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Landslides and Debris Flow Induced by Rainfall

Ronaldo I. Borja

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LANDSLIDES AND DEBRIS FLOW INDUCED BY RAINFALL

Rainfall infiltration weakens unsaturated earthen slopes, causing the soil mass to move rapidly downhill. Increased saturation and fluid flow are two important triggers of slope movement, and to date no physics-based modeling approach can represent the combined effects of these two factors in a systematic and quantitative way. In this article I briefly review a commonly used analytical approach based on the limit equilibrium methods for quantitative analysis of slope stability, and highlight their inability to handle the effect of rainfall infiltration on the triggering of slope failure. I describe an alternative analysis approach based on continuum modeling and show some examples where I have used this approach for studying the effect of rainfall infiltration on the stability and movement of unsaturated earthen slopes.

Landslides versus Debris Flows

Landslides occur when earth material moves rapidly downhill after failing along a shear zone. Debris flows can be differentiated from landslides by the pervasive, fluid-like deformation of the mobilized material. The formation of debris flows most often occurs as a result of a landslide partially or completely mobilizing into a debris flow (Johnson, 1984). A physics-based characterization of landslides and debris flow initiation is important because of the rapid and destructive nature of these events.

Hydrologically-driven slope instability threatens lives and property worldwide. As an illustration, the 0.22 m storm of January 4, 1982, superimposed on approximately 0.6 m of pre-storm seasonal rainfall, triggered thousands of landslides in the central Coast Ranges of California. The landslides in the San Francisco Bay Area during the January 1982 storm resulted in 24 fatalities and millions of dollars worth of property damage (Smith, 1982). One of these failures was the debris flow that occurred in the 1200 block of Oddstad Boulevard in the city of Pacifica. The debris flow scar at the Oddstad site extended 230 m down a slope of approximately 21 degrees. It is interesting to note that the slide was not purely translational; it had a complex, irregular failure surface located above the colluvium-bedrock contact. This landslide was particularly devastating in that three children lost their lives.

Examples of large-scale hydrologically-driven slope failure within the last twenty years include the following cases. In Mameyes, Puerto Rico (1985), 0.56 m of rainfall within a 24-hour period (with rates as high as 70 mm/hr) triggered debris flows resulting in 129 deaths (Jibson, 1992). In Rio Limón, Venezuela (1987), 0.174 m of rainfall in less than five hours triggered numerous shallow landslides and debris flows resulting in 210 deaths (Schuster, 2002). In Rio de Janeiro and Petropolis, Brazil (1988), intense rainfall triggered landslides that resulted in 320 deaths (Nieto and Barany, 1988). In Antofagasta, Chile (1991), rainfall rates as great as 60 mm/hr during a three-hour period triggered landslides that resulted in 101 deaths (Van Sint Jan and Talloni, 1993). In Vargas, Venezuela (1999), heavy rainfall exceeding 0.9 m over a three-day period, with daily values greater than the 1,000 year return period, triggered thousands of landslides and resulted in an estimated 30,000 deaths (Martínez, 2000). In Guinsaugon, Philippines (2006), heavy rainfall triggered massive landslides, burying an elementary school that had 246 students and 7 teachers (Lagmay et al., 2006).

Despite decades of extensive slope stability model development, the fundamental controls connecting the hydrologic and geotechnical processes triggering slope failure are still not well quantified. This lack of understanding is a direct result of the simplified physics in current models, with the omission of the effect of partial saturation from slope stability calculations. It is known that increasing the degree of saturation decreases the capillary pressure, which in turn weakens the slope. Despite the expected significant impact, such interplay between the increase in saturation and increase in potential for slope failure is yet to be fully quantified. Existing mechanical models for slope failure initiation are far from being predictive, particularly when the failure is induced by a complex hydrologic loading history.

In this article I briefly review the limit equilibrium methods commonly used in engineering practice to assess the stability of earthen slopes. These methods cannot accommodate the influence of partial saturation and fluid flow, and so I describe an alternative continuum mechanics approach that couples the solid deformation, fluid flow, and increased saturation in one combined modeling framework. At the conclusion of this article, I present numerical simulations demonstrating how the continuum method may be used to assess the stability of earthen slopes and predict their movement under complex hydrologic boundary conditions.

