Structural Engineering and Mechanics, *Vol. 52, No. 6 (2014) 1257-1271*
DOI: http://dx.doi.org/10.12989/sem.2014.52.6.1257

Behavior of double lining due to long-term hydraulic deterioration of drainage system

Jong-Ho Shin[1a], In-Keun Lee[2b] and Eun-Jung Joo[*1]

[1]Department of Civil Engineering, Konkuk University, Seoul, Republic of Korea
[2]Institute of Land and Housing, LH Cooperation, Daejeon, Republic of Korea

(Received April 3, 2014, Revised October 6, 2014, Accepted October 29, 2014)

Abstract. The hydraulic deterioration of the drainage system in tunnel linings is one of the main factors governing long-term lining-ground interactions during the lifetime of tunnels. Thus, in the design procedure of a tunnel below the groundwater table, the possible detrimental effects associated with the hydraulic deterioration should be addressed. Hydraulic deterioration in double-lined tunnels can occur because of reasons such as clogging of the drainage layer and drain-pipe blockings. In this study, the coupled mechanical and hydraulic interactions between linings due to drain-pipe blockings are investigated using the finite-element method. A double-lined structural model incorporating hydraulic behavior is developed to represent the coupled structural and hydraulic behavior between the linings and drainage system. It is found that hydraulic deterioration hinders flow into the tunnel, causing asymmetric development of pore-water pressure and consequent detrimental effects to the secondary lining.

Keywords: doubled-lined tunnel; lining; hydraulic deterioration; drain-pipe blocking; numerical analysis

1. Introduction

Research on short-term fluid-structure-soil interaction generally considering fluid in storage tanks or concrete dams under dynamic loadings has been found in the literature (Shariatmadar and Mirhaj 2011, Park and Cho 2012). However, the long-term fluid-structure-soil interaction including the water in soils has rarely been shown. For tunnels acting as drains, the long-term interaction between groundwater, linings, and ground may occur throughout the lifetime of the tunnel. Fig. 1 shows evidence of hydraulic effects on tunnels, such as sedimentation in drain pipes, leaking, and structural damages due to pore-water pressure (Shin *et al*. 2005, Chu *et al*. 2011).

It has been reported that one of the most critical factors causing such detrimental effects is the hydraulic deterioration of a drainage system (Lee *et al*. 2002, Chabot *et al*. 2013). Structural damages of linings caused by pore-water pressure have also been reported (Shin *et al*. 2002, Joo and Shin 2014). Recent research has indicated that lining damage mostly occurs during the rainy season when the ground water level rises (KISTEC 2007). Fig. 2 summarizes the factors

∗Corresponding author, Ph.D. Student, E-mail: ejjoo@konkuk.ac.kr
[a]Professor, E-mail: jhshin@konkuk.ac.kr
[b]Ph.D., E-mail: iklee57@lh.or.kr

http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)

(a) Blocked drain-pipe (Chu *et al*. 2011) (b) Leaking (c) Pressurized leaking (d) Structural damage (Shin *et al*. 2005)

Fig. 1 Evidences of hydraulic deteriorations

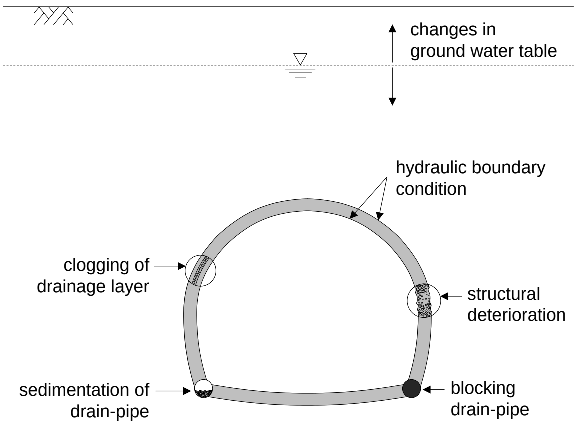
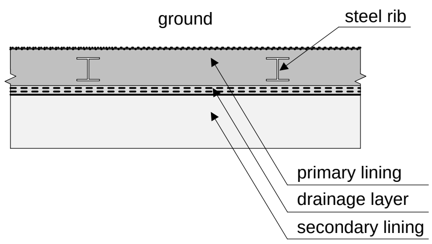


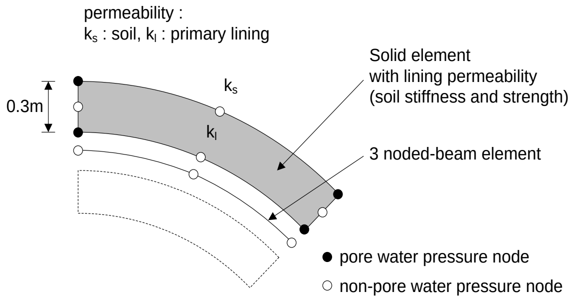
Fig. 2 Influencing factors of structural and hydraulic interaction

influencing the interaction. The drainage system consists of filter layers and drain pipes. The hydraulic deterioration of the drainage system could be mainly caused by the malfunction of the filter layer and drain-pipe blockings. The malfunction of drainage systems may occur initially because of the squeezing force generated during the concrete placement of secondary linings (Murillo *et al*. 2014). In addition, the clogging of the drainage layers (Reddi *et al*. 2000, Lee *et al*. 2002) could be another source of hydraulic deterioration during operation. Squeezing and clogging of filter layers hinder flow into tunnels by reducing the permeability of the drainage layer and consequently results in development of pore-water pressure, causing additional stresses in the linings of a double-lined NATM tunnel. Thus, the behavior is termed as coupled structural and hydraulic interactions.

The effect of hydraulic deterioration in drainage systems was investigated by Shin *et al*. (2002, 2005) and Yoon *et al*. (2014). The effect of local hydraulic deterioration caused by filter clogging based on peripheral discharge was further investigated by Shin (2008), who pointed out that the local deterioration of a drainage system may cause structural damages to the secondary lining. However, in these previous studies, the peripheral boundary discharge was generally modeled as shown in Fig. 3. This model is not likely to be valid in a double-lined NATM tunnel where discharge takes place through drainage layers and drain pipes. In this case, drain-pipe blocking can be another source of hydraulic deterioration, which causes the development of pore-water pressure on the linings and causes structural damages in the linings (KICT 2009; Lee *et al*. 2012; Jung *et al*. 2013)



(a) NATM tunnel lining



(b) Modeling of lining

Fig. 3 Single-lined model with peripheral discharge (Shin 2008)

In a double-lined NATM tunnel, flow into the tunnel occurs through three different layers (the ground, primary (shotcrete) lining, and drainage (filter) layer), before being collected by drain pipes. Flow resistance occurs when flow takes place from a layer with high permeability to a layer with low permeability. A water head develops corresponding to the magnitude of flow resistance in the low permeability layer. Consequently, it can be said that the development of pore-water pressure depends on the relative permeability among layers.

