Environmental Geology
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 ($9.8\ m/sec^2$)

$Wt. = \rho g V = \gamma V$

where W = weight (N), ρ = density (mass/vol), g = acceleration due to gravity, V = volume, γ = specific weight (N/cu. m)

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 ($N = 1\ kg\text{-}m/sec^2$), d = distance of mass displacement (m)

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

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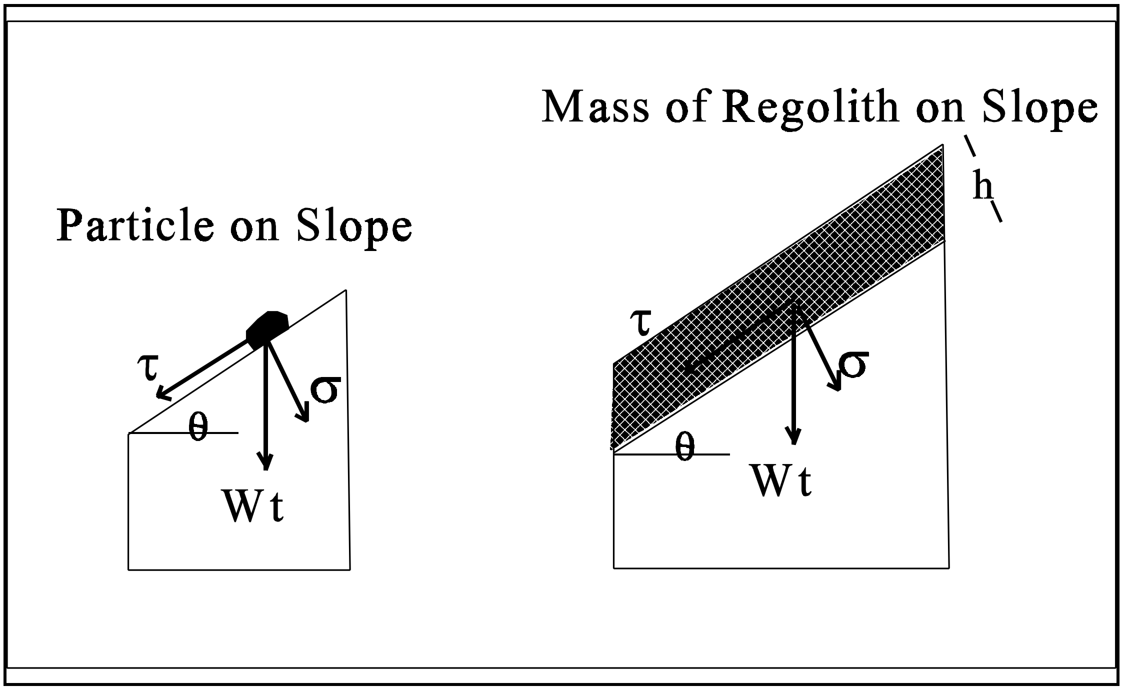
2. **Forces acting on Slope Material**



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... $$F = \sigma / \tau$$ (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.

