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Change of groundwater inflow by cutoff grouting thickness and permeability coefficient

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Abstract. The groundwater during tunnel excavation not only affects the stability of the tunnel and constructability but also causes the subsidence of the upper ground due to the lowering of groundwater. Generally, the cutoff grouting is applied as a countermeasure to reduce the groundwater inflow during tunnel excavation, and the cutoff grouting is often applied in the range of plastic zone around the tunnel. However, grouting in the plastic zone is only appropriate for ground reinforcement purposes, and guidelines for the application range of cutoff grouting and the targeted permeability coefficient of the grouting zone are required. In this study, the relationship between groundwater inflow into tunnel and application range of cutoff grouting and permeability coefficient is proposed and compared with numerical analysis results. It was found that grouting with tunnel radius thickness is appropriate to reduce the groundwater inflows effectively. More than 90% reduction in groundwater inflow can be achieved when the annular area of the tunnel radius thickness is grouted with a permeability reduction ratio of 1/50~1/200.

Keywords: cutoff grouting; grouting zone; groundwater inflow; tunnel

1. Introduction

Tunnels do not always have to be completely waterproofed, and the permissible water leakage rate is generally managed depending on the purpose of the tunnel. The permissible water leakage rate is classified mainly according to the purpose of the tunnel as shown in Table 1 which was devised by the STUVA and the Stuttgart Otto-Graf-Institute at the end of the 1960s (Girnau and Haack 1969, Henke *et al.* 1975). However, it should also be related to the tunnel structure, surrounding ground characteristics, and the influence of leakage on stability of adjacent structures and supply from the source of groundwater. Unacceptable groundwater inflow into a tunnel can cause settlement of surrounding ground, damage of adjacent structures, and reduction or depletion of local water supplies that rely on springs and wells.

Waterproofing is an expensive element in tunnel construction, often time consuming, labor intensive and can delay the occupation of tunnels. In general, cut-off grouting is applied as a countermeasure to reduce groundwater inflow into tunnels. Many researchers only studied on the applicability and effect of various grouting materials on homogeneous ground. Kim and Park (2017) applied the bio grouting and evaluated the improved strength of the loose sandy ground. Zheng *et al.* (2016) performed laboratory tests to study the effect of compensation grouting on soil structure. Chang *et al.* (2016) investigated ground improvement of compressibility, permeability, static and liquefaction strengths of in-situ grouted ground by performing field and laboratory tests. It was found that the effect of grouting on reducing hydraulic conductivity of the CL soils was insignificant.

Table 1 STUVA's Permissible daily leakage water rates in German tunneling

Tightness Class	Moisture Characteristics	Intended Use	Permissible Daily Leakage Water Quantity (l/sq. m), Given a Reference Length of:	
			10 m	100 m
1	Completely dry	Storerooms and workrooms, restrooms	0.02	0.01
2	Substantially dry	Frost-endangered sections of traffic tunnels; station tunnels	0.1	0.05
3	Capillary wetting	Route sections of traffic tunnels for which Tightness Class 2 is not required	0.2	0.1
4	Weak trickling water	Utility tunnels	0.5	0.2
5	Trickling water	Sewage tunnels	1.0	0.5

Tsuji *et al.* (2017) presented a case study of successful grouting work in reducing the abundant water inflow into a 500 m deep underground gallery (around 3.5 MPa of groundwater pressure) from a fractured rock mass. Liu *et al.* (2018) presented a coupled seepage–erosion water inrush model to investigate the influence of cut-off grouting thickness on the seepage–erosion process. It was found that

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the seepage–erosion process was attenuated as the cut-off grouting thickness increased.

In general, the plastic zone around the tunnel is often determined as the target range of grouting injection. However, grouting of plastic zones is only suitable for ground reinforcement work, and the injection range for cut-off grouting should be determined considering the permeability of the surrounding ground before and after grouting. In this study, the effect of cut-off grouting applied around the tunnel was examined mathematically according to the hydraulic characteristics of the surrounding ground, the grout injection range, and the reduction rate of permeability after grouting.

