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Seepage Force Considerations in Tunnelling

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ABSTRACT

In this paper, the seepage force problems arising from the flow of groundwater into a tunnel were studied. Firstly, the effect of seepage forces acting on the tunnel lining was studied for the case of shallow drainage-type tunnels and these results were compared with the lining stresses developed for waterproof-type tunnels. Secondly, the effect of seepage forces on the tunnel face stability was studied. In this study, two factors were considered simultaneously. The first factor considered was the effective stress acting on the tunnel face, and the other was the seepage force. Consequently, reasonable design concepts applicable to the design of tunnel lining and to the evaluation of the support pressure required for maintaining the stability of the tunnel face were suggested for underwater tunnels.

1. INTRODUCTION

Underwater tunnels can be designed either as a waterproof-type or a drainage-type, according to the groundwater control methodology. In the case of waterproof-type tunnels, the tunnel lining is designed to support the hydrostatic water pressure. In the case of drainage-type tunnels, the tunnel lining is designed without consideration for the porewater pressure and it is assumed that either the groundwater level will draw down to the tunnel invert or the groundwater will flow into the filter layer located between the ground and the lining so that the water pressure acting on the lining will be zero. However, if a drainage-type tunnel is located under a river, the groundwater flow will show steady-state flow conditions and seepage forces will act on the tunnel lining. Moreover, seepage forces acting on the tunnel face due to groundwater flow may seriously affect the stability of the tunnel face.

2. SEEPAGE FORCES ACTING ON THE TUNNEL LINING

2.1 Analysis conditions

A hypothetical circular drainage-type tunnel under the groundwater level was considered to evaluate the effect of seepage forces on the tunnel lining. For the study of a more practical and accurate design of the tunnel lining for drainage-type tunnels, numerical analyses were performed with the following drainage concepts of a tunnel: 1) dry condition; 2) drainage concept with consideration for the seepage force; and 3) waterproof concept with consideration for the hydrostatic water pressure.

The computer code used in this analysis was the finite element program 'PENTAGON-3D', and it is possible to perform the seepage analysis as well as the mechanical analysis (Lee and Nam 2001). The analysis of a drainage-type tunnel with the consideration of seepage forces can be performed by superposing the results of the seepage analysis and the mechanical analysis. The non-linear stress analysis used for calculation of the stress change during excavation is performed through the Mohr-Coulomb model. The steady-state flow equation is then solved and the porewater pressures are stored at all nodes. As the finite element meshes used for the seepage analysis and the mechanical analysis are identical, the nodal forces can be calculated, assembled and superposed into the overall nodes. The analysis condition is shown in Figure 1.

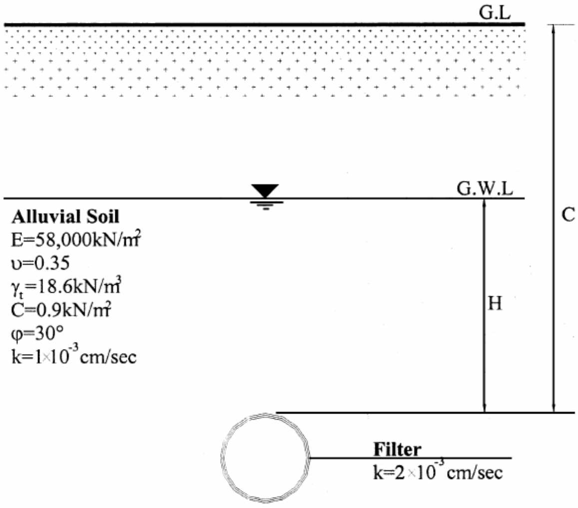

Figure 1. Analysis condition

Table 1. Maximum loads acting on the tunnel lining

Case	Tunnel depth (C/D)	Groundwater level (H/C)	Lining Loads		
			Axial force (kN)	Moment (kN-m)	Stress (kN/m^2)
WP1	2.0	0.5	96.73	0.44	349.24
D1			1.96	0.43	34.53
WP2	2.0	1.0	155.98	0.71	566.04
D2			1.89	0.21	24.72
WP3	2.0	1.5	215.82	0.71	764.20
D3			4.23	1.36	103.01
WP4	3.0	0.5	126.55	0.60	459.11
D4			2.15	0.73	54.54
WP5	3.0	1.0	215.82	1.04	785.78
D5			4.49	2.65	187.37
WP6	3.0	1.5	305.09	1.04	1,079.1
D6			6.49	2.72	198.16
WP7	4.0	0.5	155.98	0.79	570.94
D7			3.07	1.56	111.83
WP8	4.0	1.0	275.66	1.37	1,010.43
D8			6.63	4.42	310.00
WP9	4.0	1.5	394.36	1.36	1,402.83
D9			8.89	4.12	298.22

