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The effect of seepage forces at the tunnel face of shallow tunnels

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ABSTRACT: In this paper, seepage forces arising from the groundwater flow into a tunnel were studied. First, the quantitative study of seepage forces at the tunnel face was performed. The steady-state groundwater flow equation was solved and the seepage forces acting on the tunnel face were calculated using the upper bound solution in limit analysis. Second, the effect of tunnel advance rate on the seepage forces was studied. In this part, a finite element program to analyze the groundwater flow around a tunnel with the consideration of tunnel advance rate was developed. Using the program, the effect of the tunnel advance rate on the seepage forces was studied. A rational design methodology for the assessment of support pressures required for maintaining the stability of the tunnel face was suggested for underwater tunnels.

1 INTRODUCTION

Tunnel faces are subjected to many problems regarding stability during construction, but there has been little research with respect to the stability of the tunnel support and the surrounding ground. When a tunnel is excavated below the groundwater level, the groundwater flows into the excavated surface of the tunnel and seepage forces act on the tunnel face. The stability of tunnel face will be significantly affected by these seepage forces. In this study, a procedure to estimate the seepage pressure acting on the tunnel face is suggested for the case when the tunnel is excavated with constant advance rate in the presence of groundwater flow.

2 SEEPAGE FORCES ACTING ON THE TUNNEL FACE

2.1 Estimation of seepage forces acting on the tunnel face

The groundwater flow passing through soil grains occurs in response to an energy gradient and a measure of this gradient is provided by the difference in hydraulic head (Freeze and Cherry 1979). When a tunnel is excavated below the groundwater level, the groundwater flows into the excavated surface of the tunnel and there exists a difference in hydraulic head around the tunnel. The force that acts on the soil grain due to the differential head is known as the seepage force and it is exerted in the direction of groundwater flow. In this case, the seepage force is in addition to the effective stress of the ground and may affect the tunnel support pressure or the tunnel face stability.

The seepage force acting in a unit volume of soil grains can be expressed as $i\gamma_w$, where γ_w is the unit weight of water and i is the hydraulic gradient. Consequently, to calculate the seepage force, the distribution of hydraulic head around the tunnel should be calculated first by solving the groundwater flow equation. In order to calculate the seepage forces acting on the tunnel face under a steady-state condition, PENTAGON-3D was used in this study. The PENTAGON-3D is a finite element analysis program for solving 3-dimensional continuum problems such as tunnels, earth retaining structures, structural mechanics, and steady-state groundwater flow. To calculate the hydraulic gradient, the failure surfaces in front of the tunnel face should be pre-determined or assumed. To solve this problem, the modified upper bound solution with the consideration of seepage forces proposed by Lee et al. (2001) was adopted:

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

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.

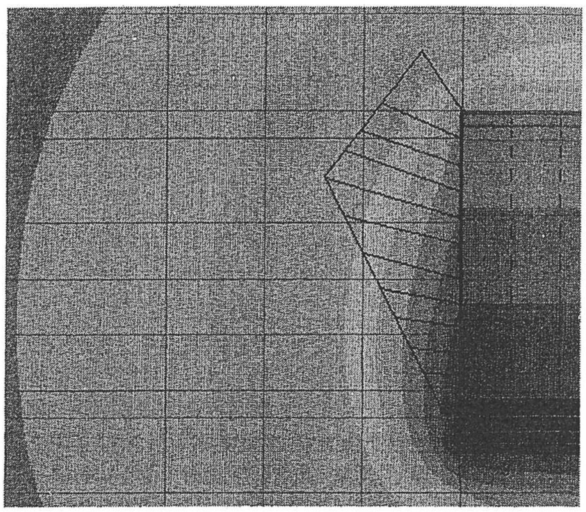


Figure 1. Hydraulic head distribution and failure surface.

