PROCEEDINGS OF THE SIXTH INTERNATIONAL SYMPOSIUM
COMPTES RENDUS DU SIXIEME SYMPOSIUM INTERNATIONAL
10-14 FEBRUARY 1992 / CHRISTCHURCH / 10-14 FEVRIER 1992

Landslides
Glissements de terrain

Editor/Rédacteur

DAVID H. BELL
Geology Department, University of Canterbury, Christchurch
New Zealand / Nouvelle Zélande

OFFPRINT

A.A. BALKEMA / ROTTERDAM / BROOKFIELD / 1992

Landslides, Bell (ed.) © 1991 Balkema, Rotterdam. ISBN 90 5410 032 X

Sensitivity of stability analyses to groundwater data

Richard M. Iverson
US Geological Survey, Vancouver, Wash., USA

ABSTRACT: Serious errors in limit-equilibrium slope-stability analyses can result from use of groundwater data that are inadequate or incorrectly interpreted. This paper assesses the causes and effects of these errors for statically determinate, infinite slopes. Despite their geometric simplicity, infinite slopes can exhibit a limitless variety of groundwater-flow fields and pore-pressure effects. The geometry of subaerial infinite slopes constrains the direction of the pore-pressure gradient to be normal to the ground surface, but it does not constrain the gradient magnitude. Lacking adequate data on the gradient magnitude, infinite-slope analyses routinely employ assumptions about groundwater, such as that of slope-parallel flow. As a consequence, factor-of-safety estimates can err by as much as 50%.

1 INTRODUCTION

Despite the widely acknowledged importance of groundwater in contributing to slope instability, few studies have systematically evaluated the sensitivity of slope-stabiltity analyses to groundwater information. Furthermore, controversy persists over how groundwater effects should be incorporated in limit-equilibrium analyses of slopes (King, 1989, 1990; Morrison and Greenwood, 1989, 1990). Physical issues concerning groundwater effects have been clouded by mixing them with the procedural issues that are inherent to limit-equilibrium methodology.

As part of a broader effort to understand groundwater effects on slope stability (cf. Iverson and Reid, 1991), this paper systematically quantifies groundwater effects in a general limit-equilibrium analysis of infinite slopes. Infinite-slope analyses hold the unique advantage of static determinacy, and they consequently require no assumptions other than that of a planar, one-dimensional slope. Furthermore, the infinite-slope analysis described here allows for the possibility of hydraulic heterogeneity and anisotropy. It identifies geometric constraints on the pore-pressure gradient in an infinite slope, and it shows why knowledge of both this gradient and the water-table depth is essential in making limit-equilibrium calculations. The analysis illustrates the sensitivity of factors of safety to the pore-pressure gradient, as well as the potential for egregious error if groundwater data are inadequate or incorrectly interpreted. Some of the insights drawn from this infinite-slope analysis also apply to more complex limit-equilibrium analyses, because an infinite slope can be viewed as a single, isolated slice in a slope of more complex geometry.

2 FACTOR-OF-SAFETY EQUATION

Consider a state of static equilibrium in an infinite slope, which is inclined at the angle θ. Slope-parallel and slope-normal Cartesian coordinates originate on the surface of the slope and are designated x and y (figure 1). Employing these coordinates, the well-known Cauchy equations for effective-stress equilibrium reduce to a simple form required by the infinite-slope geometry (cf. Iverson and Major, 1986; Iverson and Reid, 1991):

$$d\sigma'/dy = \gamma_t\cos\theta - \gamma_w\cos\theta - \gamma_w\overline{(\partial h/\partial y)} \quad (1a)$$

$$d\tau/dy = \gamma_t\sin\theta - \gamma_w\sin\theta - \gamma_w\overline{(\partial h/\partial x)} \quad (1b)$$

in which σ' is the effective normal stress (positive in compression) acting in the y direction, τ is the shear stress acting in the x direction on planes

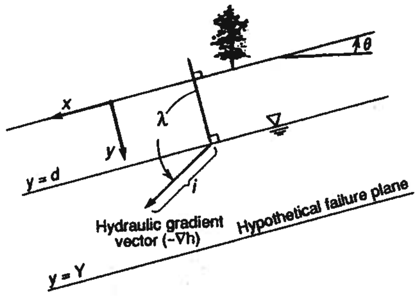

Fig. 1 Infinite slope with variables defined

normal to y, γ_t is the total unit weight of the soil, γ_w is the unit weight of the pore water, h is the hydraulic head of the pore water, and $\overline{\partial h/\partial y}$ and $\overline{\partial h/\partial x}$ are the mean magnitudes of the y and x components of the hydraulic head gradient. The three body-force terms on the right-hand sides of (1a) and (1b) have simple physical interpretations: the first term is due to the total weight of the soil, the second is due to the hydrostatic buoyancy force that partially counteracts the weight of the soil, and the third is due to the hydrodynamic seepage force associated with groundwater flow. The force due to the soil weight acts throughout the soil, which extends in depth from y=0 to y=Y, whereas the buoyancy and seepage forces act only below the water table, which exists at depth y=d (figure 1). The total unit weight of the soil is defined rigorously by