2. Inflow rate estimation

The analytical equation for estimating groundwater inflow rate into a tunnel can be derived based on the mirror image tunnel method (Harr 1962, Fernandez 1994). The mirror image tunnel method makes it easy to analyze the groundwater flow regime around a tunnel by placing a mirror image tunnel opposite side of the initial groundwater line (Fig. 1(a)). The mirror image tunnel continuously discharges water (-Q) into the ground and the same amount of water flows into the actual tunnel (+Q). The flow lines and equipotential lines around the tunnels are shown in Fig. 1(b), and the initial groundwater line is the boundary equipotential line. The groundwater level is assumed to be maintained the initial level, i.e., there's no groundwater level drawdown. The ground around tunnels is assumed to be homogeneous and isotropic.

On the basis of Darcy's law, the total inflow (or outflow) rate per unit length of tunnel can be obtained as Eq. (1) and the total head is derived as Eq. (2).

$$Q = A \cdot k \cdot i = 2\pi r \cdot 1 \cdot k_r \cdot \frac{\partial h}{\partial r} \tag{1}$$

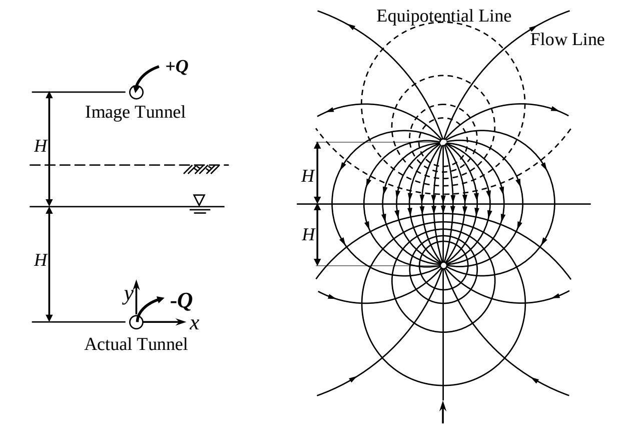
$$h = \frac{Q}{2\pi k_r} \ln r + C_1 \tag{2}$$

where i = head gradient, k_r = permeability of ground around the tunnel, r = radial distance from the center of tunnel, and C_1 = constant.

The piezometric head variation around two tunnels can be derived by superimposing the head variation around each tunnel.

$$\begin{aligned} h &= h_{actual tunnel} + h_{image tunnel} \\ &= \frac{Q}{2\pi k_r} \ln r_1 + \frac{-Q}{2\pi k_r} \ln r_2 + C_2 \\ &= \frac{Q}{4\pi k_r} \ln \frac{x^2 + y^2}{x^2 + (2H - y)^2} + C_2 \end{aligned} \tag{3}$$

where, $h_{image\ tunnel}$ = piezometric head around the image tunnel, $h_{actual\ tunnel}$ = piezometric head around the actual tunnel, Q = water inflow rate, H = depth of the actual tunnel from the groundwater level, x, y = horizontal and vertical coordinate with the origin at the center of the actual tunnel,



(a) Placing the image tunnel (b) Equipotential lines and flow line

Fig. 1 Mirror image tunnel method (Fernandez and Moon 2010)

and C_2 = constant.

Two boundary conditions, $h|_{y=H} = H$ $h|_{x=a,y=0} = 0$ are used to calculate the constant, C_2 and to derive the analytical equation for estimating inflow rate, Q.

$$h = \frac{Q}{4\pi k_r} \ln \frac{x^2 + y^2}{x^2 + (2H - y)^2} + H \tag{4}$$

$$Q = \frac{4\pi \cdot k_r \cdot H}{\ln\left(1 + \left(2H/a\right)^2\right)} \tag{5}$$

where a = radius of tunnel.

The porewater pressure around a tunnel can be estimated as

$$\begin{aligned} p &= (h - y) \cdot \gamma_w \\ &= \left[H - \frac{H}{\ln\left(1 + \left(2H/a\right)^2\right)} \ln\left(\frac{x^2 + (2H - y)^2}{x^2 + y^2} \right) - y \right] \cdot \gamma_w \\ &= \left[1 - \frac{1}{\ln\left(1 + \left(2H/a\right)^2\right)} \ln\left(\cos^2\theta + \left(2H/r - \sin\theta\right)^2 \right) \right. \\ &\quad \left. - \frac{r \sin\theta}{H} \right] \cdot H \cdot \gamma_w \end{aligned} \tag{6}$$

where, r = distance from the center of the actual tunnel, θ = counter-clockwise angle from the tunnel spring line, and γ_w = unit weight of water.