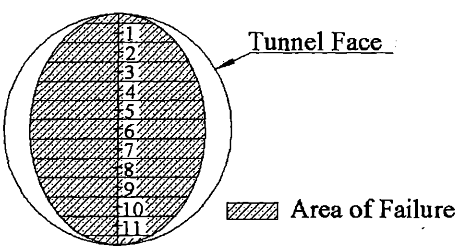


Figure 2. Division of failure surface.

The major steps involved in calculating the seepage pressure are as follows. Figure 1 shows the total head distribution around the tunnel face determined by seepage analysis and failure surface determined by limit analysis. From this figure the seepage pressure could be calculated. First, divide the failure area into sections as shown in Figure 2 and calculate hydraulic head difference between the failure surface and the tunnel face in each section. Then calculate the hydraulic gradient 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 the ratio of the average seepage pressure to the hydrostatic pressure at the same groundwater level.

2.2 Example problem

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 tunnel has a circular cross section with a diameter equal to 5.0m. The properties of the ground material used for analysis are presented in Table 1.

Table 1. Properties of the ground.

Soil type	Unit weight (kN/m^3)	Cohesion (kN/m^2)	Friction angle (deg.)
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 the case of a drainage type tunnel, it is assumed that groundwater flows into all of the excavated surfaces including the tunnel face. In the case of a water-proof type tunnel, the groundwater flows only into the tunnel face. In both types of tunnels, the analyses to obtain seepage forces were conducted for 21 cases of ground conditions by varying C/D from 2.0 to 4.0, and H/D from 1.0 to 4.0.

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 water-proof types although the former case has lower values than the latter case. The ranges of the average seepage pressure were $18.2kN/m^2$ to $47.6kN/m^2$ for the drainage type tunnel and $21.9kN/m^2$ to $62.4kN/m^2$ 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.

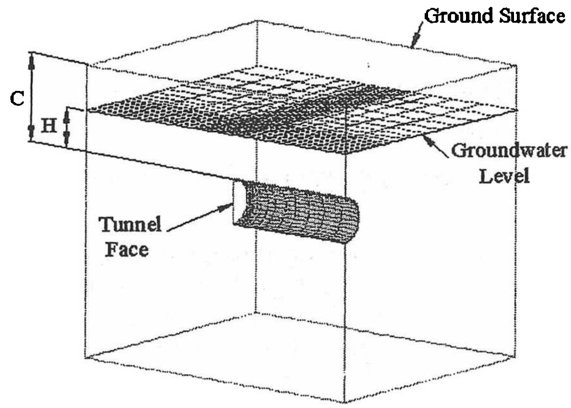


Figure 3. 3-Dimensional condition for seepage analysis.

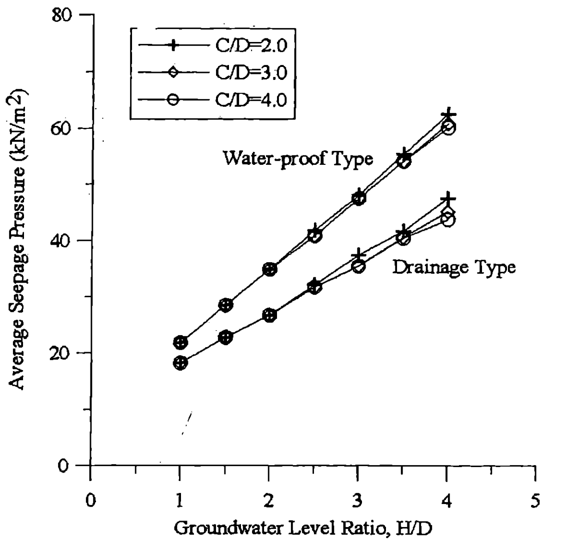


Figure 4. Average seepage pressure with the variation of the H/D ratio.