$$\gamma_t = \frac{1}{Y}\left[\int_0^d \gamma_u dy + \int_d^Y \gamma_s dy\right] = \frac{1}{Y}[\overline{\gamma_u}d + \overline{\gamma_s}(Y-d)] \tag{2}$$

in which γ_u is the unit weight of the unsaturated soil above the water table, γ_s is the unit weight of the saturated soil below the water table, and overbars denote mean values of these quantities. Like the definition of γ_t above, definitions of the mean hydraulic gradients $\overline{\partial h/\partial y}$ and $\overline{\partial h/\partial x}$ used in (1a) and (1b) can be given in terms of definite integrals. The integrals account implicitly for the effects of hydraulic heterogeneity and anisotropy, as shown in detail by Iverson (1990).

Simple expressions for the effective normal and shear stresses at depth Y result from integration of (1a) and (1b) over the depth interval y=0 to y=Y:

$$\sigma' = [\gamma_t Y - \gamma_w(Y-d)]\cos\theta - \gamma_w(\overline{\partial h/\partial y})(Y-d) \tag{3a}$$

$$\tau = [\gamma_t Y - \gamma_w(Y-d)]\sin\theta - \gamma_w(\overline{\partial h/\partial x})(Y-d) \tag{3b}$$

The limit-equilibrium factor of safety (FS) at depth Y is given by the ratio of resisting stress to driving stress, as expressed by the Coulomb failure rule:

$$FS = \frac{\sigma'\tan\phi + c}{\tau} \tag{4}$$

in which ϕ is the soil's angle of internal friction, and c is its cohesion. Both ϕ and c are assumed to be constant. Substitution of (3a) and (3b) into (4) and division of the resulting numerator and denominator by $\gamma_t Y$ yields a normalized expression for the limit-equilibrium factor of safety in an infinite slope with an arbitrary groundwater-flow field:

$$FS = \frac{[(1-\Gamma)\cos\theta - \Gamma(\overline{\partial h/\partial y})]\tan\phi + \dfrac{c}{\gamma_t Y}}{(1-\Gamma)\sin\theta - \Gamma(\overline{\partial h/\partial x})} \tag{5}$$

in which $\Gamma = (\gamma_w/\gamma_t)[1-(d/Y)]$. With FS=1, (5) can be solved for the hypothetical failure-plane depth, Y. It then represents an alternative form of the limit-equilibrium equation of Iverson and Major (1987).

Equation (5) can be simplified because the infinite-slope geometry imposes constraints on the components of the hydraulic head gradient, $\overline{\partial h/\partial y}$ and $\overline{\partial h/\partial x}$. The hydraulic head in an infinite slope is described by

$$h = \frac{p}{\gamma_w} - y\cos\theta - x\sin\theta \tag{6}$$

in which p is the pore-water pressure and $-y\cos\theta - x\sin\theta$ is the vertical elevation with respect to a horizontal datum that passes through the origin (figure 1). Because the water table in a subaerial infinite slope necessarily parallels the ground surface, the x component of the hydraulic head gradient equals the elevation gradient along the ground surface, and $\partial p/\partial x = 0$ (Iverson, 1990). Consequently, from (6) it follows that

$$\overline{\partial h/\partial x} = -\sin\theta \tag{7a}$$

$$\overline{\partial h/\partial y} = \frac{1}{\gamma_w}\frac{\partial p}{\partial y} - \cos\theta \tag{7b}$$

in which $\partial p/\partial y$ is the mean gradient of p between the water table and depth y=Y. In contrast to $\partial p/\partial x$, $\partial p/\partial y$ is constrained only by the requirement that both (7a) and (7b) are satisfied -- a requirement to be detailed in the next section.

