EVALUATION OF RESIDUAL PORE WATER PRESSURES ON LININGS FOR UNDERSEA TUNNELS

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Abstract：Long-term observations for tunnels have shown two interesting aspects：an increase in leakage for watertight tunnels；and a decrease for leaking tunnels. An increase in leakage may exceed the capacity of drainage system and a decrease in leakage cause unexpected water pressure on the lining. Both excess leakage and additional water pressure are detrimental to running tunnels. Therefore，during tunnel operation，the flow behaviors around tunnel should be appropriately controlled. One of the most significant key elements in evaluating tunnel safety is the development of water pressure on the lining due to the deterioration of the drainage system. The increased water pressure on the lining is termed here as “residual water pressure”. The subsea tunnels generally need strict and careful monitoring of hydraulic effect to keep safe operation. Establishment of a well-organized maintenance program is therefore essential during operation. However，most aged-subsea tunnels do not have well-equipped monitoring systems，in addition even in new tunnels，the monitoring systems are often malfunctioned just after several years of operation. In this study，a new indirect and nondestructive method evaluating residual water pressure on the lining is proposed based on a characteristic water pressure curve obtained by numerical analysis. If the amount of water inflow，the height of water table and average ground permeability are known，the water pressures on the lining can be evaluated using the proposed analytical equations and the characteristic curves. It is shown that the method is particularly useful for tunnels of which measured data are not available and particularly for the aged-tunnels without monitoring systems. Applicability of the proposed method is illustrated by solving an example problem.

Key words：subsea tunnel；pore water pressure；lining permeability；hydraulic boundary condition

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海底隧道衬砌上孔隙水压力的估算

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摘要：从长期观察的结果来看，隧道表现出两种不同方式：一种是对于全封闭隧道表现出渗流量的增加；另一种是对于排水隧道表现出的渗流量减少。渗流量的增加有可能超出排水系统排水能力的情况，而渗水的减少则有可能导致衬砌发生不可预测的水压力增加或减小。由于这种渗流量的增加或减少都将对隧道产生不良的影响。因此，在隧道正常运行中，应对隧道周边的地下水进行适当地控制。在隧道安全性评价上，其最重要的因素之一就是研究排水系统劣化而导致衬砌的作用水压力增大(在此称为孔隙水压力)。为了保障隧道的安全运行，应该对此进行严密的监控。然而，对于大部分运行已久的海底隧道而言，其不仅缺乏装备优良的监视系统，甚至连运营仅几年的新隧道也常常出现监测仪器发生故障的问题。以间接和非破坏的方式，通过数值模拟，将所获得的孔隙水压力进行曲线拟合，以便对作用于衬砌的孔隙水压力进行合理地评价。对于给定的隧道内渗流量、地下水位及地基渗透系数，采用本法可以评估孔隙水压力。对于缺乏监测数据和监视系统运行较长的隧道，所提出的方法较为适用，最后通过实例来说明其合理性。

关键词：海底隧道；孔隙水压力；衬砌渗透性；水力边界条件

1　INTRODUCTION

Generally，tunnel is constructed below ground water table，therefore it is crucial to control ground water during construction stage and onward phase of maintenance. Underwater tunnels are influenced by the long-term variation of both water pressure on the lining and leakage into the tunnel. Water pressure can cause additional stresses in the lining and consequent damages to tunnel structures. Meanwhile，leakage may result in malfunction of tunnel facilities or exceed drainage capacity. The full understanding of water pressure and leakage development mechanism，therefore，is required during tunnel operation. Drainage systems for drained tunnels provide flow paths and drain pipes. In practical，it is generally assumed that in drained tunnels without malfunction，and no water pressures act on the linings. Y. N. Lee et al.[1，2]，however，reported that the drainage systems are squeezed during concrete placement and clogged in the long term due to migration of soil particles，which will cause restriction of flow and develop consequent water pressure on the lining. If the influence of deterioration is not properly considered in the phase of design，the lining could be under excessive stress conditions，which may cause damages to lining structures as shown Fig.1[3].

