Mass Wasting and Hillslope Processes

I. Hillslope Physics / Physical Properties of Regolith

A. Basics of Slope Stability

1. Fundamental Terms

a. Energy - ability to do physical work

(1) Mechanical Energy

(a) **Potential Energy - energy of position**

$$Ep = mgh$$

where Ep = potential energy (joules), m = mass (kg), g = acceleration due to gravity (9.8 m/sec^2), h = height of material above reference surface (m)

Units: $1 J = 1 kg\text{-}m^2/sec^2$

(b) **Kinetic Energy - energy of motion**

$$Ek = 0.5mV^2$$

where Ek = kinetic energy (joules), m = mass (kg), V = velocity (m/sec)

Units: $1 J = 1 kg\text{-}m^2/sec^2$

b. **Force - push or pull action on a mass of material**

Newton's Second Law: $F = ma$

where F = force (newtons), m = mass (kg), a = acceleration (m/sec^2)

Units: $1 N = 1 kg\text{-}m/sec^2$

c. **Weight = pulling force of the Earth under the influence of gravity**

$$Wt = F = mg$$

where Wt = weight (N), F = force (N), m = mass (kg), g = acceleration due to gravity (9.8 m/sec^2)

d. **Stress - Force acting per unit surface area.**

$$stress = F/A$$

where stress is in N/m^2, A = area ($m \times m = m^2$)

e. **Work - displacement of mass when acted upon by force**

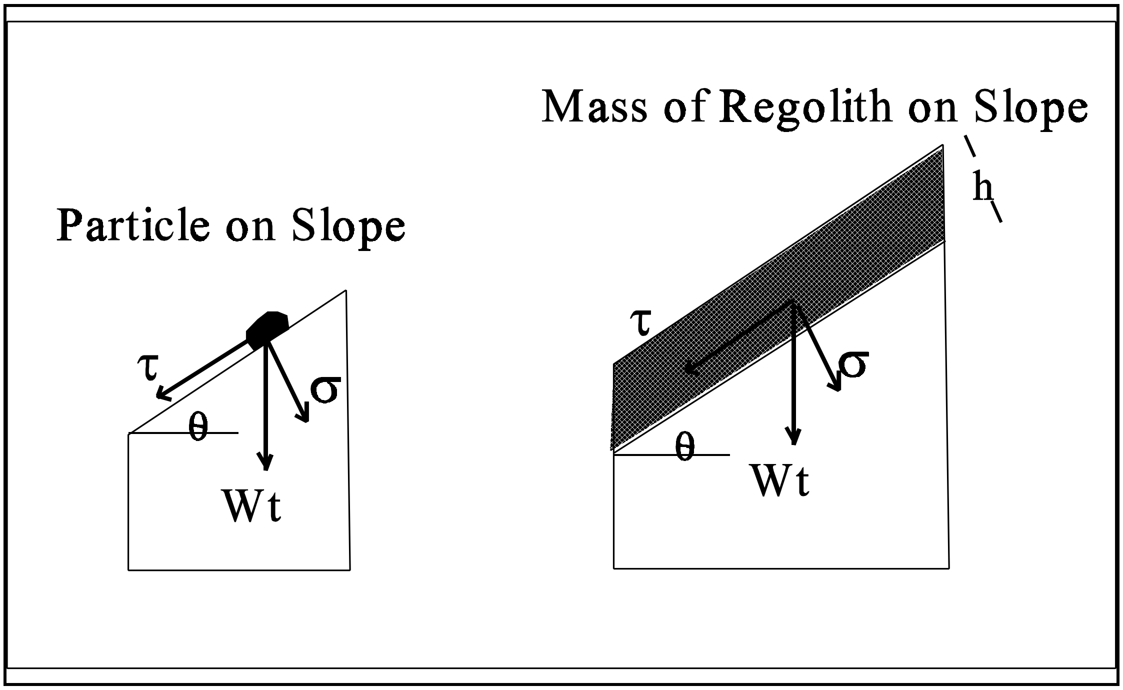
e.g. sliding mass of regolith

$W = Fd$

where W = work (J), F = force (N = 1 kg-m/sec^2), d = distance of mass displacement (m)

Units 1 J = 1 N-m = 1 kg-m^2/sec^2

2. Forces acting on Slope Material



Particle-on-Slope Equations:

τ = shear force parallel to slope (N)
σ = normal force perpendicular to slope (N)
θ = slope angle relative to horizontal plane (degrees)
Wt = weight of particle or mass of material (N)

$$Wt = mg = \text{weight of particle (N)}$$

$$\sigma = Wt (\cos \theta) = \text{normal force (N)}$$

$$\tau = Wt (\sin \theta) = \text{shear force (N)}$$

Mass-on-Slope Equations:

** Note: here we assume that a mass of regolith overlies a potential failure plane. The failure plane is a surface in 3-d with area. Thus, forces are applied per unit area, resulting in stresses. **

τ = shear stress parallel to failure plane (N/m^2)
σ = normal stress perpendicular to failure plane (N/m^2)
θ = slope angle relative to horizontal plane (degrees)
γ = specific weight of mass = Wt / volume (N/m^3)
h = thickness of regolith above failure plane (m)

$$Wt = mg = kg\text{-}m/sec^2 = N$$

$$\gamma = Wt / volume = N/m^3 = \text{specific weight}$$

$$\sigma = \gamma h (\cos^2\theta) = \text{normal stress } (N/m^2)$$

$$\tau = \gamma h (\cos \theta) (\sin \theta) = \text{shear stress } (N/m^2)$$

In-Class Activity: Force Analysis of Particle-on-Slope Model

(1) Choose our class favorite block-of-rock sample and set up the inclined plane.
(2) Determine the mass of our block-of-rock sample by using the balance in the room.
(3) Using the appropriate equations listed above, calculate the force vectors and fill in the table below. Show your calculations in the space provided!

Mass of Rock Block ____________ kg

Weight of Rock Block ____________ N

Slope Angle (Degrees)	Normal Force (N)	Shear Force (N)
0		
10		
20		
30		
40		
50		
60		

Given that shear force is oriented downslope and normal force is oriented perpendicular to slope, answer the following questions:

A. Which of the two forces will drive the rock-block downslope when it fails?

B. Which of the two forces will tend to resist downslope movement of the rock block?

C. Intuitively, when do you think the block will begin sliding down the slope (choose 1: shear = normal, shear < normal, shear > normal)?