A more concise version of the infinite-slope factor-of-safety equation results from substitution of (7a) and (7b) into (5):

$$FS = \frac{[\cos\theta + (\frac{d}{Y} - 1)\frac{1}{\gamma_t}\frac{\partial p}{\partial y}]\tan\phi + \frac{c}{\gamma_t Y}}{\sin\theta} \qquad (8)$$

It is convenient to express (8) as the sum of a friction term (T_f), groundwater term (T_w), and cohesion term (T_c):

$$FS = T_f + T_w + T_c \qquad (9a)$$

in which

$$T_f = \frac{\tan\phi}{\tan\theta} \qquad (9b)$$

$$T_w = \frac{[(d/Y) - 1](\partial p/\partial y)\tan\phi}{\gamma_t \sin\theta} \qquad (9c)$$

$$T_c = \frac{c}{\gamma_t Y \sin\theta} \qquad (9d)$$

Each of the terms in (9a-d) represents a dimensionless ratio of resisting stress to driving stress, and the magnitudes of the terms can be compared to evaluate the relative influence of friction, groundwater, and cohesion on the factor of safety. It is mandatory that $T_f \geq 0$ and $T_c \geq 0$, but typically $T_w < 0$ because $\partial p/\partial y > 0$ and $d/Y < 1$. Thus, the groundwater term typically reduces the factor of safety.

Over forty years ago Haefeli (1948) developed an equation analogous to (8), albeit in well-disguised form. However, the more commonly used infinite-slope equations, such as those of Taylor (1948), Skempton and DeLory (1957), and Graham (1984), are special cases of (8) that require additional assumptions – either that $\partial p/\partial y = \gamma_w \cos\theta$ (which implies that the hydraulic head gradient parallels the slope) or that $\partial p/\partial y = p/(Y-d)$ (which implies that p is known at depth Y).

3 INFINITE-SLOPE CONSTRAINTS ON $\partial p/\partial y$

Constraints on $\partial p/\partial y$ demanded by the infinite-slope geometry are considerably less stringent than the constraints implicit in the equations of Taylor (1948), Skempton and DeLory (1957), and Graham (1984). The mandatory infinite-slope constraints can be quantified by considering orthogonal vector components of the mean hydraulic head gradient, $\overline{\nabla h}$ (cf. Iverson and Major, 1986; Iverson and Reid, 1991). Designating i as the magnitude of $\overline{\nabla h}$, the x and y components of $\overline{\nabla h}$ are given by

$$\overline{\partial h/\partial x} = -i\sin\lambda \qquad (10a)$$

$$\overline{\partial h/\partial y} = i\cos\lambda \qquad (10b)$$

in which λ is the angular direction of $-\overline{\nabla h}$ measured with respect to an outward-directed surface-normal vector (figure 1). If the slope is hydraulically isotropic, λ specifies the direction of groundwater flow. Equating (10a) and (7a) yields

$$i = \frac{\sin\theta}{\sin\lambda} \qquad (11)$$

and substituting (11) into (10b) yields an expression for $\overline{\partial h/\partial y}$ that is substituted into (7b) to obtain

$$\frac{\partial p}{\partial y} = \gamma_w\left(\frac{\sin\theta}{\tan\lambda} + \cos\theta\right) \qquad (12)$$

This equation shows that $\partial p/\partial y$ in an infinite slope can be expressed as a function of λ without specifying i or $\overline{\nabla h}$. Moreover, because (7a) dictates that $-\overline{\nabla h}$ has a positive component parallel to the slope, it is necessary that $0 < \lambda < 180°$ (figure 1). These constraints place broad but important bounds on $\partial p/\partial y$ and its role in affecting slope stability.

Figure 2 depicts graphs of (12) that illustrate how $\partial p/\partial y$ (normalized by γ_w) varies as a function of λ for several values of the slope angle, θ. The figure shows that the condition $\partial p/\partial y > 0$ results for all cases in which $\lambda < 180° - \theta$, that is, for all values of λ smaller than that which specifies a vertically downward $-\overline{\nabla h}$. Thus, unless $-\overline{\nabla h}$ is vertically downward or directed more normally into the slope, $\partial p/\partial y$ is positive, T_w is negative, and groundwater tends to destabilize the slope. Figure 2 also shows that this destabilizing groundwater effect varies systematically as a function of the slope angle. Moreover, the destabilizing effect is most pronounced for small values of λ, because (12) requires that $\partial p/\partial y \to \infty$ as $\lambda \to 0$. This result contrasts with that of Iverson and Major (1986), whose limit-equilibrium analysis did not incorporate the infinite-slope water-table constraint given by (12). As a consequence, one of Iverson and Major's (1986) conclusions, that the value $\lambda = 90° - \phi$ universally produces a maximum destabilizing influence, does not rigorously apply to subaerial infinite slopes.