The porewater pressure variation along the spring line (θ = 0) is

$$p_{sp} = \left[1 - \frac{\ln\left(1 + \left(2H/r\right)^2\right)}{\ln\left(1 + \left(2H/a\right)^2\right)} \right] \cdot H \cdot \gamma_w \tag{7}$$

It should be noted that the image tunnel is located opposite to the subsea tunnel from the ground surface instead of groundwater level, and the inflow rate into the subsea tunnel can be estimated using Eq. (8) instead of Eq. (5).

$$Q \approx \frac{2\pi \cdot k_r \cdot H}{\ln\left(1+\left(2D/a\right)^2\right)} \tag{8}$$

where, D = depth of tunnel from the ground surface.

3. Groundwater inflow rate reduction due to grouting

3.1 Groundwater inflow reduction

In order to determine the grouting injection pressure, the thickness of the grouting zone, the type and concentration of grout, etc., it is necessary to estimate the groundwater inflow reduction rate after grouting. The groundwater flow rate (Q_r) from the surrounding ground into the grouting zone can be estimated as Eq. (9) which uses the outer radius of the grouting zone, b instead of tunnel radius, a in Eq. (5).

$$Q_r = \frac{4\pi k_r \Delta h_r}{\ln\left(1+\left(2H/b\right)^2\right)} \tag{9}$$

where, Δh_r = head loss in the surrounded ground (Fig. 2), and b = the outer radius of the grouting zone.

The analytical equation for estimating the groundwater flow rate (Q_g) from the grouting zone into the tunnel can be derived as Eq. (10) if it is assumed that the same head loss (Δh_g) in the radial direction occurs across the grouting zone around the tunnel.

$$Q_g = \frac{2\pi k_g \Delta h_g}{\ln\left(b/a\right)} \tag{10}$$

where, k_g = reduced permeability of the grouting zone, and Δh_g = head loss across the grouting zone (Fig. 2).

The flow rate from the surrounding ground (Q_r) is equal to the flow rate across the grouting zone (Q_g) in order to achieve continuity of flow at each domain, and thus

$$Q_g = Q_r \quad \Rightarrow \quad \frac{k_g \Delta h_g}{\ln\left(\frac{b}{a}\right)} = \frac{2k_r\left(H-\Delta h_g\right)}{\ln\left(1+\left(2H/b\right)^2\right)} \tag{11}$$

Thus, the normalized hydraulic head losses (Δh_g and Δh_r) can be obtained as Eqs. (12) and (13), respectively.

$$\frac{\Delta h_g}{H} = \frac{1}{1+C\,{k_g}/{k_r}} \tag{12}$$

$$\frac{\Delta h_r}{H} = 1-\frac{\Delta h_g}{H} = \frac{C}{C+{k_r}/{k_g}} \tag{13}$$