(4) Place the rock-block on the inclined plane and determine the critical angle at which it slides down the slope. Calculate the following:

Critical Angle of Rock-Block Sliding (degrees): _______________

Critical Normal Force at Critical Angle _______________ (N)

Critical Shear Force at Critical Angle _______________ (N)

D. How do your inclined-plane results compare to your prediction in question C above?

E. List some ideas as to why your results turned out like they did. What other physical factors have not been accounted for in our set of equations / slope analysis?

B. Other Physical Properties Effecting Slope Stability

1. Driving and Resisting Forces
    a. Driving Force = Shear Stress (discussed above)
    b. Resisting Force = Shear Strength

        (1) Shear Strength = measure of resistance of slope to shear motion or failure.

2. Slope Stability Ratio

    Slope Safety Factor (dimensionless ratio)

        F = resisting force / driving force = shear strength / shear stress

        F > 1: Strength > Stress: Stable Slope
        F < 1: Strength < Stress: Unstable Slope
        F = 1: Slope Failure Threshold

3. Shear Strength Factors (Coulomb Equation):
    a. Internal Friction of Material
        (1) plane friction - resisting force at grain boundaries
        (2) interlocking friction - resisting force at irregular grain boundaries (grains forced to move up and over one another)
    b. Effective Normal Stress
        (1) Normal Stress: force perpendicular to failure plane
        (2) Effective Normal Stress - accounts for internal pore pressure of material
            (a) Pore Pressure in Granular Material
                i) dry material: pore pressure = 0
                ii) fully saturated material: pore pressure is positive
                    a) positive hydraulic lift
                iii) partially saturated material: pore presssure is negative
                    a) suction between grains due to surface tension of water and capillary force

    c. Cohesion - force of molecular attraction between grains and particles
            (a) clay - high cohesive force due to electrostatic attraction at molecular level
            (b) sand/gravel - noncohesive, due to lack of electrostatic attraction
            (c) Cohesion Factor also includes vegetative root strength

Coulomb Equation (Measure of Total Shear Strength)

$$S = c + \sigma' \tan\phi$$

where S = total shear strength (N/m^2), *c* = cohesion (N/m^2), σ' = effective normal stress (N/m^2), ϕ = angle of internal friction

so... $$F = S / \tau$$ (Safety Factor)

$F < 1$: slope failure
$F > 1$: Slope stability
$F = 1$: slope failure threshold

In-Class Exercise

A 3.6 m thick mass of regolith rests on top of a sloping bedrock surface. The hillslope angle is 8 degrees. A geotechnical engineering firm conducted an in-situ slope stability analysis with the following results:

regolith cohesion = 2155 N/m^2
effective normal stress = 71855 N/m^2
angle of internal friction = 10^o
specific weight of regolith = 25921 N/m^3

Calculate the safety factor for the slope (show your work):

Questions
(1) Is the slope stable or unstable with respect to shear strength vs. shear stress? Why?

(2) What slope stability factors could easily be changed (say during the course of a week), that would result in driving the slope to a critical threshold? (Do some thinking and hypothesizing here). Directly relate your ideas to the pertinent equations used to calculate slope stability.

II. Mass Wasting Processes and Classification

A. Stages of weathering and crustal denudation
  1. Weathering, fragmentation, diminution of bedrock
    a. Chemical Processes
    b. Physical Processes
  2. Mass Wasting- mass movement of weathered rock materials downslope under the force of gravity: "gravity transfer"
  3. Erosion and transportation of sediment by surface waters.

This process can be viewed as a continuum, at any given time there exists unweathered material, hill slpe material in storage on slopes, sediment in transport and sediment in temporary storage along drainage system networks.

B. Components of mass wasting process
  1. Gravity and potential energy created by crustal relief.
    a. generally tectonics is responsible for uplifting the earth's crust, and setting gravitational and weathering process in action.

  2. Weathered/fragmented earth materials (from clay, to sand, to boulder and/or including soil).

    a. As the term "mass" suggests, these materials are often subject to mass movement downslope, during slope failure.

  3. Steepness of slope.

    a. Loosened earth materials will lie at rest on a slope under the resistive force of friction. There is a critical point at which, the steepness of slope is such that the downslope vector force component becomes greater that the force of friction, resulting in slope failure.

    b. Angle of Repose- the steepest angle that can be assumed by loose fragments on a slope without downslope movement.

      (1) the precise angle is a function of the type of material lying on the slope: sharp angular boulders will have a steeper angle of repose than sand. Common angle of repose for average talus debris at the base of a slope = 35-40 degrees from horizontal.

  4. Moisture/water included in pore spaces and fractures within weathered material.

GRAVITY IS THE DRIVING FORCE OF THE MASS WASTING AND EROSION-TRANSPORTATION PROCESS.

C. Types of Mass Wasting Processes (after Varnes)
  1. Material Types
    a. Rock (consolidated bedrock)
    b. Debris (coarse regolith)

        c. Earth (fine regolith)

2. Mass Movement Types

    a. **FALL** -free vertical drop of material
        (1) Subclass
            (a) rock fall
            (b) debris fall
            (c) earth fall
        (2) Other Terms
            (a) Talus = cone-like accumulatiions of rock debris at the base of bedrock cliffs, generally a temporary accumulation of rock fall debris.
                i) landform, or alternately block apron
            (b) Scree = deposit (= sediment) alternately block mantle

    b. **Topple** - block rotation / tipping
        (1) Subclass
            (a) rock topple
            (b) debris topple
            (c) earth topple

    c. **SLIDE**: mass sliding along well-defined failure surface

        (1) Subtypes
            (a) Translational / Planar Slide
                i) rock slide
                ii) rock-block slide
                iii) debris slide
                iv) earth slide
            (b) Rotational Slide (Slump)

                i) Characteristics
                    a) slope collapse along a basal,
                    b) concave upward rupture surface, with subsequent downslope movement and backward rotation of the slump block.
                    c) The nose of the slump commonly experiences flow conditions resulting in a lobate form to the debris.
                ii) Subtypes
                    a) rock slump
                    b) debris slump
                    c) earth slump

        (2) Landform Products:
            (a) Landslide scar on upslope portion where slide originated
            (b) Lobate/hummocky pile of debris at downslope resting point.
            (c) A possible damming of lower valley drainage and subsequent

lake development.

d. **Lateral Spread**:
  - (1) rock spread
  - (2) debris spread
  - (3) earth spread

e. **FLOW:** - intermixing of material within mass (confined to channel or hollow)
  - (1) Subtypes
    - (a) rock flow
    - (b) debris flow
    - (c) earth flow

  - (2) Special Considerations
    - (a) **CREEP:** very slow, imperceptible, movement of slope materials. Gradual downslope creeping of soil and regolith (partially weathered rock). Involves the entire area of the hillslope under the force of gravity.

