Lecture 17: The Role of Water in Slope Stability

Key Questions

1. How does the weight of water influence the factor of safety?

2. What does too much water do to the cohesion strength of the sediment?

3. How does water interact with clay minerals in the sediment?

4. How does water decrease the “friction force” and hence the factor of safety?
Sultan River Landslide

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Slope Model
The slope fails if $FS$ is less than "1"
Water makes slopes unstable
1. Water adds weight
One gallon of water weighs 8 lbs
If a 100 by 200 foot slope soaks up 2 inches of rain, the slope weight increases by 200,000 lbs.

Burien, WA near Shorewood Drive SW and 131st Street
The slope fails if $FS$ is less than “1”
2. Too much water in the voids spaces reduces or eliminates the **cohesion force** holding the grains together.

Remember, the cohesion force requires air and water in the pores spaces.
The slope fails if \( FS \) is less than "1".
3. Slopes with high clay contents are more unstable when wet.
Scanning electron microscope image of clay
Clay minerals have a “negative” surface charge
water is polar
clay minerals attract water molecules to their surfaces
dry, more friction, hence more resistant to sliding

wet, less friction, hence lower strength
The slope fails if $FS$ is less than "1".

$$FS = \frac{\text{resisting forces}}{\text{driving forces}} = \frac{\text{friction} + \text{cohesion}}{W \times \cos \theta \times \mu + c} = \frac{W \times \sin \theta}{W \times \sin \theta}$$

Wet clay reduces friction.

Friction = $F_f$

Cohesion = $c$
4. Water buoys up the grains which reduces the friction force
Slope Model
shear plane
\[ F_N = W \times \cos \theta = \text{normal force} \]

\[
\cos \theta = \frac{\text{adjacent}}{\text{hypotenuse}}
\]
friction force = normal force $\times$ coefficient of friction

or friction force = $F_N \times \mu$
What happens when the grains are immersed in water?
Archimedes' Principle
the buoyant force is equal to
the weight of the displaced water
\( P = \rho_w \cdot g \cdot h \) = hydrostatic pressure

- \( P \) = water pressure
- \( \rho_w \) = water density
- \( g \) = acceleration of gravity
- \( h \) = depth to the balloon
$P = \text{water pressure}$

$\rho_w = \text{water density}$

$g = \text{acceleration of gravity}$

$h = \text{depth to the balloon}$

$P_1 = \rho_w \cdot g \cdot h_1$

$P_2 = \rho_w \cdot g \cdot h_2$
Cubic grain immersed in water (side length “L”)

Fluid pressure at the top = \( P = \rho gh \)

Fluid pressure at the bottom = \( P = \rho g(h + L) \)

\( \rho \) = water density
\( g \) = acceleration of gravity
\( h \) = depth below the water surface
Cubic grain immersed in water (side length “L”)

Fluid pressure at the top = $P = \rho gh$

$\Delta P = \rho gL = \text{change in pressure}$

Fluid pressure at the bottom = $P = \rho g(h + L)$

$\rho = \text{water density}$

$g = \text{acceleration of gravity}$

$h = \text{depth below the water surface}$
Cubic grain immersed in water (side length “L”)

Fluid pressure at the top = \( P = \rho gh \)

\[\Delta P = \rho gL = \text{change in pressure}\]

Fluid pressure at the bottom = \( P = \rho g(h + L) \)

Area = \( L^2 \)

Force = pressure \times area

\( \rho \) = water density
\( g \) = acceleration of gravity
\( h \) = depth below the water surface
Cubic grain immersed in water (side length “L”)

Fluid pressure at the top = \( P = \rho gh \)

\( \Delta P = \rho gL = \text{change in pressure} \)

Fluid pressure at the bottom = \( P = \rho g(h + L) \)

Area = \( L^2 \)

Force = \( \Delta P \times L^2 \)

\( \rho = \text{water density} \)

\( g = \text{acceleration of gravity} \)

\( h = \text{depth below the water surface} \)
Cubic grain immersed in water (side length “L”)

