Groundwater Flow Systems and Slope Stability: A Historical Perspective

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ABSTRACT
Terzaghi's Law of Effective Stress identified the critical role of pore pressure in reducing the effective stress in slopes. It is inconceivable today to consider problems of slope stability and landslide susceptibility without reference to it: i.e., if the effective stress is reduced without a change in total stress, an increase in pore pressure must be responsible. The three-dimensional distribution of pore pressure or hydraulic head beneath a slope defines the prevailing groundwater flow system, therefore groundwater flow systems in landslide-prone areas are of interest to both geotechnical engineers and hydrogeologists. This issue was brought to life in the 1970s by the work of Deere and Patton and has now incorporated advances in unsaturated soil mechanics, geologically heterogeneous flow systems and poroelastic theory.

RÉSUMÉ
Loi de stress du Terzaghi effectif identifié le rôle essentiel des pores de pression dans la réduction du stress efficace dans les pentes. Il est aujourd'hui inconcevable pour examiner les problèmes de stabilité de la pente et de sensibilité de glissement de terrain sans référence à celle-ci. C'est, si le stress efficace est réduit sans un changement total de stress, une augmentation de la pression des pores doit être chargée. La distribution en trois dimensions des pores pression ou hydraulique tête sous une pente définit le système d'écoulement des eaux souterraines en vigueur, systèmes d'écoulement des eaux souterraines dans les zones sujettes aux glissements de terrain sont donc d'intérêt pour les ingénieurs de géotechnique et hydrogéologues. Ce problème a été apporté à la vie dans les années 1970 par le travail de Deere et Patton et a maintenant incorporés avances en mécanique des sols insaturés, systèmes de flux géologiquement hétérogènes et théorie poroelastic.

1 INTRODUCTION

According to Sidle and Ochiai (2006, Table 1.1), the vast majority of the most destructive landslides of the past century have been triggered either by the infiltration of rain or snowmelt into permeable sloped terrain or by earthquakes or some combination of both.

The Third Hans Cloos Lecture by Schuster and Highland (2007) to the International Association of Engineering Geology and the Environment concerned the great risk of rainfall-induced landslides incurred by urban development on hillsides in Rio de Janeiro, Brazil, Hong Kong, China, Los Angeles and San Francisco, California and Caracas, Venezuela among other places. These have caused immense loss of life and property. Here in western Canada the concern is often more focused on the hazards that landslides play in the blocking of transportation corridors in Alberta and British Columbia. However, Hungr (2004) estimated that the loss of life in British Columbia from landslides is three persons per year.

The link between the water pressures in soils and rock discontinuities and the consequent slope instability was based upon Terzaghi's work pre-World War II. However, Krynine and Judd (1957) devoted less than a page of their textbook *Principles of Engineering Geology and Geotechnics* to the matter of "Sliding Caused by Pore Pressure." Similarly, in their textbook *Soil Mechanics*, Lambe and Whitman (1969) simply identified the likelihood of slope instability caused by rapid drawdown of an adjacent water body resulting in high shear stress when low permeability soils form the slope.

However, since the 1970s much progress has been made in understanding the link between slope stability and hydrogeological processes such that Wyllie and Mah's (2004) revision of Hoek and Bray's *Rock Slope Engineering* (1974) noted that "by far the most important effect of groundwater in a rock mass is the reduction in stability resulting from water pressures within the discontinuities." Therefore, the association appears now well established among geotechnical engineers and engineering geologists that water infiltration into permeable sloped terrain may initiate slope instability and lead to potential loss of life and property. But the appreciation of the hydrogeological setting of sloped terrain with its potential to cause slope instability – i.e., the spatial distribution of hydraulic head and hydraulic conductivity in sloped terrain rather than the mere measurement of pore pressure – is a more subtle issue that is critical to landslide studies and which is the theme of this paper.