      - i) creep is enhanced by water saturated conditions, and freeze/thaw process with the upheaving and compressing of materials on a slope, slowly pushing material down slope.

      - ii) Factors influencing creep process:
        - a) > slope > creep rate;
        - b) > vegetative cover/rooting < creep rate;
        - c) > moisture content > creep rate.

    - **(b)** **SOLIFLUCTION** - special case of creep in cold climate areas. Involves the downslope movement (at slow rates) of partially thawed/water saturated soil and regolith over an impermeable "permafrost" layer.

      - i) permafrost- permanently frozen subsoil in cold climate areas. Forms an impermeable layer relative to the overlying "active layer" of soil which experiences thawing during the warm weather/summer season.soil flow

    - (c) **AVALANCHE**: trapped basal cushion of air and/or water
      - i) snow avalanche
      - ii) debris avalanche:
        - a) rapidly "sliding" debris - (typically originates from a debris slide)

In-Class Activity - Flow Behavior

The chart below summarizes the typical physics of sediment-water mixtures found in the geomorphic environment at large.

Flow Type	Velocity (m/s)	Solids (by weight)	Water (by weight)
Debris Flow	0.6-31	70-90%	10-30%
Hyperconcentrated Flow		40-70%	30-60%
Normal Water Flow	1-15	<40%	>60%

(1) Use the black wooden "flume" in the classroom to investigate the flow behavior of the three types of materials listed in the table above.

(A) In groups of 2-3, create sediment water mixtures by weight, using the sediment samples available.

-use equal amounts of sand, gravel, clay to create three mixtures by weight

Mixture 1: 70% solids and 30% water (by weight)
Mixture 2: 50% solids and 50% water (by weight)
Mixture 3: 30% solids and 70% water (by weight)
Mixture 4: 100% water

(B) Set the ramp angle to 35 degrees, place the black flume on the ramp.

(C) Pour each mixture onto the ramp and observe the flow behavior. Use a meter stick and stop watch to calculate the approximate flow velocity down the ramp. Pay attention to the geometry of the deposits that result at the base of the flume. Fill in the table below.

Mixture	Travel Distance (m)	Travel Time (sec)	Velocity (m/sec)	Observations
1	_________	________	________	
2	_________	________	________	
3	_________	________	________	
4	_________	________	________	

Answer the Questions:

(A) Classify each mixture as debris flow, hyperconcentrated flow, or normal stream flow.

(B) Which mixture traveled displayed the highest velocity? the lowest velocity?

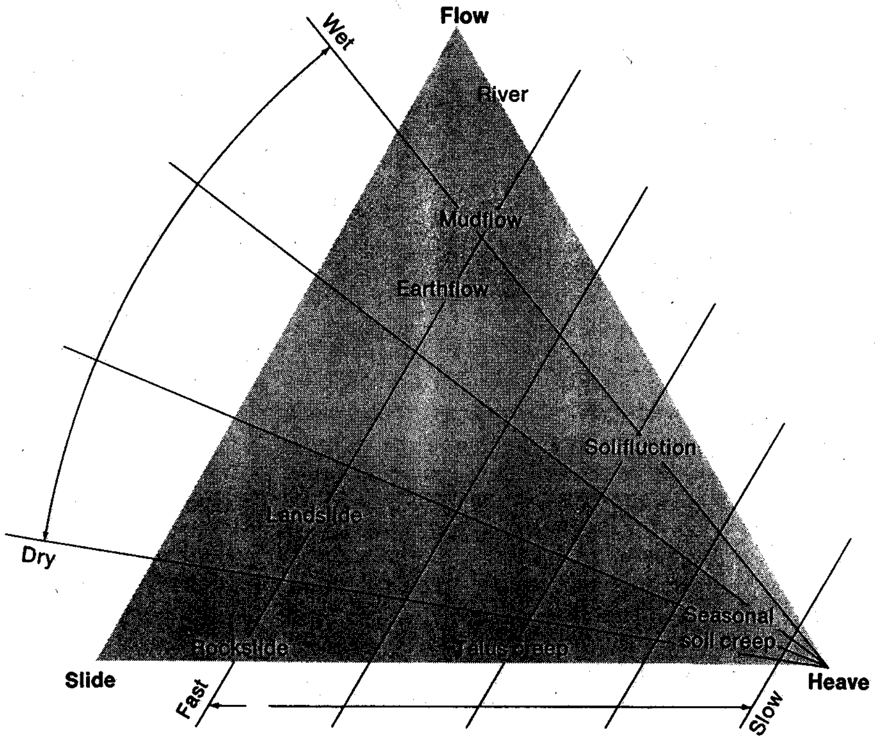
(C) Classify each mixture as either having "turbulent" flow behavior (i.e. mixing), or "laminar flow behavior (i.e. little to no mixing of material during flow).

(D) For each mixture, describe the geometric form of the deposits that result at the base of the flume.

TABLE 4.6 Classification of mass movement types in different parent materials.

Type of Movement			**Type of Material**		
			Bedrock	*Engineering Soils*	
				Predominantly coarse	Predominantly fine
Falls			Rockfall	Debris fall	Earth fall
Topples			Rock topple	Debris topple	Earth topple
Slides	*Rotational*	*Few units*	Rock slump	Debris slump	Earth slump
	Translational		Rock block slide	Debris block slide	Earth block slide
		Many units	Rockslide	Debris slide	Earth slide
Lateral Spreads			Rock spread	Debris spread	Earth spread
Flows			Rock flow (deep creep)	Debris flow (soil creep)	Earthflow
Complex			Combination of two or more principal types of movement		

From D. J. Varnes, 1978, "Landslides: Analysis and Control," *TRB Special Reports 176: Landslides,* Transportation Research Board, National Research Council, Washington, D.C. Used by permission.



