Goals of Mass Movement Lectures

1. Intro. to mass movements (this week)

     Impacts of mass movements

     Types of mass movements

2. Slope stability analysis (next week)

3. Geomorphic transport laws for mass wasting processes (next week)

# How do landscape materials get from mountain tops to valley floors?

The processes that move materials into stream, creeks, and rivers are collectively called mass movements or mass wasting.

This includes all sorts of landslides, debris flows, and rock falls.

Mass Movement

Mass movements are important processes in all types of landscapes, in all climatic settings, and even in the ocean.
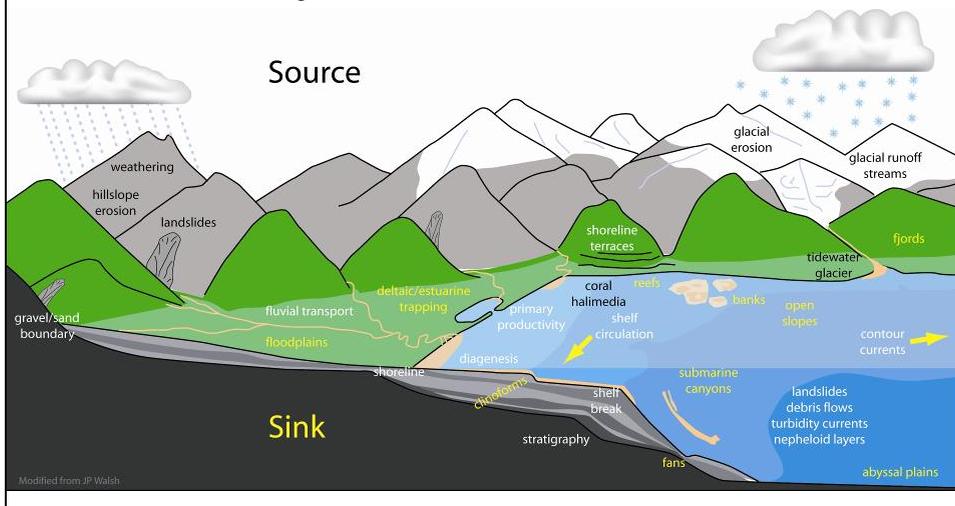
Source

Sink

Modified from JP Walsh

$$\frac{dz}{dt} = U - E - \nabla \cdot q_s$$

All landscapes must obey this fundamental statement about sediment transport!

Change in landscape surface elevation (rate)

Bedrock erosion rate (P+W)

Sediment flux divergence (written in 3D)

Uplift rate of the landscape surface

The whole landscape in one equation!

Photo courtesy of Bill Dietrich

$$\frac{dz}{dt} = U - E - \nabla \cdot q_s$$

All landscapes must obey this fundamental statement about sediment transport!

Our discussion today will focus on mass wasting processes that cause erosion and deposition at the Earth's surface.

The whole landscape in one equation!

Photo courtesy of Bill Dietrich

Frequency and Magnitude of Mass Movements

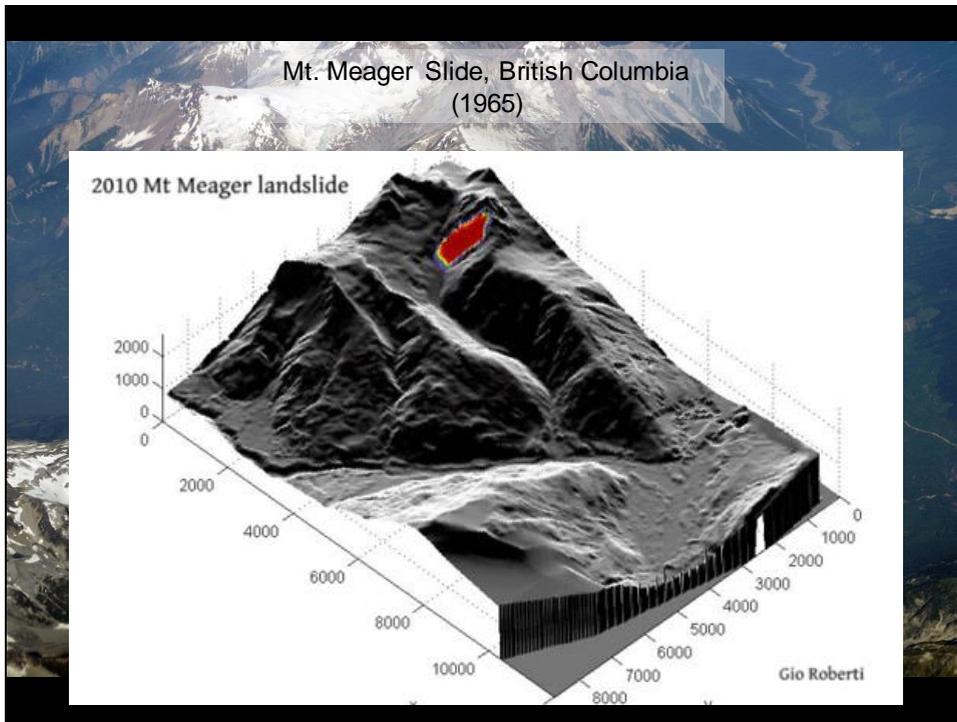Frank Slide, Turtle mountain, Alberta (1903)
(Canada's Worst Natural Disaster)

31 million m^3

Hope Slide, British Columbia (1965)

47 million m^3

Hope Slide, British Columbia (1965)

Dry, rubbly debris
(*ca.* 80 m thick)

Muddy debris
(*ca.* 15 m thick)

N

400 m

Orwin, Clague, Gerath,
Landslides, 2004

Mt. Meager Slide, British Columbia
(1965)

45 million m^3

Mt. Meager Slide, British Columbia (1965)

2010 Mt Meager landslide

Gio Roberti

Mass Movement

Simply put, mass movement will occur when the resisting forces holding rock in place are overcome by the gravitational forces.

This generally happens when the resisting forces are reduced due to water pressure.

We will formalize this idea mathematically when we consider how to predict when a slope will be unstable through slope stability analysis.
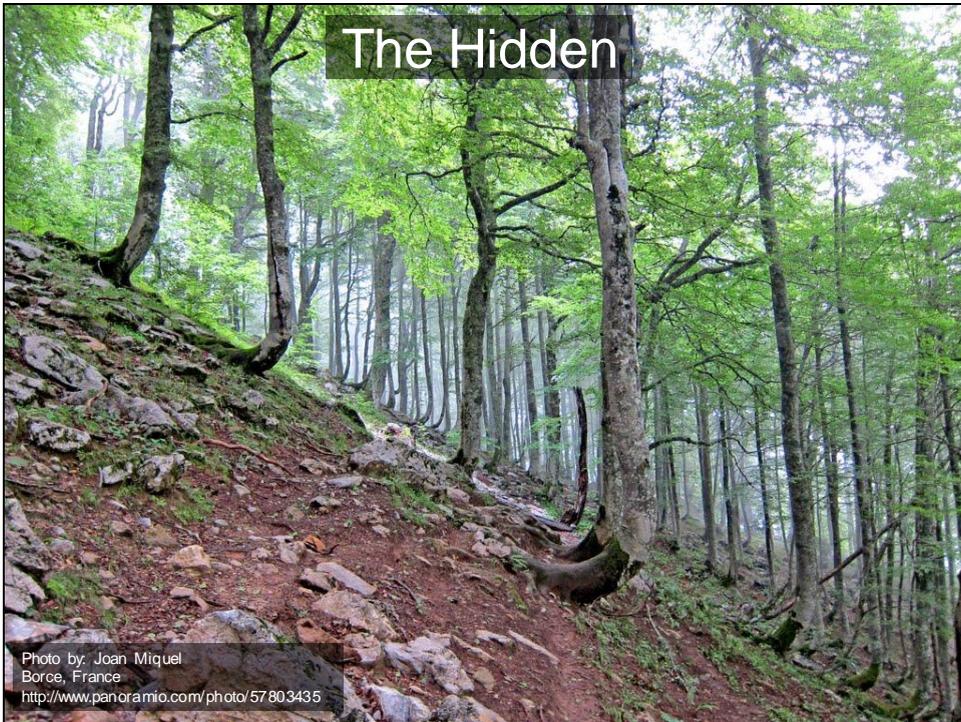
Rates of mass movement

Conceptually, mass movement can be though of as working at two levels:

1. **The obvious** – we can see the evidence very clearly (ie: houses falling down a cliff in North Vancouver).

