\left(x+l\right)e^{-\lambda_1|(x+l)|} - \sin\lambda\left(x-l\right)e^{-\lambda_1|(x-l)|}\right\}$$

Lower water source conditions

When the water source appears in the lower part of the tunnel, the surrounding rock in a certain range of the lower part will collapse and soften. Therefore, the foundation under the beam is analyzed by sections, and the calculation model is shown in Fig. 6.

Taking the midpoint of the local collapse section as the origin, the two beams are extended to the two ends to form an infinite beam with the subgrade coefficient of k_2, then the differential equation of deflection curve is as follows:

$$\omega = -\frac{q}{4lk_2b\lambda_2}\left\{2\left(\cos\lambda_2|x|\boldsymbol{e}^{-\lambda_2|x|} - \sin\lambda_2|x|\boldsymbol{e}^{-\lambda_2|x|}\right) - \left[\cos\lambda_2\left|(x+l)\right| - \sin\lambda_2\left|(x+l)\right|\right]\boldsymbol{e}^{-\lambda_2|(x+l)|}\right.$$
$$\left. -\left[\cos\lambda_2\left|(x-l)\right| - \sin\lambda_2\left|(x-l)\right|\right]\boldsymbol{e}^{-\lambda_2|(x-l)|}\right\} + \frac{q_1}{k} \tag{25}$$

The rotation angle, bending moment and shear force at $x=\pm l$ are as follows:

$$\omega_l = -\frac{q}{4lk_2b\lambda_2}\left\{2\left(\cos\lambda_2 l - \sin\lambda_2 l\right)\boldsymbol{e}^{-\lambda_2 l} - \left(\cos\lambda_2 l - \sin\lambda_2 l\right)^2\boldsymbol{e}^{-\lambda_2 2l} - 1\right\} + \frac{q_1}{k}$$
$$= \frac{q}{4lk_2b\lambda_2}\left[1 - \left(\cos\lambda_2 l - \sin\lambda_2 l\right)\boldsymbol{e}^{-\lambda_2 l}\right]^2 + \frac{q_1}{k}$$

$$\theta_l = \frac{q}{2lk_2b}\left(2\cos\lambda_2 l\boldsymbol{e}^{-\lambda_2 l} - 1 - \cos\lambda_2 2l\boldsymbol{e}^{-2l\lambda_2}\right) = \frac{q}{2lk_2b}\left(2\cos\lambda_2 l\boldsymbol{e}^{-\lambda_2 l} - 1 - \left(\cos^2\lambda_2 l + \sin^2\lambda_2 l\right)\boldsymbol{e}^{-2l\lambda_2}\right)$$
$$= -\frac{q}{2lk_2b}\left((1 - \cos\lambda_2 l\boldsymbol{e}^{-\lambda_2 l})^2 + \sin^2\lambda_2 l\boldsymbol{e}^{-2l\lambda_2}\right) \tag{26}$$

$$M_{0l} = \frac{q}{8l\lambda_2^3}\left\{2\left(\cos\lambda_2 l + \sin\lambda_2 l\right)e^{-\lambda_2 l} - 1 - \left[\cos\lambda_2 2l + \sin\lambda_2 2l\right]e^{-\lambda_2 2l}\right\}$$
$$= -\frac{q}{8l\lambda_2^3}\left[1 - \left(\cos\lambda_2 l + \sin\lambda_2 l\right)e^{-\lambda_2 l}\right]^2$$

$$F_{s0l} = -\frac{q}{4l\lambda_2^2}\left\{2\sin\lambda_2 l e^{-\lambda_2 l} \mp \sin\lambda_2 2l e^{-\lambda_2 2l}\right\}$$

However, there is no such shear force and bending moment at the actual x = L, so it is necessary to add the

concentrated force and concentrated couple opposite to the direction of the shear force and bending moment, so the concentrated force and concentrated couple at the end points of the two beams are $F_{sl}-F_{s0l}$ and M_l-M_{0l}, respectively.