Only in the case where the permeability of the drainage layer (k_f) is less than the permeability of the primary lining (k_l), pore-water pressure develops on the secondary lining. Drain-pipe blocking can result in pore-water pressure being developed in the drainage layer, which may act as direct loadings on the secondary lining.

In this study, the structural and hydraulic interaction of a double-lined tunnel are simulated using numerical methods and the mechanism of pore-water pressure development and its effects are investigated.

2. Numerical modeling of lining-to-lining interactions

The modeling of a double-lined tunnel with drainage systems is based on a coupled mechanical and hydraulic problem. To model the behavior, a method combining the displacement and pore-water pressure is required. In this study, the coupled finite-element scheme ICFEP was adopted; the program developed and enhanced by Potts and Zdravkovic (1999) based on Biot's theory (1941) and Booker and Small (1975). The finite-element schemes can be written as

$$\begin{bmatrix} K_G & L_G \\ {L_G}^T & -\beta \cdot \Delta t \cdot \Phi_G \end{bmatrix} \begin{Bmatrix} \Delta d_{nG} \\ {\Delta p_{nG}}^{t_2} \end{Bmatrix} = \begin{Bmatrix} \Delta R_G \\ \Phi_G \cdot {p_{nG}}^{t_1} \cdot \Delta t \end{Bmatrix} \tag{1}$$

where K_G is the average global stiffness matrix over the time interval $(t_1,\ t_2)$, ΔR_G is the right-side incremental load vector, L_G is the global coupling matrix, Φ_G is the global flux matrix, Δd_{nG} and Δp_{nG} are the unknown incremental nodal displacement and pore pressure, respectively, and Δt denotes the time interval $(t_1 - t_2)$. β is a numerical integration parameter.

The hydraulic deterioration of the drain-pipe is simulated by considering the structural and hydraulic behavior of the lining and drainage system with a special modeling scheme.

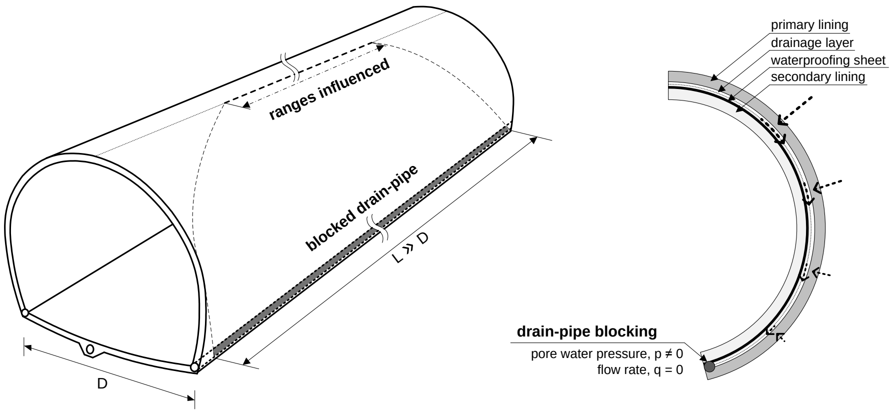
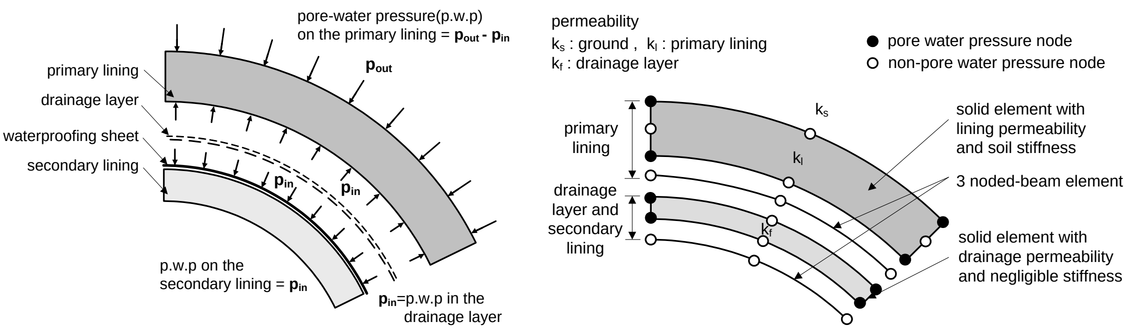


Fig. 4 Drain-pipe blocking problems in a double-lined structure



(a) Pore-water pressure mechanism (b) Modeling of double-lined structure

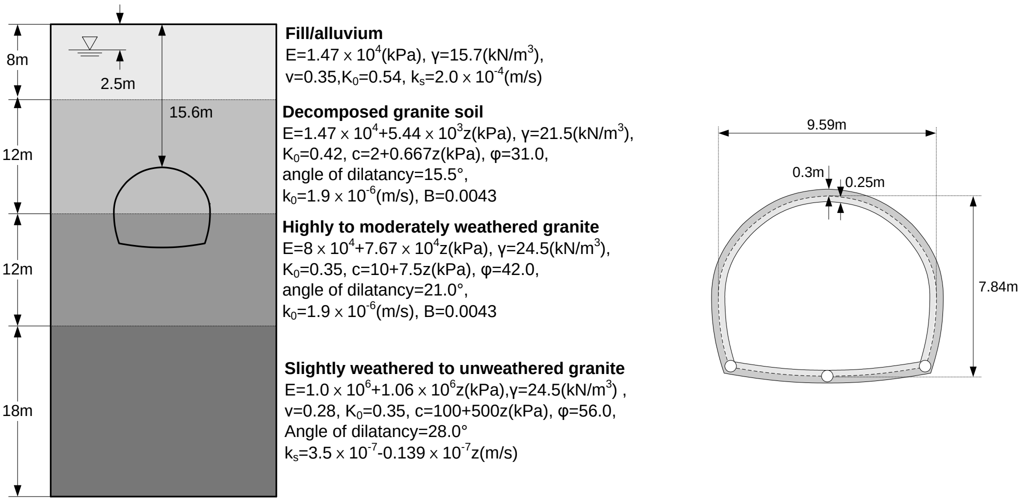
Fig. 5 Modeling of a double-lined lining

2.1 Modeling of structural and hydraulic behavior of double linings

The modeling scheme describing the coupled structural and hydraulic behavior of the single lining was proposed by Shin *et al*. (2002) (Fig. 3). In the present study, however, particular attention is paid to the modeling of lining-to-lining interactions for double-lined tunnel caused by hydraulic deterioration due to drain-pipe blockings.

