# A framework to capture the loss of hydromechanical stability of unsaturated shallow slopes subjected to rainstorms

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**Abstract:** Rainfall-induced shallow landslides affect urban communities worldwide. Although soils can fail in different ways, including localized slip and chaotic flows, these mechanisms depend on local geomorphic features and physical properties. Most physically-based models cannot capture these diverse mechanisms, as they postulate frictional failure as the only form of instability. This paper outlines geomechanical models that can be used at different length scales to bridge the gap between stability analyses for unsaturated conditions and the growing body of constitutive laws for unsaturated soils. A range of techniques to identify the loss of hydromechanical stability in unsaturated geosystems, from soil specimens to single slopes and landscapes, is therefore outlined. It is shown how these techniques capture transitions across multiple modes of failure in response to changes in degree of saturation, thus allowing for a synergistic assessment of coexisting risks of slips of limited mobility and destructive flowslides in the same geological setting. Examples of applications for selected case studies are used to show that, in addition to improved predictions, this framework facilitates unified triggering and runout analyses, thus enabling a holistic landslide risk assessment under changing climate.

## Introduction

Surface infrastructure and the natural terrain have always been subjected to climate agents. In a civil engineering context, factors such as rainfall input, surface moisture, and subsurface pore water pressure are key components in design, monitoring, and long-term management of such assets. During the last several decades, however, global shifts in climate, combined with relentless urbanization, have increasingly exposed existing and new infrastructure, as well as ecosystems, to destabilizing trends [1]. Despite inherent difficulties in quantifying of how global climate changes may affect the long-term projections of quantities relevant for slope stability at a given site (e.g., rainfall intensity, frequency and duration), it is widely accepted that the practice of geohazard assessment is entering into an uncharted territory, with growing needs of better predictions and mitigation strategies. Computational methods play a crucial role in this context. For example, in the domain of slope stability numerous works have shown the advantages of combining solvers for coupled multi-physical analyses with classical cornerstones of the geotechnical practice, such as limit equilibrium methods. If linked with principles of unsaturated soil strength, these methods have been shown to illuminate the impacts that climate can have on the stability of geosystems. In this paper, however, we argue that the growing risks of high-intensity events, combined with shifts in predisposing climate factors, can prime natural and artificial earthen systems to deform in ways that had not been experienced before, thus generating a wider, and possibly catastrophic, range of failures. Most notably, consideration of deformation processes taking place before, during, and after ground instability can constitute an invaluable resource to characterize the geomechanical properties of the ground and identify failure precursors, thus offering new avenues to harness the growing body of remotely sensed surface displacements [2]. Hence, here we posit that proper consideration of the deformation properties of the ground is essential to enable a comprehensive assessment of the diverse range of failure modes that emerge in response to changes in the degree of saturation at all the length scales of interest, from a material element to a heterogeneous landscape.

For this purpose, this paper outlines a set of deformation-driven stability analyses aimed at capturing multiple modes of saturation-induced soil failure, including volumetric collapse and solid-fluid transition, while recovering standard shear failure as a particular case [3]. To reduce the computational costs, while maximizing the scalability of the methodology, our analyses will rely up to the extent possible on analytical or semi-analytical procedures, thus allowing selected approximations of system geometry and conditions which illuminate specific facets of the triggering and post-triggering mechanisms involved in rainfall-induced unsaturated ground failure. After detailing the key features of closed-form stability indicators [4] and their role on suction transients [5], selected examples of a field-scale application to a case study of rainfall-induced flowslides will be discussed [6].