2.2 Analysis results

The stresses of the tunnel lining were calculated according to the three drainage concepts with a variation in the groundwater level and tunnel depth. The groundwater flows into the tunnel drainage system and the seepage forces are generated due to the difference of total head from the surrounding ground to the tunnel lining.

Table 1 shows the maximum loads developed on the tunnel lining according to the three aforementioned drainage concepts. In Table 1, WP and D refer to a waterproof-type tunnel and drainage-type tunnel with seepage forces, respectively. In the case of a dry tunnel, the loads acted on the tunnel lining approached zero, which is consistent with the concepts of NATM. As shown In Table 1, there were large differences in tunnel supporting stresses depending on the drainage conditions. In the case of a drainage-type tunnel with the consideration of seepage forces, stresses acting on the tunnel lining reached up to 30% of those of the waterproof-type tunnel. The lining stresses consist of two components: the axial stress; and the bending stress developed from the bending moment. In the case of a waterproof-type tunnel, the results showed that the tunnel lining must support the hydrostatic water pressure and that the axial stresses were more dominant than the bending stresses. In the case of a drainage-type tunnel with the consideration of seepage forces, it showed that the tunnel lining must resist the seepage forces developed from the steady-state groundwater flow, and in this case, the bending stresses were more dominant than the axial stresses. From the results of FEM analysis, it was concluded that it could be dangerous for the case of a drainage-type tunnel not to take the seepage forces acting on the tunnel lining into consideration under steady-state flow conditions, e.g. underneath the river. Consequently, for a reasonable and safe design of tunnels, it is necessary to take into consideration the groundwater conditions properly and to reflect the effects in the design of the tunnel lining.

3. SEEPAGE FORCES ACTING ON THE TUNNEL FACE

3.1 Analysis Methods

In order to calculate the seepage forces acting on the tunnel face under a steady-state condition, the PENTAGON-3D was again used. To calculate seepage forces, a failure surface in front of the tunnel face should be predetermined or assumed. The upper bound solution proposed by Leca and Dormieux (1990) was modified by Lee and Nam (2001) to take into account seepage forces. The modified solution is adopted in this study. Eq. (1) is the modified upper bound solution with the consideration of seepage forces.

$$N_s\left[(K_p-1)\frac{\sigma_s}{\sigma_c}+1\right]+N_\gamma(K_p-1)\frac{\gamma D}{\sigma_c}\le(K_p-1)(\frac{\sigma_T-\sigma_{S.F}}{\sigma_c})+1 \qquad (1)$$

where σ_s refers to the surcharge, σ_c is the unconfined compressive strength of the soil, σ_T is the retaining pressure applied to the tunnel face, $\sigma_{S.F}$ is the seepage pressure acting on the tunnel face, K_p is the Rankine's earth pressure coefficient for passive failure, γ is the unit weight of soil, D represents the tunnel diameter, and N_s and N_γ are weighting coefficients. One example of failure surface estimated from the upper bound solution is shown in Figure 2.

Major steps involved in calculating the seepage pressure are as follows. Figure 2 shows the total head distribution around the tunnel face determined by seepage analysis and failure surface estimated from limit analysis. From this figure, the seepage pressure can be calculated as follows. First, divide the failure area into several sections as shown in Figure 2 and calculate hydraulic head difference between the failure surface and the tunnel face in each section and seepage forces. By summing up all the seepage forces, the total seepage force acting on the tunnel face can be obtained. Next, calculate the average seepage pressure by dividing the total seepage force by the total failure area. Finally, determine the seepage pressure ratio, SPR that is defined as the ratio of the average seepage pressure to the hydrostatic pressure at the same groundwater level.