2 AMONTON'S LAW OF FRICTION

The theoretical basis for this discussion is the nature of the forces on an inclined plane, perhaps an unstable soil slope or a fracture within a rock mass, and their vectorial representation. Figure 1 shows the components of force on a block of soil or rock that has just started to slide down a plane inclined at an angle θ. The two components of the force (F) caused by this mass (m) are, firstly in the down-slope direction relative to the inclined plane:

$$F_t = mg \cdot \sin\theta \qquad [1]$$

and secondly acting normal to the inclined plane:

$$F_n = mg \cdot \cos\theta \qquad [2]$$

The frictional resistance to sliding is given by Amonton's Law. As the inclination of the plane is increased, the frictional force per unit area, $\tau(f_s)$ at which the block begins to slide is therefore:

$$\tau(f_s) = \{f_s \cdot F_N\} / A \qquad [3]$$

where A is the contact area between the sliding block and the slope and f_s is the is the coefficient of static friction. Turcotte and Schubert (2002) show that $f_s \sim 0.85$ for a variety of very different rock types under drained conditions, i.e., the pore pressure is zero.

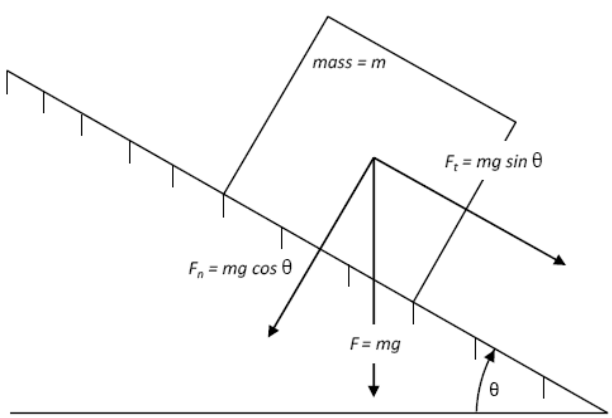

Figure 1. Amonton's Law of Friction.

Terzaghi's law of effective stress can be incorporated into Amonton's law of friction such that:

$$\tau = f_s\,(\sigma_N - p_w) \qquad [4]$$

where σ_N is the effective normal stress acting on an inclined plane, which is water saturated, and p_w is the pore pressure within the plane. Thus increased pore pressure results in a decrease in frictional resistance to sliding.

As pointed out by Hodge and Freeze (1977), Terzaghi had already shown that Coulomb's Law would mean that an increase in pore pressure in a slope would reduce the shear strength of the soil by reducing the effective stress:

$$\tau = c_e + \sigma_e \tan\phi_e$$

where τ is the shear strength of the soil, c_e is the effective cohesion, σ_e is the effective stress and ϕ_e is the effective angle of internal friction.

Hoek and Bray (1974) presented an example of a symmetrical wedge failure in a pit slope, in which both surfaces of the wedge dip at 45˚ to the slope face and have friction angles of 30˚ and cohesive strengths of 4880 kg/m^2. Hoek and Bray showed that for a slope face ≥64˚ the slope will fail under saturated conditions, i.e., the factor of safety (FS) ≤1.0, whereas the same slope when drained never falls below FS=1.2. Goodman and Bray (1976) developed stability curves for toppling blocks under dry conditions and subsequently Cho and West (2000) developed them for conditions in which the pore pressure was non-zero.

3 GROUNDWATER FLOW SYSTEMS

While the association of groundwater pressure with slope instability may be traced back to Terzaghi's practice, the spatial distribution of pore pressure and hydraulic head within sloped terrain to slope failure is of a more recent understanding. Regional groundwater flow systems extend flow-net analysis to heterogeneously permeable slopes.

In 1940, M.K. Hubbert presented a conceptual model of gravity-driven groundwater flow in a regional setting. Hubbert's (1940) flow system, which is shown in Figure 2, is the result of steady-state groundwater flow from regional uplands to lowland streams. Hubbert (1940) identified the driving force as the fluid potential, Φ, that is the sum of the pore pressure and the topographic elevation of the measuring point (i.e., a piezometers) relative to a datum such as sea level.

Working in Alberta and Saskatchewan in the 1960s, Meyboom, Toth and Freeze further developed the concept of steady-state, gravity-driven groundwater flow systems to include the effects on the hydraulic-head distribution of heterogeneous formations within the flow system. Such features would cause groundwater discharge to occur in areas different from those predicted by Hubbert's simple model and the measurement of hydraulic heads that were initially difficult to explain (see Freeze and Cherry, 1979 and Toth, 2009).