Fig.1　Lining failure due to water pressure[3]

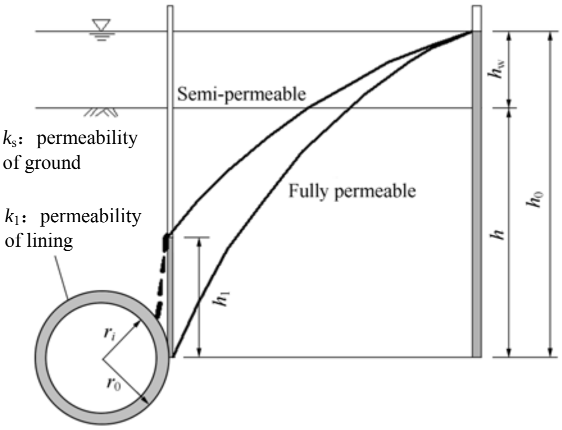
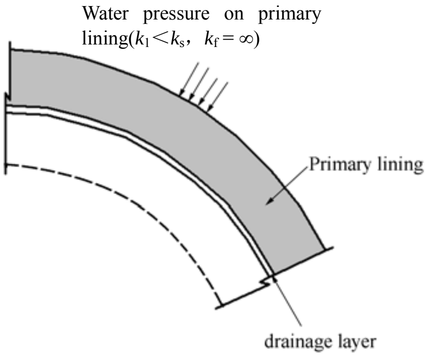


Fig.2　Flow behaviors around a subsea tunnel

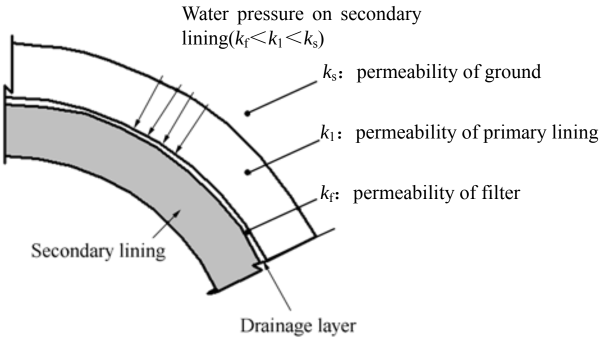
Fig.2 shows flow behavior around a tunnel. If the tunnel acts as a fully permeable drain where no flow restriction exists，water head behind the lining will be zero. However，if the lining is less permeable than the surrounding ground，flow restriction appears and corresponding water pressure will be developed.

It is repeatedly reported that the magnitude of water pressure on the lining is significantly dependant on the relative permeability between the lining(or drainage system) and the surrounding ground[4，5]. Although the initial drainage system works properly，it will deteriorate in the long term due to blockage of drain paths. This lays the importance of maintenance particularly focused on water pressure on the lining.

Fig.3 shows the mechanism of water pressure development for a NATM tunnel with a drainage system. When the drainage system is clogged and restriction of flow occurs，pore water pressure will be developed on the secondary lining，which is normally designed as non-structural members. Pore water pressure caused by the deterioration of drainage system is termed as “residual pore water pressure” here.



(a) Normal drainage system($k_l<k_f$)



(b) Deteriorated drainage system($k_l<k_f$)

Fig.3　Water pressure development on the linings

Magnitude of pore water pressure on the linings will depend on the relative permeability，drainage system，primary linings and ground. Table 1 shows the possibility of water pressure development on the linings[5].

Deterioration of drainage system generally takes long time. Thus，for a tunnel with a drainage system monitoring and controlling of residual water pressure，it is necessary to keep the function of tunnel. This requires evaluating water pressure on the linings. However，an aged-tunnel or a tunnel without a monitoring system does not provide any information about pore water pressure. In addition，installation of new monitoring system is generally not allowed，as it may cause the destruction of the stabilized water proofing sheets. Therefore，non-destructive and indirect evaluation method of pore water pressure is required in this case. In this paper，a new evaluation method of pore water pressure is proposed on the basis of a numerical and analytical approach.

Table 1　Water pressure development mechanism[5]

Relative permeability		Water pressure on		Remarks
		Primary lining	Secondary lining	
$k_s>k_l$	$k_l>k_f$	○	○	Squeezing/clogging
	$k_l<k_f$	○	－	
$k_s<k_l$	$k_l>k_f$	－	○	Squeezing/clogging
	$k_l<k_f$	－	○	

Note：○ is the development of water pressure on the lining.