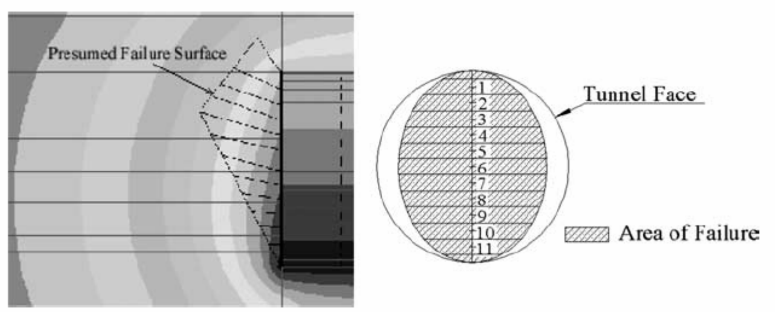

Figure 2. Hydraulic head distribution and failure surface

3.2 Analysis Results

The schematic diagram for modeling and obtaining the seepage forces acting on the tunnel face according to the variation of the groundwater level (*H*) and the tunnel depth (*C*) is illustrated in Figure 3. The properties of the ground material used for analysis are presented in Table 2.

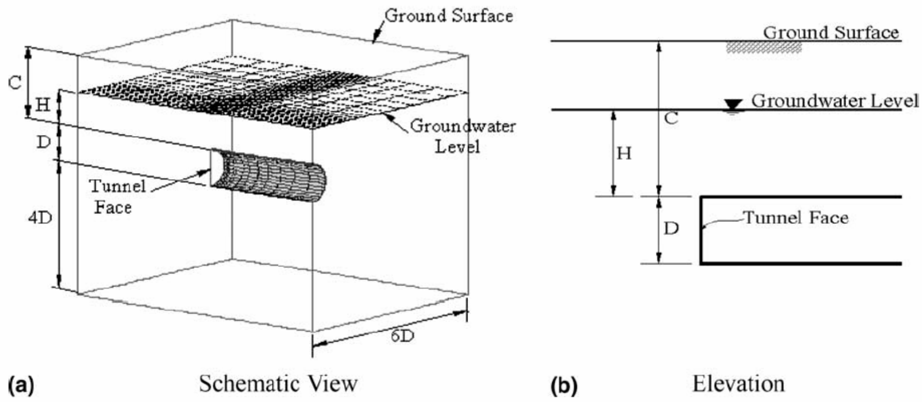

Figure 3. Dimensional condition for seepage analysis

Table 2. Properties of the ground

Soil type	Unit weight (kN/m^3)	Cohesion (kN/m^2)	Friction angle
Sand	15.2	0.0	35.0°

In this study, two types of tunnels were considered – a drainage type tunnel and a water-proof type tunnel. In case of the drainage type tunnel, it is assumed that groundwater flows into all of the excavated surfaces including the tunnel face. The tunnel construction by NATM can be included in this category. In case of the water-proof type tunnel, the groundwater flows only into the tunnel faces. The tunnel construction by the shield can be included in this category.

The values of average seepage pressures during tunnel excavation calculated from numerical analyses are presented in Figure 4. In this figure, it can be seen that the average seepage pressures have an almost linear relation with the *H/D* ratio both for the drainage and the waterproof types, although the former case has lower values than the latter case. The ranges of the average seepage pressure were 18.2-47.6 kN/m^2 for the drainage type tunnel and 21.9-62.4 kN/m^2 for the water-proof type tunnel. As the average seepage pressure is positively linear to the *H/D* ratio, the seepage pressure ratio shows little variation. The values of seepage pressure ratio during tunnel excavation calculated from numerical analyses are presented in Figure 5. As shown in Figure 5, the values of the SPR were about 22% for the drainage type and about 28% for the water-proof type and this value does not show much change with the variation of *H/D* ratios.