By resorting to numerical flow models, Freeze simulated steady-state flow systems containing heterogeneous layered formations, see Figure 3. Each formation has an anisotropic ratio in hydraulic conductivity of K_x/K_y of 100 and the shaded formations are 100 times more permeable than the rest of the basin. Thus upland recharge with a hydraulic head of 1000 cm is directed downwards towards high permeability formations that distribute flow towards discharge areas present where the water table intersects the toe of the valleys in the basin. The discharge areas have heads of about 900 cm at point G, which constitutes a local discharge area, and 550 cm at point A, a regional groundwater discharge area and likely a perennially flowing river.

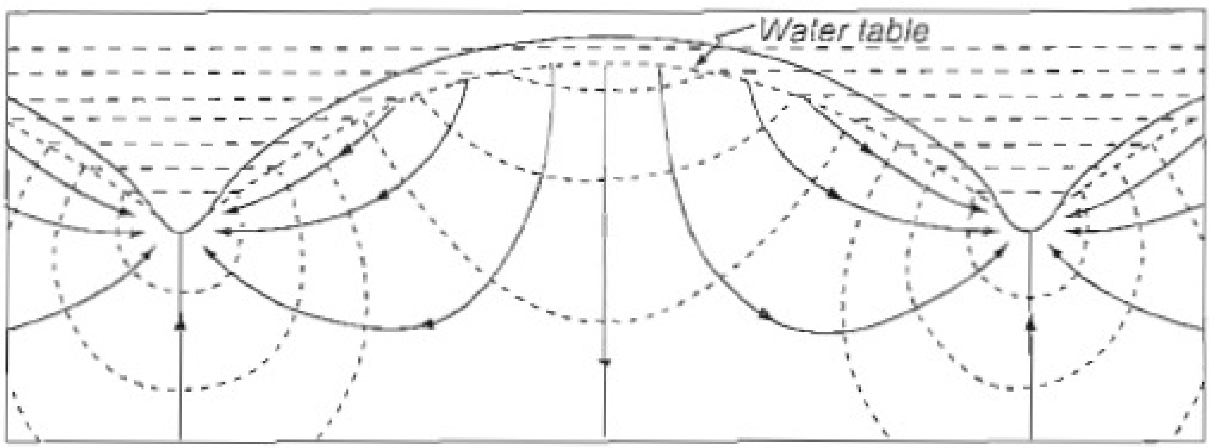

Figure 2: Hubbert's (1940) Figure 45 with the caption that read "Approximate flow pattern in uniformly permeable material between the sources distributed over the air-water interface and the valley sinks."