So we can get the following conclusions:

$$\begin{cases} F_{sl}-F_{s0l}=-2EI\lambda_2^{\ 3}e^{-\lambda_2 l}\left[\left(C_3-C_4\right)\sin\lambda_2 l-\left(C_3+C_4\right)\cos\lambda_2 l\right] \\ M_l-M_{0l}=-2EI\lambda_2^{\ 2}e^{-\lambda_2 l}\left[C_3\sin\lambda_2 l-C_4\cos\lambda_2 l\right] \end{cases} \tag{27}$$

The solution is as follows:

$$\begin{cases} C_3=A\cos\lambda_2 l-B\left(\sin\lambda_2 l+\cos\lambda_2 l\right) \\ C_4=A\sin\lambda_2 l-B\left(\sin\lambda_2 l-\cos\lambda_2 l\right) \end{cases} \tag{28}$$

Among them:

$$\begin{cases} A=\dfrac{\mathrm{F}_{sl}-\mathrm{F}_{s0l}}{2EI\lambda_2^{\ 3}} \\ B=\dfrac{\lambda_2\left(M_l-\mathrm{M}_{0l}\right)}{2EI\lambda_2^{\ 3}} \end{cases} \tag{29}$$

The deflection under the action of bending moment and shear force is as follows:

$$\omega_2^2=\left[e^{-\lambda_2 x}\left(C_3\cos\lambda_2 x+C_4\sin\lambda_2 x\right)\right] \tag{30}$$

The deflection and rotation angle of the two beams at x=l are as follows:

$$\begin{aligned} \omega=\omega_2^1+\omega_2^2&=\frac{q}{16lEI\lambda_2^5}\left[1-\left(\cos\lambda_2 l-\sin\lambda_2 l\right)\boldsymbol{e}^{-\lambda_2 l}\right]^2+\frac{q_1}{k}+e^{-\lambda_2 l}\left(C_3 cos\lambda_2 l+C_4 sin\lambda_2 l\right) \\ &=\frac{q}{16lEI\lambda_2^5}\left[1-\left(\cos\lambda_2 l-\sin\lambda_2 l\right)\boldsymbol{e}^{-\lambda_2 l}\right]^2+\frac{q_1}{k}+e^{-\lambda_2 l}\left(A-B\right) \end{aligned} \tag{31}$$

$$\begin{aligned} \theta=\theta_2^1+\theta_2^2&=-\frac{q}{2lk_2 b}\left(2(1-\cos\lambda_2 l\boldsymbol{e}^{-\lambda_2 l})^2+\sin^2\lambda_2 l\boldsymbol{e}^{-2l\lambda_2}\right)-\lambda_2 e^{-\lambda_2 l}\left[\left(C_3-C_4\right)cos\lambda_2 l+\left(C_3+C_4\right)sin\lambda_2 l\right] \\ &=-\frac{q}{8lEI\lambda_2^4}\left(2(1-\cos\lambda_2 l\boldsymbol{e}^{-\lambda_2 l})^2+\sin^2\lambda_2 l\boldsymbol{e}^{-2l\lambda_2}\right)-\lambda_2 e^{-\lambda_2 l}\left(A-2B\right) \end{aligned} \tag{32}$$

For three section beams, the deflection curve equation is as follows:

$$\omega=\frac{e^{-\lambda_1(x-l)}}{2\lambda_1^{\ 3}EI}\left[F_{sl}\cos\lambda_1\left(x-l\right)-\lambda_1 M_l(\cos\lambda_1\left(x-l\right)-\sin\lambda_1\left(x-l\right))\right]+\frac{q_1}{k} \tag{33}$$

