MANAGEMENT OF NATURAL HAZARDS
IN MOUNTAIN BASINS

Hillslope processes and landslides

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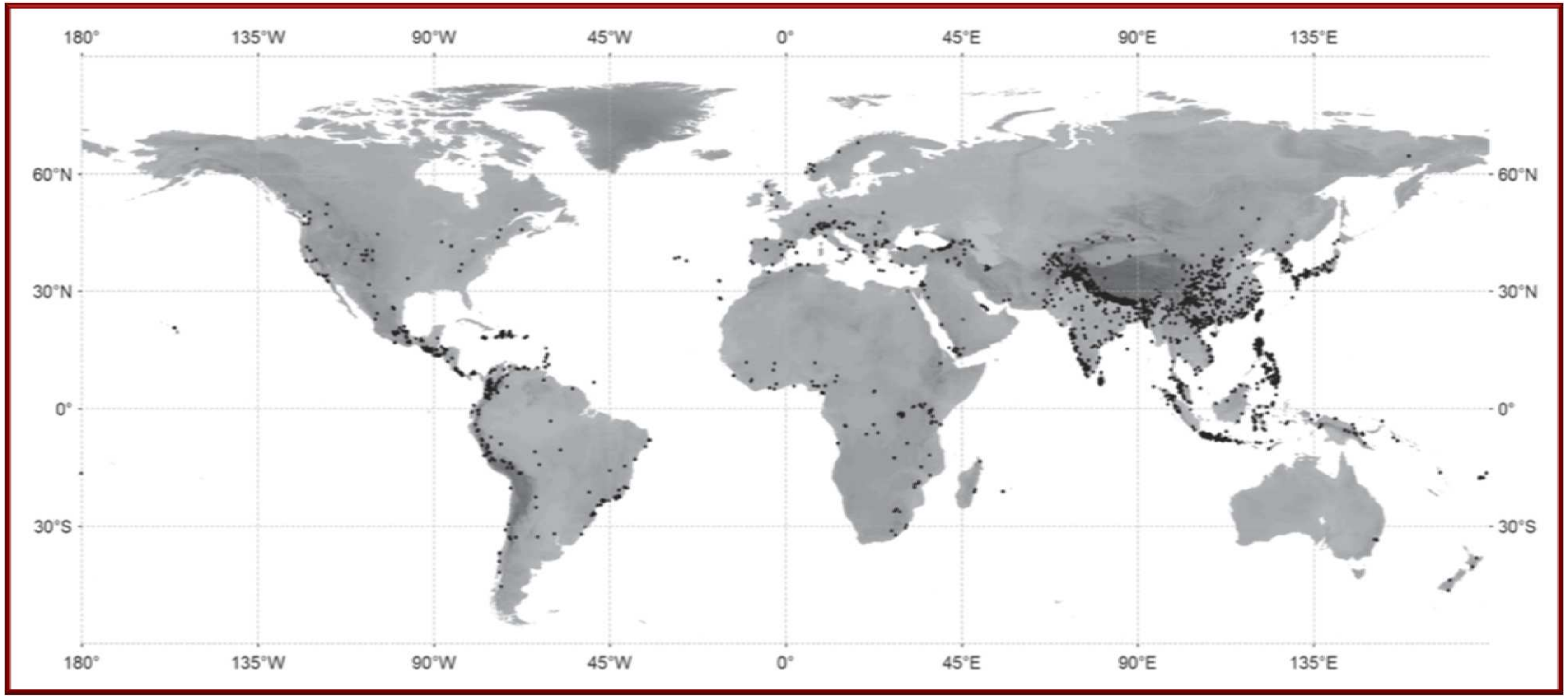
Credits to:
P.R. Bierman, D.R. Montgomery (2014) «Key concept in Geomorphology»
Dr. F. Guzzetti (CNR-IRPI Perugia) for landslide statistics
Prof. G. Bischetti (University of Milano) for role of vegetation

Landslide: a world-scale overview

- 32,322 fatalities caused by 2620 landslides in the 7-yr period 2004-2010

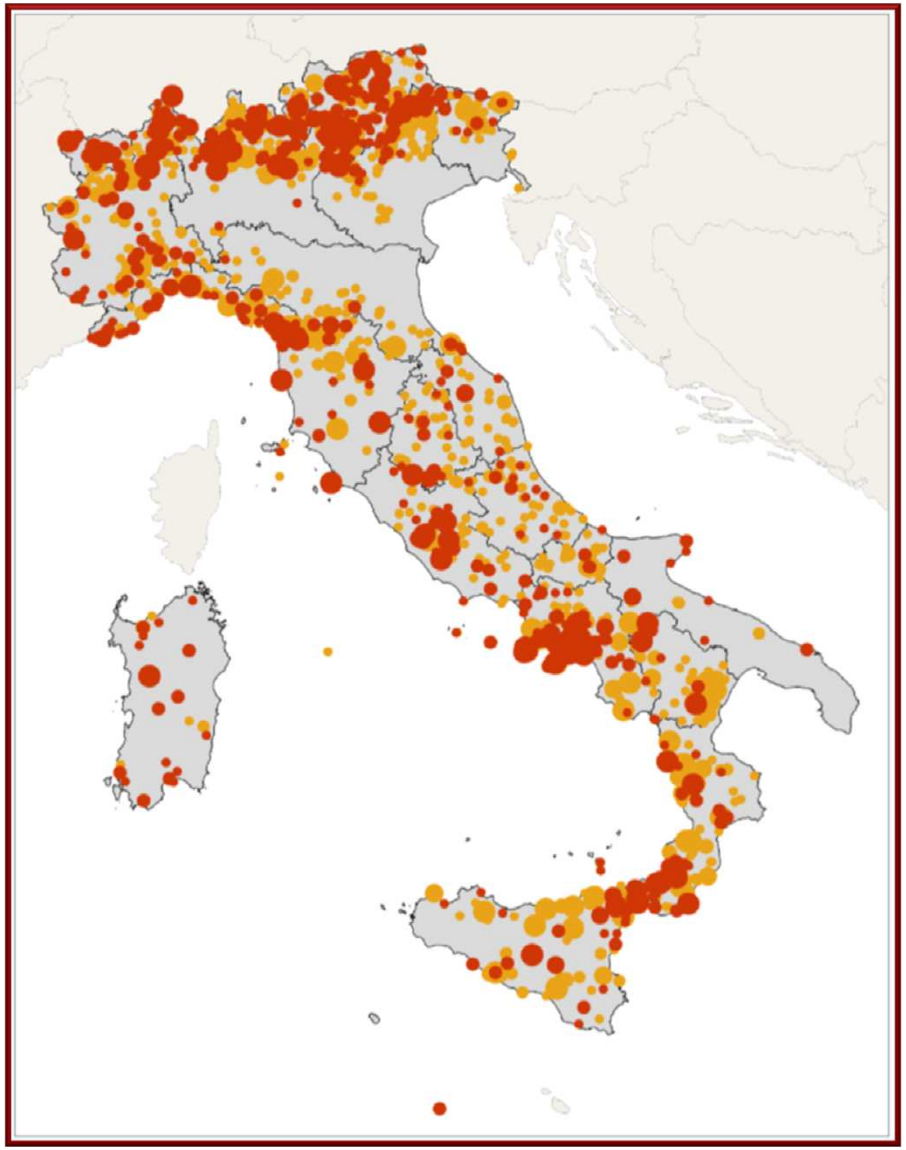


Petley (2012)

Landslide in Italy with victims

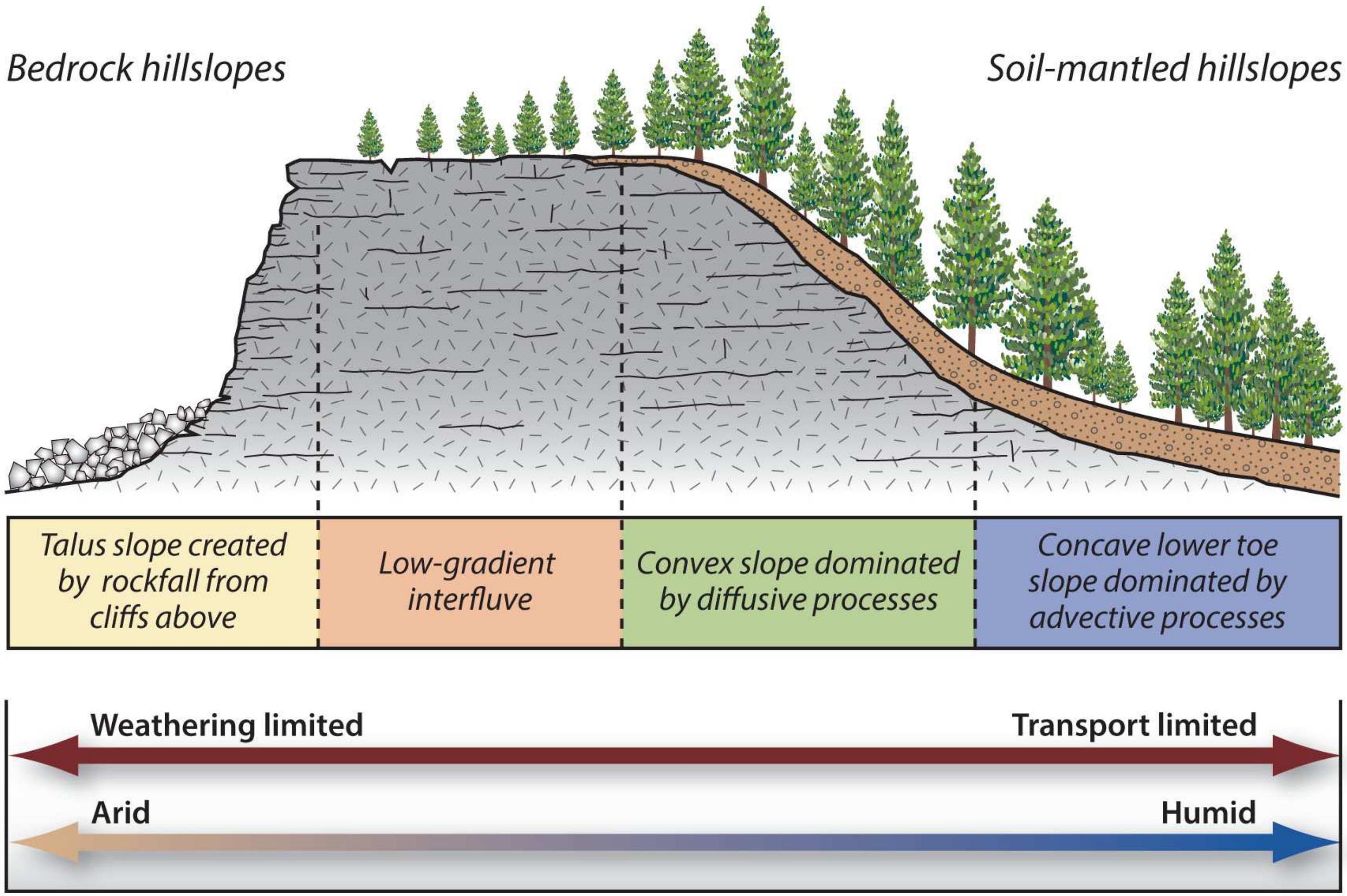
Between 1964 and 2013:

- 3043 casualties
- 151,551 homeless & evacuees



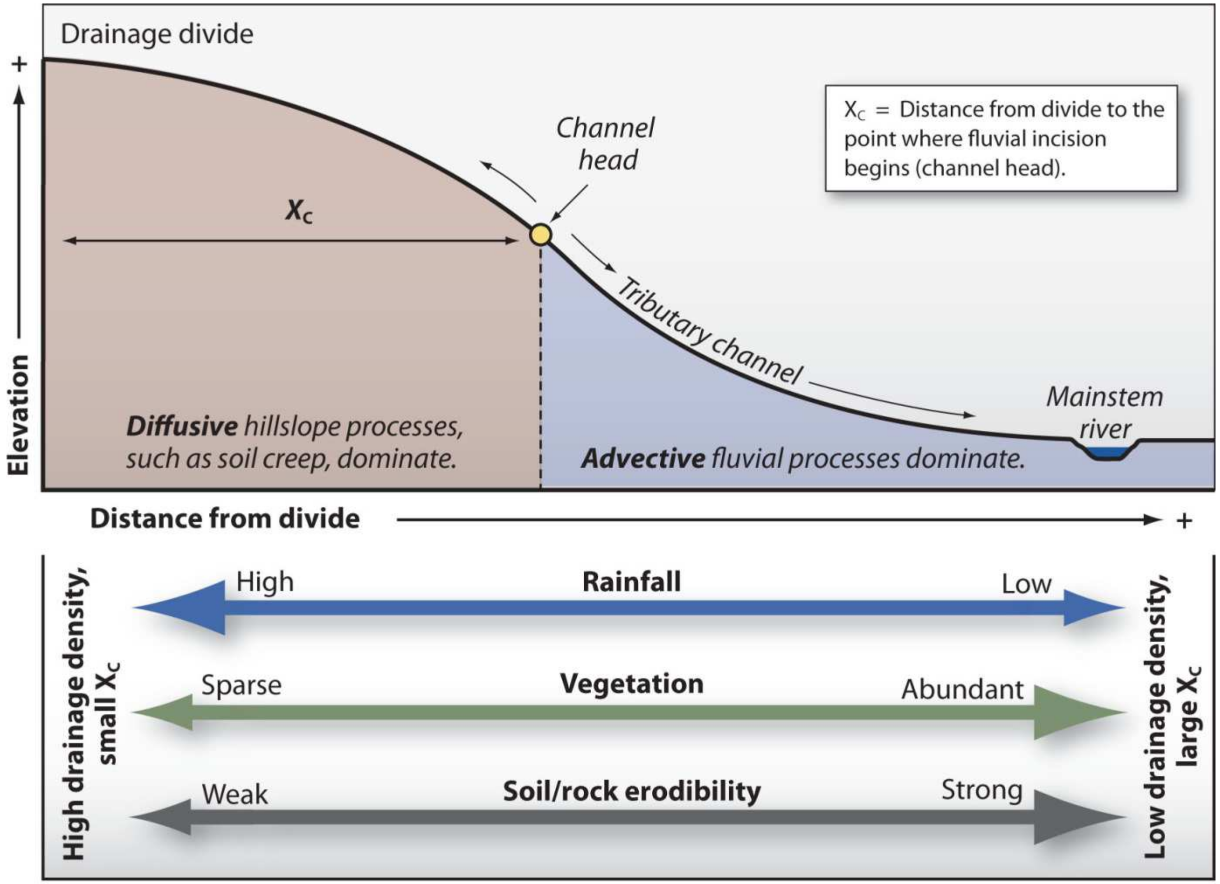
http://polaris.irpi.cnr.it

Hillslopes: types and formation



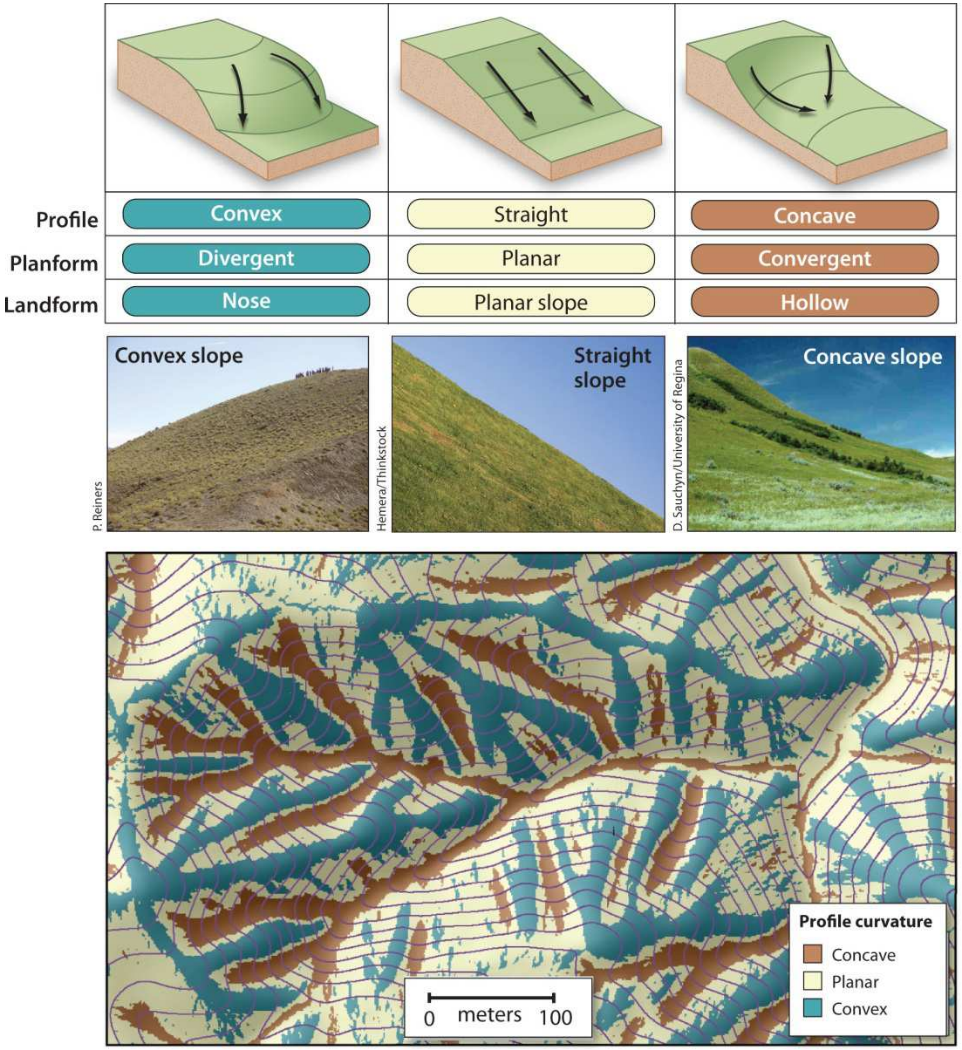
Hillslope shape, soil cover, and the surface processes that transport mass downslope generally vary with climate. In arid regions with little rainfall, bare rock is common, talus slopes are mantled with rockfall from cliffs above, and the removal of mass from slopes is limited by the rate at which the rock weathers (**weathering limited slopes**). In more humid climates, the rate at which mass is removed from slopes is limited by sediment transport capacity (**transport limited slopes**), soil covers rock, and the soil cover may thicken downslope.

Hillslopes: diffusive vs advective processes



The transition between **diffusive** and **advective** processes on hillslopes determines the location of the channel head (X_C). Channel head locations vary in a complex fashion with climate, relief, vegetation cover, soil/rock erodibility, and near-surface hydrology. Drainage density is inversely related to X_C. Channel heads close to the drainage divide generate high-drainage densities and are common in areas with high rainfall, weak soils, and no vegetation (e.g., badlands). Large X_C values, where channel heads are located far from drainage divides, favor development of long, rolling hills.

Hillslopes: types

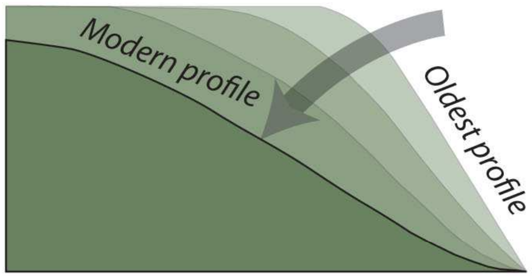


Hillslope geometry can be characterized by profile and planform shape. Patterns of mass flux down slopes are dependent on hillslope geometries. For example, on convex **noses,** flow diverges. Conversely, in concave **hollows,** flow converges. Most landscapes are composed of different slope geometries. The lower panel shows how areas of profile curvature (colors) generally correspond with areas of planform curvature (as indicated by purple topographic contours); hollows are typically concave and convergent, whereas noses are typically convex and divergent.

Hillslopes: types and dynamics

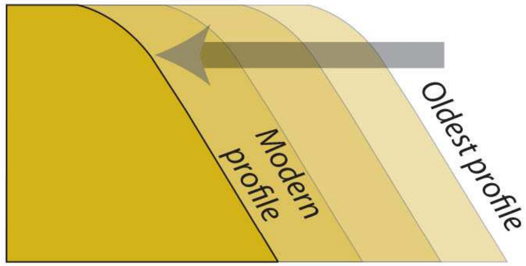
Slope profiles

Humid regions



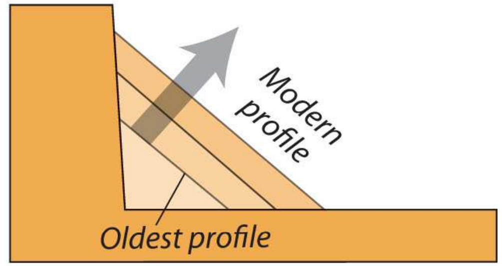
Slope decline

Arid regions



Parallel retreat

Steep terrain



Slope replacement

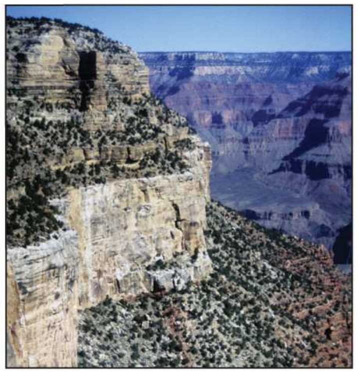
Process description

Hillslopes in humid regions tend to be **soil-mantled** and erode by slope-dependent **diffusive processes,** resulting in progressive rounding and lowering of hillslope profiles. Over time, this results in the decay of hillslope profiles as gradients gradually decline.