**The material scale**

To assess the margin of safety of a slope it is essential to quantify the soil strength under varying saturation conditions. For this purpose, unsaturated soil mechanics provided key contributions, starting with the early attempts of extending the effective stress principle [7]. These efforts have later been refined with augmented effective stress expressions [8] or by deploying suction and net stress as separate state variables [9]. Although these concepts are widely used via slope stability analyses based on limit equilibrium [10], they may be ineffective for high mobility failures, such as flowslides [11]. This difficulty stems from their inability to account for the plastic deformability of soil prior to and during failure. Concepts of mechanics can resolve this problem by describing instability with more general techniques that capture failure controlled by plastic volume change. A classic example is the second-order work criterion [12], widely deployed for processes such as shear banding or static liquefaction. In the latter case, this criterion can identify the loss of strength by identifying vanishing ($d^2W = 0$) or negative

$(d^2W < 0)$ values of the second order work input when failure occurs before reaching the Mohr-Coulomb envelope, such as in loose sand. This is depicted in Figure 1a, showing the possibility of spontaneous collapse through sharp pore pressure growth at the instability line.

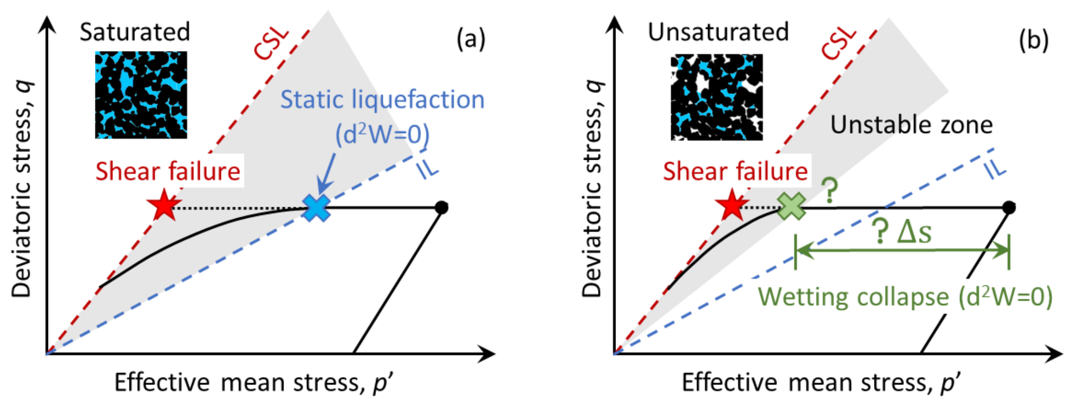


Figure 1: (a) Constant shear stress test in a saturated loose sand. Instability conditions at the instability line render spontaneous collapse possible; (b) Scenario for unsaturated soils: a critical suction at collapse must be defined to confirm if wetting instability is possible.

However, in the context of subaerial slopes and earthen systems the use of these techniques produces overconservative results. This is shown in Figure 1b, where effective stress reduction at constant shear stress, a stress path often used to model rainfall induced failure, is considered in the context of unsaturated soils. In this scenario, most soils would not suffer a collapse at the instability line. Rather, a critical value of suction must be identified to confirm if a spontaneous collapse is possible or if, instead, it must be ruled out, having shear failure as the only relevant mode of instability. Buscarnera and di Prisco [13] explained this limitation of the stability techniques developed for saturated soils as an outcome of the need to specialize them to the energetics of multi-phase flow processes for unsaturated conditions. Specifically, they pointed out that it is crucial to account for two effects: (i) the skeleton stress in the unsaturated matrix, and hence the role of capillary bridges and water content on stress transmission; (ii) the work required to move fluid interfaces and change the degree of saturation.