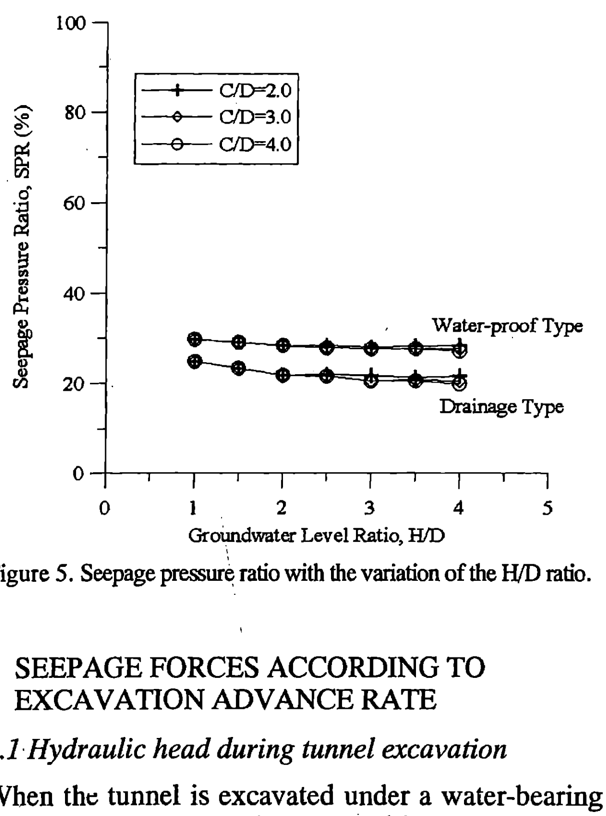


Figure 5. Seepage pressure ratio with the variation of the H/D ratio.

3 SEEPAGE FORCES ACCORDING TO EXCAVATION ADVANCE RATE

3.1 Hydraulic head during tunnel excavation

When the tunnel is excavated under a water-bearing ground, the loss of hydraulic head in the vicinity of the tunnel face does not take place immediately after excavation. In other words, it takes time after tunnel 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 goes down and storativity is increased. 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 in the mathematical model, because hydraulic head alters simultaneously with the process of excavation (Goodman, 1965).

3.2 Numerical model with the consideration of excavation advance rate

Anagnostou(1993) studied the effect of the excavation advance rate on the hydraulic head around the tunnel and suggested a modified governing equation for the groundwater flow analysis. The effect of continuous tunnel excavation on the piezometric head can be analyzed by reformulating and solving the diffusion equation within a frame of reference which is fixed to the advancing tunnel face. The original diffusion equation is shown in equation (2).

$$s\frac{\partial h}{\partial t} = \frac{\partial}{\partial x_i}\left(k\frac{\partial h}{\partial x_i}\right) \quad (2)$$

where s is the specific storage coefficient, k is the coefficient of permeability, and h is the hydraulic head. From the view of the frame of reference at the tunnel face, the hydraulic head distribution shows a quasi-steady state and the original diffusion equation is reformulated as equation (3) provided that the tunnel axis is parallel to x_1 and that the ground is isotropic (Anagnostou, 1993).

$$\frac{\partial}{\partial x_m^*} k \frac{\partial h^*}{\partial x_m^*} + sv\frac{\partial h^*}{\partial x_1^*} = 0 \quad (3)$$

In equation (3), v is the tunnel advance rate along the x_1-axis and x^*_m is the position vector of a point in the face-fixed frame of reference as shown in Figure 6. That is:

$$x_m^* = x_m - x_m^f(t) \quad (4)$$

where $x^f_m(t)$ and x_m denote the position vectors of the tunnel face and of the point, respectively, in the spatially fixed coordinate system. Equation (3) can be numerically solved by the finite element method. For this study, the finite element program to solve the steady state saturated groundwater flow equation, GW1 (Istok, 1989) was modified and renamed 'GACET'. The computer code 'GACET' solves three dimensional steady-state saturated groundwater flow equation with the consideration of tunnel excavation advance rate according to the modified diffusion equation (3).