Hillslopes in arid regions tend to form bedrock slopes that erode by progressive back-wearing. Processes such as **rock fall** preserve the initial shape and gradient of hillslopes, thereby promoting **parallel slope retreat.**

Slope replacement occurs in very steep terrain where surface processes cannot remove debris that accumulates below a cliff. In this case, a **talus slope** builds up as the base of the cliff. The cliff is "replaced" by a more gently sloping pile of broken rock (**scree**).

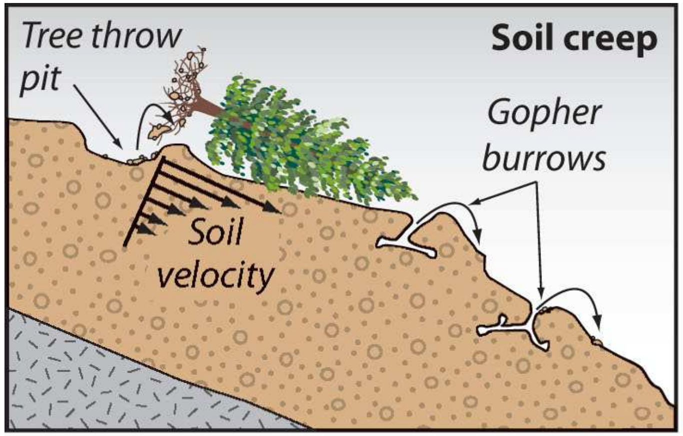
D. Montgomery

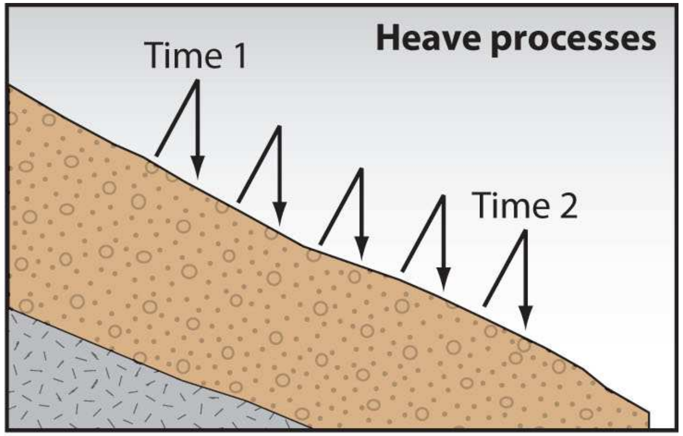


D. Montgomery

M. Hansen

Hillslopes: diffusive transport processes

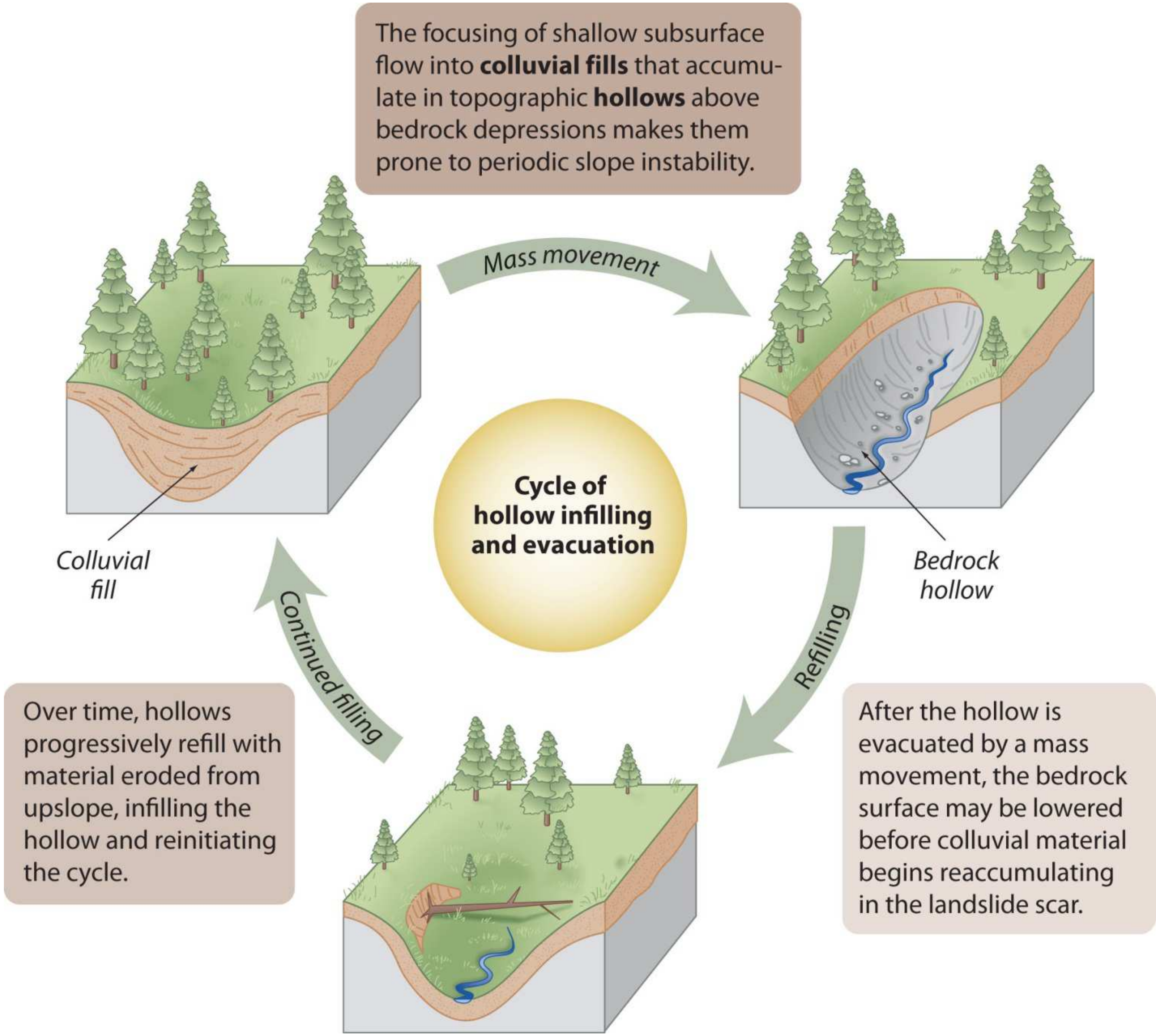




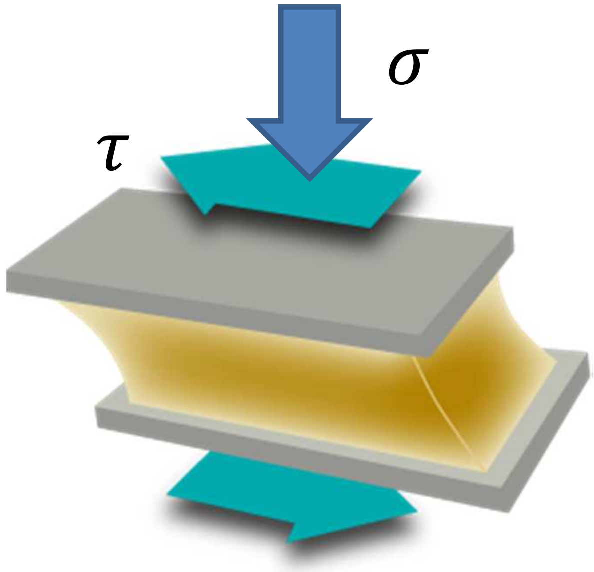
Soil creep describes the suite of processes that move soil and regolith downslope at a velocity proportionate to the to slope angle. Processes contributing to soil creep include tree-throw, animal burrowing, and deformation of fine-grained soil.

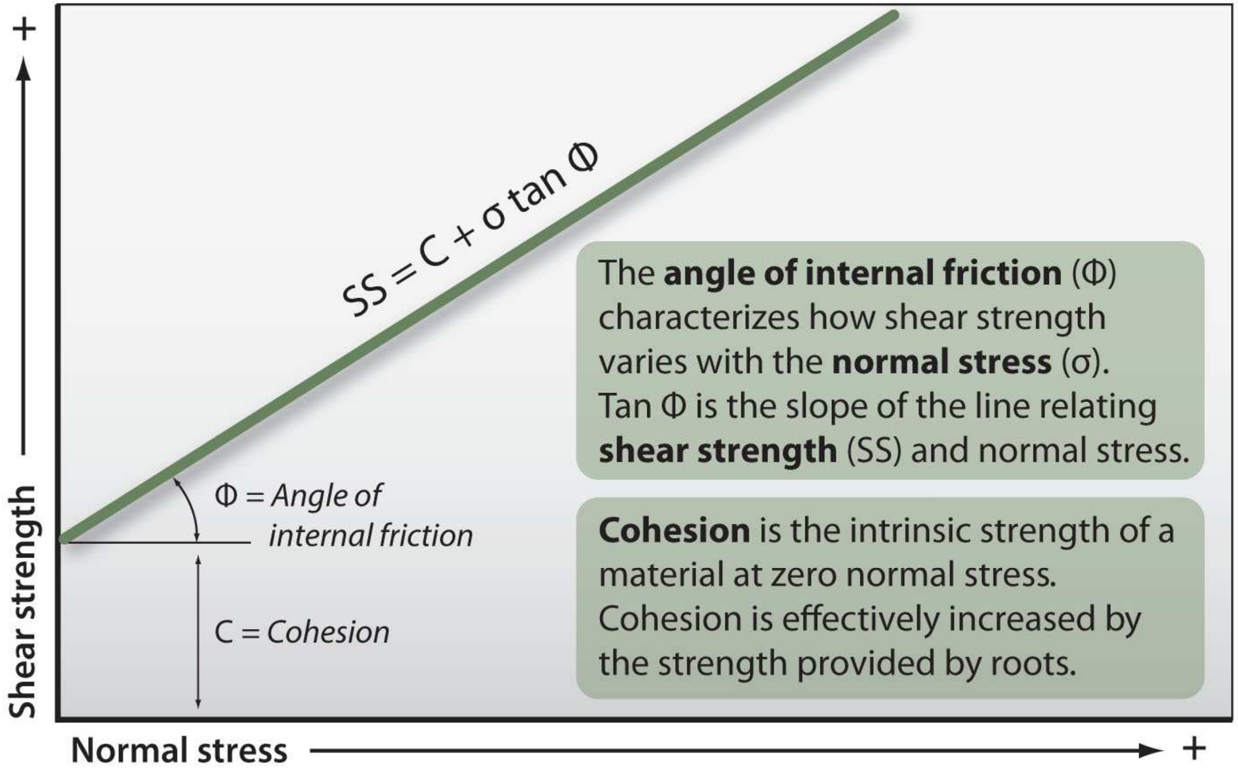
Heave contributes to soil creep. Heaving soil rises up perpendicular to the slope through the wetting and expansion of clays or the freezing of interstitial water. When the soil thaws or dries and shrinks, the material drops vertically under the influence of gravity, causing net downslope movement of soil.