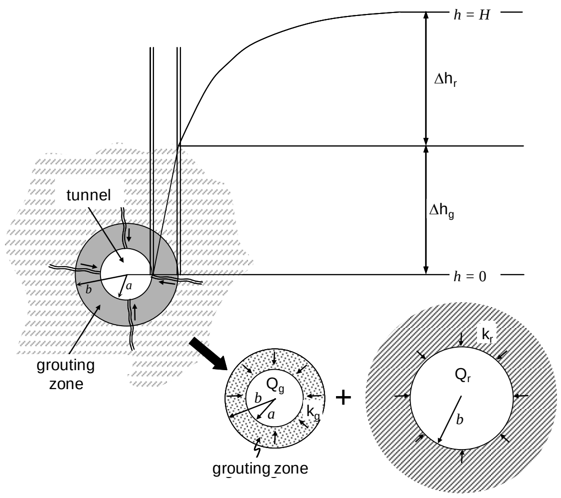


Fig. 2 Continuity of flow and head loss across the grouting zone

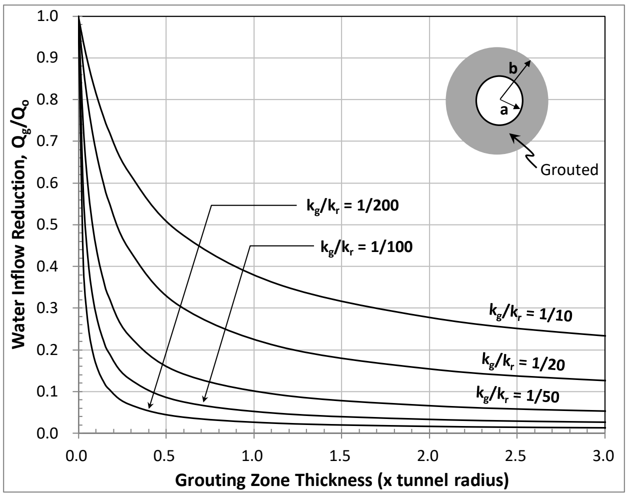


Fig. 3 Inflow reduction ratio as a function of the thickness of grouting zone (for a=1.8 m, H=38 m)

$$C = \ln\left(1+\left(2H/b\right)^2\right) \Big/ 2\ln\left(b/a\right) \tag{14}$$

where, H = depth of tunnel below the groundwater level (use the depth of tunnel, D, below the ground surface for subsea tunnels), a = radius of the tunnel, and b = outer radius of the grouting zone.

Therefore, the inflow rate into the tunnel after grouting can be estimated using Eq. (15), and the reduction rate of groundwater inflow (Q_g/Q_o) can be estimated as Eq. (16).

$$Q_g = Q_r = \frac{4\pi k_r H}{\ln\left(1+\left(2H/b\right)^2\right)} \cdot \frac{C}{C+\left({k_r}/{k_g}\right)} \tag{15}$$

$$\frac{Q_g}{Q_o} = \frac{\ln\left(1+\left(2H/a\right)^2\right)}{\ln\left(1+\left(2H/b\right)^2\right)} \cdot \frac{C}{C+\left({k_r}/{k_g}\right)} \tag{16}$$

where, Q_r = groundwater flow rate from the surrounding ground into the grouting zone, Q_g = groundwater inflow rate into the tunnel after grouting, Q_o = groundwater inflow rate into the tunnel before grouting.

Fig. 3 shows an example relationship between the inflow reduction ratio (Q_g/Q_o) and the thickness of grouting zone for various permeability ratio, k_g/k_r. The water inflow rates, Q_g were estimated using the proposed analytical equation (Eq. (15)). As shown in Fig. 3, grouting with tunnel radius thickness ($(b-a)/a$=1.0) is suitable to effectively reduce the groundwater inflows. The relationships shown in Fig. 3 indicates that for relatively large reduction of permeability in the grouting zone (k_g/k_r = 1/50~1/200) the groundwater inflow reduction ratio is estimated as 2~11%, which means tunnel radius-thick grouting reduces the inflow rate by 89-98%. The groundwater inflow reduction ratio of 26-42% or the reduction of water inflow rate of 58-74% is estimated due to relatively small permeability reduction ratio (k_g/k_r) of 1/10–1/20 in the grouting zone.

3.2 Porewater pressure change

It should be noted that the hydraulic pressure acting on the outer perimeter of the grouting zone increases as the permeability of the grouting area reduces. Thus, the required strength of the grouting zone for the stability of the tunnel needs to be estimated based on the increased hydraulic pressure after grouting. The hydraulic pressure acting on the outer perimeter of the grouting zone can be estimated as Eq. (17).

$$p_g = \left(\Delta h_g - y\right)\cdot\gamma_w = \left[\frac{1}{1+C\left(k_g/k_r\right)} - \frac{b\sin\theta}{H}\right]\cdot H\cdot\gamma_w \quad (17)$$

