Landslide Hazard Assessment & Mitigation

DML – 502 Lecture - 5

Subject Code: DML-505
Course Title: Landslide Hazard Assessment & Mitigation

“To understand mapping and hazard assessment techniques of landslides and protection against landslide.”

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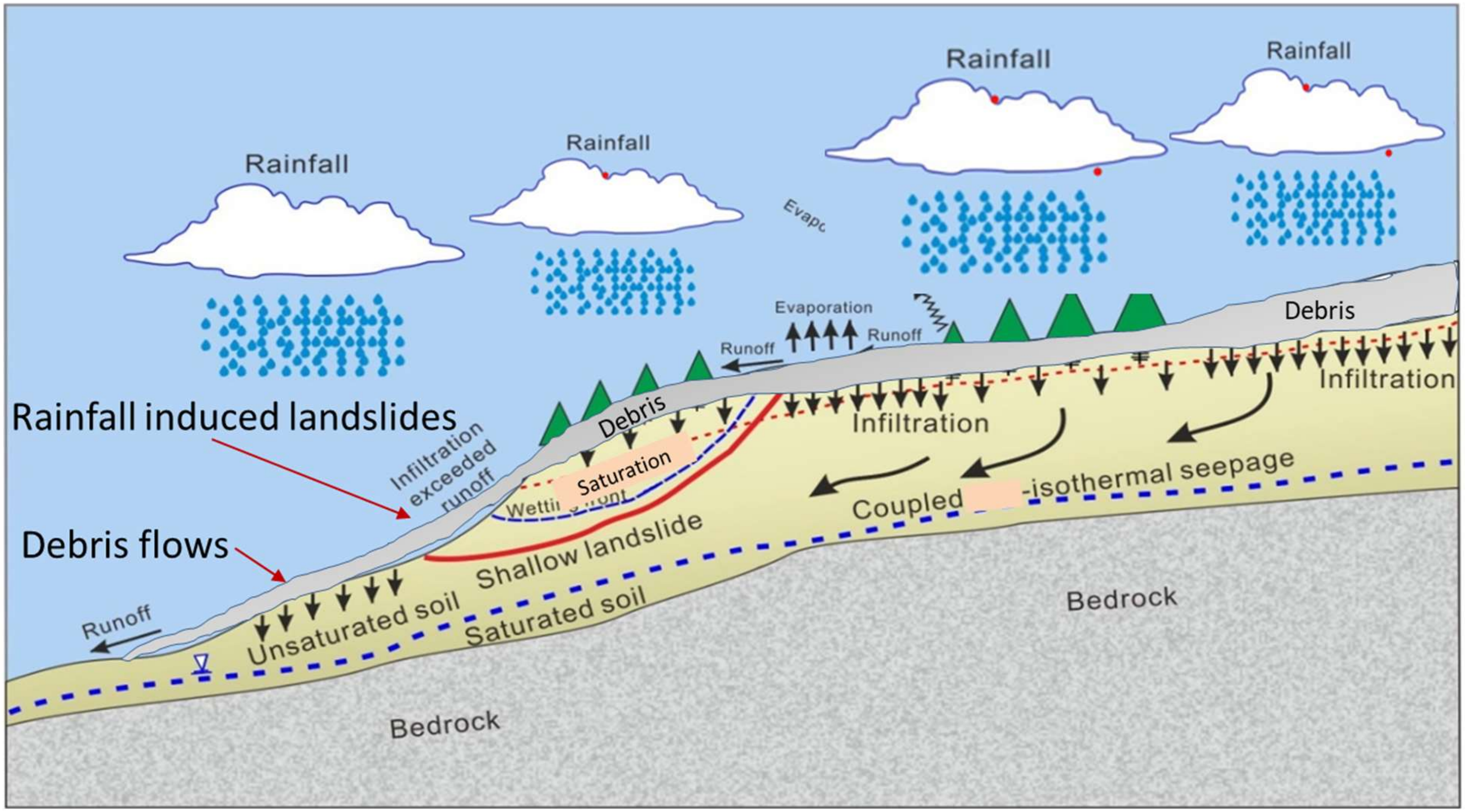
Causative factors of landslides – natural including inherent factors and external factors as well as anthropogenic factors; Impacts of natural causative factors like lithology, structure, slope morphometry, relative relief, hydrogeological conditions and land use and land cover on stability of slopes ; **Impacts of external factors like concentrated rain fall and earth quakes on slope stability;** Various causes of slope instability in Himalaya; extreme hydro-meteorological conditions leading to landslide dams and related damages;

