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EMPIRICAL EQUATION FOR TUNNEL INFLOW ASSESSMENT: APPLICATION TO A CASE HISTOR

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Abstract: *The study quantifies the influence that some geo-structural parameters (i.e. discontinuities dip and dip direction, aperture and spacing), hydrogeological features (recharge, water table altitude, piezometric gradient) and tunnel characteristics (depth and radius) have on tunnel drainage processes. With this aim in mind a discreet network flow modelling was carried out with a parametrical approach. The tunnel inflows was also calculated using analytic formulas, valid for infinite, homogeneous and isotropic aquifer, in which the permeability value is given as a modulus of equivalent hydraulic conductivity. The numerical simulations allowed us to create a sufficient data set of tunnel inflows, in different geological-structural settings, enabling a correction of the traditional analytic equation, setting-up an empirical formula in which tunnel inflow explicitly depends on the geostructural characteristics. This empirical equation was applied in a medium depth tunnel, excavated in sedimentary rocks without waterproofing. The results showed that the traditional analytic equations give the highest overestimation for the stretches with a great anisotropy. On the contrary, the corrected empirical relation allows an estimation of the tunnel inflow that better reproduces the observed values.*

Keywords: *tunnel inflow; numerical modeling; joint orientation; discontinuous rock mass.*

INTRODUCTION

From the hydrogeological point of view, the tunnel construction brings about two kind of problems: the first is related to the forecast of water inflow location, and the second is related to the forecast of the drainage processes, drained discharge and drawdown, which can interfere with the superficial hydrogeological setting. For the quantitative evaluation of the tunnel inflow some Authors suggested using analytic formulas generally valid for an infinite, homogeneous and isotropic aquifers (El Tani, 2003; Goodman et Al, 1965; Jacob and Lohman, 1952; Lei, 1999; Park et Al, 2008; Perrochet et Al, 2005 and 2007) or for finite aquifers having small thickness (Custodio, 2005), or anisotropic aquifers (Kawecki, 2000). All these equations, both related to isotropic or anisotropic aquifers, allow us to evaluate the tunnel inflows in conditions of complete saturation and for homogeneous media. When tunnels are drilled in rock masses, the

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difficulties to forecast the water inflow location or the drainage processes increases, because the hydraulic behavior is neither homogeneous nor isotropic and the water flow is controlled by joints features, joints dip and dip directions, and by fracturing degree (Scesi and Gattinoni, 2009; Gattinoni and Scesi, 2007, Lee and Farmer, 1993, Min et Al, 2004; Snow, 1969; Louis, 1974). For the large number of variables involved and the lack of data available during the planning stage, the discontinuous medium is frequently compared to an equivalent continuum, and analytic relations applicable for infinite, homogeneous and isotropic media are used to quantify some drainage processes. Alternatively, to consider the real rock mass complexity, some Authors prefer to use numerical models (Dunning et Al, 2004; Gattinoni et Al, 2008; Molinero et Al, 2002).

Our study is aimed at integrating the two approaches (analytical and numerical), in order to define corrections factors applicable to most commonly used analytical formulas, able to take into account the rock mass geostructural setting. To obtain this, the groundwater flow in presence of tunnel drainage was initially simulated using a distinct element numerical code, pointing out the tunnel inflow and the water table drawdown for different geostructural characteristics (joint set number, orientation, spacing, aperture and persistence) and hydrogeological conditions (tunnel depth in comparison to the water table). Afterward, for the same configurations used in numerical model, tunnel flow rates were calculated using some analytic formulas valid for an infinite, homogeneous and isotropic aquifer. Modelling results and analytical formulas were compared, the latter generally greatly overestimate tunnel inflow, because it does not take into account the medium anisotropy. Therefore some corrective coefficients were pointed out, and applied to analytic formulas so as to consider, the geological-structural setting. Then, this empirical relation was applied in the study of a case history concerning a medium depth tunnel, excavated in sedimentary rocks masses, without waterproofing. The tunnel was divided into hydrogeological and geostructural homogeneous stretches; for each stretch, the tunnel inflow was calculated using both the traditional analytic formulas and the new empirical one, and the results were compared with the monitoring data.