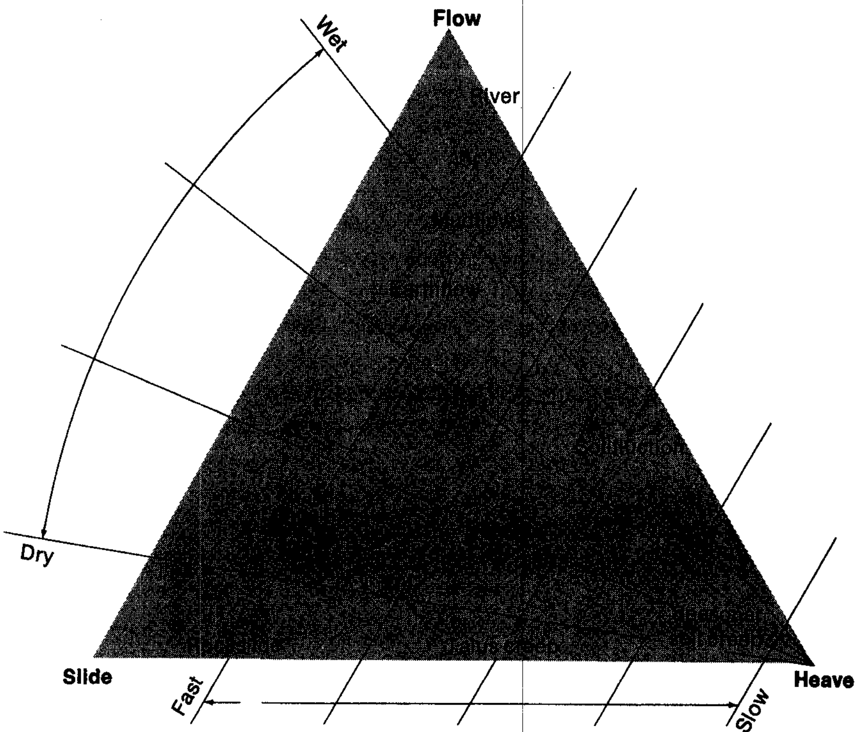


Figure 4.27
Classification of mass movement processes.
(From M. A. Carson and M. Kirkby, *Hillslope Form and Process*, copyright 1972 Cambridge University Press, Cambridge.)

TABLE 4.5 Factors that Influence Stress and Resistance in Slope Materials

Factors that Increase Shear Stress	Factors that Decrease Shear Strength
Removal of lateral support	Weathering and other physicochemical reactions
Erosion (rivers, ice, waves)	Disintegration (lowers cohesion)
Human activity (e.g., quarries, road cuts)	Hydration (lowers cohesion)
Addition of mass	Base exchange
Natural (e.g., rain, talus)	Solution
Human (e.g., fills, ore stockpiles, buildings)	Drying
Earthquakes	Pore water
Regional tilting	Buoyancy
Removal of underlying support	Capillary tension
Natural (e.g., undercutting, solution, weathering)	Structural changes
Human activity (mining)	Remolding
Lateral pressure	Fracturing
Natural (swelling, expansion by freezing, water addition)	

After Varnes (1958).

In most analyses the vertical height of the water table above the slide plane is expressed as a fraction of the soil thickness above the plane (m), where $m = 1.0$ if the water table is at the surface, and $m = 0$ if it is at or below the sliding plane. Thus, the pore pressure can be expressed as

$$\mu = \gamma_w \, mh \cos^2\theta$$

and

$$F = \frac{c + (\gamma - m\gamma_w)\, h \cos^2\theta \tan\phi}{\gamma h \sin\theta \cos\theta}$$

The following hypothetical example will show how to determine whether the slope is stable or close to failure. If laboratory tests tell us that $\phi = 10°$, $c = 45$ lb/ft^2,

