Study on Mechanism of Simultaneous Backfilling Grouting for Shield Tunneling in Soft Soils

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ABSTRACT: The shield tail void formed in unit time in tunneling is simplified as a three-dimensional annular space with shied advancing at certain speed. As the filling process can not be observed in-situ, it is very difficult to simulate it in detail. Taking the cementitious grouts used in grouting injection as Newton fluid and Bingham fluid respectively, based on the typical four grouting holes design, the distribution of grouts pressure in cross section is obtained with the diffusion model of grouts pressure and the principle of superposition. With further consideration of grouts infiltration into the surrounding strata and its hardening process, the distribution of grouts pressure in longitudinal section is obtained. Therefore, the diffusion model of grouts pressure for simultaneous backfilling grouting in shield tunneling is founded. Finally, the comparison between theoretical result and the site observation is made.

1. INTRODUCTION

As for the modern, pressurized face shield machine, ground deformation is the main concern encountered during construction, and grouting through the tunnel rings is the key solution. At present, simultaneous backfilling grouting technology has been studied by many researchers. However, most of their studies are concentrated on the physical and mechanical characters of grouts (Zhao 2008), its penetration and diffusion into the surrounding strata (Yang 2005), the corresponding pumping technology, and ground settlement induced by the close of tail void (Ou and Cherng 1995). Due to the process of grouts diffusion in tail void is very difficult to be observed or modeled (Nomoto et al 1999), few corresponding studies have been carried out. A sort of lining piezometer wa adopted by *Hashimoto et al* (2004) to monitor grouts pressure after the tunnel boring machine in Japan, but the initial diffusion process of grouts pressure was not studied. Grouts pressure is measured by piezometers near grouting holes in construction, but not in tail void.

The flow of grouts in tail void is depended on its rheological property and the shield gap size. Therefore, as for the geometry space of shield tail void, based on the study of rock crack grouting by predecessors (Ruan 2005), especially on the diffusion law of Newton fluid and Bingham fluid, taking grouts pressure as the main parameter, and the filling process is divided into two relatively independent processes, the diffusion model of grouts pressure for simultaneous backfilling grouting is established.

2. ASSUMPTIONS AND PRECONDITIONS

In order to establish the diffusion model, some assumptions are made as follows:

- Isotropic homogeneous incompressible and stable fluid, large viscosity, dynamic shear stress of Bingham fluid remains unchanged during grouting.
- The diffusion velocity in tail void is slow and unchanged, the mutual penetration of grouts and surrounding strata is ignored, and the flow is laminar.
- The volume of tail void is fixed in unit time with certain tunneling speed, and this part of void is filled by grouts, the influence of the earlier injected grouts will not been considered.
- During the filling process of cross-section grouting, grouts viscosity remains unchanged, and its change is mainly seen in the change of grouts pressure in longitudinal section.

In this paper, the inert and harden grouts are treated as Newton fluid and Bingham fluid, the typical four grouting holes design is assumed, the grouts pressure is taken as the controlling factor, and the flux of each grouting hole is not a variation value.

3. DERIVATION OF GROUTS PRESSURE FORMULA

Assuming that the thickness of tail void is δ, tunneling speed is v, width of tail void formed in unit time is S ($S=v$), so the corresponding volume formed in unit time is V=π(D^2-d^2)×$(S/4)\times k$ (D and d are outer diameters of shield tailskin and tunnel lining respectively, k is the grouting ratio). The upside grouting hole is located at $\theta=45^0$ (the positive direction of Y-axis is at $\theta=0^0$, clockwise rotation, Fig.1), grouting pressure is p_s, grouting flux to the upward and downward is q_1 and q_2. The corresponding parameters about downside grouting hole is $\theta=135^0$, p_x, q_1' and q_2'.

Taking the tunnel center as coordinate origin, vertical axis as Z axis, Cartesian coordinate system is established in the tunnel cross section plane. The shape of tail void and the arrangement of grouting holes are symmetric to vertical axis.

