Assessment of the effects of internal drainage on the design of tunnels

Évaluation des effects du drainage intérieur sur le projet des tunnels

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ABSTRACT: There is no universally accepted procedure for taking into account the effects of groundwater upon tunnels. Numerical models are employed herein in an attempt to better understand the advantages and disadvantages of draining a tunnel below groundwater. The adopted models are validated by comparison with published results (experimental, analytical and numerical) and with an analytical solution developed by the authors. Numerical and analytical results are compared in terms of rates of water inflow, axial forces and bending moments in tunnel lining. The benefits of draining the tunnel can be assessed, in terms of lining design, by means of the results presented herein, which also allow estimates of rates of infiltration for the analysed situations.

RÉSUMÉ: Il n'y a pas de procédé consacré pour la consideration des effects de l'eau souterraine sur les tunnels. Cet étude utilise des modèles numériques pour essayer d'atteindre une meilleure comprehension des avantages du drainage d'un tunnel au-dessous de la nappe phréatique. Les modèles adoptés sont validés par des comparaisons avec des resultats publiés (experimentales, analytiques e numériques) aussi bien qu'avec une solution analytique développée par les auteurs. Les resultats numériques et analytiques sont comparés para rapport aux débits d'eau, forces axiales et moments de flexion sur le revêtement. Les resultats présentés permettent de juger les avantagcs du drainage vis-à-vis le projet du revêtement, aussi bien qu'évaluer le debit d'eau.

1 INTRODUCTION

The numerical analyses presented in this paper, which were validated by comparisons with published data and with an original analytical solution, allow direct evaluation of the effects of the following factors on a) water inflow rates; and b) axial forces and bending moments in the tunnel lining:

- different soil-lining hydraulic conductivity ratios;
- different tunnel geometries (soil cover);
- different groundwater level positions; and
- different soil-lining stiffness relations.

The software FLAC, version 3.3, was used for the analyses.

2 ANALYSIS METHODOLOGY

2.1 *Phases of the analysis*

The problem of analysing a tunnel in an homogeneous medium, subjected to water flow, was divided in two phases: a) flow analysis; b) stress-strain analysis of the soil-lining interaction, due to the water flow.

A transformation of the results of the flow analysis is necessary to prepare the input for the stress-strain analysis.

2.2 *Flow Analysis*

The input data for the flow analysis are the geometry and boundary conditions, the hydraulic conductivity of the soil, and the density of water.

Flow analyses are quite usual in engineering practice and the results are flow rates and pore pressure distribution in the soil.

2.3 *Result Transformation*

Pore-pressures or flow velocities must be transformed into forces or stresses, for input to the stress-strain analysis.

In the present case, seepage forces were calculated for each element of the model and properly distributed as nodal forces.

2.4 *Stress-Strain Analysis of the Soil-Lining Interaction*

The results of the flow analysis are then applied to a model with the same geometry, but with boundary conditions and material properties properly adjusted for stress-strain analysis.

A linear elastic model was adopted, under plane strain conditions, for which the displacement field would be given by the Navier equations (Timoshenko, 1970). However, to avoid the development of tensile forces between the lining and the soil, no-tension elements were introduced there. These tensile forces would develop only for very high soil-lining hydraulic conductivity ratios.

3 VALIDATION OF THE METHOD OF ANALYSIS

Both the flow and the stress-strain analyses had to be validated.

For this, two different 2-D problems were analysed:

- a circular tunnel 5 m in diameter, 12 m of soil cover and 18 m above an impervious stratum. The lining was 25 cm thick, with hydraulic conductivities ranging from $k = 10^{-8}$ m/s to $k = 10^{-10}$ m/s. The soil hydraulic conductivity was kept constant at $k = 10^{-8}$ m/s. Properties and geometry are similar to those adopted by Fitzpatrick et al. (1981), allowing a direct comparison with published values concerning flow rates.
- a circular well 2.5 m in radius, with a 25 cm thick lining. Hydraulic conductivities were taken the same as for the tunnel model. Water pressures of 100 kPa around the outer boundary and of 0 kPa on the inner boundary were assumed. The geometry is similar to that of Atkinson & Mair (1983). For the stress-strain analysis, Young's modulus of the soil was kept constant, while Poisson's ratio and the lining stiffness were varied. Again, it is possible to compare flow rates obtained by numerical and analytical means.

3.1 *Flow Analysis*

Figure 1 shows the adopted mesh for the circular tunnel analysis.