Hillslopes: types and dynamics



Shear strength of rocks and soils



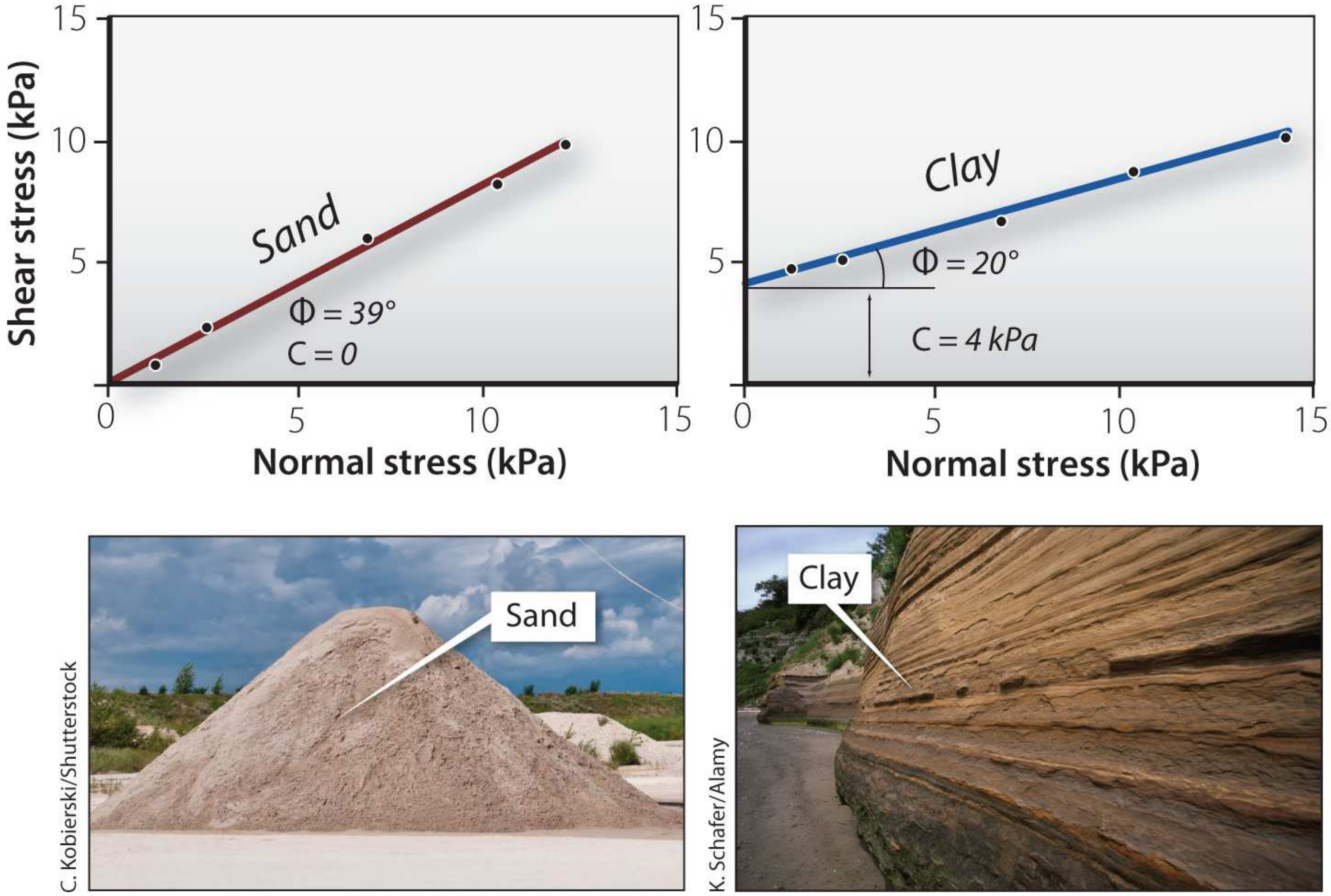


Coulomb criteria describe material strength as a combination of frictional and cohesive strength. Due to their granular nature, sands typically have higher **friction angles** (30–40°) than do clays (10–20°), although clays often exhibit significant **cohesion.** Lacking cohesion, dry sand cannot hold slopes higher than its **angle of repose,** equal to Φ. In contrast, cohesive clay can hold a short vertical face, even though it is less able to resist shear at higher normal stress.

- Mohr-Coulomb failure criterion

$$SS = C + \sigma \, tan\Phi$$

Strength of rock and soil



Strength of rock, soil and roots

Typical strength of Earth materials

Material	Friction angle (degrees)	Cohesion (kPa*)
Soil		
Sandy soil	30–40	0
Soft organic clay	22–27	5–20
Stiff glacial clay	30–32	70–150
Rock		
Intact sandstone (lab)	35–45	>10,000
Intact shale (lab)	25–35	>1,000
Sandstone (field)	17–21	120–150
Shale (field)	15–25	40–100

*1 Pa = 1 kg/ms^2; 1 kPa = 1000 Pa
lab = laboratory data on small samples
field = data collected from field measurements

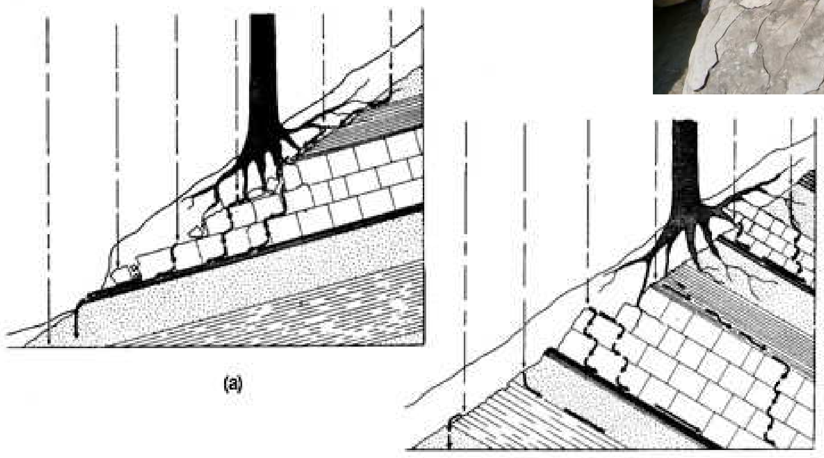
Typical values of apparent cohesion associated with vegetation

Vegetation	Apparent cohesion (kPa*)
Grass	0–1
Stumps	0–2
Chaparral	0–3
Hardwoods	2–13
Conifers	3–20

*kPa = kg/ms^2

Factors favouring mass movements

- Weak parental substrate (lithology)
- Highly fractured and deformed rocks (tectonics)
- Rock weathering
- Orientation of strata
- Topography (slope)
- Precipitation regime
- Vegetation removal

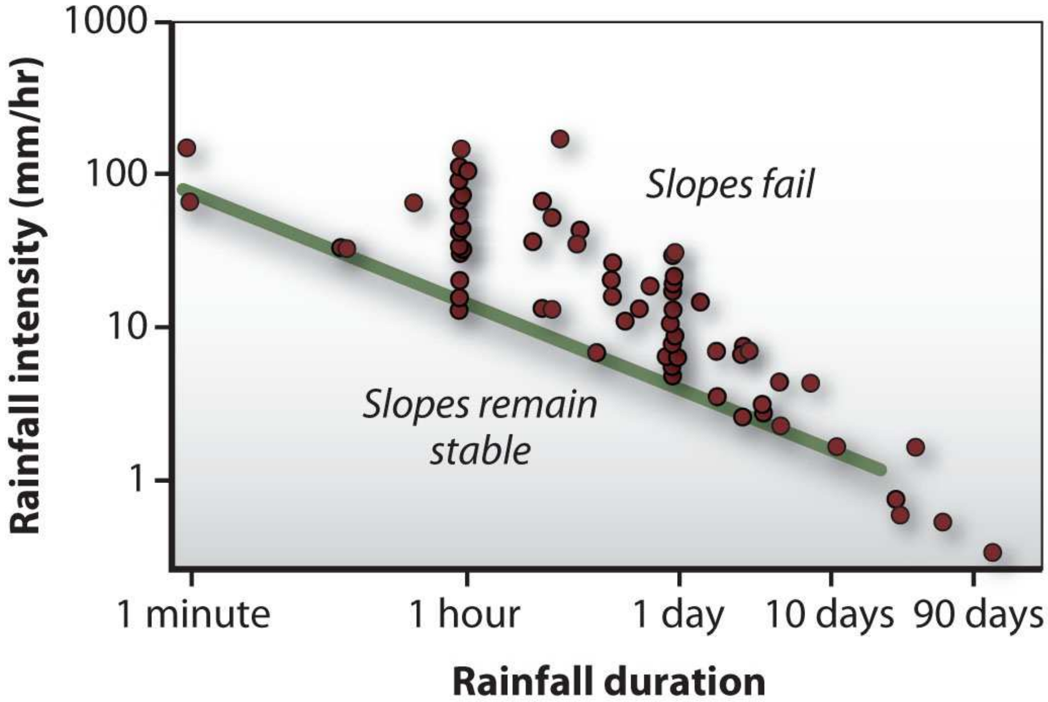


(a) (b)

Triggering causes for mass movements

Triggering causes	Group
• Prolonged/intense precipitation • Hillslope toe erosion by channel dynamics	Rainfall and floods
• Rapid snowmelt (with deep snowpack) • Permafrost degradation (at high elevations only) • Ice expansion in rock fractures (for rockfalls)	Temperature
• Anthropic modification of subsurface hydrology • Variations in hillslope geometry, cover and loading	Humans (directly)
• Earthquakes	