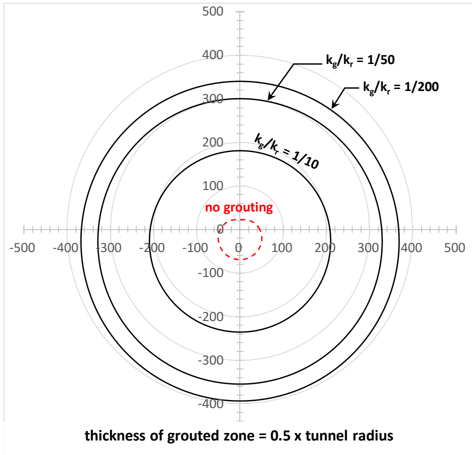
The distribution of piezometric head after grouting can be estimated by replacing Q in Eq. (4) with Q_g. Thus,

$$h = \frac{H}{\ln\left(1+\left(2H/b\right)^2\right)}\cdot\frac{C}{C+\left(k_r/k_g\right)}\cdot\ln\frac{x^2+y^2}{x^2+\left(2H-y\right)^2}+H \quad (18)$$

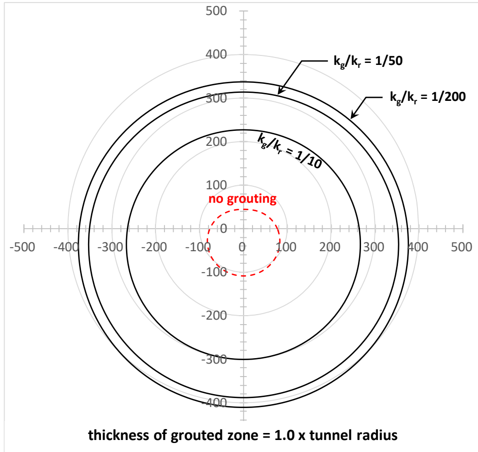
The distribution of porewater pressure after grouting can be estimated as

$$p = (h-y)\cdot\gamma_w = \left[H - \frac{H}{\ln\left(1+\left(2H/b\right)^2\right)}\cdot\frac{C}{C+\left(k_r/k_g\right)}\ln\left(\frac{x^2+(2H-y)^2}{x^2+y^2}\right)-y\right]\gamma_w$$

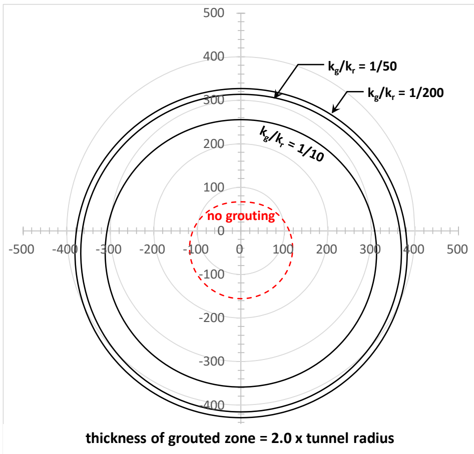
$$= \left[1 - \frac{1}{\ln\left(1+\left(2H/b\right)^2\right)}\cdot\frac{C}{C+\left(k_r/k_g\right)}\cdot\ln\left(\cos^2\theta+\left(2H/r-\sin\theta\right)^2\right) - \frac{r\sin\theta}{H}\right]\cdot H\cdot\gamma_w \quad (19)$$