Table 1 shows that differences between flow ratios remained below 5%.

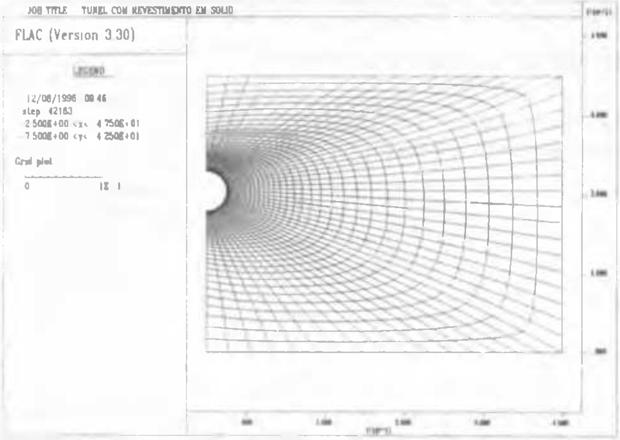


Figure 1. Mesh used for validation (circular tunnel).

Table 1. Comparison between published and obtained values (tunnel).

ks/kr Ratio	published values * (l / day / m^2)	validation analysis (l / day / m^2)	difference (%)
1	1,90	1,88	1,1
2	1,84	1,81	1,6
5	1,68	1,63	3,0
10	1,45	1,42	2,1
50	0,71	0,68	4,2
100	0,43	0,42	2,3

* Fitzpatrick et al. (1981)

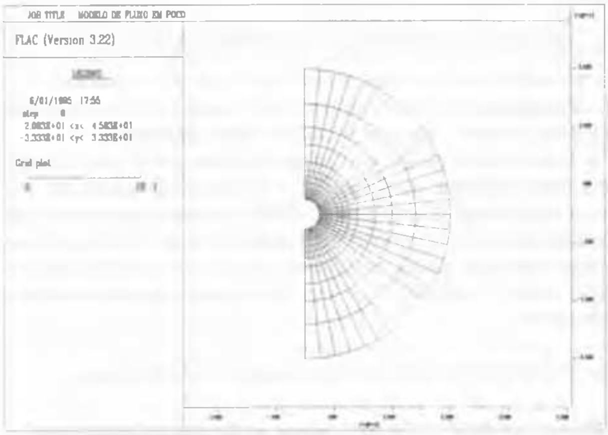


Figure 2. Mesh used for validation (circular well).

Figure 2 shows the adopted mesh used for the circular well analysis.

The calculated flow rates were compared with flow rates obtained analytically along the steps presented below.

Darcy's law, for flow through an homogeneous, isotropic medium is:

$$Q = k \times i \times A \tag{1}$$

where Q is the flow rate, i the gradient and A the area.

On the other hand, according to Verruijt (1970), for radial confined flow the expression for the potential function is:

$$H = C_1 \ln(r) + C_2 \tag{2}$$

where H is the hydraulic head and r the radius.

The gradient for this situation is, therefore:

$$i = \frac{\partial H}{\partial r} = \frac{C_1}{r} \tag{3}$$

Equation 1 then becomes, for this case:

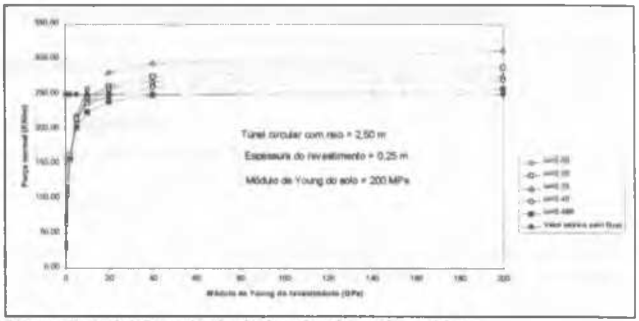


Figure 3. Axial force in the lining for the well problem.

$$Q = k \times C_1 \times 2 \times \pi \tag{4}$$

If the proper boundary conditions for the problem at hand are applied to Equation 2, it follows that:

$$C_1 = \frac{C}{\ln\left(\frac{r_e}{r_i}\right)} \tag{5}$$

where r_e and r_i are the outer and inner radii and C is the total hydraulic head.

For the circular well analysed, $r_e = 25$ m, $r_i = 2.5$ m and $C = 100$ kPa, yielding $C_1 = 4.34$ and a flow rate of 2.73×10^{-7} m^3/s. The flow rate resulting from the numerical analysis was 2.74×10^{-7} m^3/s, a difference of less than 1%.