3.1 Derivation of grouts pressure formula in tunnel cross section

Compared to Newton fluid, the flow of Bingham fluid has to overcome the static shear stress τ_0 (Zheng 2005). Most of fluid belongs to Bingham fluid, especially the grouts with high density and thickness recently developed (Shanghai Tunnel Engineering Co., Ltd. 2008). So, taking Bingham fluid as the main research object, and the derived formulae will be more close to reality.

(1) The filling path of grouts flow is from θ=45^0 to the upward

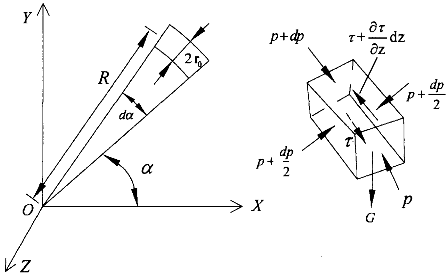

Fig.1 Forces on fluid microelement from θ=45^0 to the upward and corresponding coordinate system

Grouts flows from $\alpha = 45^0$ to $\alpha = 90^0$, angle starts from the positive X-axis, counterclockwise rotation (Li 2009).

Taking any single micro-fluid from the flow area for instance, just as shown in Fig.1, flow velocity in the coaxial thin layer keeps unchanged along the flow line because of its laminar flow, so shear stress on the left and right side equals zero ($\tau = \tau_0 + \mu\ \gamma = \tau_0 + \mu \cdot du/dz$, $d\tau/dR$=0). The influence of inertial force is ignored, and sums of all the projective forces along the flow line equal zero. So, we can get the equilibrium equation as follow:

$$p(2r_0)dz\cos\frac{d\alpha}{2} - (p+dp)(2r_0)dz\cos\frac{d\alpha}{2} + (\frac{\partial\tau}{\partial z}dz)\frac{2r_0\left[(R-r_0)d\alpha+(R+r_0)d\alpha\right]}{2} - \rho g\frac{2r_0\left[(R-r_0)d\alpha+(R+r_0)d\alpha\right]}{2}dz\cos(\alpha+\frac{d\alpha}{2})=0 \qquad (1)$$

So, $p \quad p_s + \rho g R\left(\sin\pi/4 - \sin\alpha\right) - A\ R\ \left(\pi/4 - \alpha\right)$ (2)

Where, $A = \left(A_1 + A_2\right)^{\frac{1}{3}} / \left(S\delta^3\right) + A_3^{\ 2} / \left[S\delta^3\left(A_1 + A_2\right)^{\frac{1}{3}}\right] - A_3 / \left(S\delta^3\right)$ (3)

Where, $A_1 = \tau_0^{\ 3}S^3\delta^6 - 64\mu^3 q_1^{\ 3} - 48\mu^2 q_1^{\ 2} S\tau_0\delta^2 - 12\mu q_1 S^2\tau_0^{\ 2}\delta^4$ (4)

$$A_2 = 4\tau_0\left[-\mu q_1\left(\tau_0/S\right)\left(16\mu^2 q_1^{\ 2} + 12\mu q_1 S\tau_0\delta^2 + 3S^2\tau_0^{\ 2}\delta^4\right)\right]^{\frac{1}{2}} \times S^2\delta^3 \qquad (5)$$

$$A_3 = 4\mu q_1 + S\tau_0\delta^2 \qquad (6)$$

As for Newton fluid, τ_0=0, δ_0=0, then $A = -12\mu q_1 / \left(S\delta^3\right)$ (7)

So, $p = p_s + \rho g R(\sin\pi/4 - \sin\alpha) + 12\mu q_1 R/(S\delta^3)(\pi/4\text{-}\alpha)$ (8)

Where, $\pi/4 \le \alpha \le \pi/2,\ 0 \le \theta \le \pi/4$ (9)

(2) The filling path of grouts flow is from $\theta=45^0$ to the downward

Grouts flow from $\alpha = 45^0$ to $\alpha = 180^0$, angle starts from the positive Z-axis, clockwise rotation.