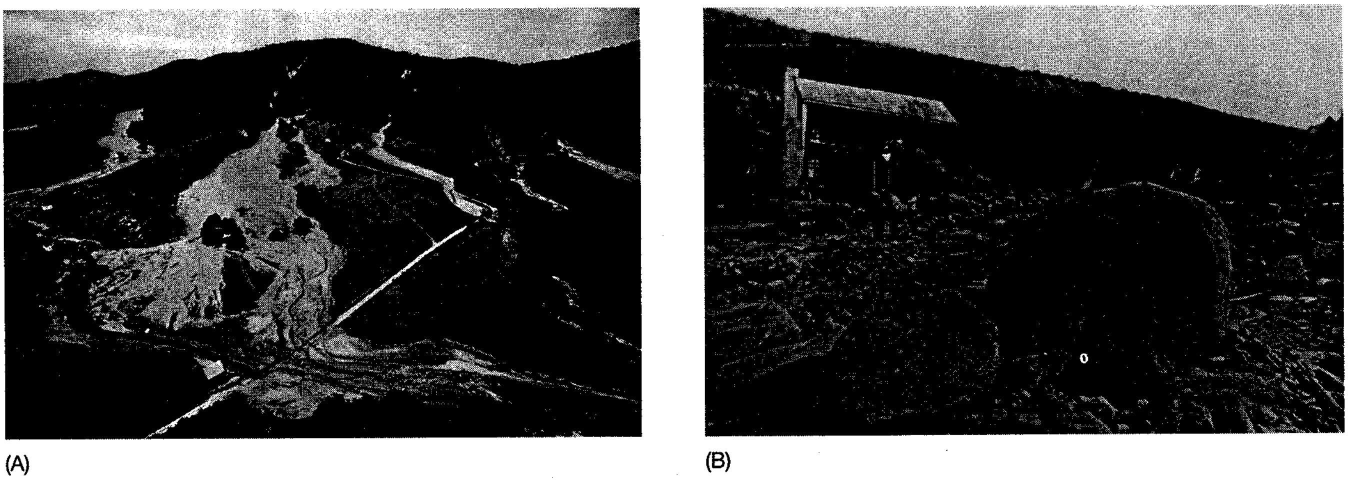

(A) (B)

FIGURE 4.39
Debris flow and avalanches in Nelson County, Va., during 1969. (A) Flows deposited debris on small fans at the base of first-order hillslope channels (near Lovingston). (B) Catastrophic erosion and impact forces from these flows removed some structures and devastated others (view from Davis Creek).

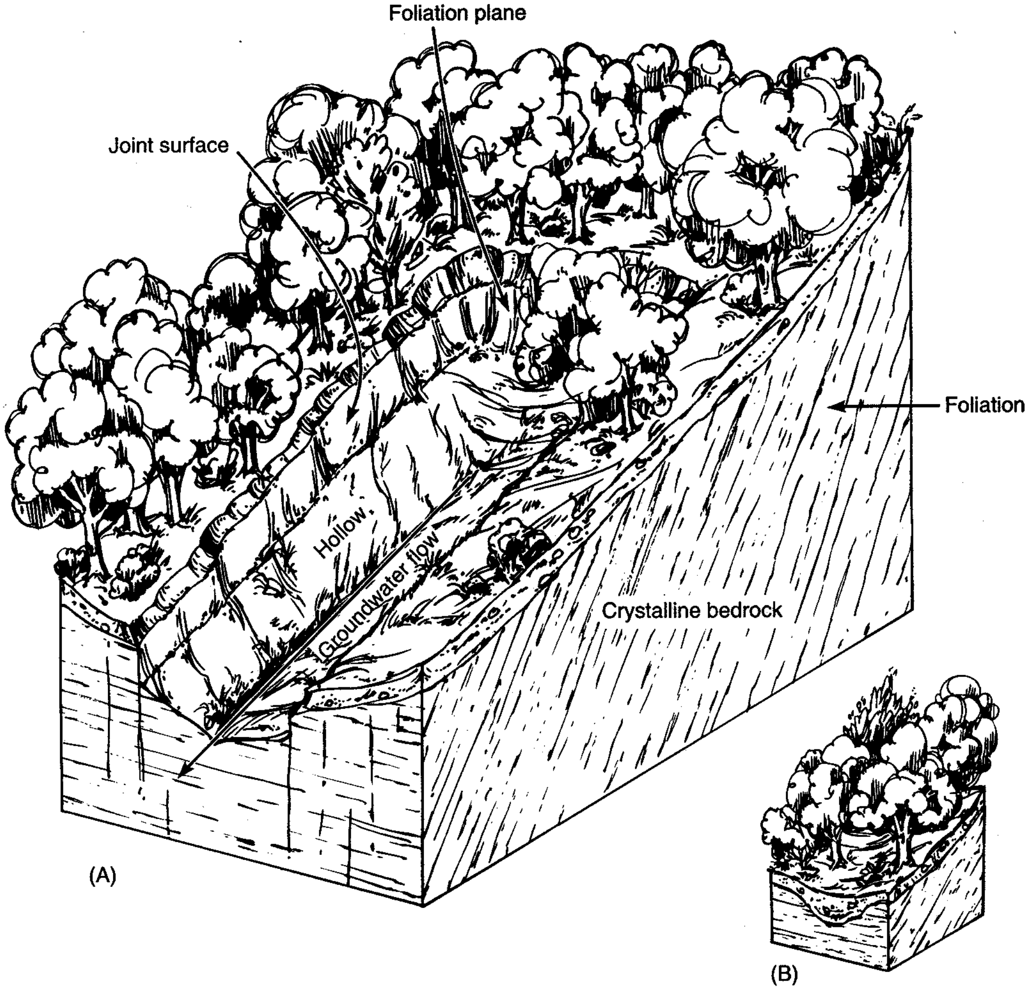
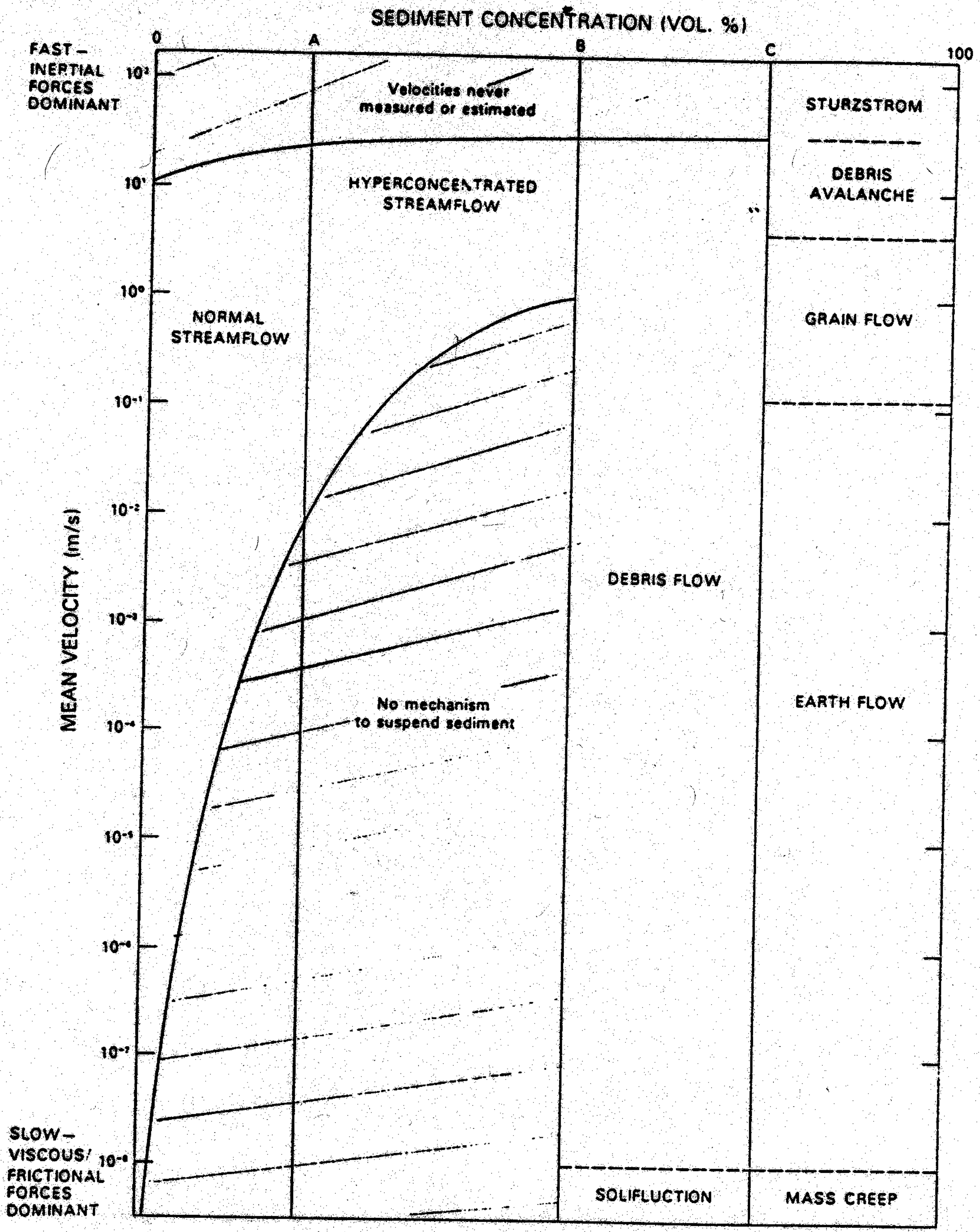