To represent the effects of these blockings, it is assumed that the affected length L is sufficiently greater than the total length of the tunnel diameter, as shown in Fig. 4. The effects of drain-pipe blockings on the hydraulic deterioration of the drainage layer are considered. To represent both the hydraulic behavior of the drainage layer and structural behavior of the secondary lining, an additional combined element concept is successively superimposed on the model of the primary lining.

Fig. 5 shows the model proposed to simulate the hydraulic and structural behavior of double-lined systems. The primary lining is represented by a combined element proposed in previous studies (Shin *et al*. 2002, 2005). To represent the flow behavior of the drainage layer, solid elements with very low stiffness and negligible structural effects are used. Because there is no hydraulic behavior in the secondary lining owing to a waterproofing sheet being generally placed over it, the secondary lining is simply represented using beam elements. It is assumed that all



(a) Ground profile (b) Tunnel profile

Fig. 6 Model tunnel profile and material parameters

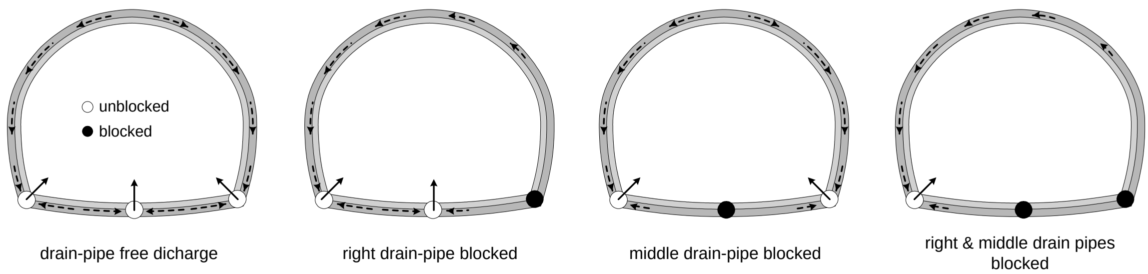


Fig. 7 Analysis cases for drain-pipe blockings (k_l/k_s=0.1; k_f/k_l=10)

elements are fully bonded. Although full bonding does not appear practical, the low stiffness and negligible structural effects of the drainage layer allow considerable relative movements between linings. The pre-yield behavior of the ground is assumed to be isotropic and linear-elastic, yet spatially varying, while the post-yield behavior is represented by the Mohr-Coulomb model.

Drain-pipe blockings can be modeled by imposing appropriate hydraulic boundary conditions. Blocking of drain pipes are modeled by prescribing the flow rate of a node to zero, while unblocked drain pipes are represented by setting the pore-water pressure of the node to zero.

3. Numerical analysis

3.1 Model tunnel and analysis cases

For comparative study, the model tunnel previously used by Shin (2008) was adopted, as shown in Fig. 6. The material parameters used are also listed in Fig. 6(a). The permeability models need to be related to model flow behavior. The flow behavior of the decomposed granite soil is modeled using the non-linear permeability model proposed by Vaughan (1989)

$$k = k_0 exp(-Bp') \tag{2}$$

where k_0 is the permeability for p'= 0 (p' is the mean effective stress) and B is the material property with the units m^2/kN. Furthermore, stress and strain conditions for the long-term analysis are obtained from the construction analyses, which include excavation and lining installation.

Actual hydraulic and structural interactions occur among the ground, primary lining, and drainage layer. It is assumed that the phreatic surface is maintained at a depth of 2.5 m below the ground surface throughout the analysis. On the right and left sides, vertical boundaries of the model are assumed to remain at their initial hydrostatic values.

Since the primary focus of this study is the deterioration of the drainage system caused by drain-pipe blocking, hydraulic conditions of the drainage layer are maintained as k_l/k_s = 0.1 and k_f/k_l = 10 (parameters shown in Fig. 5). To investigate the lining behavior due to drain-pipe blocking, three analysis cases are considered: right drain-pipe blocking, middle drain-pipe blocking, and right and middle drain-pipes blocking. Schematics for the cases are shown in Fig. 7.

4. Results

The results are analyzed in terms of the flow, pore-water pressure, and lining behavior. Particular attention is paid to pore-water pressure on the secondary linings, as it acts directly on the secondary lining and may cause structural damages. Moreover, the behavior of the secondary linings is compared with that of the primary lining.

4.1 Seepage velocity vectors and pore-water pressure distribution around tunnels

Fig. 8 shows the seepage velocity vectors for various cases of drain-pipe blockings. The magnitudes of velocity vectors around the blocked drain pipes are almost zero, while seepage concentration occurs around the unblocked drain pipes.

