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Research Paper

The role of uncertainty in bedrock depth and hydraulic properties on the stability of a variably-saturated slope

Guilherme J.C. Gomes [a,b], Jasper A. Vrugt [b,c], Eurípedes A. Vargas Jr. [a,*], Julia T. Camargo [d], Raquel Q. Velloso [a], Martinus Th. van Genuchten [e,f]

[a] Department of Civil Engineering, Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro, Brazil
[b] Department of Civil and Environmental Engineering, University of California, Irvine, CA, USA
[c] Department of Earth System Science, University of California, Irvine, CA, USA
[d] Department of Civil and Environmental Engineering, Stanford University, Stanford, CA, USA
[e] NIDES Interdisciplinary Center for Social Development, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil
[f] Department of Earth Sciences, Utrecht University, Utrecht, The Netherlands

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ABSTRACT

We investigate the uncertainty in bedrock depth and soil hydraulic parameters on the stability of a variably-saturated slope in Rio de Janeiro, Brazil. We couple Monte Carlo simulation of a three-dimensional flow model with numerical limit analysis to calculate confidence intervals of the safety factor using a 22-day rainfall record. We evaluate the marginal and joint impact of bedrock depth and soil hydraulic uncertainty. The mean safety factor and its 95% confidence interval evolve rapidly in response to the storm events. Explicit recognition of uncertainty in the hydraulic properties and depth to bedrock increases significantly the probability of failure.

1. Introduction

Hilly landscapes are typically mantled with soil and underlain by a weathered bedrock zone that may extend tens of meters beneath the surface before reaching fresh bedrock [1]. The design, construction, and maintenance of buildings, infrastructure, and other man-made structures in such environments depends critically on the stability of the soil and underlying bedrock. It is well-known that precipitation exerts a strong control on hillslope stability via infiltrating water, which elevates pore pressures within the soil mantle and reduces the shear strength. Thus, the more water is stored in the soil mantle, the more susceptible a hillslope is to landsliding. Numerous contributions to the geotechnical literature have investigated the triggering mechanisms and probability of occurrence of rainfall-induced landslides. This body of work has shown that the stability of hillslopes is controlled by many different factors including surface topography [2], depth to unweathered bedrock [3–6], the hydraulic properties [7,8] and shear strength [9–11] including their spatial variability [12,13].

The stability of a hillslope is commonly characterized by a single integrated measure of its load carrying capacity. This measure, coined the factor of safety or safety factor (SF), requires detailed computational analysis since field experiments are often impractical, time-consuming, labor-intensive and expensive. Many different methods have been developed in the geotechnical literature to compute the SF of a slope, ranging from simplified infinite slope approaches to more advanced limit equilibrium methods and sophisticated numerical procedures. These methods differ in their underlying assumptions and rigor, and consequently, may provide conflicting results. Slope stability analyses are further complicated by our inability to characterize adequately the hillslope interior. Indeed, soil properties and/or related variables deemed necessary for the different methods cannot be measured in the field with infinite precision, and consequently, the computed SF values are subject to considerable uncertainty [14].

Conventional (deterministic) methods for slope stability analyses calculate the SF without recourse to the underlying uncertainty in soil and hillslope properties [15,16]. Probabilistic methods allow

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[*] Corresponding author.

E-mail addresses: guilhermejcg@yahoo.com.br (G.J.C. Gomes), jasper@uci.edu (J.A. Vrugt), vargas@puc-rio.br (E.A. Vargas Jr.), juliatcamargo@gmail.com (J.T. Camargo), raquelvelloso@puc-rio.br (R.Q. Velloso), rvangenuchten@hotmail.com (M.Th. van Genuchten).

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designers to address issues beyond those that can be dealt with using deterministic methods. Such methods allow us to calculate confidence intervals of the SF due to uncertainty in soil properties and stratigraphic conditions, data errors, and model structural inadequacies [15,17]. The impact of uncertainty in the soil properties on the SF is relatively easily quantified using statistical methods [15], and has been explored by different authors [7,9,11,18,19]. This includes treatment of uncertainty in the porosity [20], specific weight [11,17], cohesion [11,17], and friction angle [11,17] of the soil mantle, and the spatial variability of the hydraulic conductivity [7,20]. Data errors arise from improper, incomplete and/or inaccurate measurement methods [15]. For example, the subsurface stratigraphy can exhibit considerable spatial variability, which, if poorly characterized, compromises the accuracy of slope stability studies [3,4]. What is more, spatiotemporal variability of the moisture content and distribution of the hillslope interior controls slope stability, yet is difficult to characterize adequately with porous flow simulators due to large uncertainties in the hydraulic properties and boundary conditions of the considered soil-bedrock domain [15,21].

Geotechnical stability analyses under transient soil-water conditions require knowledge of the soil hydraulic properties, namely the water retention function (or soil-water characteristic curve, SWCC) and the unsaturated soil hydraulic conductivity function, HCF. These two constitutive relationships generally exhibit considerable spatial variability, and are very time consuming, labor intensive, and costly to measure at the scale of a hillslope [22,23]. Whereas several authors have investigated the effect of the saturated hydraulic conductivity on slope (in) stability [12,24–26], relatively few contributions in the geotechnical literature have explored properly the coordinated impact of SWCC and HCF uncertainty on the SF values derived from slope stability studies [4,6,18,27]. We agree wholeheartedly with Liang and Uchida [23] that a detailed characterization of the temporal and spatial variability of the moisture content of the soil mantle is warranted in slope stability studies. Such studies should also include proper recognition of uncertainty in the soil hydraulic properties [8].