MODEL DESCRIPTION AND IMPLEMANTATION

To simulate the drainage processes in a fractured medium a rock mass was considered (consisting of a paragneiss lithotype or a sedimentary no fractured and karstic rock), entirety crossed from joints sets having variables orientation, spacing and aperture. A rectangular domain was chosen (150 x 250m^2), to the right side of which a tunnel having a radius of 5 m and N-S direction was positioned. This tunnel position was necessary to allow (in numerical modelling) the drainage. It is clear that this type of hypothesis implies the symmetry of the system. For each geostructural setting the hydraulic conductivity tensor (Kiraly, 1969) and the equivalent hydraulic conductivity (Louis, 1974) were calculated (Scesi and Gattinoni, 2009). The simulations were carried out using the UDEC code (Universal Distinct Element Code, Itasca, 2001), a two-dimensional numerical program based on a distinct element method that can simulate the water flow along the discontinuities separating the blocks (considered impermeable) including, thanks to the deformable nature of contacts, the aperture changing with depth. In the following, the parameters used for modelling are listed:

a) geomechanical characteristics (with reference to the Mohr-Coulomb constitutive model chosen for the modelling): for intact rock specific yield = 27 kN/m3, Young s modulus = 20 GPa; Poisson s coefficient = 0.25; for joints normal and tangent stiffness = 105 MPa, fiction angle = 30 , null cohesion;
b) geometrical characteristics of the discontinuities: number of the joint set ranging from 1 to 4, joint set orientation with strike parallel to the tunnel axes (N-S), dip direction toward East or West and dip ranging between 0 and 90 , aperture ranging from 1.29E-04 m to 2.04E-04 m, spacing ranging from 1 to 20 m, persistence always equal to 100% (at first fully interconnected joints were considered);
c) tunnel project parameters: tunnel radius equal to 5 m, lining or waterproofing not present, tunnel depth ranging between 15 and 300 m;
d) hydrogeological features: water table from 15m to 135m above tunnel, no recharge.

The following boundary and initial conditions were applied:
- impermeable boundary along the bottom and along the border of tunnel location;
- constant load on the opposite side as regards the tunnel location;
- no displacements on the bottom and along the groundwater supply boundary;
- lythostatic load with lateral thrust coefficient equal to 0.5;
- hydrostatic load depending on the supplying boundary conditions and complete saturation below water table.

ANAL SIS OF MODELLING RESULTS

By considering all the above listed parameters and their related range of variation, more than 1000 simulations were performed. During the modelling, both the tunnel pre and post-excavation conditions were simulated until the new steady state was reached. Some target points were chosen along the tunnel border and inside the domain in order to monitor the tunnel inflow and the water pressures during the simulations. At the end of each simulation were derived both the tunnel inflow and the water table drawdown along the tunnel axis. It is important to highlight that, as non recharge was considered in the model, no radius of influence could be pointed out. In the following, the modelling results are discussed, analysing the influence of geostructural parameters on the drainage processes and evaluating the sensitivity of the tunnel water inflow and drawdown as to different parameters.

oint set number and orientation influence

The simulations were carried out considering 1, 2, 3 and 4 joint sets, with variables orientation. The results allow us to observe that, for the same equivalent permeability, the tunnel water inflows vary with varying structural conditions. In particular, for the same K_{eq} of 10E-7m /s the simulated water inflows range from values less than 1E10 m^3/s in the presence of a single joint set, to values of 5E-7m^3/s in the presence of two conjugate joint sets having a dip equal to 80 , to values higher than 1E-6 m^3/s for two conjugate joint sets having a dip of 30 (Fig. 1). Therefore, it is clear that the joints orientation plays an essential role in that: it governs the orientation of the permeability tensor and influences the fractures interconnection degree.