(a) Thickness of grouting zone = 0.5 x tunnel radius

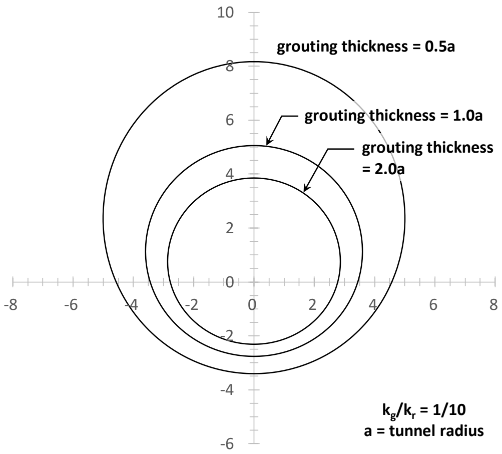


(b) Thickness of grouting zone = 1.0 x tunnel radius

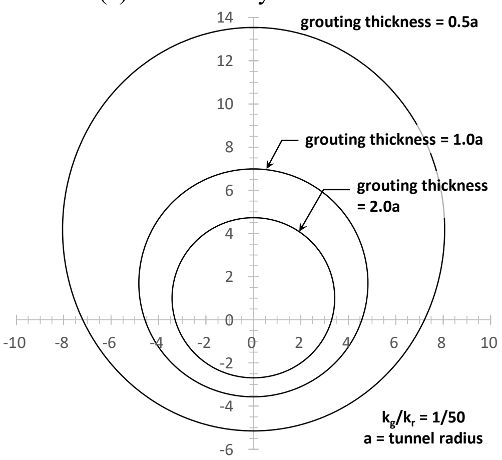


(c) Thickness of grouting zone = 2.0 x tunnel radius

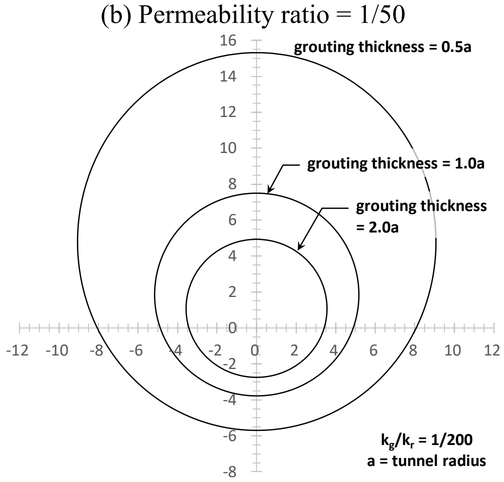
Fig. 4 Hydraulic pressure acting on grouting zone (for a=1.8 m, H=39 m)



(a) Permeability ratio = 1/10

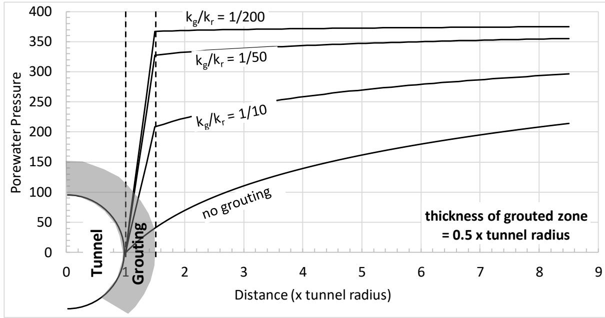


(b) Permeability ratio = 1/50

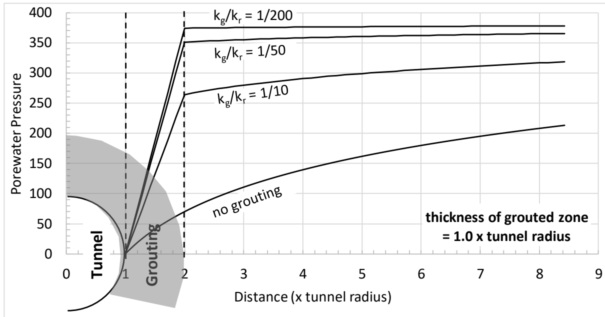


(c) Permeability ratio = 1/200

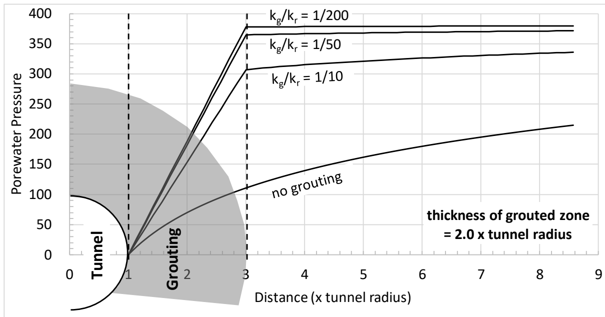
Fig. 5 Normalized hydraulic pressure acting on grouting zone (for a=1.8 m, H=39 m)