2　CHARACTERISTICS OF PORE WATER PRESSURE DEVELOPMENT

2.1　Analysis model

As mentioned above，the main factor defining the magnitude of pore water pressure on the lining is the relative permeability. Complication of theoretical approaches and difficulties in field instrumentation make it difficult to provide full understanding of the effect of various hydraulic boundary conditions on tunnel structures. Numerical approaches can be an alternative way for carrying out parametric study. In this paper，numerical simulation technique is adopted to investigate the development mechanism of residual water pressure for various hydraulic conditions.

Flow behaviors through the ground and lining can be modeled using composite elements as shown in Fig.4. The lining including drainage system is modeled by both the solid elements，of which permeability is that of lining，and the beam elements，of which elasticity is that of lining. Representative ground condition used for this study is shown in Fig.5.

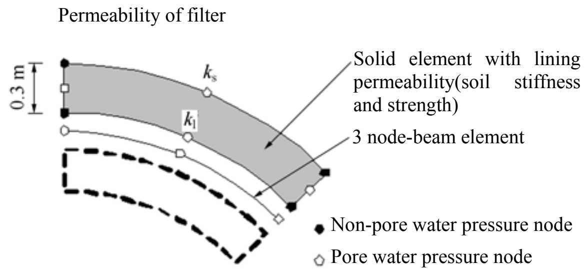


Fig.4 Modeling of hydraulic and structural behavior of linings

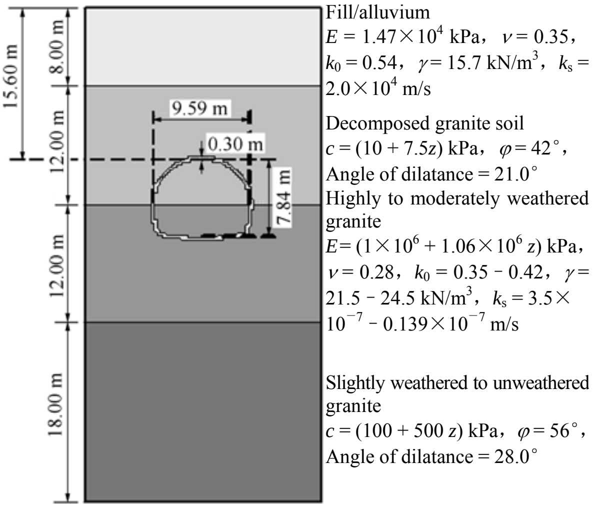


Fig.5 Ground and tunnel profiles

To model the pre-yield behavior of ground，a small strain nonlinear elastic model[6] for decomposed granite soil and isotropic linear elastic model for other materials are adopted. The non-linear equations for the tangent moduli can be found in relevant study[7]. The relevant parameters are given in Tables 2 – 4，where G is the tangent shear modulus，K is the tangent bulk modulus，E_d is the deviatoric strain，ε_v is the volumetric strain and all other parameters are coefficients. Mohr-Coulomb model is used to represent the post-yield behavior. Elastic lining behavior is assumed. To simulate strain-dependant permeability，non-linear permeability model proposed by P. R. Vaughan[8] is adopted：

$$k = k_0 \mathrm{e}^{-Bp'} \tag{1}$$

where k_0 is the permeability when average effective stress is 0，B is the experience parameter and p' is average effective stress. Tables 2 – 4 shows the main parameters used.

Table 2 Material parameters for calculation(pre-yield soil constitutive models)

Material	A	B	C/%	α	γ	E_dmin /%	E_dmax /%	G_min /MPa
Decomposed granite soil	1 515	1 485	2×10^{-4}	0.955	0.818	9×10^{-3}	0.35	9.706

Material	R	S	T/%	δ	λ	$\varepsilon_\mathrm{vmin}$ /%	$\varepsilon_\mathrm{vmax}$ /%	K_min /MPa
Slightly weathered to unweathered granite	475	465	2×10^{-4}	0.848	0.872	5×10^{-3}	0.50	6.438

Note：(1) Fill and highly to weathered granite will adopt isotropic linear elastic model；(2) Model for decomposed granite soil will considered small strain nonlinear elastic.