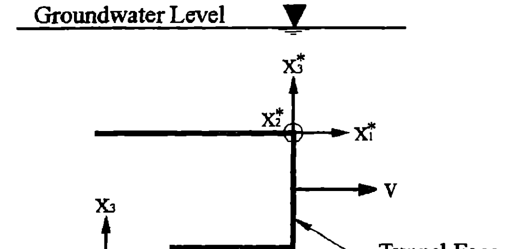


Figure 6. Concept of face-fixed frame of reference.

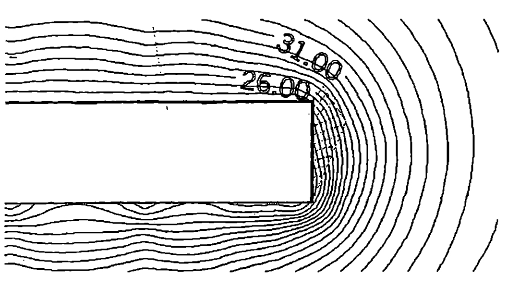
3.3 Example problem

3.3.1 Description

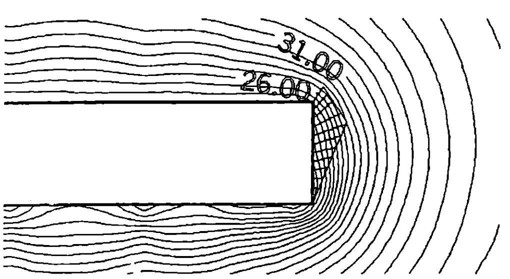
To study the effect of tunnel advance rate on the seepage forces acting on the tunnel face with the computer code GACET, the example problem shown in Figure 3 was also chosen as a hypothetical site. The tunnel has a circular cross section with a diameter equal to 5.0m. Tunnel depth and groundwater level were set to 4 times the tunnel diameter(C/D=H/D=4.0). Two types of tunnels were considered here which are same as the example problems in section 2 - a drainage type tunnel and a water-proof type tunnel. As mentioned above, factors that affect changes in the time-dependent hydraulic head around the tunnel face include excavation advance rate, storativity and permeability of the ground mass. Therefore, the groundwater flow analyses using the program GACET were conducted for 80 cases of ground conditions by varying specific storage (s) from 5×10^{-5} to 1×10^{-3}(/m), permeability (k) from 1×10^{-6} to 1×10^{-3}(cm/sec) and tunnel advance rate (v) from 0 to 20(m/day).

3.3.2 Results

It was found by solving equation (3) that the quasi-steady hydraulic head is governed by the dimensionless parameter, Dsv/k, where D is the diameter of the tunnel, s is the specific storage coefficient, and k is the coefficient of permeability (Anagnostou, 1993). Therefore, this dimensionless parameter was used for the parameter study. Figure 7 shows results of the quasi-steady state groundwater analysis obtained using the program GACET and by obtaining failure surfaces from the upper bound solution. The steady-state hydraulic head distribution around the tunnel remains the same with the same values of Dsv/k parameter, even though the ground condition and tunnel excavation advance rate are different. Consequently, the value of Dsv/k can be a good parameter to study the influence of the ground condition and the tunnel advance rate on the tunnel face stability. Figure 8 shows the relationship between the dimensionless parameter, Dsv/k, and the seepage pressure ratio (SPR). When the tunnel advance rate is equal to zero (Dsv/k=0), the values of the seepage pressure ratio were about 20% for the drainage type and about 27% for the water-proof type, and these values coincide with the results of steady-state groundwater analysis in the case of C/D=H/D=4.0 shown in section 2. On the other hand, it is shown that the seepage force is increased at large values of Dsv/k. When the tunnel is excavated with continuous advance rate, the hydraulic head around the tunnel face shows transient or quasi-steady state; in this case, enough groundwater drainage to the excavation surface cannot occur and residual porewater pressures will act on the tunnel face. If the permeability of the ground is relatively high and storativity is relatively low, the value of Dsv/k is small and this phenomenon does not seriously affect the stability of the tunnel face. However, as the value of Dsv/k increases, the seepage pressures acting on the tunnel face will significantly increase up to 80% of the hydrostatic porewater pressure in poorly permeable ground.