Limit Equilibrium Methods

Limit equilibrium methods calculate an index called ‘factor of safety’ that measures how close a given slope is to failure. A factor of safety close to the number one means that slope failure is impending, whereas a value much greater than one suggests that the slope is stable. ‘Failure’ is defined by a slip surface which cuts through the slope, causing the mass of earth to move above it. Examples of limit equilibrium methods include the Culmann method for planar failure surface and the methods of slices for circular failure surface. Because the limit equilibrium methods assume that failure is due to slip on a surface, they cannot be used to predict the initiation of debris flow and other ‘diffuse’ failure mechanisms where no such failure surface forms.

The slip surface can take many shapes. A planar surface is associated with a translational slide, whereas a curved surface is associated with a combined translational and rotational slide. The simplest curved failure surface is a circle defined by a center and a radius. In general, failure surfaces have much more complicated shapes, and are three-dimensional. However, most limit equilibrium methods are restricted to two-dimensional geometry. The main idea behind the limit equilibrium methods is to find the most critical failure surface that gives the minimum factor of safety. Because of the infinite possibilities that the shape and position of the failure surface can take, a computer program is necessary to search for the critical failure surface. With a planar failure surface the iterative search consists of finding the critical position of such plane, whereas with a circular failure surface the search consists of finding the radius and center of the most critical circle that gives the minimum factor of safety.

The driving force behind slope failure is the gravity load. In limit equilibrium solutions, the gravity load is represented by the weight of the mass of earth above the failure surface represented as a vertical force passing through the center of gravity of the earth mass. Landslide occurs when the shear strength developed on the failure surface is not sufficient to resist the driving force. This can be illustrated with a block resting on a rough plane; if the plane is tilted, the block will slide downhill when the gravity load exceeds the frictional resistance developed on the block/plane interface. In earthen materials, the shear strength on the failure surface is developed from frictional and cohesive resistance, with the frictional resistance dominating in coarse-grained soils such as sand, and the cohesive resistance dominating in fine-grained soils such as clay. To increase the factor of safety, the gravity load must be decreased and/or the shear resistance must be increased.

The presence of water in a slope can influence the factor of safety in a complex way. A water-saturated soil is heavier than a dry soil of the same porosity, thus increasing the driving force acting on the slope. Where the potential failure surface is under the water table, the pore water pressure decreases the effective normal stress acting on the failure surface, which in turn decreases the frictional resistance. Where the potential failure surface cuts the unsaturated zone above the water table, capillary pressure due to surface tension increases the effective normal stress in the soil matrix, thus increasing the frictional resistance. On the other hand, the increase in saturation induced by rainfall infiltration could break the menisci between the soil grains and decrease the capillary pressure, thereby decreasing the frictional resistance. Furthermore, when there is enough precipitation to produce groundwater flow, an additional driving force on the solid matrix is generated by seepage, thus further reducing the factor of safety. These complex processes are highly interrelated in the sense that slope strengthening due to one factor could be offset by slope weakening due to another factor. As noted earlier, such complex processes are not accommodated by limit equilibrium solutions.

Continuum Methods

Continuum methods provide a physics-based characterization of the processes involved in hydrologically-driven slope failure initiation. In contrast to limit equilibrium solutions, continuum methods do not provide a factor of safety for a given slope; instead, they provide deformation and stress distributions within the slope. An advantage of continuum methods is that they can account for the mechanical, chemical, and thermodynamic processes involved. A disadvantage lies in the fact that the continuum solution could be complicated and requires robust algorithms and powerful computational hardware.

The first step in a continuum solution is to write the relevant governing equations representing the conservation laws that must be satisfied by the solution. In hydrologically-driven slope failure initiation, we impose the equilibrium condition and the conservation of fluid mass in the form of partial differential equations (PDEs). In addition, we specify the relevant boundary and initial conditions. Rainfall infiltration induces a boundary condition on the surface of the slope in the form of a prescribed fluid flux, which also serves to drive the solution to the next equilibrium configuration. Initial conditions define the starting point of a time-evolving solution (i.e., transient condition), such as the movement of the slope and the pore pressure distribution within the slope.