3.2 *Stress Strain Analysis*

For the stress-strain validation the well problem was chosen, for comparison with the analytical data published by Atkinson & Mair (1983).

Atkinson & Mair (1983) point out that their results are only valid for very stiff tunnel linings. For those conditions they show that the axial force in the tunnel lining is not dependent on the drainage conditions and equals the axial force for the case of hydrostatic loading of the lining. The relevance of that restriction was evaluated by means of a parametric study, in which Young's modulus of the lining and Poisson's ratio of the soil were varied. Figure 3 shows that differences in axial forces may reach 20%.

These results are similar to the ones presented by Wood (1975); comparison of stresses in several points of the model show differences below 1%. For a thorough comparison the reader is referred to Bilfinger (1997).

3.3 *Conclusions about the Validation*

As shown above, the proposed method yields good results both for flow analysis and for stress-strain analysis.

Table 2 summarises an evaluation of the influence of the discretisation. Differences remain below 4%.

Table 2. Variation of axial force due to differences in the discretisation.

	Coarse Mesh	Normal Mesh	Refined Mesh
Number of elements	84	390	1380
Axial Force (kN)*	278,8	274,8	269,2
Difference in relation to refined model (%)	3,5	2,2	0

* for E_{rev} = 40.000 MPa

4 EVALUATION OF THE FACTORS THAT INFLUENCE FLOW RATE

Several numerical analyses of a circular tunnel were conducted to assess the relevance of the main factors that influence flow rates to a drained tunnel, namely:

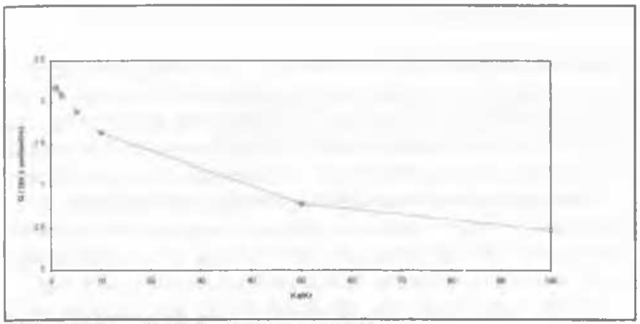
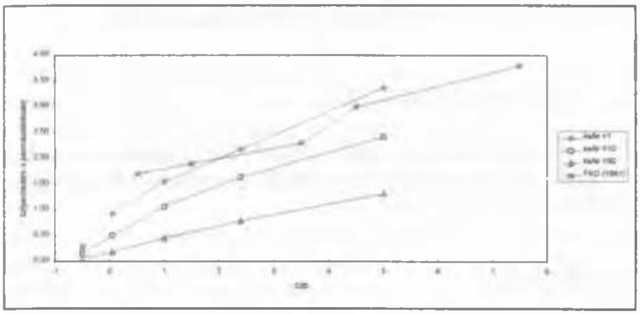


Figure 4. Normalised flow rates versus k_s/k_r



*FKO (1981): data published by Fitzpatrick et al. (1981)

Figure 5. Normalised flow rates versus relative depth below groundwater level.

- depth of the tunnel crown below groundwater level (C), and
- soil-lining hydraulic conductivity ratio (k_s/k_r).

Figures 4 and 5 show results of analyses performed under the assumption of homogeneous lining with constant hydraulic conductivity.

Figure 4 shows that, as expected, flow rates decrease as the lining becomes relatively less pervious (increase in the k_s/k_r ratio). Flow rates were normalised with respect to the product (soil hydraulic conductivity) x (tunnel perimeter). In all analyses, the diameter was 5 m, depth below groundwater level was 12 m and lining thickness was 0.25 m.

Figure 5 shows the influence of the C/D ratio (relative depth below groundwater level) on water inflow rates. Numerical data from Fitzpatrick et al. (1981), for $k_s/k_r = 1$, are added for comparison.

Figure 5 makes it possible to choose the hydraulic conductivity of the lining (at least relative to the surrounding soil) so as not to exceed an economically acceptable flow rate.

Figures 6 and 7 show results obtained under the assumption of localised drainage through discrete voids across the lining, which can be regarded either as construction imperfections or as drains.

