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Steady-state groundwater inflow into a circular tunnel

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A R T I C L E I N F O

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A B S T R A C T

The prediction of groundwater inflow into a tunnel is important for designing the tunnel drainage system and to minimize environmental impacts and the risk of tunnel instabilities and subsidence damage. Analytical solutions exist to calculate tunnel inflow, and, increasingly, numerical groundwater models are used to this end. In order to represent different types of tunnel support structures, this study reviews different boundary conditions that can be set at the tunnel perimeter to calculate tunnel inflow and recognizes different ways to account for the tunnel lining. Analytical solutions and numerical models to calculate tunnel inflow are compared and factors influencing the accuracy of numerical solutions are highlighted. The study suggests that numerical models provide estimates of tunnel inflows with sufficient accuracy for practical purposes if the tunnel is lined and has no drainage layer surrounding the lining, and if the hydraulic conductivity of the lining is several orders of magnitude lower than the hydraulic conductivity of the aquifer, or if the lining is thick. Otherwise, the extent of the model domain must be large with respect to the extent of the tunnel to provide accurate results. It was shown that inflows are higher for lined tunnels with a drainage layer than for unlined tunnels, if the head in the drainage layer corresponds to the level of the tunnel center or invert. If the head in the drainage layer corresponds to the level of the tunnel crown, inflows are higher for unlined tunnels. The study further suggests that for unlined tunnels, inflows are higher at the invert than at the crown. For lined tunnels with a drainage layer, the reverse is true. Differences between inflows at the crown and invert decrease with increasing depth of the tunnel under the groundwater table. The numerical solution for flow into lined tunnels without drainage layer using a transfer (Cauchy type, or 3rd-kind) boundary condition produces lower inflows compared to using a specified head (Dirichlet type, or 1st-kind) boundary condition. Using a transfer boundary condition is especially inaccurate if the lining is thick.

1. Introduction

The prediction of groundwater inflow into a tunnel is an important issue in tunnel engineering. Groundwater inflow into a tunnel can lead to problems during construction; also groundwater drawdown due to the drainage effect of the tunnel can cause surface subsidence and have other environmental impacts. Engineers need estimates of tunnel groundwater inflow for the design of the tunnel drainage systems. Several authors presented analytical solutions to calculate steady-state inflow into a circular tunnel (e.g., Lei, 1999; El Tani, 2003; Kolymbas and Wagner, 2007; Park et al., 2008). Closed form solutions have also been used successfully to account for different situations. El Tani (2010), for example, used a modified Helmholtz equation to consider a semi-infinite aquifer drained by a circular tunnel in different heterogeneous aquifer settings. In addition, efforts have been made to account for the transient nature of tunnel inflow. Maréchal and Perrochet (2003) used the analytical solution of Jacob and Lohman (1952) for artesian wells to model aquifer drainage by a tunnel. Perrochet (2005a), Perrochet and Dematteis (2007) and Yang and Yeh (2007) introduced transient solutions for calculating drilling speed-dependent discharge rates into tunnels gradually excavated in homogeneous and heterogeneous aquifers, and Perrochet (2005b) developed a simple analytical formula to calculate transient discharge inflow rates into tunnels or wells under constant drawdown. Other authors focused on analytical solutions to calculate pore water pressures in order to estimate the effective stress distribution at the tunnel perimeter (e.g., Fernández and Alvarez, 1994). However, analytical solutions to calculate tunnel inflow are only applicable in rather simple situations. To represent more complex geological situations at an actual site in a flexible way, numerical approaches that can account for spatially distributed hydraulic properties and boundary conditions (BCs) are necessary. The advance of computational performance of computers led to a strong increase in the use of numerical groundwater models in tunnel engineering. Many numerical groundwater models use finite element techniques (e.g., Bear, 1972). Such models can not only account for complex geometrical situations, it is also possible

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to calculate the spatial distribution of the hydraulic head field, and to calculate the spatial distribution of the tunnel inflow. This is relevant for applications that require making a distinction between inflow at the tunnel crown and at the invert (e.g., Butscher et al., 2011a). In addition, numerical models can effectively be applied to transient conditions (e.g., Font-Capo et al., 2011).