Physical processes leading to rainfall-induced landslides: Shallow Landslides and Debris Flows



Variables

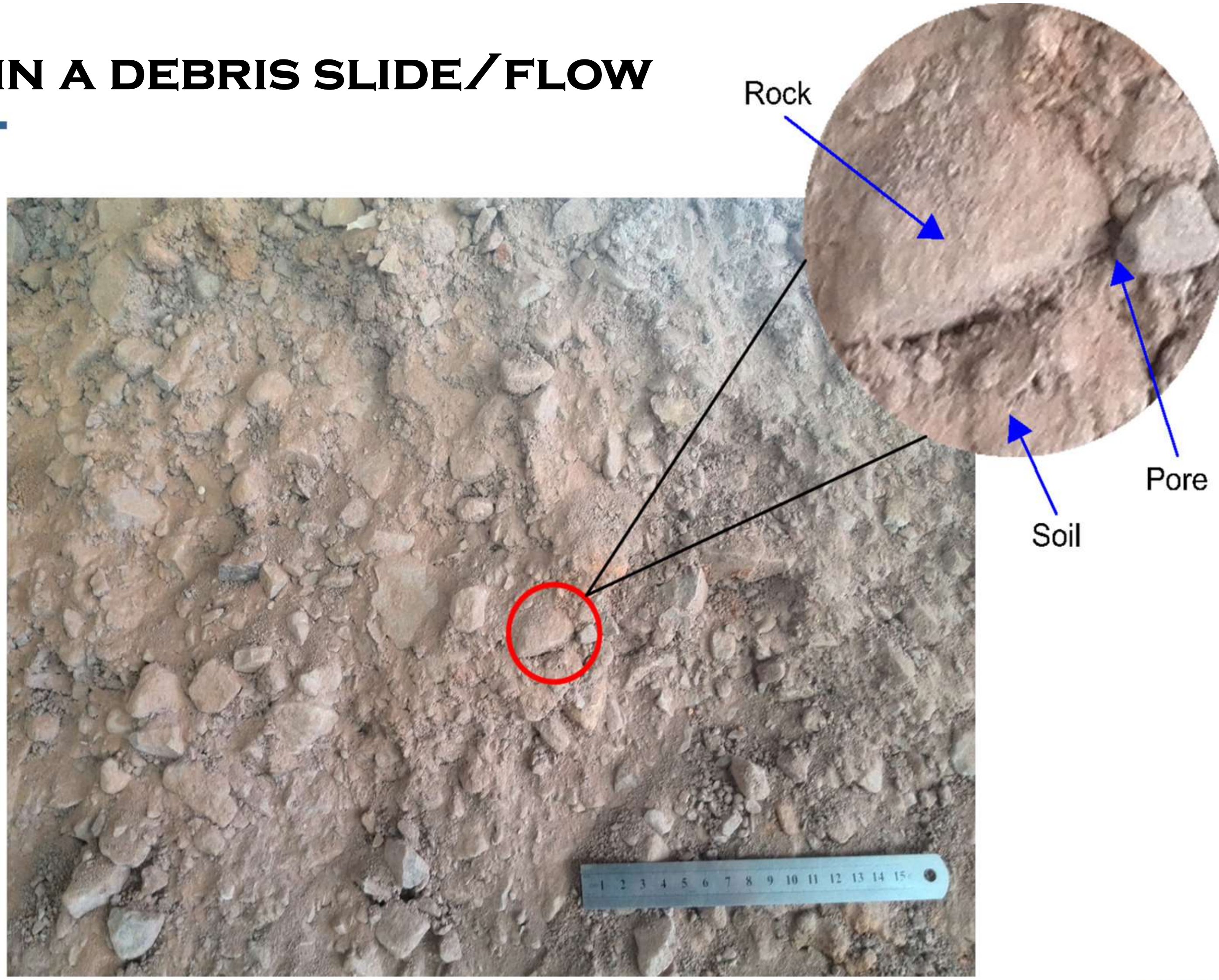
- Rainfall
- Runoff
- Saturation
- Water level
- Shear strength

Sensors

- Rain gauge
- Discharge meter
- Moisture sensor
- Water level sensor
- Tilt angle, displacement
- Acceleration