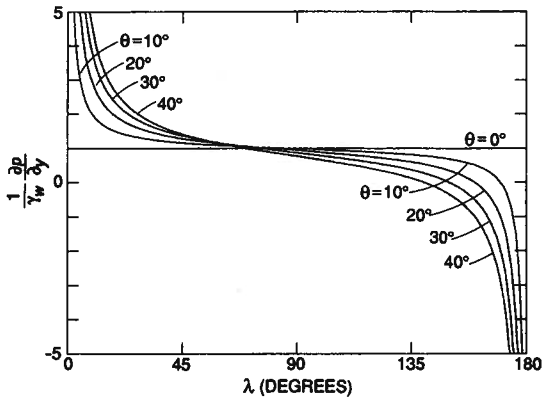

Fig. 2 Normalized pore-pressure gradient magnitude, $(1/\gamma_w)\partial p/\partial y$, as a function of the hydraulic gradient direction, λ, for infinite slopes with various inclinations, θ

4 EFFECT OF GROUNDWATER ON *FS*

A quantitative understanding of groundwater effects on slope stability can be gained by examining equations (9) and analyzing the influence of T_w, T_f, and T_c on the factor of safety. Equation (9d) shows that one effect of adding groundwater to a slope with cohesion is to reduce T_c and *FS* by simply increasing the total weight of the soil. However, (9c) shows that if there is no cohesion, this simple added-weight effect might either increase or decrease *FS*, depending on the change in d. A more interesting and generally more important effect of groundwater, its effect on friction, is represented by (9b) and (9c) together, because both T_f and T_w contain $\tan\phi$. In physical terms, groundwater generally reduces the effective normal stress, which in turn reduces friction. An assessment of this groundwater effect can be made by evaluating the relative contributions of T_w and T_f to the factor of safety, while disregarding any contribution of T_c.

The ratio T_w/T_f measures the relative contributions of groundwater and friction to the factor of safety. The ratio can be evaluated by combining (9b), (9c), and (12), which yields

$$\frac{T_w}{T_f} = \frac{[(d/Y)-1](\partial p/\partial y)}{\gamma_t \cos\theta} = \frac{\gamma_w}{\gamma_t}\left(\frac{d}{Y}-1\right)\left(\frac{\tan\theta}{\tan\lambda}+1\right) \qquad (13)$$

Inspection of this equation reveals some obvious effects of the relative water-table depth, d/Y: $T_w/T_f \rightarrow 0$ as $d/Y \rightarrow 1$, and $T_w/T_f \rightarrow (-\partial p/\partial y)/\gamma_t \cos\theta$ as $d/Y \rightarrow 0$. Thus, if all other factors are constant, higher water tables lead to greater instability. In comparison with this rather obvious effect, the effects of $\partial p/\partial y$ or λ in conjunction with those of d/Y are subtle, diverse, and sometimes surprising.

Figure 3 is a graph of (13), which illustrates how T_w/T_f (multiplied by γ_t/γ_w, which typically has a value of about 2) varies as a function of λ and d/Y for a typical slope angle (θ=30°). Graphs for other values of θ appear very similar to figure 3, although for smaller θ values the curves are more closely spaced and the point where the ordinate equals zero shifts to the right. Most significantly, the curves of figure 3 show that the magnitude of T_w commonly is similar to that of T_f (i.e., $T_w/T_f \approx -1$ is common), particularly for slopes that are nearly saturated (i.e., $d/Y \rightarrow 0$). This demonstrates that the effects of groundwater can be as important as those of friction in determining the factor of safety. For small values of λ, figure 3 shows that the effects of groundwater are particularly important and can even exceed those of friction. On the other hand, groundwater has no effect on the factor of safety (T_w=0) if the hydraulic gradient is vertical ($\lambda = 180° - \theta$). The effect of λ and θ on T_w/T_f is clarified by considering special cases of (12) in which the value of λ reduces $\partial p/\partial y$ (normalized by γ_w) to a simple function of θ. Table 1 (Appendix) lists such cases and includes comments on their physical significance. The algebraic expressions listed in the table show, for any particular λ, how $\partial p/\partial y$ and T_w/T_f vary systematically as a function of θ.

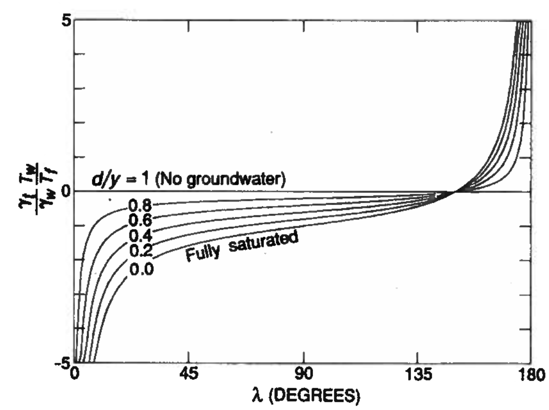

Fig. 3 Normalized measure of groundwater influence on the factor of safety, $(\gamma_t T_w)/(\gamma_w T_f)$, as a function of the hydraulic gradient direction, λ, for infinite slopes with inclination $\theta = 30°$ and various water-table depths, d/Y

Table 1 also shows that the condition of vertically downward flow ($\lambda = 180° - \theta$) demands that $\partial p/\partial y = 0$, which indicates that the slope is saturated with water at atmospheric pressure. Larger values of λ can occur only under a condition of tension-saturated or unsaturated flow (cf. Philip, 1991), which is physically incompatible with the condition $d/Y \leq 1$ implicit in the infinite-slope analysis. Thus, the parts of the curves in figures 2 and 3 that indicate stabilizing influences of groundwater flow ($T_w/T_f > 0$ or $\partial p/\partial y < 0$) have qualitative but no quantitative validity. They show only that flow is unsaturated and that some stabilizing influence might be expected.