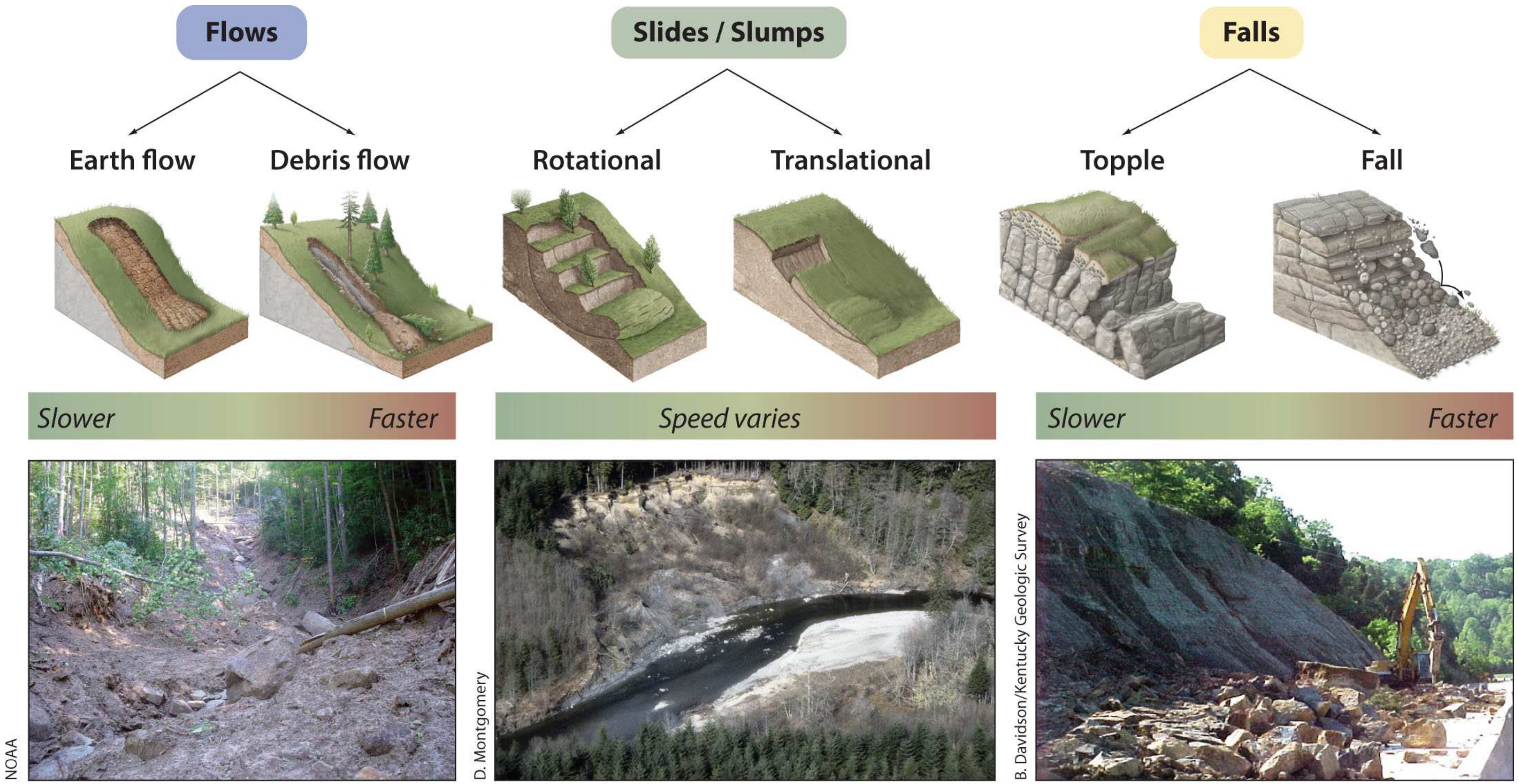
Triggering causes for mass movements



Threshold: the <u>minimum</u> rainfall intensity, cumulated rainfall, rainfall duration for possible landslide <u>occurrence</u>

Landslides that trigger debris flows are a geomorphic process that occurs when a **threshold** is exceeded. In this case, rainfall is the trigger, saturating the ground and causing slopes to fail. Both rainfall intensity and duration, not just cumulative rainfall, are important in determining slope stability. The combinations of rainfall intensities and durations that trigger slope failure vary regionally, reflecting differences in slope strength, topography, and near-surface hydrology.

Type of mass movements on hillslopes

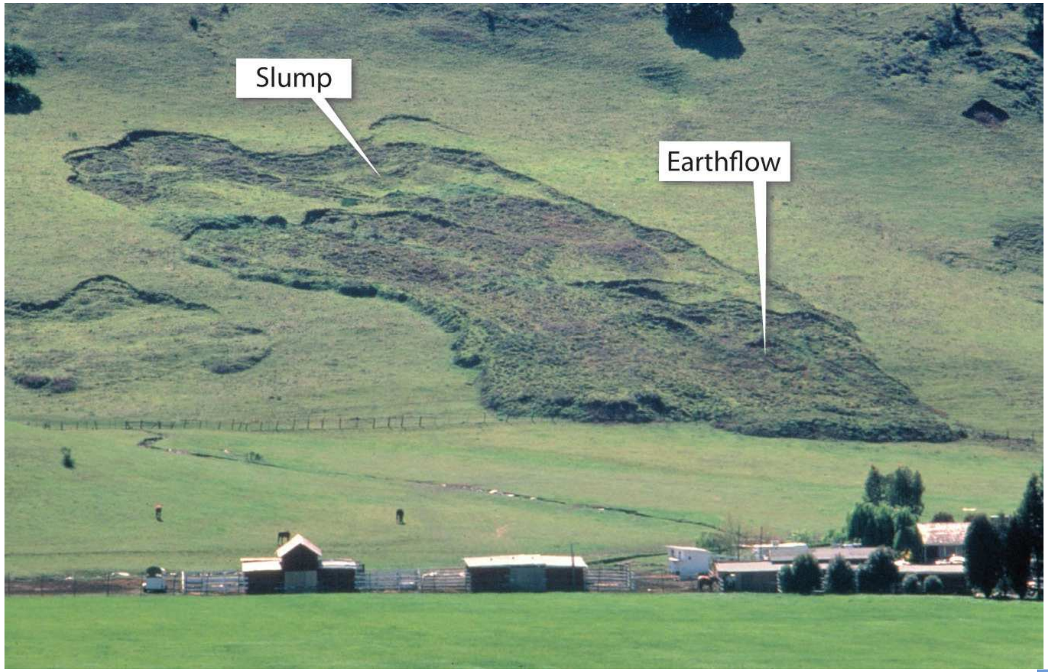


For **flows, shear** occurs throughout the moving mass and there is no well-defined **shear plane**; material is disrupted throughout the flow.

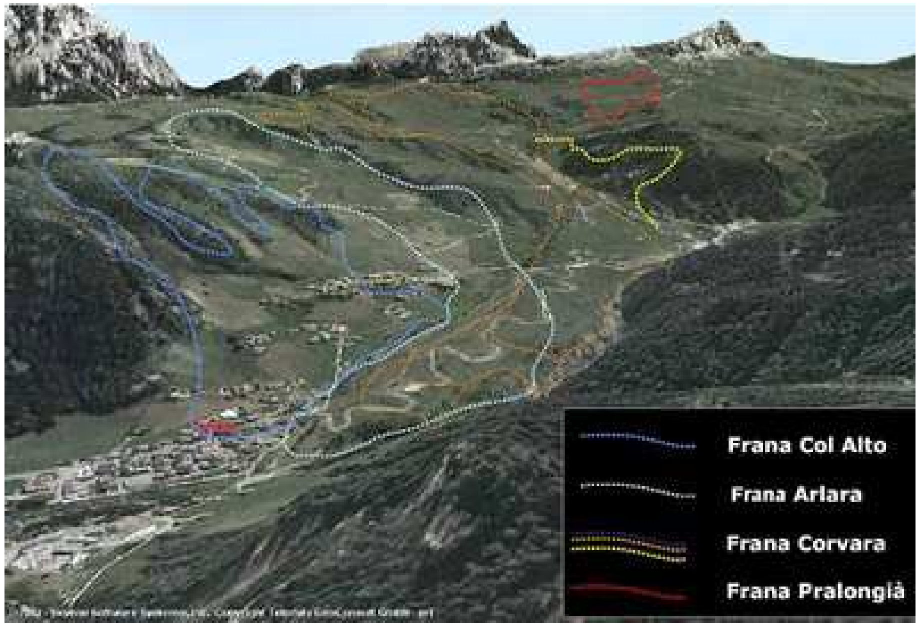
For **slides** and **slumps,** failure occurs along a well-defined shear plane; blocks of material within the failure may move as coherent units, preserving relict structures.

For **falls,** rock or soil moves downward through the air. Falls occur along very steep faces, such as cliffs or eroding stream banks.

Earthflows

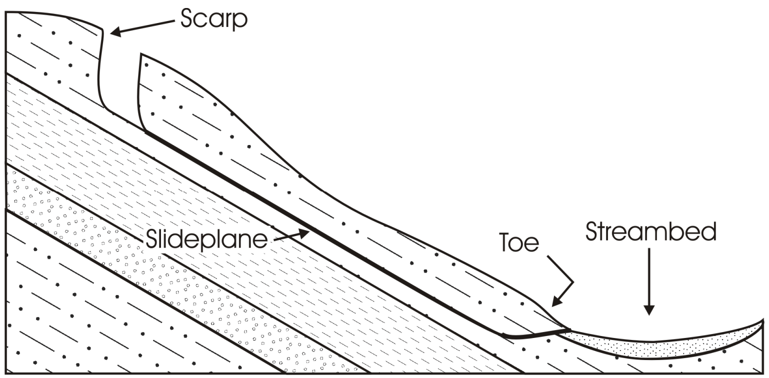


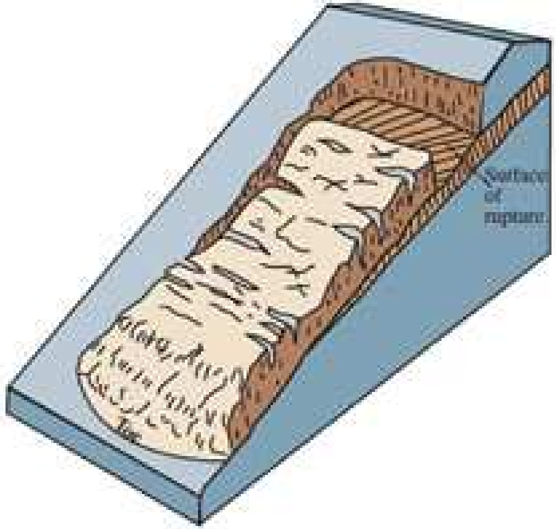
A rapid or slow intermittent flow-like movement of plastic, clayey earth.