The distribution of pore-water pressures due to drain-pipe blockings is shown in Fig. 9. There is a significant increase in pore-water pressure in areas around the blocked drain pipes. The most significant feature caused by the drain-pipe blockings is the unbalanced distribution of pore-water

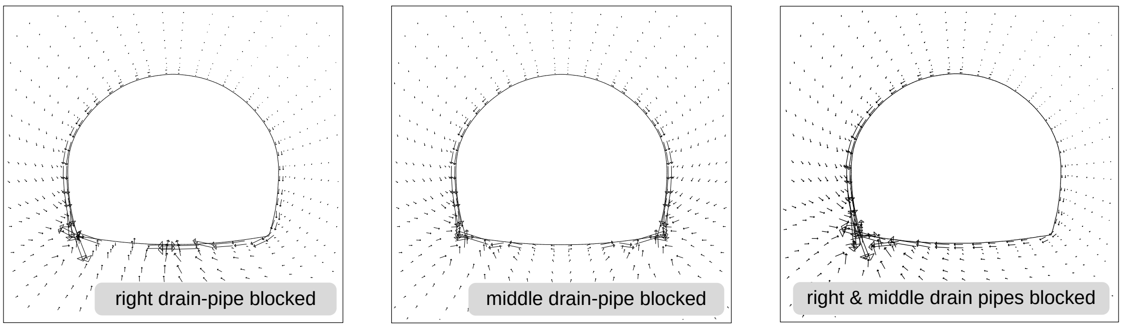


Fig. 8 Seepage velocity vectors

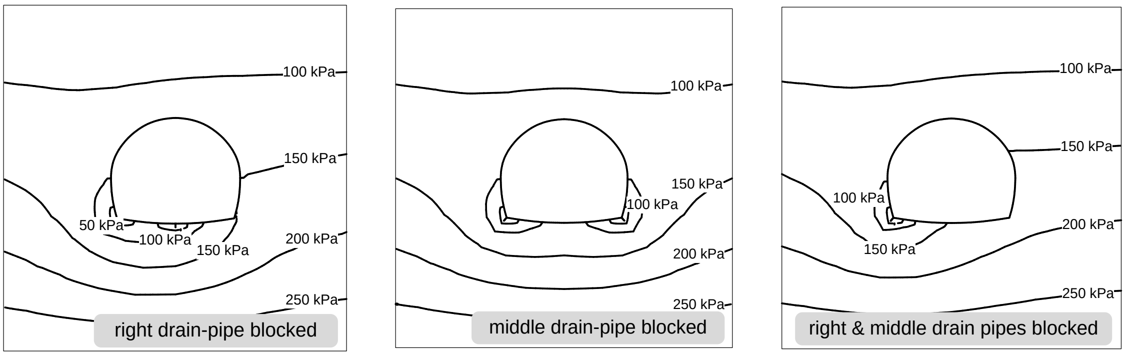


Fig. 9 Distribution of pore-water pressure

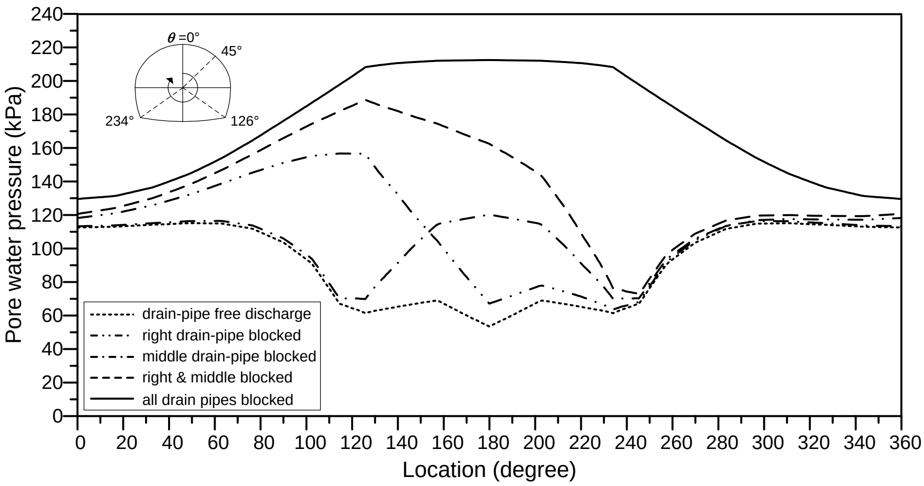


Fig. 10 Pore-water pressure on the outer boundary of the primary lining

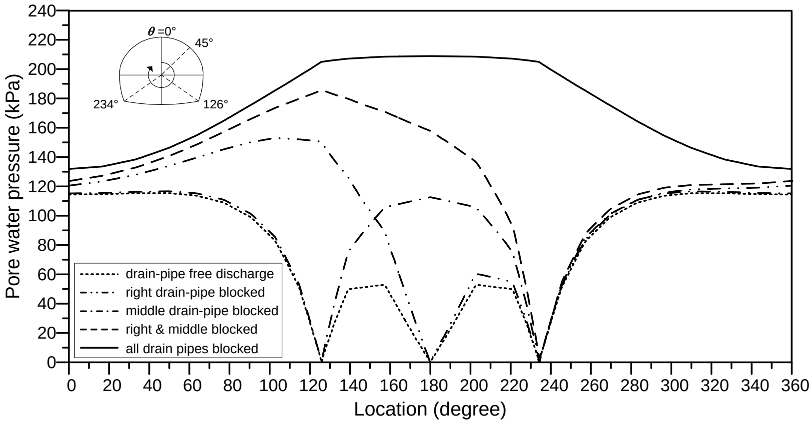
pressure for the case of right and middle drain pipes blocking. When the right and middle drain pipes are blocked, pore-water pressure around the left drain-pipe almost recovers to hydrostatic pressures.

4.2 Pore-water pressure on the lining due to drain-pipe blockings

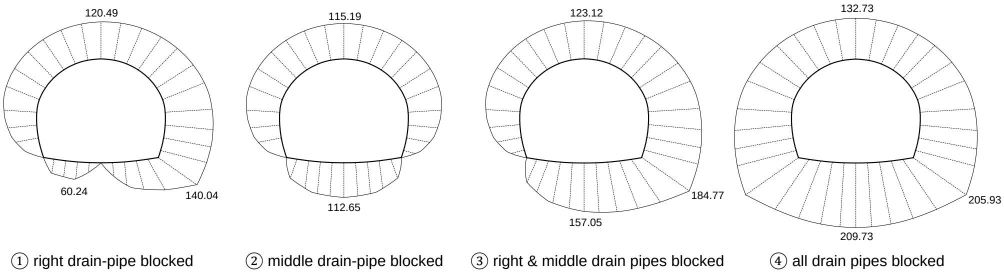
Figs. 10-11 present the pore-water pressures on the outer boundary of the primary lining and in the drainage layer, respectively. The pore-water pressure in the drainage layer directly acts as loads on the secondary linings due to a waterproofing sheet placed over it. Drain-pipe blocking result in asymmetric distribution of pore-water pressure and the magnitude of pore-water pressure is highly dependent on the blocking type. The pore-water pressure in the drainage layer acts both on the inner boundary of the primary and secondary lining.

