The Evaluation of the Groundwater Influence on the Stress and Strain Behavior around a Tunnel by Analytical Methods

Pierpaolo Oreste
Department of Environmental, Land and Infrastructural Engineering, Politecnico di Torino (Italy) Corso Duca degli Abruzzi 24, I-10129 Torino, Italy

Abstract: The presence of an aquifer in the soil causes a change in a relevant way of the stability conditions of a tunnel. The flow of water in the pores, in fact, modifies the stress and strain state of the soil and causes an increase in the thickness of the plastic zone. As a result the loads transmitted on the lining increase. In this study a calculation procedure by finite differences method, able to determine the stress and strain state of the soil in the presence of the water flow in the pores, is presented. More particularly, using the proposed procedure, it is possible to determine the convergence-confinement curve of the tunnel and the trend of the plastic radius varying the internal pressure. A calculation example is used to detect the great influence that the presence of the aquifer has on the stress and strain state of the soil and on the pressure-displacement relationship of the tunnel wall.

Keywords: Tunnel Stability, Deep Tunnel, Circular Tunnel, Underwater Tunnels, Convergence-Confinement Curve, Groundwater, Tunnel Support, Excavation Face, Pore Pressure, Stress and Strain Around the Tunnel

Introduction

The groundwater presence in the soil has an important effect on the stability of a tunnel. The flow of water towards the tunnel, in fact, substantially alters the stress state around the void perimeter (Bobet, 2003; Fahimifar et al., 2014; Fernandez and Moon, 2010; Haack, 1991; Hwang and Lu, 2007), increasing the thickness of any existing plastic zone. As a result, the loads acting on the lining increase.

Even at the face, the static conditions are exacerbated by the presence of a groundwater flow towards the tunnel, which may lead to the soil breakage for a portion more or less extended ahead of the face (Oreste, 2013).

It is, therefore, fundamental to detect critical conditions for the tunnel stability, when an aquifer is present (Carranza-Torres and Zhao, 2009; Nam and Bobet, 2006; Li et al., 2014; Wang et al., 2008).

The numerical methods, both two-dimensional and three-dimensional ones (Do et al., 2014; 2015; Oreste, 2007), are able to study in detail the stress and strain state around a tunnel and in the support structure. In the presence of groundwater and of water flow in a porous medium, it is necessary to provide coupled numerical analysis, in which the stress and strain analysis is developed in parallel to the water flow analysis. For these reasons, the numerical methods, especially the three-dimensional ones, appear to be very slow when they have to analyze the behavior of a tunnel in a porous medium with groundwater.

Through the analytical calculation methods, it is possible to approach the study of some aspects of tunnel static easily and fast. Several analytical methods are available in the literature and are able to assess the stress and strain state around a tunnel (Oreste, 2003), ahead of the excavation face (Oreste, 2009a), in the support and reinforcement structures (Oreste, 2008; Osgoui and Oreste, 2007; 2010), when it is possible to introduce some simplifying assumptions of the problem in the calculation. These methods are characterized by a relatively high speed of calculation, which allows one to develop extensive parametric analyzes, probabilistic analyzes (Oreste, 2005a; 2014a) or back-analyses (Oreste, 2005b).

In this study is presented a numerical solution by finite difference method that allows to analyze in detail the stress and strain state of the soil around the tunnel, in the presence of a water flow in the pores. From the calculation it is possible to determine the convergence-confinement curve of the tunnel, the evolution of the plastic radius varying the total internal pressure applied...
to the tunnel walls, the stresses and displacements that develop in the soil around the tunnel, for a certain total pressure applied to the walls.

A calculation example for a specific case will illustrate the influence of the groundwater flow in the soil pores on the convergence-confined curve of the tunnel and on the stress and strain state of the soil.

Materials and Methods

The analysis of the behavior of a circular and deep tunnel can be developed through the convergence-confinement method for the cylindrical geometry (Ribacchi and Riccioni, 1977; Lembo-Fazio and Ribacchi, 1986; Panet, 1995; Orestes, 2009b). This method allows to obtain the relationship between the radial displacement of the tunnel wall and the internal pressure applied to the tunnel perimeter. Proceeding with then the intersection of the convergence-confinement curve of the tunnel with the reaction line of the support, one can determine the final displacement of the tunnel wall and the load acting on the support structure (Oreste, 2014b).

