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The use of discrete fracture network simulations in the design of horizontal hillslope drainage networks in fractured rock

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ABSTRACT

Characteristics of fracture networks are explored in a discrete fracture network framework to provide design guidelines for horizontal drainage networks in fractured rock. Central to the study is defining how fracture attributes relate to fracture network structure and network-scale fluid flow, and in turn, how flow characteristics of fracture networks influence horizontal drain length and orientation. Multiple realizations of stochastic fracture networks, generated from both synthetic and field-specific data sets, serve as a basis for understanding physical fracture network structure and resultant global flow and for performing intersection analyses of hillslope drains with flowing fractures. Study results indicate that the logarithm of the standard deviation of fracture transmissivity, $\log(\sigma_T)$, is the single most important attribute for drainage network design, as higher values of $\log(\sigma_T)$ describe heterogeneous flow patterns where only a small portion of the network conducts a significant quantity of fluid. Thus recommended drain lengths for intersecting significantly conductive fractures increase with increases in $\log(\sigma_T)$. Fracture trace length, orientation, and density also play a role, albeit secondary to the distribution of transmissivity, in defining drain length as a function of drain orientation relative to the mean fracture set orientation. The spatially discontinuous nature of fracture networks and the wide range in transmissivity values found in natural fracture networks tend to produce high degrees of variability in computed intersection distances between drains and fractures conducting significant quantities of fluid. To account for this variability, a conservative approach is recommended where horizontal drain lengths along a pre-defined orientation are scaled by discrete fracture network computed intersection distances equal to the upper 95th confidence interval.

1. Introduction

The presence of water is one of the most critical factors contributing to hillslope instability. The installation of horizontal drains and drain networks is common practice used to decrease the elevation of the water table surface. Lowering of the watertable dries a large portion of the hillslope, which increases the shear strength of the soil and decreases the probability of slope failure. Effectiveness of hillslope drainage is typically described in terms of the increase in the factor of safety, defined as the ratio of shear strength to shear stress, once horizontal drains are installed.

The need for design guidelines for horizontal drains used to promote hillslope stability has been noted by several researchers (Choi, 1974; Kenney et al., 1977; Prellwitz, 1978; Nonveiller, 1981; Forrester, 2001). Drainage system design is most developed for irrigated areas (Donnan, 1946; Israelsen, 1950; Maasland, 1956; Kirkham, 1958; Talsma and Haskew, 1959; U.S. Department of the Interior, 1978) with analytic solutions focusing on simplified conditions including idealized slopes, constant pre-drain groundwater levels and recharge, homogeneous hydraulic conductivity, and regularly-spaced drains that are typically parallel to the slope (Hooghoudt, 1940; Bouwer, 1955; Schmid and Luthin, 1964; Wooding and Chapman, 1966; Childs, 1971; Towner, 1975; U.S. Department of the Interior, 1978; Lesaffre, 1987; Ram and Chauhan, 1987; Fipps and Skaggs, 1989). Many of the limitations of the analytic solutions, such as complex hillslope geometry, transient water levels and recharge, heterogeneous hydraulic conductivity fields and complex drain configurations, can be relaxed through the use of numerical models of hillslope drainage and stability (e.g., Angeli et al., 1998; Cai et al., 1998; Rahardjo et al., 2003; Pathmanathan, 2009). Numerical models are also useful for quantifying the sensitivity of design parameters to overall hillslope drain performance and resultant factor of safety.

Previous research on hillslope drainage and stability has primarily focused on soil and unconsolidated sediment where flow occurs through the interconnected pore space of the medium. Many watersheds are underlain by fractured rock that are either directly involved in slope stability or are host aquifers that can adversely influence the stability of overlying soils (Al Homoud and Tal, 1997; Montgomery et al., 1997; Jiao et al., 2005; Furuya et al., 2006; Gerscovich et al., 2006; Ghosh et al., 2009). In these cases, drainage networks installed within the

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overlying soil are likely to be ineffective to sufficiently lower pore pressures in or reduce recharge from the underlying fractured rock mass. Installation of a drainage network within the fractured bedrock must then be considered.

Fractured rock presents a very different challenge to the design of hillslope drainage networks. This is because fractured rock typically has little or negligible primary porosity and permeability in the rock matrix itself, and connected networks of discontinuous fractures impart secondary porosity and permeability that govern the flow of groundwater. Unlike porous media where flow occurs at the pore-scale, flow in fractured rock systems occurs through complex patterns of interconnected, conductive fractures (e.g., Long et al., 1982; Smith and Schwartz, 1984; Renshaw, 1999; de Dreuzy et al., 2001; Berkowitz, 2002; Neuman, 2005; Reeves et al., 2008a,b; Klimczak et al., 2010; Reeves et al., 2010). Hence, the design of horizontal hillslope drainage networks in fractured rock must take into account the characteristics of the fracture networks to maximize the probability for drains to intersect fractures conducting significant amount of flow that, in turn, will sufficiently reduce pore pressures.

In this paper, we provide guidelines for the design of horizontal hillslope drainage networks for fractured rock by utilizing a discrete fracture network framework to explore how specific fracture attributes relate to physical network structure, how networks conduct flow given various geometric configurations and degrees of heterogeneity in hydraulic properties, and how network-scale flow characteristics influence horizontal drain orientation and length. Stochastic fracture networks generated from both synthetic and field-specific data sets serve as a basis for understanding physical network structure and global flow, and for performing intersection analyses of hillslope drains with fractures conducting a significant amount of flow. Emphasis is placed on linking the most relevant fracture attributes with horizontal hillslope drainage network design.