2. **The hidden** – movements that of themselves are so small that they cannot be seen very easily, but over time can be significant.

The Obvious

https://www.youtube.com/watch?v=23NZTzpw6cY

The Hidden

Photo by: Joan Miquel
Borce, France
http://www.panoramio.com/photo/57803435

Mid-20th century frequency and magnitude of geomorphic processes

There is a competition between the Frequency and Magnitude of geomorphic events

The most frequent events do not do the greatest amount of work (not surprising)

The largest events do the lots of work, but they are infrequent.

Moderately sized transport events do the most geomorphic work in the landscape as a consequence of the frequency of moderate sized events

Persistence wins!
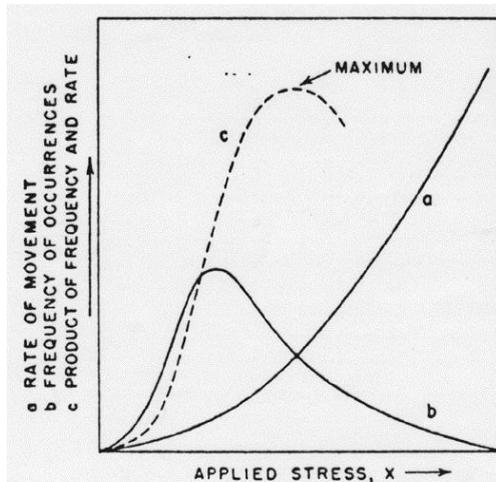
FIG. 1.—Relations between rate of transport, applied stress, and frequency of stress application.

From: Wolman, M. G. & Miller, J. P. (1960). Magnitude and frequency of forces in geomorphic processes. *Journal of Geology*, 68, 54-74.

Classification of Mass Movements

FLOWS
- •Debris Flows
- •Earth Flows

FALLS
- •Rock Falls
- •Rock topples

HEAVES
- •Results in creep

SLIDES
- •Slump
- •Spread
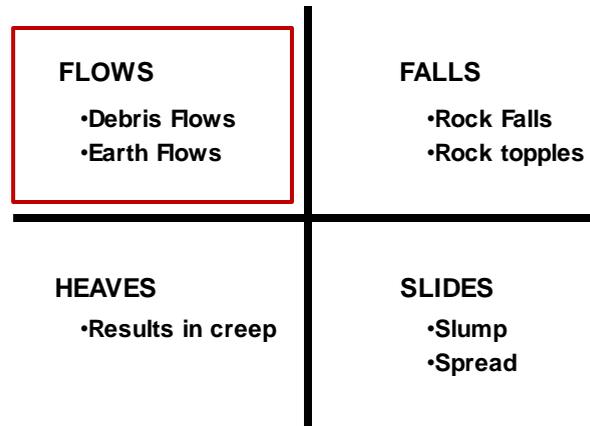
Flows

Spatially continuous movement in which surfaces of shear are short lived, closely spaced and usually not preserved. The distribution of velocities resembles that in a viscous fluid.

Surface

Bed of Flow

Original

Moving
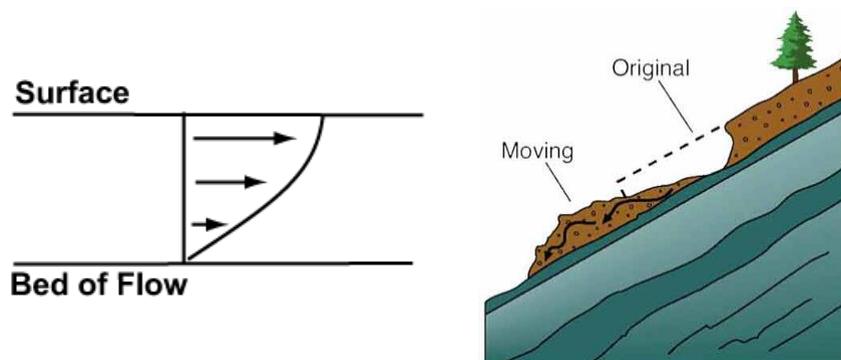
Examples of flows: Debris flow tracks

USGS

Scars formed by debris flow in greater Los Angeles
during the winter of 1968-1969.

Some Cool Debris Flows

Ilgraben, Switzerland, 28 July 2014

Badakshan District of Varduj, Afghanistan, June 2007

Debris flows typically have a point source

Originate when poorly consolidated rock or soil masses are mobilized by the addition of water by:

- Periods of extended rainfall
- Localized areas of intense rainfall
- Ponding on surface upstream of flow
- Snowmelt or rain on snow

Source area for debris flow near Bamfield
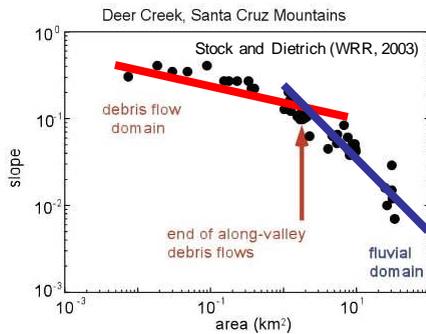

Debris flow track near Bamfield

Debris flow track near Bamfield; looking upslope

Debris flow track near Bamfield; looking downslope

Anatomy of a debris flow deposit

PHASE 3 | PHASE 2 | PHASE 1
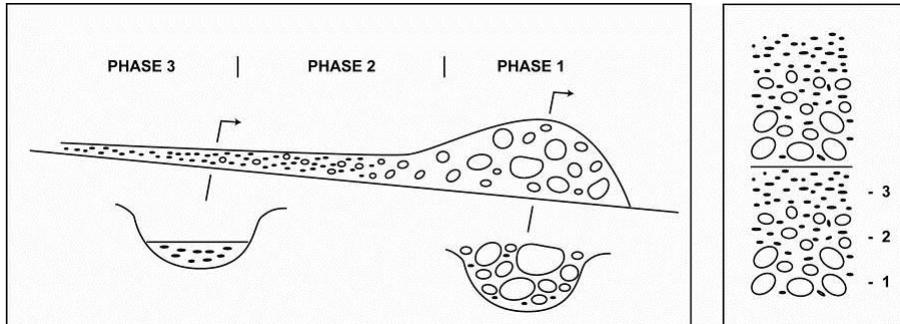
Anatomy of a debris flow channel

Bare channel sides

Lateral ridges

Snout
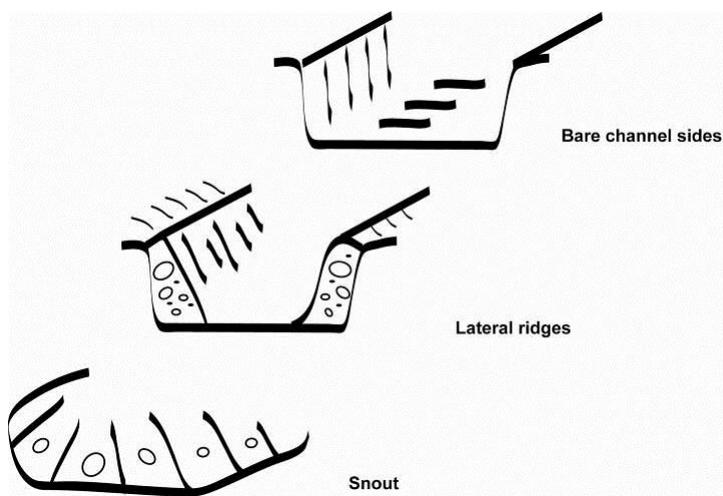
Debris flow failure mechanisms

Deer Creek, Santa Cruz Mountains

Stock and Dietrich (WRR, 2003)

debris flow domain

end of along-valley debris flows

fluvial domain

slope

area (km^2)

Most debris flows originate on slope >15%

Many debris flows originate at channel headwaters (hollows)

But, they may also be formed by other types of initial failure upstream of the debris flow location.