Figure 6 shows normalised flow rates obtained for five different drainage conditions:

a) 1 drain in the invert of an impervious lining;
b) 3 drains, 1 in the invert and 2 symmetrically located in the springline, across an impervious lining;
c) 4 drains, same as b) above, plus an extra drain in the crown, across an impervious lining; and
d) 3 drains, same as b) above, but for $k_s/k_r = 100$.

Results from Figure 5 are superimposed for comparison.

Figure 7 shows the same data from Figure 6, but taking the case $k_s/k_r = 1$ with no drains as a reference.

Figure 7 suggests that for tunnels deeper than C/D = 2 the inflow relationships remain essentially constant.

Notice that for C/D ratios below zero (water level below tunnel crown) the case with 1 single drain across the invert presents seemingly higher inflow rates. This is, in fact, due to the reduced wet perimeter.

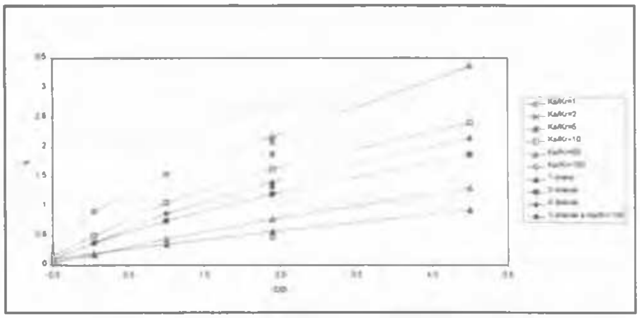


Figure 6. Normalised flow rates for different drainage conditions.

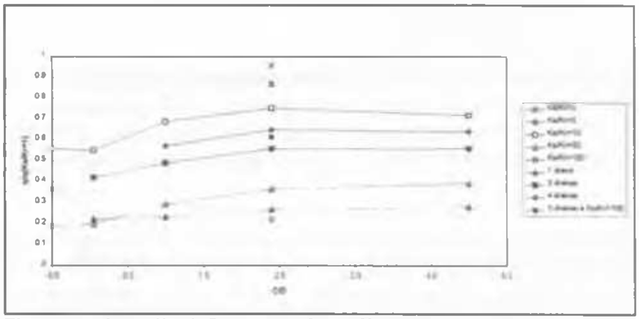


Figure 7. Normalised flow rates for different drainage conditions, referred to the case of $k_s/k_r=1$, with no drains.

5 EVALUATION OF THE FACTORS THAT INFLUENCE LOADING OF THE LINING

Loading of the lining was evaluated in terms of bending moments and axial forces. The same circular tunnel of the previous item was analysed, with similar geometry and drainage conditions, but for varying stiffness ratios, as represented by the following non-dimensional quantities (Duddeck & Erdmann, 1982):

$$\beta = \frac{ER}{E_{rev}A} \tag{6}$$

$$\alpha = \frac{ER^3}{E_{rev}J} \tag{7}$$

where E is Young's modulus of the soil, R is the tunnel radius, E_{rev} is Young's modulus of the lining, A is the lining cross section and J the lining moment of inertia.

Results in terms axial forces in the invert of the tunnel lining are summarised in Figures 8 to10, each of which for a different hydraulic conductivity ratio. Those figures show normalised axial forces as a function of the stiffness ratio (β from equation 6), for varying relative depths. Normalisation is attained by dividing the forces resulting from the analyses by the corresponding force for the case of an impervious lining (no-flow situation).

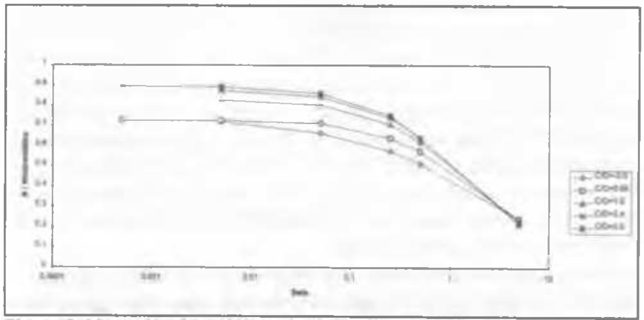


Figure 8. Normalised axial force in lining invert - $k_s/k_r = 1$.