5 EFFECT OF INADEQUATE DATA

Figure 3 and table 1 demonstrate that a complete lack of groundwater data can lead to egregious errors in factor-of-safety estimates. A related problem, however, is the potential for incomplete or incorrectly interpreted groundwater data to cause errors in computed factors of safety. This potential can be appreciated by considering an example of a typical infinite-slope problem.

Consider an infinite slope inclined at an angle $\theta = 30°$, and for which values of γ_t, ϕ, and c are known. Suppose, for example, that a single piezometer is installed in the slope at a known depth $y = y^*$ and that the piezometer indicates the pore pressure at this depth is $p^* = \gamma_w y^*/3$. If y^* corresponds with the failure-plane depth, Y, then knowledge of p^* suffices to determine the factor of safety exactly. This is the situation considered by Graham (1984) and many others. However, the failure-plane depth Y may be unknown *a priori*, so that the piezometer depth y^* is unlikely to correspond with Y. In this circumstance, to what extent does knowledge of p^* constrain the factor of safety?

This problem has two important elements. First, because Y is unknown, the relative piezometer depth y^*/Y is unknown. Second, although p^* is known, the water-table depth d and average pore-pressure gradient $\partial p/\partial y$ are unknown, and an infinite number of combinations of d and $\partial p/\partial y$ (or, equivalently, an infinite number of λ values) can satisfy the requirement that $p = p^*$ at $y = y^*$ (cf. Iverson, 1990). Without additional information, the analyst in this circumstance has no alternative but to make educated guesses about the unknown values.

Table 2 (Appendix) employs the information $p = p^*$ at $y = y^*$ in conjunction with information from table 1 and (13) to summarize some scenarios in which various guesses about Y, λ, $\partial p/\partial y$, and d are made. Cases 1, 2, and 3 of table 2 each represent a guess about y^*/Y, and case 4 is a reference case in which $y^* = Y$ (i.e., the pore pressure is measured precisely on the failure plane). Within each of the cases 1, 2 and 3, three guesses are made about λ, each of which corresponds to a distinct value of d/Y obtained from table 1 and an accompanying value of $\partial p/\partial y$ obtained from the definition

$$\frac{p^*(y^*)}{Y} = \frac{1}{Y}\int_d^{y^*} \frac{\partial p}{\partial y} dy = \frac{\partial p}{\partial y}\left(\frac{y^*}{Y} - \frac{d}{Y}\right) \tag{14}$$

Thus, table 2 contains nine guesses about groundwater conditions, and each of the guesses is quite reasonable; each guess is associated with values of λ and y^* that are representative rather than extreme, as demonstrated by figure 3. Each guess leads directly to a value of T_w/T_f, but a factor of safety can be calculated from this T_w/T_f value only if the values of ϕ and c are also known. For illustrative purposes, table 2 lists values of FS that result from assuming $\phi = 40°$ and $c = 0$.

The numerical results listed in table 2 demonstrate several important points. First, values of T_w/T_f can vary by more than 300%, and values of FS can vary by more than 50%, depending on which guesses about the hydraulic gradient direction λ and the relative piezometer depth y^*/Y are used. Values of y^*/Y influence the factor of safety much more strongly if λ is relatively small. For a fixed y^*/Y, a tradeoff exists between the guessed value of λ (and, hence, of $\partial p/\partial y$) and the corresponding water-table depth. One result of this tradeoff is perhaps surprising: guesses of λ that correspond with shallow water tables (small d/Y) lead to larger factors of safety than do guesses of λ that correspond with deeper water tables. Clearly, then, interpretations of the measured pore pressure $p^*(y^*)$ that assume a relatively high water table are not conservative! Interpretations that assume a lower water table lead to lower factors of safety because they require a larger $\partial p/\partial y$, and this larger $\partial p/\partial y$ more than compensates for the lower water table in terms of provoking instability. Finally, it is noteworthy that computed values of FS converge toward the correct value of FS as $y^* \to Y$. This is consistent with the fact that FS can be determined without error if p^* is known on the failure plane.