Siva Subramanian, Fan X…. Yunus et al., *(JGR: Earth Surface, 2020)*

Materials in a debris slide/flow



Zhou et al. Int. J. Geomech., 2017, 17(4): 04016106

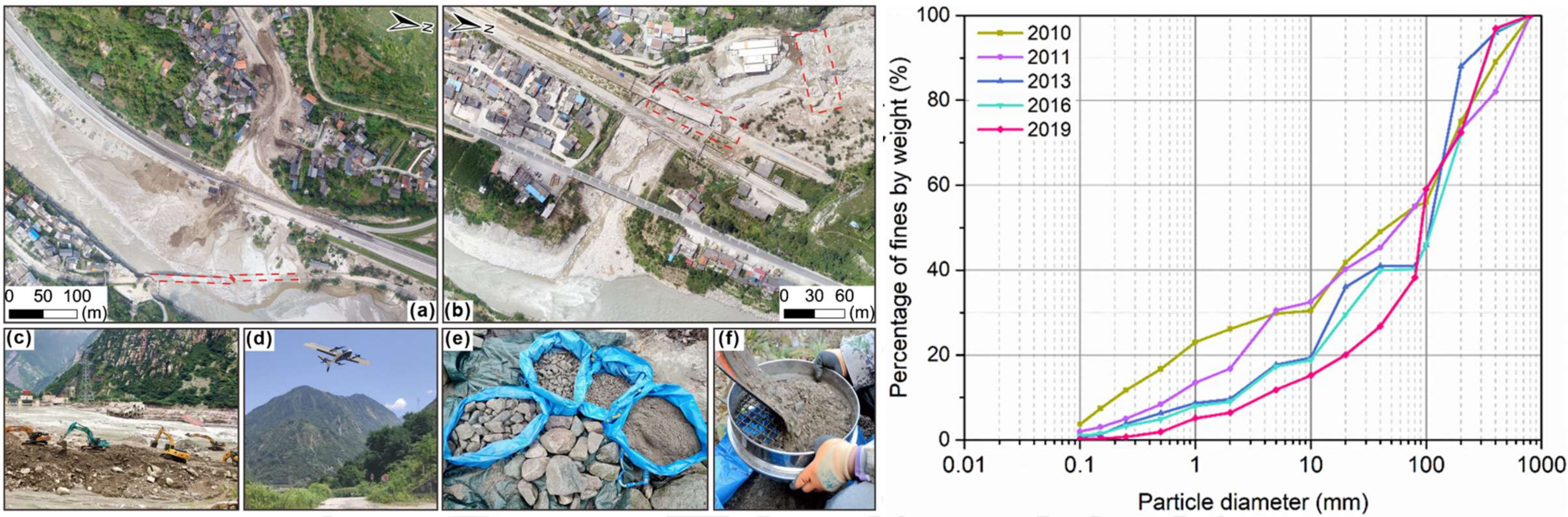
Landslides in materials of debris (soil + rock)