The deflection and rotation angle at x=l are as follows:

$$\omega_l=\frac{F_{sl}-\lambda_1 M_l}{2\lambda_1^{\ 3}EI}+\frac{q_1}{k} \tag{34}$$

$$\theta_l=-\frac{F_{sl}-2\lambda_1 M_l}{2\lambda_1^{\ 2}EI} \tag{35}$$

The conditions of continuous deformation from x=l are as follows:

$$\frac{q}{8l\lambda_2^2}\left[1-\left(\cos\lambda_2 l-\sin\lambda_2 l\right)\boldsymbol{e}^{-\lambda_2 l}\right]^2+e^{-\lambda_2 l}\left(a-b\right)=F_{sl}-\lambda_1 M_l \tag{36}$$

$$-\frac{q}{4l\lambda_2}\left((1-\cos\lambda_2 l\boldsymbol{e}^{-\lambda_2 l})^2+\sin^2\lambda_2 l\boldsymbol{e}^{-2l\lambda_2}\right)-\lambda_2 e^{-\lambda_2 l}\left(a-2b\right)=-F_{sl}+2\lambda_1 M_l \tag{37}$$

$$\begin{cases} a=\mathrm{F}_{sl}-\mathrm{F}_{s0l} \\ b=\lambda_2\left(M_l-\mathrm{M}_{0l}\right) \end{cases} \tag{38}$$

$$M_{0l}=-\frac{q}{8l\lambda_2^3}\left[1-\left(\cos\lambda_2 l+\sin\lambda_2 l\right)e^{-\lambda_2 l}\right]^2 \tag{39}$$

$$F_{s0l}=-\frac{q}{4l\lambda_2^2}\left\{2\sin\lambda_2 l e^{-\lambda_2 l}-\sin\lambda_2 2l e^{-\lambda_2 2l}\right\} \tag{40}$$

$$\begin{cases} \frac{q}{8l\lambda_2^2}\left[1-\left(\cos\lambda_2 l-\sin\lambda_2 l\right)\boldsymbol{e}^{-\lambda_2 l}\right]^2+e^{-\lambda_2 l}\left(\mathrm{F}_{sl}-\mathrm{F}_{s0l}-\lambda_2\left(M_l-\mathrm{M}_{0l}\right)\right)=F_{sl}-\lambda_1 M_l \\ -\frac{q}{4l\lambda_2}\left((1-\cos\lambda_2 l\boldsymbol{e}^{-\lambda_2 l})^2+\sin^2\lambda_2 l\boldsymbol{e}^{-2l\lambda_2}\right)-\lambda_2 e^{-\lambda_2 l}\left(\mathrm{F}_{sl}-\mathrm{F}_{s0l}-2\lambda_2\left(M_l-\mathrm{M}_{0l}\right)\right)=-F_{sl}+2\lambda_1 M_l \end{cases} \tag{41}$$

$$\begin{cases} \left(e^{-\lambda_2 l}-1\right)\mathrm{F}_{sl}+\left(\lambda_1-\lambda_2 e^{-\lambda_2 l}\right)M_l \\ \quad+\frac{q}{8l\lambda_2^2}\left\{(1-e^{-\lambda_2 l})\left[1-\left(\cos\lambda_2 l-\sin\lambda_2 l\right)\boldsymbol{e}^{-\lambda_2 l}\right]^2+2e^{-2\lambda_2 l}\left(2\sin\lambda_2 l-\sin\lambda_2 2l e^{-\lambda_2 l}\right)\right\}=0 \\ \left(1-\lambda_2 e^{-\lambda_2 l}\right)\mathrm{F}_{sl}+2\left(\lambda_2^2 e^{-\lambda_2 l}-1\right)M_l \\ -\frac{q}{4l\lambda_2}\left\{(1-e^{-\lambda_2 l})\left[(1-\cos\lambda_2 l\boldsymbol{e}^{-\lambda_2 l})^2+\sin^2\lambda_2 l\boldsymbol{e}^{-2l\lambda_2}\right]+2e^{-2\lambda_2 l}\left(\sin\lambda_2 l-\sin\lambda_2 2l e^{-3_2 l}\right)\right\}=0 \end{cases} \tag{42}$$

By solving the above equation, it can be concluded that:

$$\begin{cases} \mathrm{F}_{sl}=\frac{D_1}{D} \\ M_l=\frac{D_2}{D} \end{cases} \tag{43}$$