Table 3 Lining properties parameters for calculation (shotcrete)

A/m^2	I/m^4	E/kPa	μ	k/(m • s^{-1})
0.3	0.002 25	2.0×10^7	0.2	3.4×10^{-6} – 3.4×10^{-9}

Table 4 Material properties parameters for calculation (permeability models)

Material	k_0/(m • s^{-1})	β
Decomposed granite soil	1.9×10^{-6}	0.004 3
Slightly weathered to unweathered granite	1.9×10^{-6}	0.004 3

Note：(1) Fill and high to moderately weathered granite will adopt isotropic permeability model(spatially varying，m/s)；(2) Nonlinear permeability will consider Eq.(1).

Coupled displacement-pore water pressure analyses are performed using the ICFEP(Imperial College finite element program[5]). Analytical cases are listed on Table 5. Decrease in $k_\mathrm{l}/k_\mathrm{s}$ ratio represents deterioration of drainage system. The permeability of primary lining is assumed to be that of surrounding

Table 5 Analytical cases

Hydraulic boundary conditions	Prescriptions
Extreme conditions	Impermeable(q，rate of inflow = 0)
	Fully permeable(P，pore water pressure = 0)
Partially permeable	k_l/k_s = 0.1，$k_\mathrm{l} = k_\mathrm{f}$
	$k_\mathrm{l}/k_\mathrm{s}$ = 0.01，$k_\mathrm{l} = k_\mathrm{f}$
	$k_\mathrm{l}/k_\mathrm{s}$ = 0.001，$k_\mathrm{l} = k_\mathrm{f}$

ground($k_l = k_f$). Thus, throughout this paper, it is assumed that the pore water pressures act on the secondary linings.

2.2 Results

Fig.6 shows the results of pore water pressure normalized by hydrostatic pressure along the tunnel height. Pore water pressure increases with a decrease in permeability of drainage system. A characteristic curve can be obtained by re-plotting the above results with respect to k_l/k_s ratio as shown in Fig.7.

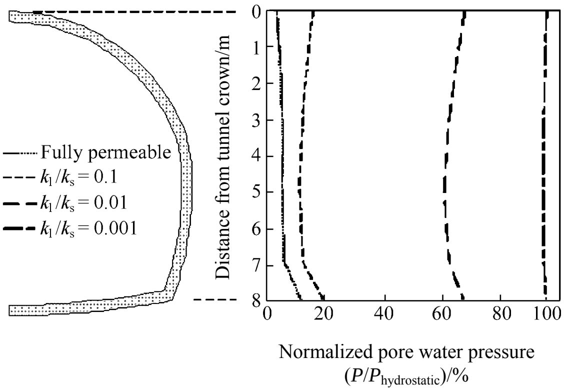


Fig.6　Distribution of pore water pressure along tunnel height

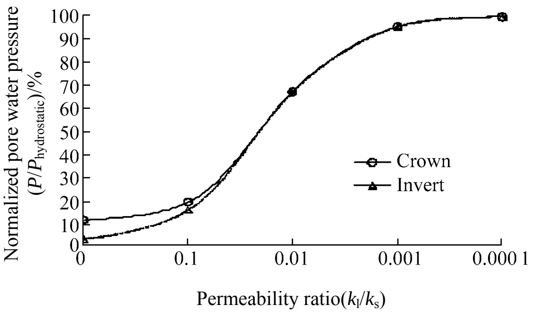


Fig.7　Characteristics of pore water pressure development

Fig.7 implies two significant aspects: firstly, it indicates that deterioration of drainage system(which means, here, reduction in k_l/k_s ratio) increases pore water pressure; and secondly, if the permeability ratio is known, the pore water pressure can be determined using the curve. In this study, the second significance is mainly concerned.

3 EVALUATION OF RESIDUAL PORE WATER PRESSURE

3.1 Basic concept and assumptions

Exact pore water pressure can only be obtained by instrumentation. However, installation of measuring system in the running tunnel is generally not allowed, as it may cause damages to the stabilized water proofing systems. Thus, if the permeability ratio(k_l/k_s) is known, the pore water pressure developed on the linings can be determined using the characteristic curve described in the previous section. In this paper, an analytical method is considered to evaluate the permeability ratio. It is assumed that permeability of the ground is homogeneous and isotropic, and the permeability of primary lining is the same as that of surrounding ground, thus the pore water pressure acts on the secondary linings.