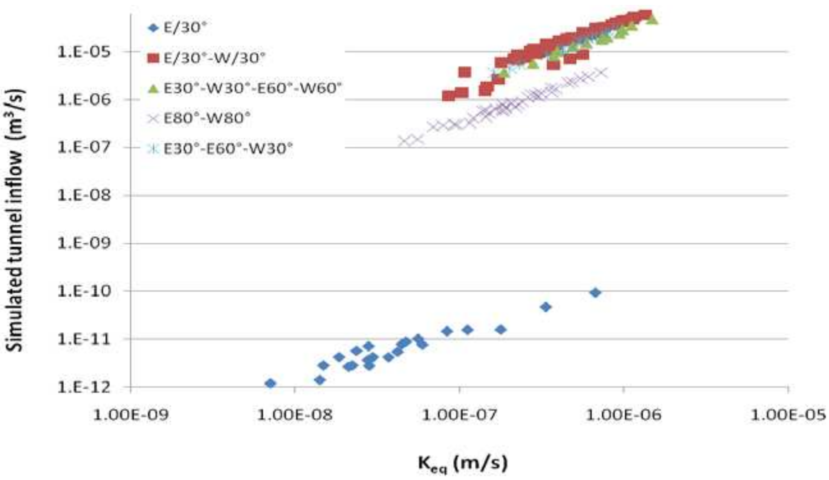


Fig. 1. Trend of the tunnel inflow versus the e uivalent hydraulic conductivity for several geostructural setting, for a water table above the tunnel e ual to 5   m.

Also, moving from 1 to 2 discontinuity families a significant increase of discharge occurs; on the contrary, moving from 2, 3 or 4 discontinuity families the range of discharge is almost unchanged (equivalent permeability being equal and discontinuities characteristics being similar) (Fig. 1). This is explained considering the medium fracturing degree; because, for only one joint set the average Unitary Rocky Volume (URV) is in between 50 and 1200 m^3/m, while for 2 joint sets the average URV come down to values in between 10 and 300 m^3/m. Moreover, from one to several joint sets, the interconnection degree increases: with a single joint set it is zero, while already with 2 joint sets, with a spacing equal to 20 m, interconnection degree is higher than unity.

Later, the effect of joints dip were evaluated considering two joint sets in the simulations (symmetrical conditions). The results show that the flow decreases with an increase of joints dip, this effect is amplified for high frequencies, that is for low spacing values. In saturated medium, the tunnel water inflow has a predominantly horizontal trend, as a consequence the joints with low dip angle favour the drainage processes and increase the discharges (Fig. 2). This trend is observed up to joints dips of 30 ; below these dips (Fig. 2) the flow rates are lower, due to the decrease of the joint sets interconnection degree. On the contrary, joints having an orientation approximately perpendicular to the direction of the water flow (sub-vertical) cause a decrease of flow rates, associated with a greater drawdown.

Influence of joints spacing

The sensitivity analysis, carried out in relation to the discontinuities spacing, shows that by increasing the fracturing degree (high frequency and low spacing), both tunnel inflow and drawdown increase (Fig. 2). Obviously, the increase of flow rates as far as joints frequency has a linear behaviour, characterized by as great a dip as high is the discontinuity aperture. This pattern confirms the validity of the model. The most interesting result is that, for the same joints aperture, the growth rate of the discharge with the frequency substantially depends on the discontinuities orientation (Fig. 2).

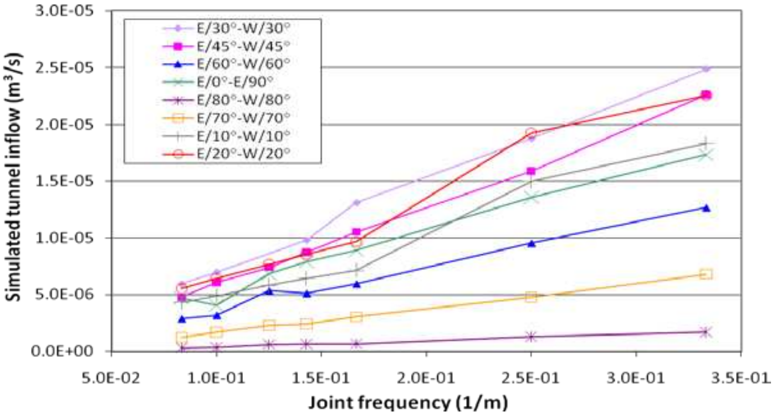
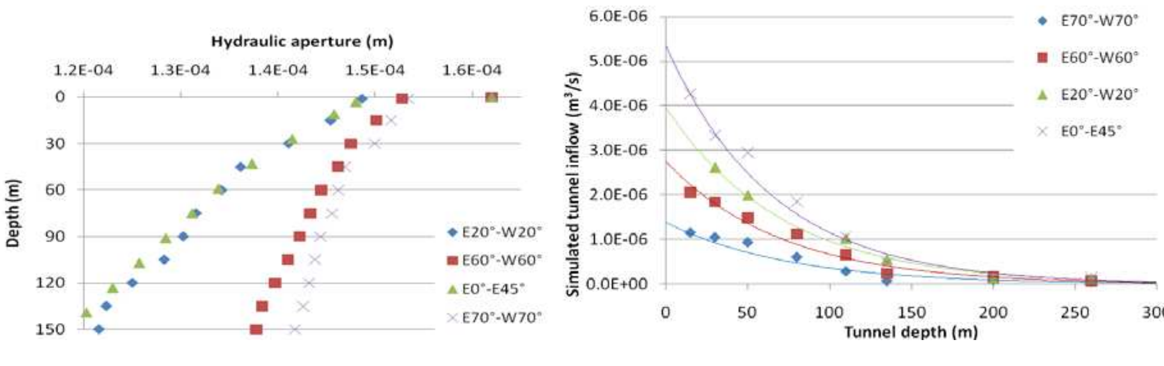