The primary lining has pore-water pressure on both the outer and inner boundaries of the lining. In this case, the net pore-water pressure shown in Fig. 12 is more structurally meaningful compared to the pore-water pressure on the outer boundary. It is interesting to note that the net pore-water pressure on the primary lining increases around the unblocked drain pipes, while it decreases on the secondary lining. This happens because seepage concentration around the unblocked drain-pipe increases the hydraulic gradient and pore-water pressure in the primary lining.

It is identified that the water pressure on the secondary lining due to drain-pipe blocking have increased approximately ten times more than the water pressure on the primary lining. Ferreira

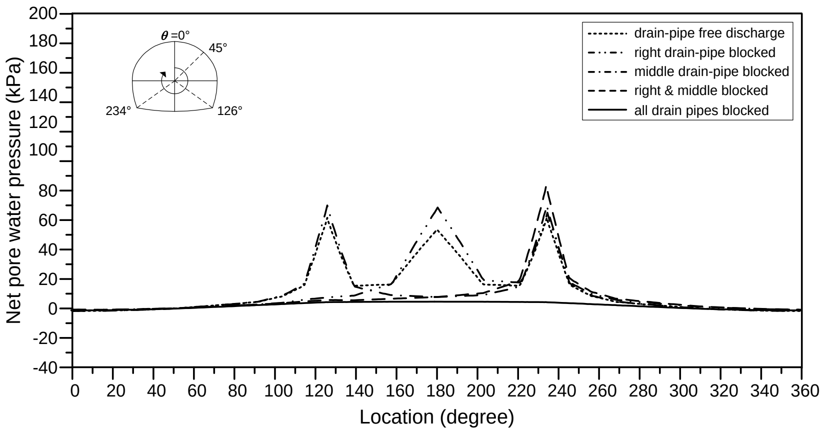


(a) Pore-water pressure-location(degree)



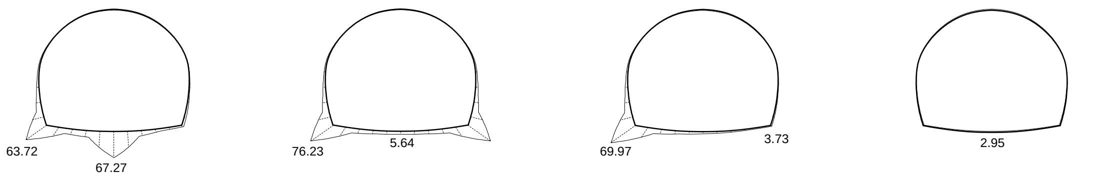
(b) Pore-water pressure distribution

Fig. 11 Pore-water pressure on secondary lining



(a) Net pore-water pressure-location(degree)

Fig. 12 Net pore-water pressure on the primary lining



① right drain-pipe blocked ② middle drain-pipe blocked ③ right & middle drain pipes blocked ④ all drain pipes blocked

(b) Net pore-water pressure distribution

Fig. 12 Continued

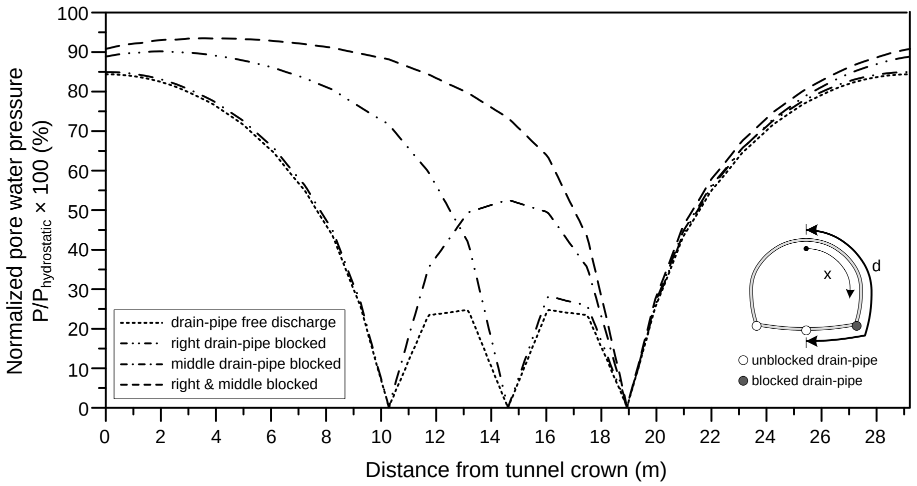


Fig. 13 Water loads on the secondary lining

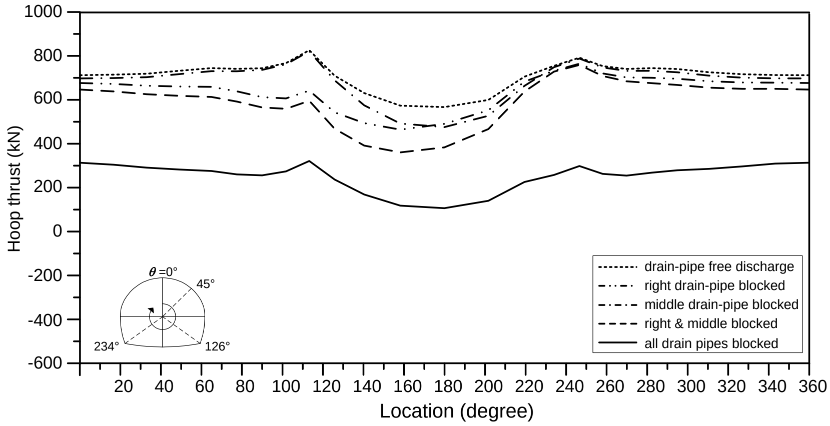
(1995), Lee *et al*. (1996) reported that the water pressure on the secondary lining can cause structural damage to the lining. Thus it would be appropriate to consider the water pressure as design loads in the design of the secondary lining. Fig. 13 presents the normalized water pressures on the secondary linings which can be defined as

$$\frac{p}{p_0} = \left(\frac{p}{p_0}\right)_{max} \left(1 - \frac{x}{d}\right)^2 \tag{3}$$