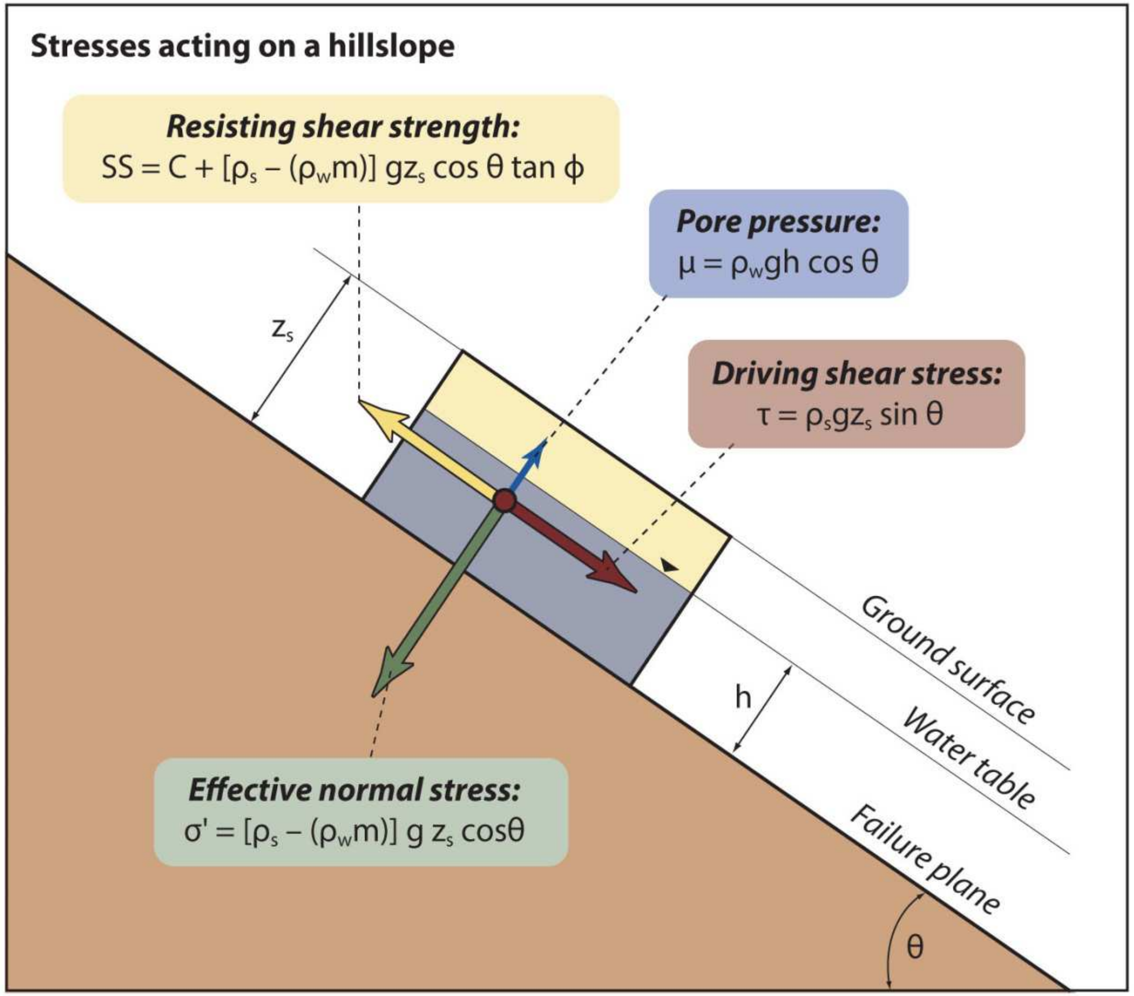
Translational slides

Mass moves along a roughly planar surface with little rotation or backward tilting





Translational slides: the infinite-slope model



Definition of terms:

z_s = slab thickness normal to failure plane
h = water-table height normal to failure plane
ρ_s = soil density
ρ_w = water density
g = gravitational acceleration
C = soil cohesion
$m = h/z_s$ = proportion of soil slab that is saturated

θ = failure plane angle above horizontal
ϕ = angle of internal friction

σ = normal stress
μ = pore pressure
τ = shear stress
SS = shear strength

The **infinite-slope model** is often used to analyze the stability of slopes to shallow, planar landslides. The model is a balance between the **shear strength** of the slope materials and the **shear stress** provided by gravity, due to the downslope-oriented component of the mass of the soil. It considers the **pore pressure** effect on the stress balance as well as the effect of slope.

Translational slides: the infinite-slope model

Factor of safety

Affected by precipitation/temperature

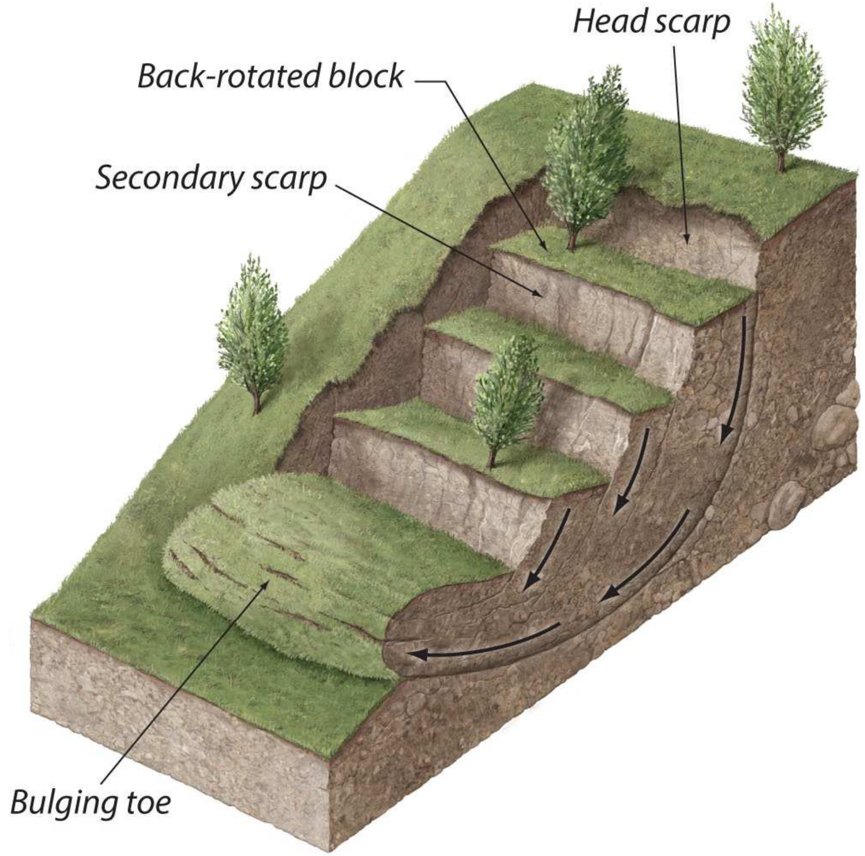
$$FS = \frac{Resisting\ shear\ strength}{Driving\ shear\ stress} = \frac{C + [\rho_s - (\rho_w m)]g z_s \cos\Theta \tan\Phi}{\rho_s g z_s \sin\Theta}$$

FS > 1 → stable slope

FS ≤ 1 → unstable or failed slope

Rotational slides

A slide in which the surface of rupture is curved concavely upward and the slide movement is roughly rotational



Rotational landslides generate characteristic landforms that are indicative of the underlying physical processes. Near the **head** of the slide there are often multiple back-rotated blocks, each bordered by **scarps** and each having a back-tilted top. At the **toe** of the slide, material may pile up, increasing ground elevation.

Rotational slides

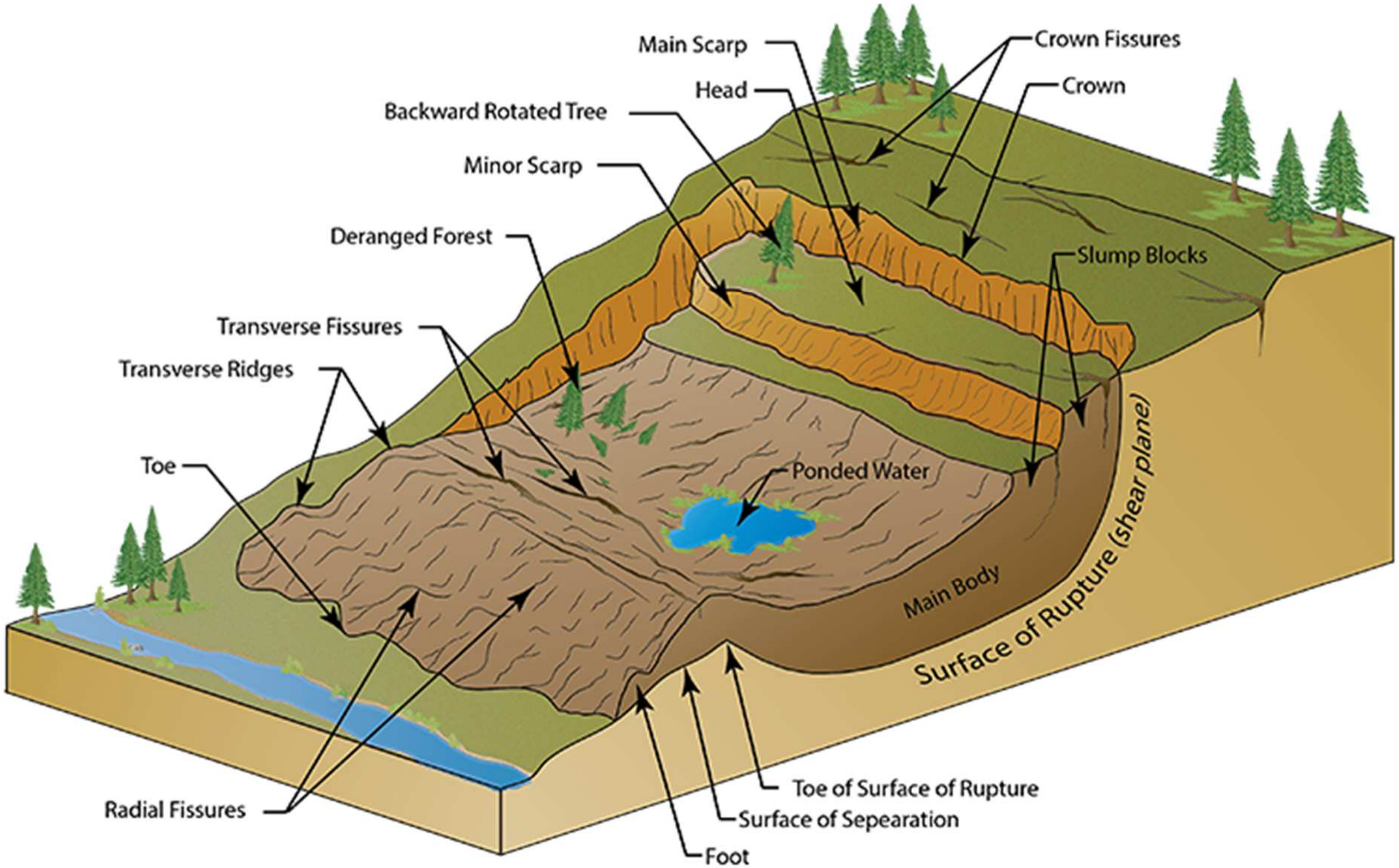
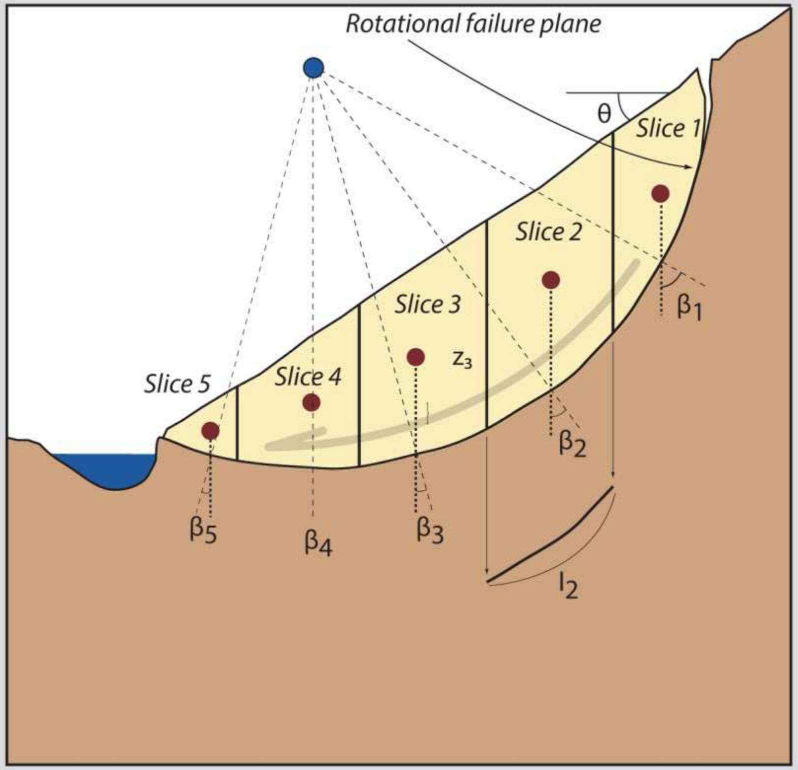