(a) v=5m/day, k=1×10^{-4} (cm/sec) and s=5×10^{-5} (/m)



(b) v=20m/day, k=1×10^{-3} (cm/sec) and s=1×10^{-4} (/m)

Figure 7. Hydraulic head distributions around the tunnel (Dsv/k=0.014 in both cases).

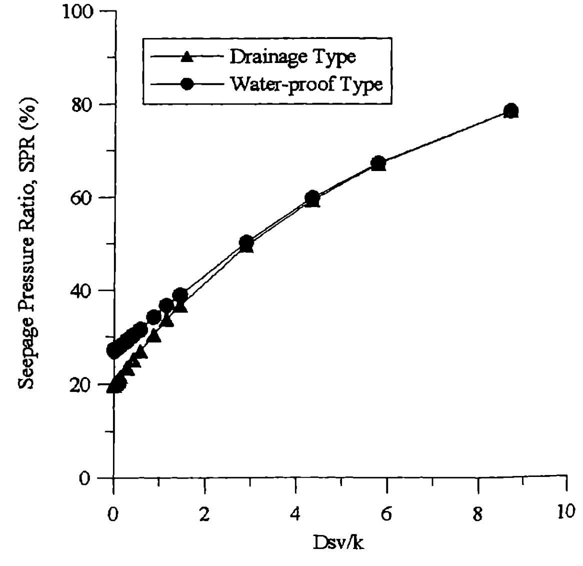


Figure 8. Dimensionless parameter Dsv/k - seepage pressure ratio (SPR) relationship.

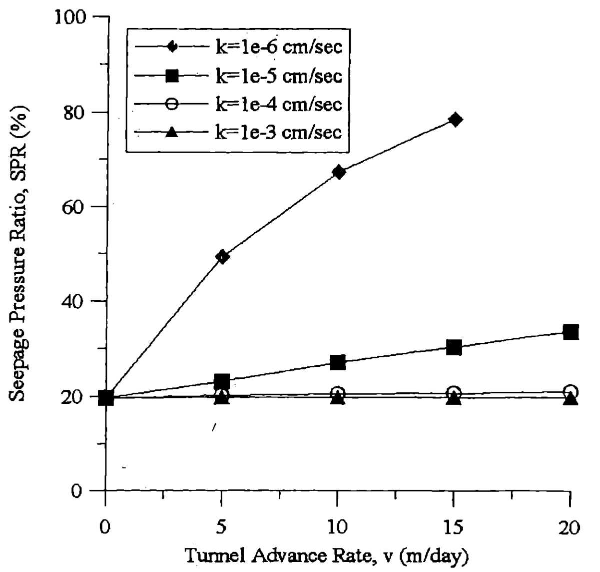


Figure 9. Tunnel advance rate (v) - seepage pressure ratio (SPR) relationships (In case of $s=1\times10^{-4}$/m).

Figure 9 shows the values of the SPR as a function of the tunnel advance rate and the permeability of the ground. Seepage pressures on tunnel face increase at higher tunnel advance rates. This phenomenon becomes more significant with the lower permeabilities. Therefore, according to Figure 9, it can be concluded that if the permeability of the ground is lower than 1×10^{-4} cm/sec, the tunnel advance rate must be carefully controlled for the safe tunnel construction.

4 CONCLUSIONS

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

(1) The values of the seepage pressure ratio defined as the ratio of the average seepage pressure acting on the tunnel face to the hydrostatic pressure, was about 22% for the drainage type and about 28% for the water-proof type.

(2) The dimensionless value of Dsv/k can be a good parameter to study the influence of seepage on the support pressures at the tunnel face with the consideration of the tunnel advance rate. As the value of Dsv/k increases, the amount of 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/sec, the tunnel advance rate must be carefully controlled considering the rational design of support at the tunnel face.

ACKNOWLEDGEMENTS

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