CI 350

MSc in Engineering Geology for Ground Models

Stability of Soil Slopes

Classification of Slope Movements

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Slope Instability in Numbers

- Landslides in the USA cause $3.5 billion damage and 25-50 fatalities per year
- Similar socio-economic impact in other countries e.g. China, Japan and India
- In the UK large-scale landslides are rare. However the cost from small scale landslides blocking roads and railways is high.

Aberfan 1966:

Flow slide of mining waste from a tip above the village.

Crest of Aberfan waste deposited on glacially formed and mantled hills: before disaster

Aberfan 1966:

Flow slide of mining waste from a tip above the village.

Aberfan 1966:

116 children and 28 adults were killed

Scotland, August 2004

View of the northern A85 Glen Ogle debris flow two days after the event

Winter et al 2008

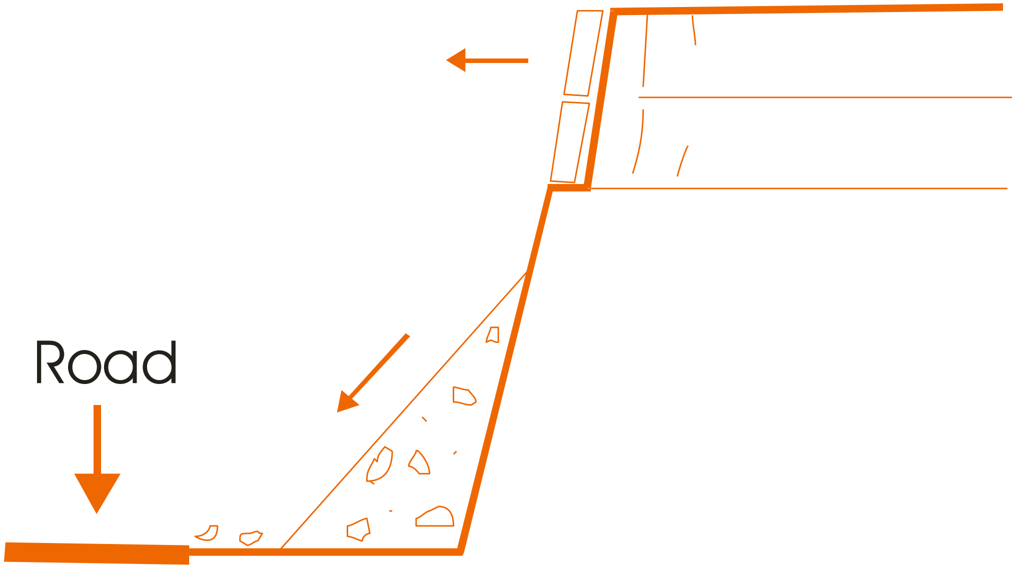
Scotland, August 2004

Debris flow above the A83 to the west of Cairndow

Winter et al 2008

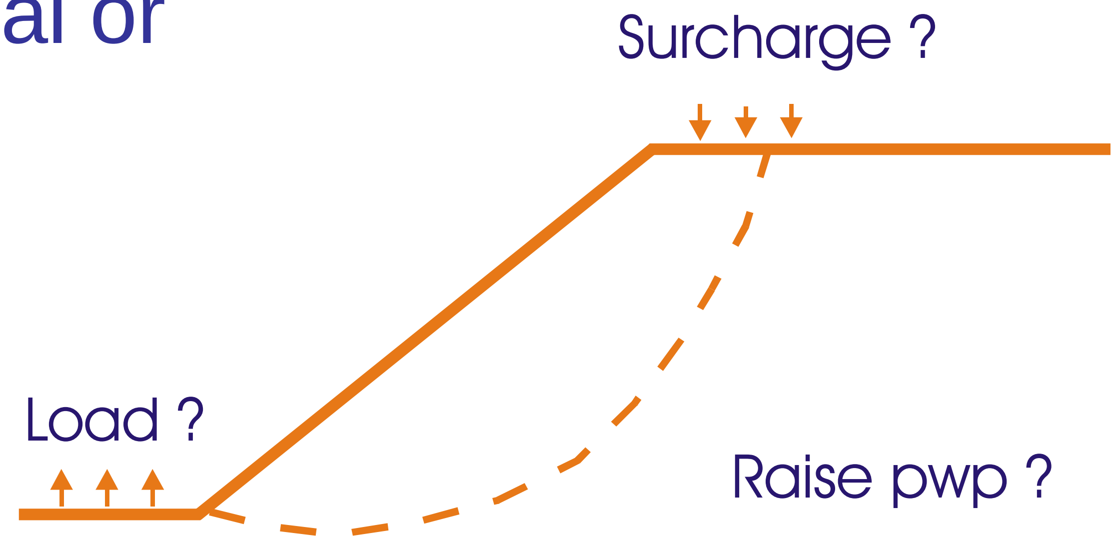
Engineering problems involving "slope stability"

- Rock Falls



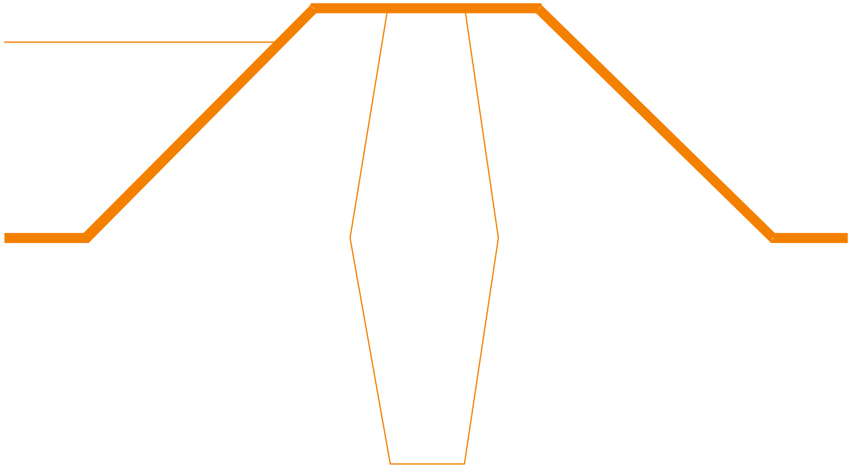
Engineering problems involving "slope stability"

- Rock Falls
- Slopes (Natural or "engineered")



Engineering problems involving “slope stability”

- Rock Falls
- Slopes (Natural or “engineered”)
- Embankments



Engineering problems involving "slope stability"

- Rock Falls
- Slopes (Natural or "engineered")
- Embankments
- Waste Tips

Course topics

- **Classification**
  - Types of movement
  - Strength properties
  - Pore water pressure conditions
- **Stability analysis**
  - General slope stability concepts
  - Planar movements
  - Rotational movements
  - Compound movements
  - Factors affecting slope stability analysis

Classification of Mass Movement

Movement of masses of geological material on the earth's surface in response to gravity

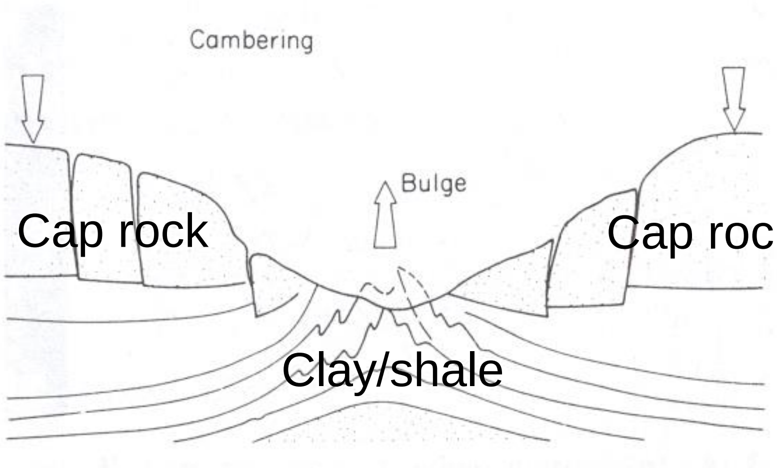
- Valley rebound: small elastic movements
  - Valley floor anticline
  - Bedding plane flexure
  - Modified drainage pattern

Classification of Mass Movement

Movement of masses of geological material on the earth's surface in response to gravity

- Valley rebound
- Camber and Bulge: large plastic movements

two aspects of the same phenomenon as a consequence of periglacial conditions



from Blyth & de Freitas (1984)

Classification of Mass Movement

Movement of masses of geological material on the earth's surface in response to gravity

- Valley rebound
- Camber and Bulge
- Creep
  - "True" creep
  - Seasonal creep

Soil creep, evidenced by bent tree trunks

Classification of Mass Movement

Movement of masses of geological material on the earth's surface in response to gravity

- Valley rebound
- Camber and Bulge
- Creep
- Subsidence
  - Natural
  - Man-made

Subsidence in Arizona due to groundwater pumping

Classification of Mass Movement

Movement of masses of geological material on the earth's surface in response to gravity

- Valley rebound
- Camber and Bulge
- Creep
- Subsidence
- **Landslide**

Classification of Landslides

- **Falls**

  involve immediate separation of the falling material from parent rock or soil mass

- **Slide**

  moving material remains in contact and movement takes place along discrete shear surfaces

- **Flows**

  material becomes disaggregated and movement occurs without necessarily forming discrete shear surfaces

Large landslides often change from one type to another as they progress

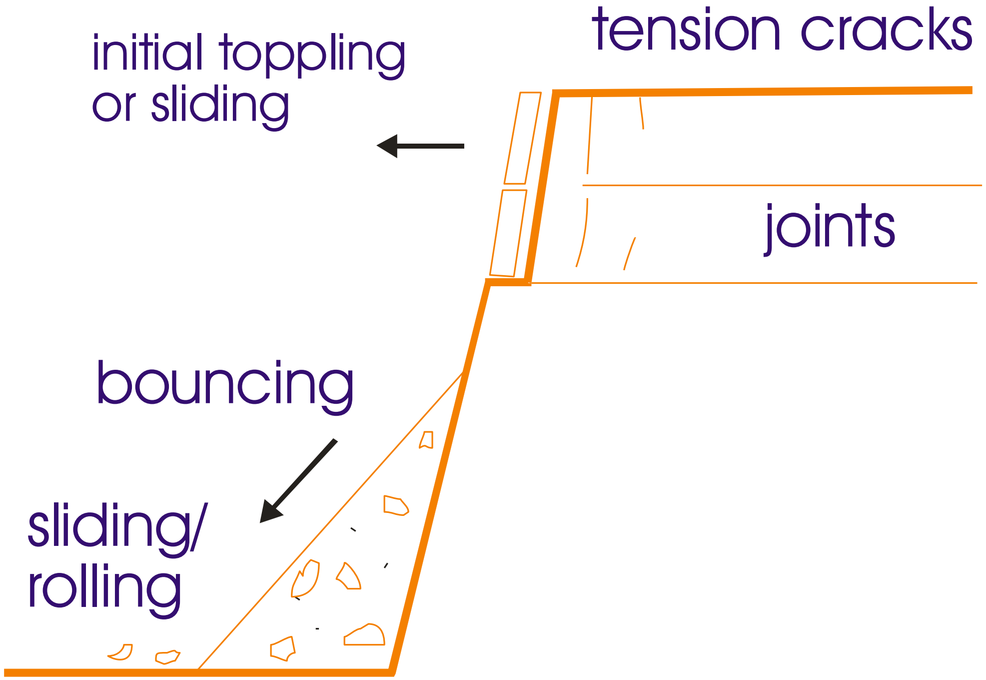
Otomura Landslide
Japan August 2004

FALLS, FLOW or SLIDE???