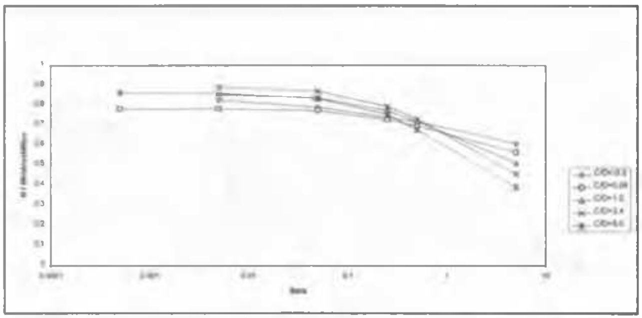


Figure 9. Normalised axial force in lining invert - $k_s/k_r = 10$.

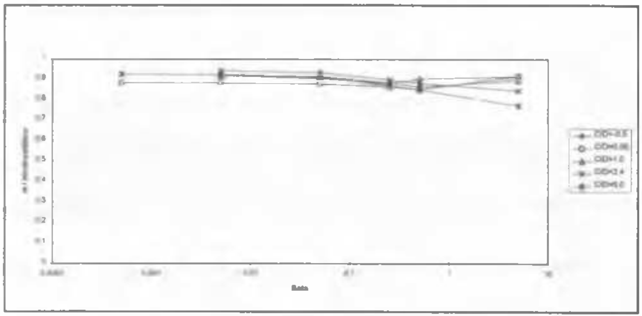


Figure 10. Normalised axial force in lining invert - $k_s/k_r = 50$.

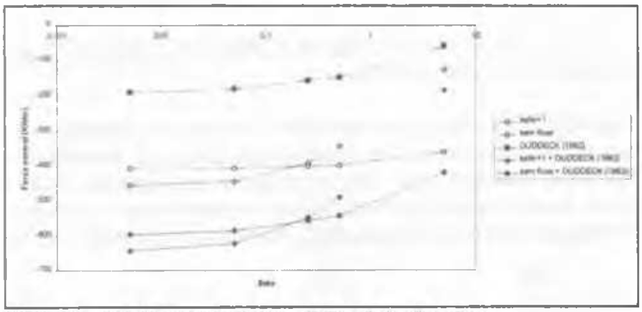


Figure 11. Axial Forces in lining - C/D = 2.4 – D = 5m.

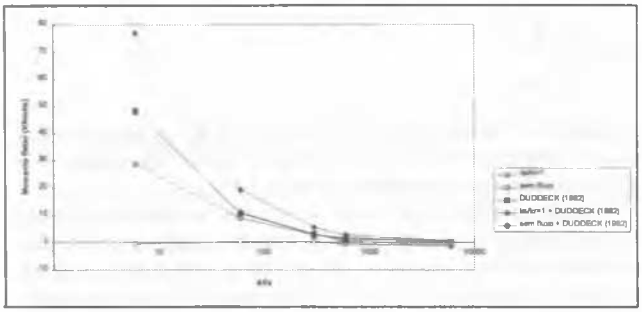


Figure 12. Maximum bending moments in lining - C/D = 2.4 – D = 5m.

Figures 8 to 10 show that, as expected, as the hydraulic conductivity of the lining decreases the axial force in the tunnel lining approaches the value corresponding to hydrostatic loading. Moreover, a significant reduction of axial forces may be expected in drained tunnels in relatively stiff soil (high β).

Figures 11 and 12 show, for C/D = 2.4 and D = 5 m, the axial forces and bending moments due to water and soil loading of the lining. The curve labelled "Dudeck" refers to *effective* soil loading upon the lining, as proposed by Duddeck & Erdmann (1982), considering a stress relief of 30% of the "*in situ*" stresses, $k_0 = 0.5$, and water level at the surface. The other curves refer to water loading of the tunnel for different drainage conditions, or to combined soil and water loading.

Once again, figures show that significant reductions in loading may be achieved by means of drainage, provided the soil is relatively stiff (high α and β).

6 CONCLUSIONS

The study showed that the benefits of providing drainage to a tunnel depend on a series of factors. Drainage of a tunnel can reduce significantly the bending moments and axial forces, but only for tunnels in relatively stiff soil (high α and β). For tunnels in relatively soft soil, the benefits of drainage are not significant.

The direct and indirect costs of drainage can be related to inflow rates. Figure 5 makes it possible to choose the hydraulic conductivity of the lining (at least relative to the surrounding soil) so as not to exceed an economically acceptable flow rate.

On the other hand, the efficiency of the waterproofing of a tunnel can be evaluated numerically using Figure 6: for a known inflow rate and geometry, it is possible do determine the corresponding k_s/k_r ratio or the equivalent drainage condition.

7 ACKNOWLEDGMENTS

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