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Assessing the timing and magnitude of precipitation-induced seepage into tunnels bored through fractured rock

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ABSTRACT

Seepage into tunnels bored through fractured rock is a common occurrence that can cause significant problems for the construction process, tunnel longevity, and regional hydrogeology. Predictions of seepage using analytical solutions and numerical models are often inaccurate due to the inherent assumptions, volumetric averaging of fractures, and lack of important hydrogeological features. This study seeks to better understand tunnel infiltration processes through the application of a high-resolution, integrated hydrologic model. First, a conceptual model is developed for this research using the factors shown by previous studies to control net infiltration and seepage. A stochastic fracture continuum is generated for bedrock using FRACK, which maps discrete fracture networks to a finite difference grid with heterogeneous, anisotropic permeability fields. An integrated hydrologic model, ParFlow is then used to investigate the control exhibited by factors such as climatic forcing; vegetation; soil type and depth; bedrock type; fracture spacing; and tunnel depth on the timing and magnitude of seepage into tunnels. Simulations are run using hourly meteorological forcing. Surface and subsurface properties are adjusted individually to investigate the change in seepage response for varying hydrogeology and land cover. Results show that fracture spacing and connectivity, bedrock type, and overburden are particularly important pieces in obtaining reliable seepage estimates. Higher fracture spacing causes higher total seepage at a more constant rate than a lesser spacing, which exhibits a much larger range of fluctuation in seepage volumes. More permeable and porous bedrock increases lag times while reducing seepage volumes that remain relatively constant over time. Thicker and less conductive soils both increase lag times and reduce seepage magnitude. Tunnels, precipitation, infiltration, seepage, fractured rock.

1. Introduction

Designing tunnels requires creative applications of geotechnical engineering to predict the responses of soil, rock, and water. The response of soil and rock to tunneling are well understood, however the way in which water infiltrates into tunnels is difficult to predict. In fractured rock, water flowing into tunnels is a common occurrence that can cause significant problems. Potential impacts on the following prompted increased attention to seepage over the past few decades:

- Tunnel and underground construction (Cesano et al., 2000; Chen and Tolon, 2012; Fernandez and Moon, 2010a; Huang et al., 2011; Kitterod et al., 2000; Li et al., 2009; Wang et al., 2017).
- Water resources and environment (Gargini et al., 2008; Gleeson et al., 2009; Kim et al., 2005; Rademacher et al., 2003; Scanlon et al., 2002, 2006; Seyfried et al., 2005; Shimojima et al., 1993; Vincenzi et al., 2009).
- Quality of nuclear waste repositories (Bagtzoglou and Cesano, 2007; Liu and Bodvarsson, 2001; Philip and Knight, 1989; Reeves et al., 2008; Trautz and Wang, 2002).

As a result, a number of approaches have been used to predict tunnel seepage beneath the water table. Analytical solutions have been derived to estimate inflows under a variety of groundwater scenarios and boundary conditions. These solutions, such as those derived by Philip and Knight (1989) and Perrochet and Dematteis (2007) contain inherent simplifying assumptions that include homogeneity, isotropy, no recharge, and radially infinite boundary conditions. Field-scale experiments and observations have also been used to predict seepage. For example, Heuer (1995, 2005, 2012) created a relatively robust field method by which the

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histograms of hydraulic conductivity from packer test data are used to predict seepage volumes. There also exist a number of numerical models that simulate seepage in the saturated zone. Many of these models, however, do not include the influence of the unsaturated zone, climatic forcing, vegetation, overburden, and fractures, which are all crucial pieces in obtaining reliable estimates.

Less research has focused on tunnels bored in the unsaturated zone in fractured rock, which are not usually lined and can therefore be more susceptible to seepage (Vincenzi et al., 2009). Empirical and observational methods have been utilized in those tunnels bored through the unsaturated zone for various fractured formations of igneous, metamorphic, and sedimentary rock in various climates to predict the geological conditions under which seepage might occur. This extensive body of research has resulted in some general conclusions about precipitation-induced infiltration and seepage including: (1) A lag time exists between precipitation and seepage that is negatively correlated to the magnitude of the event and positively correlated to the cavity depth (Dobson et al., 2012; Shimojima et al., 1993; Rademacher et al., 2003). (2) This relationship is complicated by climate and wetting front conditions, which vary the hydrologic properties of soil and fractured rock with time (Dobson et al., 2012; Rademacher et al., 2003; Shimojima et al., 1993). (3) Differing hydrogeologic properties also affects seepage rates: lower permeability and porosity of matrix, and lower capillarity all increase seepage (Trautz and Wang, 2002; Wang et al., 1999; Javadi et al., 2016). (4) Structural heterogeneity of fractures and soils, and their orientation causes variable flow rates in response to spatially and temporally variable precipitation (Dobson et al., 2012; Flint et al., 2001; Gleeson et al., 2009; Maxwell, 2010; Shimojima et al., 1993; Wang et al., 1999; Zhou et al., 2006) that results in fingering, preferential flow, and varying behavior at fracture intersections (Olofsson, 1994; Pruess, 1998; Zhou et al., 2006). (5) Preferential flow causes more steeply dipping fractures to carry more water than fractures with a shallower dip, which serve as connective pathways (Cesano et al., 2000; Gleeson et al., 2009; Wang et al., 1999) and can impact seepage from as far away as one half to three times the cavity depth (Flint et al., 2001; Rademacher et al., 2003; Wang et al., 1999).