Soil–rock mixtures formed by a debris slide

Soil–rock mixtures formed by debris-flow deposits

Zhou et al. Int. J. Geomech., 2017, 17(4): 04016106

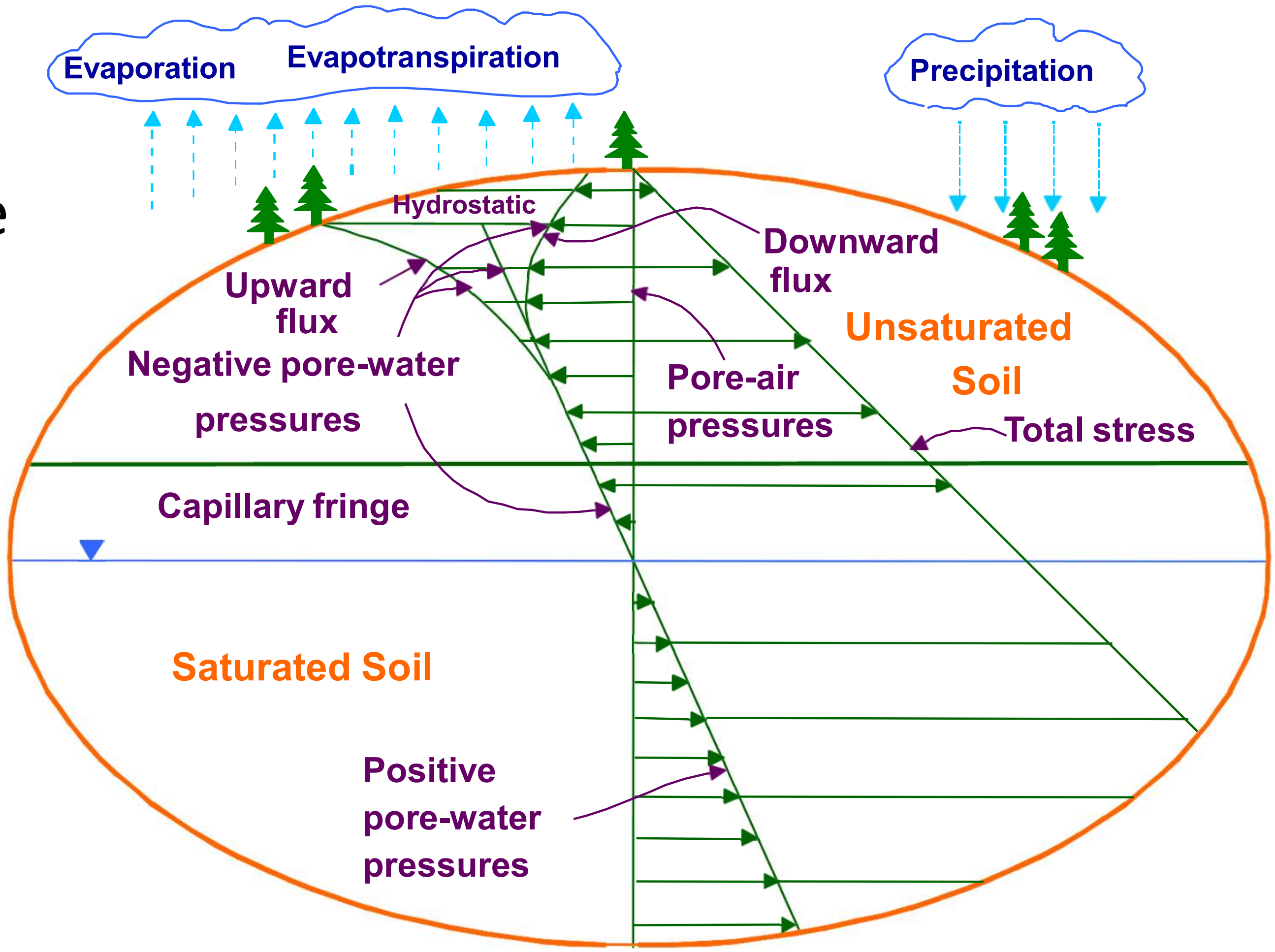
Diameter Boundary of Soil and Broken Rocks