Among them:

$$D=\begin{vmatrix} \left(e^{-\lambda_2 l}-1\right) & \left(\lambda_1-\lambda_2 e^{-\lambda_2 l}\right) \\ \left(1-\lambda_2 e^{-\lambda_2 l}\right) & 2\left(\lambda_2^2 e^{-\lambda_2 l}-1\right) \end{vmatrix}$$

$$D_1=\begin{vmatrix} -\frac{q}{8l\lambda_2^2}\left\{(1-e^{-\lambda_2 l})\left[1-\left(\cos\lambda_2 l-\sin\lambda_2 l\right)\boldsymbol{e}^{-\lambda_2 l}\right]^2+2e^{-2\lambda_2 l}\left(2\sin\lambda_2 l-\sin\lambda_2 2l e^{-\lambda_2 l}\right)\right\} & \left(\lambda_1-\lambda_2 e^{-\lambda_2 l}\right) \\ \frac{q}{4l\lambda_2}\left\{(1-e^{-\lambda_2 l})\left[(1-\cos\lambda_2 l\boldsymbol{e}^{-\lambda_2 l})^2+\sin^2\lambda_2 l\boldsymbol{e}^{-2l\lambda_2}\right]+2e^{-2\lambda_2 l}\left(\sin\lambda_2 l-\sin\lambda_2 2l e^{-3_2 l}\right)\right\} & 2\left(\lambda_2^2 e^{-\lambda_2 l}-1\right) \end{vmatrix}$$

$$D_2 = \begin{vmatrix} \left(e^{-\lambda_2 l}-1\right) & -\dfrac{q}{8l\lambda_2^2}\left\{(1-e^{-\lambda_2 l})\left[1-\left(\cos\lambda_2 l-\sin\lambda_2 l\right)\boldsymbol{e}^{-\lambda_2 l}\right]^2+2e^{-2\lambda_2 l}\left(2\sin\lambda_2 l-\sin\lambda_2 2le^{-\lambda_2 l}\right)\right\} \\ \left(1-\lambda_2 e^{-\lambda_2 l}\right) & \dfrac{q}{4l\lambda_2}\left\{(1-e^{-\lambda_2 l})\left[(1-\cos\lambda_2 l\boldsymbol{e}^{-\lambda_2 l})^2+\sin^2\lambda_2 l\boldsymbol{e}^{-2l\lambda_2}\right]+2e^{-2\lambda_2 l}\left(\sin\lambda_2 l-\sin\lambda_2 2le^{-3_2 l}\right)\right\} \end{vmatrix}$$

Engineering example analysis and finite element verification

Project overview

Relying on actual project of the tunnel in the section of Xi'an Metro Line 4 (lijiacun station-Hepingmen station) was constructed by shield method, the average buried depth of the tunnel in this section is about 14.0 m, the distance between the tunnel bottom and the ground surface is about 20.0 m, and the distance between the left lines and right lines is 12.0 m. The section tunnel passes through the old loess and silty clay, the geological profile of the section reveals that the overburden of the tunnel is miscellaneous fill, plain fill, new loess (collapsible) and ancient soil, and the overburden of the section tunnel is medium sand and old loess. According to the construction experience of Xi'an metro shield tunnel, the samples collected from the site are tested in the laboratory, the physical and mechanical parameters of surrounding rock and segment structure parameters are shown in Table 1 and Table 2. The 1 # connecting passage of the tunnel in this section is constructed from the left line to the right line, the excavation and initial support are divided into upper and lower pilot tunnels. When the upper pilot tunnel is excavated and connected, the lower pilot tunnel is excavated to install the first grid arch, the underground water pipeline is damaged, and then the local dynamic water source is leaked out, the water yield is very large, the influence of the section of the left tunnel about 10 m away from the east side of the connecting passage is more significant, especially the water gushing phenomenon behind the segment near the upper part of the tunnel, according to the field exploration, the vertical distance between the damaged pipeline and the tunnel structure is 7.5m. The engineering geological section of the tunnel crossing the stratum is shown in Fig. 7.