Within these observations, there is an underlying theme that infiltration and subsequent seepage most commonly occur where a fracture network acting as a flow conduit is in connection with an overlying source of water, be it a groundwater reservoir in permeable soil, a horizon of permeable conductive soil, or a location of direct recharge (Gargini et al., 2008; Gleeson et al., 2009; Moon and Jeong, 2011; Olofsson, 1994; Rademacher et al., 2003; Scanlon et al., 2005, 2006; Seyfried et al., 2005; Shimojima et al., 1993; Tomonaga et al., 2017; Vincenzi et al., 2009, 2014). The crucial pieces governing these occurrences are land-atmosphere interactions (Maxwell, 2010), the land surface (Atchley and Maxwell, 2011; McCulley et al., 2004; Olofsson, 1994; Scanlon et al., 2002; Wohling et al., 2011), subsurface heterogeneity (Kollet, 2009; Maxwell, 2010), and preferential flow in soil and fractures (Maxwell, 2010; Pruess, 1998; Shimojima et al., 1993). The research presented here estimates how features like land cover, fracture spacing, soil and geology affect the timing and magnitude of precipitation-induced seepage to unlined tunnels using an integrated hydrologic model.

2. Conceptual models and methodology

ParFlow, the Common Land Model (CLM), and FRACK were used for modeling this system in an integrated manner. The governing equations used within each model are listed in the following sections. As the use of integrated hydrologic models (such as ParFlow) is novel in understanding tunnel seepage, we provide more complete details of the methods below.

2.1. Parflow

ParFlow is a parallel, fully integrated, physical hydrologic model that simulates three-dimensional variably saturated subsurface flow and two-dimensional shallow overland flow. A brief description of the governing equations is provided below. For more detailed explanations of ParFlow, refer to Ashby and Falgout (1996), Jones and Woodward (2001), and Kollet and Maxwell (2006).

Three-dimensional variably saturated subsurface flow is solved using Richards' (1931) equation:

$$\Delta S_s S_w \left(\frac{\delta \psi_p}{\delta t}\right) + \phi\left(\frac{\delta S_w(\psi_p)}{\delta t}\right) = \nabla \cdot \boldsymbol{q} + q_s \tag{2.1}$$

in which $\boldsymbol{q}$ is given by:

$$\boldsymbol{q} = -K_s(x)k_r(\psi_p)\nabla(\psi_p - z) \tag{2.2}$$

and S_s is the specific storage coefficient $[L^{-1}]$, S_w is the degree of saturation, ψ_p is pressure head [L], t is time [T], ϕ is the porosity [$-$], q_s is a source sink term $[T^{-1}]$, $K_s(x)$ is saturated hydraulic conductivity $[LT^{-1}]$, k_r is relative permeability [$-$] and is a function of pressure head, ψ_p, given by the van Genuchten (1980) relationships, where:

$$k_r(\psi_p) = \frac{\left(1 - (\alpha\psi_p)^{n-1}\left(1 + (\alpha\psi_p)^n\right)^{-m}\right)^2}{\left(1 + (\alpha\psi_p)^n\right)^{\frac{m}{2}}} \tag{2.3}$$

in which α $[L^{-1}]$ is inversely related to the air-entry pressure of the medium, $n = (1 - m)^{-1}$ [$-$] and is related to the distribution of pore size; these values are determined empirically.

Soil moisture is also a function of pressure head, ψ_p, and is calculated with:

$$S_w(\psi_p) = \frac{S_{sat} - S_{res}}{\left(1 + (\alpha\psi_p)^n\right)^m} + S_{res} \tag{2.4}$$

in which S_{sat} is relative saturated water content [$-$] and S_{res} is the relative residual saturation.

Two-dimensional shallow overland flow is integrated with subsurface flow by solving the kinematic wave approximation. This is then input to the overland flow boundary condition while preserving continuity conditions of pressure and flux at the land-surface boundary:

$$q = -K_s(x)k_r(\psi_p)\nabla(h_s - z) = \left(\frac{\delta\|\psi_s, 0\|}{\delta t}\right) - \nabla \cdot (v\|\psi_s, 0\|) + q_r(x) \tag{2.5}$$

where ψ_S [L] is the surface ponding depth and is assumed to be ψ_p [L] at the saturated ground surface (Kollet and Maxwell, 2006), v is depth-averaged surface water velocity vector $[LT^{-1}]$, and q_r is a source/sink term $[LT^{-1}]$ (e.g. precipitation).

This assumes that:

$$S_{f,i} = S_{o,i} \tag{2.6}$$

in which $S_{o,i}$ is the bed slope (gravity forcing), and is equal to $S_{f,i}$, the friction slope, and so Manning's equation can be used to approximate flow with a depth-discharge relationship:

$$v = \frac{S_{f,i}^{\frac{1}{2}}\psi_S^{\frac{2}{3}}}{\eta} \tag{2.7}$$

in which η $[LT^{-1/3}]$ is Manning's coefficient (Kollet and Maxwell, 2006).