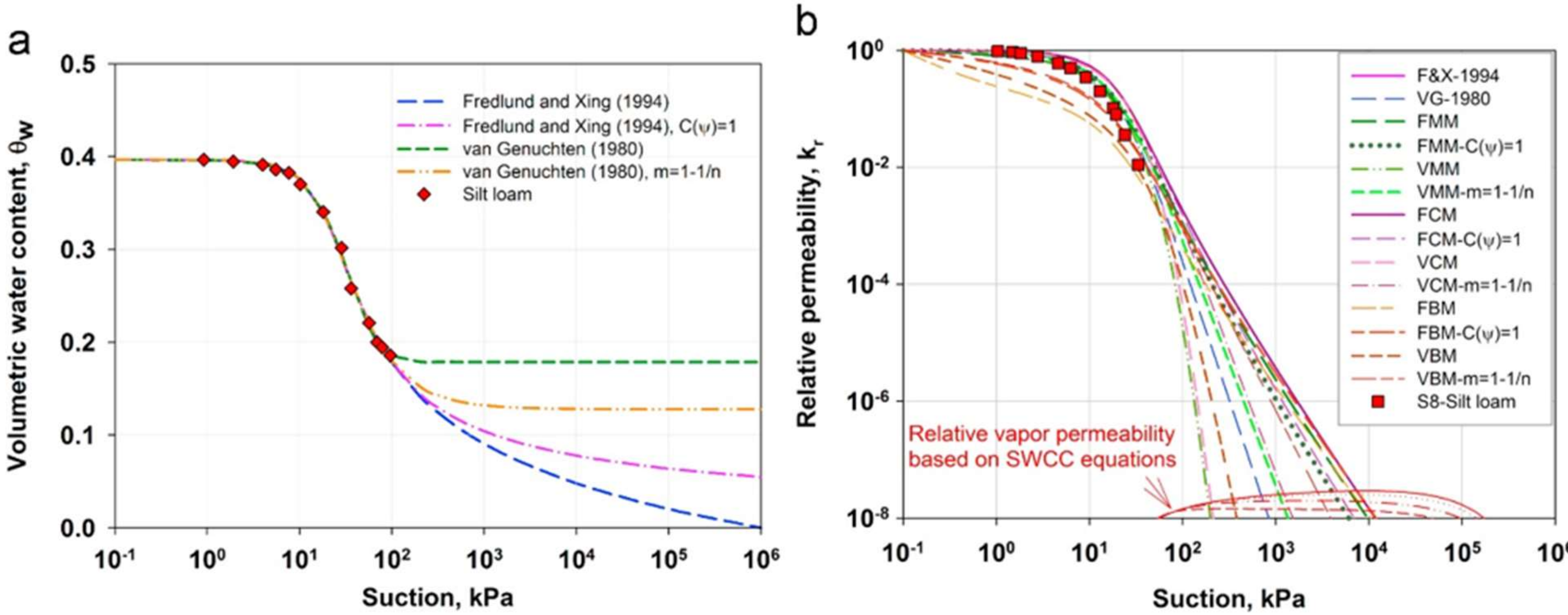
Field investigation after the 20 August 2019 debris flow event. **a** Image of the Cutou debris flows captured by UAV after the event. It destroyed the National Highway 213 and Chengdu–Wenchuan expressway; **b** image of debris flow in Banzi catchment captured by UAV after the event; **c** the Chediguan debris flow ran out to the opposite bank of the Minjiang River; **d** high-precision images of debris flow disaster area were captured by UAV; **e** field sieving tests were performed in Gaojia catchment after the 20 August 2019 event; and **f** coarse sediments were sieved in the field, and fine deposits were collected and sieved.

Unsaturated/saturated states of soils/debris

Visualization of the Role of the Surface Flux Boundary *Condition*



UNSATURATED/SATURATED STATES OF SOILS/DEBRIS



Soil-Water Characteristic Curve (SWCC) and Permeability:

The SWCC describes the relationship between matric suction (ψ) and volumetric water content (θ). The SWCC provides valuable insight into how water is retained in the soil and how it influences the soil's permeability.

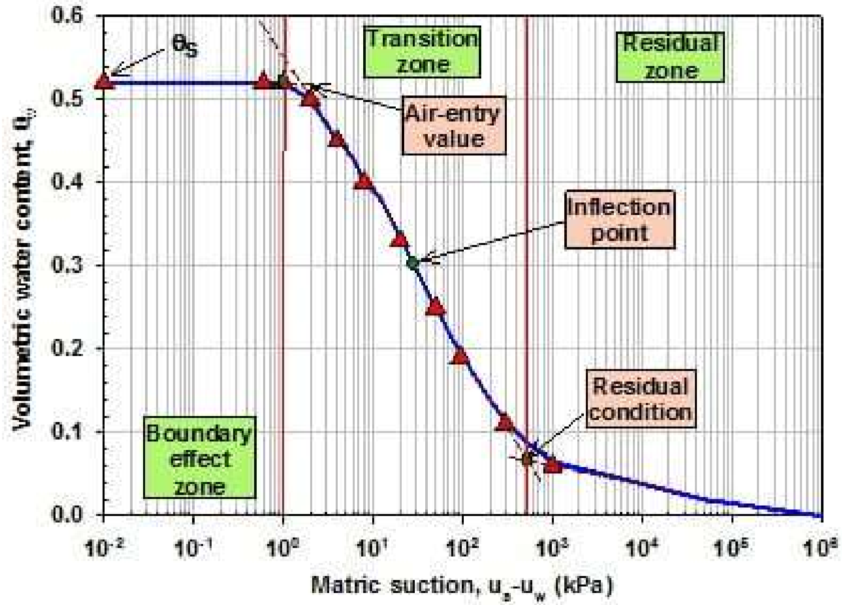
UNSATURATED/SATURATED STATES OF SOILS/DEBRIS

Soil-Water Characteristic Curve (SWCC)

The relationship between the volumetric water content θ and the soil suction (negative pore-water pressure) is represented by the Soil-Water Characteristic Curve (SWCC). This curve is critical for understanding the hydraulic behavior of unsaturated soils. At lower water contents, the soil experiences higher suction, meaning the water is held tightly within the pores, contributing to the soil's apparent cohesion. As the soil becomes wetter, suction decreases, leading to a reduction in this apparent cohesion.

