Hydraulic Deterioration and Significance of Tunnel Drainage Systems

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1. Introduction

Long term interaction between ground water and lining may occur throughout the life time of the tunnel. Lining damages due to pore water pressure have been frequently reported (Shin et al, 2005). One of the most critical factors causing such failures is hydraulic deterioration of a drainage system as shown in Fig 1(a), which presents the evidence of hydraulic deterioration. It is generally known that deterioration of drainage systems occurs due to squeezing force during concrete placement and/or clogging the filters (Reddi et al, 2000, Lee et al, 2002), hinders flow into tunnels by reducing permeability, and consequently develop pore water pressure which causes additional stresses in the tunnel lining system as shown in Fig 1(b) (Shin et al, 2002, Shin et al, 2005, Shin, 2008).

The tunnel lining design guide (ASCE 1984, ICE, 2004) indicates that the tunnel design should include provision for such interaction. Therefore, the design procedure of a tunnel below ground water table has to address any detrimental effects associated with the deterioration of the drainage system. Unfortunately, however, the complicated structural and hydraulic boundary conditions of the problem and the long time period required to measure the tunnel and ground behavior are the main difficulties in modeling the structural and hydraulic interaction in tunnels. In this study attempts to model this feature numerically, and identify the effects on the tunnel in the long term were made.

(a) drain-hole sediments coated with scale  (b) a failure of a secondary lining

Fig 1. Examples of hydraulic deteriorations

There are two possibilities of hydraulic deterioration in the long-term: deterioration of drainage layers along the tunnel periphery and blocking of drain-holes. Moreover the deterioration
can be whole or local. In this study, various types of deterioration were considered. To this end the research carried out by Shin (2008), Shin et al (2007) and Shin et al (2005) were reviewed and compared. Particular concerns were given to pore water pressure on the tunnel lining.

2. Numerical representation of hydraulic deterioration

A double lining model concept was developed to simulate the lining to lining interaction (Shin et al, 2005). Fig 2 shows a typical lining structure of a bored tunnel (i.e., New Austrian Tunnelling Method: NATM). To model the hydraulic behaviour, Shin et al (2002) used a lining with a finite permeability was considered by introducing a special scheme combining structural beam element, which give direct solutions for lining distortions, forces and moments, and thin quadrilateral solid elements, which can have a prescribed permeability of concrete lining. The hydraulic deterioration can be represented numerically by reducing the permeability of the lining. Lining behaviour is modeled using the 3-noded Mindlin beam elements (Day and Potts 1990) and is assumed to be isotropic and linear elastic. The ground is modelled by 8-noded isoparametric solid continuum elements. For the analysis, ICFEP(Imperial College Finite Element Program) was adopted.

Fig 2. Modeling of a doubled-lined tunnel

Fig 3(a) and (b) show the concept of whole and local lining deterioration (Shin et al, 2005). The concept of drain hole blocking deterioration caused by filter clogging (which assumed peripheral boundary discharge) as shown in Fig 3(c), was made by Shin (2008). Results published by the separated research were reviewed and compared.
Fig 3. Types of hydraulic deterioration, where $k_i$ = permeability of ground, $k_l$ = permeability of primary lining and $k_f$ = permeability of drainage layer.

Analysis models considered were two-dimensional. This is basically assumed based on the concept shown in Fig 4, of which deterioration is local, however, sufficiently long enough in comparing with tunnel peripheral length. Hydraulic deterioration is represented by reducing permeability.

Fig 4. 2D model for local hydraulic deterioration

The model tunnel for review is shown in Fig 5. For comparative study the model previously used by Shin et al (2002) was adopted. The material parameters used are also listed in Fig 5. Analysis method and computer program used were explained in Shin et al (2005).

Fig 5. Analysis model
To compare the effect of the deterioration, three types of hydraulic deterioration are considered: whole lining deterioration (drainage layer deterioration), local deterioration and drain hole blindings. The analysis was performed for three types of deterioration and relative permeability for each deterioration cases.

3. Results and discussion

The results (Shin et al., 2005, KISTEC, 2007 and Shin, 2008) were analyzed in terms of hydraulic and structural behavior. Flow behavior is mainly described based on pore-water pressure on the lining. The influence of hydraulic deterioration was highlighted by comparing the results with those from the two extreme hydraulic boundary conditions: fully permeable and impermeable boundaries, and from the various finite permeable boundary conditions.

Pore water pressure developed on the lining is dependent on the tunnel structure, which is single or double. In this paper doubled-lined NATM lining is concerned, which is generally represented as shown in Fig 6.

Net pressure on the primary lining is generally negligible. Thus the pore water pressure on the secondary lining is mainly concerned.

The most significant features caused by deterioration can be found by comparing the distribution of pore water pressure. Particularly the unbalanced distribution of pore water pressure is noticeable as shown in Fig 7.

In cases of local and unbalanced drain-hole blocking, the distribution of pore water pressure is asymmetrical. This is very important as the asymmetrical pore water pressure may cause torsional behavior of tunnel in the longitudinal axis. The influence becomes significant with an increase in relative permeability.
It is interesting to compare pore water pressure on the lining for the different types of deterioration. The cases considered are (a) deterioration of drainage layers, (b) local deterioration and (c) drain holes blockings.

Fig 8 presents pore water pressure distribution for the case of whole hindrance of flow. It is smooth and gradual in magnitude. The difference between tunnel crown and invert is not significant.
Fig 8. Distribution of pore water pressure: whole hindrance of flow

Pore water pressure distribution for the case of local hindrance of flow is shown in Fig 9. In this case the relative permeability (lining permeability to soil permeability) is assumed as 0.1. In the range of deteriorated area, there is significant increase in pore water pressure. This means that local hindrance increase pore water pressure considerably. The behavior is important in view structural behavior. Concentrated local pore water pressure may cause significant moment in the linings.

Fig 9. Distribution of pore water pressure: local hindrance of flow

Fig 10 presents pore water pressure distribution for the case of drain hole blocking. The difference along the tunnel is significant. In the points of open drain holes, there is negligible pore water pressure. The results shows that the drain hole blockings increases pore water pressure significant.
This hydraulic behavior is also important in the terms of structural behavior. Concentrated local pore water pressure may cause significant moments in the linings. The unbalanced or non-symmetric pore water pressure can result in torsional distortion in tunnel in the direction of tunnel axis. Therefore, it needs to be aware that the significance of the deterioration of the drainage system exists during tunnel operation.

4. Conclusions

In this paper, hydraulic behavior of tunnel linings due to long-term hydraulic deterioration of tunnel drainage system was reviewed. Comparisons were made in terms of pore water pressure on the linings based on previous studies. The effect of hydraulic deterioration of lining and the significance of drainage can be summarized in two aspects as:

a. considerable increase in pore water pressure develops in the area of hindrance of flow and at around blocked drain holes
b. non-symmetry and unbalance in pore-water pressure on the lining causes the distortion of tunnel

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References