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Optimum model extent for numerical simulation of tunnel inflow in fractured rock

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ABSTRACT

The objective of this study is the introduction of an optimum model extent in discontinuous rock masses for tunnel inflow assessment using numerical models. Tunnel groundwater inflow is an important problem in tunneling, and numerical simulation is widely used for estimating the amount of tunnel inflow. An adequate size of the model domain is of very high importance when using such models. On the one hand, if the tunnel boundary is too close to the outer model boundary, the simulated inflow rate into the tunnel is significantly overestimated (which will be shown in the present study). On the other hand, if the model domain is very large, models may become "unhandy", and simulations become very expensive with respect to computer memory and CPU. In this technical note, an approach is presented that derives an optimum model extent for numerical simulation of tunnel inflow in fractured rock. The approach uses the two-dimensional universal distinct element code (UDEC). The impact of different model parameters, such as tunnel radius, groundwater level, joint spacing, joint dip/dip direction and joint aperture on the optimum model extent has been evaluated. Based on the results, an optimum model extent chart is presented that allows modelers a quick determination of the optimum model extent as a function of the most significant parameters, which are the tunnel depth under the groundwater level, tunnel radius and joint spacing.

1. Introduction

Water inflow into tunnels is an important problem in tunneling in fractured rock masses. According to Palmstrom and Stille (2007), water inflow is one of the main issues in underground excavation and many factors such as the nature of the discontinuities and environmental conditions play an important role in this scenario. Tunnel inflow causes interruptions in tunnel excavation and makes dewatering measures necessary. In addition, it may lead to a decrease in rock mass stability. Due to the impossibility of identifying and determining all factors that affect water inflow into tunnels during exploration, estimating the amount of inflow into the tunnels remains difficult.

Estimating the amount of water inflow into a tunnel can be supported using numerical modeling methods such as Finite Element Method (FEM), Discrete Fracture Model (DFM), Discrete Element Method (DEM) and Finite Volume Method (FVM). The application of numerical methods is typically more complex and time consuming than the use of analytical equations that estimate tunnel inflow (e.g., El Tani, 2003; Perrochet, 2005; Kolymbas and Wagner, 2007; Farhadian et al., 2012). However, numerical simulations can help in the analysis in particular in situations where geometries are complex and where heterogeneities and anisotropies exist due to fracture networks or sedimentary structures (e.g., Gattinoni et al., 2008; Molinero et al., 2002; Hwang and Lu, 2007; Zangerl et al., 2008; Gattinoni and Scesi, 2010).

A jointed rock mass is characterized by the presence of geological structures of different scales, such as faults and dykes, with a typical dimension of tens to hundreds of meters; or joints, bedding planes and foliations with typical dimensions ranging from a few centimeters to tens of meters (Esmaieli et al., 2010). For engineering purposes, with respect to model size, one of the critical design parameters for numerical modeling is the relative dimension of geological fractures.

In well-defined and connected rock fractures, the flow behavior of a jointed rock mass is controlled by the fracture characteristics.

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In numerical simulations however, also the extent of the model domain relative to the dimension of geological fractures and other geometric parameters can have a significant impact on calculated flow. In the case of small model dimension, the tunnel boundary may be too close to the outer model boundary. As a result, calculated groundwater flow into the tunnel is overestimated. The reason for this is that tunnel drainage causes a drawdown of the hydraulic head in the tunnel surroundings, which cannot be reproduced by a constant head boundary. Hence, the hydraulic head defined at this boundary is too high. When the model size is very large, numerical simulation requires more memory, strong CPU power and more time to implement, handle and run the model.

Few publications have considered the effects of the model dimension on calculated tunnel inflow. Indraratna and Ranjith (1998) analyzed a given type of joint pattern with different hydraulic boundary conditions in order to evaluate realistic parameters that control the water inflow into a tunnel. Results showed that block sizes and the boundary condition play an important role for water inflow to tunnels in discontinuous rock masses. Cesano et al. (2003) presented a method to quantify the degree of fractured rock hydraulic heterogeneity to predict groundwater inflow into the tunnel. Six experiments were used to evaluate the relation between the variability in fracture properties and in direction and magnitude of flow in different model sizes. Moon and Fernandez (2010) and Moon and Jeong (2011) investigated effects of the model size based on water inflow rates into a tunnel and pore water pressure distribution around the opening for different joint types. Butscher (2012) showed for continuous media that accurate results of groundwater inflow to tunnels are only obtained if the extent of the model domain is large relative to the extent of the tunnel. However, none of the studies has so far systematically investigated the impact of the model domain size on calculated tunnel inflow and derived an optimum model extent dependent on used model parameters.