Based on these principles, their analysis showed that by using the hydro-mechanical energy input (i.e., the work required to deform the skeleton and change the degree of saturation) at the boundary of an unsaturated soil element, it is possible to obtain the following expression:

$$d^2W = \left[\dot{\sigma}_{ij} - S_r \dot{u}_w \delta_{ij} - (1 - S_r)\dot{u}_a \delta_{ij}\right]\dot{\varepsilon}_{ij} - n(\dot{u}_a - \dot{u}_w)\dot{S}_r \tag{1}$$

where $\sigma_{ij}$ is the stress increment, $u_w$ and $u_a$ water and air pressure increments, respectively, $\varepsilon_{ij}$ the skeleton strain increment, $S_r$ the degree of saturation, $n$ porosity, and $\delta_{ij}$ the Kronecker delta. Notably, this expression does not depend on the constitutive hypotheses for the soil matrix nor on specific expression for its water retention properties. As a result, it can be considered an outcome of the balance equations regulating momentum balance and fluid mass balance within the soil volume. At the same time, it relies on a simplified depiction of the movement of fluid interfaces and can be augmented by accounting for such effects [14]. Nevertheless, the simplicity of Eq. 1 offers some key advantages. In fact, it can be readily recast either in terms of common effective stress formulations or dual stress variable models. This enables a straightforward connection of the formulation with the most widely used constitutive laws for unsaturated soils [15], thus enabling an assessment of evolving stability margins at material point level with full consideration of the extent of pre-failure soil strain. This feature was recently used to rationalize the stability nature of wetting collapse by connecting the second order work with controllability analyses [16].

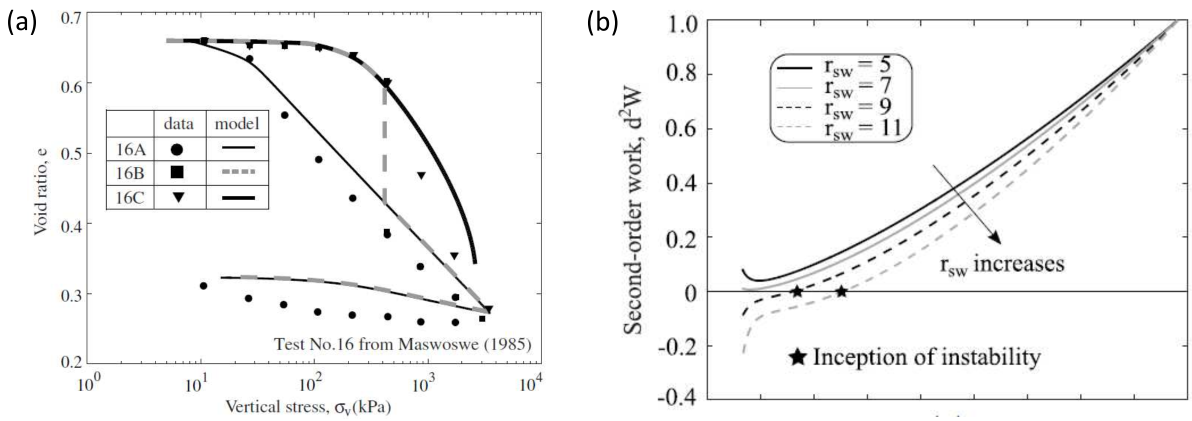


Figure 2. (a) calibration of a constitutive law for wetting collapse measurements (data reported by Maswoswe, [17]; model by Chen et al [16]); (b) material stability analysis.

The essential concept is that vanishing values of second-order work, commonly associated with instability, can be specialized by identifying a corresponding constitutive singularity, which redefines them in terms of loss of controllability by rendering explicit the modes of deformation that can manifest even under zero energy input (i.e., that became unstable). Figure 2 shows a re-examination of classical wetting collapse measurements, from which it can be inferred that the most common forms of saturation-induced porosity loss are not unstable, but rather fully controllable. Nevertheless, the study also indicates how to identify problematic levels of soil collapsibility (through the parameter $r_{sw}$, here modeling the sensitivity of the yield pressure to suction [18]), which may lead to spontaneous collapse. In this context, a material point analysis provides an initial screening that points out that a wetting instability involves strong coupling between deformation and suction change, with the collapse being accompanied by a sharp drop in suction and consequent loss of strength [16].