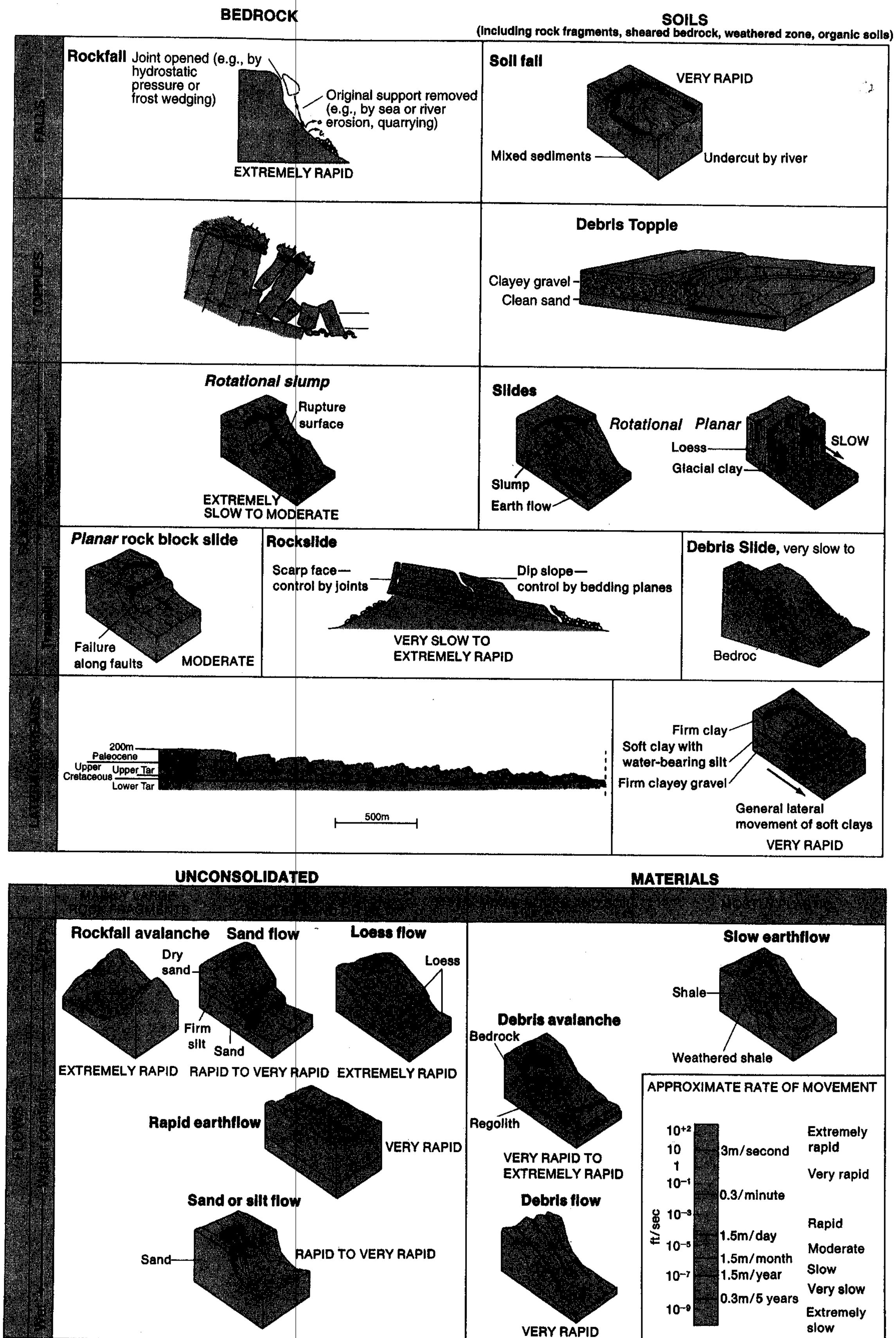


Figure 4.36
Classification of landslides.

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

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	Earthflow (soil creep)
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.

The sliding phenomenon can also be produced by a variety of events that reduce the internal resistance of the debris. From observation, sliding usually occurs after prolonged or exceptionally heavy rainfall, indicating that the lowering of resistance is predominantly a function of water. In the past, the water effect was interpreted to be lubrication along the sliding surface. Terzaghi (1950), however, refuted this notion by pointing out that water applied to many common minerals, such as quartz, is actually an antilubricant. Furthermore, most soils in humid regions contain more than enough water to cause lubrication at all times, yet they also fail after rainstorms. Clearly water affects strength in other ways. You will recall that shear strength is a function of cohesion (c), effective normal stress (σ'), and friction (ϕ) such that

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

The response of these factors (c, σ', ϕ) to wetting is significantly more important in the initiation of slippage than is lubrication (Sidle and Swanston 1982). For example, the rise of the water table or the piezometric surface, which accompanies all prolonged rainfalls, may be the most common culprit in sliding. As the water table rises, the pore pressure (μ) at any point within the saturated mass increases, ultimately resulting in a decrease in effective normal stress (σ') and a concomitant reduction in shear strength. Numerous recent studies have focused upon linkages between landslide initiation and shallow groundwater dynamics (i.e., Miller and Sias 1998; Van Asch et al. 1999; Matsuoka 1996). Miller and Sias (1998) showed that the spatial variability in landsliding was controlled by groundwater flux. Figure 4.38 shows the close relationship between rainfall, groundwater flux, and landsliding (Matsukura 1996). Significant progress has also been made to define rainfall intensity and cumulative rainfall thresholds important in the initiation of landslides (i.e., Schrott and Pasuto 1999). Iverson (2000) provides a detailed theoretical analysis of landslide initiation by rainfall initiation.