Falls

Falls may arise due to:

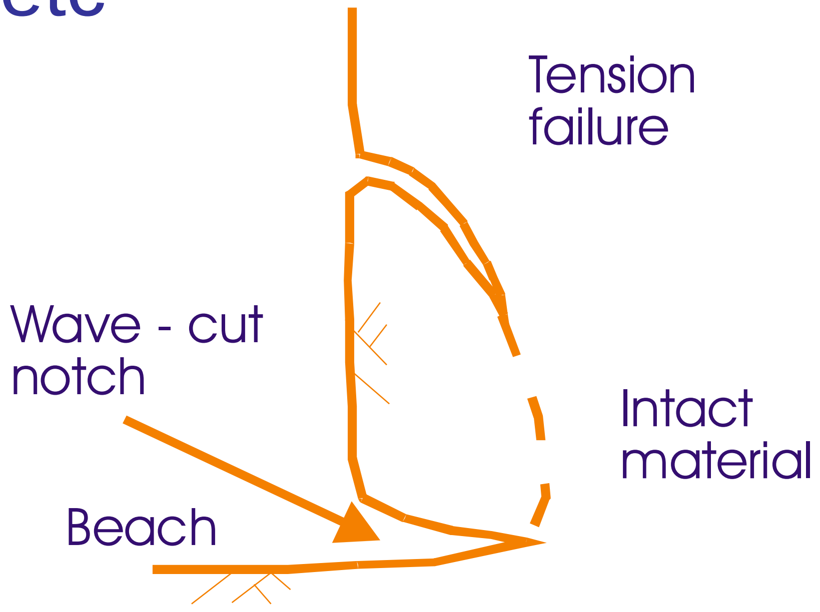
- Shear surfaces in response to gravity stresses



Falls

Falls may arise due to:

- Shear surfaces in response to gravity stresses
- Undermining due to wave action, river erosion, seepage, etc



Falls

Falls may arise due to:

- Shear surfaces in response to gravity stresses
- Undermining due to wave action, river erosion, seepage, etc
- Temperature changes

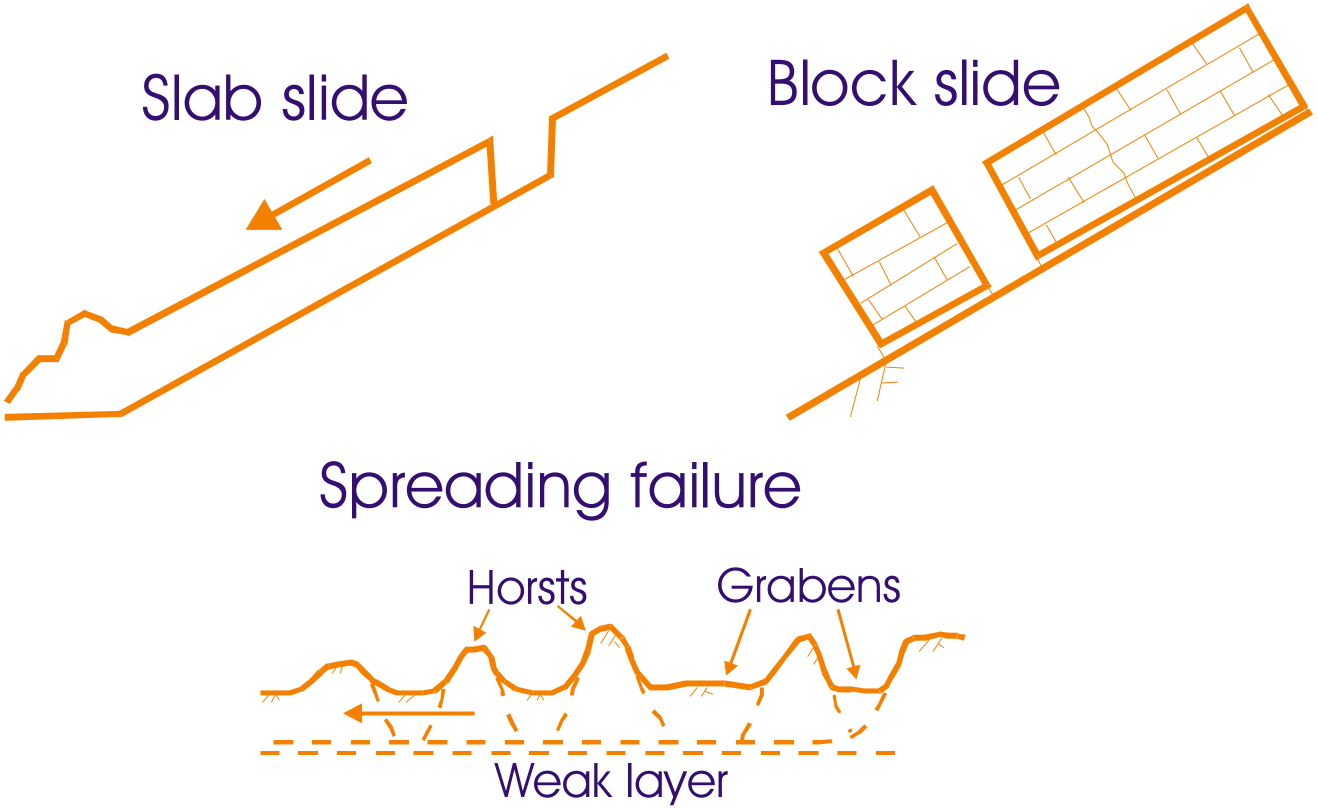
Falls

Falls may arise due to:

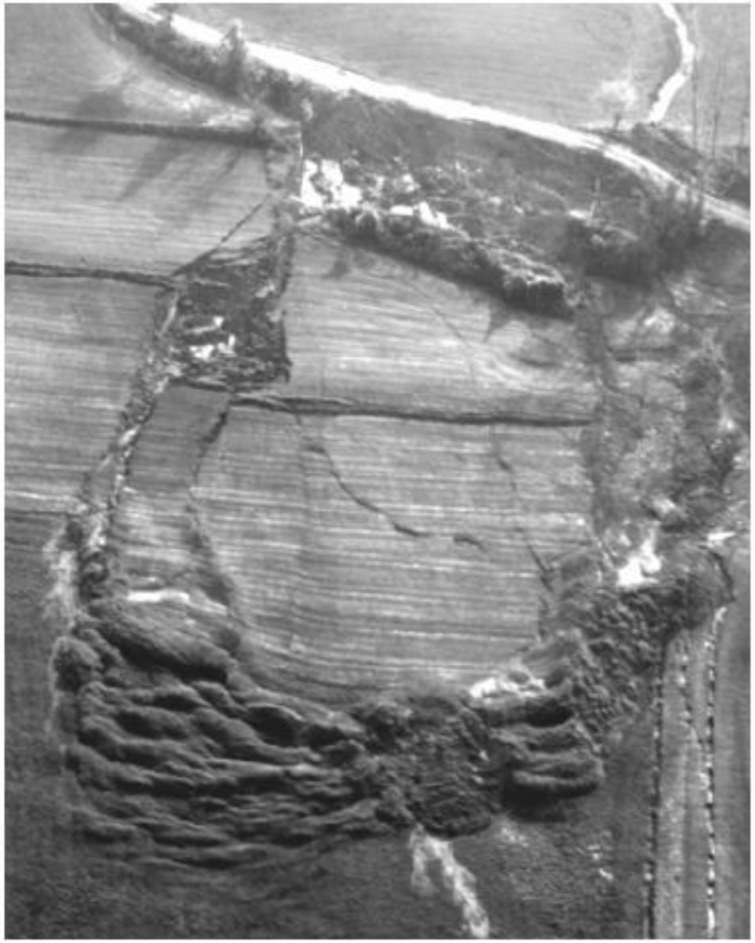
- Shear surfaces in response to gravity stresses
- Undermining due to wave action, river erosion, seepage, etc
- Temperature changes
- Effect of water in joint bonded rock or in tension cracks