In the next sections, it will be shown how these predictions can be linked with concepts of transient pore pressure change (consolidation) applied to unsaturated soils and deployed to recover augmented factors of safety for multi-modal slope stability analysis.

**The slope scale**

The theory of material stability can be used to obtain closed-form indicators of a loss of hydro-mechanical control, with each index playing a role conceptually similar to that of a safety factor for a particular mode of failure. In this context, infinite slopes are a straightforward domain of application. In fact, unsaturated slopes can be exposed to various triggering agents, such as earthquakes, rainfall, and human activities, leading to activation mechanisms (e.g., shear-induced failure, wetting-induced collapse [19]). For slopes subject to rainfall, external forces generally remain constant with sustained water injection. Depending on the hydraulic control conditions, two main perturbation modes can be considered, namely suction-control or water content-control, with each of them having a corresponding stability index [20]. As a result, slope stability conditions can be assessed by tracking the values of these stability indices along saturation.

Such screenings based on material stability are idealized at the constitutive level with perfectly controlled hydromechanical loading conditions. However, for unsaturated slopes under rainfall events, the saturation process is neither suction-controlled nor water-content controlled but experiences more complex suction transients due to pore fluid diffusion. Therefore, disclosing the intrinsic connection between material stability and temporal spikes in suction loss (and, hence, strength deterioration), requires specific tools. Here, the role of the previously defined stability indices on the spatiotemporal behavior of the hydromechanical coupled slope systems is therefore examined. For simplicity, let us consider a one-dimensional consolidation process of an unsaturated layer on horizontal ground (the addition of shear stress is straightforward and does not alter significantly the arguments). In this context, water mass balance is used to model suction transients. Considering Darcy's flow and an uncoupled water retention curve (a unique relationship between s and $S_r$), it can be shown that [5]:

$$\frac{k_{ij}^{w}}{\gamma_w} s_{,ij} + \frac{1}{\gamma_w}\frac{\partial k_{ij}^{w}}{\partial s} s_{,i} s_{,j} - k_{ij,i}^{w} z_{,j} + n\frac{\partial S_r}{\partial s} s_{,t} - S_r\left[C_{ijkl}^{e}\left(\sigma_{ij,t}^{net} + \frac{\partial \sigma_{ij}'}{\partial s} s_{,t}\right)\delta_{kl} + \varepsilon_{ij,t}^{p}\delta_{ij}\right] = 0 \quad (2)$$

where commas indicate differentiation with respect to either time (i.e., $\frac{\partial a}{\partial t} = a_{,t}$) or a spatial coordinate (e.g., $\frac{\partial a}{\partial x} = a_{,x}$ and $\frac{\partial^2 a}{\partial x^2} = a_{,xx}$), $\gamma_w$ the water unit weight, $k_{ij}^{w}$ ( $S_r$ ) the hydraulic conductivity tensor function of the degree of saturation $S_r$, $z$ the depth coordinate, $C_{ijkl}^{e}$ the elastic compliance tensor (inverse of the elastic stiffness matrix $D_{ijkl}^{e}$,) $\sigma_{ij}' = \sigma_{ij}^{net} + \chi(S_r)s\delta_{ij}$ is the effective stress, $\sigma_{ij}^{net}$ the net stress, $\chi(S_r)$ the effective stress coefficient being a function of $S_r$, and superscripts "e" and "p" denote elastic and plastic strain contributions, respectively. Specifically, for an elastoplastic material with a hydromechanical coupled hardening law, the suction diffusion equation can be expressed as:

$$\frac{k_{ij}^{w}}{\gamma_w} s_{,ij} - C_1^{ep} s_{,t} + C_2^{ep}\left(s_{,i}, \sigma_{ij,t}^{net}\right) = 0,\ C_1^{ep} = -\frac{B}{H}\left(H - H_\chi\right),\ B = n\frac{\partial S_r}{\partial s} - S_r C_{ijkl}^{e}\frac{\partial \sigma_{ij}'}{\partial s}\delta_{kl} \quad (3)$$