The type of landslide that ultimately occurs at a site is influenced by a range of factors, most importantly lithology and structure. Structural discontinuities, because they control material strength limits, play a large role in the morphology of landslides. Rocks with pronounced structure, such as foliation or inclined bedding, and prominent joint planes will tend to yield planar landslides and rockfalls, respectively. In contrast, failures in homogeneous materials and horizontally stratified units tend to be rotational in character. For example, Jacobsen and Pomeroy (1987) report that slumps and rotational earthflows account for most of the slope failures reported in the Appalachian Plateau, which occur primarily in colluvium and flat-lying fine-grained sedimentary rocks. In some cases, the style of movement is regulated primarily by the depth of weathered residuum. Crozier (1986) cogently reviews the effects of material and structure on landslide form. Often overlooked is the influence of relict bedrock structures on slope stability. Irfan (1998) clearly showed the control of landslides by relict joints in saprolitic soils. This study argues for detailed analyses of stability for development in regions characterized by saprolite at the surface.

Rockslides are usually associated with major structural features within the rock such as the stratigraphy of the rock sequence, joint patterns, and orientation of the foliation in metamorphic rocks. Massive rock units normally

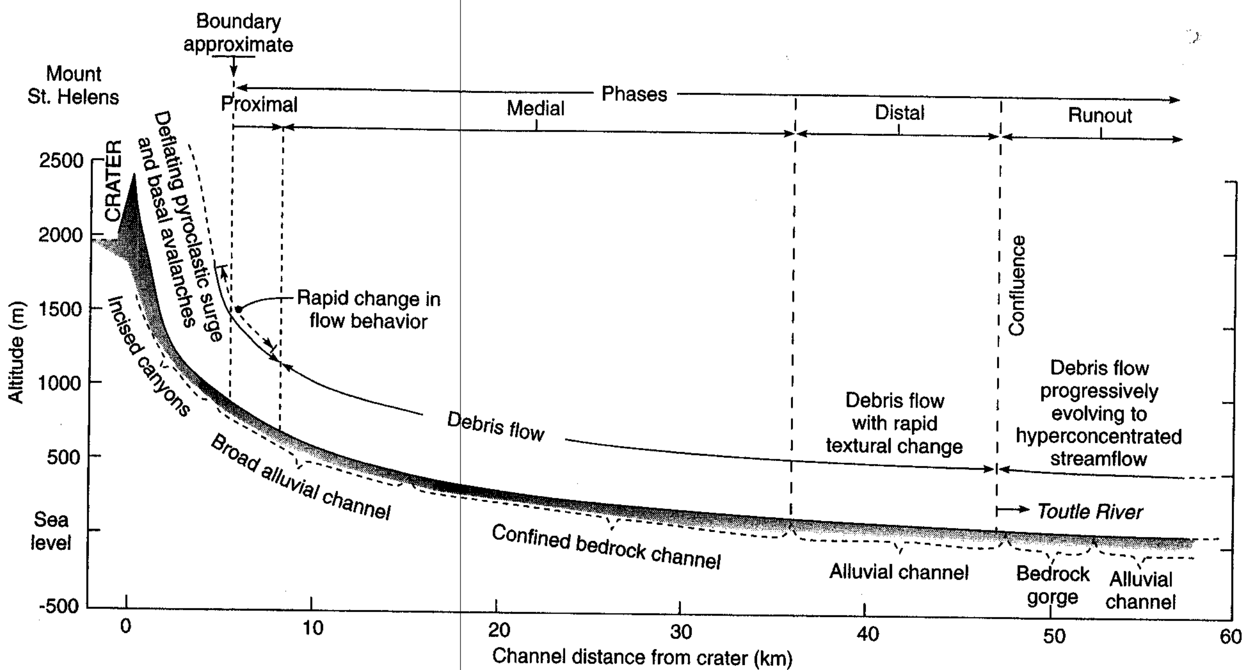


Figure 4.43
Transformations of debris flow along its path originating at Mount St. Helens.
(After K. M. Scott, U.S. Geological Survey Professional Paper 1447-A 1988.)