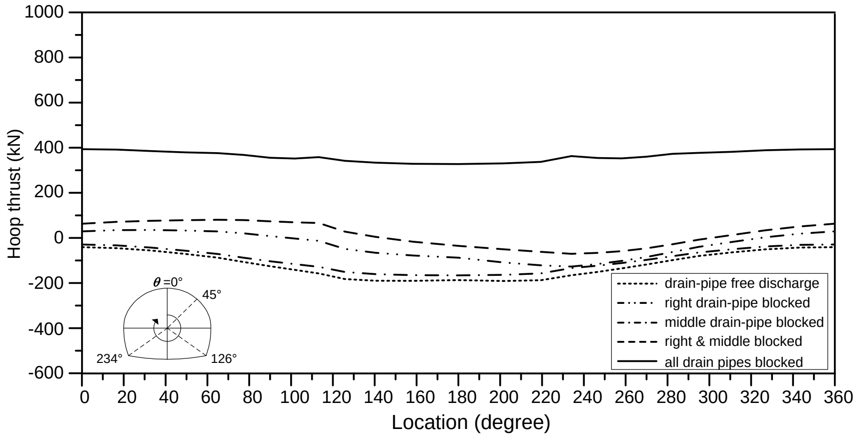
where $p_0 = h \times \gamma_w$ is the hydrostatic pressure at a given lining position, $(p/p_0)_{max}$ is the pore-water pressure ratio (%) at the crown of the tunnel, x is the peripheral distance (m) from the tunnel crown, d is the distance (m) from the tunnel crown to unblocked drain-pipe (x and d are defined in Fig. 13).

4.3 Lining behavior

Fig. 14 presents the hoop thrusts (axial forces) in the lining. Although the distribution of hoop thrusts depends on the mode of blockings, the hoop thrusts of the primary lining are completely different from those of the secondary lining. In the primary lining, generally, the blocking of drain pipes reduces hoop thrusts. Simultaneously, it results in tension in some parts of the secondary linings.



(a) primary lining



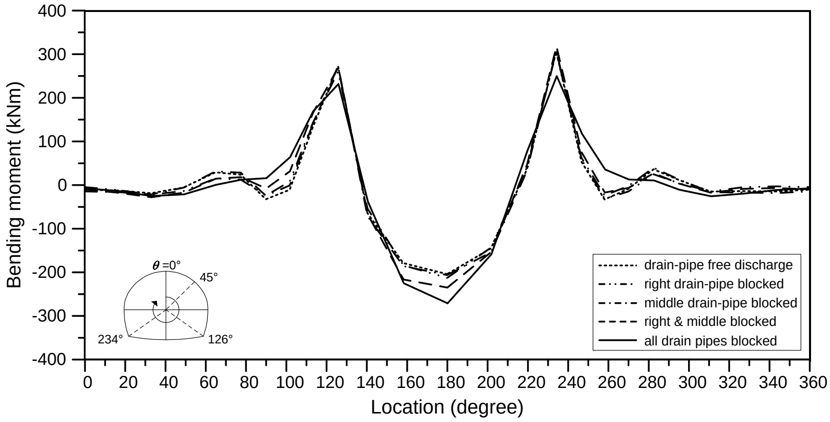
(b) secondary lining

Fig. 14 Hoop thrusts in the linings

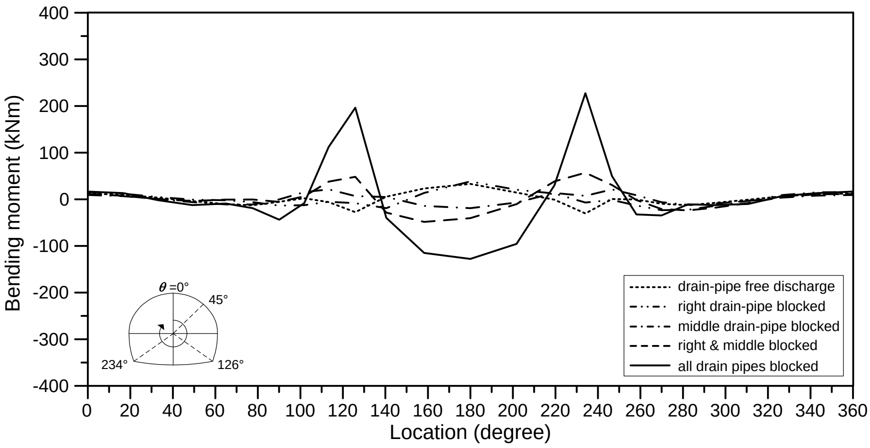
The moments in the linings are presented in Fig. 15. The primary lining supports ground loadings (or total stress) consisting of effective stress and pore-water pressure, which does not change appreciably because of hydraulic deterioration. On the other hand, the secondary lining resists pore-water pressure in the drainage layer and the forces transferred from the primary lining. In the case of the secondary lining, the effect of pore-water pressure is dominant. Moreover, the blocking of the drain-pipe increases the pore-water pressure and consequently increases moments in the lining.

Fig. 16 shows the stress distribution in the linings. It can be seen from this figure that stresses in the primary lining are not heavily dependent on the blocking types. However, stresses develop in the secondary lining. Maximum stresses occur at the corners or in the invert. Drastic changes in stresses are observed in the area between the corner and invert.

Fig. 17 shows the lining deformation. The deformation of the invert of the secondary lining depends on the blocking types. The blocking moves the secondary lining upward and to the left side, which is unblocked. A maximum unbalanced deformation occurs for the case of the right drain-pipe blocking, causing slight torsion along the axis in the counter clockwise direction.