Similarly available, $p = p_s + \rho g R\ (\cos\pi/4 - \cos\alpha)\text{-}AR\ (\pi/4\text{-}\alpha)$ (10)

Newton fluid: $p = p_s + \rho g R\ (\cos\pi/4 - \cos\alpha) + 12\mu q_2 R/(S\delta^3)(\pi/4 - \alpha)$ (11)

Where, $\pi/4 \le \alpha \le \pi,\ \pi/4 \le \theta \le \pi$ (12)

(3) The filling path of grouts flow is from $\theta=135^0$ to the upward

Grouts flow from $\alpha = 45^0$ to $\alpha = 180^0$, angle starts from the negative Z-axis, counterclockwise rotation.

Similarly available, $p = p_x\text{-}\rho g R\ (\cos\pi/4 - \cos\alpha)\text{-}A\ R\ (\pi/4\text{-}\alpha)$ (13)

Newton fluid: $p = p_x\text{-}\rho g R\ (\cos\pi/4 - \cos\alpha) + 12\mu q_1' R/(S\delta^3)(\pi/4 - \alpha)$ (14)

Where, $\pi/4 \le \alpha \le \pi,\ 0 \le \theta \le 3\pi/4$ (15)

(4) The filling path of grouts flow is from $\theta=135^0$ to the downward

Grouts flow from $\alpha = 45^0$ to $\alpha = 90^0$, angle starts from the positive X-axis, clockwise rotation.

Similarly available, $p = p_x\text{-}\rho g R\ (\sin\pi/4 - \sin\alpha)\text{-}AR\ (\pi/4\text{-}\alpha)$ (16)

Newton fluid: $p = p_x\text{-}\rho g R\ (\sin\pi/4 - \sin\alpha) + 12\mu q_2' R/(S\delta^3)(\pi/4 - \alpha)$ (17)

Where, $\pi/4 \le \alpha \le \pi/2,\ 3\pi/4 \le \theta \le \pi$ (18)

3.2 Derivation of grouts pressure formula in longitudinal tunnel section

The grouts pressure in tail void will decrease with its hardening process and the infiltration into surrounding strata. As for the soft soil, grouts keep in liquid state in the range of about five lining rings away from shield tail, and the grouts pressure should be considered in this range.

(1) Influence of grouts hardening process

The chemical reaction will take place after grouts are mixed, and rheological parameters of any cement grouts are time-dependent. The relation between rheological parameters and time can be described in exponential function, $\mu = \mu_0\ e^{\lambda_1 t}$ and $\tau = \tau_0\ e^{\lambda_2 t}$. Coefficient λ_1 and λ_2 can be determined by measured data. Viscosity is time-dependent in the process of grouts diffusion, but the static shear stress remains almost unchanged.

(2) Grouts infiltration into surrounding strata

There are three main interaction ways between grouts and surrounding strata, i.e. infiltration, compaction and fracturing grouting (Cooperative group of Geotechnical grouting theory and engineering examples 2001). And this paper only considers the infiltration process resulting in the decrease of grouts pressure.

The corresponding deformation in strata will occur because of tunneling. Assuming that the width of this disturbance area is equal to the width l_s of the annular space out of tail void, and the soil after deformation is still in elastic stage. Taking the micro-element in vertical plane as research object, the length of the micro-element is the sum of l_s and δ. ε_t is the time-dependent strain. According to generalized Hooke's Law (Song and Cai 1998), we can get the loss of pressure due to infiltration.

$$\Delta p = E\ \delta \cdot \varepsilon_t / l_s \times (1-\upsilon)/(1-\upsilon-2\upsilon^2) \tag{19}$$

3) Grouts pressure formula in longitudinal tunnel section

Taking Newton fluid for instance, the ultimate distribution of grouts pressure in longitudinal section is obtained.