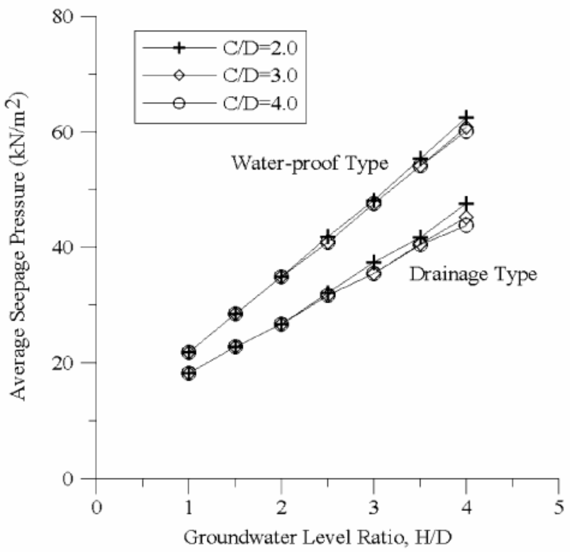

Figure 4. Average seepage pressure with the variation of the H/D ratio

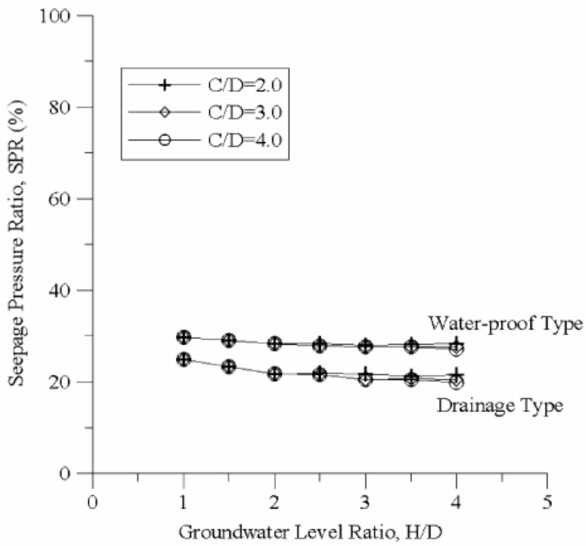

Figure 5. Seepage pressure ratio with the variation of the H/D ratio

4. APPLICATIONS

4.1 Seepage forces considering tunnel advance rate

Including the studies of the groundwater analysis around the tunnel face in the previous paragraph, most of the studies were carried out based on the steady-state groundwater condition. The loss of hydraulic head in the vicinity of the tunnel face may not take place immediately after excavation to reach a steady-state hydraulic head distribution. The time to reach the steady-state condition fully depends on the ground condition, i.e., the storativity and the permeability of the ground, and the excavation advance rate. The time required to achieve the steady-state increases, as the permeability decreases and storativity increases. Besides the extreme case of highly permeable ground or very slow excavation, the excavation advance rate must be taken into consideration as an additional parameter n the mathematical model, because hydraulic head alters simultaneously with the process of excavation. One can readily verify that the time-dependent hydraulic head field is governed by the ratio of the excavation advance rate, v, to the ground permeability, k. The hydraulic head field may be not affected by the tunnel excavation when $v/k \rightarrow \infty$, i.e., the case in which the impervious lining is installed before any significant seepage occurs. In other words, the excavation induced disturbance of the hydraulic head field decreases as the v/k-ratio increases. Lee and Nam (2004) studied this effect by using the modified governing equation suggested by Anagnostou (1993). Figure 6 shows a typical relationship between the dimensionless parameter, Dsv/k, and the seepage pressure ratio (SPR) where D is the tunnel diameter, s is the specific storage coefficient, and K is the coefficient of permeability. Seepage pressures acting on the tunnel face are increased with the increase of Dsv/k.

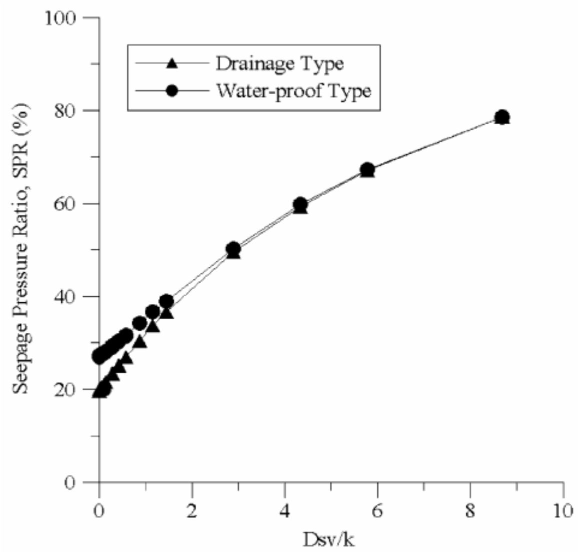

Figure 6. Dimensionless parameter *Dsv/k*-seepage pressure ratio relationship.