Fluid pressure at the top = \( P = \rho gh \)

Fluid pressure at the bottom = \( P = \rho g(h + L) \)

\( \Delta P = \rho gL = \text{change in pressure} \)

Area = \( L^2 \)

Force = \( \rho gL^3 = \rho gV = \text{buoyancy force} = F_B \)
The magnitude of buoyancy force is equal to the weight of the volume of fluid the grain displaces (Archimedes’ Principle): $F_B = \rho g V$.
Cubic grain immersed in water

The grain weight is reduced by $F_B$
buoyancy force

\[ W_{\text{new}} = W_{\text{dry}} - \text{buoyancy force} \]

buoyancy force = the weight of the volume of water the grain displaces
The total weight pushing on the shear plane is reduced.

The weight of each grain is reduced by the buoyancy force.

Friction force.
friction force = normal force $\times$ coefficient of friction

or friction force = $F_N \times \mu$
The slope fails if $FS$ is less than “1”.

\[ FS = \frac{\text{resisting forces}}{\text{driving forces}} = \frac{\text{friction} + \text{cohesion}}{W \times \sin \theta} = \frac{W \times \cos \theta \times \mu + c}{W \times \sin \theta} \]

**Water decreases friction and cohesion and increases $F_p$ all of which reduce $FS$.**
$$\frac{FS}{\text{driving forces}} = \frac{\text{resisting forces}}{\text{friction + cohesion}}$$

$$F_p$$
\[ \downarrow \text{FS} = \frac{\text{resisting forces}}{\text{driving forces}} = \downarrow \text{friction} + \text{cohesion} \uparrow \]

\[ F_p \]
\[ \downarrow \text{FS} = \frac{\text{resisting forces}}{\text{driving forces}} = \downarrow \text{friction + cohesion} \]

\[ \uparrow F_p \]
\[ \frac{\text{resisting forces}}{\text{driving forces}} = \text{friction + cohesion} \]
FS = \frac{\text{resisting forces}}{\text{driving forces}} = \frac{\text{friction} + \text{cohesion}}{F_p}
\[ FS = \frac{\text{resisting forces}}{\text{driving forces}} = \frac{\text{friction} + \text{cohesion}}{F_p} \]
USGS Experimental Debris-Flow Flume

Sept. 13, 2001
Debris-flow Experiment

Flow Discharging from Headgate (0 m)

33 m

66 m

90 m

USGS Experimental Debris-Flow Flume

Willamette National Forest

H. J. Andrews Experimental Forest

Flume Administrative Offices

4 miles to Highway 126
Seattle Landslides: Winter 1996-97

Winter storms brought a mix of heavy rain, rapid snowmelt, and saturated soils triggering more than 100 slides in Seattle.

Where landslides occurred

Slopes of 10% or more

Map modified from "Puget Sound Bluffs: The Where, Why, and When of Landslides Following the Holiday 1996/97 Storms"

Slope locations based on USGS topographic data.
Seattle Area, Washington

Cumulative Precipitation Threshold

Landslides likely

Cumulative Precipitation Threshold
\[ P_3 = 3.5 - 0.67P_{15} \]

Landslides unlikely

\[ P_{15}, \text{ 15-DAY CUMULATIVE PRECIPITATION BEFORE } P_3, \text{ INCHES} \]

\[ P_3, \text{ 3-DAY CUMULATIVE PRECIPITATION, INCHES} \]
Seattle Area, Washington

Precipitation Intensity-Duration Threshold

$\text{Mean Rainfall Intensity, Inches per Hour}$

$\text{Rainfall Duration, Hours}$

$I = 3.257D^{-1.13}$

Landslides very likely

Landslides unlikely

Threshold

March 1997

January 1986

Other
The Pe Ell landslide occurred on December 3rd, 2007, blocking State Highway 6 and destroying three structures.

http://www.dnr.wa.gov/ResearchScience/Topics/GeologicHazardsMapping/Pages/landslides_dec07storm.aspx
Dec 11, 2004 - Massive landslide on the Sultan River, CA