Slides

- Translational



Translational



Planar landslide immediately after failure

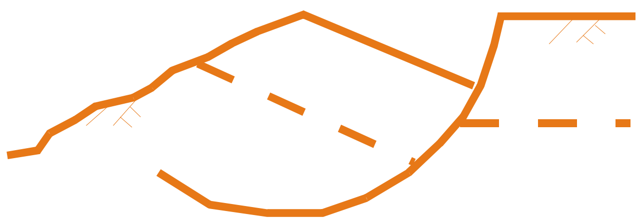
Example of planar sliding mechanism

Bottino et al 2011

Slides

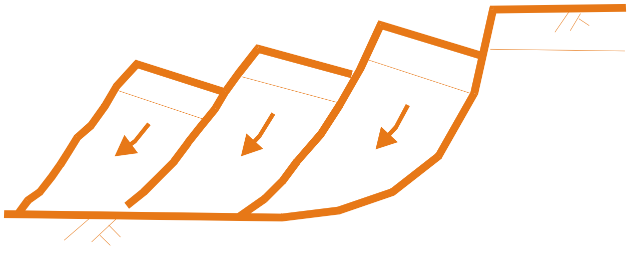
- Translational
- Rotational

Circular



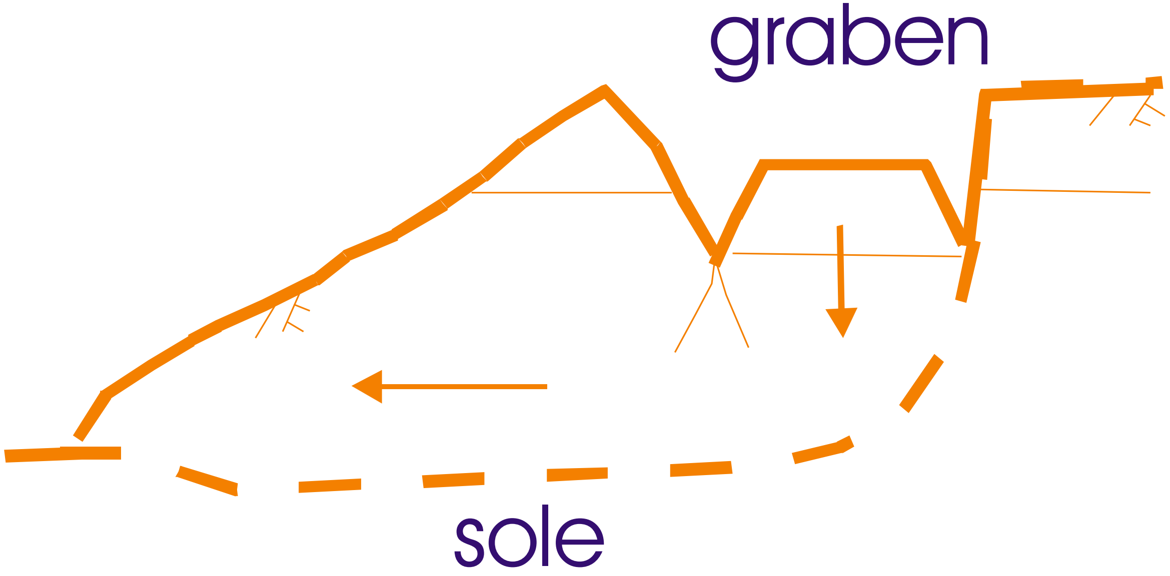
Successive

Multiple



Slides

- Translational
- Rotational
- Compound



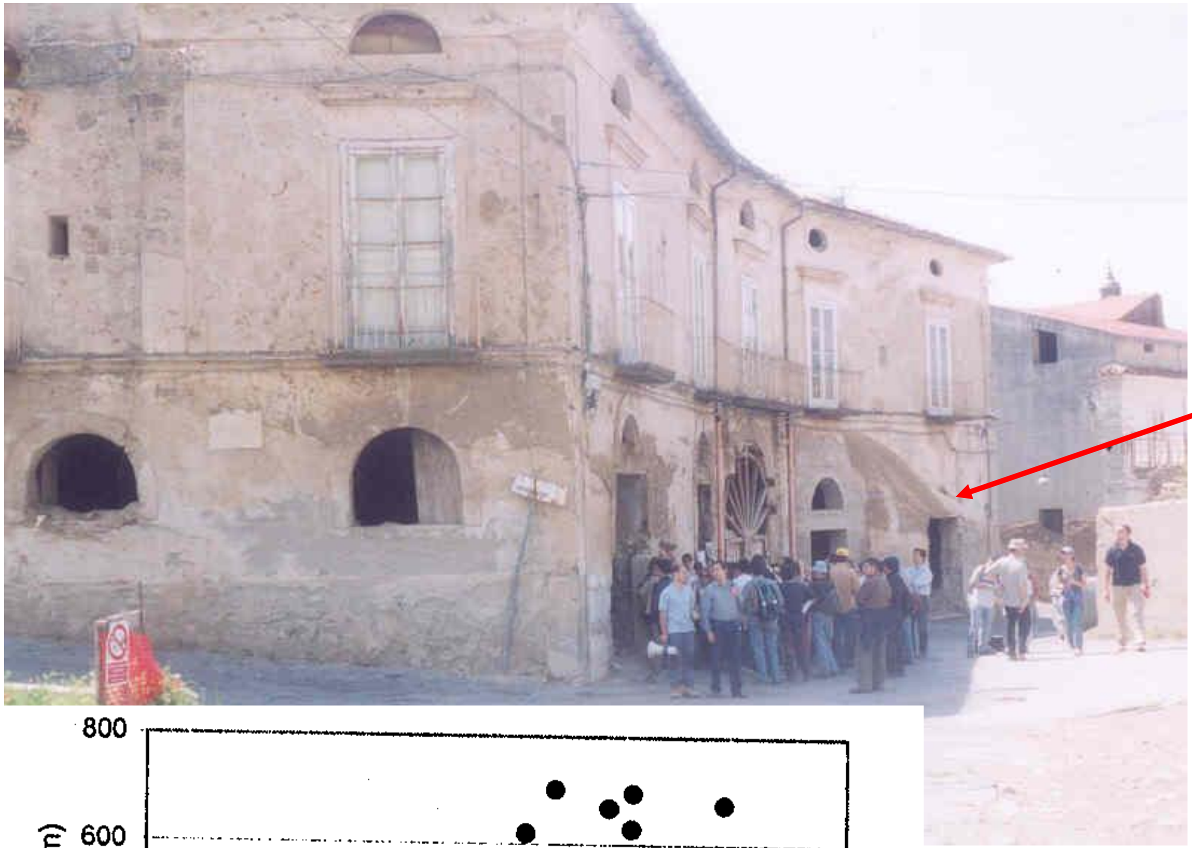
Flows

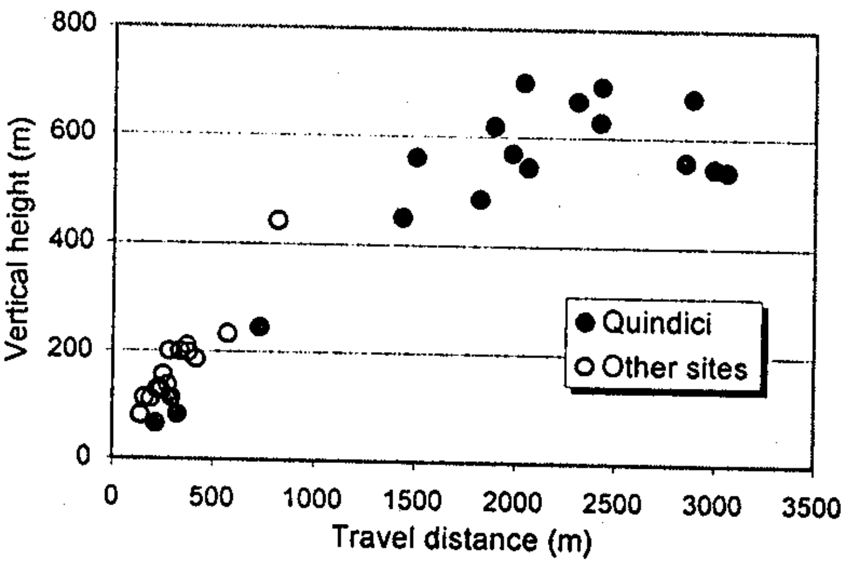
- Flow is a mass movement involving greater internal deformation than a slide. Slides can degenerate into flows.
- Characterised by large run outs and high velocity
- Occur as a result of movement on a large number of shear surfaces or by soil behaving as fluid.
- Debris from falls or slides can behave as a flow-high pore pressures.
- High pore pressures can result from collapse of initial loose grain structure

Engineering Hazards: Debris Flows
e.g. Quindici, near Naples

- After 20hours of continue rainfall

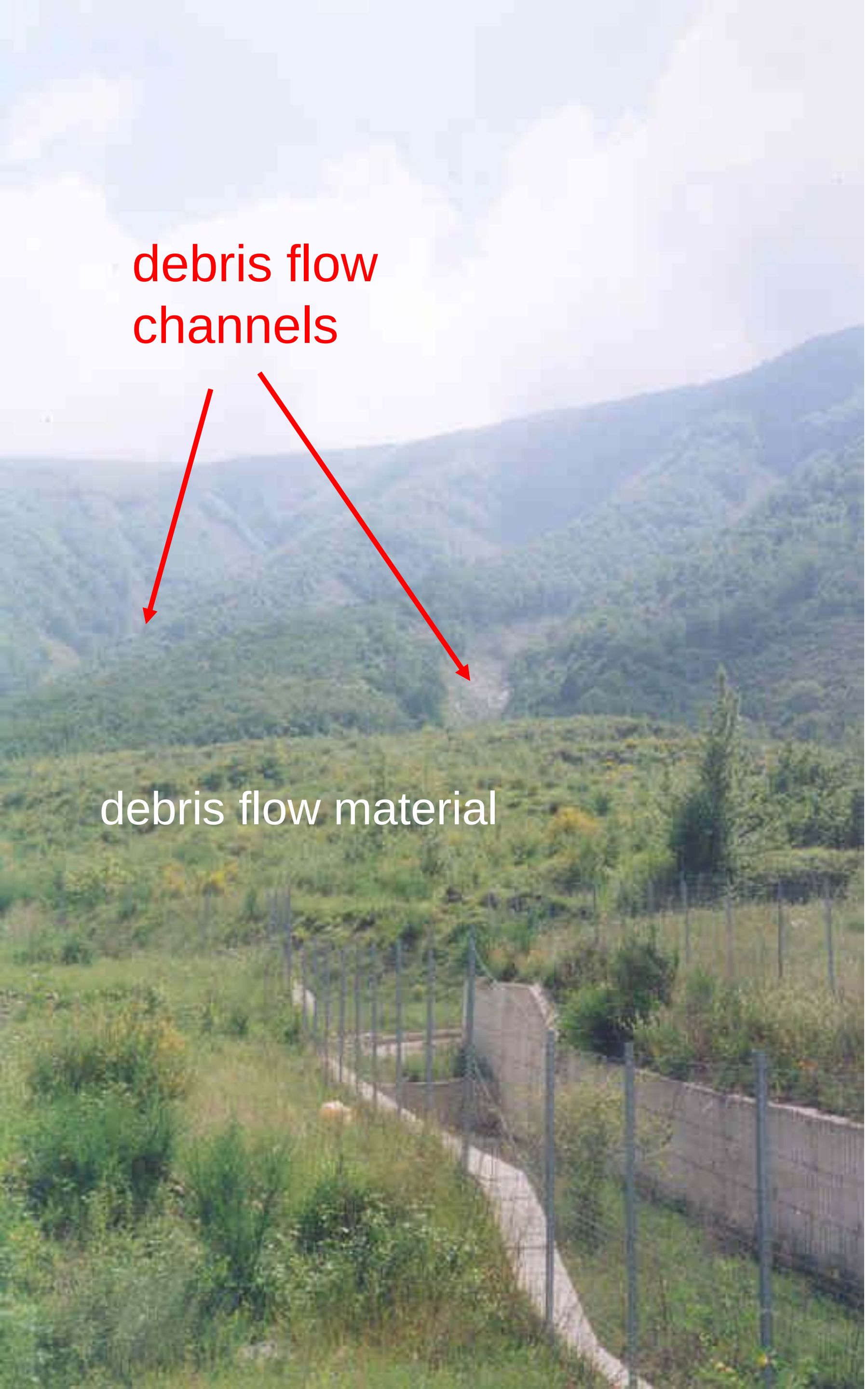
- In highly heterogeneous,
  very permeable pyroclastic deposits





(after Calcaterra et al., 1999)

travel distances of debris flows can be large (11 deaths in Quindici, 148 in surrounding area)



Mitigation measures:
Permeable stepped flow channels

However, deforestation of slopes may be a problem

Barrier protecting against debris flows on Charles Creek, Vancouver Canada (debris removed before picture taken)