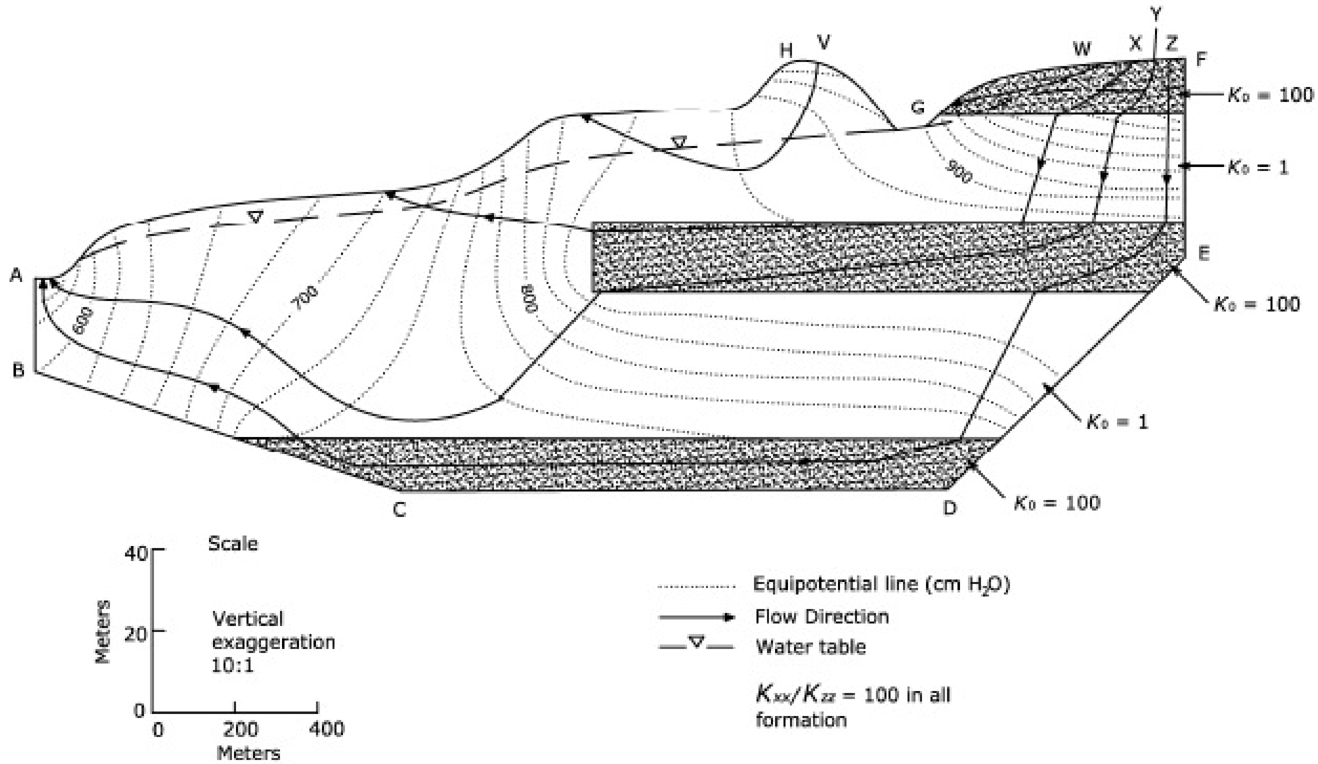

Figure 3: Steady-state regional flow in a vertical cross section through a groundwater basin (from Freeze, 1972).

4 HISTORICAL DEVELOPMENT

4.1 Deere and Patton

It appears that the first explicit treatments of slope stability in this hydrogeological context were in symposium papers by D.U. Deere and F.D. Patton of the University of Illinois given in 1970. The context of their work was slope stability in open-pit mines (Patton and Deere, 1971a, b) and in residual soils (Deere and Patton, 1971).

Patton and Deere (1971a) was presented in South Africa and identified three principal types of slope failure in open pit mines: (1) local failures involving a single bench, (2) large-scale wedge failures involving several benches, and (3) failures of sheared and decomposed rock involving several benches. Within this analysis, Patton and Deere indicated that the motivation for studying the groundwater flow system was "to determine if the mine will be located in a regional groundwater recharge area, a discharge area or in some intermediate area".

Figure 4 presents their elementary flow systems. They recognised that the high pore pressures likely to be encountered in discharge areas would create a greater risk of slope failure. Furthermore, they pointed out that mine drainage systems would necessarily require an understanding of the regional flow system before any successful design could be undertaken. Therefore, they concluded that "knowledge of the regional flow system is the starting point for understanding fluid pressures in a mine pit."

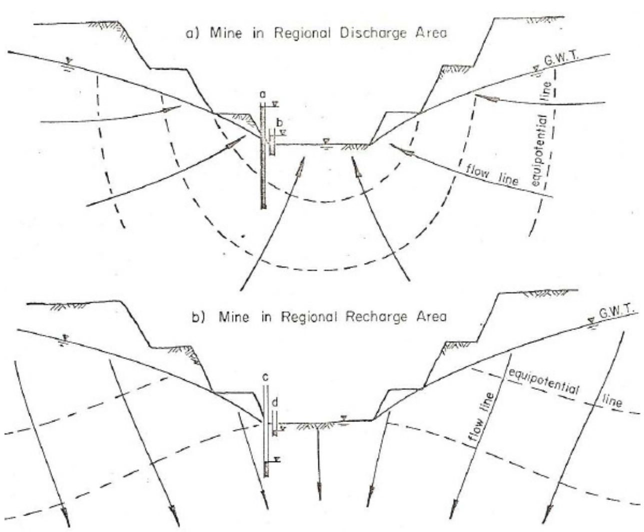

Figure 4: Open pit mines in different parts of a groundwater flow system (from Patton and Deere, 1971a,b)

In the mid 1970s, Patton encouraged an employee, R.A.L. Hodge, to develop this topic during his graduate studies with R.A. Freeze at the University of British Columbia. Consequently, the first peer-reviewed paper on the topic was published in the *Canadian Geotechnical Journal* by Hodge and Freeze in 1977 under the title 'Groundwater Flow Systems and Slope Stability'. Numerical simulation allowed consideration of a much increased complexity of hydraulic conductivity contrasts, as Figure 3 demonstrates.