Il metodo delle curve caratteristiche si basa sulle seguenti fondamentali equazioni (Ribacchi e Riccioni, 1977; Lembo-Fazio e Ribacchi, 1986; Panet, 1995): L'equazione di equilibrio assialsimmetrico delle forze nella direzione radiale (Equation 1) e le due equazioni di congruenza delle deformazioni (Equation 2). Inoltre, per il terreno a comportamento elastico al contorno della galleria valgono le due equazioni dell’elasticità per il campo di deformazione piano e geometria assialsimmetrica, mentre per la porzione di terreno a comportamento plastico (all’interno della fascia plastica), sono validi il criterio di rottura e la relazione tra le deformazioni principali plastiche (la cosiddetta legge di flusso) (Ribacchi e Riccioni, 1977; Lembo-Fazio e Ribacchi, 1986; Panet, 1995).

The convergence-confinement method is based on the following fundamental equations (Ribacchi and Riccioni, 1977; Lembo-Fazio and Ribacchi, 1986; Panet, 1995): The equation of axisymmetric equilibrium of forces in the radial direction (Equation 1) and the two equations of strain congruence (Equation 2). Also, for the soil with elastic behavior around the tunnel the two equations of the elasticity, for the plane field strain and axisymmetric geometry, can be applied; while, for the soil portion with elastic-plastic behavior (inside the plastic zone), the failure criterion and the relationship between the main plastic strains (the so-called flow law) are valid (Ribacchi and Riccioni, 1977; Lembo-Fazio and Ribacchi, 1986; Panet, 1995):

$$
\frac{d\sigma_r}{dr} = \frac{\sigma_s - \sigma_c}{r}
$$  \hspace{1cm} (1)

Where:
- $\sigma_r$ = The radial stress applied to the tunnel perimeter
- $\sigma_s$ = The radial and circumferential stresses
- $\sigma_c$ = The radial and circumferential strains
- $u$ = The radial displacement of the soil (positive when directed towards the tunnel centre)
- $\sigma_R$ = Radial stress applied to the tunnel perimeter
- $E$ and $\nu$ = Elastic modulus and Poisson ratio of the soil
- $R$ = Tunnel radius
- $\rho_0$ = Lithostatic pressure
- $c$ and $\varphi$ = Soil cohesion and friction angle
- $\psi$ = Soildilatancy angle
- $\sigma_R$ = Radial stress applied to the tunnel perimeter

In general, there is always a stretch of the convergence-confined curve with an elastic behavior, defined by Equation 3a, for values of $\sigma_R$ greater than a certain critical pressure $\sigma_{Rpl}$ (Equation 4). For values of $\sigma_R$ lower than $\sigma_{Rpl}$ (if $\sigma_{Rpl}$ is positive), the relationship between $u_R$ and $\sigma_R$ is defined by Equation 3b:

$$
\sigma_{Rpl} = \frac{2 \cdot \rho_0 - \sigma_c}{N_p + 1}
$$

With:

$$
N_p = \frac{1 + \kappa}{1 - \kappa}; \ \sigma_c = \frac{2 \cdot c \cdot \cos \varphi}{1 - \kappa}
$$

When $\sigma_{Rpl}$ is negative, the convergence-confined curve is entirely described by Equation 3 and has a linear shape for its entire extension.

In the presence of groundwater in the soil, it is necessary to refer to effective stresses and no longer to the total stresses. In addition, the $\kappa$ Equation 1 is modified, as the forces acting on the infinitesimal soil element around the tunnel are different (Fig. 1).
Fig. 1. Stresses acting on the infinitesimal soil element around the tunnel. Legend: \( \sigma_\theta \) and \( \sigma_r \): Circumferential and radial stresses; \( p_w \): Water pressure in the soil pores

In fact, proceeding to the equilibrium of forces in the radial direction, we obtain:

\[
(\sigma_r \cdot r \cdot d\theta + p_w \cdot r \cdot d\theta + 2 \cdot \sigma_\theta \cdot dr \cdot \sin \left( \frac{d\theta}{2} \right) + 2 \cdot p_w \cdot dr \cdot \sin \left( \frac{d\theta}{2} \right) \equiv \left( \sigma_r + \frac{d\sigma_r}{dr} \right) \cdot (r + dr) \cdot d\theta
\]

\[
+ \left( p_w + \frac{dp_w}{dr} \right) \cdot (r + dr) \cdot d\theta
\]