Result analysis

The segment weight q_1 = 140 kPa in this case, in order to simplify the calculation, when water inrush occurs in the upper part of the tunnel, the collapsible load acting on the segment can be regarded as isosceles triangle distribution, the maximum load is q = 0.25 kPa, the width of elastic foundation beam is 4 m, and the collapsibility range L is 5 m along the left and right sides of the tunnel with the collapsibility point as the center.

The actual values of the above parameters are substituted into the matlab program of the tunnel structure internal force and deformation calculation formula (2-17), the distribution curve of displacement and internal force of tunnel lining structure under upper collapsible condition is shown in Fig. 8 (a) - 8 (d). From the figure, the displacement and internal force of each section of the tunnel lining structure from the collapse center can be compared under the condition of upper collapse, Thus, the deformation and stress distribution along the tunnel length can be obtained, which can provide a certain basis for the defect reinforcement under the condition of collapse of the upper part of the tunnel structure.

It can be seen from Fig. 8 (a) - 8 (d) that the tunnel structure and internal force deformation are basically symmetrically distributed about the collapse center, showing a single wave peak uplift state, when the water inrush accident occurs, the lower tunnel structure directly opposite to the collapsibility center will produce large settlement, and its maximum deflection and angle are 2.3345 mm and 0.0248 rad respectively, the internal force

and deformation of tunnel structure are concentrated in the range of 20 m around the collapsible center, and the area of 10 m around the collapsible center is temporarily called the strong influence area. The closer to the collapsible area, the greater the increment of deformation and internal force, and the growth law is close to linear growth; when the distance from the collapse center decreases from 10 m to 0 m, the corresponding deflection, rotation angle, shear force and bending moment increase to 2.3345 mm, 2.48 rad, 2560 kN·m and 1280 kN， The range of collapsible area (10-20 m) is called weak influence area temporarily, and the change rate of deformation and internal force is small, beyond this range, the deformation and internal force of the region are almost unchanged and tend to be stable, which is temporarily called no influence region, indicating that the internal force and deformation of the segment are related to the horizontal distance from the collapse center. Because the collapsible range is 10 m under the working condition, the tunnel damage range caused by water inflow is about 4 times of the collapsible range, and the maximum deformation exceeds the deformation control value of relevant specifications, which is consistent with the actual damage situation of tunnel structure.

Therefore, when the tunnel has happened local collapsibility due to water immersion, the bending normal stress and shear stress of the collapsible center section exceed the allowable normal stress and shear stress of the section. So when the water gushing event occurs, grouting measures should be taken in time to reinforce the cavity area near the collapsible center of the tunnel.

Finite element simulation of loess subway tunnel response under local collapsibility

The above calculation model establishes the analytical solution of the internal force and deformation of the tunnel structure under the condition of local collapsibility, and obtains the internal force and deformation curve of the tunnel structure depending on the working conditions. In order to better verify the correctness and accuracy of the calculation theory, it is necessary to carry out on the internal force and deformation of the actual tunnel structure with numerical simulation, and more intuitively reveal the tunnel structure internal force response mechanism under the condition of local collapsibility, also better judge the weak point of tunnel lining structure under the condition of local collapse.

Model overview

The finite element software FLAC 3D is used to model and analyze the distribution law of internal force and deformation of loess metro tunnel structure under the upper collapsible condition. In order to reduce the influence of boundary effect, the boundary size of the model is generally 3-5 times the distance from the tunnel excavation center, and the buried depth of the supporting project is 14 m, so the model size is 80 m long, 80 m wide and 57 m high. The left boundaries and right boundaries are 40 m away from the center of the tunnel, and the upper boundary is taken from the surface. The three-dimensional numerical model is shown in Fig. 9. Because the leakage water source of the relying project is mostly caused by the damaged water supply pipeline in the city, it is assumed that the water source is columnar water source, and the head height is 7m, the outlet state of the pipeline is simulated by applying the corresponding nodal pore pressure to the nodes of the pipeline opening. In the model, solid element is used to simulate the stratum, shell element is used to simulate the segment, and the constitutive model is Mohr Coulomb. The initial geostress only considers the self weight stress, the porosity of surrounding rock is 0.6, the permeability coefficient is controlled in 3.0 × 10-4 ~ 6.0 × 10-4 cm / s, the segment lining is made for C50 concrete, 30 cm thick; the initial support is made for C25 shotcrete, 30 cm thick, and the secondary lining is made for C35 concrete, 45 cm thick. The physical and mechanical parameters of surrounding rock and supporting structure are shown in table 2.