Imposing the governing PDEs point by point within the slope is not a trivial task and cannot be done by manual calculations. Like the limit equilibrium methods, continuum methods are solved numerically by a computer program to account for the various complex processes involved. There are many numerical techniques available for solving the continuum problem, including the finite element, finite difference and finite volume methods. In a majority of these numerical techniques, the domain of the problem is divided into a grid and the relevant PDEs are imposed in an approximate way. The grid is defined by a finite number of nodes and elements. In the finite difference method the PDEs are imposed directly on the grid nodes, whereas in the finite element method the PDEs are converted into a ‘variational equation’ that is imposed over smaller non-intersecting subdomains, or finite elements, comprising the total domain. In the end, the governing equations are converted into a set of simultaneous equations, usually non-linear, that is solved by a numerical equation solver to yield the unknown degrees of freedom. For the problem of interest the relevant degrees of freedom are the slope displacements and pore water pressures evaluated at the nodes of the grid. Both degrees of freedom vary spatially and temporally, reflecting the heterogeneous and transient nature of the solution.

Unlike the limit equilibrium methods, continuum methods do not calculate a factor of safety. However, since the displacements and soil stresses are calculated spatially and temporally, it is possible to inspect the solution point-by-point. By looking at the stresses within the slope, we can identify the most critically stressed point at which failure is likely to initiate, as well as track the progression of the slip surface (if local failure involves formation of such surface) until the inception of a global collapse. Also, unlike the limit equilibrium solutions, continuum methods do not assume the shape and position of the slip surface; instead, they are predicted by the method and considered part of the solution.

Recent advances in computational modeling of failure processes allow the inspection of the type of instability that could arise at the most critically stressed zone in a slope. By performing a so-called 'local bifurcation analysis,' we can infer if the type of instability is diffuse, or whether failure is expected to occur over a narrow zone. An example of a diffuse instability is that of pore collapse, which occurs over a finite volume that typically had a high initial porosity such as very loose sands. Such instability does not define a shear zone and therefore is not associated with the formation of a slip surface. Instead, diffuse instability in slopes is generally linked to debris flow initiation.

In some branches of earth sciences such as geomorphology and geography, an additional interest lies in quantifying the mechanism of slope movement following the inception of a slip surface or debris flow failure. Simulation of debris flow poses an additional challenge to the modeler because of the complex phase transformation that could occur in the soil throughout the process. At the inception of debris flow the soil transforms from a solid-like material to a fluid-like material. Debris flow typically occurs at a very rapid pace with significant inertia loads, and therefore is considered as a dynamic process. In addition, the soil moves like a fluid with a high viscosity. From a modeling standpoint, the process can be modeled using computational fluid dynamics (CFD) algorithms in which the soil is considered as a heavy viscous fluid. When the flow stops, the soil resolidifies and regains capacity to resist static loads. In addition, the solidified soil forms a free surface defining the new topography of a given site.

Generic Simulations

I present the results of two simulations below that were generated to demonstrate two modeling aspects of the slope stability problem. The first simulation shows the effect of rainfall infiltration on the stability of an unsaturated slope using finite element modeling. In the second example the debris flow process using CFD is simulated by treating the moving debris as a viscous fluid.

In the first example, a 2 m thick soil layer is resting on a 30-degree slope (Figure 1). Beneath this soil layer is rigid, impermeable bedrock. The initial water table lies 1.5 m from the surface in the bed-normal direction, dividing the soil layer into two parts: a fully saturated region and a partially saturated region. The soil is assumed to be normally consolidated, using the critical state soil model I described (Borja, 2004). The lower boundary of the domain is assumed rigid and impermeable, while the upper boundary has a prescribed flux due to rainfall infiltration. At the left and right boundaries, constraints are introduced so that the displacements and pressures at these two faces are equal. The result is that the domain is effectively periodic in the bed-parallel direction. For example, fluid flowing out of the domain at the lower end is exactly balanced by fluid flowing in at the upper end. The resulting simulation captures the behavior of an infinite slope, becoming a one-dimensional problem with variation only in the bed-normal direction.

