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Deformation Calculation for the Existing Tunnel Induced by Undercrossing Shield Tunneling

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ABSTRACT: An analytical solution was presented to calculate the vertical displacement of existing tunnels based on the elastic foundation beam theory and cavity expansion theory with stress-induced initial anisotropy, the analytical solution was then degenerated into isotropic results and was verified by an example. Multiple factor analysis revealed that the maximum deformation of the tunnel is at the quadrature point; larger the plastic radius a, greater influence on vertical displacement of existing tunnel; and the influence weakens with the increase of vertical distance; vertical deformation of existing tunnel approximately follows a linear relationship with lateral pressure coefficient. The analytical solution was a simple relational expression contains several factors, so it has general applicability to similar problems.
Keywords: Undercrossing construction; Vertical displacement; Shield tunnel; Cavity expansion

I. INTRODUCTION

The stress field and displacement field of soil will be changed when a shield is operating, then the existing tunnel may be disturbed and potential deformation will weaken the tunnel using life, also that can directly threaten the safe operation of driving in the existing tunnel. Therefore, that has great significance to study the deformation features of the existing tunnel.

Due to the little influence on road traffic and surrounding buildings, and less time in construction, shield tunneling is popular in tunneling [1]. It has been over 30 years since shield tunneling was adopted and studied, and the research focused on the approaches to limit the ground settlement. For example, the classical Peck formulation [2] and its modified expressions [3~4]. The question of crossing construction is a new topic which appeared recent years [5], so the research is usually based on the method of numerical simulation [6~7] and less model experiments [8]. But the design and construction of model experiments is in great difficulty with high cost, and the results is often not representative.

Based on the above, an analytical solution was presented to calculate the vertical displacement of existing tunnels based on the elastic foundation beam theory and cavity expansion theory with stress-induced initial anisotropy, the analytical solution was then degenerated into isotropic results and was verified by an example.

II. BASIC ASSUMPTIONS

(1) The soil was a homogeneous, isotropic and elastic material, and the shield tunnel travel through the existing tunnel vertically;
(2) The cross sections of the shield tunnel was round and the problem was simplified as a plane strain problem of elasticity;
(3) Harmonious deformation between the existing tunnel and surrounding soils. Ignore the time effect of shield construction.

III. EQUATION FOUND

As is shown in Fig.1, existing operating tunnel can be simplified as a beam on elastic foundation, the differential equation is described as follows.

$$E_p I_p \frac{d^4\omega_p}{dy^4} + k\omega_p = kf(y) \qquad (1)$$

Among them E_pI_p is Both the tunnel bending stiffness, E_p is modulus of elasticity of both the tunnel，0.8 times preferable segment concrete elastic modulus[9], $I_p$is the segment ring cross section moment of inertia; k is Both the coefficient of soil reaction; $\omega_p$is both the tunnel deflection；$f(y)$ is Both the tunnel formation in the vertical deformation.

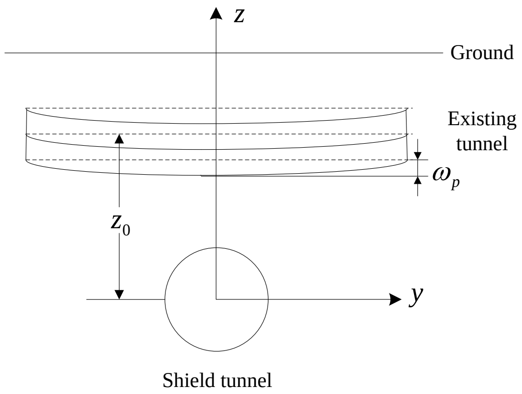

Fig. 1 Calculation diagram of beam on elastic foundation

Assuming that Both the outer wall of tunnel lining coordinated with tunnel deformation of surrounding soils, Additional earth pressure effect on the existing tunnel:

$$E_p I_p \frac{d^4\omega_p}{dy^4} = k\left[f(y) - \omega_p\right] \tag{2}$$

As is shown in Fig.2, shield construction can be described by cavity expansion theory.

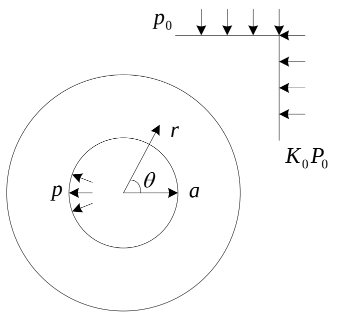

Fig. 2 sketch of cavity expansion theory

Holes in the anisotropic stress distribution of the initial stress condition:

$$\begin{aligned}
\sigma_r &= \frac{p_0}{2}[(1+K_0)(1-\frac{a^2}{r^2}) - (1-K_0)(1-\frac{4a^2}{r^2}+\frac{3a^4}{r^4})\cos 2\theta] + p\frac{a^2}{r^2} \\
\sigma_\theta &= \frac{p_0}{2}[(1+K_0)(1+\frac{a^2}{r^2}) + (1-K_0)(1+\frac{3a^4}{r^4})\cos 2\theta] - p\frac{a^2}{r^2} \\
\tau_{r\theta} &= \frac{p_0}{2}[(1-K_0)(1+\frac{2a^2}{r^2}-\frac{3a^4}{r^4})\sin 2\theta]
\end{aligned} \tag{3}$$

Among whichσ_r, σ_θ, $\tau_{r\theta}$ was respectively radial stress, hoop stress, and shear stress; $p_0$was the initial vertical stress; $p$was grouting pressure; $K_0$was coefficient of earth pressure at rest; $a$was initial radius of holes; θ is the angle inFig.2.