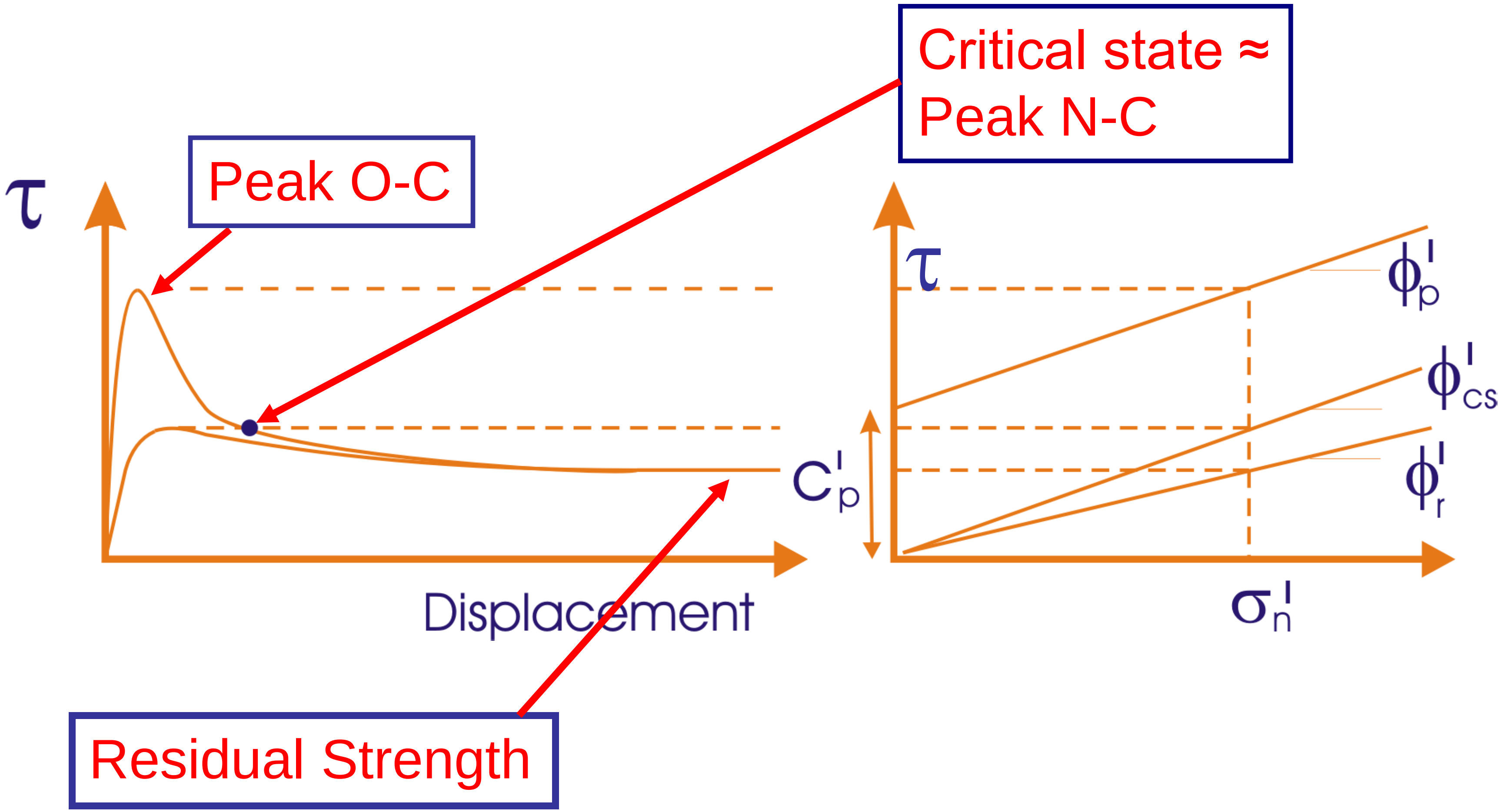
From Mancarella & Hungr 2010

Learning Objectives

1. Distinguish between landslides and general mass movements like creep and subsidence
2. Understand the differences between falls, flows and slides.
3. Understand the basic kinematic mechanism governing the development of translational, rotational and compound slides.

Geotechnical Classification of Landslides

Shear Strength

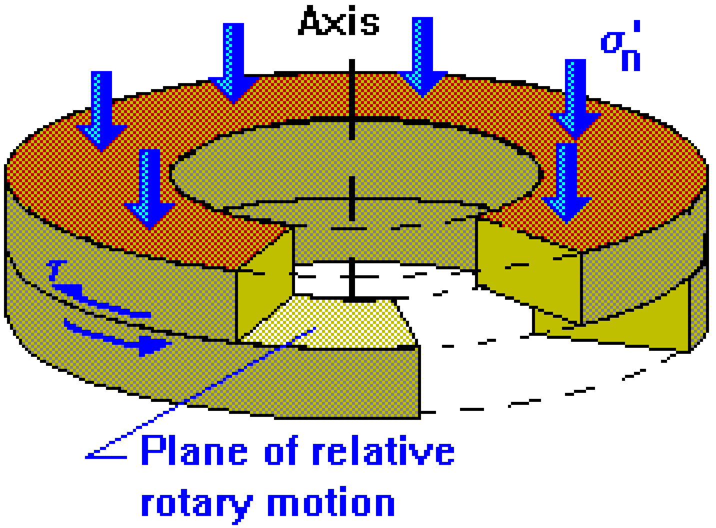


Residual Shear Strength

Minimum drained strength attained at slow rates of shearing

Ring Shear Apparatus:

Unlimited shear displacement is possible through continuous rotation



Ring Shear Apparatus

Residual Shear Strength

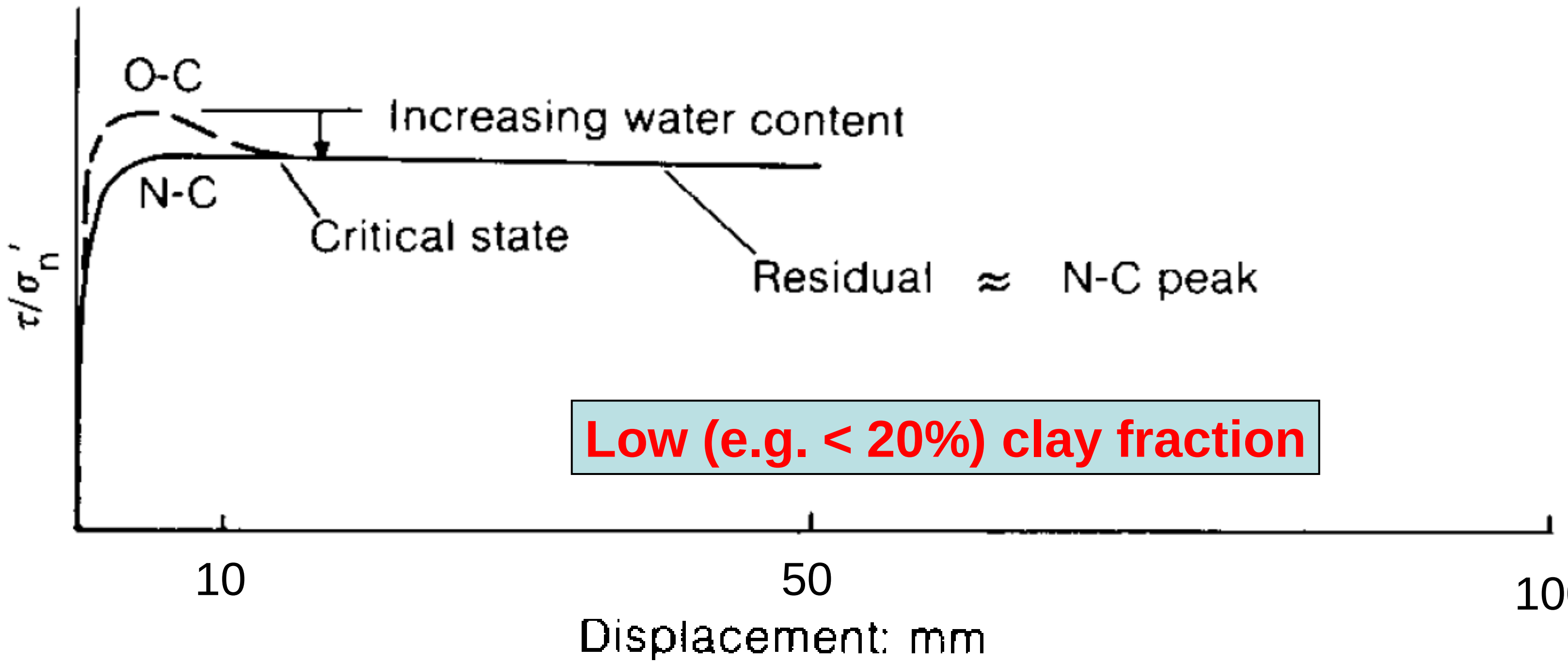
Minimum drained strength attained at slow rates of shearing

Ring Shear Apparatus:

Unlimited shear displacement is possible through continuous rotation

Residual Shear Strength

In low plasticity soils **residual** strength is only <u>slightly less</u> than the **critical state** strength

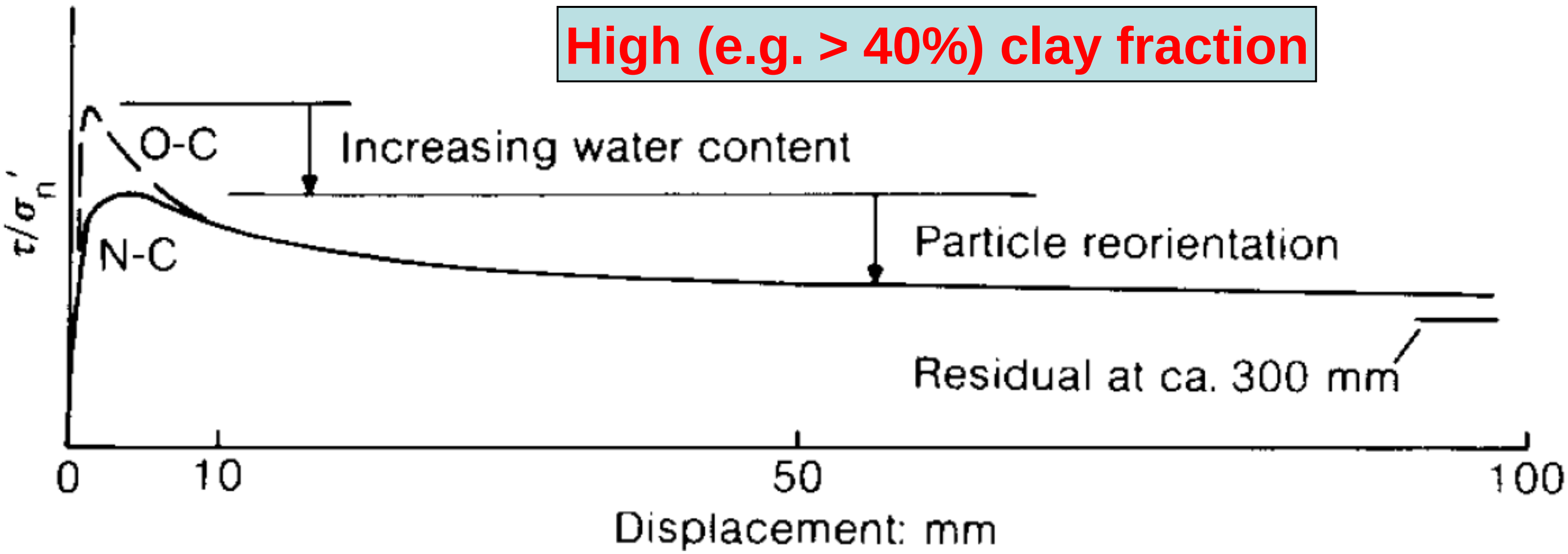


From Skempton (1985)

Stress-displacement curves at constant σ_n

Residual Shear Strength

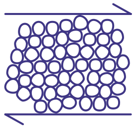
In high plasticity soils **residual** strength is significantly less than the **critical state** strength