FIGURE 4.40
Schematic model of a colluvium-filled hollow. (A) Hollow excavated to bedrock by a recent debris avalanche/debris flow. (B) Hollow has been refilled with calluvium and slope wash after a few hundred years. The site is now primed for another debris flow event once again.



FLUID TYPE	NEWTONIAN	NON-NEWTONIAN		
INTERSTITIAL FLUID	WATER	WATER-FINES		WATER+AIR +FINES
FLOW CATEGORY	STREAMFLOW		SLURRY FLOW	GRANULAR FLOW
FLOW BEHAVIOR	LIQUID	PLASTIC		

Figure 4. Fitting appropriate existing flow nomenclature into proposed rheologic classification.

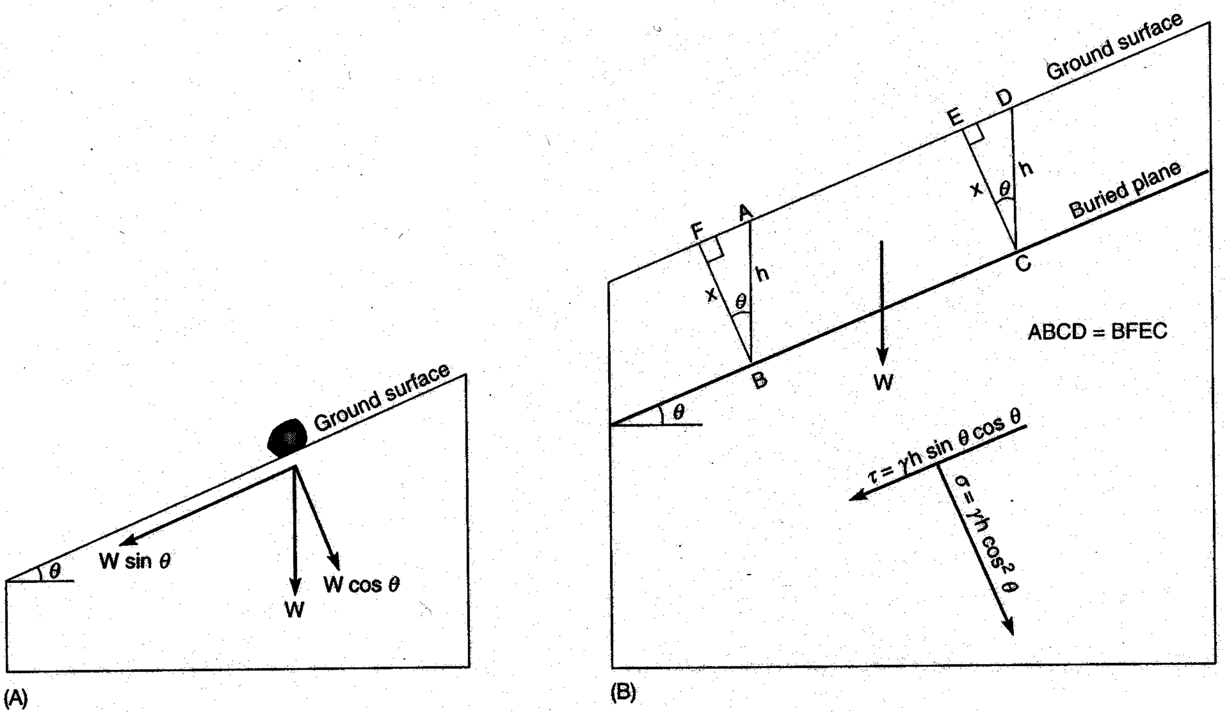


FIGURE 4.18

Analyses of slope stability. (A) Forces acting on a particle resting on a slope surface. (B) Stresses acting on a planar surface covered by unconsolidated material.