Transform formula using elastic mechanics stress coordinates:

$$\begin{cases}
\sigma_y = \dfrac{\sigma_r+\sigma_\theta}{2} + \dfrac{\sigma_r-\sigma_\theta}{2}\cos 2\theta - \tau_{r\theta}\sin 2\theta \\
\sigma_z = \dfrac{\sigma_r+\sigma_\theta}{2} - \dfrac{\sigma_r-\sigma_\theta}{2}\cos 2\theta + \tau_{r\theta}\sin 2\theta
\end{cases} \tag{4}$$

Then the formula can be described as follows:

$$\sigma_z = -\cos 2\theta \cdot \frac{2pa^2}{r^2} + \cos 2\theta \cdot \frac{p_0}{2}[\left(1+K_0\right)(1+\frac{a^2}{r^2}) + \left(1-K_0\right)(1+\frac{3a^4}{r^4})\cos 2\theta]$$
$$-\cos 2\theta \cdot \frac{p_0}{2}[(1+K_0)(1-\frac{a^2}{r^2}) - (1-K_0)(1+\frac{3a^4}{r^4} - \frac{4a^2}{r^2})\cos 2\theta] + \frac{p_0}{4}\left(1+K_0\right)(1 \quad (5)$$
$$+\frac{a^2}{r^2}) + \frac{p_0}{4}(1-K_0)(1+\frac{3a^4}{r^4})\cos 2\theta + \frac{p_0}{4}[(1+K_0)(1-\frac{a^2}{r^2}) - (1-K_0)(1+\frac{3a^4}{r^4} -$$
$$\frac{4a^2}{r^2})\cos 2\theta] + \frac{p_0}{2}(1-K_0)(1-\frac{3a^4}{r^4} + \frac{2a^2}{r^2})\sin^2 2\theta$$

In which, $r = \sqrt{y^2 + z_0{}^2}$; $\cos 2\theta = \frac{y^2 - z_0{}^2}{y^2 + z_0{}^2}$;

y and z_0 was shown in Fig.1. And with this the basic equation of the problem was found:

$$E_p I_p \frac{d^4\omega_p}{dy^4} = -\cos 2\theta \cdot \frac{2pa^2}{r^2} + \cos 2\theta \cdot \frac{p_0}{2}[\left(1+K_0\right)(1+\frac{a^2}{r^2}) + \left(1-K_0\right)(1+\frac{3a^4}{r^4})\cos 2\theta]$$
$$-\cos 2\theta \cdot \frac{p_0}{2}[\left(1+K_0\right)(1-\frac{a^2}{r^2}) - (1-K_0)(1+\frac{3a^4}{r^4} - \frac{4a^2}{r^2})\cos 2\theta] + \frac{p_0}{4}\left(1+K_0\right)(1+\frac{a^2}{r^2}) + \quad (6)$$
$$\frac{p_0}{4}\left(1-K_0\right)(1+\frac{3a^4}{r^4})\cos 2\theta + \frac{p_0}{4}[\left(1+K_0\right)(1-\frac{a^2}{r^2}) - (1-K_0)(1+\frac{3a^4}{r^4} - \frac{4a^2}{r^2})\cos 2\theta] +$$
$$\frac{p_0}{2}\left(1-K_0\right)(1-\frac{3a^4}{r^4} + \frac{2a^2}{r^2})\sin^2 2\theta$$

IV. SOLUTION AND ANALYSIS

The boundary conditions:According to symmetry, maximum deflection was at y=0, so both curve slope and the beam rotation angle were 0, that is to say,

$$E_p I_p \omega_p = Q = 0, \quad \omega_p = \theta_p = 0 \quad (7)$$

And also, at $y=i_p$, the fix end, both curve slope and the beam rotation angle were 0,

$$\omega_p = 0, \theta_p = 0 \quad (8)$$

In which $i_p$was the width parameters of settlement trough and can be determined by using experiential equations [10].