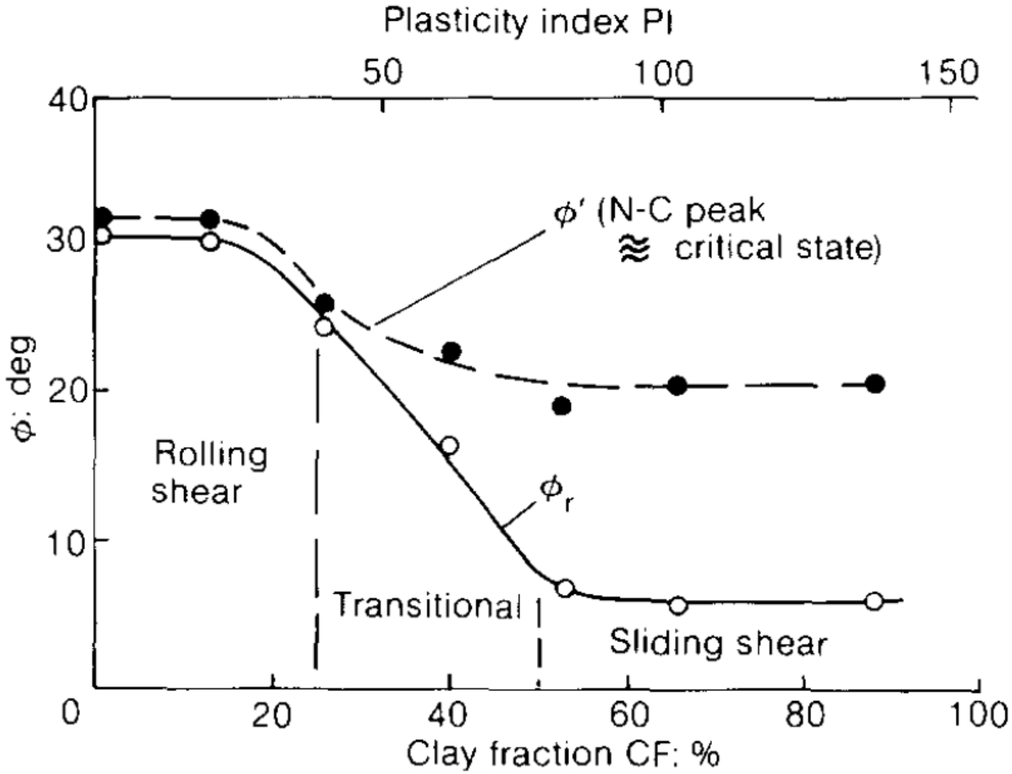
From Skempton (1985)

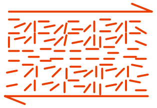
Stress-displacement curves at constant σ_n

Residual Shear Strength



Low plasticity soils





High plasticity soils

Ring shear tests on sand-bentonite mixtures
From Lupini *et al* (1981)

Geotechnical Classification of Landslides

- "First time slides"

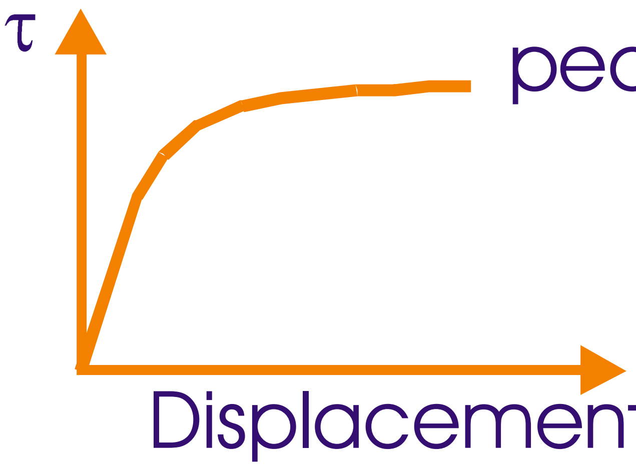
If a slide is occurring for the first time through previously unsheared ground the full range of soil strength (peak to residual) is available

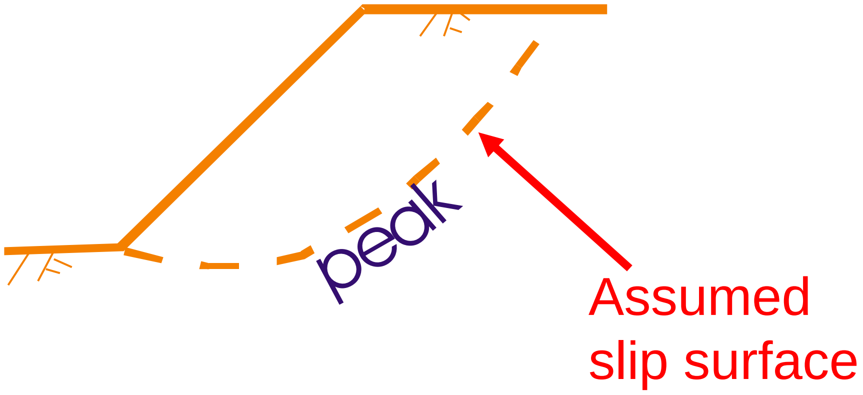
Examples:

- Railway & Motorway Cuts
- Embankments
- Dams

Geotechnical Classification of Landslides

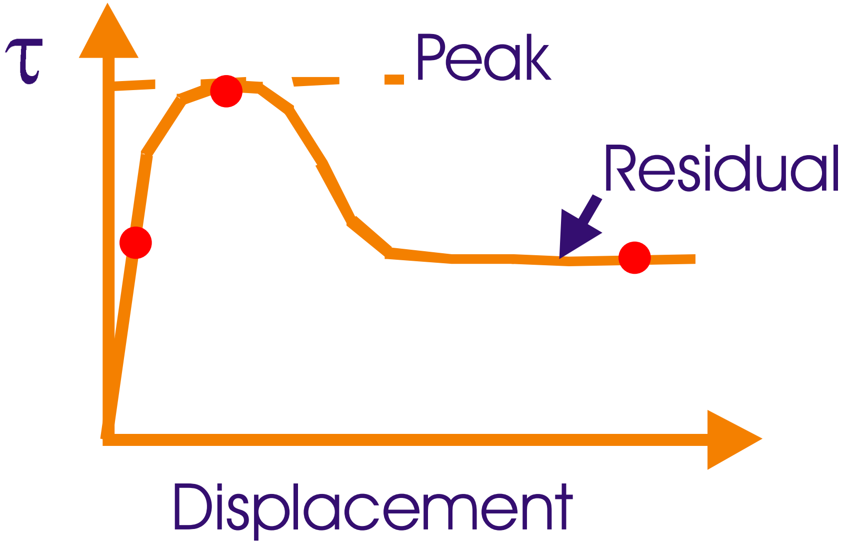
- "First time slides" in <u>low plasticity</u> soils

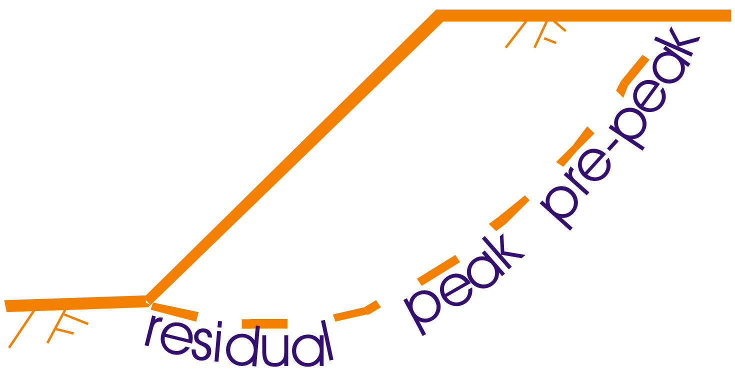




Geotechnical Classification of Landslides

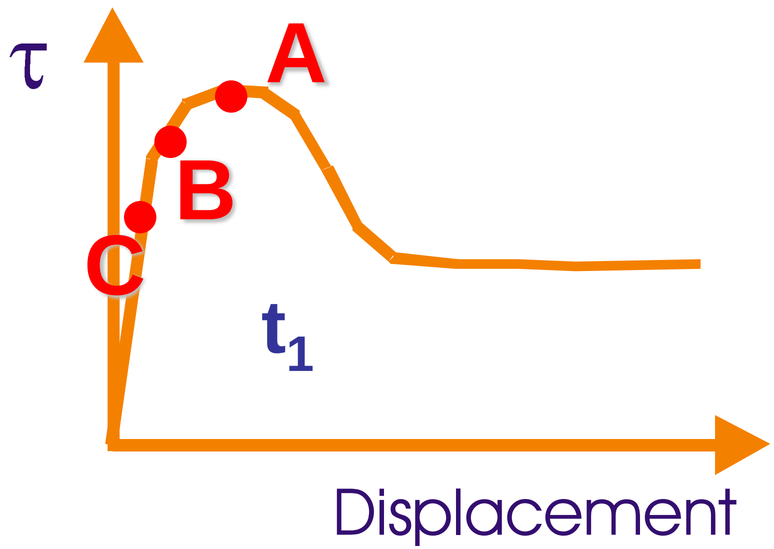
- "First time slides" in <u>high plasticity</u> soils

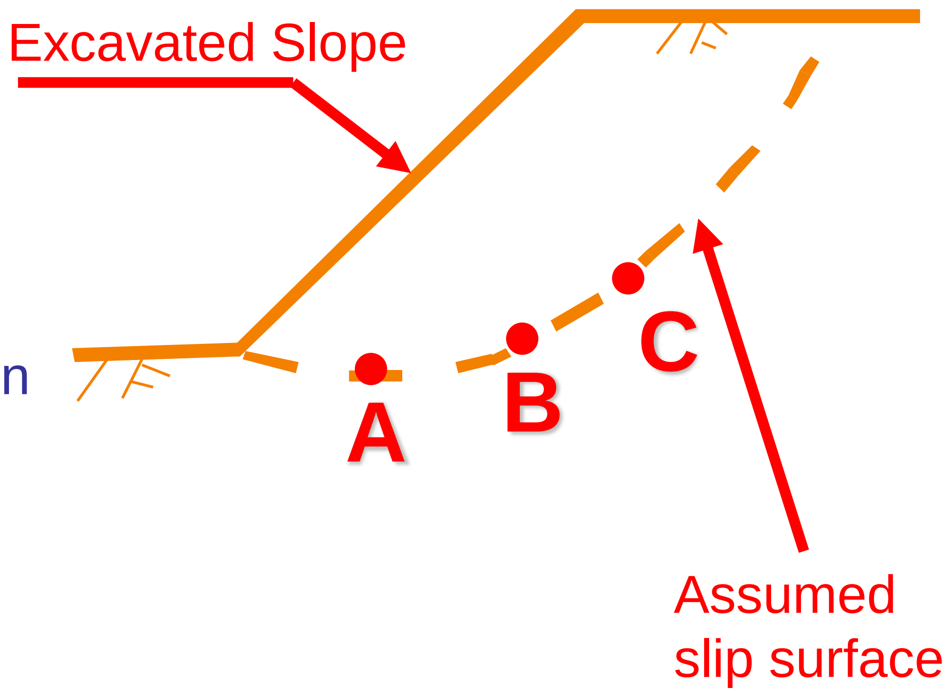




<u>Progressive Failure</u>: Failure does not occur on the whole surface at the same time