In this work, we define the optimum model extent (ME) as the minimum dimension at which calculated groundwater inflow into the tunnel is not biased by the proximity of the outer model boundary condition. The aim of the study is to develop a chart that allows the modeler to quickly determine the optimum model extent dependent on used model parameters. Developing the optimum model extent required an identification of the most significant parameters that impact this extent. Therefore, parametric studies with various sizes of the model extent were performed in the present study to determine the optimum model extent. Among possible significant parameters are those determining groundwater flow in the tunnel surroundings, which are joint parameters (orientation, spacing and aperture), tunnel parameters (radius, depth) and hydraulic parameters (groundwater level) (e.g., Snow, 1969; Scesi and Gattinoni, 2009; Moon and Fernandez, 2010; Nikvar Hassani et al., 2015). The paper describes the models used for this study, presents the parametric study and resulting parameters that influence the model extend and proposes a chart to determine the optimum model extent.

Table 1
Parameters used for modeling study.

Type of parameter		Parameter	Range of variation
Geomechanical characteristics (with reference to the Mohr-Coulomb constitutive model chosen in the modeling)	Intact rock	Specific weight	26 KN/m^3
		Bulk modul	1.9 GPa
		Sheare modul	1.74 GPa
	Joints	Normal and tangential stiffness	100 MPa/mm
		Friction angle	35
		Cohesion	Null
Geometrical characteristics of the discontinuity		Set number	2
		Set strike	Parallel to the tunnel axis (N–S)
		Joint set	E/30°-W/30° E/45°-W/45° E/60°-W/60° E/0°-E/90°
		Aperture	1×10^{-4}–1×10^{-3} m^3
		Spacing	2–10 m
		Persistence	100%
Tunnel design parameters		Radius	1–5 m
		Lining or waterproofing	Not present
		Depth	100 m
Hydrogeological characteristics		Water table above tunnel	10–100 m
		Recharge	Not present
		Joint permeability	83.3 m s kg^{-1}
		Mass density	1000 kg/m^3
		Bulk modulus	2 GPa

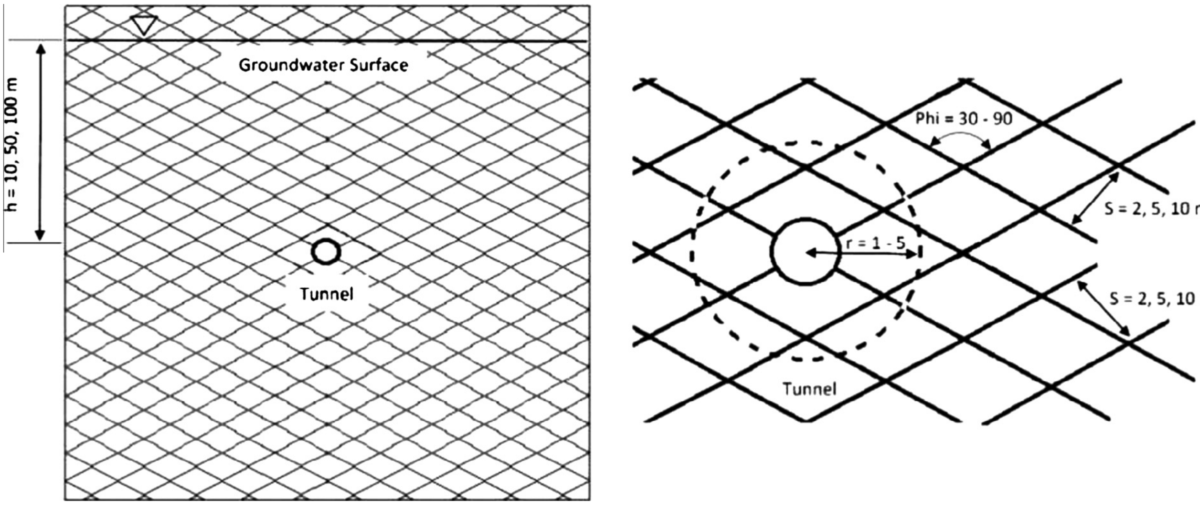

Fig. 1. Geometrical model parameters (*r*: tunnel radius; *h*: depth of tunnel below groundwater level; *s*: joint spacing; *phi*: angle between joint sets) and their variation in scenarios.