6 CONCLUDING DISCUSSION

The results of this investigation demonstrate that the destabilizing influences of saturated groundwater flow can vary significantly, even for a simple infinite-slope geometry. Part of the variation is due to the effect of the water-table depth, but part is due to the more interesting effect of the pore-pressure gradient. In an infinite slope the pore-pressure gradient is necessarily oriented normal to the slope, but it can vary infinitely in magnitude. Even if the slope is homogeneous, a pore-pressure measurement at a single depth is insufficient to determine the pore-pressure gradient, because the effect of the gradient cannot be distinguished from that of the water-table depth. Consequently, unless the pore-pressure measurement is made precisely on the potential failure plane, the measurement is inadequate for calculating a factor of safety. A hydrologic interpretation (i.e., an educated guess) is necessary in order to distinguish the water-table and pore-pressure-gradient effects. An incorrect guess can result in substantial errors in the computed factor of safety. Under routine circumstances, these errors can be as large as 50%, which is commonly comparable to the error that would be introduced by using a soil friction angle in error by about 10°. Such a large potential error points to the overiding need to assess groundwater conditions rigorously in conjunction with slope-stability analyses.

Rigorous assessments of groundwater conditions aim to define completely the pore-pressure and hydraulic head distributions throughout a slope. Such assessments require both piezometric data at a variety of locations and a model to codify the data. The model can be formal, involving analytical or numerical solution of the groundwater-flow equation with appropriate boundary conditions, or it can be informal, involving trial-and-error flow-net sketching by hand. In any case, the model is essential and is most reliable when it is constrained by data from as many piezometers as possible. Even for infinite slopes, in which the model is rather tightly constrained by the slope geometry (Iverson, 1990), data from tens of piezometers may be necessary to construct a meaningful flow net if the slope contains hydraulic heterogeneities (e.g., Iverson and Major, 1987).

The complexity of slope-stability analysis and the destabilizing influence of groundwater flow is compounded if slopes are two- or three-dimensional and contain hydraulic heterogeneities (cf. Reid and Iverson, 1991). Not only is the variety of possible groundwater flow fields greater than in infinite slopes, but the effective-stress fields are statically indeterminate. Thus limit-equilibrium analyses in such instances require assumptions about the forces or moments that act between slices of the slope, and these assumptions frequently spawn debate about how to account properly for groundwater effects (King, 1989, 1990; Morrison and Greenwood, 1989, 1990). In these multi-dimensional problems, the guiding physical principle is the same as that in the one-dimensional infinite-slope problem: the pore-pressure or hydraulic head distribution throughout the slope must be assessed in sufficient detail that a flow net can be constructed. Only then can appropriate groundwater forces (expressed as either boundary pore pressures or seepage body forces) be determined and applied to each slice. Assumptions of hydrostatic pore-pressure distributions or slope-parallel hydraulic gradients, which are used in some commercial software packages, may be grossly incorrect.

REFERENCES

Graham, J. 1984. Methods of stability analysis. *Slope Instability*, D. Brunsden and D.B. Prior, eds., New York: Wiley. 171-215.

Haefeli, R. 1948. The stability of slopes acted upon by parallel seepage. *Proc. 2nd ICSMFE* 1: 57-62.

Iverson, R.M. 1990. Groundwater flow fields in infinite slopes. *Geotechnique* 40: 139-143.

Iverson, R.M., & J.J. Major 1986, Groundwater seepage vectors and the potential for hillslope failure and debris flow mobilization. *Water Resources Research* 22: 1543-1548.

Iverson, R.M., & J.J. Major 1987. Rainfall, groundwater flow, and seasonal movement at Minor Creek landslide, northwestern California: physical interpretation of empirical relations. *Geol. Soc. Amer. Bull.* 99: 579-594.

Iverson, R.M., & M.E. Reid 1991. Gravity-driven groundwater flow and slope failure potential: 1. elastic effective-stress model. *Water Resources Research*, in press.

King, G.J.W. 1989. Revision of effective stress method of slices. *Geotechnique* 39: 497-502.

King, G.J.W. 1990. Discussion and reply for "Revision of effective stress method of slices". *Geotechnique* 40: 651-654.

Morrison, I.M., & J.R. Greenwood 1989. Assumptions in simplified slope stability analysis by the

method of slices. *Geotechnique* 39: 503-509.
Morrison, I.M., & J.R. Greenwood 1990. Discussion and reply for "Assumptions in simplified slope stability analysis by the method of slices". *Geotechnique* 40: 655-658.
Philip, J.R. 1991. Hillslope infiltration: planar slopes. *Water Resources Research* 27: 109-118.
Reid, M.E., & R.M. Iverson 1991. Gravity-driven groundwater flow and slope failure potential: 2. effects of material properties, slope morphology, and hydraulic heterogeneity. *Water Resources Research*, in press.
Skempton, A.W., & F.A. DeLory 1957. Stability of natural slopes in London clay. *Proc. 4th ICSMFE* 2: 378-381.
Taylor, D.W. 1948. *Fundamentals of Soil Mechanics*. New York: Wiley.