where $C_1$ is the diffusivity coefficient with superscript "*ep*" indicating values for elastoplastic materials, $H$ and $H - H_\chi$ are the customized stability index for suction-controlled and water-content-controlled wetting tests under constant loading (i.e., $\sigma_{ij,t}^{net} = 0$), respectively. From a mathematical standpoint, the stability of such a parabolic PDE is ensured when $C_1^{ep} > 0$ with its violation causing the differential problem to be ill-posed and suggesting the possibility of unstable suction fields. The positiveness of $C_1^{ep}$ is associated with the sign of terms $B$, $H$, and $H$-$H$_$\chi$. Since it can be readily shown that B is always negative (see [5] for details), Eq. (3) reveals the connection between material stability and diffusive stability and suggests that a local loss of material stability is responsible for the activation of a diffusive instability at the slope scale. This result corroborates the use of material stability metrics as indicators to identify non-standard failure modes, including coupled mechanisms accompanied by sharp pore pressure growth. However, to carry out simulations in the vicinity of such events, it is necessary to regularize the singularity of the elastoplastic soil model responsible for the ill-posedness of the diffusion equation and, consequently, the numerical breakdown of coupled simulations both in the vicinity of triggering and during the post-failure regime.

A strategy to circumvent numerical ill-posedness is viscoplasticity. For example, Perzyna-type models [21] can be shown to suppress diffusive instabilities by restoring a positive diffusion coefficient, $C_1^{vp} = -B > 0$ , thus providing a robust strategy to simulate coupled soil deformation and suction changes in the post-instability regime. Fig. 3 presents an example of 1D consolidation of unsaturated soil layer subjected to water injection for both elastoplastic and viscoplastic materials. It is readily apparent that the elastoplastic simulation fails at the onset of the collapse instability. However, the simulation can be run smoothly well into the unstable regime simply with the incorporation of minor amounts of viscosity, thus resolving the rapid accumulation of deformation due to the wetting collapse. Furthermore, the use of viscosity enables the quantification of the possible time lag between rainfall infiltration and accelerating movement (delayed instability), here obtained as an outcome of the underlying creep simulation capabilities resulting from the use of viscoplasticity [22].

While the analyses discussed here are restricted to 1D consolidation and volumetric wetting collapse, extensions to incorporate the role of shearing are readily obtained with an extension of the constitutive formulation and field equations for multi-dimensional cases.

**The regional scale**

As previously discussed, the stability theory can be applied at the slope scale to define suction dependent safety indices regarding various failure mechanisms, including frictional slips and flowslides [20]. These indices can capture distinct failure modes observed in laboratory tests, promoted by suction and porosity variations. Most notably, this method can be utilized to