Liang and Uchida [23] evaluated, in a recent study, the impact of soil hydraulic parameter uncertainty on distributed moisture contents simulated with a three-dimensional variably-saturated flow model. Using a detailed depth to bedrock map of a small catchment in Japan and different parametrizations of the soil hydraulic functions, these authors found that saturation develops predominantly at the soil-bedrock interface. The bedrock surface connects sparsely saturated regions [28], and thus determines, along with regolith thickness, the water pressure within the soil mantle's pores. Indeed, depth to bedrock is a key variable that controls subsurface flow [29], and triggers landslides during rainfall events [30–32].

As hillslope interiors are costly, labor-intensive, and difficult to access, most slope stability studies use a relatively simple description of the bedrock surface [3,6,7,11]. Resulting topographic maps often do not do justice to complex field measurements of the bedrock depth, which often demonstrate significant spatial variability [3,33] with a geometry that is difficult to characterize adequately with some closed-form mathematical expression, while hydraulic and strength parameters can vary abruptly at the soil-bedrock interface. Whereas some authors have used high-resolution bedrock depth maps to assess hillslope stability [28,32,34,35], existing studies in the literature do not properly recognize the effect of bedrock depth uncertainty on slope stability assessments.

The purpose of the present study is to evaluate the marginal and joint impact of bedrock depth and hydraulic uncertainty on the stability and probability of failure of a natural soil-mantled hillslope in Rio de Janeiro, Brazil. The soils in our experimental watershed are unsaturated during most of the year, but this state can rapidly change during periods of heavy rainfall. Therefore, [3] advocated monitoring variations in pore water pressures (both negative and positive) at specific sites during the year in order to assess their impact on slope stability. We use the calibrated geomorphologic model of [33] to generate plausible maps of the bedrock depth. The model was calibrated against a rich data set of distributed bedrock depth measurements using Bayesian inference with the DREAM algorithm [36,37]. Posterior maps of the simulated bedrock depth topography serve as input to a three-dimensional finite-element (FE) water flow model of the bedrock-soil domain, and are used to evaluate hillslope stability for a 22-day rainfall record via numerical limit analysis [38] using the ensemble of simulated transient pore water pressures. Our analysis will also consider soil hydraulic parameter uncertainty derived from pedotransfer functions using the Rosetta program [39]. We are particularly interested in the coordinated impact of both sources of uncertainty (bedrock depth and soil hydraulic properties) on the mean SF and its associated 95% confidence interval instead of looking at their marginal impact. The framework presented herein allows geotechnical engineers to address slope stability issues beyond those that can be addressed using deterministic methods, and provides a basis for reliability analyses of geotechnical hazards.

The remainder of this paper is organized as follows. Section 2 reviews the different building blocks of our integrated fluid flow and numerical limit analysis methodology. This framework is used herein to assess the SF values and corresponding failure probabilities. In Section 3 we are particularly concerned with quantification of soil hydraulic and bedrock depth uncertainties. This is followed in Section 4 with a detailed description of three different case studies of the same hillslope. Section 5 presents results of the three case studies, whereas Section 6 discusses the implications of our findings to hydrologic and geotechnical modeling. Finally, Section 7 concludes this manuscript with a summary of our main findings.

2. Modeling framework

We developed an integrated framework for stochastic slope stability analyses. The probabilistic framework couples a Monte Carlo algorithm with a three-dimensional variably-saturated flow model of the soil mantle and assesses hillslope stability via numerical limit analysis (NLA). The flow model solves numerically in three-dimensions Richards' equation and simulates transient values of the pressure head, $\psi(\cdot)$, for the spatial coordinates, x and y, and depth, z, of the hillslope and time, t, of the supplied rainfall data record. The values of $\psi(x,y,z,t)$ in the center of each tetrahedral element are used to characterize the soil-mantle's water pressures. These locations are indicated schematically with the red dot in the mesh of Fig. 1. The evolving pore water pressures then serve as input to NLA to solve numerically for the transient stress and velocity distributions of the soil-mantle, which in turn are used to calculate the SF during the rainfall record. The Monte Carlo algorithm is used to quantify the impact of uncertainty in the bedrock depth and the soil hydraulic properties on hillslope stability by repeated numerical solution of the NLA equations for the ensemble of pore water pressures simulated with the Richards-based flow model.

Our framework is coded in MATLAB and integrates the two numerical models so that users do not have to port data from one model to the next [10], thus simplifying considerably slope stability analyses. The MATLAB code has a built-in routine which generates automatically prismatic and tetrahedral FE meshes for the hillslope water flow model and NLA equations, respectively. The code furthermore has pre- and postprocessing capabilities to simplify model setup and visualization of the results. Fig. 1 provides a schematic overview of our coupled framework. Users have