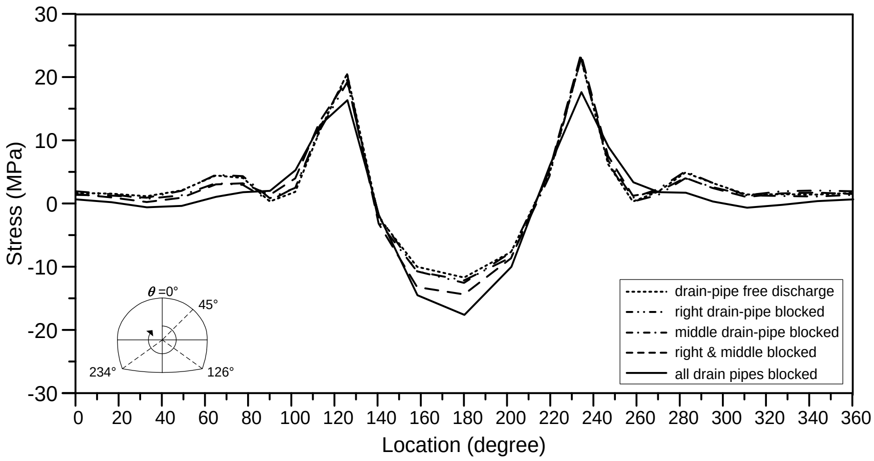


(a) primary lining



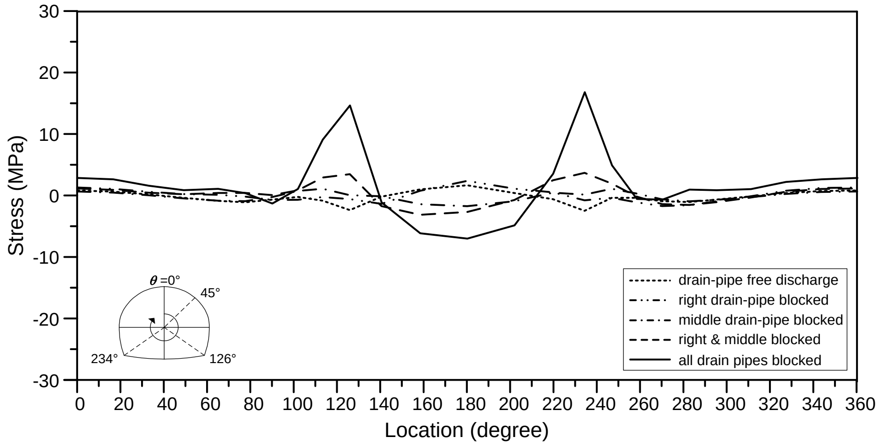
(b) secondary lining

Fig. 15 Bending moments in the linings



(a) primary lining

Fig. 16 Stresses in the linings due to drain-pipe blocking



(b) secondary lining

Fig. 16 Continued

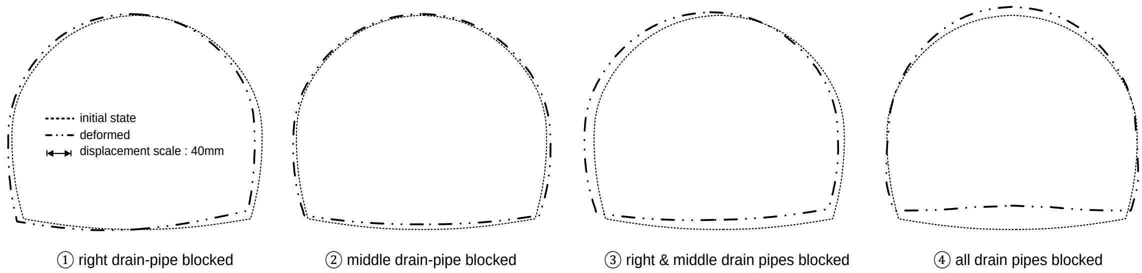


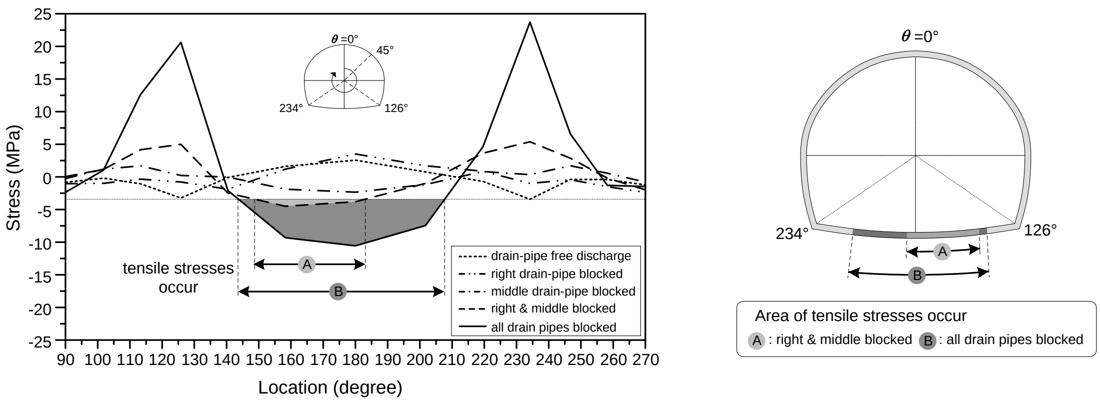
Fig. 17 Deformation of the secondary lining

5. Design consideration of secondary lining

In double-lined NATM Tunnel, the lining system consists of primary lining, drainage layer, waterpoofing sheet and secondary lining. Although the thickness and the structural resistance of the drainage layer and waterpoofing sheet are negligible in comparison with those of linings, its hydraulic effects inducing structural behavior is significant.

Numerical results in this study has shown that the behavior of the primary lining is governed by the relative permeability between soil and shotcrete, meanwhile that of the secondary lining is mainly dependent on the flow capacity and deterioration of drainage system such as clogging and blocking. Particularly, drain-hole blockings can cause significant stress changes and concentration at the area of invert due to unbalanced water pressures. The most influencing case is the blocking of both middle and side drain holes at the same time. In this case significant tensile stresses occur at the invert as shown in Fig. 18.

Tunnel design requires ensuring long-term serviceability, and hydraulic deterioration can be categorized as one of the serviceability limit state in terms of design aspects. Although there might not be any abrupt damages to the tunnel due to drain-hole blockings, slow leakage through invisible cracks would be the sign of the start of an operational problem. Therefore, some measures such as minimum rebar ratio restricting tensile behavior are recommendable.



(a) Stress distribution around invert (b) Area of tensile stresses occur

Fig. 18 Consideration area for secondary lining design

6. Conclusions

The interaction between linings due to long-term hydraulic deterioration of the tunnel drainage system was investigated using the coupled numerical method. A double-lined structural model incorporating flow behavior of a lining and filter was devised to represent the groundwater-lining-soil interactions. It is shown that the combined scheme of a double-beam solid-element model is adequate to represent the structural and hydraulic interactions between the primary and the secondary linings. Numerical representation of the drainage layer can be successfully made by setting the relative permeability between the filter, the primary lining, and the ground, while drain-pipe blocking can be modeled by imposing appropriate hydraulic boundary conditions. It is concluded that a double-lined model is appropriate for conducting a detailed investigation on the long-term behavior of the secondary lining.