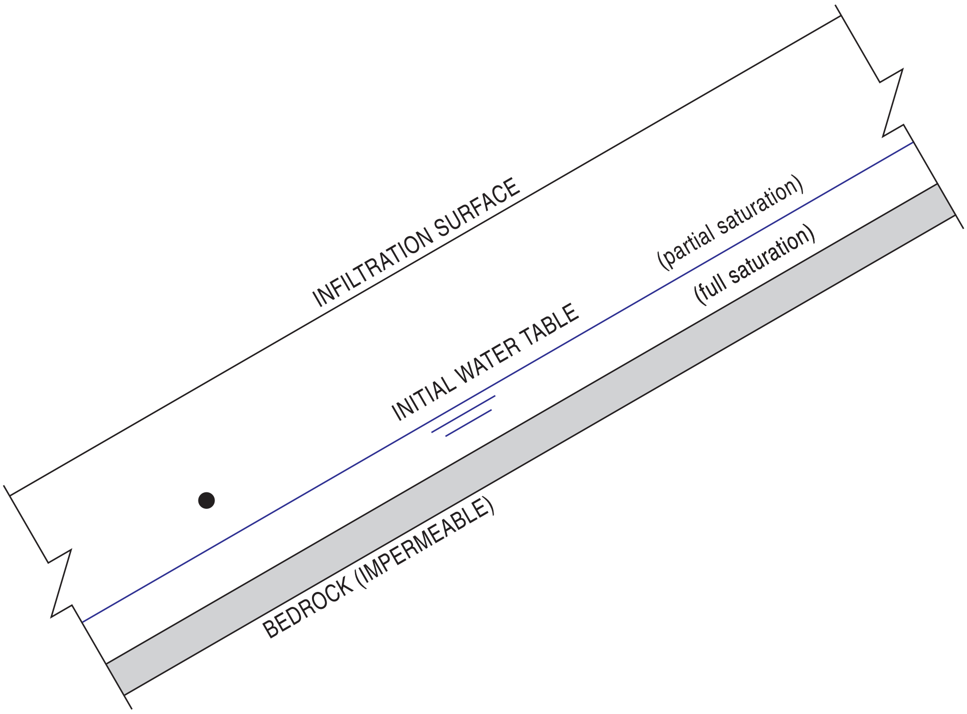

Figure 1: Problem geometry for a generic infinite slope subjected to rainfall infiltration and seepage.

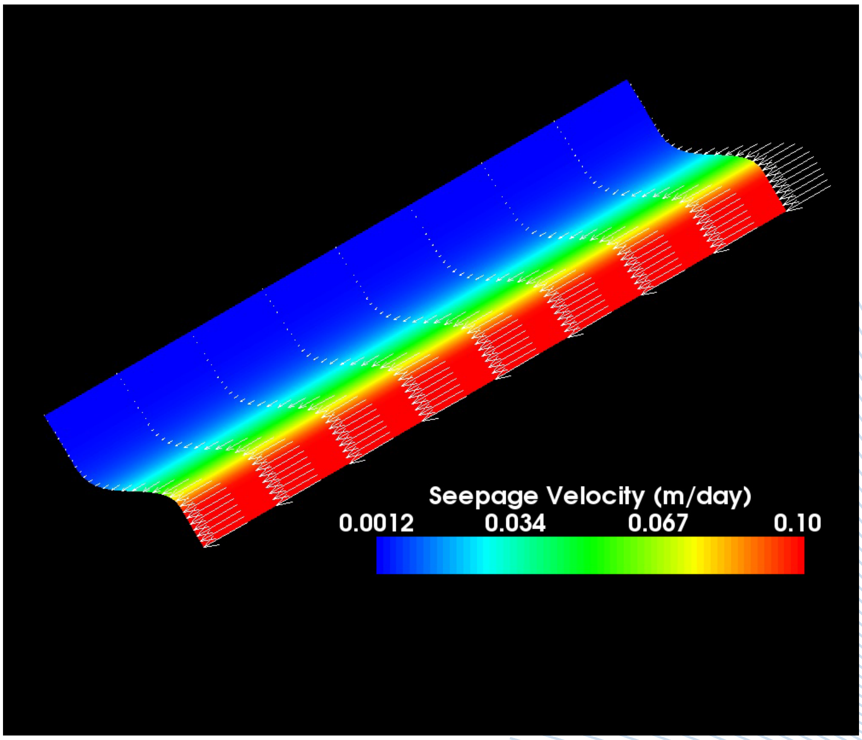

Figure 2: Seepage velocity in a generic infinite slope. Maximum seepage velocity occurs in the saturated region (red zone)