The next major contribution to this issue was the forensic analysis of the Vaiont Slide in northern Italy by Hendron and Patton (1985) for the US Army Corps of Engineers. In an earlier analysis written prior to Deere and Patton's 1970 papers, Kiersch (1964) of Cornell University had noted the importance of the hydrogeological factors associated with the 1963 slide that produced a flood wave that overtopped the new dam and killed almost 3,000 people down-valley. While Kiersch's article in *Civil Engineering* was subtitled 'Geologic causes of tremendous landslide accompanied by destructive flood wave', Hendron and Patton identified the importance of the hydrogeology of the south slope of the reservoir and of the clay interbeds that formed the failure surface of the October 1963 landslide.

Hendron and Patton's schematic section through the Vaiont Valley (Figure 5) presented a conceptual model of the flow system with a karst recharge area and bedding planes dipping in the direction of the slide and parallel to groundwater flow. The discharge area was characterised by interbedded clay-rich units that interfered with the flow resulting in elevated pore pressures in a zone that was critical for slope stability. The effect of the weak clay interbeds was to produce "an inclined multiple-layer artesian aquifer system at and below the surface of sliding" (Hendron and Patton, 1985, p.93).

Figure 6 presents the simultaneous time series of reservoir level, a piezometer installed into the soon-to-fail slide mass and the rate of benchmark movement on the surface of the slide mass prior to its failure in October 1963. The reservoir level reflects the precipitation falling on the watershed and intentional reservoir lowering as a remedial measure. These data from Hendron and Patton (1985) are among the first published showing the relationship between a failing slope and the pore pressures that preceded its failure. Bull (2009) has pointed out that in California "the onset of heavy rains rarely triggers widespread hillslope failures", rather it is the accumulation of infiltration raising the water table and pore pressures that leads to eventual slope failure. The steady rise of the pore pressure in the piezometer shown in Figure 6 and the simultaneous rise in benchmark movement substantiate that point.

4.2 USGS' Investigations of Slope Failure Potential

The US Geological Survey was quite slow to develop a hydrogeological view of slope stability. For example, it had long studied the Slumgullion earth flow in south-western Colorado (Varnes and Savage, 1996) but by 1996 had not even obtained measurements of pore pressure partly because of the difficulty of drilling into the slide and installing piezometers. More recent analysis of the earth flow demonstrated a strong hydrologic effect on its rate of movement of 1-2 m/yr. However the flow system within the earth flow and the underlying bedrock apparently remains undefined (Savage et al., 2003).