3.2 Permeability ratio(k_l/k_s)

The amount of inflow of ground water, q, into a tunnel is proportional to permeability of surrounding materials, k. The flow rate into the tunnel, q_0, is governed by the permeability of surrounding ground as follows:

$$q_0 \propto k_s \tag{2}$$

where k_s is permeability of the surrounding ground.

Thus, there would be no residual pore water pressure on the lining. If there is some restriction of flow, pore water pressure will develop on the lining and the corresponding flow rate, q_l is proportional to the permeability of drainage system.

$$q_l \propto k_l \tag{3}$$

The q_0 can be calculated for a fully permeable tunnel, for instance, by using the equations proposed by R. E. Goodman et al.[9]. Meanwhile q_l is the amount of discharged ground water in the collection wells and can be measured easily. In this study, and an attempt to evaluate k_l/k_s ratio is made as

$$\frac{q_l}{q_0} = f\left(\frac{k_l}{k_s}\right) \tag{4}$$

According to R. E. Goodman et al.[9], the q_0 can be expressed by

$$q_0 = \frac{2\pi k_s h_0}{\ln\dfrac{2h}{r_0}} \tag{5}$$

where h_0 is distance from center of the tunnel to the ground water table，h is the depth of the tunnel below the ground surface，and r_0 is outside radius of the lining. The parameters are described in Fig.2. If q_s is the restricted flow rate across surrounding ground，then q_s can be determined as

$$q_s = \frac{2\pi k_s(h_0 - h_1)}{\ln\dfrac{2h}{r_0}} \tag{6}$$

where h_1 is the hydraulic head on the secondary lining. The q_1 is the measured flow rate at the collection well and expressed as

$$q_1 = \frac{2\pi k_1 h_1}{\ln\dfrac{r_0}{r_i}} \tag{7}$$

where r_i is inside radius of the lining. Based on the continuity of flow，Eqs.(6) and (7) are equal and the ratio of water head can be expressed as

$$\frac{h_1}{h_0} = \frac{1}{1 + C\dfrac{k_1}{k_s}} \tag{8}$$

where C is a parameter and can be written as $C = \ln\dfrac{2h}{r_0}\Big/\ln\dfrac{r_0}{r_i}$.

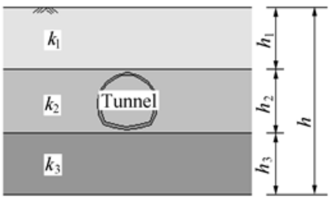
By combining Eqs.(5)，(7) and (8)，the permeability ratio is obtained：

$$\frac{k_1}{k_s} = \frac{1}{C}\left(\frac{1}{1 - \dfrac{q_1}{q_0}} - 1\right) \tag{9}$$

Eq.(9) only requires theoretical flow rate for the fully permeable tunnel，measured flow rate in the collection well and the height of ground water table. This approach would be very useful as a simple method to evaluate residual pore water pressure.

3.3 Consideration in actual conditions

The proposed permeability equations assume homogeneous and isotropic ground conditions，and circular tunnel with significant water depth. Generally，the shape of tunnel is，however，not circular. Equivalent cross-sectional area concept can be considered. Representative permeability，$k_{s(eq)}$ for a layered ground requires estimation of equivalent and representative permeability. One possible method for it is thickness-weighted average permeability as shown in Fig.8.



$$k_{s(eq)} = \frac{h_1}{\dfrac{h_1}{k_1} + \dfrac{h_2}{k_2} + \dfrac{h_3}{k_3}}$$

$k_{s(eq)}$：average permeability of ground
k_1，k_2，k_3：permeability of each ground
h：total thickness of ground
h_1，h_2，h_3：thickness of each ground

Fig.8　Estimation of average permeability of ground

Over estimation of q_0 decreases the ratio of $k_1/k_{s(eq)}$，and increases pore water pressure. Thus，underestimation of $k_{s(eq)}$ increases pore water pressure.