Fig. 2. Trend of the tunnel inflow versus the joints fre uency (joints aperture constant) for several symmetrical geostructural setting having 2 joint families with different dip.

Influence of joints aperture and tunnel depth

The simulations confirmed the increase in tunnel water inflow with the increase of surface joint aperture, with a power law closely related to the equivalent permeability increasing. The hydraulic aperture decreases with depth following a typical exponential law (Fig. 3a), whose pattern depends on the geostructural characteristics of the rock mass: the faster the aperture decreases, the greater the joints horizontal component is. The drainage process was analyzed, varying tunnel depth (piezometric load kept constant); the obtained results show that the water inflows decrease with the increase of the tunnel depth, following an exponential law (Fig. 3b). It is possible to observe that for small depths (less than 150 m) the trend is well approximated to a linear function, while for high depths the reduction of hydraulic joints aperture also determines a sharp reduction of the discharge, till reaching an asymptotic value, having a magnitude depending on the chosen value of the residual hydraulic aperture (in Figure 3b, a_{res} = 0.6E-4 m).



(a) (b)

Fig. 3. Aperture (a) and tunnel inflow (b) decreasing with the depth increase for several geostructural setting, considering the same joint spacing (e ual to m).

Influence of hydraulic head

Many simulations were realized by keeping a constant water table, coinciding with the soil surface, and by varying the tunnel depth. In this way, it was possible to assess simultaneously the influence of the hydraulic and the lythostatic load. The results obtained showed an increasing of the water inflows and of the water table drawdown (Fig. 4) with greater hydraulic load. In particular, for geostructural conditions characterized by an high permeability in the horizontal direction, the tunnel water inflow reaches a peak value for depth of about 100 m (Fig. 4a). Then it slightly decreases, maybe for the aperture reduction due to the lythostatic load. For geostructural conditions characterized by higher permeability in the vertical direction, however, the tunnel water inflows are generally less and the trend leads to saturation (Fig. 4a), but without peak values (at least in the depth range analyzed).

As regards the trend of the water table drawdown (Fig. 4b), it is important to note that the values obtained from numerical modelling are well below those assumed by traditional analytical formulas (primarily the relation of Goodman). These relations consider a drawdown equal to the load affecting above the tunnel: in more detail, for high hydraulic loads (greater than 60-70 m) the water table drawdown is in between 65 and 80% of the initial load, while for lower loads, the estimated water table drawdown is of the order of 25-60% compared to the initial one. The greatest drawdown are observed in the geostructural conditions characterized by an high permeability along the vertical direction, especially for lower hydraulic loads.