1) From $\theta=45^0$ to the upward ($\pi/4 \le \alpha \le \pi/2,\ 0 \le \theta \le \pi/4$)

$$p = p_s + \rho g R(\sin \pi/4 - \sin \alpha) + (12\mu_0 e^{\lambda_1 t} q_1 R / S\delta^3) \times (\pi/4 - \alpha) - E\ C_1\ C_2 \tag{20}$$

2) From $\theta=45^0$ to the downward ($\pi/4 \le \alpha \le \pi,\ \pi/4 \le \theta \le \pi$)

$$p = p_s + \rho g R\ (\cos \pi/4 - \cos \alpha) + (12\mu_0 e^{\lambda_1 t} q_2 R / S\delta^3) \times (\pi/4 - \alpha) - E\ C_1\ C_2 \tag{21}$$

3) From $\theta=135^0$ to the upward ($\pi/4 \le \alpha \le \pi,\ 0 \le \theta \le 3\pi/4$)

$$p = p_x - \rho g R\ (\cos \pi/4 - \cos \alpha) + \left(12\mu_0 e^{\lambda_1 t} q_1' R / S\delta^3\right) \times (\pi/4 - \alpha) - E\ C_1\ C_2 \tag{22}$$

4) From $\theta=135^0$ to the downward ($\pi/4 \le \alpha \le \pi/2,\ 3\pi/4 \le \theta \le \pi$)

$$p = p_x - \rho g R\ (\sin \pi/4 - \sin \alpha) + \left(12\mu_0 e^{\lambda_1 t} q_2' R / S\delta^3\right) \times (\pi/4 - \alpha) - E\ C_1\ C_2 \tag{23}$$

Where, $C_1 = \delta \cdot \varepsilon_t / l_s$, $C_2 = (1-\upsilon)/(1-\upsilon-2\upsilon^2)$

From the grouts pressure distribution in longitudinal section, we know that it is relevant to many factors. When all the other factors are fixed, grouts pressure diffusion depends on time. Grouts pressure on lining and surrounding strata near shield tail will decrease with time lapse until reach its balance with surrounding pore pressure.

4 ANALYSIS EXAMPLE AND ENGINEERING APPLICATION

The buried depth of a metro shield tunnel in Shanghai is 13m, strata from up to down are miscellaneous fill, silt soft soil, stiff clay and sand. D=6340mm, R=3.27m, d=6200mm, v =2cm/min, S =0.02m, δ =0.10m. p_s =0.16MPa, p_x =0.23MPa, W/C =0.65, τ_0 =90 Pa , μ =28.1 $\times e^{0.0165t}$ $Pa.s$, $C_1 = \delta \cdot \varepsilon_t / l_s$ =0.015, $E = \beta E_S$=1.39MPa, ρ=1500kg/m^3. We assume that grouts flux at each grouting hole is equal, flux to the downward and upward from each grouting hole is equal, and the injection ratio is 150%. Then, we can get the specific distribution of grouts flux:

$$q_1 = q_2' = q/4 = 1.24\times10^{-4} m^3/s \text{,} \quad q_1' = q_2 = 3q/4 = 3.71\times10^{-4} m^3/s \tag{24}$$

4.1 Grouts pressure in tunnel cross section

From Eq.(8), (11), (14) and (17), pressure distribution is calculated as follow.

a) From θ=45^0 to the upward (θ=0, $\alpha=\pi/2$; $\theta=\pi/4$, $\alpha=\pi/4$)

$\theta=\pi/4$, p=0.16MPa; $\theta=\pi/6$, p=0.152MPa; θ=0, p=0.146MPa.