On the other hand，the flow rate can be evaluated from the amount of collected water as shown in Fig.9. Water depth can be obtained nearby construction sites，otherwise from boring hole. Overestimation of h decreases $k_1/k_{s(eq)}$ ratio and increases pore water pressure. Measured inflow rate，q_1 can be erroneous as it includes any water losses such as evaporation. Generally q_1 is underestimated，which decreases $k_1/k_{s(eq)}$ ratio and gives higher pore water pressure than actual values.

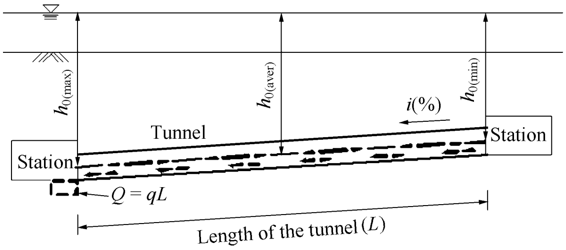


Fig.9　Evaluation of flow rate from collection well

4　EXAMPLE APPLICATION TO AN UNDERWATER TUNNEL

The proposed method in this paper is applied to an example problem shown in Fig.10. An under water tunnel with total water head 28.8 m is shown. Rock cover is 21.5 m，and excavation diameter ϕ 9.6 m is considered.

Inflow rate without restriction，q_0 is calculated using the equation of R. E. Goodman et al.[9] and obtained as $q_0 = 61.71\ \mathrm{m^3 \cdot d^{-1} \cdot m^{-2}}$. Measured inflow rate is $q_1 = 10.4\ \mathrm{m^3 \cdot d^{-1} \cdot m^{-2}}$. Consequent $k_1/k_{s(eq)}$ ratio is obtained using Eq.(8)，as $k_1/k_{s(eq)} =$ 0.002. Residual water pressure is now determined

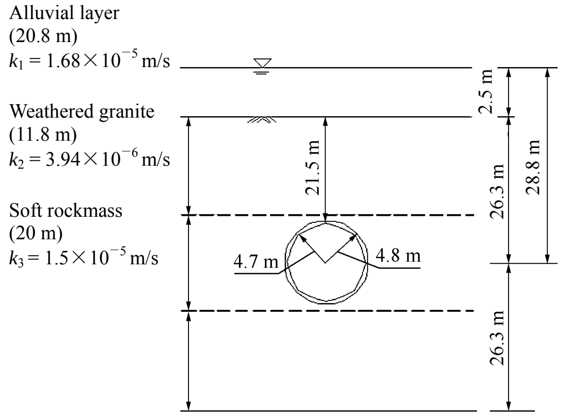


Fig.10 Example problem for analysis

using both characteristic curve and the $k_1 / k_{s(eq)}$ ratio as shown in Fig.11，which represents the upper bound of Fig.7，as 90% of hydraulic pressure.

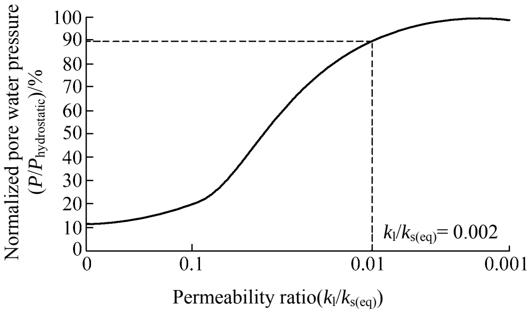


Fig.11 Evaluated residual pore water pressure

5 CONCLUSIONS

In this paper，a simple method to evaluate residual pore water pressures on the drained tunnel linings is proposed. A method combining numerical and analytical approaches was presented，which consists of four steps：

(1) Select representative ground and tunnel profile from site study.

(2) Perform numerical parametric study for various relative permeability，and obtain the characteristic water pressure curve.

(3) Evaluate permeability ratio from measured inflow rate and water depth using analytical equations.

(4) Determine the residual pore water pressure using the characteristic curve and permeability ratio.

It is shown that the proposed method provides a convenient and easy way evaluating the residual pore water pressure. It would be particularly useful for quick check of linings safety in the phase of operation. Practical application of the proposed method，however，requires careful consideration as it assumes general restriction of flow under a specific ground condition. In some cases，local flow restriction and different ground stiffness may influence pore water pressure distribution around tunnels.

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