Selection of test section

The test sections are symmetrically arranged every 10 m along the tunnel axis from the collapsibility center. The test section number of the collapse center is # 1, and a total of 20 test sections are arranged.

Analysis of model calculation results

Ten test sections are selected symmetrically along the collapse center as typical test sections, and the internal force and deformation values of typical test sections are extracted as shown in table 4, and the finite element results are compared with the theoretical results as shown in Fig. 10. It can be seen from Fig. 10 that the theoretical derivation results is consistent with the finite element calculation results, which verifies the correctness of the calculation theory, under the upper collapsible condition, the finite element calculation results show that the internal force and deformation curve of the tunnel structure presents a single peak uplift symmetrical distribution, and the maximum internal force and deformation of the tunnel section # 1 where the collapsible center is located reach the maximum value at the same time, the maximum deformation is 2.3347 mm, the minimum deformation is 2.33326 mm, it has excceeding the displacement limit of 2 mm in metro design code, when the seepage distance is 7.5 m, the collapsibility range of the tunnel structure is about 3 times of the tunnel section size, that is, the affected area is about 20 m away from the collapsibility center along the tunnel axis. Therefore, when the water inrush accident occurs, grouting reinforcement should be carried out in the affected area in time.

In addition, as shown in Fig.10, the theoretical calculation result is slightly larger than the finite element calculation result due to many reasons. The numerical calculation simulates the real construction of the site - the lining structure is constructed after the soil excavation, and then simulates the water gushing process. Therefore, the stress state of the surrounding rock is a dynamic change process, which can affect the internal force calculation of the lining structure, but the theoretical calculation is the static analysis and calculation under the known soil mechanical state. Furthermore, to simplify the calculation steps, the numerical simulation appropriately simplified the leakage water source, which could not fully reflect the evolution behavior of loess collapsible region under the condition of local water immersion, resulting in the simulation results slightly less than the theoretical calculation results.

Conclusions

With the help of theoretical derivation, case analysis and numerical simulation, the response mechanism of metro tunnel structure under local collapsibility in loess stratum is studied, the main conclusions are as follows:

a) This paper analyzes the law of loess stratum permeability and the evolution of collapsible morphology under the condition of local collapsibility, based on the Winkler elastic foundation beam model, this paper discusses the calculation principle of tunnel structure response law under the influence of local collapsibility (water pressure, collapsible surrounding rock pressure) in loess stratum, and derives the analytical solution of metro tunnel structure internal force under different collapsibility conditions (upper water source condition, side water source condition, bottom water source condition), so as to obtain the expression of tunnel structure internal force and deformation.

b) When the upper part of the metro tunnel in loess stratum is collapsible, the soil collapses and acts on the lining segment of the tunnel due to the collapsible deformation. The internal force and deformation of the segment in the main influence range show a nonlinear trend, resulting in the dislocation and damage of the segment;

c) Based on the actual project of tunnel water gushing in a section of Xi'an line 4, this paper analyzes the

analytical solution derived from the theory, obtains the distribution law of deformation and internal force along the collapsible center under the upper collapsible condition, and delimits three obvious influence zones: strong, weak and No. It should focus on the prevention of loess subway tunnel engineering under similar local collapsible conditions;

d) The finite element numerical simulation is carried out to verify the correctness of the calculation theory. The results of the finite element numerical simulation are consistent with the results of the theoretical derivation. When the seepage distance is 7.5 m, the collapsibility range of the tunnel structure is within 3 times of the tunnel section size, and the influence area is about 40 meters away from the collapsibility center along the tunnel axis m. The calculation method in this paper can effectively predict the influence range of loess tunnel structure under the condition of local collapsibility, and emergency measures should be taken in time to reduce the damage range of segment after the occurrence of water inrush accident.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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