The numerical simulation utilizes mixed finite elements in which the displacement and pore pressure degrees of freedom are coupled by the governing field equations. A stabilized finite element formulation is employed to allow the same (low-order) bilinear interpolation for these two degrees of freedom to be used, based on the developments presented by White and Borja (2008). As the simulation proceeds, the infiltrating rainfall leads to local increases in saturation throughout the domain, as well as increased groundwater flow, shown in Figure 2. This, in turn, leads to a weakening of the soil and plastic deformation localized in the transition zone between the unsaturated and fully saturated regions. Ultimately, this deformation forms a distinct tabular shear band, as shown in Figure 3. At the conclusion of the simulation, the slope loses all its residual strength and fails along the weakened zone.

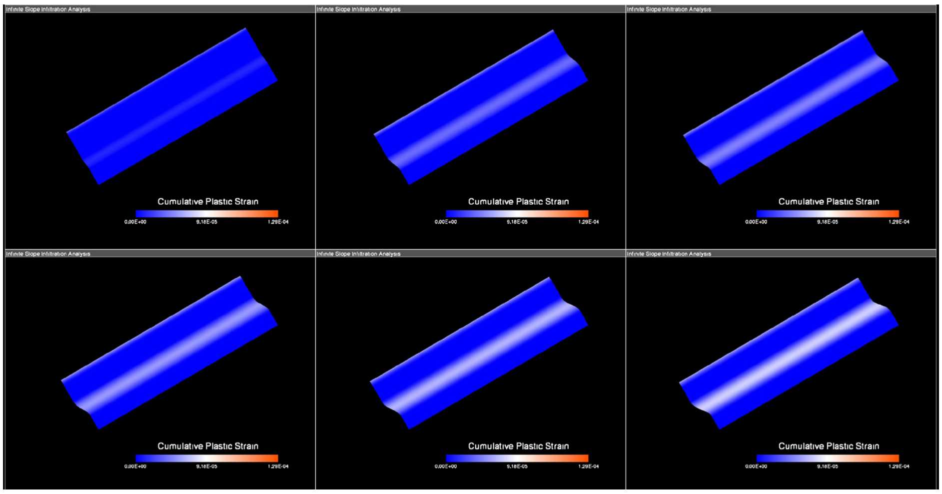

Figure 3: Progressive development of plastic shear zone in an infinite slope subjected to rainfall infiltration. Plastic deformation (white region) concentrates in the transition zone between the partially saturated and fully saturated regions.

The second example involves simulation of debris flow, and once again this problem is addressed by continuum modeling. Because the problem of debris flow entails very large deformation, we employ a Eulerian framework for the dynamic equation of equilibrium to avoid severe mesh distortion. The equilibrium equations are approximated by the finite difference (FD) method. In addition, we use the Constrained Interpolation Profile (CIP) method described by Yabe and Aoki (1991) and Yabe et al. (2001) to achieve an accurate approximation of the advection phase of velocity, and the Tangent of Hyperbola for Interface Capturing (THINC) technique proposed by Xiao et al. (2005) to treat the free surface generated by the flow process. In order to describe the flow behavior of flowing sediment, the Mohr-Coulomb failure criterion is introduced as the yield shear strength of the non-Newtonian fluid, treated as a Bingham fluid. By adjusting the values of the internal friction angle and the cohesion, suitable flow behavior of debris flow can be described.

Figure 4 shows snapshots of a two-dimensional debris flow simulation in which the red region is the flowing soil mass. We have used 20,000 calculation grids (200 by 100 grid points) with a non-slip boundary condition on the ground. An implicit time integration algorithm is used to define the evolution of the solution with time. Through simulations such as the one shown in Figure 4, we can quantify the spatial and temporal evolutions of sediment velocity, travel distance, and final surface configuration. In addition, we can define a new surface topography that may be of interest to surface geologists. The above simulations can also be used to assess the feasibility of various countermeasures for engineering applications. For example, we can estimate the impact force that flowing sediment can generate on a retaining wall and use this calculated force to design this retaining structure.