Examples of flows: Earthflow

Typically high viscosity flows formed from weathered volcanic rock

Confluence of Muskwa and Chisca rivers, northern British Columbia.

Martin Geertsema, 2002

2001 9 25

The Bolshaya Talda earthflow in Russia

http://blogs.agu.org/landslideblog/2015/04/20/bolshaya-talda-1/

Anatomy of an Earthflow

- Large slow moving flows common in the western part of the interior plateau of BC
- Form in weathered volcanic rock that forms clay materials
- Several km in length and typically composed of ~10^6 m^3 of material.
- Often have a defined slide plane and shear surfaces
- Movement and rotation of blocks mean there is mixing
- Flows occur over several thousands of years
- Have velocities up to 1 m/a.
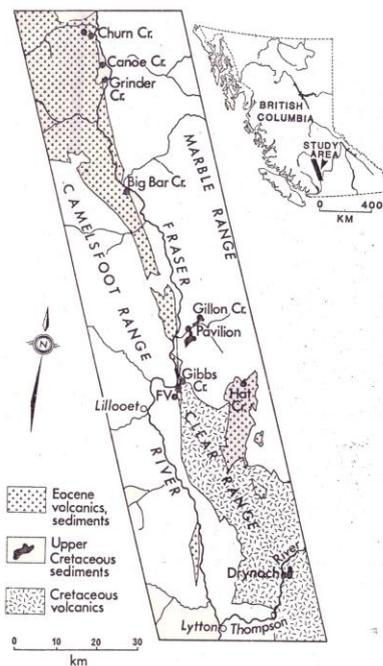
Bovis, 1986

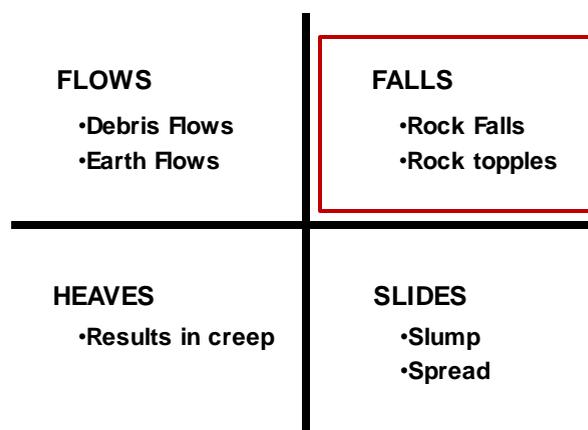# Anatomy of an Earthflow

- Large slow moving flows common in the western part of the interior plateau of BC
- Form in weathered volcanic rock that forms clay materials
- Several km in length and typically composed of ~10^6 m^3 of material.
- Often have a defined slide plane and shear surfaces
- Movement and rotation of blocks mean there is mixing
- Flows occur over several thousands of years
- Have velocities up to 1 m/a.

Pavillion Earth Flow

Bovis, 1986
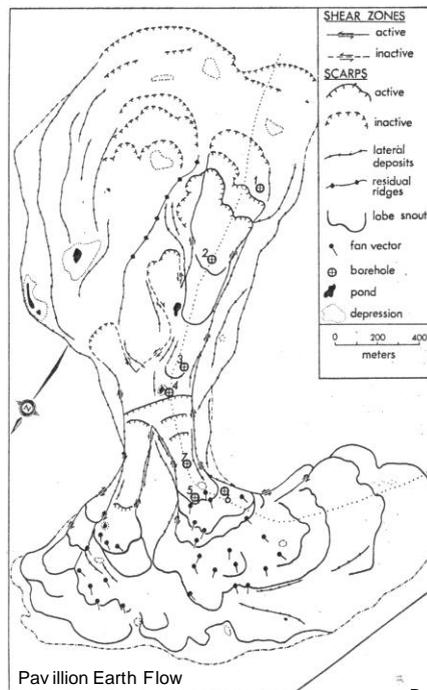
Churn Creek Earth Flow

Grinder Earth Flow

Big Bar Earth Flow

Examples of flows: Earthflow

Drynoch Earthflow

Toe of Drynoch Earthflow along Thompson River

June Ryder

Classification of Mass Movements

FLOWS
- Debris Flows
- Earth Flows

FALLS
- Rock Falls
- Rock topples

HEAVES
- Results in creep

SLIDES
- Slump
- Spread

Falls

Falls begin with the detachment of rock from a steep slope along a surface on which little or no shear displacement takes place. The material then falls or rolls through the air.

Topple is a forward rotation, out of the slope, of a mass of soil or rock about a point or axis below the center of gravity of the displaced mass.

Rockfall in the Talkeetna Mountains, Alaska

Topple, Moses Coulee

Talus Slopes Fraser Canyon

Talus Slopes Fraser Canyon
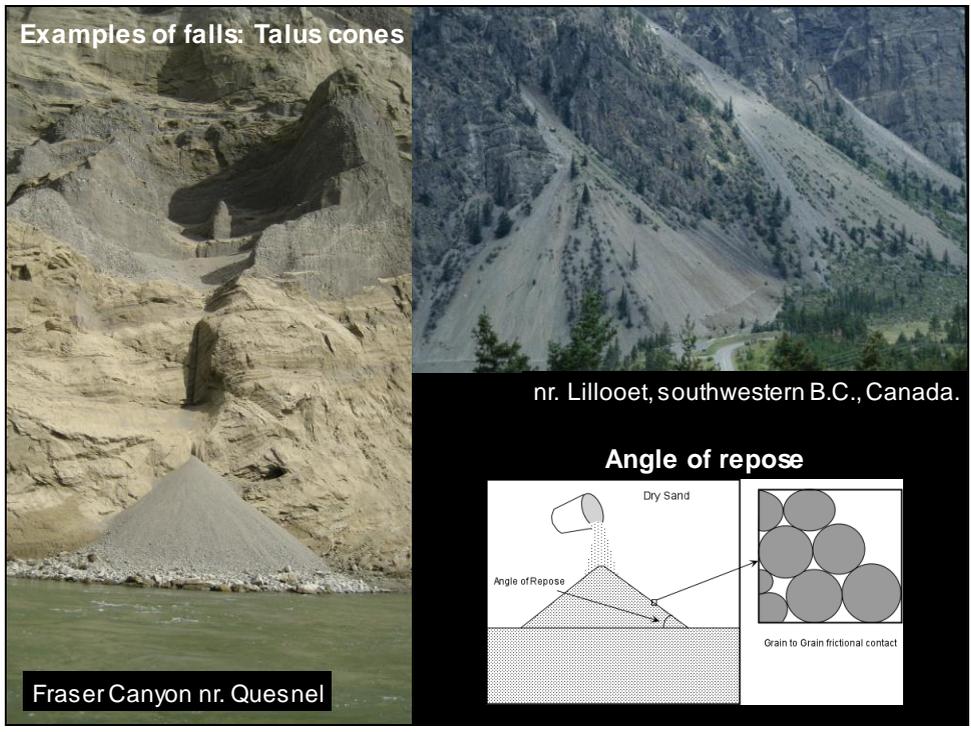
Examples of falls: Talus cones

nr. Lillooet, southwestern B.C., Canada.

