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Predicting external water pressure and cracking of a tunnel lining by measuring water inflow rate

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ABSTRACT

The flow of water into a tunnel, through the surrounding rock mass and the tunnel lining, has important implications for tunnel design and tunnel condition assessment. The hydraulic conductivity of the lining is a major controlling factor on the water inflow rate. Previous work had been mainly based on the assumption of constant hydraulic conductivity of the lining. In this work, the existing analytical models of water flow through a tunnel lining under steady-state, saturated conditions are extended to incorporate a linear variation of hydraulic conductivity with distance from the tunnel wall. The inhomogeneity of a lining is shown to have a significant impact on water inflow rate and water pressure distribution according to the model. The relation between lining inhomogeneity and other hydraulic parameters was established. This model can be used to predict the hydraulic pressure and crack condition at the outer face of the lining based on measured water inflow rate and the crack condition at the inner face, with significantly increased accuracy compared with the existing models based on constant hydraulic conductivity. Design charts are also developed for engineering applications.

1. Introduction

Groundwater inflow is a problem for tunnels worldwide, and numerous cases of tunnel lining failure due to water inflow have been reported (ITA, 1991). Chemically aggressive water inflow can cause degradation of concrete lining (Gérard et al., 2002) and excessive hydraulic pressure in the lining can trigger concrete spalling (Jansson and Boström, 2010) and affect the structural stability of the tunnel (Fang et al., 2016). A numerical approach was developed to assess the hydraulic conductivity of the tunnel lining according to the water inflow rate when the other parameters are given (Bagnoli et al., 2015). Tunnels can be classified into three types with respect to interaction with water: unlined tunnels, drained lined tunnels and water-sealed lined tunnels (Butscher, 2012). The inflow water problem has been extensively studied for all the three cases (Polubarinova-Kochina, 1963; Goodman et al., 1965; Heuer, 1995; Zhang and Franklin, 1993; El Tani, 2003; Hwang and Lu, 2007; Lei, 1999; Kolymbas and Wagner, 2007; Park et al., 2008; Fernandez and Moon, 2010a, 2010b; Huang et al., 2013; Fang et al., 2016).

These previous approaches for solving tunnel water inflow problems assume that the lining has a homogeneous hydraulic conductivity. The surrounding rock mass is also commonly assumed to have homogeneous hydraulic conductivity, although two studies with inhomogeneous properties have been conducted (Table 1). Schematic illustration of the hydraulic conductivity distribution of the three types of tunnel under homogeneous conditions is shown in Fig. 1.

The hydraulic conductivity of a homogeneous lining, which primarily depends on the crack width and crack density, can be estimated from the crack features of the lining (Fernandez and Moon, 2010a). The water flow rate through a crack has a cubic relationship with crack width, and a linear relationship with crack density (Snow, 1965). A reduction factor for crack roughness has been developed for application to water flow through cracked concrete (Reinhardt, 1997).

Calculations of water inflow are very sensitive to the hydraulic conductivity of the lining and inhomogeneity of the lining can potentially cause significant differences in the results. The hydraulic conductivity of a lining is typically deduced from observations of joint and crack features on the inner face of the lining. Such features can vary through the lining which would affect the hydraulic conductivity along the water flow path. However such variation within the lining cannot be directly observed, and thus there is a need for methods to predict and account for this.

This paper presents an analytical solution for water inflow rate and hydraulic pressure distribution in tunnel linings with inhomogeneous hydraulic conductivity, assuming saturated conditions and steady-state flow. The solution uses the hydraulic conductivity of the surface of the lining inside the tunnel as the reference value. Variation in hydraulic conductivity is considered linear within the lining. In combination with

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Table 1
Framework for water inflow prediction models.

Type of tunnel	Rock mass	Lining/lining-like zone	Reference
Unlined	Homogenous		Goodman et al. (1965) Lei (1999) El Tani (2003)
	Inhomogeneous		Zhang and Franklin (1993)
Lined drained	Homogenous	Homogenous	Kolymbas and Wagner (2007) Park et al. (2008)
	Homogenous	Inhomogeneous	NONE
	Inhomogeneous	Homogenous	NONE
	Inhomogeneous	Inhomogeneous	NONE
Lined water sealing	Homogenous	Homogeneous	Fernandez and Moon (2010a) (unlined tunnel with a lining-like zone)
	Homogenous	Inhomogeneous	Addressed in this paper
	Inhomogeneous	Homogenous	Fernandez and Moon (2010b) (unlined tunnel with a lining-like zone)
	Inhomogeneous	Inhomogeneous	NONE

the observations of cracking at inner surface and the water inflow rate, this model can be used to estimate the level of inhomogeneity within the lining including the water pressure and as the crack condition at the outer face of the lining.

2. Water inflow through a homogeneous lining

To calculate the water inflow rate of a tunnel lining, a tunnel can be defined in a cylindrical coordinate system. The origin of the coordinate system is the centre point of the tunnel. All points are defined by an angle θ, and the distance r (Fig. 2).