Diagram by Jim Rodgers

Rotational slides

The methods of slices

Setup



Definition of terms:
N = number of slices
i = slice number, index variable
● = center of mass of each slice
● = center of rotation above failure plane

Values measured in the field:
θ = angle of surface below horizontal
C = cohesion of material
ρ_s = density of soil (or rock)
ρ_w = density of water
φ = angle of internal friction
g = acceleration of gravity

Values measured from the sketch:
$l_1 \ldots l_N$ = length of bottom of each slice
$z_1 \ldots z_N$ = height of each slice
$\beta_1 \ldots \beta_N$ = angle at failure plane from vertical at center of mass of each slice to extended radius line

Calculated values:
$W_i = \rho_s g A$ (A = Area; assumes 1m width for each slice)
$\mu_i = \rho_w g z_i \cos\theta$

Model

$$\textit{Factor of safety} = \frac{\textit{Resisting}}{\textit{Driving}} = \frac{\sum_{i=1}^{N} [C_i l_i + (W_i \cos\beta_i - \mu_i l_i) \tan\varphi_i]}{\sum_{i=1}^{N} W_i \sin\beta_i}$$

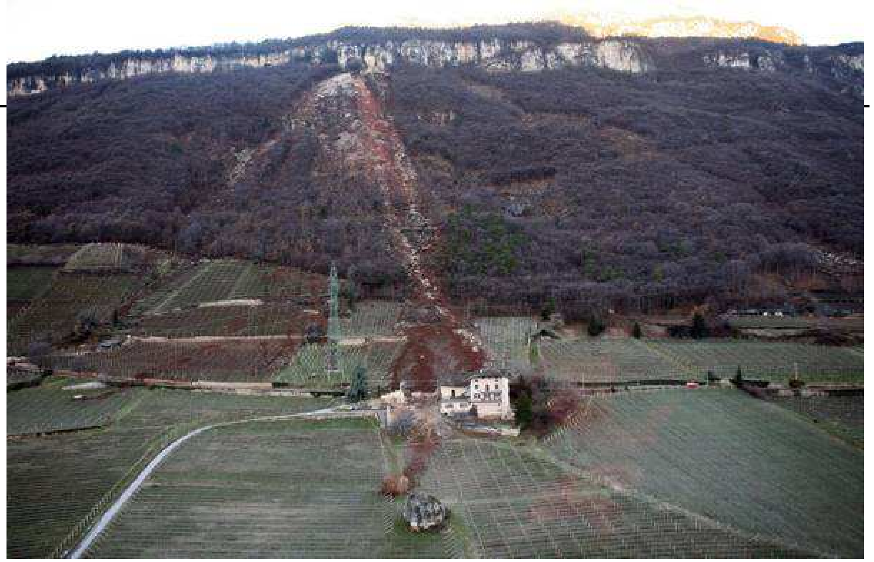
FS > 1 Stable

FS < 1 Failure

The **method of slices** is a useful way to analyze the stability of a **rotational landslide**. The method approximates the **force balance** of slides with circular failure surfaces by approximating the failure surface as a series of chords and solving the force balance for each of these subsections. Summing the results determines the overall stability of the slide mass.

Rockfalls

Falls are abrupt movements of masses of rocks that become detached from steep slopes or cliffs

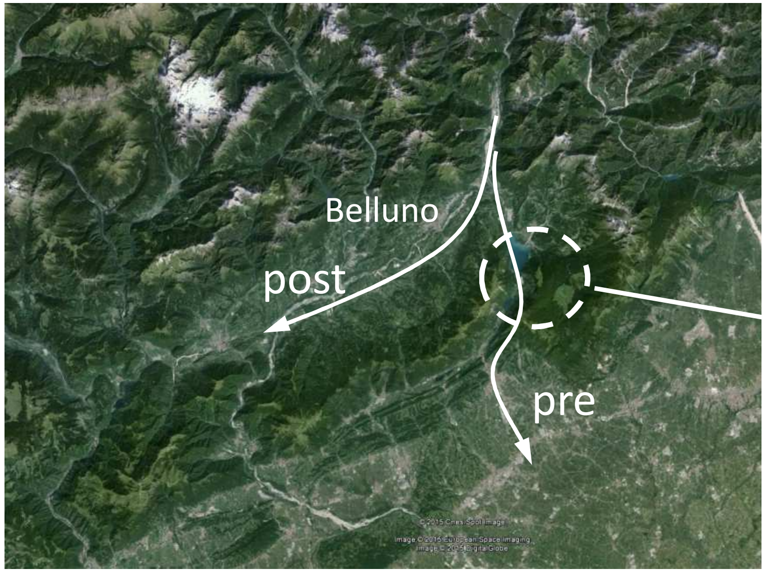


Separation occurs along discontinuities such as fractures, joints, and bedding planes, and movement occurs by free-fall, bouncing, and rolling.

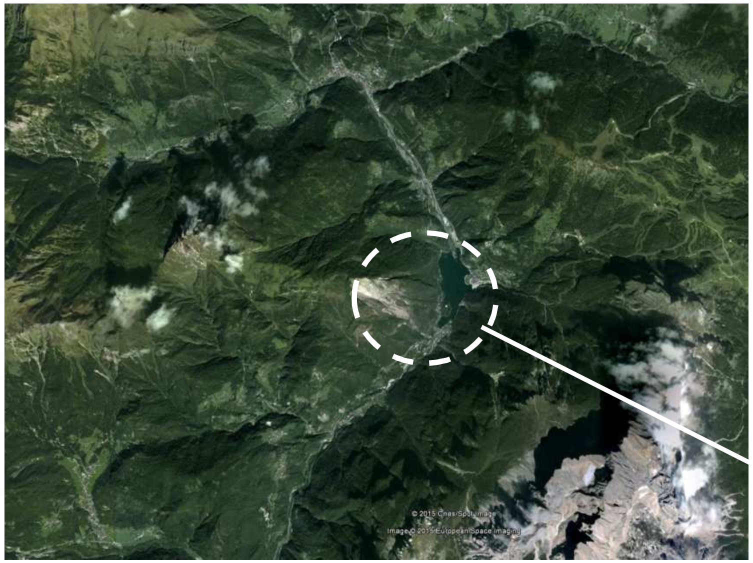
Toppling failures are distinguished by the forward rotation of a unit or units about some pivotal point, below or low in the unit, under the actions of gravity and forces exerted by adjacent units or by fluids in cracks

Large landslides of the past

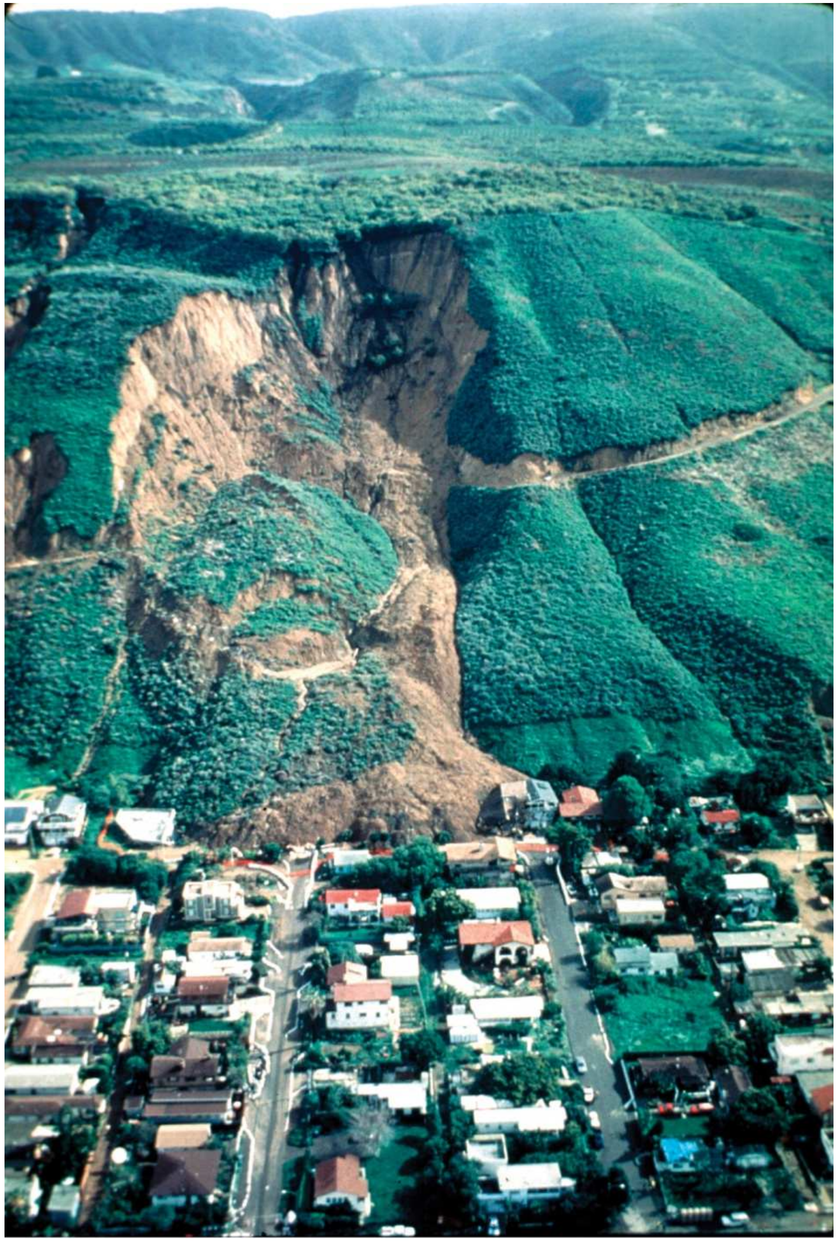
«Fadalto» post-glacial landslide (created the Santa Croce Lake and deviated the Piave River)