Angle of repose

Fraser Canyon nr. Quesnel

Classification of Mass Movements

FLOWS
•Debris Flows
•Earth Flows

FALLS
•Rock Falls
•Rock topples

HEAVES
•Results in creep

SLIDES
•Slump
•Spread

Heaves

Periodic expansion and contraction of a soil or sediment mass that is usually linked to clay swelling and dewatering or freezing and thawing. Heave leads to downslope creep of hillslope materials as the strength of the materials is decreased.
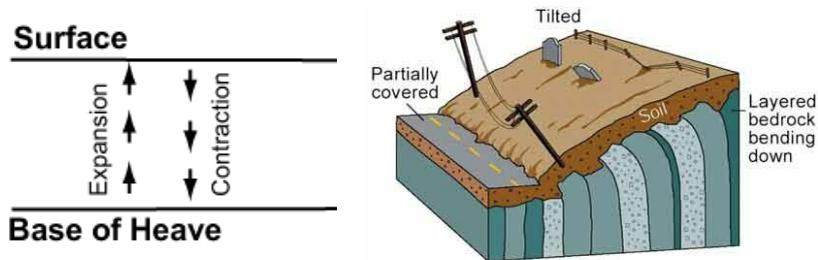
Solifluction & Gelifluction

Solifluction: downslope movement caused by vertical heave as soil freezes and downslope movements when the soil thaws.

Gelifluction: Slippage of the soil along a slide plane when it is thawed

Both are simply a form of creep induced by freeze-thaw heave cycles.
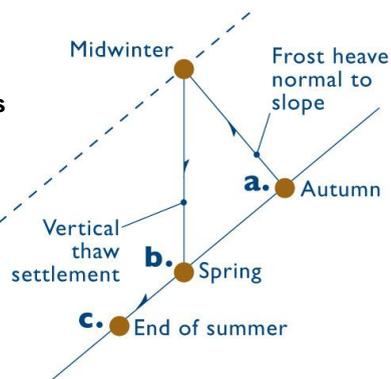
Examples of heave: Soil creep
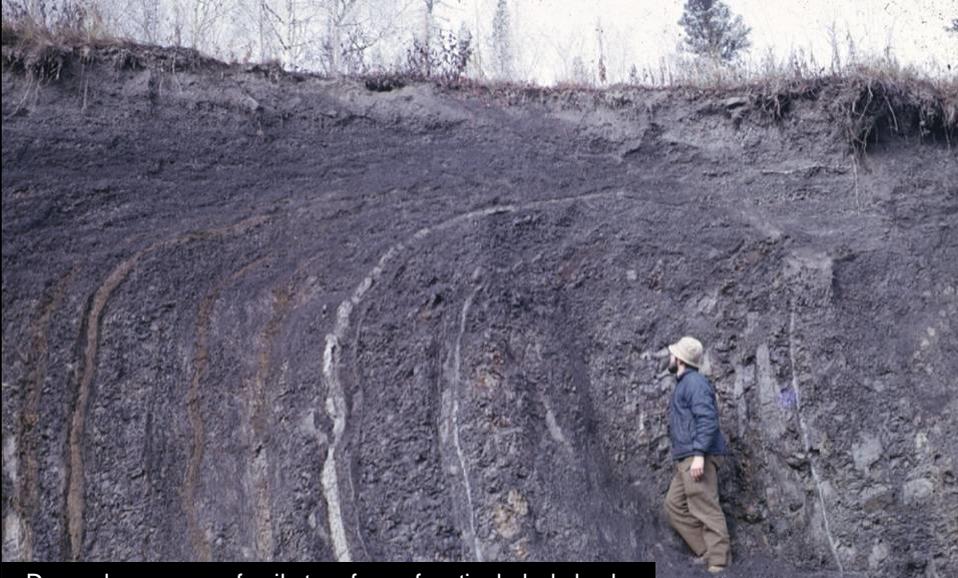
Downslope creep of soil at surface of vertical shale beds
South of Dawson, Yukon, Canada

Frank Nicholson

Aspen growth in Utah shows progressive soil creep downslope.

Ian Alexander

Classification of Mass Movements

FLOWS
- Debris Flows
- Earth Flows

FALLS
- Rock Falls
- Rock topples
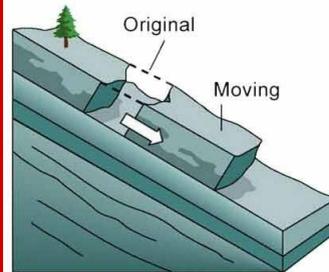
HEAVES
- Results in creep
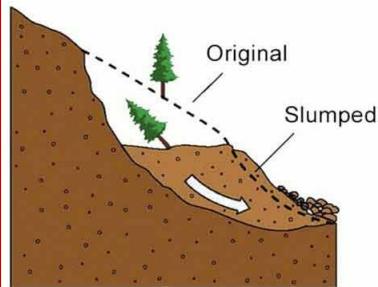
SLIDES
- Slump
- Spread

Slides

Downslope movement of soil or a rock mass occurring dominantly along a surface of rupture or relatively thin zones of intense shear.
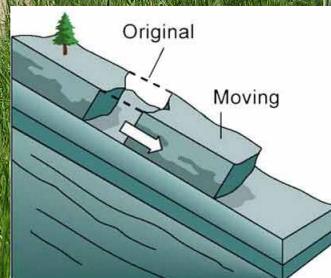
Surface

Slide Plane
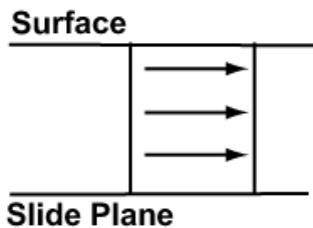
A) Pure slide (translational)

Original

Moving

B) Rotational slide
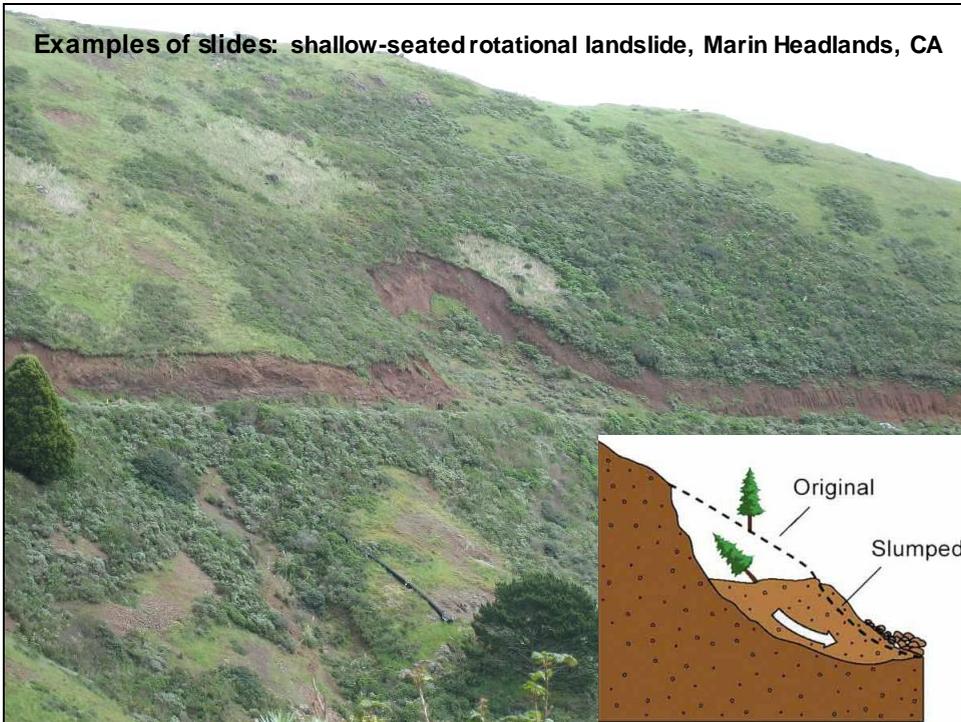
Original

Slumped

Deep-seated landslide: Hope Slide, BC
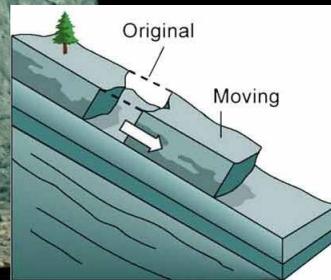
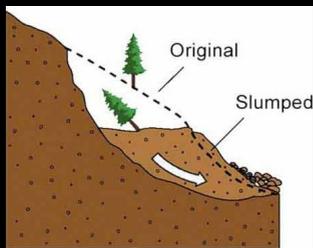Examples of slides: shallow-seated landslide, Briones Regional Park, CA