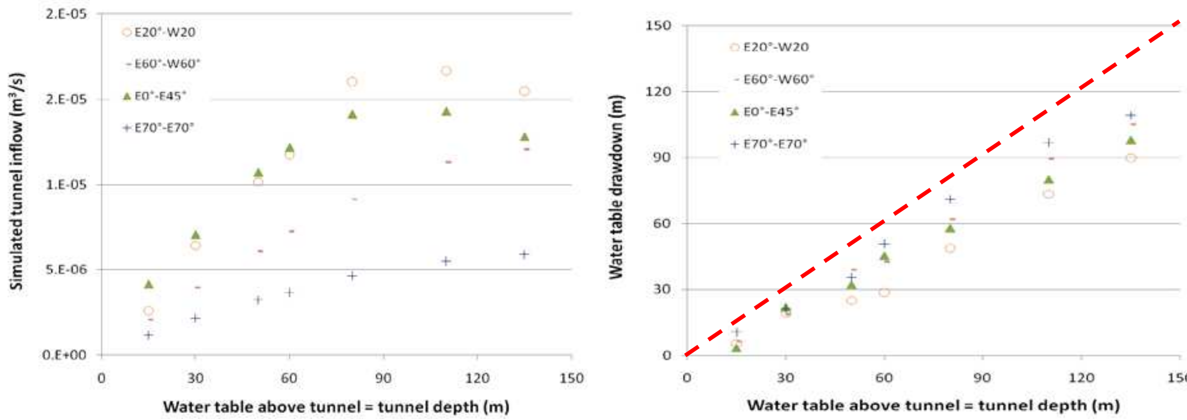


Fig. 4. Trend of (a) the tunnel inflow and (b) the water table drawdown with the hydraulic load, with reference to different geostructural setting.

COMPARISON BETWEEN MODELLING AND ANAL TICAL RESULTS

For the same configurations used in the numerical modelling the tunnel inflow was also calculated using the analytical formula of Goodman (1965). The comparison between the modelling results and those obtained through the use of the Goodman analytical formula allowed us to show that this significantly overestimates the tunnel water inflow and that the greater this overestimation, the higher the joints dip is (Fig. 5). The simulated water inflow can be fitted as a function of the tunnel water inflow calculated with the analytical relation with an exponential function, whose coefficients depend on the geostructural characteristics. Therefore, an empirical relation able to estimate the tunnel water inflow was pointed out, with particular reference to the case of depth below 150 m. For this depth it is possible to observe an increasing dependence of the drainage processes to the structural setting. Based on the exponential performance highlighted in Figure 5, the following relation was defined:

$$Q = aQ_G^b \qquad (1)$$

where Q (m^3/s) is the actual tunnel inflow, Q_G (m^3/s) is the tunnel inflow calculated with the Goodman s equation, a and b are empirical dimensionless coefficients depending on the geostructural setting. In particular, these empirical coefficients depend on: the joint dip, the hydraulic conductivity anisotropy ratio, and the orientation of the hydraulic conductivity tensor. To determine the coefficients a and b the following parameter F was defined:

$$F = \frac{\sum_{i=1}^{m} \cos \alpha_i}{m} \left(\frac{K_{min}}{K_{max}} \right)^{0.5\varphi} \quad (2)$$

where m is the number of discontinuity sets, α_i is the dip of i^th discontinuity set, K_{min} and K_{max} are respectively the minimum and maximum components of the hydraulic conductivity tensor, while φ can assume the following values:

$$\varphi = \begin{cases} -1 & if \quad \theta_{min} > 45° \\ 1 & if \quad \theta_{min} \leq 45° \end{cases} \quad (3)$$

where θ_{min} is the angle between the K^{min} direction and the horizontal plane. The empirical dimensionless coefficients a and b are then defined as a function F:

$$b = \ln 3.463 F^{0.0342} \quad (4)$$

$$a = \begin{cases} 3.448 F^{0.8834} & if \quad F < 0.737 \\ 3.2411 F^{0.6805} & if \quad F \geq 0.737 \end{cases} \quad (5)$$

The empirical equation thus obtained was verified considering both symmetric and asymmetric geostructural setting conditions, with an average overestimation lesser than 10%.