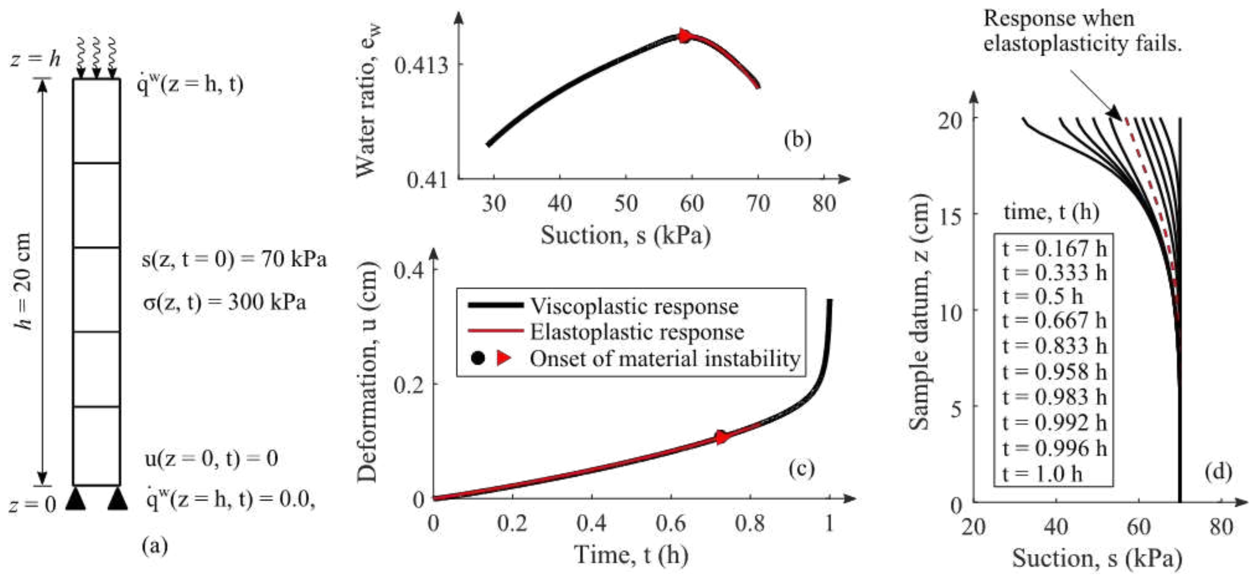


Figure 3. Wetting collapse of elastoplastic and viscoplastic materials: (a) model setup; (b) $s$-$e_w$ at the top surface; (c) time history of surface deformation; (d) isochrones of nodal suction.

perform landslide susceptibility mapping by updating the safety margins for each slope unit [23]. In this process, key inputs such as the slope inclination, thickness, and local stratigraphy can be extracted from Digital Terrain Models (DTM) embedded in Geophysical Information Systems (GIS). By examining the spatiotemporal distribution of the safety index, the hazard susceptibility at regional scale can be computed.

Also for these applications, mapping the potential of rainfall-induced landslides in unsaturated slopes requires the computation of pore pressure transients through subsurface flow analyses (e.g., via Eq. 2). However, such computations must enforce the water mass balance for each slope unit of the DTM. Hereafter, a computational approach to facilitate such computation in an efficient, yet rigorous, form is discussed. Such an approach relies on a vectorized Finite Element (FE) algorithm [24] able to cope with the spatial variability of the soil stratigraphy at regional scale. When using the vectorized FE algorithm, each dataset is first treated as a georeferenced grid within a GIS platform. Each grid is then transitioned into a column vector and arranged into different subsets that share the same FE discretization. The computation is then conducted on sequences of vectorized subsets rather than individual slope units, thus greatly reducing the computational costs of a regional, spatially distributed analysis. The spatiotemporal distribution of the safety indices for each slope unit is in fact updated based on the computed pore pressure transients, enabling the identification of the time and depth at which stability criteria are first violated. The failure time and depth can thereby be determined at regional scale and mapped across the entire DTM.

This approach has been recently used to analyze a series of shallow rainfall-induced flowslides that occurred in Campania (Southern Italy) [25]. The laboratory data and corresponding parameter calibration are discussed in Li et al. [6]. The results obtained in terms of landslide susceptibility for two municipalities, Siano and Lavorate, are illustrated in Fig. 4. It can be shown that the model successfully captures most of the landslide source areas reported by field surveys, involving slips and flow slides, especially in the cluster areas labeled A, B, and C. This result would have not been possible without considering the site-specific soil stratigraphy across the heterogeneous landscapes. Most notably, the study found that the use of multiple slope failure indicators (i.e., slips and flows) is crucial to maximize the correct prediction of failure hotspots without excessive computation of false positives. Specifically, it can be shown that the proposed model leads to performance indicators (defined as an area ratio between true and false positives) two or three times higher than those of regional models based exclusively on frictional failure [6].