Examples of slides: shallow-seated rotational landslide, Marin Headlands, CA

Examples of slides: Deep-seated rotational landslide

La Conchita slump.
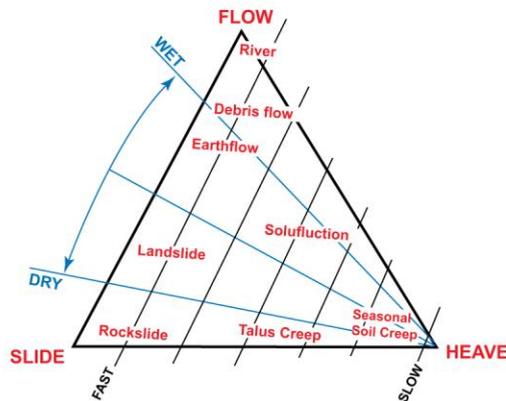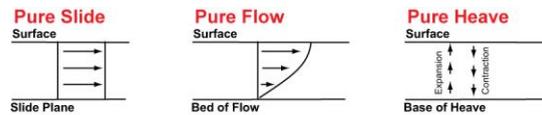March 4, 1995
Santa Barbara, California.

Christiane Mainzer

Examples of slides: Deep-seated rotational landslide, La Conchita
Ann Dittmer

Classification of Mass Movements

Pure Slide — Surface / Slide Plane
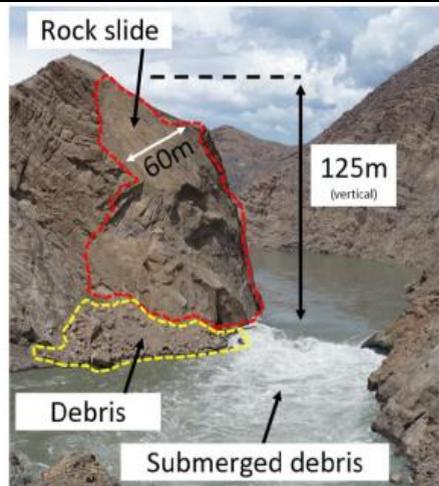**Pure Flow** — Surface / Bed of Flow
Pure Heave — Surface / Base of Heave (Expansion, Contraction)

FLOW
WET
River
Debris flow
Earthflow
Solufluction
Landslide
DRY
Seasonal Soil Creep
Rockslide
Talus Creep
SLIDE
FAST
SLOW
HEAVE

Big Bar Landslide

What happened at French Bar Canyon?

Plunging flow undercut the wall and it failed.

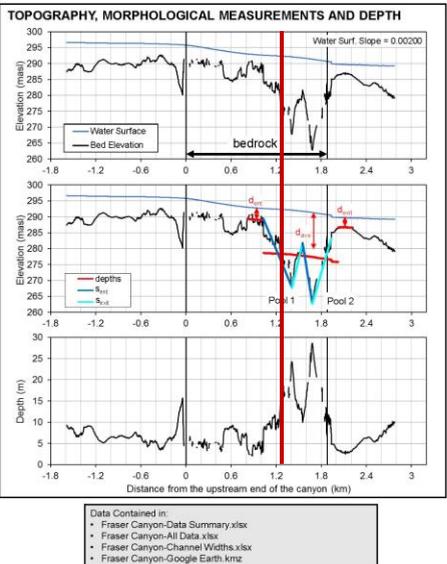The rock prior to slide.

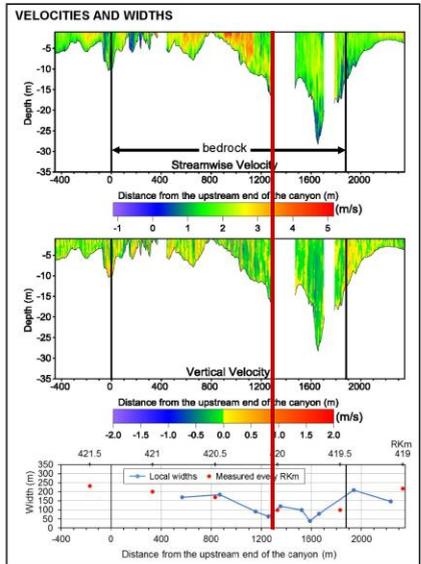Rock slide

60m

125m (vertical)

Debris

Submerged debris

Scale of the landslide site, for perspective.

https://bc.ctvnews.ca/photos-show-big-bar-area-before-and-after-landslide-1.4510958

French Bar
Canyon Exit
September 2019

French Bar Canyon

Conceptual model for flow in a bedrock canyon

Big Bar Landslide
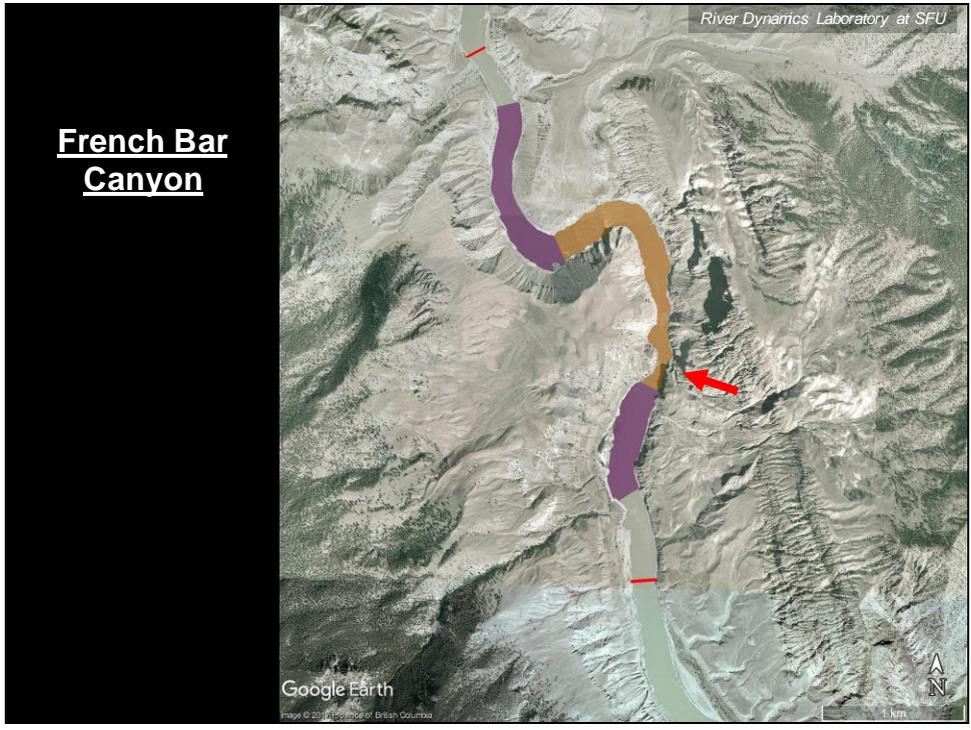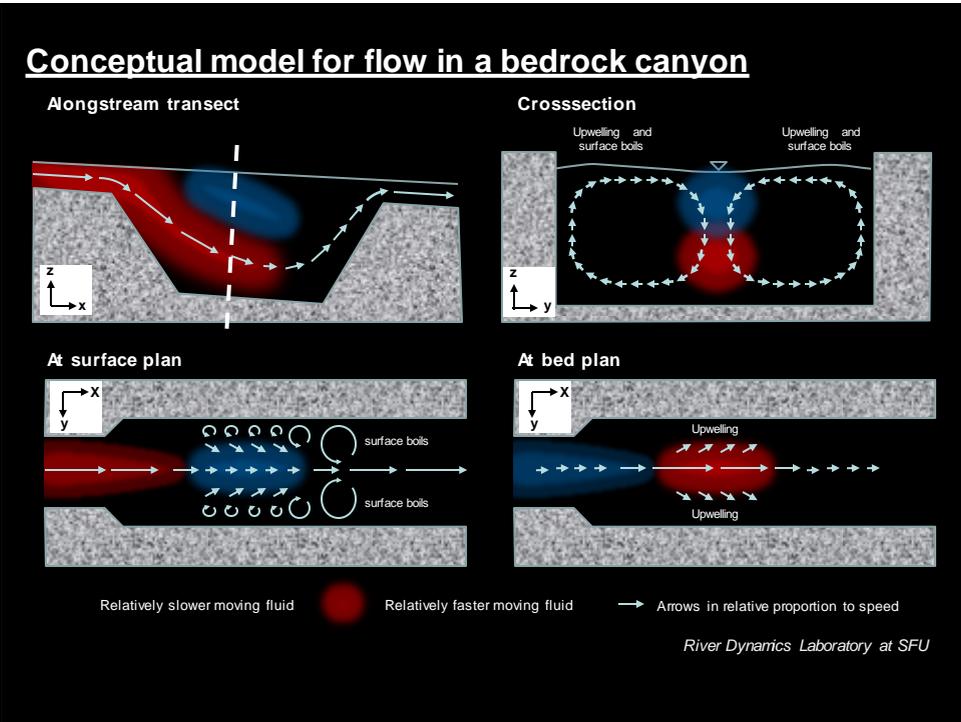
Goals of Mass Movement Lectures