Before we examine these properties, however, it may be helpful to look again at the concept of driving force, which was briefly discussed in chapter 1. Figure 4.18A depicts a boulder resting on a sloping surface. The force of gravity acts vertically on the particle, and the force magnitude stems from the weight of the particle *mg* (mass times the acceleration of gravity). Actually, the weight may be resolved into two components, one acting perpendicular to the sloping surface and one acting parallel to it. The component acting parallel to the surface tends to promote downslope movement and is measured as $W \sin \theta$, where W is the weight in pounds or kilograms. The perpendicular component tends to keep the boulder in place by pushing it into the surface and thereby resisting the downslope motion; its magnitude is determined as $W \cos \theta$. Clearly, downslope movement of the particle is enhanced on steeper slopes because the sine value increases and the cosine value decreases as the angle θ is increased.

In the analysis of slope processes, however, engineers and scientists are usually concerned with the force acting on some potential plane of failure existing below the ground surface along which movement of a block of overlying material takes place (fig. 4.18B). In this case the exerted force derives primarily from the weight of the debris overlying the plane. Because the total weight of this material cannot be determined like that of a single, discrete boulder, it is calculated indirectly by multiplying the unit specific weight (γ) of the material (lb/ft³ or kg/m³) times the vertical distance (h) from the plane to the ground surface. The resolved components are now $\gamma h \sin \theta \cos \theta$ in the downslope direction and $\gamma h \cos^2\theta$ perpendicular to the plane. The reason for the change in equations is that the block of soil, represented by the parallelogram ABCD, is equal to the rectangle BFEC, and the angles FBA and DCE are equal to θ. Therefore,

$$\cos \theta = \frac{x}{h} \text{ and } x = \cos \theta h$$

Because $W = \gamma x$, substituting from above gives us $W = \gamma h \cos \theta$. Thus, the pressure acting perpendicular to the plane is

$$\sigma = W \cos \theta = \gamma h \cos \theta \cos \theta = \gamma h \cos^2\theta$$

and the shear is

$$\tau = W \sin \theta = \gamma h \cos \theta \sin \theta$$

Notice from the above that in the case of the buried plane, we are no longer talking about force because the value γh is given in units of *stress*, which by definition is the force acting on a specific area. Because γ is in lb/ft² and h is in ft, γh = lb/ft³ × ft = lb/ft².