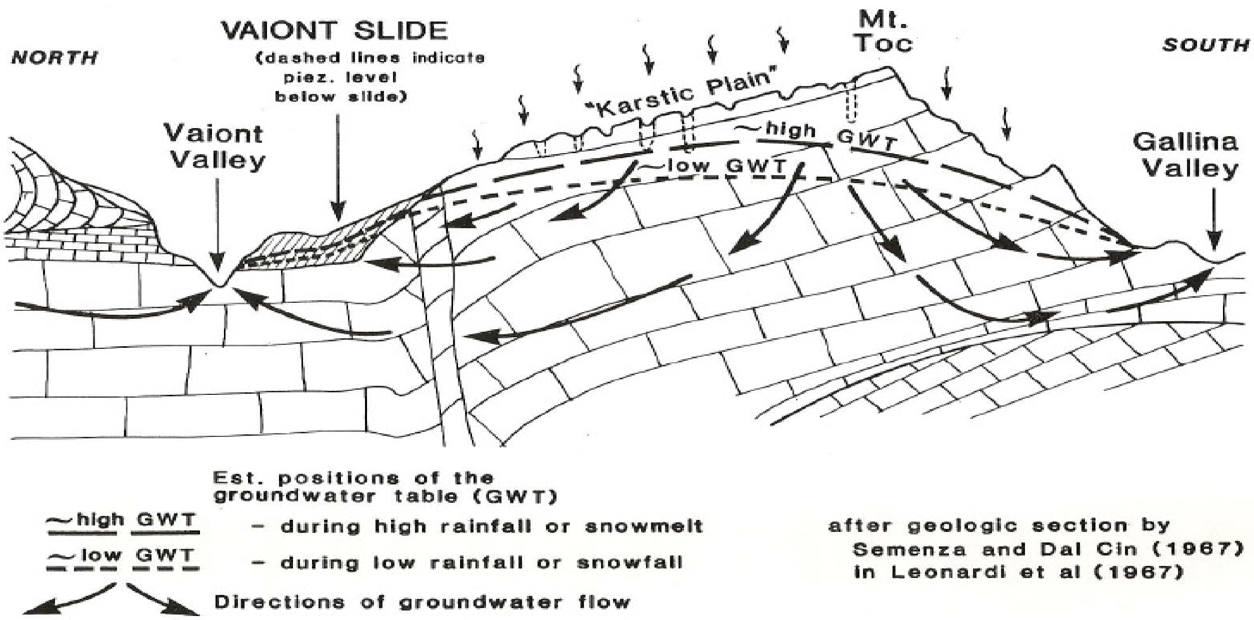

Figure 5: Schematic groundwater flow system through the Vaiont Valley showing the hypothetical groundwater flow system (from Hendron and Patton, 1985)

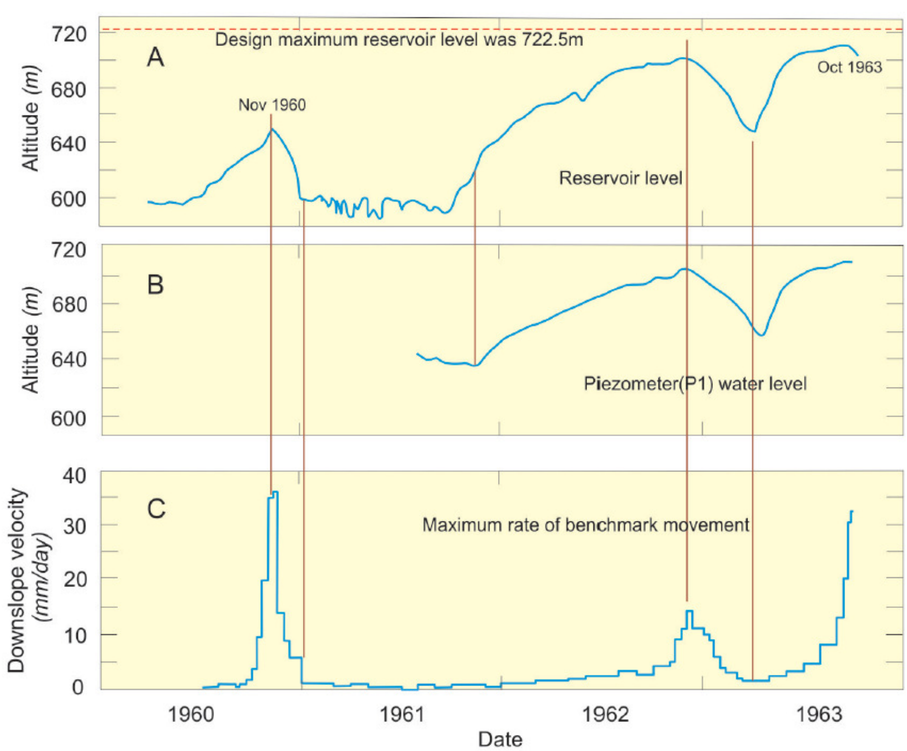

Figure 6: Reservoir and piezometer hydrographs and benchmark displacement prior to the catastrophic landslide into the Vaiont reservoir, Italy, October 9, 1963 (data from Hendron and Patton, 1985, figure after that of Bull, 2009).

Iverson and Reid of the USGS (1992) set out to examine how topography affects both gravitational groundwater flow and effective stress fields. They saw their work as linking hydrogeology and geomorphology, although the link to geotechnical engineering is obvious. Iverson and Reid included poroelastic effects in their models of groundwater flow systems and introduced the concept of the Coulomb failure potential, which they defined as the ratio of maximum shear stress to effective normal stress. They concluded that groundwater flow in a fully saturated, homogeneous hillslope with elastic strain would cause the greatest slope failure to occur at the slope toe.