Where:
- \( d\theta \): Infinitesimal angle that indicates the width of the infinitesimal element of Fig. 1
- \( r \): Distance from the tunnel centre
- \( p_w \): Water pressure in the soil pores

From which:

\[
\frac{dp_w}{dr} = \frac{\gamma_w}{k} \cdot \frac{Q}{(2 \cdot \pi \cdot r)}
\]

\[\text{(7)}\]

To assess in detail the trend of the water pressure \( p_w \) with the distance from the tunnel center, an analysis of the water flow has to be developed. It is useful to consider the steady-state condition (constant flow over time). More particularly, for the Darcy law is (Bear, 1972; Wang et al., 2008):

\[
v = k \cdot i = k \cdot \frac{dh}{dr} = \frac{k \cdot dp_w}{\gamma_w \cdot dr}
\]

\[\text{(6)}\]

Where:
- \( v \): Water velocity in the radial direction
- \( k \): Permeability coefficient of the soil
- \( i \): Hydraulic gradient
- \( h \): Piezometric height
- \( \gamma_w \): Specific weight of water

and, then, the flow of water towards the tunnel \( Q \) (considering 1 meter depth in the geometry of the problem) is given by the following relation:

\[
k \cdot \frac{dp_w}{dr} \cdot (2 \cdot \pi \cdot r) = Q
\]

From which:

\[
\frac{dp_w}{dr} = \frac{\gamma_w \cdot Q}{k \cdot (2 \cdot \pi \cdot r)}
\]

\[\text{(7)}\]

Which, integrated by \( R \) (tunnel radius), where the water pressure at the lining extrados is \( p_{w,\text{ext}} \), up to the generic distance \( r \), where the water pressure is \( p_w \), leads to the following relation:

\[
p_w = \frac{\gamma_w \cdot Q}{k} \cdot \ln \left( \frac{r}{R} \right) + p_{w,\text{ext}}
\]

\[\text{(8)}\]

To obtain the value of \( p_{w,\text{ext}} \) it is necessary to analyze the situation inside the tunnel lining, characterized by a thickness \( t \) and by a permeability coefficient \( k_{\text{sup}} \). The Equation 7 now becomes:

\[
\frac{dp_w}{dr} = \frac{\gamma_w}{k_{\text{sup}}} \cdot \frac{Q}{(2 \cdot \pi \cdot r)}
\]

\[\text{(9)}\]

The Equation 9, integrated by \( (R-t) \) (lining intrados, where \( p_w \) is nil) to \( R \) (lining extrados, where the water pressure is equal to \( p_{w,\text{ext}} \)), provides the following equation:

\[
p_{w,\text{ext}} = \frac{\gamma_w}{k_{\text{sup}}} \cdot \frac{Q}{2 \cdot \pi} \cdot \ln \left( \frac{R}{R-t} \right)
\]

\[\text{(10)}\]

Substituting Equation 10 in Equation 8, the expression of \( p_w \) in the soil can be rewritten in the following way:
\[ p_s = \frac{\gamma_w \cdot 0 \cdot Q}{2 \cdot \pi \cdot k} \left[ \ln \left( \frac{r}{R} \right) + \frac{k}{k_{sup}} \cdot \ln \left( \frac{R}{R-t} \right) \right] \]

\[ = \frac{\gamma_w \cdot Q}{2 \cdot \pi \cdot k} \left[ \ln \left( \frac{r}{R} \right) + \frac{k}{k_{sup}} \cdot \ln \left( \frac{R}{R-t} \right) \right] \]  

(11)

Assuming \( p_n \) reaches the water pressure \( p_w,0 \) (in undisturbed conditions) to the tunnel depth, for a distance \( r = \alpha \cdot R \), the flow rate \( Q \) value is obtained:

\[ Q = \frac{p_{w,0} \cdot 2 \cdot \pi \cdot k}{\gamma_w} \left[ \ln(\alpha) + \frac{k}{k_{sup}} \cdot \ln \left( \frac{R}{R-t} \right) \right] \]