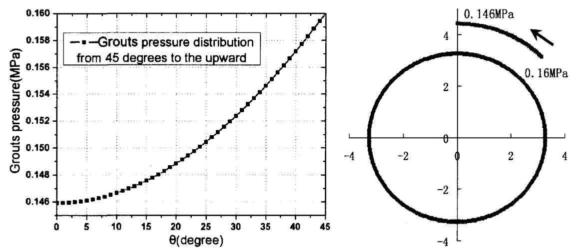

Fig.2 Pressure distribution from θ=45^0 to the upward

b) From θ=45^0 to the downward ($\theta=\pi/4$, $\alpha=\pi/4$; $\theta=\pi$, $\alpha=\pi$)

$\theta=\pi/4$, p=0.16MPa; $\theta=\pi/3$, p=0.17MPa; $\theta=\pi/2$, p=0.194MPa; $\theta=3\pi/4$, p=0.228MPa; $\theta=\pi$, p=0.242MPa.

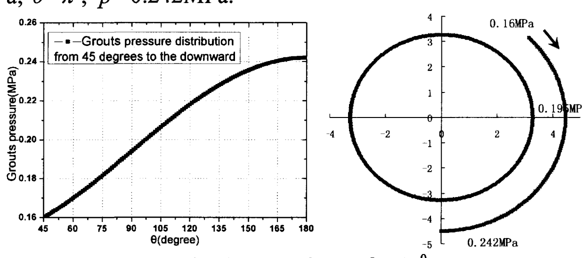

Fig.3 Pressure distribution from θ=45^0 to the downward

c) From θ=135^0 to the upward ($\theta=3\pi/4$, $\alpha=\pi/4$; θ=0, $\alpha=\pi$)

$\theta = 3\pi/4$, p =0.23MPa; $\theta = 2\pi/3$, p =0.22MPa; $\theta = \pi/2$, p =0.196MPa; $\theta=\pi/4$, p=0.162MPa; θ=0, p= 0.148MPa.

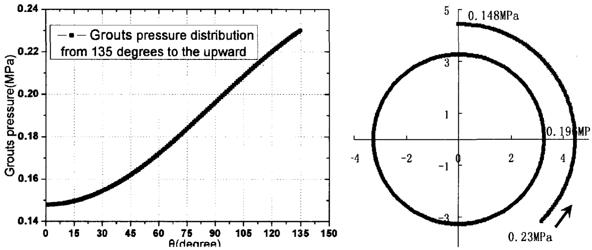

Fig.4 Pressure distribution from θ=135^0 to the upward

d) From θ=135^0 to the downward ($\theta=3\pi/4$, $\alpha=\pi/4$; $\theta=\pi$, $\alpha=\pi/2$)
$\theta=3\pi/4$, p=0.23MPa; $\theta=5\pi/6$, p=0.238MPa; $\theta=\pi$, p=0.244MPa.

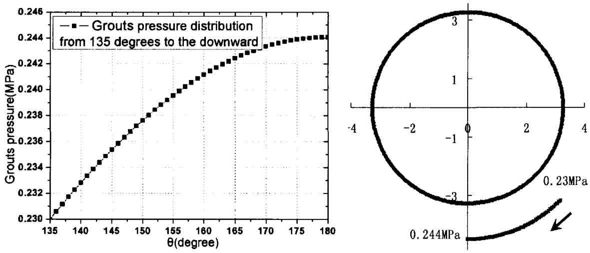

Fig.5 Pressure distribution from θ=135^0 to the downward

Make superposition of grouts pressure at the same location, we can get the final pressure distribution in cross section.

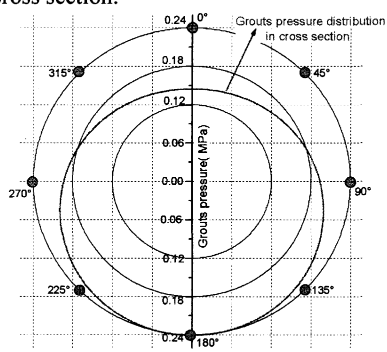

Fig.6 Final distributions of grouts pressure in cross section.

From the final pressure distributions in cross section, we know that the maximum pressure at vault reaches 0.147MPa, the arch bottom is 0.241MPa, and the calculated results are in good agreement with the actual situation in soft soil in Shanghai.