4.2 Convergence-confinement method considering seepage forces

The convergence-confinement method (CCM) is a procedure that allows the load imposed on a support installed behind the face of a tunnel to be estimated. The three basic components of the convergence-confinement method are: the Longitudinal Deformation Profile (LDF); the Ground Reaction Curve (GRC); and the Support Characteristic Curve (SCC) (Carranza-Torres and Fairhurst 2000). Lee et al. (2005) proposed the modified convergence-confined method by taking seepage forces into account to simulate a drainage type of underwater tunnel. Figure 7 represents a typical result of the study. The figure shows that the LDP as well as the GRC changes significantly by including seepage forces in the convergence-confinement method.

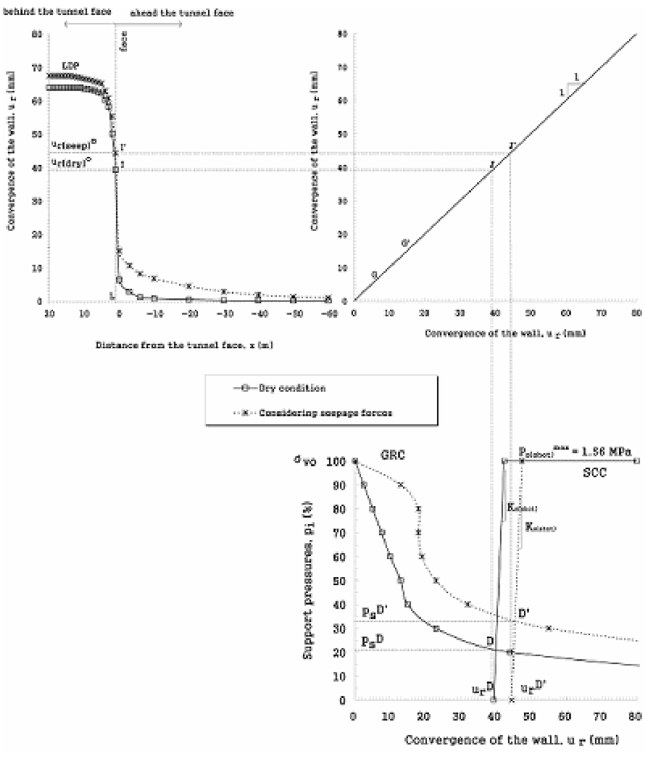

Figure 7. Convergence-confinement methods with and without considering seepage forces.

5. CONCLUSIONS

The existence of groundwater seriously affects the tunnel stability. While the effect of effective overburden pressure is reduced slightly by the arching effect induced by tunnel excavation, the seepage pressure remains to be dealt with. Conclusions drawn from this study are summarized as follows:

1. From the analysis of a circular drainage-type tunnel with consideration for seepage forces, stresses acting on the tunnel lining reached up to 30% of the hydrostatic porewater pressure in the waterproof-type tunnel.
2. According to the results of the numerical analyses under the condition of the steady-state groundwater flow, the ratio of the average seepage pressure to the hydrostatic porewater pressure, named the seepage pressure ratio, was about 22% for the drainage type tunnel and about 28% for the water-proof type tunnel.
3. The dimensionless value of *Dsv/k* can be a good parameter to study the influence of seepage on the tunnel face stability with the consideration of the tunnel advance rate. As the value of *Dsv/k* increases, the seepage pressures acting on the tunnel face may increase significantly up to 80% of the hydrostatic porewater pressure in poorly permeable ground. If the permeability of the ground mass is lower than 1×10^{-4} cm/s, the tunnel advance rate must be carefully controlled considering the stability of the tunnel face.
4. The longitudinal deformation profile as well as the ground reaction curve to be used for convergence-confinement method changes a lot by considering seepage forces.

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