The effects of drain-pipe blocking in the linings can be summarized as follows:

• Increase in pore-water pressure rarely increases the ground loading on the primary lining, but increases the proportion of pore-water pressure in the ground loading. Thus, the behavior of the primary lining is not strongly dependent on the hydraulic behavior of drainage system. It can be assumed that the pore-water pressure on the primary lining obtained by the single-lined model acts on the secondary lining. This indicates that the single-lined model is also appropriate for studying the effects of pore-water pressure on the secondary lining.

• Although seepage concentration occurs around the unblocked drain pipes, causing a slight increase in pore-water pressure around drain pipes on the primary lining, the net pore-water pressure on the primary lining is considerably small.

• In the double-lined model, it can be assumed that the pore-water pressure acting in the drainage layer acts on the secondary lining as a water pressure load. Thus, the pore-water pressure obtained from the single-lined model can roughly be used for the structural analysis of the secondary lining.

• Drain-pipe blockings cause a significant asymmetric pore-water pressure on the secondary lining, which acts as a water pressure load on the secondary lining. Asymmetric pore-water pressure causes distortional behavior of secondary linings with regard to the tunnel axis.

• Drain-pipe blockings can cause significant tensile stress at the area of invert. Therefore, some measures such as minimum rebar ratio can be conceivable.

Acknowledgments

This study was supported by the research fund of the National Research Foundation of Korea (2012R1A2A1A01002326). This support is gratefully acknowledged.

References

Biot, M.A. (1941), “General theory of three dimensional consolidation”, *J. Appl. Phys*, **12**, 155-169.

Booker, J.R. and Small, J.C. (1975), “An investigation of the stability of numerical solutions of Biot’s equations of consolidation”, *Int. J. Solid. Struct.*, **11**, 907-917.

Chabot, J.D.S., Sandrone, F. and Gamisch, T. (2013), “The importance of drainage system in railway tunnels and possibilities to reduce the LCC”, *Proceedings World Tunnel Congress, WTC 2013*, 441-448.

Chu, I.C., Nam, S.H., Baek, S.I., Jung, H.S. and Chun, B.S. (2011), “Bond characteristics of scale according to the drainage pipe's material in tunnel”, *Korean Geo-Environ. Soc.*, **12**(11), 51-57.

Ferreira, A.A. (1995), *Cracks and Repairing of the Carvalho Pinto Road Tunnel (Brazil)*, Exchange of correspondence with Health and Safety Executive, U.K.

Jung, H.S., Han, Y.S., Chung, S.R., Chun, B.S. and Lee, Y.J. (2013) “Evaluation of advanced drainage treatment for old tunnel drainage system in Korea”, *Tunn. Underg. Space Tech.*, **38**, 476-486.

Joo, E.J. and Shin, J.H. (2014), “Relationship between water pressure and inflow rate in underwater tunnels and buried pipes”, *Géotechnique*, **64**(3), 226-231.

KICT (Korea Institute of Construction Technology) (2009), “Report on Development of Safety, Maintenance and Disaster Prevention Technology”, Internal Report. (in Korean)

KISTEC (Korea Infrastructure Safety & Technology Corporation) (2007), “Safety Evaluation and reinforcement of tunnels under residual pore-water pressure”, Internal Report. (in Korean)

Lee, Y.N., Byun, H.K. and Shin, O.J. (1996), “Cracking of subway tunnel concrete lining and its repair”, *Proc. Conf. on North American Tunnelling’96*, 325-329.

Lee, I.M., Park, Y.J. and Reddi, Lakshmi N. (2002), “Particle transport characteristics and filtration of granitic soils from the Korean peninsula”, *Can. Geotech. J.*, **39**, 472-482.

Lee, J.H., Chu, I.C., Kim, H.G., Lee, C.K., Chung, K.T. and Chun, B.S. (2012), “Evaluation of technology for preventing drainage pipe blockage in deteriorated tunnel”, *Proceedings of 2012 International Offshore and Polar Engineering Conference*, 606-611.

Murillo, C.A., Shin, J.H., Kim, K.H. and Colmenares, J.E. (2014), “Performance Tests of Geotextile Permeability for Tunnel Drainage System”, *KSCE J. Civil Eng.*, **18**(3), 827-830.

Park, S.W. and Cho, J.R. (2012), “Adaptive fluid-structure interaction simulation of large-scale complex liquid containment with two-phase flow”, *Struct. Eng. Mech.*, **41**(4), 559-573.

Potts, D.M. and Zdravkovic, L. (1999), *Finite Element Analysis in Geotechnical Engineering: Theory*, Thomas Telford, London, U.K.

Reddi, L.N., Ming, X., Hajra, M.G. and Lee, I.M. (2002), “Permeability reduction of soil filters due to physical clogging”, *J. Geotech. Geoenviron. Eng.*, ASCE, **126**(3), 236-246.

Shariatmadar, H. and Mirhaj, A. (2011), “Dam-reservoir-foundation interaction effects on the modal characteristic of concrete gravity dams”, *Struct. Eng. Mech.*, **38**(1), 65-79.

Shin, J.H., Addenbrooke, T.I. and Potts, D.M. (2002), “A numerical study of the effect of ground water movement on long-term tunnel behaviour”, *Geotechnique*, **52**(6), 391-403.

Shin, J.H., Potts, D.M. and Zdravkovic, L. (2005), “The effect of pore-water pressure on NATM tunnel linings in decomposed granite soil”, *Can. Geotech. J.*, **42**, 1585-1599.

Shin, J.H. (2008), “Numerical modeling of coupled structural and hydraulic interactions in tunnel linings”, *Struct. Eng. Mech.*, **29**(1), 1-16.

Vaughan, P.R. (1989), *Non-linearity in Seepage Problems :Theory and field observation*, *De Mello Volume*, 501-516, Edgard Blucher Ltd., Sao Paulo, Brazil.

Yoon, J.U., Han, J.W., Joo, E.J. and Shin, J.H. (2014), “Effects of Tunnel Shapes in Structural and Hydraulic Interaction”, *KSCE J. Civil Eng.*, **18**(3), 735-741.

CC