(12)

and, therefore, the expression of \( p_s \) can be rewritten as:

\[ p_s = p_{w,0} \cdot \frac{\ln(\alpha) + \frac{k}{k_{sup}} \cdot \ln \left( \frac{R}{R-t} \right)}{\ln(\alpha) + \frac{k}{k_{sup}} \cdot \ln \left( \frac{R}{R-t} \right)} \]

(13)

The water pressure on the tunnel wall, in correspondence of the lining extrados, therefore is:

\[ p_{s,ext} = p_{w,0} \cdot \frac{k}{k_{sup}} \cdot \ln \left( \frac{R}{R-t} \right) \]

(14)

The derivative \( dp_{s,0}/dr \) takes, therefore, the following form:

\[ \frac{dp_s}{dr} = \frac{p_{w,0} \cdot \ln(\alpha) + \frac{k}{k_{sup}} \cdot \ln \left( \frac{R}{R-t} \right)}{r} \]

(15)

Results

To analyze the trend of stresses, strains and radial displacements around the tunnel varying \( r \) and in the presence of groundwater, it should proceed with a numerical solution using the finite differences method. This solution, starting from a great distance from the tunnel center (high value of \( r \)), for which is assumed nil the derivative \( dp_{s,0}/dr \) and \( \sigma_r \) is put equal to a certain percentage of \( \sigma_0 \), allows to calculate the radial and circumferential stresses and the radial displacements for concentric rings, moving towards the tunnel wall, where \( r = R \). At the generic ring the following calculation steps are developed:

- Evaluation of the radial stress \( \sigma_r \) on the inner radius of the ring from the derived \( du/dr \) calculated on the outer radius in the previous step.
- Determination of the circumferential stress \( \sigma_\theta \) on the inner radius of the ring, on the basis of the following equations (Equation 16a if the elasticity theory is valid, Equation 16b if the ring has elastic-plastic behavior) (Ribacchi and Riccioni, 1977):

\[ \varepsilon_\theta = \frac{1}{E} \left[ (\sigma_\theta - p_0) \cdot (1 - \nu^2) - (\sigma_r - p_0) \cdot (\nu^2 + \nu) \right] = \frac{u}{r} \] (16a)

\[ \sigma_\theta = \sigma_r \cdot N_\theta + \sigma_\sigma \] (16b)

- Determination of the derivative \( du/dr \) on the inner radius of the ring, on the basis of the following equations (Equation 17a if the elasticity theory is valid, Equation 17b if the ring has elastic-plastic behavior) (Ribacchi and Riccioni, 1977):

\[ \varepsilon_r + N_\sigma \cdot \varepsilon_\sigma = \frac{du}{dr} \cdot \frac{N_\sigma \cdot u}{r} \]

\[ = \frac{1}{E} \left[ (\sigma_\theta - p_0) \cdot (1 - \nu^2) - (\sigma_r - p_0) \cdot (\nu^2 + \nu) \right] + (\sigma_\sigma - p_0) \cdot (N_\nu - N_\sigma \cdot v^2 - 2v - v^2) \] (17b)

- Comparison of the circumferential stress \( \sigma_\theta \) calculated in step 3 with the soil strength for the existing confinement stress \( \sigma_c \): In the case the circumferential stress is greater than the soil strength, the starting of the soil plasticization is detected and the plastic radius (distance from the tunnel center of the extreme outer of the plastic zone) is evaluated.

Continuing the procedure for concentric rings until reaching the tunnel wall (\( r = R \)), a pair of values \( \sigma_{w,u} \) is obtained; the series of the \( \sigma_{w,u} \) pairs each corresponding to a different initial value of \( \sigma_c \) at a great distance from the tunnel center, allows to draw the convergence-confinement curve when the groundwater is present. It is also possible to identify the plastic radius, that is the value of the distance from the tunnel center where the transition from elastic to elastic-plastic behavior is detected.

By adopting the above solution to the case of a circular tunnel of radius \( R = 3 \) m and 75 m deep, it is possible to determine the influence of the groundwater presence on the convergence-confinement curve of the...
tunnel. The tunnel is excavated in a soil having cohesion $c = 0.2$ kPa, friction angle $\phi = 20^\circ$, dilatancy angle $\psi = 20^\circ$, elastic modulus $E = 350$ MPa, Poisson's ratio $\nu = 0.3$ and the specific weight of the soil $\gamma = 20$ kN/m$^3$. It is assumed the presence of a lining with a thickness of 0.3 m and a permeability coefficient $k_{\text{sup}}$ equal to $0.1 \cdot k$ (with $k$ permeability coefficient of the soil). The parameter $\alpha$ was assumed equal to 20: That is, it is considered that at a distance equal to $20 \cdot R$ the piezometric height of the water table reaches the initial unperturbed value.