«Piz peak» landslide in 1771 (created the Alleghe Lake and aggraded the Cordevole River)



Recent large (and complex) landslides



Human-triggered landslides

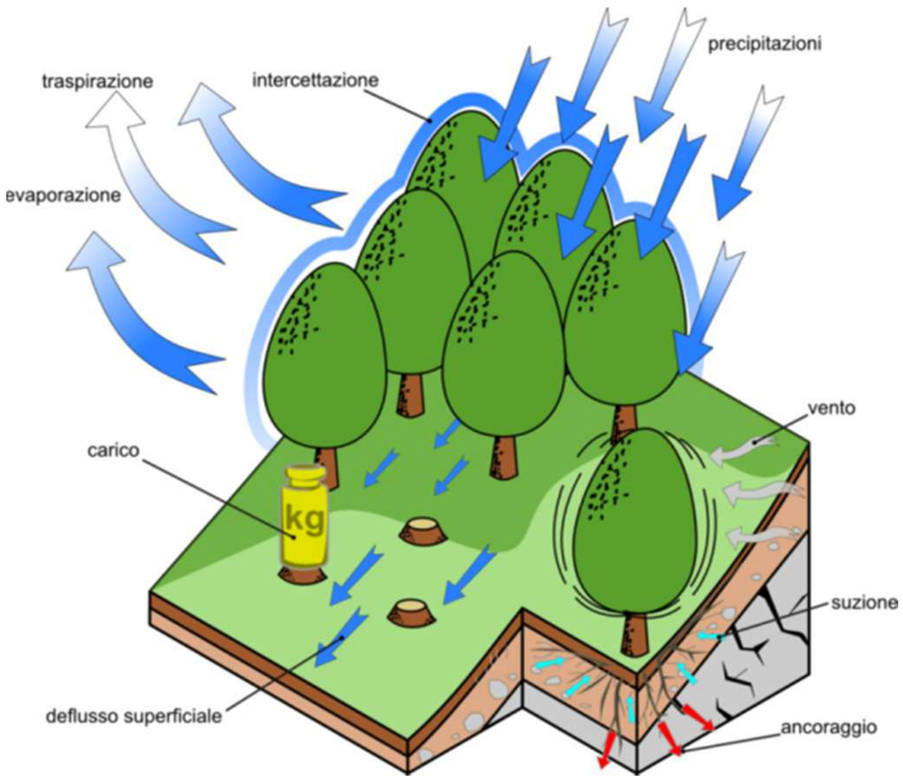
Vajont (Friuli, 1963)

- Slide mass 270 Million m^3
- Triggered by hydropower reservoir filling
- >1900 casualties

Laces (Bolzano, 2010)

- Slide mass 400 m^3
- Triggered by irrigation system leakage
- 9 casualties

The effects of vegetation on slope stability



Surcharge

weight of vegetation on a slope exerts both a downslope (destabilizing) stress and a stress component perpendicular to the slope which tends to increase resistance to sliding (+/-).

Soil binding

binding of soil particles (+)

Root reinforcement

roots mechanical reinforce a soil by transfer of shear stress in the soil to tensile resistance in the roots (+)

Buttressing and arching

anchored and embedded stems can act as buttress piles or arch abutments in a slope, counteracting shear stresses. (+)

Windthrowing

destabilizing influence from turning moments exerted on a slope as a result of strong winds blowing downslope through trees (-)

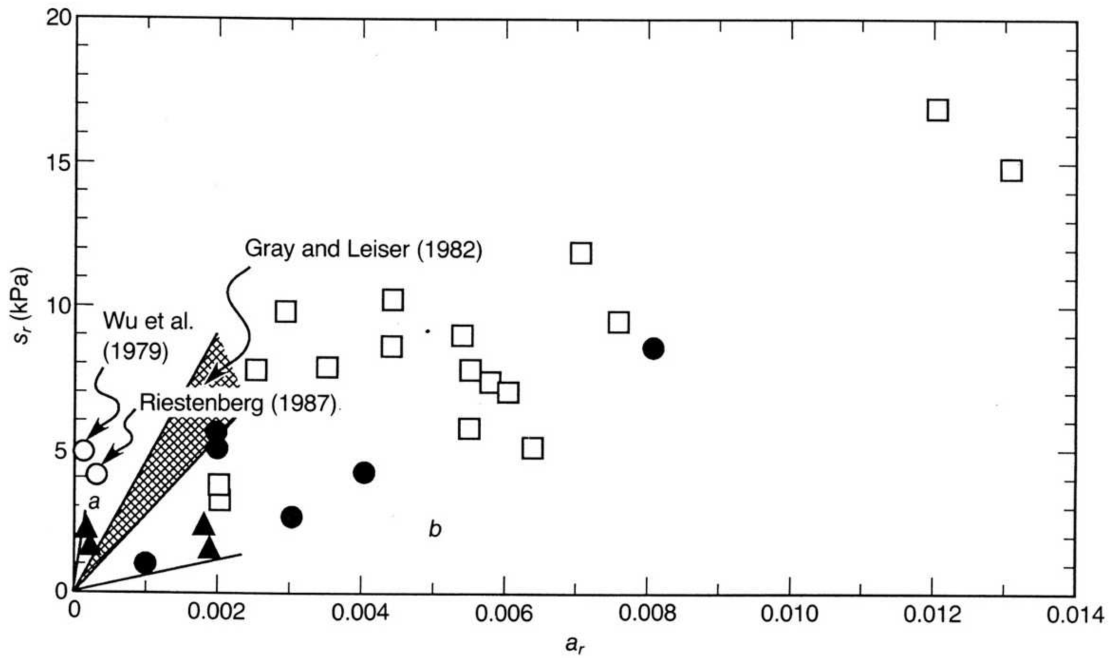
Root wedging

The tendency of roots to invade cracks, fissures, and channels in a soil or rock mass and thereby cause local instability by wedging (-/+).

The effects of vegetation on slope stability

Additional cohesion depends on:

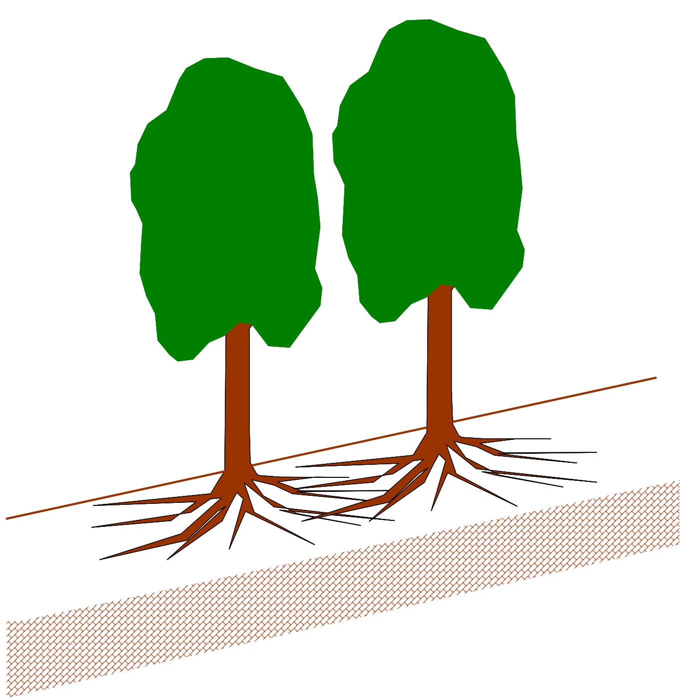
- Root spatial density
- Root diameter(s)
- Local environmental conditions



The effects of vegetation on slope stability

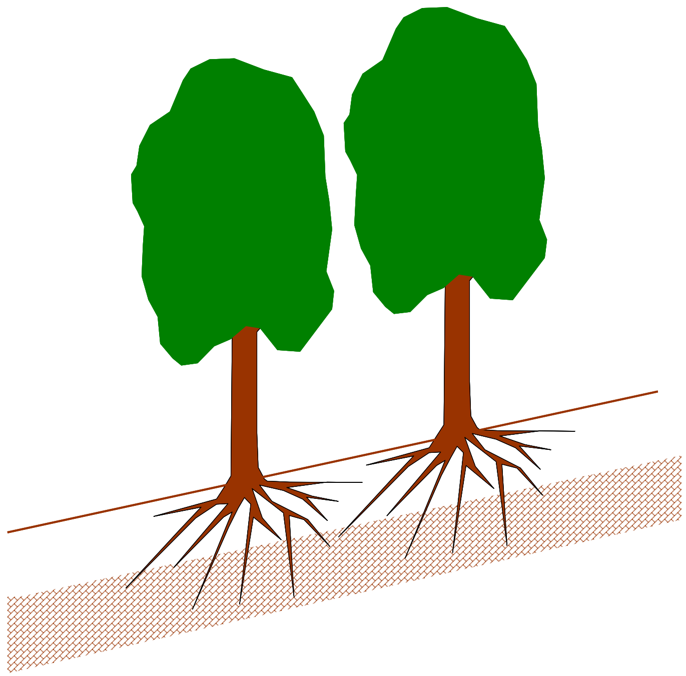
Reference	C_r **[kPa]**	**Species and landscape**
	Shear tests in situ	
Endo & Tsuruta (1969)	2.0÷12.0	Alder in nursery (Japan)
Ziemer (1981)	3.0÷21.0	*Pinus contorta* California (USA)
O'Loughlin & Ziemer (1982)	6.6	beech in New Zealand
	Shear tests in laboratory	
Waldron (1977)	1÷1.7	Yellow pine
Waldron et al. (1983)	3.7÷6.4	Yellow pine (54 months)
	Back analysis	
Swanston (1970)	3.4÷4.4	spruce in Alaska (USA)
O'Loughlin (1974)	1.0÷3.0	coniferous in British Columbia (Canada)
Buchanan & Savigny (1990)	2.6÷3.0	Red alder, spruce, douglas fir and cedar Washington (USA)
O'Loughlin & Ziemer (1982)	3.3	Mixed forest in New Zealand
Gray & Meghan (1981)	10.3	coniferous in Idaho (USA)
Bischetti et al (2002)	4.5÷6.5	Mixed ash and hazel trees in Valcuvia (Italy)

The effects of vegetation on slope stability



Shallow soil with bedrock substrate impenetrable for roots

(very) weak reinforcement



Bedrock hosts part of the root system

important reinforcement

The effects of vegetation on slope stability

- Increase in factory of safety more relevant where soils are poorly cohesive