Progressive Failure

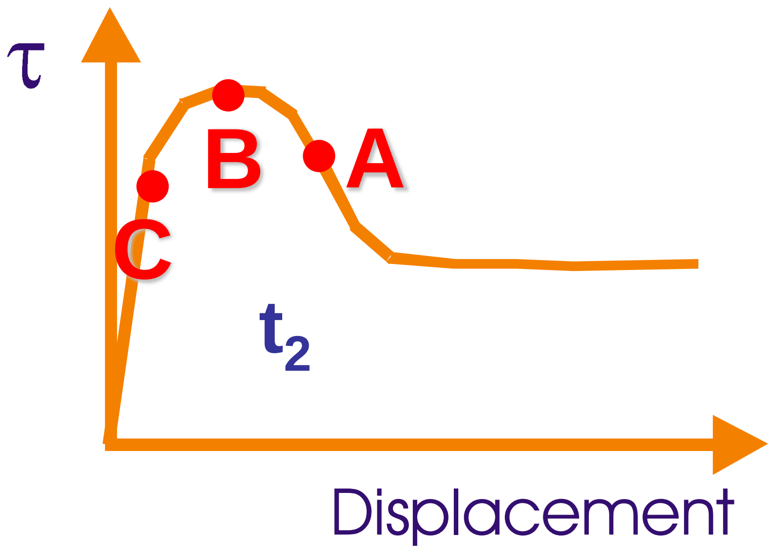


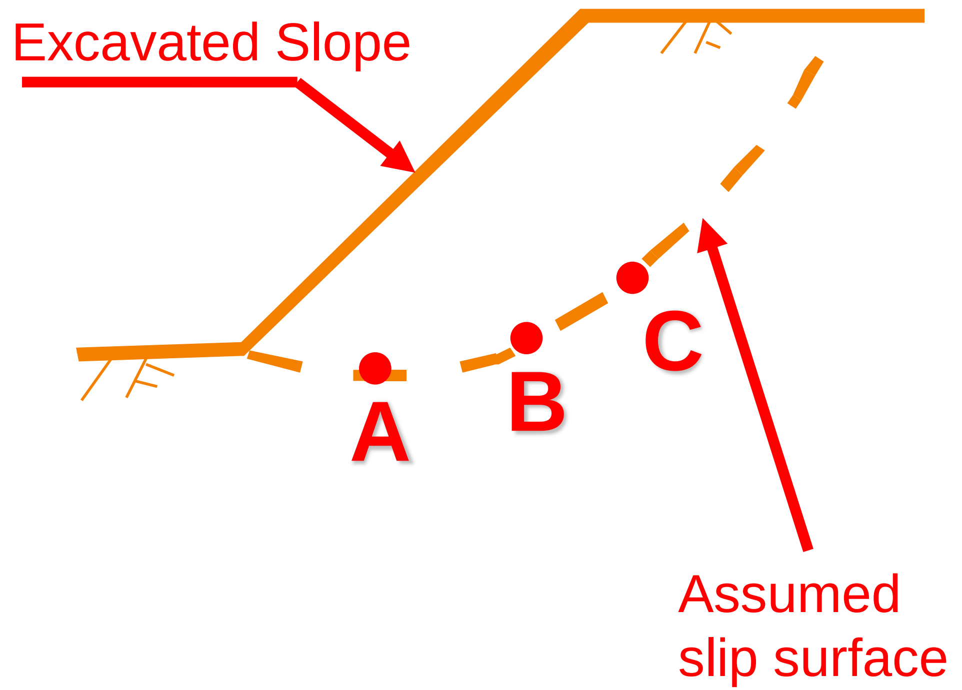


- Time t_1: Immediately after excavation

Local failure at A

Progressive Failure





- Time t_1: Local failure at A
- Time t_2: After some swelling

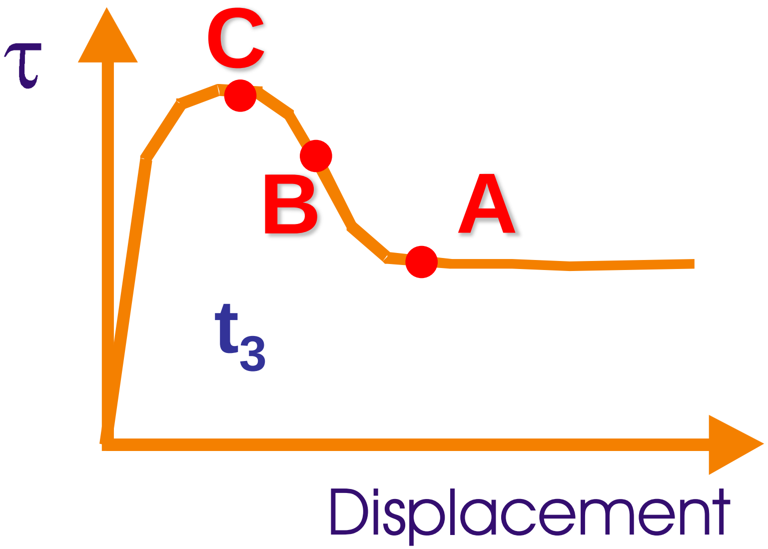
↓

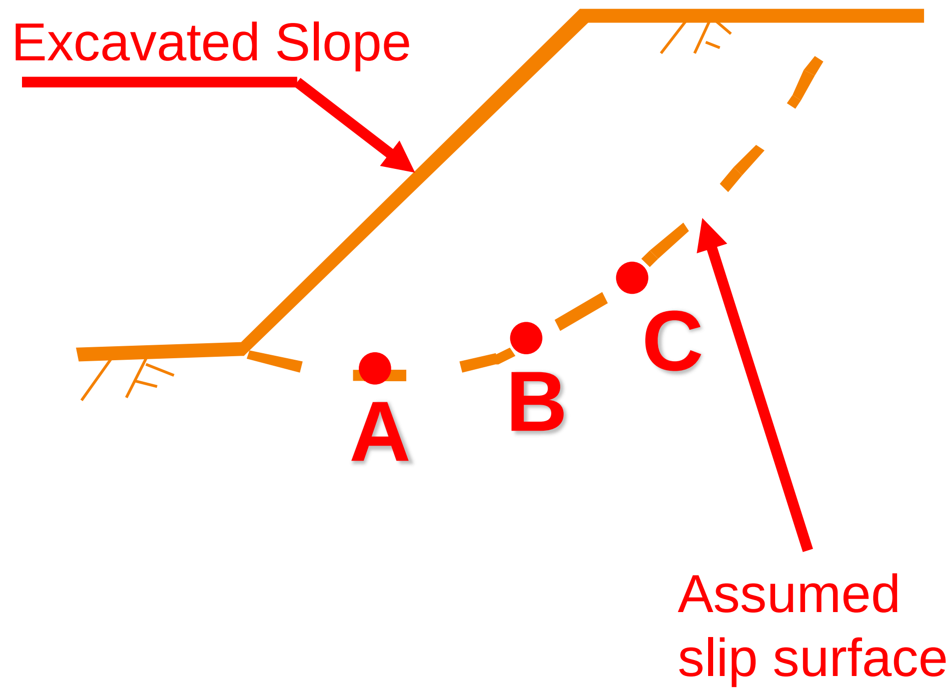
Failed soil elements at A support lower shear stress and hence load is transferred to neighbouring elements at B, C

↓

Failure extends to B

Progressive Failure





- Time t_1: Local failure at A
- Time t_2: Failure extends to B
- Time t_3: After further swelling

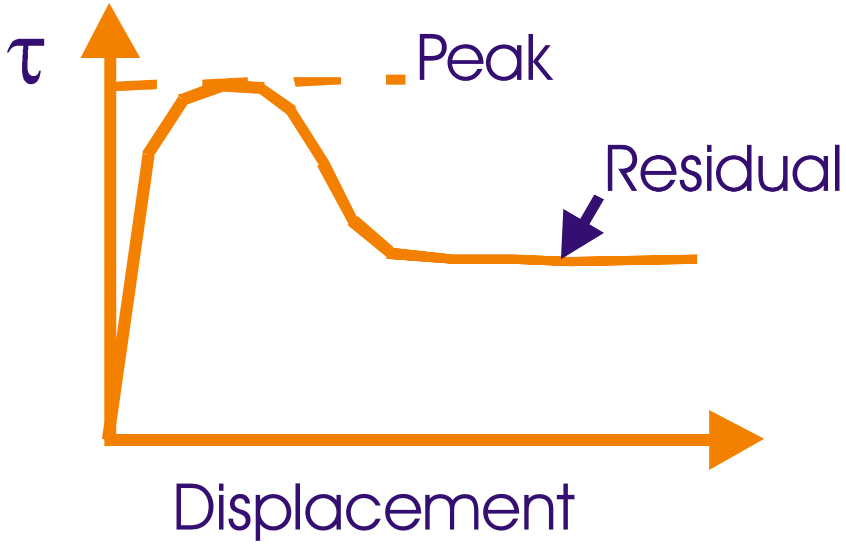
Displacement at B are large enough so that shear stress there fall below the peak

Failure progress further up

Progressive Failure

Necessary Conditions:

- Brittle behaviour

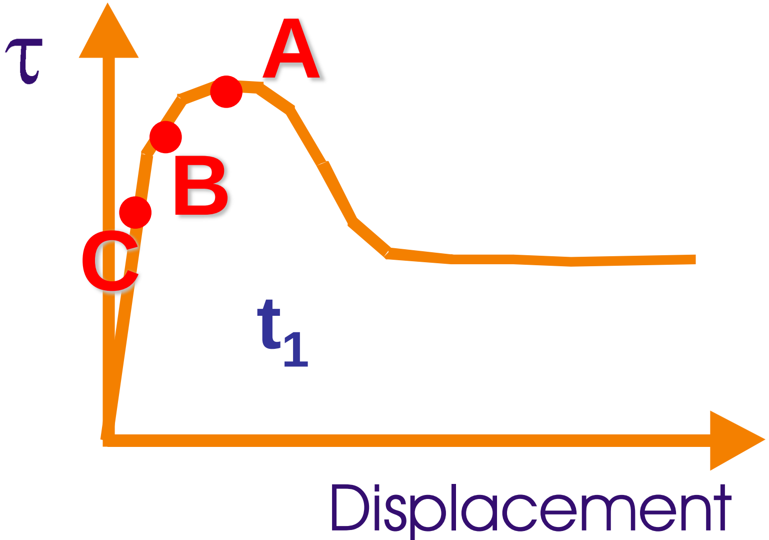


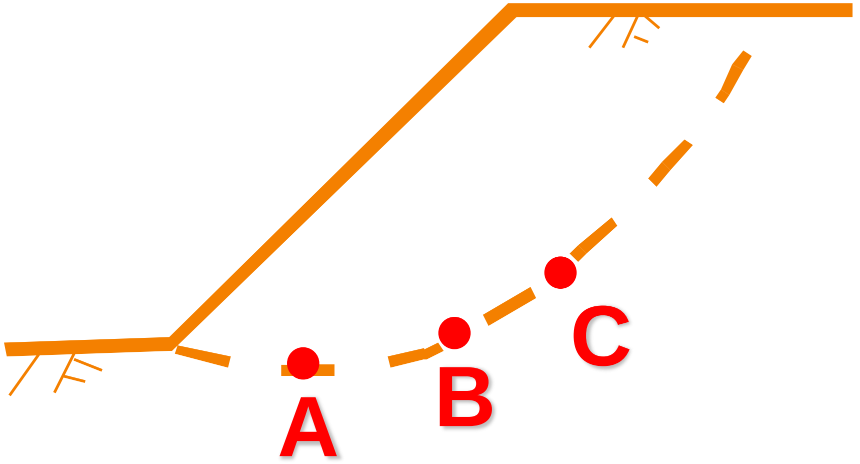
$$\boxed{I_B = \frac{\tau_p - \tau_r}{\tau_p}}$$

Progressive Failure

Necessary Conditions:

- Brittle behaviour
- Non-uniform distribution of shear stress

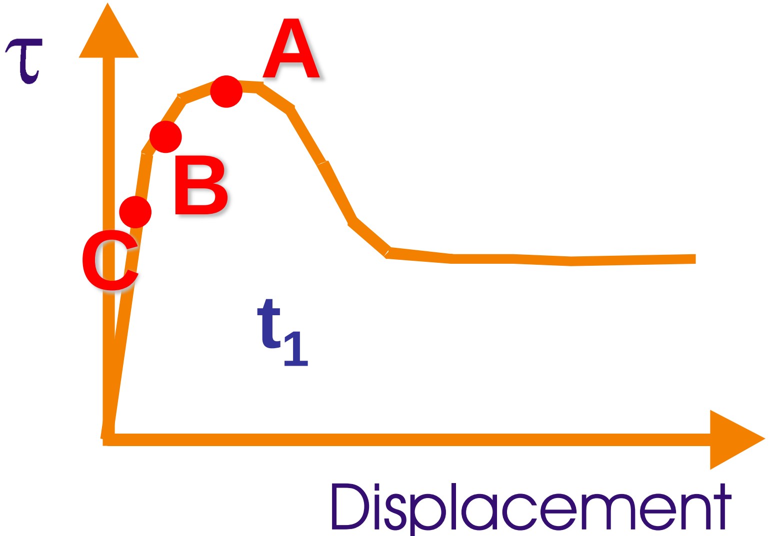


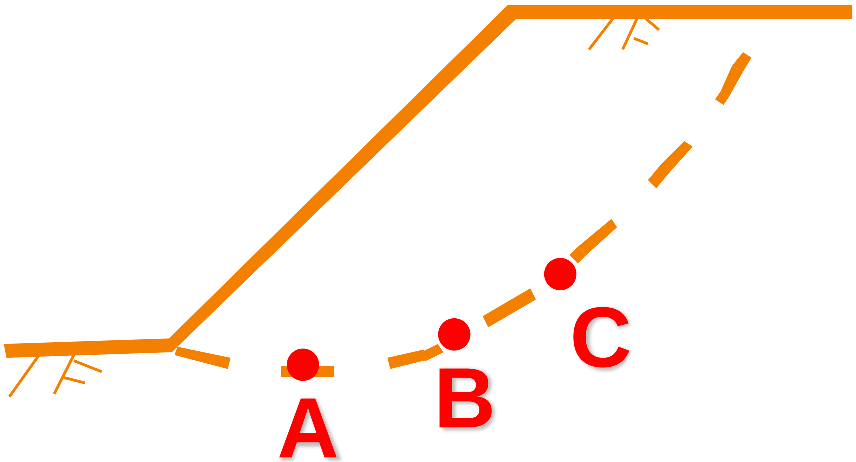


Progressive Failure

Necessary Conditions:

- Brittle behaviour
- Non-uniform distribution of shear stress
- Local failure

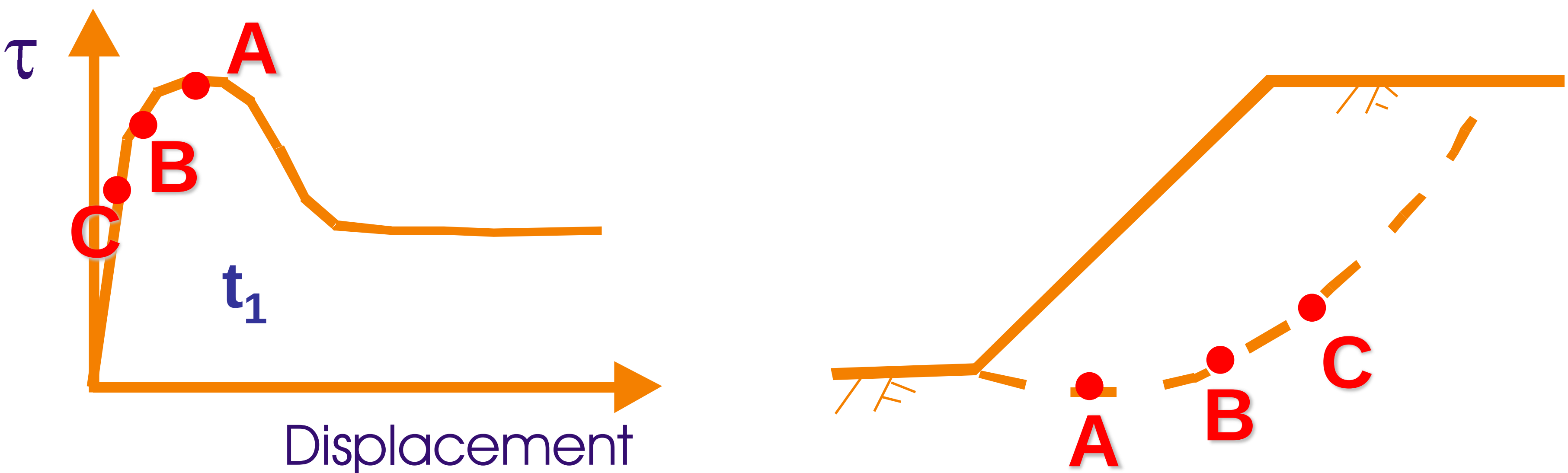




Progressive Failure

<u>Necessary Conditions</u>:

- Brittle behaviour
- Non-uniform distribution of shear stress
- Local failure
- Boundary conditions that “allow” the development of large strains



Geotechnical Classification of Landslides

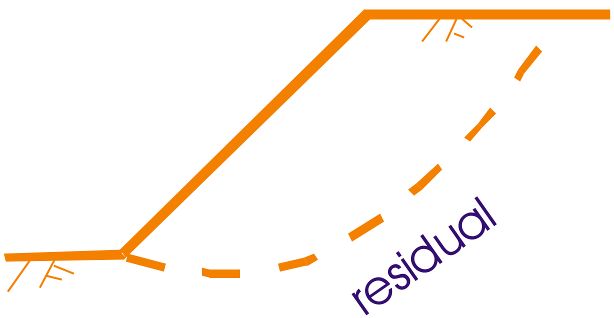
- “First time slides”
- Slides on Pre-existing Shears

Examples:

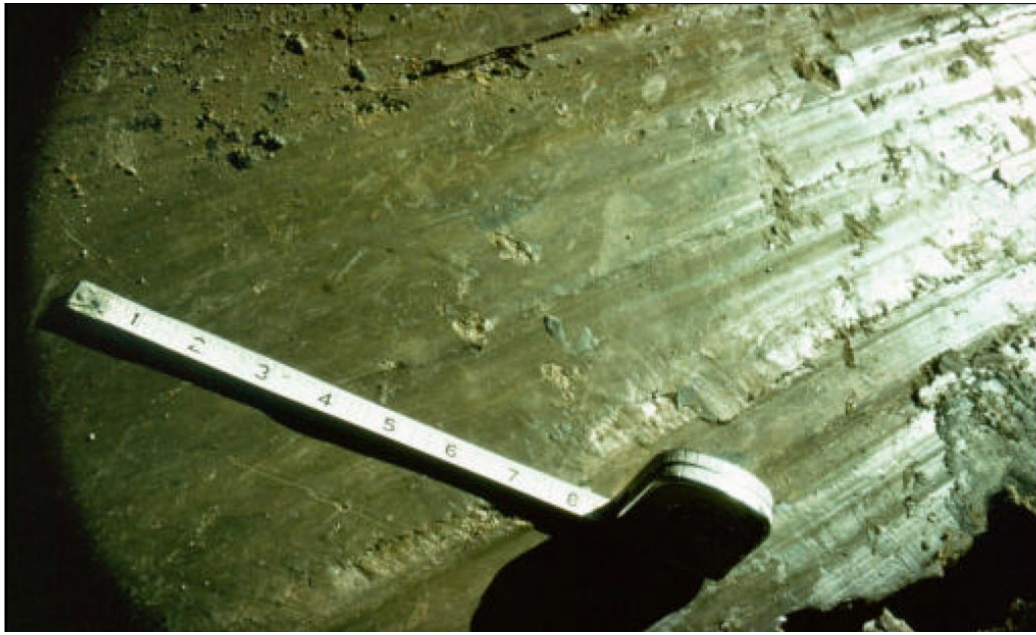
- Existing landslides
- Solifluction slides
- Shear surfaces induced by tectonics
- Shearing due to stress relief

Geotechnical Classification of Landslides

- "First time slides"
- Slides on Pre-existing Shears



Usually involve
RESIDUAL strength



Shear surface exposed in a trial pit
From Bromhead (1992)

Pore Water Pressure Conditions

- Short-term failures ⟺ Undrained Behaviour

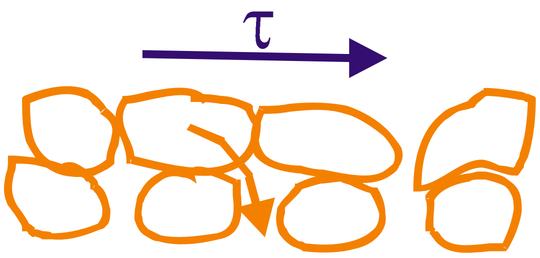
$\Delta u = \Delta u(p) + \Delta u(q)$

$\Delta u(p)$ change in u arising as a change in mean total stress p

$\Delta u(q)$ change in u arising as a change in deviator (shear) stress q

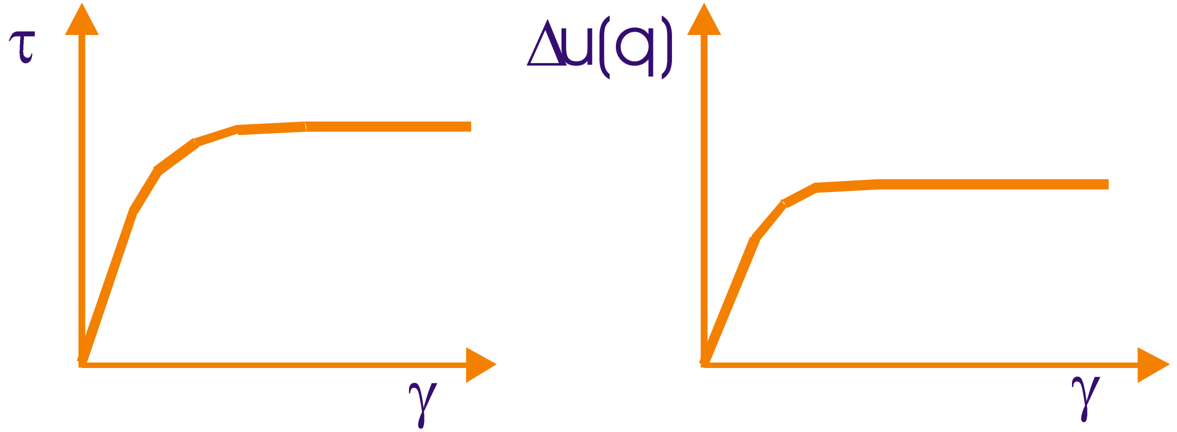
Pore Water Pressure Conditions

➢ Short-term failures ⟺ Undrained Behaviour



Loose packing

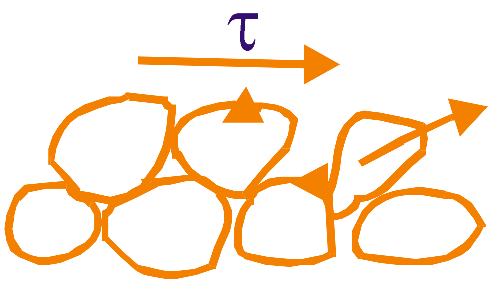
Initial grain packing collapses resulting in compressive (+)ve values of Δu(q)