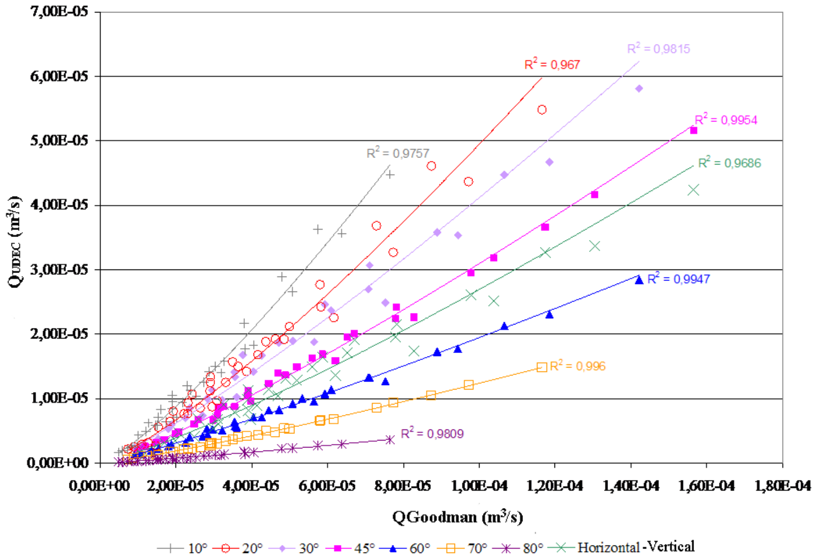


Fig. 5. Simulated tunnel inflows versus the ones calculated with Goodman e uation (points) for different geostructural setting (2 joint families with changing dip).

APPLICATION TO A REAL CASE

A small diameter tunnel, located at a medium depth, and realized within sedimentary rocks having medium-low hydraulic conductivity, was analyzed. The tunnel, without waterproofing, developed below the water table for a length of 5.5 km (Fig. 6). The tunnel was divided into 8 hydrogeological and geostructural homogeneous stretches (Fig. 6). For each one the hydraulic conductivity tensor and the corresponding equivalent hydraulic conductivity were calculated based on the geostructural survey (Table 1). Integrating this information with the results of pumping tests, it was also possible to consider the decreasing of permeability with depth. For the tunnel inflow calculation the equivalent hydraulic conductivity at the tunnel depth was then considered. The hydraulic conductivity ellipses (Fig. 6), in the vertical planes orthogonal to the tunnel direction, show a considerable medium anisotropy, in particular, in the stretches 2, 4 and 6, the main component of the hydraulic conductivity is almost vertical.

From the geostructural and hydraulic characterization of the medium, it was possible to calculate the tunnel water inflow in each homogeneous stretch both with the Goodman s equation and with the new empirical relation previously described. The results were compared with the tunnel monitoring data. The results comparison (Fig. 7) showed that the Goodman s equation provides highly overestimated values of the tunnel water inflow, especially in that sections where the rock mass anisotropy is higher, with maximum hydraulic conductivity in the direction close to the vertical. This overestimation is effectively corrected by using the empirical relation proposed, which provides values comparable to those actually observed in the tunnel (Fig. 7). These results confirm the importance of considering the discontinuous nature of the medium, with particular reference to its structural setting.

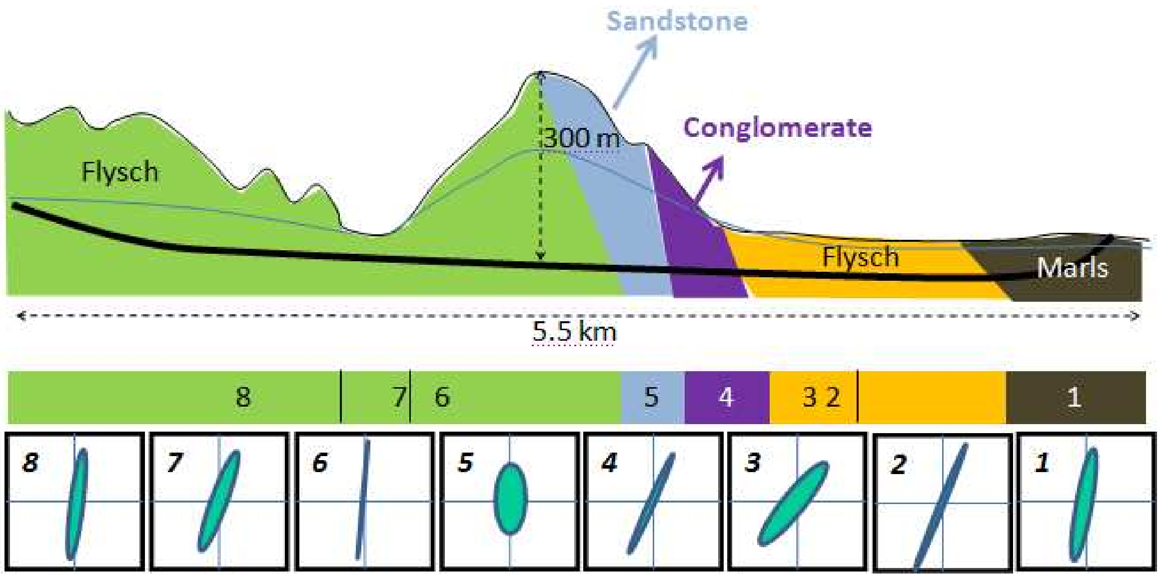


Fig. 6. Geological cross-section along the tunnel (the blue line is the water table), with the division into homogeneous stretches. Below each stretches the corresponding hydraulic conductivity ellipses (in the plane orthogonal to the tunnel axes) are shown.