For a tunnel under the water table (Fernandez and Moon, 2010a), the hydraulic gradient i can be described as

$$i = \frac{\mathrm{d}h}{\mathrm{d}r} \tag{1}$$

where dh is the change in total hydraulic head, which comprises both hydraulic pressure head and elevation head, and dr is the change in radius. According to Darcy's law, the water discharge Q per unit length of the tunnel for a homogenous lining (Fetter, 2001) is

$$Q = 2\pi K r\frac{\mathrm{d}h}{\mathrm{d}r} \tag{2}$$

where K is the hydraulic conductivity of material.

For a permeable lining zone of a tunnel, the hydraulic head at the outer surface and inner surface of lining will affect the water inflow rate. The outer surface and inner surface of lining were defined using the term extrados and intrados in a published document (ITA, 1991). The water inflow rate was discussed by introducing the boundary conditions of the hydraulic head at the outer lining surface and the inner lining surface (Fernández, 1994) as

$$Q = \frac{2\pi K(h_{outer} - h_{inner})}{\ln\left(\frac{(a+d)}{a}\right)} \tag{3}$$

where water head at the outer surface at the spring line of the lining is defined as h_{outer}; h_{inner} is the water head at the inner surface at the spring line of the lining; a is the tunnel inner radius (from the centre to the inner surface) and d is the lining thickness.

For a non-pressurised tunnel, the pressure head at the inner surface is taken to be zero, so the hydraulic head loss across the lining is equal to the pressure head at the outer surface of the lining (at the spring line). The datum level is defined as the spring line of the tunnel. Therefore, the water head reduction caused by a lining, and the water head at the spring line at the outer surface, h_{outer} can be calculated as (Fernández, 1994)

$$h_{outer} = \frac{H}{1 + \gamma\left(\frac{K}{K_m}\right)} \tag{4}$$

where H is the vertical distance from the spring line of the tunnel to the water table (or equivalent phreatic pressure head); K is the equivalent hydraulic conductivity of the lining; K_m is the hydraulic conductivity of the surrounding rock mass and γ is a coefficient related to tunnel radius and lining thickness, which is defined by

$$\gamma = \ln\left(\frac{2H}{a+d}\right)\Big/\ln\left(\frac{a+d}{a}\right) \tag{5}$$

3. Water inflow through an inhomogeneous lining

Previous research only considered the condition when the lining is homogeneous, i.e. K is a constant. Assuming a homogeneous lining is a practical simplification for a thin lining where the lining inhomogeneity would not be expected to have a significant effect on water inflow. Inhomogeneity of a lining needs to be considered when the lining is thick. For a lining which is inhomogeneous, the hydraulic conductivity $K(r)$ is a function of r. A study of crack spacing in reinforced concrete showed that differences in strain in reinforcing elements would result a linear variation of crack spacing (Bazant and Oh, 1983). A linear form of variation of K with respect to r is assumed in this work since the crack spacing has been shown to have a linear relationship with hydraulic conductivity (Reinhardt, 1997). This study only analyses a linear variation of hydraulic conductivity, however other types of variation are also possible. The method applied in this study could also be applied to other types of lining inhomogeneity as long as the lining hydraulic conductivity varies continuously.

An equation is established to describe the water inflow rate (q_l) for a unit arc length of a unit length of tunnel lining (dθr) based on Darcy's law as shown in Eq. (6). The hydraulic conductivity of a tunnel lining is considered to change continuously with the radial direction ($K(r)$).

$$q_l = \mathrm{d}\theta r K(r)\frac{\mathrm{d}h}{\mathrm{d}r} \tag{6}$$

where dθr is the flow area of unit arc length of a unit length tunnel and $K(r)$ is the hydraulic conductivity of the lining, which varies with distance from the tunnel centre.

The hydraulic head variation caused by the lining inhomogeneity is shown in Fig. 3.

The hydraulic head decreases linearly through the homogeneous lining as shown in the right hand side of Fig. 3. The hydraulic conductivity through the lining is a constant under the homogeneous assumption. The hydraulic head decrease will be affected by the variation of the hydraulic conductivity through the lining in an inhomogeneous case. The left hand side of Fig. 3 shows the condition when hydraulic conductivity of the lining increases from the inner side of lining surface to the outer side of the lining surface.

An inhomogeneous hydraulic conductivity coefficient can be defined as

$$C_l = \frac{K_{outer}}{K_{inner}} \tag{7}$$

where K_{inner} and K_{outer} are the hydraulic conductivity of the inner surface of the lining and outer surface of the lining, respectively. The value of K_{inner} can potentially be determined directly by observation and measurement of crack density and crack width according to Reinhardt (1997).

$$K_{inner} = \zeta\frac{w^3\rho g}{12\mu\Delta} \tag{8}$$