1. Intro. to mass movements (last week)

   Impacts of mass movements

   Types of mass movements

2. Slope stability analysis (this week)

3. Geomorphic transport laws for mass wasting processes (this week)

Slope stability analysis

How do we predict this?

What controls downslope mass movements?

Slope movement occurs when gravitational forces exceed the frictional resistance of the material resting on the slope.

Whether a slope will fail or remain stable is usually considered in terms of a *Factor of Safety*

$$FS = \frac{\text{Sum of resisting forces}}{\text{Sum of driving forces}}$$

If FS = 1, the forces are exactly balanced

If FS > 1, the slope is stable   If FS < 1 the slope is unstable

What controls downslope mass movements?

Whether material moves depends upon:

1. Magnitude of the driving force: The primary driving force is gravity. So movement is dependent on the mass & density of the material involved and the slope angle.

2. Magnitude of the resisting force: Controlled by frictional resistance and response to imposed stress the material resting on the slope.

In order to understand the driving force and frictional forces, we need to review some simple physics

---

A review of some simple physics

Consider the forces active on a block at rest
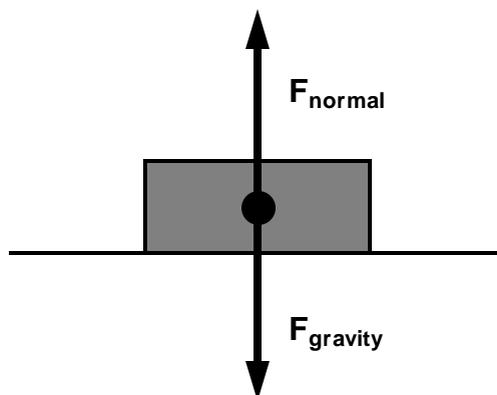
F$_{normal}$

F$_{gravity}$

Newton's Third Law:

To every action (applied force) there is an equal and opposite reaction (force).

F$_{gravity}$ = F$_{normal}$

F$_{gravity}$ = Mass x g

= Mass of Block x 9.81m/s^2

If a force is applied to the block, it must overcome friction in order to move

F_n

$F_{applied}$

F_g
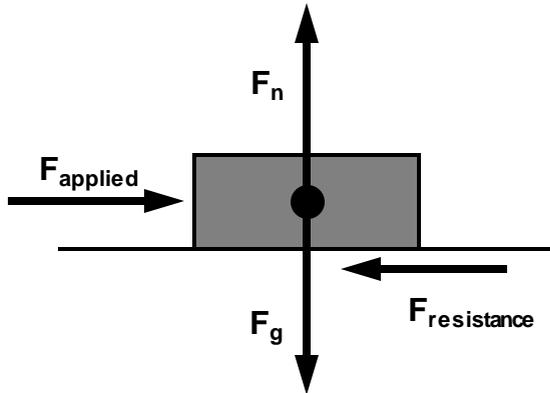
$F_{resistance}$

$F_{resistance} \; \alpha \; F_n$
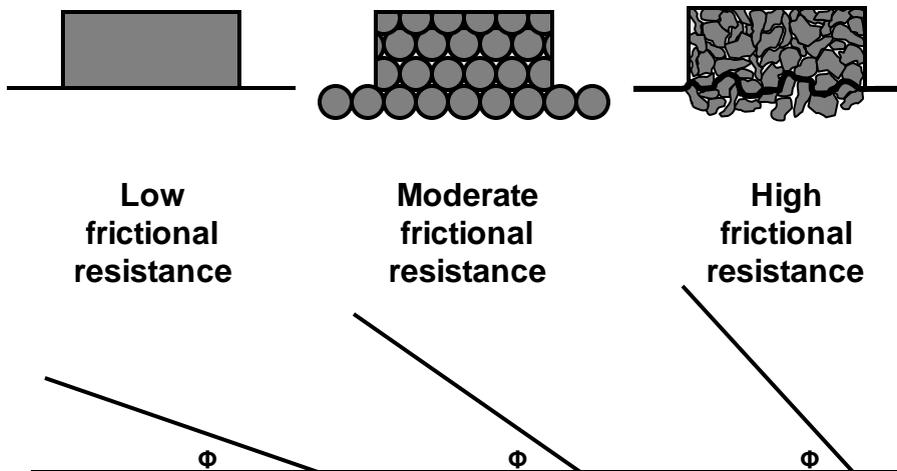
$F_{resistance} = F_n \; x \; C_f$

C_f is the *coefficient of friction* which depends on surface roughness

When sliding begins: $\dfrac{F_a}{F_n}$ = C_f **= tan Φ** **(friction angle)**

A review of some simple physics

Friction is dependent on the material surfaces

Low frictional resistance

Moderate frictional resistance

High frictional resistance

Φ　　　　Φ　　　　Φ
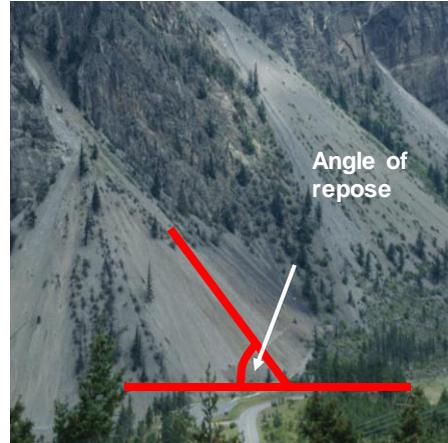
Angle of Internal Friction

If the friction that resists movement is not along a plane, but instead between the grains, this is internal friction.

Failure occurs when the angle of internal friction is exceeded.

For most practical purposes, the angle of internal friction is equivalent to the angle of repose.

Angle of repose

Driving & Resisting Forces

$\theta = 30^{0}$

The primary driving force in the landscape is gravity. On a slope, F_g is divided into two vector components: the downslope component and the normal component F_n.