4.2 Grouts pressure distribution in longitudinal section.

For the segment ring with 1200mm width, the duration of shield driving is about 60 min/ring. Considering the transportation of muck, segments, cement grouts, and the shield maintenance, the progress of tunneling is about 10 rings/day. Taking the grouting hole at $\theta=45^0$ for example, using Eq.(20)~(23), the final pressure distribution in longitudinal section is calculated.

$$p=(p_s+p_x)/2-\rho gR/\sqrt{2}+3\pi\times\left(28.1\times e^{0.0165t}\right)q_1R/S\delta^3-E\,C_1\,C_2 \tag{25}$$

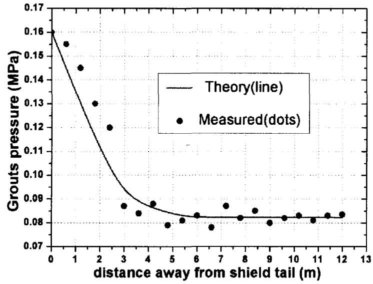

Fig.7 Final distributions of grouts pressure in longitudinal section at $\theta=45^0$

As Fig.7 shows, grouts pressure decreases rapidly in the range of three or four rings from shield tail. Corresponding data is from 0.16MPa to 0.08MPa. Grouts pressure becomes stable at the fifth ring away from shield tail in longitudinal section. So, calculated results match the general rules of pressure dissipation. From further observation, we know that theoretical values are a little smaller than the measured values. That is because of the time factor for pressure diffusion, which is not completely considered in the example calculation. It is obvious that the further away from shield tail, the greater the gouts pressure loss.

5. CONCLUSIONS

(1) The cross section and longitudinal section can be divided into two relatively independent processes, according to the grouts pressure distribution in simultaneous backfilling grouting in shield tunnel.

(2) Based on the typical four grouting holes design, grouts pressure formula in cross section is derived. Considering the hardening process and infiltration into surrounding strata, grouts pressure formula in longitudinal section is founded. The engineering example shows that the proposed equation obtained matches the actual situation well.

ACKNOWLEDGMENTS

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Study on Shiziyang Tunnel Engineering Geology and Shield Tunneling

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ABSTRACT: The Shiziyang tunnel is in passenger dedicated rail line connecting Guangzhou, Shenzhen and Hong Kong. It will be the longest underwater tunnel and have the highest technical level in China. This article describes the tunnel's design and construction schemes, analyzes and summarizes the characteristics of this tunnel, in terms of its geological and hydro geological formations; and defines the strata graphic classification. According to sub-formation and characteristics of the tunnel, this article discusses the problems that may arise in the construction of the tunnel in sub-strata, declares the key points in technology of shield tunneling in three major aspects: soft ground, the upper-soft and lower-hard mixed ground and hard rock (medium hard rock) ground.

KEY WORDS: railway tunnel; underwater tunnel; Shield; mixed ground; construction

1 INTRODUCTION

Currently, the Shiziyang underwater railway tunnel which connecting Guangzhou, Shenzhen and Hong Kong in the passenger dedicated line is being constructed. Also some other highway underwater tunnels are being constructed. A large number of underwater tunnels in coastal areas and urban traffic systems need to be designed and planed and constructed [1].

The passenger dedicated line of the Shiziyang tunnel in the area of the Pearl River Delta is located in the interval between Dongyong Station and Humen Station. The tunnel's length is 10800m. It is the key project of the Guangzhou-Shenzhen-Hongkong passenger dedicated line[2,3]. Shiziyang tunnel is a large-section underwater tunnel. It passes through mixed strata which has frequent changes in litho logy with large differences in physical and mechanical properties. In the strata there are wide variations of weathered bedrock interface, intensive distribution of fault broken rock, obvious differences in water content. Thus Shiziyang tunnel is challengeable and has some risks in engineering.

This article is to describe the tunnel's design and construction projects, analyze and