Then the general solution of the basic equation of the problem was:

$$\omega_p = C_1 + C_2 y + C_3 y^2 + C_4 y^3 - \frac{1}{16K_p}[\frac{A-2p_0}{3}y^4 + (24K_2 + \frac{2AK_4}{3z_0{}^2})y^2 + (8z_0K_3 -$$
$$\frac{AK_4 y^2}{3z_0{}^2} - \frac{AK_4}{z_0})y \cdot \arctan\frac{y}{z_0} - (3a^4A + 8K_2y^2 + 8K_2z_0{}^2 - \frac{AK4}{3} + 4K_3z_0{}^2)Ln(y^2 + z_0{}^2)] \quad (9)$$

We can determine the constantsC_1~C_4through the boundary conditions above-mentioned, the results are as follows:

$$C_1 = \frac{1}{16K_p}[-4\pi^2 i_p{}^4\left(A-2p_0\right)/3 + \frac{2\pi i_p{}^2}{K_1}(3a^4A + 16\pi^3 i_p{}^2K_2 + 8z_0{}^2K_2) + \frac{\pi i_p{}^2AK_4}{3z_0{}^2K_1}(2\pi i_p{}^2 +$$
$$z_0{}^2) + \frac{\sqrt{2\pi}i_pAK_4K_5}{z_0}(\frac{\pi i_p{}^2}{3z_0{}^2} - \frac{1}{2}) + 4\sqrt{2\pi}i_pz_0K_3K_5 - (3a^4A + 8z_0{}^2K_2 + 4z_0{}^2K_3 - \frac{AK_4}{3})LnK_1] \quad (10)$$

$$C_3 = \frac{1}{32K_p}[\frac{8}{3}i_p{}^3\pi\left(A-2p_0\right) - \frac{2i_p}{K_1}(3a^4A + 16i_p{}^2\pi + 8z_0{}^2K_2) + 16i_pK_2(3 - LnK_1)$$
$$-\frac{i_pAK_4}{3z_0{}^2K_1}(2i_p{}^2 - 4K_1 + z_0{}^2) + 4\sqrt{\frac{2}{\pi}}z_0K_3K_5 - \frac{AK_4K_5}{z_0}(\frac{\sqrt{2\pi}i_p{}^2}{z_0{}^2} + \frac{1}{\sqrt{2\pi}})] \quad (11)$$

$$C_2 = C_4 = 0 \quad (12)$$

Among which ,

$$
\begin{aligned}
&A=(-1+K_0)p_0\\
&K_1=2\pi i_p{}^2+z_0{}^2\\
&K_2=a^2p-a^2K_0p_0+p_0z_0{}^2-K_0p_0z_0{}^2\\
&K_3=-4a^2p-3a^2p_0+7a^2K_0p_0-4p_0z_0{}^2\\
&+4K_0p_0z_0{}^2\\
&K_4=-3a^2+4a^2z_0{}^2+8z_0{}^4\\
&K_5=\arctan\frac{\sqrt{2\pi}i_p}{z_0}\\
&K_p=E_pI_p
\end{aligned}
\tag{13}
$$

Now we have worked out the exact analytical solution of the differential equation (6). And the analytic expression includes multiple parameters such as plastic radius *a*, coefficient of static earth pressure K_0, clear distance z_0, grouting pressure *p*, flexural rigidity of the existing tunnel E_pI_p, etc. Next, some influence factor annalysis was done and the results were as follows:

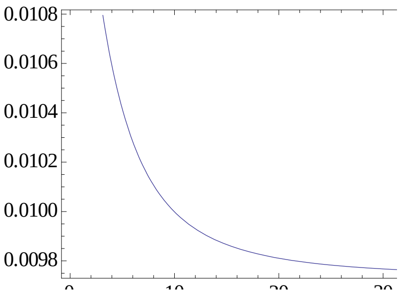

Fig. 3 The relation curves between vertical deflection values and vertical distance z_0

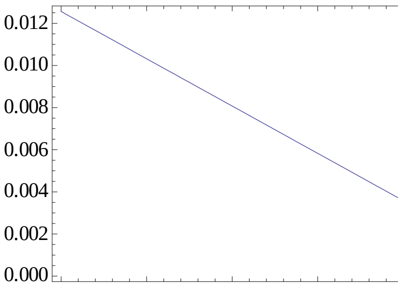

Fig. 4 The relation curves between vertical deflection values and lateral pressure coefficient K_0

In Fig.3 and Fig.4, the abscissas were parameter z_0 and K_0 respectively, while both ordinate of the figures were vertical deformation. From those figures we can see that with the increase of vertical clear distance, vertical deflection of existing tunnel decreased gradually, and the vertical deflection curve changed fast when z_0 was small, but when z_0 was greater than 20, vertical deflection did not change any more. On the other hand, vertical deflection of existing tunnel was inversely proportional to the parameter K_0.

V. CONCLUSION

An analytical solution was presented to calculate the vertical displacement of existing tunnels based on the elastic foundation beam theory and cavity expansion theory with stress-induced initial anisotropy. Multiple factor analysis revealed that the maximum deformation of the tunnel is at the quadrature point. larger the plastic radius a, greater influence on vertical displacement of existing tunnel; and the influence weakens with the increase of vertical distance; vertical deformation of existing tunnel approximately follows a linear relationship with lateral pressure coefficient. The analytical solution was a simple relational expression contains several factors, so it has general applicability to similar problems.

Also some defects exists in the proposed calculation method, for example, the analytical expression was available only when the shield tunnel travel through the existing tunnel vertically. And the plastic zone was ignored, that is to say, when the existing tunnel was in plastic zone, the results were easily affected.

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