The Soil-Water Characteristic Curve (SWCC) is a fundamental concept that describes the relationship between the soil's volumetric water content (θ) and its matric suction (ψ), which is the difference between pore air pressure (u_a) and pore water pressure (u_w).

- **Matric Suction and Apparent Cohesion**: In unsaturated soils, matric suction plays a crucial role in maintaining soil structure and strength. Matric suction creates an apparent cohesion that helps bind soil particles together, increasing the soil's shear strength.
- **Shape of SWCC**: The SWCC typically has a characteristic S-shape. At low water content, suction is high, meaning water is held tightly within the soil pores. As the soil becomes wetter (increasing θ), suction decreases, and the soil approaches saturation.
- **Importance in Landslides**: Understanding the SWCC is essential for predicting how soils will behave under different moisture conditions. As the soil becomes saturated (θ approaches θ_s), the suction decreases to near zero, leading to a significant reduction in apparent cohesion, which is critical for slope stability.



Unsaturated/saturated states of soils/debris

Traditional Mohr-Coulomb Failure Criterion

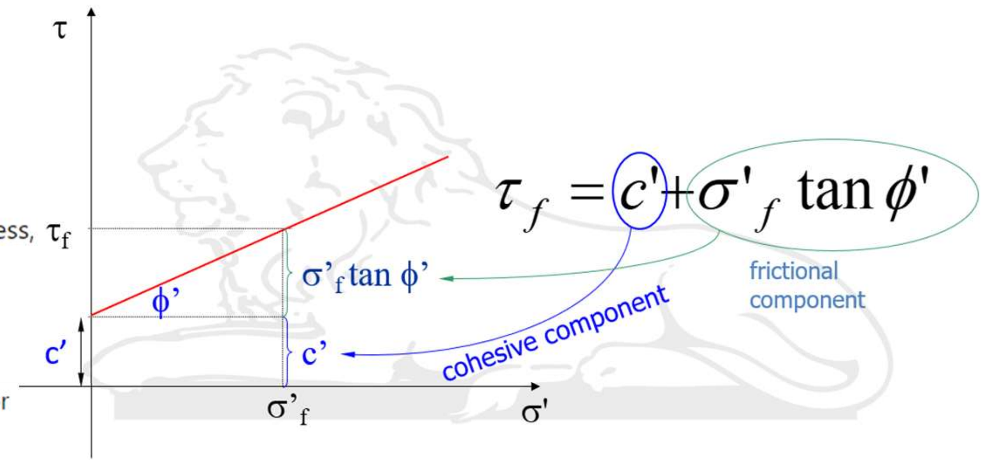
For saturated or dry soils, the shear strength (τ) of soil is given by the Mohr-Coulomb failure criterion:

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

Where:

- τ is the shear strength.
- c' is the effective cohesion (an inherent property of the soil material).
- σ' is the effective normal stress, defined as $\sigma' = \sigma - u_w$, where σ is the total normal stress, and u_w is the pore water pressure.
- ϕ' is the angle of internal friction, a measure of the soil's resistance to shear deformation.

Shear strength consists of two components: cohesive and frictional.



The Mohr-Coulomb elasto-plastic failure criterion, expressed in terms of effective stress, is crucial for understanding soil behavior under various loading conditions. This criterion combines elastic and plastic responses to model soil failure accurately. Under the elastic phase, the soil exhibits reversible deformations with a linear stress-strain relationship. However, once the applied effective stress exceeds the soil's shear strength, the soil transitions to a plastic phase, characterized by permanent deformations.

The Mohr-Coulomb elasto-plastic failure criterion provides a framework for evaluating slope stability by comparing the soil's shear strength, as influenced by effective stress, to the shear stress induced by slope loading conditions. By applying this criterion, engineers can predict the stability of slopes, design effective stabilization measures, and assess the impact of various loading conditions, including seismic events, on slope stability.