(a) Thickness of grouting zone = 0.5 x tunnel radius



(b) Thickness of grouting zone = 1.0 x tunnel radius



(c) Thickness of grouting zone = 2.0 x tunnel radius

Fig. 6 Porewater pressure variation along the spring-line (for a=1.8 m, H=39 m)

Fig. 4 shows hydraulic pressure acting on the outer perimeter of grouting zone for various thickness of grouting zone and permeability ratio, k_g/k_r. The hydraulic pressure is estimated by the proposed analytical equation, Eq. (17). The dotted lines are the hydraulic pressure distribution before injecting grout. As can be seen in Fig. 4, as the thickness of the grouting zone increases, the hydraulic pressure acting on the circumference of the grouting zone also increases. The permeability ratio, k_g/k_r also affects the hydraulic pressure acting on the outer perimeter of the grouting zone. However, if the permeability ratio is less than 1/50, the increase in hydraulic pressure due to the decrease of permeability ratio is not greatly different.

Fig. 5 shows a graphical representation of the normalized hydraulic pressure acting on the outer perimeter of grouting zone for various thickness of grouting zone and various permeability ratio, k_g/k_r in the range of 1/10~1/200. The values in Fig. 5 indicate how many times the hydraulic pressure increases after grouting. The increment of hydraulic pressure on the grouting zone is larger on a thinner grouting zone, and the influence of grouting on the stability of tunnel is smaller on the thicker grouting zone. When the surrounding ground is grouted with a tunnel diameter thickness, the hydraulic pressure on the grouted area increases only 3.9~4.9 times after grouting. However, if the thickness of grouting zone is reduced to about 1/2 (1.0 x tunnel radius), the hydraulic pressure acting on the grouted area increases about 5.1~7.5 times after grouting. It is also found that the hydraulic pressure increase rate in tunnel roof area due to grouting is 2~2.5 times the hydraulic pressure increase rate in tunnel invert area.

The porewater pressure variation along the spring-line (θ=0) can be estimated as Eq. (20), and the estimated porewater pressure variation for various thickness of grouting zone and permeability ratio, k_g/k_r is shown in Fig. 6. The porewater pressure along the spring-line does not change much with permeability ratio, k_g/k_r smaller than 1/50. A significant hydraulic pressure drop takes place across the grouting zone, and the hydraulic gradient is steeper in thinner grouting zone.

$$p_{sp} = \left[1 - \frac{\ln\left(1+\left(2H/x\right)^2\right)}{\ln\left(1+\left(2H/b\right)^2\right)} \cdot \frac{C}{C+\left(k_r/k_g\right)} \right] \cdot H \cdot \gamma_w \tag{20}$$

4. Conclusions

In general, as the range of grouting area increases, the amount of groundwater inflow decreases. However, if the thickness of grouting area is larger than the tunnel radius, the reduction rate of groundwater inflow decreases with increasing thickness of grouting area. Therefore, it could be concluded that grouting with tunnel radius thickness is appropriate to reduce the groundwater inflows effectively. More than 90% reduction in groundwater inflow can be achieved when the annular area of the tunnel radius thickness is grouted with a permeability reduction ratio (k_g/k_r) of 1/50~1/200. A 58-74% reduction in groundwater inflow rate is estimated due to relatively small permeability reduction ratio (k_g/k_r) of 1/10-1/20 in the grouting zone.

A significant hydraulic pressure drop takes place across the grouting zone, and the hydraulic pressure acting on the grouting zone increases due to reduction of the permeability in the grouting zone. When the surrounding ground is grouted with a tunnel radius thickness, the hydraulic pressure on the grouted area increases 4~5 times after grouting. Thus, it is necessary to take into account the increased hydraulic pressure on the grouting zone when designing the tunnel lining and support systems and when estimating the required strength of the grouting zone. The hydraulic pressure increases bigger on a thin grouting zone, and the stability of tunnel may be affected if the strength of grouted soil is not increased properly after grouting.

The procedure presented here did not consider groundwater level drawdown and permeability change during groundwater flow into the tunnel. The groundwater level drawdown could be a major factor affecting steady-state groundwater inflow rate, especially for shallow tunnels. It should be noted that if the groundwater level drawdown is significant, the presented procedure is no longer valid.

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