In a companion paper, Reid and Iverson (1992) used this same numerical model to examine the effects of slope morphology (e.g., straight, convex, concave) and hillslope properties (Poisson's ratio, porosity, hydraulic conductivity contrasts). They found the geometry of layered heterogeneities in the hydraulic conductivity to be especially important in affecting the seepage force field. Therefore, not only are the toes of slopes susceptible to strong outward seepage forces, but also any low permeability heterogeneity in the flow system is likely to cause a similar seepage face with concomitant increase in slope failure potential.

More recently Iverson (2000) has considered the issue of landslide initiation by rain infiltration in terms of a pressure head response function that modifies a rainfall input and an initial pore pressure distribution to produce a transient pore pressure distribution. Then Iverson proceeded to develop a dimensionless factor of safety that has friction, pressure head and cohesive terms. The pressure head distribution in the second term dictates the hydrogeological effects on slope stability. This work constitutes the present state-of-the-art in groundwater flow system studies of slope stability.

4.3 Partially Saturated Flow Systems

Finally, the incorporation of matric suction (negative pore-water pressure) measurements into slope stability calculations by workers in Hong Kong in the early 1980s and more recently by the Unsaturated Soil Mechanics group at the University of Saskatchewan has broadened our understanding of the links between groundwater hydrology, soil mechanics and slope stability.

Studies in the early 1980s of the highly weathered residual soils covering hillsides in Hong Kong throughout the rainy season (cited by Zhang et al., 2004) indicate that the persistence of negative pore-water pressures has been known for nearly 30 years. Zhang et al. (2004) showed that the pore-water pressure profile is a function of rainfall intensity, the saturated hydraulic conductivity of the soil, the soil-water characteristic curve and the water storage function. Soils with low saturated hydraulic conductivity and a large water storage function can maintain matric suction for periods likely to outlast a rainstorm and thus prevent fully saturated conditions from developing leading to slope failure.

5 DISCUSSION AND CONCLUSION

The continuing evaluation of the causes of the Vaiont disaster by the geotechnical community – engineers and geoscientists alike (see Genevois and Ghirotti, 2005 and references therein) – has lead to a much greater appreciation of how hydrogeological phenomena affect slope stability. The geotechnical engineering community has incorporated flow system theory and unsaturated zone hydrology into modern practice. As the size of any slope increases, the properties and geometry of the groundwater flow system beneath the slope become much more important because the potential presence and influence of subsurface heterogeneities increases substantially. Modern practice now incorporates not just inclinometers but also sophisticated multi-level piezometer systems of the kind developed by Patton (2006) and originally used to instrument the Downie slide near Revelstoke, B.C.

Not only instrumentation but also numerical simulation of groundwater flow in sloping, heterogeneous terrain has strongly progressed during the years since the Vaiont disaster. The approach used by Hodge and Freeze (1977) has spawned several recent and notable applications. Eberhardt et al. (2007) measured and simulated hydraulic heads within a creeping landslide in fractured and weathered crystalline rock in Switzerland to test the efficacy of a drainage adit to minimize further creep. Clarke et al. (2008) investigated an excavation-induced slope failure in a drumlin along the Dublin-Belfast motorway and demonstrated that the excavation was responsible for changing the groundwater flow pattern in such a way to induce a landslide. Eshragian et al. (2008) undertook steady-state and transient simulations to determine the mode(s) of failure for two landslides along the Thomson River in British Columbia. In addition, there is now consideration of unsaturated zone hydrology and soil mechanics, e.g., Blatz et al. (2004).

It is apparent that the investigation and simulation of regional and local groundwater flow system following the work of J. Toth (see Toth, 2009), formerly of the University of Alberta, and R.A. Freeze, formerly of the University of British Columbia (see Freeze and Cherry, 1979; Hodge and Freeze, 1977), can immensely aid geotechnical engineering studies whether it is of reservoir slopes in the Swiss Alps or of transportation corridors through permeable sloped terrain in Europe and Canada.

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