Physical processes leading to rainfall-induced landslides: Shallow Landslides and Debris Flows

Loss of Apparent Cohesion and Reduction in Unsaturated Shear Strength

As the soil progresses from unsaturated to saturated conditions, significant changes in soil mechanics occur. Apparent cohesion is primarily due to matric suction in unsaturated soils. As the soil becomes saturated, matric suction decreases to zero, leading to a loss of this additional cohesion. This reduction significantly lowers the soil's shear strength. The shear strength (τ) of unsaturated soils can be expressed using a modified Mohr-Coulomb equation:

$$\boxed{\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi_b} \qquad 0$$

Here:

- c' is the effective cohesion (inherent to the soil material),
- $(\sigma - u_a)$ is the net normal stress,
- $(u_a - u_w)$ represents matric suction,
- ϕ' is the angle of internal friction,
- ϕ_b is a parameter that reflects the contribution of matric suction to shear strength.

As saturation increases, the term $(u_a - u_w)$ diminishes, reducing the shear strength of the soil. This makes the soil more prone to failure under the same loading conditions.

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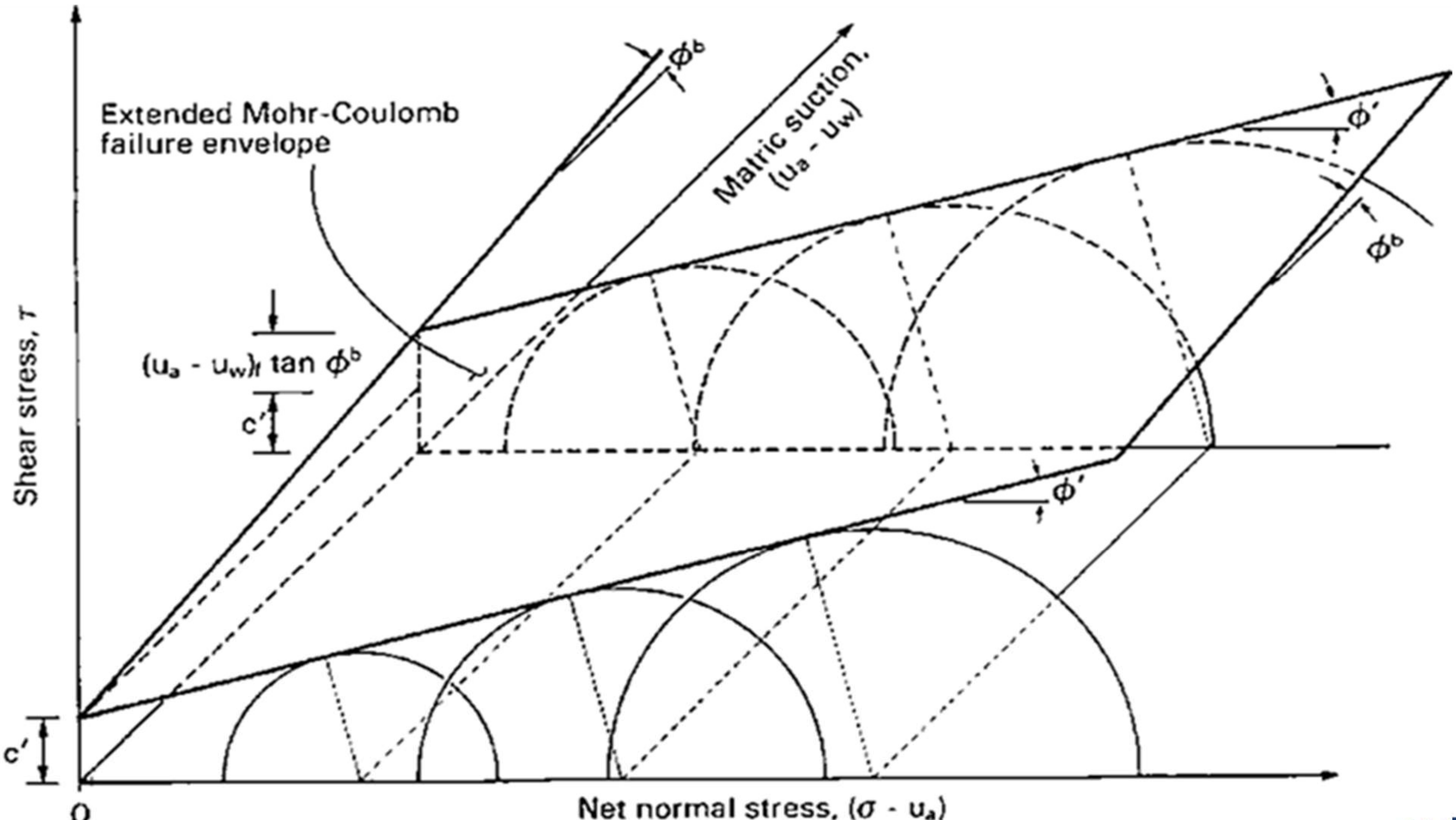