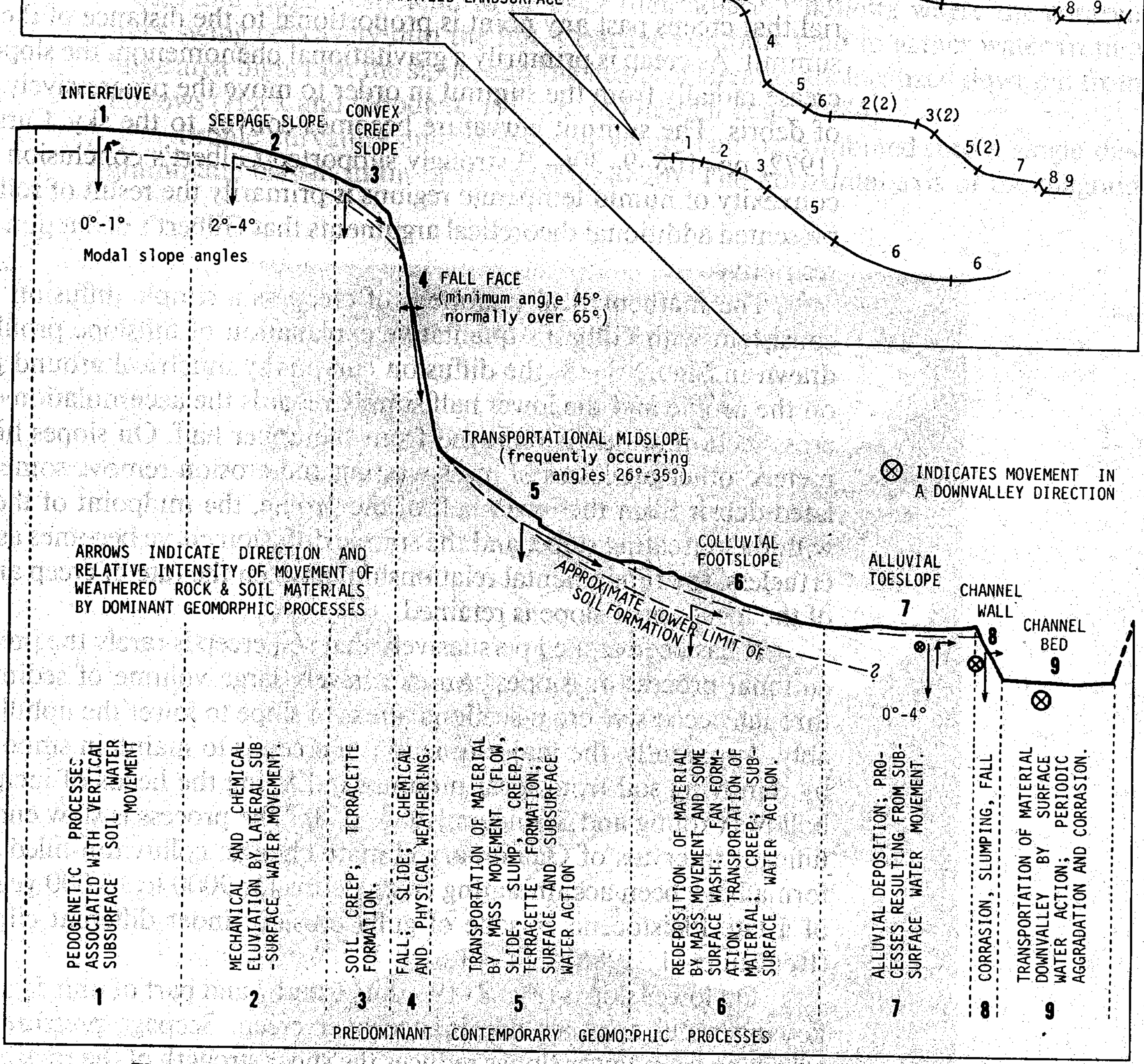
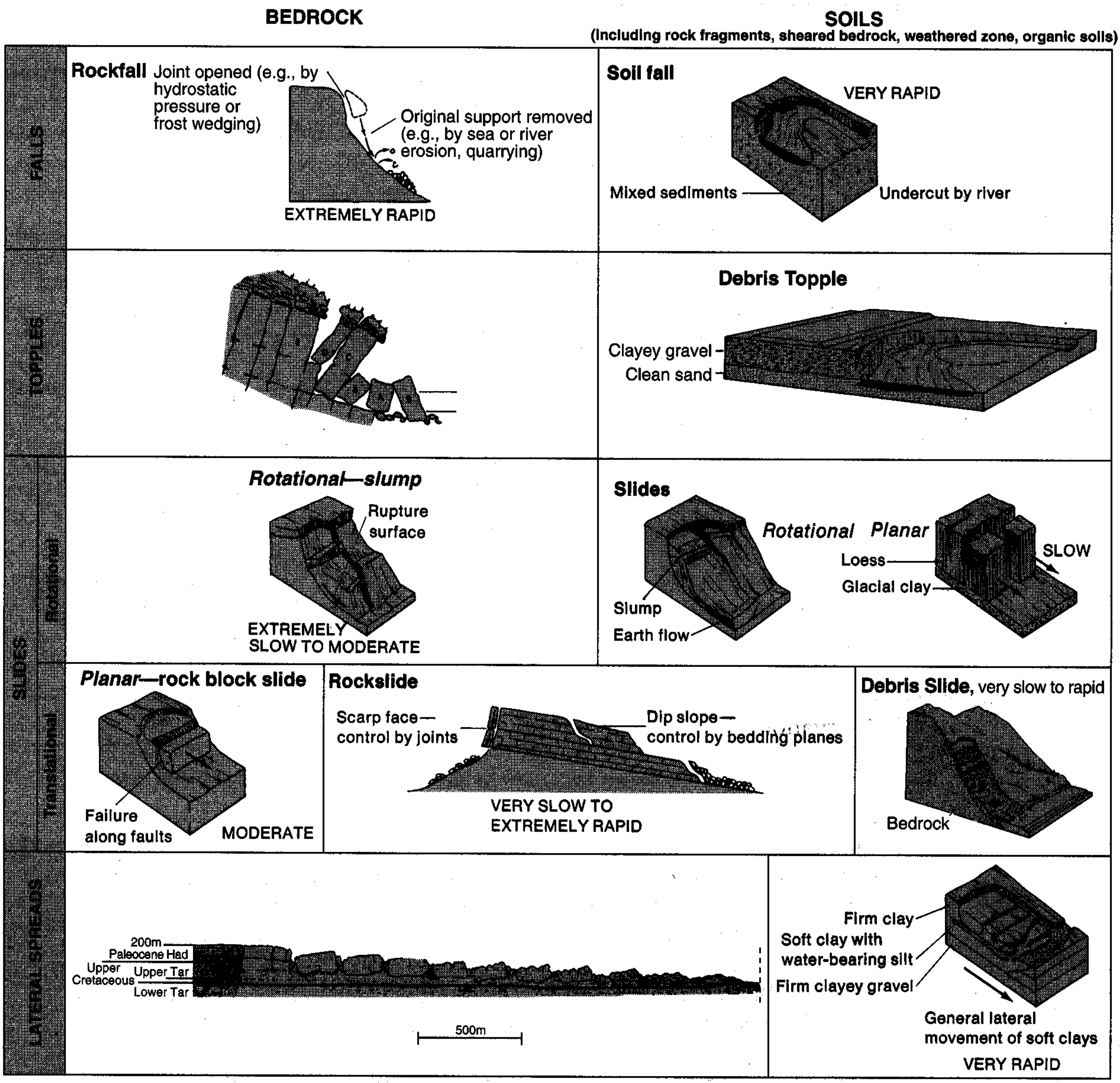
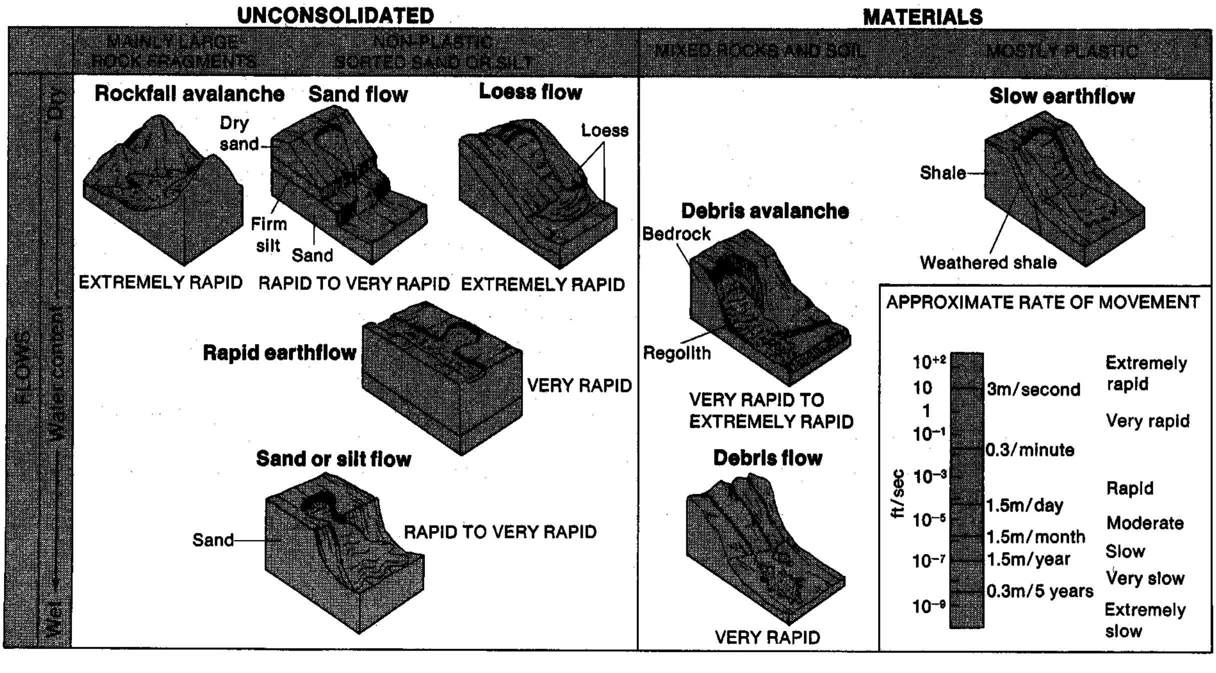


Figure 8-19. Diagrammatic representation of a hypothetical nine-unit land-surface model. (Dalrymple et al., 1968, Fig. 1.)