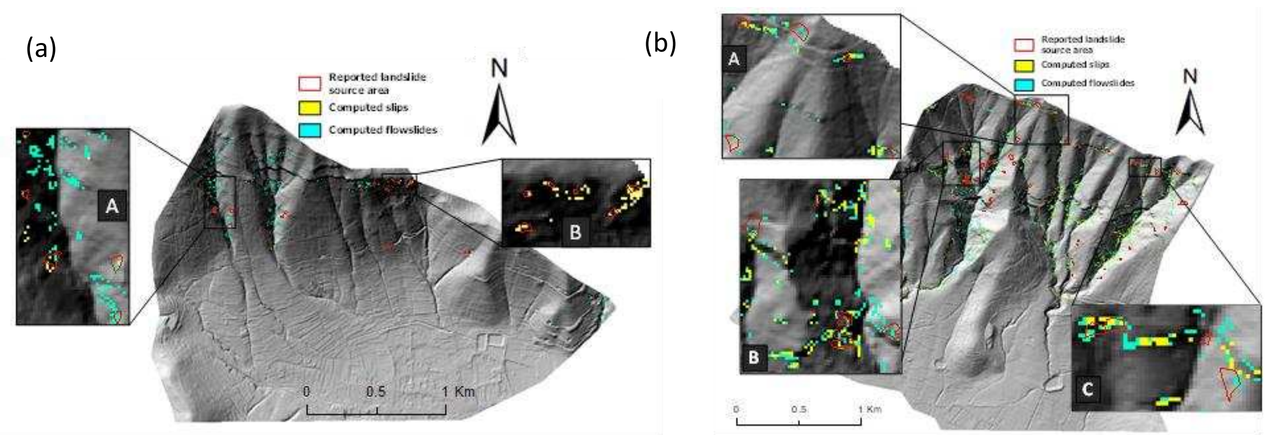


Figure 4. Computed failure triggering mechanisms at (a) Siano, (b) Lavorate.

This example shows the benefits of using augmented stability theories at field scale. In addition, given the versatility of the algorithm, extensions are possible to account for factors such as shrink/swelling potential [26] and randomly distributed properties [27] to further advance hazard prediction in the face of climate change.

**Conclusions**

This paper summarized recent results in the stability analysis of unsaturated soils by offering new perspectives about their significance for landslide hazard assessment. At the material scale, it was shown that stability principles accounting for the deformability of the skeleton and its coupling with water retention processes offer augmented capabilities to capture the risk of wetting-induced collapse prior to frictional shear failure, while encompassing the latter as a particular case. It was shown that this generalized stability analysis underpins a singularity of the underlying constitutive behavior and, hence, the existence of coupled hydro-mechanical modes of failure. At the scale of individual soil layers, such as those featuring an individual slope, it was shown that such singularities lead to anomalies of the consolidation process, which in an unsaturated context imply sharp suction variation, loss of strength and accelerating behavior. Finally, it was shown that the stability indicators derived at these scales can be conveniently recast into factors of safety specialized for a given suction-dependent constitutive law and two specific model of failure. Here, slope stability indices relevant to drained slips and undrained flowslides were discussed. The implementation of this method in a landslide triggering model applicable at regional scale can improve the performance of landslide susceptibility mapping. These results show that consideration of soil deformability and hydro-mechanical coupling prior to failure is crucial in triggering analyses, especially in unsaturated systems where the beneficial strengthening effects of suction can be suddenly lost as an outcome of a chain process of collapse, saturation, and strength loss. Given their inherent ability to account for landslide deformation and transient effects, these methods offer opportunities to streamline the workflow of landslide risk assessment by linking pre-failure deformation, triggering and post-failure motion, thus examining the stability of a slope as a dynamic system susceptible to transit across different regimes of motion depending on the interplay between the deformability and strength of the underlying soil and the time-varying suction regime.

**Acknowledgements**

G.B. acknowledges partial support of the NASA Goddard Space Flight Center (Grant: 80NSSC23K0734-P00001).

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