Table 1. Main characteristics of the tunnel homogeneous stretches.

Stretch		**1**	**2**	**3**	**4**	**5**	**6**	**7**	
Length [m]		860	980	545	415	330	1370	350	1880
Average water table [m]		50	45	60	90	140	140	40	70
Tunnel depth [m]		60	50	60	100	200	200	40	160
Joint set number		4	5	4	3	4	4	4	4
Joint set dip	α_1 [ ]	82	67	55	52	50	39	28	35
	α_2 [ ]	85	65	85	67	78	60	55	85
	α_3 [ ]	37	65	43	85	80	85	70	80
	α_4 [ ]	32	42	50	-	57	67	84	78
	α_5 [ ]	-	34	-	-	-	-	-	-
K_{eq} [E-07 m/s]		4.67	0.513	2.30	1.47	1.02	0.861	2.70	0.614
K_{min}/K_{max}		0.13	0.04	0.21	0.03	0.44	0.01	0.16	0.12
θ_{min} [ ]		8	22	36	24	1	5	20	7

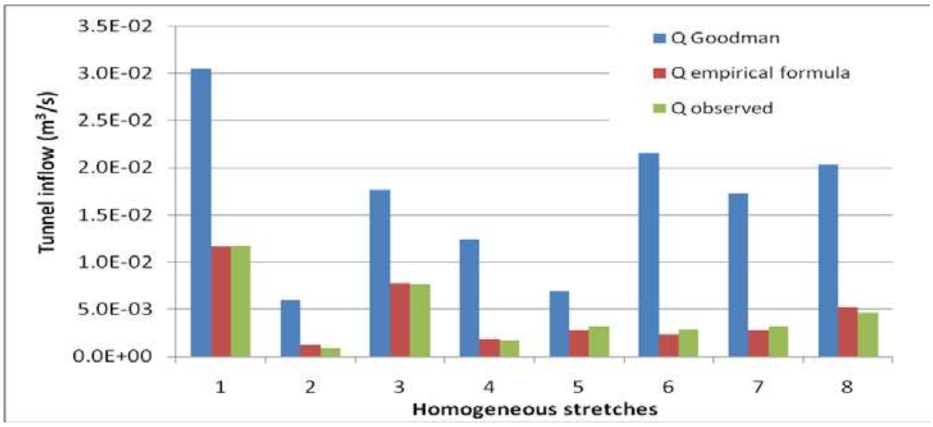


Fig. 7. Comparison between the tunnel inflows observed during the monitoring, the ones calculated through the Goodman e uation and through the empirical relation.

CONCLUSIONS

The modelling allowed to identify and quantify the influence of different parameters (number and orientation of joint sets, spacing and aperture, tunnel depth, hydraulic load) on the tunnel inflow and drawdown. The results show that the joints spacing and aperture (and consequently the tunnel depth) are the parameters that mainly control the tunnel discharge; this dependency can still be efficiently reproduced in a single parameter, depending on the previous two, that is the equivalent hydraulic conductivity. But the most interesting result is the observation that the faster the tunnel flow rate increases with the equivalent hydraulic conductivity of the rock mass the less the joint set dip is. This trend can be fitted with a linear equation, having a growing rate dependent on the geostructural setting, that is rarely played with a traditional analytical approach. According to these observations, the numerical modelling results were compared with the results obtained by the more traditional analytical formulas, and a method to adapt the simple analytical equations to the geostructural characteristics of the rock mass was pointed out. At this aim, a large number of numerical simulations, performed for different geological and structural conditions, allowed to have a database large enough to calibrate a correction to the Goodman s relation, and to define a new empirical equation in which the tunnel inflow explicitly depends on the geological and structural setting of the rock mass. The application of such as defined relation to a case history allowed us to verify the good agreement of the results to the tunnel monitoring data, compared with the results obtained using traditional formulas, especially in the tunnel stretches where the rock mass is greater anisotropic.

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