BEDROCK
SOILS
(including rock fragments, sheared bedrock, weathered zone, organic soils)
FALLS
Rockfall
Joint opened (e.g., by hydrostatic pressure or frost wedging)
Original support removed (e.g., by sea or river erosion, quarrying)
EXTREMELY RAPID
Soil fall
VERY RAPID
Mixed sediments
Undercut by river
TOPPLES
Debris Topple
Clayey gravel
Clean sand
SLIDES
Rotational
Rotational—slump
Rupture surface
EXTREMELY SLOW TO MODERATE
Slides
Rotational
Planar
Loess
Glacial clay
SLOW
Slump
Earth flow
Translational
Planar—rock block slide
Failure along faults
MODERATE
Rockslide
Scarp face—control by joints
Dip slope—control by bedding planes
VERY SLOW TO EXTREMELY RAPID
Debris Slide, very slow to rapid
Bedrock
LATERAL SPREADS
200m
Paleocene Had
Upper Cretaceous
Upper Tar
Lower Tar
500m
Firm clay
Soft clay with water-bearing silt
Firm clayey gravel
General lateral movement of soft clays
VERY RAPID


UNCONSOLIDATED
MATERIALS
MAINLY LARGE ROCK FRAGMENTS
NON-PLASTIC SORTED SAND OR SILT
MIXED ROCKS AND SOIL
MOSTLY PLASTIC
FLOWS
Water content
Dry
Wet
Rockfall avalanche
EXTREMELY RAPID
Sand flow
Dry sand
Firm silt
Sand
RAPID TO VERY RAPID
Loess flow
Loess
EXTREMELY RAPID
Rapid earthflow
VERY RAPID
Sand or silt flow
Sand
RAPID TO VERY RAPID
Debris avalanche
Bedrock
Regolith
VERY RAPID TO EXTREMELY RAPID
Debris flow
VERY RAPID
Slow earthflow
Shale
Weathered shale
APPROXIMATE RATE OF MOVEMENT
ft/sec
10⁺²
10
1
10⁻¹
10⁻³
10⁻⁵
10⁻⁷
10⁻⁹
3m/second
0.3/minute
1.5m/day
1.5m/month
1.5m/year
0.3m/5 years
Extremely rapid
Very rapid
Rapid
Moderate
Slow
Very slow
Extremely slow

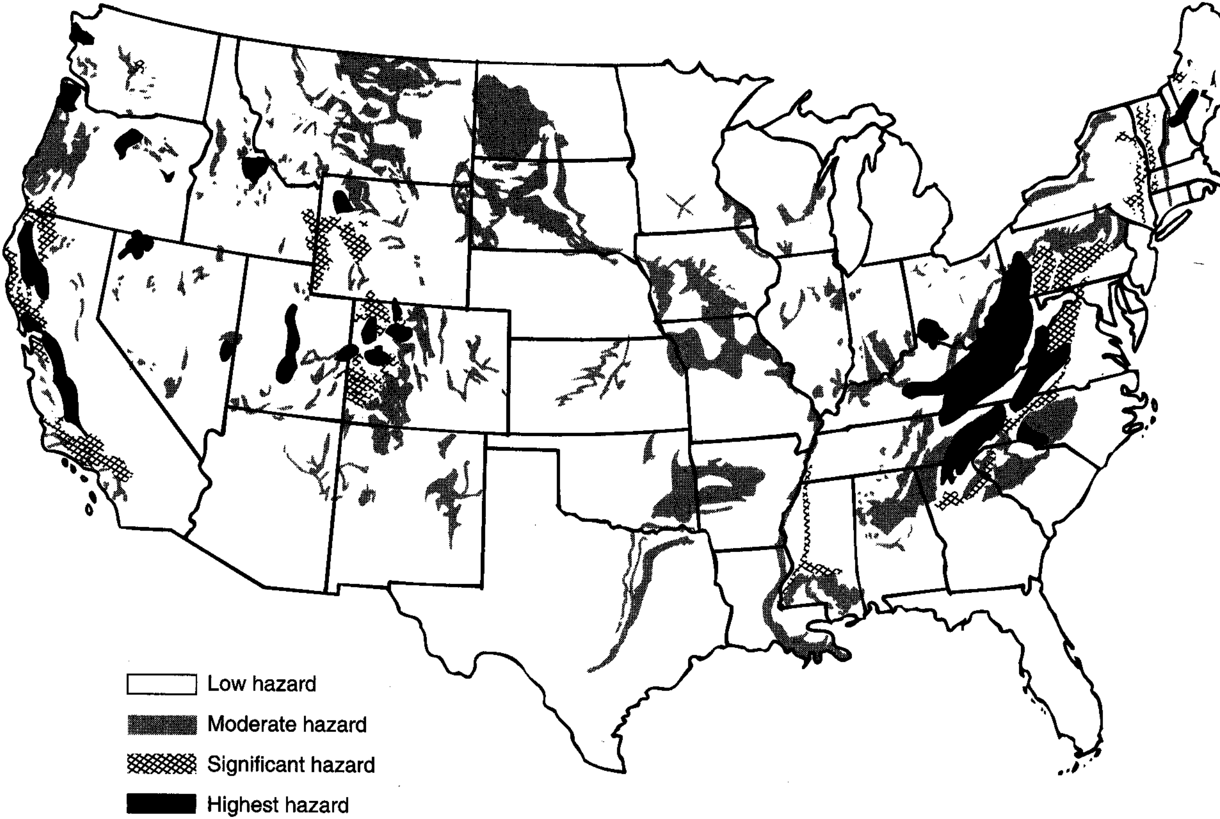


FIGURE 4.38

Major slope hazard regions in the United States. Darkest areas represent greatest severity. Details can be found in U.S. Geological Survey Professional Paper 1188.

(Hayes 1981)