Another advantage of numerical groundwater models is that they can account for a tunnel lining, which can have different hydraulic properties. Analytical solutions do either not consider a tunnel lining, or they assume inflow into a drainage layer surrounding the (impermeable) tunnel lining. In the latter case, the actual drainage of the tunnel is independent of the lining. In such a case, inflow can be represented without discretizing the lining and the drainage layer in numerical groundwater models. In cases without a drainage layer, however, one has to account for the hydraulic properties of the tunnel lining. The lining can be spatially discretized and associated with hydraulic properties (i.e., discrete elements of the finite element mesh that match the position and geometry of the lining are associated with hydraulic properties of the lining). Alternatively, the lining is not spatially discretized but a transfer rate is assigned at the tunnel perimeter representing a resistance to flow and limiting tunnel inflow.

There are many studies in the literature calculating tunnel inflow under different hydraulic conditions at the tunnel. The hydraulic conditions at the tunnel, however, have not been compiled with regard to their impact on tunnel inflows so far. In this paper, we first summarize the different ways how BC can be set at the tunnel perimeter to represent different types of tunnel support structures. We introduce existing analytical solutions and numerical models to calculate tunnel inflow, and compare the analytical solutions with numerical solutions. This comparison highlights the extent of the model domain as a constraint that limits the accuracy of numerical solutions. Subsequently, the influence of the tunnel type on tunnel inflow is analyzed using different BC at the tunnel perimeter and different representations of the tunnel lining. The choice of the BC has an impact on total tunnel inflow and the spatial distribution of the inflow. The way in which the tunnel lining is represented can impact the accuracy of inflow calculations, especially when the lining is thick.

2. Boundary conditions at the tunnel perimeter

The type of a tunnel influences tunnel inflow and the drainage effect of the tunnel in an aquifer. A tunnel can have (1) a drainage layer surrounding the tunnel lining; (2) no such layer; or (3) can be unlined. In this chapter, we will review different types of tunnel support structures. We will show how different BC at the tunnel perimeter can be used in tunnel inflow calculations to account for the hydraulic differences as a consequence of different tunnel types. We distinguish three different types of tunnel support structures. These types, the corresponding BC at the tunnel perimeter and the way how the lining is represented are summarized in Table 1.

Type I represents an open tunnel without lining. The hydraulic (total) head at the tunnel perimeter corresponds to the elevation (El Tani, 2003), i.e. the hydraulic head is not uniform but higher at the tunnel crown than at the invert. This BC is based on the assumption that atmospheric pressure (zero water pressure) is effective inside the tunnel and at the tunnel perimeter. In the following, we will call this BC "elevation head BC" and the calculated tunnel inflow using this BC is referred to as "Q_1". In numerical groundwater models, a 1st-kind BC (Dirichlet type) is set at this boundary, which involves specifying a constant value of the hydraulic head (for a given time) at the tunnel perimeter.

Type II represents a tunnel where the tunnel opening is surrounded by an impermeable lining and a drainage layer behind the lining. The hydraulic head at the tunnel perimeter (within the drainage layer) is uniform (Kolymbas and Wagner, 2007). It corresponds to the elevation of the outlet of the drainage layer, which may be adjustable (Fig. 1). In the following, we will call this BC "uniform head BC" and the calculated tunnel inflow using this BC is referred to as "Q_2". When using the uniform head BC to calculate inflow into a tunnel with drainage layer, it is assumed that

Table 1
Overview of types of tunnel support structure, boundary conditions at tunnel perimeter and representation of lining. In numerical models, discretization of the tunnel lining (type IIIa tunnels) involves specifying the hydraulic properties of the lining for the finite elements at the lining's position. The drainage layer and impermeable lining of type II tunnels do not have to be discretized.

Type I: Unlined tunnel	Type II: Lined tunnel with drainage layer	Type IIIa: Lined tunnel without drainage layer	Type IIIb: Lined tunnel without drainage layer
Drainage layer			
No	Yes	No	No
Lining			
No	Yes (impermeable)	Yes (discretized)	Yes (not discretized)
Type of BC			
1st-kind (Dirichlet), elevation head BC	1st-kind (Dirichlet), uniform head BC	1st-kind (Dirichlet), elevation head BC	3rd-kind (Cauchy), elevation head BC
Head at tunnel perimeter			
y	h_a (c.f., Fig. 1)	y	y
Variables characterizing lining			
–	–	Hydraulic conductivity k_l, thickness d	Outflow transfer rate c_t
Flow into tunnel			
Q_1	Q_2	Q_1	Q_1