$F_g \sin\theta$

$F_g \cos\theta$

θ

F_g

Driving & Resisting Forces

θ = 45⁰
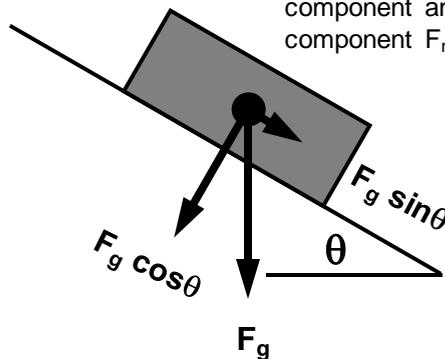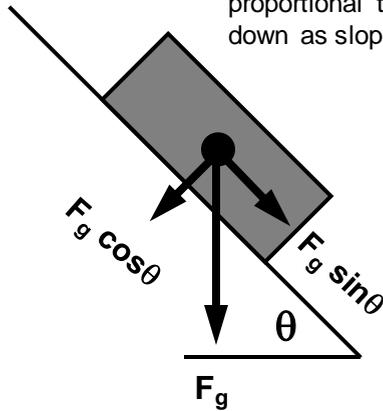
Since the frictional force is proportional to F_n, friction goes down as slope increases.

$F_g \cos\theta$

$F_g \sin\theta$

θ

F_g

Driving & Resisting Forces

θ = 60⁰
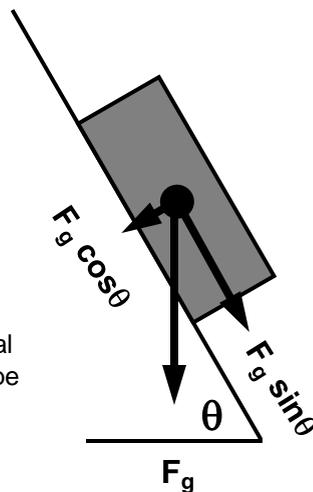
And, the downslope gravitational component increases! So, slope failure is dependent on slope.

$F_g \cos\theta$

$F_g \sin\theta$

θ

F_g

Physical Characteristics of materials

Definitions: **Stress** is a force applied to a surface area and **strain** is any deformation or change in shape or volume of a material caused by application of stress

Force → [square]
Stress exerted at contact

Force → [parallelogram]
Strain (deformation)
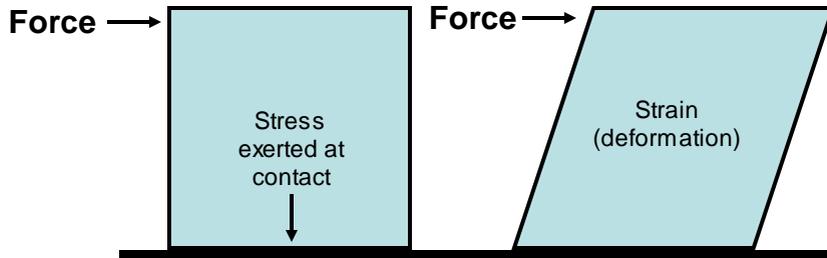
Physical Characteristics of materials

Elastic behavior follows these general rules:

1. The same stress always produces the same strain (deformation)

2. Sustaining a stress produces a constant strain (deformation)

3. Removing the stress always results in recovery

Plastic behavior is when a material can no longer recover from a stress

Viscous behavior is when a material is fluid and flows in response to stress. Newtonian fluids flow at rates proportional to applied stresses (i.e. water) while non-Newtonian fluids do not (i.e. ketchup)

Physical Characteristics of materials
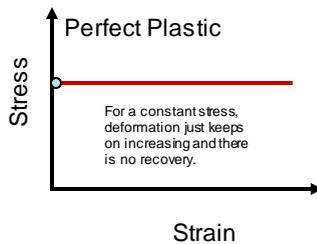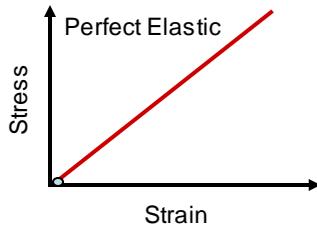
Most earth materials exhibit mixed behavior. Yield stress is sometimes referred to as the plastic limit and the breaking stress is sometimes referred to as liquid limit (Atterberg limits).

Perfect Elastic

Stress / Strain

Perfect Plastic

Stress / Strain

For a constant stress, deformation just keeps on increasing and there is no recovery.

Yield Stress

Plastic

Breaking Stress

Elastic

Failure

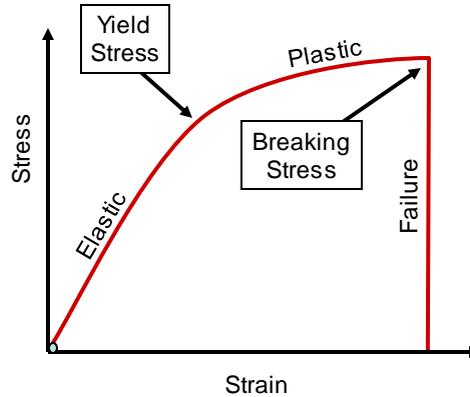Stress / Strain

---

Physical characteristics of materials

We often think about the strain rate rather than absolute strain

- Slope of line is viscosity.

- Newtonian fluids undergo greater rates of deformation with increasing stress.

- Non-Newtonian fluids change their viscosity with increases in stress.

Ice and hillslopes

Non-Newtonian Fluid

Newtonian Fluid

Stress / Strain rate
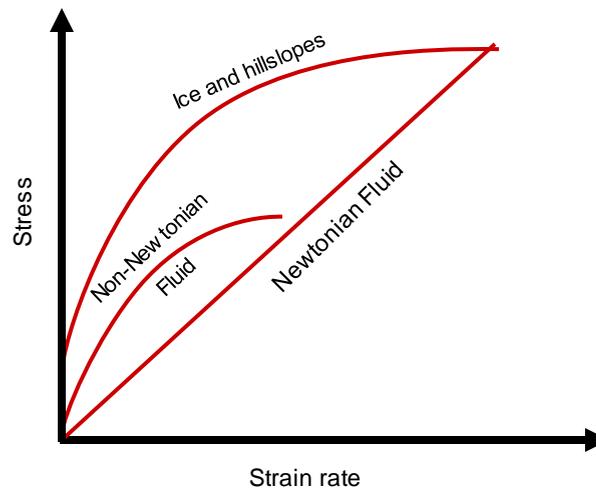
How do we predict when a slope failure will occur?

Infinite slope stability analysis

Assumes that the slope is uniform; where the top and bottom of the slope can be ignored

h — unsaturated soil — saturated soil — Bedrock-soil interface

Therefore, only one section of the slope is considered – a unit slope.
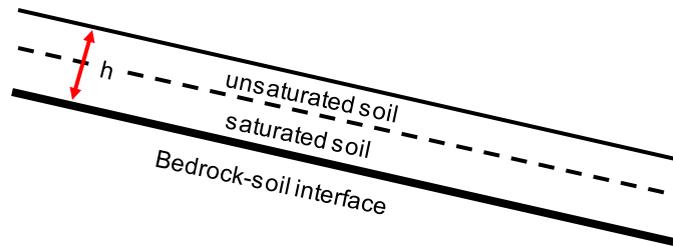

Driving forces on a hillslope: Shear stress

$$\tau = \frac{F}{A} = \frac{mg\sin\theta}{A} = \frac{\rho_b(hlw)g\sin\theta}{lw} \boxed{= \rho_b g\, h\sin\theta}$$

$F_g\sin\theta$

$F_g\cos\theta$ θ
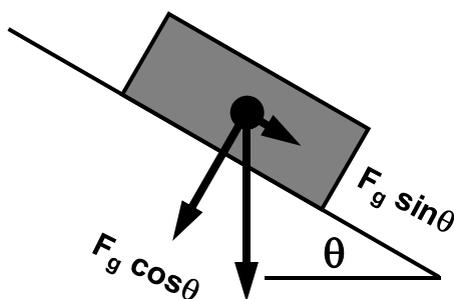
$\tau =$ shear stress (force applied over an area)