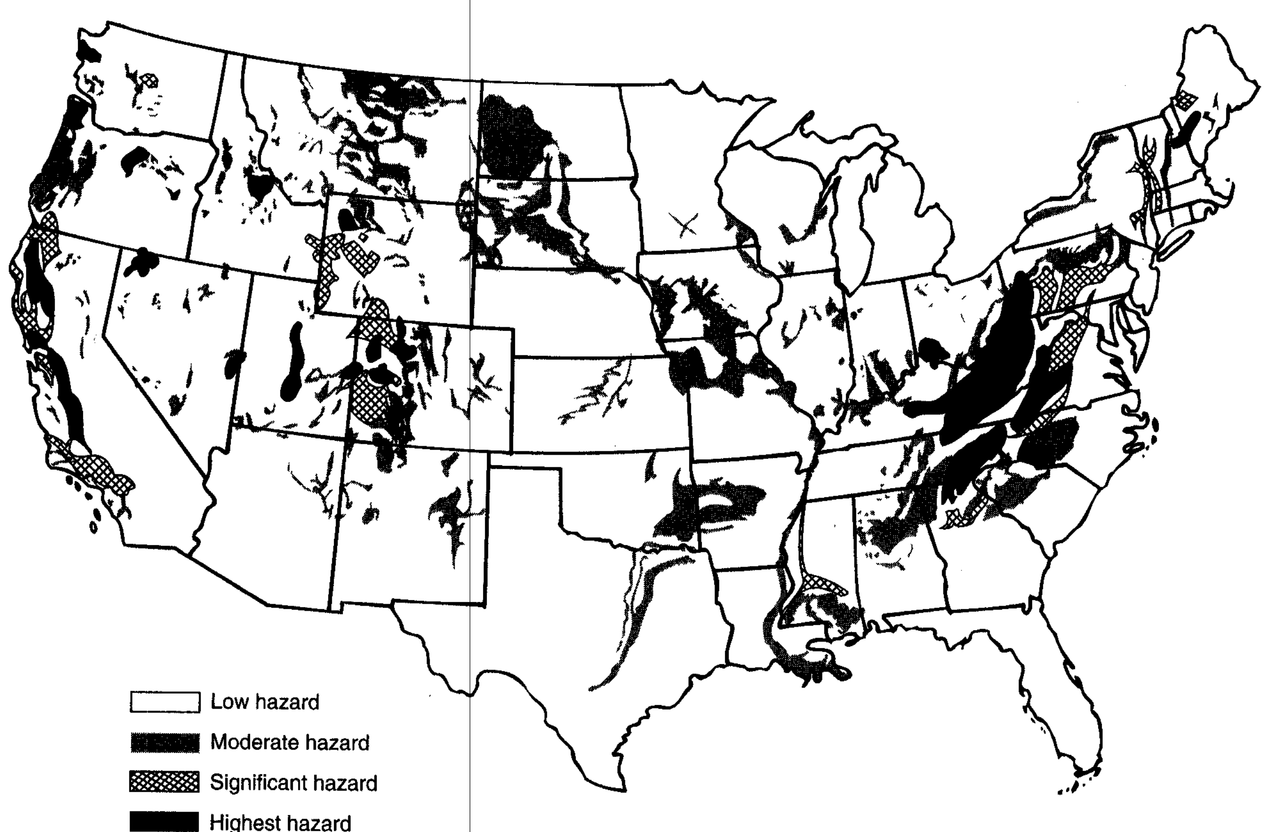


Figure 4.44
Major slope hazard regions in the United States. Darkest areas represent greatest severity. Details can be found in U.S. Geological Survey Professional Paper 1188.
(From Hays, 1981 *Facing Geologic and Hydrologic Hazards,* U.S. Geological Survey Professional Paper 1240-B.)