APPENDIX

Table 1. Cases in which $\partial p/\partial y$ reduces to a function of θ alone. [Note $\Gamma = \frac{\gamma_w}{\gamma_t}(1-\frac{d}{y})$]

λ	$\frac{1}{\gamma_w}\frac{\partial p}{\partial y}$	T_w/T_f	COMMENT
0	∞	$-\infty$	limiting value of small λ
θ	$2\cos\theta$	-2Γ	
45°	$\cos\theta + \sin\theta$	$-\Gamma(1+\tan\theta)$	
90° − θ	$\sec\theta$	$-\Gamma\sec^2\theta$	horizontal ∇h
90°	$\cos\theta$	$-\Gamma$	slope-parallel ∇h
90° + θ	$2\cos\theta - \sec\theta$	$-\Gamma(2-\sec^2\theta)$	
135°	$\cos\theta - \sin\theta$	$-\Gamma(1-\tan\theta)$	
180° − θ	0	0	downward vertical ∇h
180°	$-\infty$	∞	limiting value of large λ

Table 2. Scenarios in which the pore pressure is known to be $p^* = (\gamma_w y^*)/3$ at depth $y = y^*$, but the failure-plane depth, Y, hydraulic gradient direction, λ, and pore-pressure gradient magnitude, $\partial p/\partial y$, may vary.

y^* and p^* normalized by the guessed Y			Groundwater-flow conditions that satisfy $p=p^*$ at $y=y^*$			Normalized T_w and safety factor for $\gamma_t/\gamma_w=2$, $\phi=40°$, and $c=0$	
	$\frac{y^*}{Y}$	$\frac{p^*}{\gamma_w Y}$	λ	$\frac{1}{\gamma_w}\frac{\partial p}{\partial y}$	$\frac{d}{Y}$	$\frac{\gamma_t}{\gamma_w}\frac{T_w}{T_f}$	FS
	0.3	0.1	45°	1.366	0.23	-1.2	0.85
case 1	0.3	0.1	90°	0.866	0.18	-0.82	1.0
	0.3	0.1	135°	0.366	0.03	-0.41	1.2
	0.6	0.2	45°	1.366	0.45	-0.86	1.0
case 2	0.6	0.2	90°	0.866	0.37	-0.63	1.1
	0.6	0.2	135°	0.366	0.05	-0.40	1.3
	0.9	0.3	45°	1.366	0.68	-0.50	1.2
case 3	0.9	0.3	90°	0.866	0.55	-0.45	1.2
	0.9	0.3	135°	0.366	0.08	-0.38	1.3
case 4	1.0	0.333	flow conditions irrelevant				1.2

Bell, D.H. (ed.) 90 5410 032 X
Landslides – *Proceedings of the 6th international symposium, Christchurch, 10 – 14 February 1992*
1992, 25 cm, c.1800 pp., 3 vols, Hfl.510 / $285.00 / £155
The proceedings contain papers on 5 General and 5 Specialist themes. General themes include landslide investigations, stability analysis techniques, stabilisation measures, hazard assessment, and monitoring and instrumentation. The Specialist themes are seismicity and landslides, landslides and reservoirs, open pit mine slopes, slope stability in tropical areas, and landslides in Australasia. Volumes 1 and 2 contain a total of 224 papers, with the Theme addresses, Panel reports and Discussions in Volume 3.

FROM THE SAME PUBLISHER:

Bonnard, Ch. (ed.) 90 6191 837 5
Landslides – *Proceedings of the 5th international symposium, Lausanne, 10–15 July 1988*
1988-89, 30 cm, 1604 pp., 3 vols, Hfl.455 / $250.00 / £146
Geology & selection of parameters; Monitoring methods & field measurements; Analysis methods & forecasting behaviour; Drainage & stabilization; Evaluation & appraisal risks of instability.

Singh, B. & N.C. Saxena (eds.) 90 6191 129 1
Land subsidence – *Proceedings of the international symposium, Dhanbad, India, 11 – 15 December 1989*
1991, 25 cm, 687 pp., Hfl.165 / $90.00 / £52 (No rights India)
Subsidence, defined as vertical or lateral movements taking place on and in the earth's crust, can take place due to many natural and manmade activities, such as, solution of rocks and minerals; drainage of water from sub-soil; drifting of sub-soil and sliding of rocks; rodents; frosting and defrosting; tectonic movements; (being natural movements), pumping of water and petroleum from below ground; mining of minerals and making of underground excavations for other purposes; and settlement of foundations; (being manmade activities), etc. Subsidence movements either due to natural or manmade or both the activities besides damaging the surface properties also tend to damage surface topography, water regime, and surface environment, especially in respect of vegetation. A look on the various activities causing subsidence indicates that subsidence can take place at any place where one or more of these activities are taking place. At the conference various topics related to subsidence were discussed: Theory and modelling of subsidence phenomena from various activities; Subsidence case studies due to mining, pumping of water and petroleum from below ground, natural and other manmade causes, environmental impacts of subsidence; Monitoring of subsidence movements; Precautionary and preventive measures, including land reclamation.