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Factor of Safety for Saturated Soils

In saturated soils, the FoS is given by the ratio of the shear strength (τ_{resist}) of the soil to the shear stress ($\tau_{mobilized}$) acting on the potential failure surface:

$$\text{FoS} = \frac{\tau_{resist}}{\tau_{mobilized}}$$

The shear strength of saturated soil is typically expressed using the Mohr-Coulomb criterion:

$$\tau_{resist} = c' + (\sigma - u_w)\tan\phi'$$

Where:

- c' is the effective cohesion of the soil.
- σ is the total normal stress on the failure plane.
- u_w is the pore water pressure.
- $\sigma' = \sigma - u_w$ is the effective normal stress.
- ϕ' is the effective angle of internal friction.

Thus, the FoS for saturated soils is:

$$\text{FoS} = \frac{c' + (\sigma - u_w)\tan\phi'}{\tau_{mobilized}}$$

Factor of Safety for Unsaturated Soils

For unsaturated soils, the FoS must account for the additional shear strength provided by matric suction. The extended Mohr-Coulomb equation for unsaturated soils is:

$$\tau_{resist} = c' + (\sigma - u_a)\tan\phi' + (\psi)\tan\phi_b$$

Where:

- $\psi = u_a - u_w$ is matric suction (difference between pore air pressure u_a and pore water pressure u_w).
- ϕ_b is the angle of shear strength increase due to matric suction.

Therefore, the FoS for unsaturated soils is:

$$\text{FoS} = \frac{c' + (\sigma - u_a)\tan\phi' + (\psi)\tan\phi_b}{\tau_{mobilized}}$$

Physical processes leading to rainfall-induced landslides: Shallow Landslides and Debris Flows

The initiation of debris flows under the condition that bed shear stress (τ, kPa) is larger than the critical erosive shear stress (τ_c, kPa), and the volumetric concentration of solids in the debris flow (C_v) is smaller than an equilibrium value ($C_{v\infty}$) which is called the transport capacity of the flow.

For this based on the stability theory, we use the expression proposed by Takahashi et al. (1992):

$$C_{V\infty} = \frac{\rho_w tan\theta}{(\rho_s - \rho_w)(tan\phi_{bed} - tan\theta)} \quad (1)$$

where ρ_w (kg/m³) is the density of water usually assumed 1000 kg/m³, ρ_s (kg/m³) is the density of the solids, ϕ_{bed} (°) is the angle of internal friction of the bed material and θ (°) is the slope angle.

We expressed the erosion rate based on Takahashi et al. (1992):

$$i = \delta_e \frac{a_c}{d_L} U = \delta_e \frac{C_{V\infty} - C_V}{C_{V*} - C_{V\infty}} \frac{q_t}{d_L} \quad (2)$$

where δ_e is a back-calculated non-dimensional coefficient of erosion rate, a_c (m) is the depth within the sediment layer under the condition $\tau_c = \tau$, d_L is d_{50} mean diameter of the grain, U (m/s) is the velocity of the flow-through vertical section, C_{v*} is the volumetric fraction of solids and q_t (m²/s) is the routed total discharge of the sum of sediments and water per unit width expressed as (van Asch et al., 2014):

$$q_t = (H_s + H_w)V = (H_s + h_r T_s)V \quad (3)$$

where H_s (m) is the equivalent height of solids, H_w (m) is the equivalent height of the water, V (m/s) is the flow velocity, and T_s (s) is the time step duration. H_s (m) is calculated using the following equation.

$$H_s = (H_{si} + i_\varsigma) \times (C_V - (1 - C_V)S \quad (4)$$

H_{si} (m) is the equivalent height of solids at the beginning of the simulation, i_ς is the net erosion (solids: rock and soil) and S is the degree of saturation of bed materials (value range from 0 to 1).

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Thank you very much for your kind attention and time!

Question time