Two conditions of absence and presence of groundwater (with the free surface coincident with the ground surface) were evaluated. In the first case, the litho static stress state in the undisturbed conditions is equal to 1.5 MPa; in the second case, it is equal 0.75 MPa in terms of effective stresses, since $p_{w,0} = 0.75$ MPa. The water pressure at the lining extrados $(p_{w,\text{ext}})$, calculated by Equation 14, is equal to 0.195 MPa.

Figure 2 shows the convergence-confinement curve of the tunnel obtained from the proposed calculation procedure for the case of absence (DC-dry condition) and presence (GF-groundwater flow) of groundwater. Figure 3 shows the trend of the plastic radius (extreme distance from the tunnel center of the plastic zone) varying the internal pressure on the tunnel perimeter. In Figure 4 is shown the trend of the soil stresses and the water pressure varying the distance from the tunnel center, for a nil total pressure on the tunnel wall; Fig. 5, finally, shows the trend of the radial displacements in the soil varying the distance from the tunnel center, for the two examined conditions (DC and GF) and for a nil total pressure applied on the tunnel wall.
Discussion

From the analysis of the convergence-confinement curve for the studied case (Fig. 2), it is possible to note that the presence of groundwater can significantly modify the stress and strain behavior of the soil around the tunnel. In fact, the convergence-confinement curve in the presence of a steady flow of water towards the tunnel, involves, at constant total pressure applied internally to the tunnel perimeter, values of the radial displacement of the wall much greater than in the case of water flow absent. This has as a consequence a greater load acting on the tunnel lining. The estimated value of the load on the lining can be made by taking the intersection of the convergence-confinement curve of the tunnel with the reaction line of the lining (Oreste, 2014b).

Furthermore, reducing the internal pressure the plastic radius grow faster in the presence of groundwater (Fig. 3). For a nil internal pressure the plastic radius even varies from about 7 m (dry condition) to about 13 m (in the presence of the groundwater flow). The presence of a more extensive plastic zone around the tunnel involves a change in the pattern of the stresses (Fig. 4) and of the radial displacements in the soil (Fig. 5).

In conclusion, the presence of the groundwater flow involves a detensioning of the soil, an increase of the thickness of the plastic zone and a substantial increase of the radial displacements around the tunnel.

The effects of the presence of groundwater, therefore, are significant and cannot be neglected.

The calculation method proposed in this study, therefore, allows the analysis of the interaction between
the groundwater flow and the soil in a simple and effective way, using a finite difference solution. The stresses and strains that are calculated in the soil around the tunnel are able to provide the convergence-confinement curve of the tunnel in the presence of groundwater and also lead to the evaluation, with some precision, of the thickness of the plastic zone. Furthermore, proceeding with the intersection of the convergence-confinement curve with the reaction line of the lining, it is possible, in a simple way, to evaluate the magnitude of the loads transmitted from the soil to the tunnel lining when a groundwater flow is present.

Conclusion

The presence of a flow of water in the soil pores towards the tunnel involves a worsening of the stability conditions that cannot be neglected. It is, therefore, necessary to proceed to the evaluation of the stress and strain state that occurs in the soil in the presence of groundwater.

The numerical methods allow to study the complex mechanism of interaction between the water flow in the pores and the soil, but are generally too slow, especially when a the three-dimensional problem is studied.

The analytical methods, which introduce some simplifying assumptions to the problem, are widely used in tunneling and does lead to the evaluation of the stress and strain state in the soil around the tunnel, in a simple and effective way.

A new calculation procedure using a finite differences solution, able to evaluate the stresses and displacements that develop in the soil, in the presence of a water flow in the pores towards the tunnel, is presented in this study. This procedure allows to obtain the convergence-confinement curve of the tunnel in the presence of groundwater and to determine the thickness of the plastic zone varying the internal total pressure applied to the tunnel perimeter.

The implementation of the procedure to a specific case, has allowed to detect the influence that the water flow in the pores has on the stress and strain behavior of the soil and on the pressure-displacement relationship of the tunnel wall.

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Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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