2. Properties of fractured rock

Bedrock typically has little or no primary porosity and permeability, and networks of fractures serve as primary conduits for fluid flow. These networks are spatially discontinuous and highly irregular in geometry and hydraulic properties. The variability in geometric and hydraulic properties is the result of the complex interplay between current and past stress fields, inhomogeneous rock mechanical properties (e.g., Young's modulus, Poisson's ratio), mechanical fracture interaction and distributions of flaws or weakness in a rock mass.

Full characterization of fractured rock masses is not possible since known fracture locations and their attributes consist of an extremely small sample of the overall fracture network, i.e., any fracture characterization effort grossly undersamples a field site due to limited accessibility to the fractures themselves. Fractured rock masses are typically characterized during field campaigns that measure fracture attributes from a number of sources including boreholes (e.g., electrical resistivity, ultrasonic, optical televiewers, etc.), rock outcrops, road cuts, tunnel complexes, seismic images and hydraulic tests. These fracture data can then be used to generate representative, site-specific discrete fracture networks (DFN) through the derivation of probabilistic descriptions of fracture location, orientation, spacing, length, aperture, hydraulic conductivity/transmissivity and values of network density (e.g., Figure 1). Mapped fractures are often included into DFN models as deterministic features, though the addition of stochastic fractures honoring site-specific fracture data is always necessary to maintain proper fracture density and network connectivity.

The limited accessibility to the network leaves an incomplete understanding of the patterns of fracturing within a rock mass that can often be improved through visual inspection of representative networks generated according to site-specific statistics. Relationships between fracture statistics, network structure, and network-scale flow are explored in this section. Fracture data are only discussed in the context of common probability distributions used to describe variability of specific fracture attributes found in natural fractured rock systems. Readers are encouraged to refer to Munier (2004) and Reeves et al. (2012) for additional detail on rock fracture statistical analysis.

2.1. Network structure

Network structure is defined as the complex geometrical and hydraulic configuration of interconnected fracture segments as influenced by natural variability in fracture orientation, length, transmissivity and density. A defining characteristic of natural fracture networks is trace length which is most often a power-law distributed variable in natural fracture networks:

$$P(L > l) = CL^{-a} \tag{1}$$

where the power law exponent a lies between 1 and 3 (e.g., Davy, 1993; Bour and Davy, 1997; Renshaw, 1999; Bonnet et al., 2001). Note that average fracture length decreases as values of a increase. Networks typically consist of at least two or more fracture sets grouped by orientation, and fracture length for each set may or may not have the same value of a. The distribution of orientation about a mean set orientation is typically modeled using a Fisher distribution (Fisher, 1953):

$$p(\theta) = \frac{\kappa \cdot sin\theta \cdot e^{\kappa \cdot cos\theta}}{e^{\theta} - e^{-\theta}} \tag{2}$$

where θ (degrees) is symmetrically distributed $(-\frac{\pi}{2} \leq \theta \leq \frac{\pi}{2})$ according to a constant dispersion parameter, κ. The extent to which individual fractures cluster around the mean orientation is described by κ where higher values of κ describe higher degrees of clustering. The spacing between fractures is typically found to have a negative exponential trend which can be replicated using a Poisson point process (Ross, 1985). Hydraulic properties of fractures, whether aperture, hydraulic conductivity, or transmissivity, generally follow either log-normal trends (Stigsson et al., 2001; Andersson et al., 2002a,b) or power law trends (Gustafson and Fransson, 2005; Reeves et al., 2008a). Here we use a log-normal distribution to assign fracture transmissivity independently to individual fracture segments, T:

$$p(T) = \frac{1}{T\sqrt{2\pi\sigma_T^2}} \exp\left[\frac{-(logT - \log(\mu_T))^2}{2\log(\sigma_T^2)}\right] \tag{3}$$

where μ_T is the mean and σ_T is the standard deviation. Values of $\log(\sigma_T)$ are commonly around 1 for fractured media (Stigsson et al., 2001; Andersson et al., 2002a,b), which describes variability in transmissivity for individual fractures encompassing 5 to 6 orders of magnitude. Distributions of hydraulic conductivity and transmissivity can also be inferred from distributions of aperture values using the well-known cubic law (Snow, 1965). The generation of fracture networks involves adding individual fractures with random location, orientation, length, and transmissivity into a finite domain until a density criterion is satisfied. This density criterion can vary from one-dimensional to three-dimensional measures, and a two-dimensional fracture density criterion, defined as: $\rho_{2D} = A^{-1} \sum_{i=1}^{n} l_i$, is used in this work to relate the sum of fracture lengths, l_i, to two-dimensional domain area, A. The ρ_{2D} criterion is equivalent to the P21 density criterion used in some discrete fracture network studies (e.g., Munier, 2004).

Synthetic data consisting of two fracture sets with power law distribution of lengths with exponent values in the range $1 \leq a \leq 3$, moderate fracture density, mean orientations of $\pm 45°$ with variability described by a Fisher distribution with $\kappa = 20$, and a log-normal transmissivity distribution with $\log(\sigma_T) = 1$ are used to generate three different network types (Figure 2). Once a network is generated, the hydraulic backbone is identified by eliminating dead-end