T. Yamanouchi, N. Miura & Hidetoshi Ochiai (eds.) 90 6191 820 0
Theory and practice of earth reinforcement – *Proceedings of the international geotechnical symposium, Fukuoka Kyushu, 5–7 October 1988*
1988, 25 cm, 632 pp., Hfl.175 / $95.00 / £55
Up-to-date topics on: Theory (Stress-strain; mechanism; seismic resistance); Design (Principle, analysis & computer-aided design; long-term stability); Construction (Earth & retaining walls; foundations; embankments; slope works; excavation; near-shore works); Materials (Newly developed & re-discovered traditional materials; durability; corrosion; testing methods); Monitoring systems (Techniques for monitoring; evaluation of site damage).

Nieuwenhuis, J.D. 90 6191 187 7
The lifetime of a landslide: *Investigations in the French Alps*
1991, 25 cm, 160 pp., Hfl.85 / $45.00 / £27
The aim of this monograph is to introduce new approaches to landslide research by the detailed description of one shallow landslide and the simulation of the slide's behaviour.
Topics: Hydrology, pore pressure fluctuations and their relation with the onset of the displacements; Residual strength, strength gain and viscosity of the varved clay soils near the slide planes; A comprehensive stability model; Prediction of displacement rates and the mode of collapse; Measurements and predictions are compared, whereas the long-term behaviour of the landslide is considered through a Monte Carlo simulation.

W.F. Van Impe 90 6191 805 7
Soil improvement techniques & their evolution
1988, 25 cm, 131 pp., Hfl.80 / $43.00 / £25
Introduction; Temporary soil improvement techniques; Permanent soil improvement without addition of any material; Permanent soil improvement by adding materials; Testing the completed soil improvements; General conclusions; References. Author: Professor, Ghent State University, Belgium.

Yu Xiang & Wang Changsheng (eds.) 90 5410 016 8
Ground freezing 91 – *Proceedings of the sixth international symposium on ground freezing, Beijing, 10 – 12 September 1991*
1991–92, 25 cm, c.600 pp. 2 vols., Hfl.250 / $135.00 / £78
Artificial ground freezing (AGF) has been used to form a temporary support and/or an impermeable barrier for underground openings and other excavations for over 100 years. The design of ice walls to ensure adequate strength and tolerable deformations, during freezing and thawing stages, has been developed considerably with the application of computer-based methods. These have required a better understanding of the creep characteristics of frozen ground and also of the characterization of frost heave and thaw weakening. Ground Freezing 91 contains the proceedings of the 6th ISGF held in Beijing, September 1991. *Volume 1:* 56 papers from 13 countries on heat and mass transfer, mechanical properties, engineering design and case histories. *Volume 2:* further papers, general reports and summaries of posters. Editors: Central Coal Mining Institute, China.

Balasubramaniam, A.S., S. Chandra, D.T. Bergado, J.S. Younger & F. Prinzl (eds.) 90 6191 568 6
Recent developments in ground improvement techniques – *Proceedings of the international symposium held at Asian Institute of Technology, Bangkok, 29.11–03.12.1982*
1985, 25 cm, 598 pp., Hfl.190 / $105.00 / £60
45 papers: Ground improvement by deep compaction & piling; Reinforced earth, soil fabrics & geotextiles; Grouting ground anchors & soil nailing; Root piles, micropiles & ground freezing; Blasting operation, seepage problems & case histories.

Walker, Bruce F. & Robin Fell (eds.) 90 6191 730 1
Soil slope instability and stabilisation – *Proceedings of the extension course, Sydney, 30 November – 2 December 1987*
1987, 25 cm, 448 pp., Hfl.165 / $90.00 / £52
Landslide classification, geomorphology, & site investigations; Determination of drained shear strength for slope stability analysis; Methods of stability analysis; Groundwater prediction & control, and negative porewater effects; Slope stabilization techniques & their application; Slope stability in soft ground.

All books available from your bookseller or directly from the publisher:
A.A. Balkema Publishers, P.O. Box 1675, Rotterdam, Netherlands
For USA & Canada: A.A. Balkema Publishers, Old Post Rd, Brookfield, VT, USA