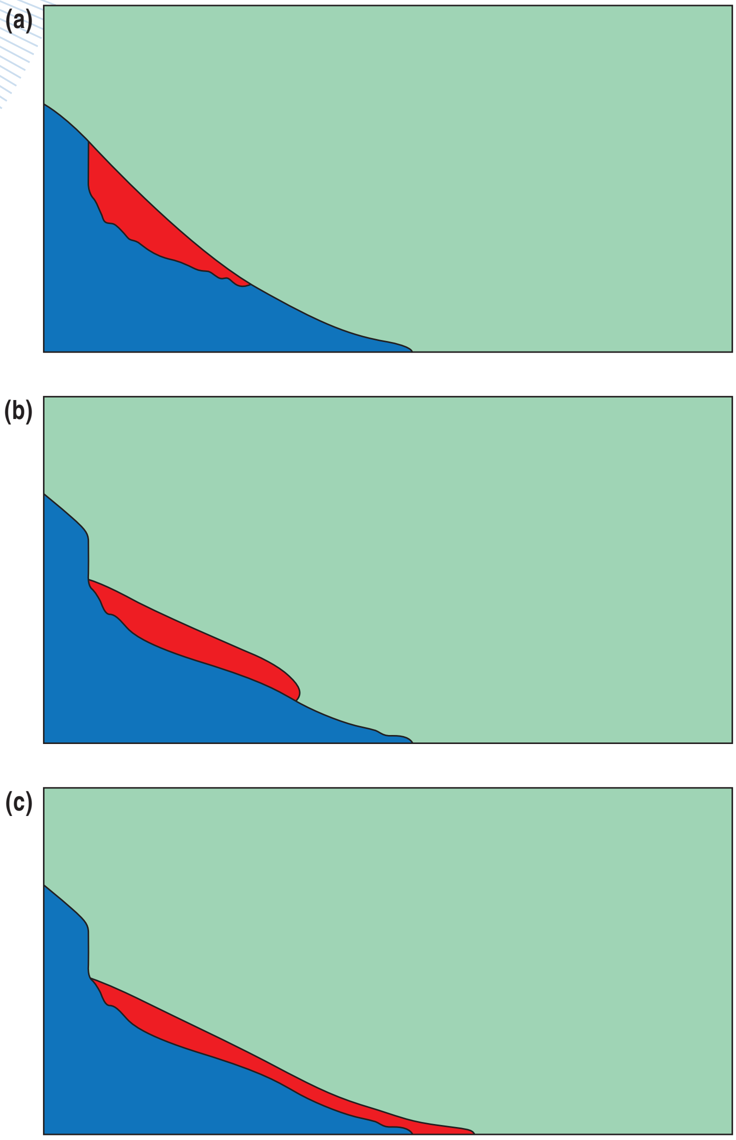

Figure 4: Simulation of two-dimensional debris flow using a Eulerian formulation. Red zone is the debris flow domain modeled as a non-Newtonian fluid; dark blue region is competent rock.

Closure

Rainfall infiltrates initially unsaturated earthen slopes causing the saturation to increase, thereby weakening the slope. Increased saturation reduces the capillary pressure and weakens the soil. Furthermore, seepage creates frictional drag on the soil matrix that also weakens the slope. A physics-based characterization is needed to accommodate these factors in the assessment of slope stability. In this article I have described a continuum approach to modeling and simulating landslide and debris flow initiation in initially unsaturated slopes. I have also described a numerical approach for simulating debris flow based on the Eulerian framework. Having these simulation tools at our disposal will assist the engineer in designing remedial schemes and assessing the feasibility of various countermeasures for slope stabilization. Furthermore, numerical simulation of actual debris flow could be of scientific value to geologists interested in unraveling historical events that shape the surface of the Earth.

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Insights

Insights is edited by Susan J. Smith, IAS Director and Professor of Geography.
Correspondence should be directed to Audrey Bowron (a.e.bowron@durham.ac.uk).