$\rho_b =$ soil density

g = gravitational acceleration

h = soil depth

l = length of slope (unit)

w = width of slope (unit)

$\rho_b\, g$ is the specific weight of the soil

Resisting forces on a hillslope: Coulomb Equation

$$S = c + (\sigma - u)\tan\phi$$

$\sigma = F_g \cos\theta$

$F_g \sin\theta$

θ
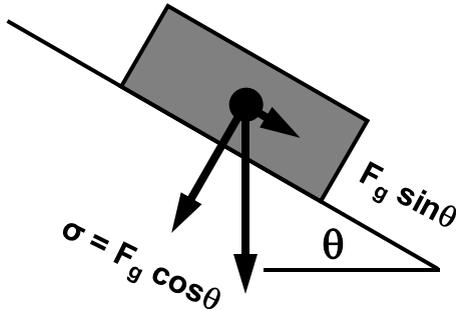
$S =$ Soil strength

$c =$ soil cohesion

$\sigma =$ normal force per unit area

$u =$ pore water pressure

$\tan \Phi =$ the angle of internal friction (resistance to internal deformation of hillslope material)

Coulomb Equation (components)

$$S = c + (\sigma - u)\tan\phi$$

Normal force per unit area (σ) is the frictional resistance on the sliding plane

$$\sigma = \rho_b g\, h \cos\theta$$

Pore water pressure (u) forces the particles apart and so it reduces the friction

$$u = \rho_w g\, h \cos\theta$$

Coulomb Equation (components)

$$S = c + (\sigma - u)\tan\phi$$

Cohesion (c) is caused by roots or interparticle bonds

Quaternary clay in Estonia (Siim Sepp, 2005).
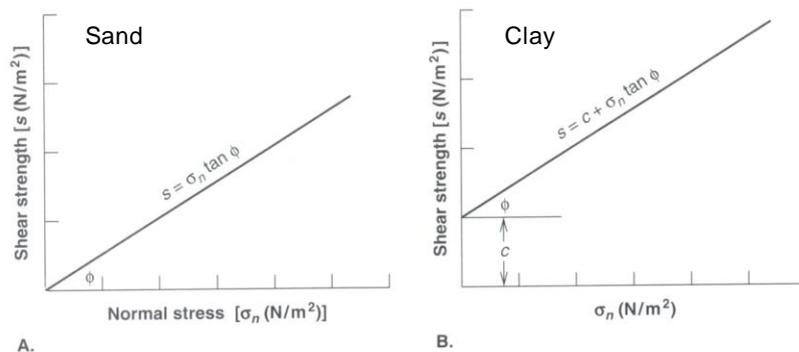

Stilt roots of a mangrove tree, Salinas - Pará - Brazil

Effect of cohesion on soil strength

Sand

$s = \sigma_n \tan\phi$

Shear strength [s (N/m^2)]

Normal stress [σ_n (N/m^2)]

A.

Clay

$s = c + \sigma_n \tan\phi$

Shear strength [s (N/m^2)]

σ_n (N/m^2)

B.

Cohesion is the intrinsic strength of a
material at zero normal stress.

Factor of Safety (FS)

For a dry soil with no cohesion.

$$FS = \frac{S}{\tau} = \frac{\left(\rho_b g\, h \cos\theta\right)\tan\phi}{\rho_b g\, h \sin\theta}$$

Here, ρ_b includes only the weight of the soil particles which occupy ~60% of the total volume, so density is ~1650kg/m^3

ρ_b = 0.6 x 2650 kg/m^3 = 1650 kg/m^3

Factor of Safety (FS)

For a dry soil with cohesion.

$$FS = \frac{S}{\tau} = \frac{c + \left(\rho_b g\, h \cos\theta\right)\tan\phi}{\rho_b g\, h \sin\theta}$$

Here also, ρ_b includes only the weight of the soil particles which occupy ~60% of the total volume, so density is ~1650kg/m^3

ρ_b = 0.6 x 2650 kg/m^3 = 1650 kg/m^3

Factor of Safety (FS)

For a wet (saturated) soil with cohesion.

$$FS = \frac{S}{\tau} = \frac{c + \left(\rho_b g\, h \cos\theta - \rho_w g\, h \cos\theta\right)\tan\phi}{\rho_b g\, h \sin\theta}$$

Here, ρ_b includes the weight of the soil particles (which occupy ~60% of the soil by volume, and the water in the pore spaces. So density is ~2000kg/m^3

ρ_b = 0.6 x 2650 kg/m^3 + 0.4 x 1000 kg/m^3 = 1990 kg/m^3

Factor of Safety (FS)

$$FS = \frac{S}{\tau} = \frac{c + \left(\rho_b g\, h \cos\theta - \rho_w g\, h \cos\theta\right)\tan\phi}{\rho_b g\, h \sin\theta}$$

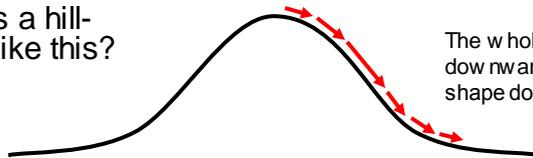What happens to FS if the slope angle is increased? ↓

What happens to FS if a wet soil loses its moisture? ↑

What happens to FS if a slope is logged and tree roots are removed? ↓

What happens to FS if h is increased? ↕ **depends on c**

Geomorphic transport laws for hillslopes

Why does a hill-slope look like this?

The whole slope is migrating downward steadily but the shape doesn't change!

Why are some slopes convex?

G.K. Gilbert: soil eroded from the upper part of the slope must pass each point below it. Therefore the slope must get steeper with distance downslope to maintain the flux. i.e. sediment flux divergence > 0

Why are some slopes concave?

Kinetic sieving moves large particles further down slope, and there are generally fewer of them, so colluvial deposits are generally concave.

More material may be entering from upslope than exiting downslope. Therefore the slope adjusts to the lesser flux. i.e. sediment flux divergence < 0

Hydraulically, there is more water to transport material as one moves downslope, so the slope relaxes as the water discharge increases to maintain the flux.

Why are some slopes straight?

They is no storage or erosion of material. i.e. sediment flux divergence = 0

The simplest geomorphic transport laws break the landscape up into two components.

Then separate transport laws are written for each component.

Diffusive slopes

Dilational disturbance by plants, animals, and heave causes downslope movement.

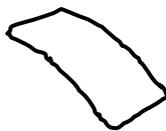First approximation: $q_s = KS$; K is a constant and S is slope
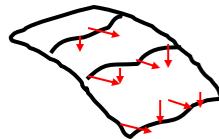
Advective slopes

Generally, advective slopes are dominated by flows, which transport sediment in proportion to boundary shear stress. This is often expressed as $q_s = A^m S^n$; m and n are coefficients

Smith and Bretherton (1972)
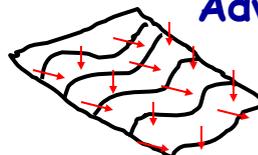
$q_s = kS$ — **Diffusive**

Steady state convex form   Perturbations damp out

$q_s = f(q_w, S)$ — **Advective**

Steady state concave form   Perturbations grow

$$q_s = KS + A^m S^n$$

$q_s = KS + A^m S^n$ in a mathematical model will make ridge and valley topography.

Model simulations by Perron et al. using a very similar model

JT Perron *et al. Nature* **460**, 502-505 (2009)
doi:10.1038/nature08174

Eaton Hollow, Pennsylvania

Tick spacing is 200 m

Napa Valley, California

Point of the Mountain, Utah

Dragon's Back, California

Gabilan Mesa, California

The whole landscape in one equation!

Intro to Geomorphology Lec 5 & 6