Loose sand / Lightly overconsolidated clay

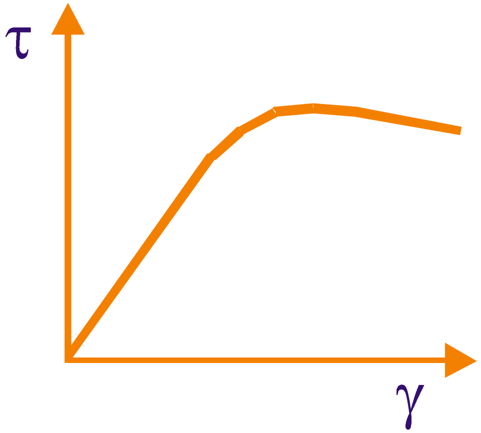
Pore Water Pressure Conditions

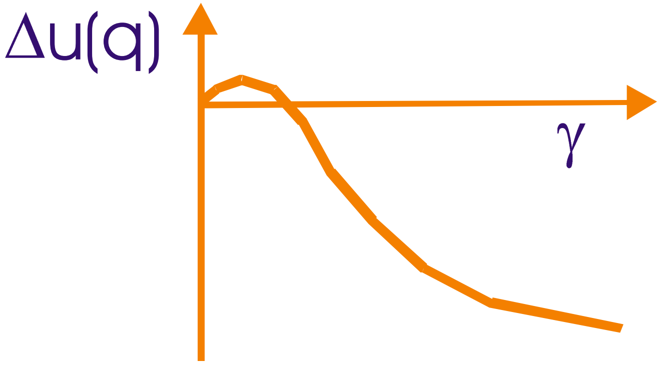
➢Short-term failures ⟺ Undrained Behaviour



Particles ride over one another resulting in tensile (-) ve values of Δu(q)

Dense packing





Dense sand / Heavily overconsolidated clay

Pore Water Pressure Conditions

- Short-term failures ⟺ Undrained Behaviour

Criteria for undrained behaviour:

- Soil is saturated
- Low permeability
- Long drainage path

Design

- Not easy to predict Δu, so effective stress analysis not attempted
- Total stress analysis, with $\tau_f = S_u$ - where S_u is the undrained strength prior to construction/excavation

Pore Water Pressure Conditions

- Short-term failures
- Long-term failures
  - All excess pwp dissipated
  - Pwp in equilibrium with hydraulic boundary conditions and therefore they can be calculated either from hydrostatic water levels or steady seepage analyses
  - Effective stress analysis is possible

Pore Water Pressure Conditions

- Short-term failures
- Long-term failures
- Intermediate-term failures

How long does it take to reach pore pressure equilibrium????

It depends!!

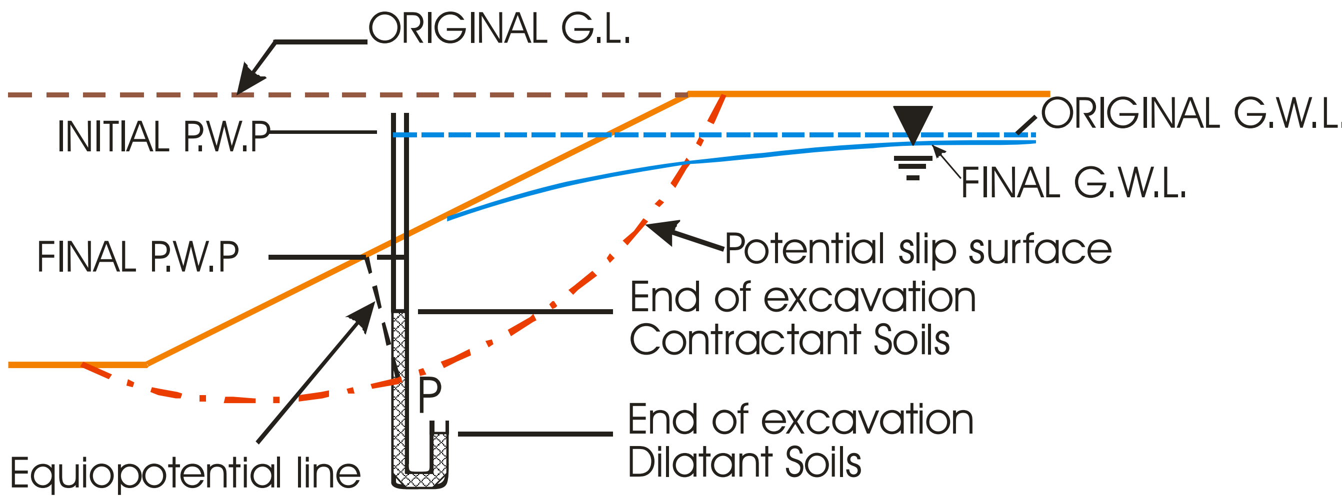
e.g.

- 10 days in Bangkok clay for 4m excavation depth
- 1 month in Mexico city clay for 4.5-8m excavation depth
- London Clay: ~ 50 years for 6-12m deep cuts
  ~ 2000 years for 44m high cliffs at Warden Point

Pore Water Pressure Conditions

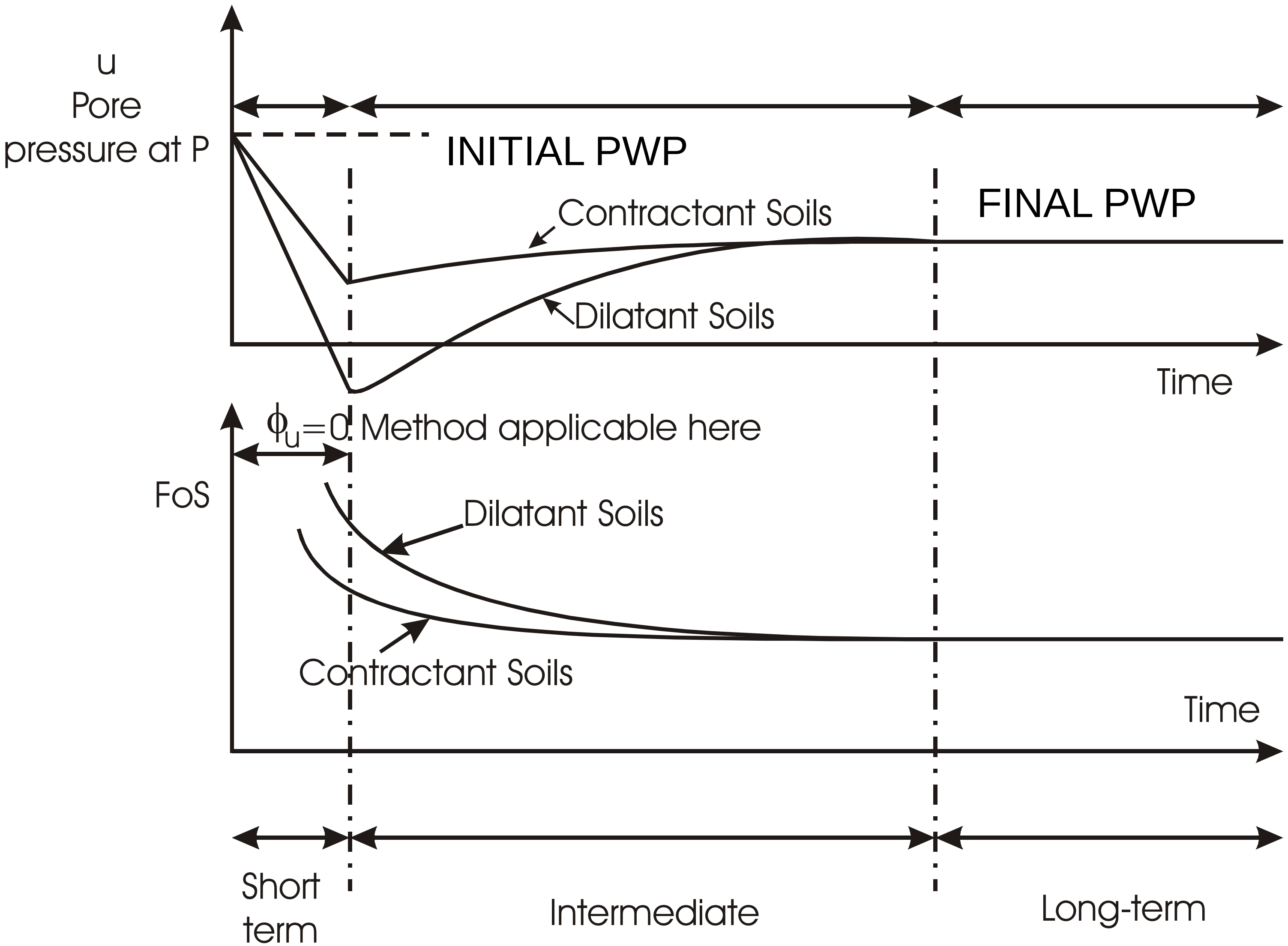
- Short-term failures
- Long-term failures
- Intermediate-term failures
  - Difficult to determine pwp during this transitional period and therefore not easy to carry out effective stress analysis
  - Some dissipation of excess pwp would have occurred - undrained strengths will have changed. It is difficult to calculate these changes and hence to carry out a total stress analysis
  - Pore pressure distribution during this transition period can only be calculated using advanced numerical analyses

Examples: Excavation

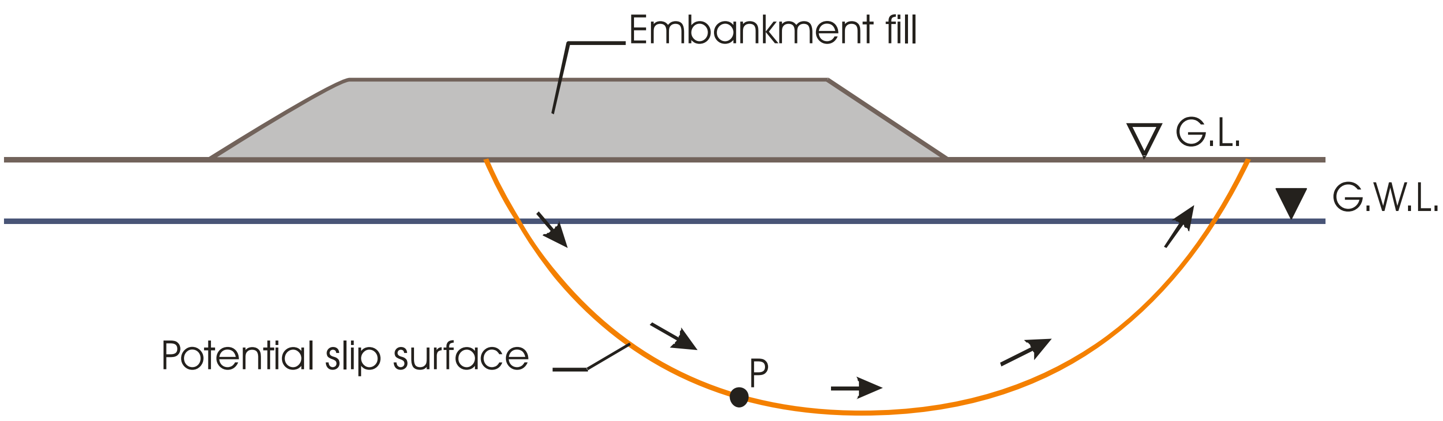


Reduction in mean stress	**Δu(p) is -ve**
For dilatant soils	**Δu(q) is -ve**
For contractant soils	**Δu(q) is +ve**
Clearly for dilatant soils	**Δu is -ve**

Examples: Excavation

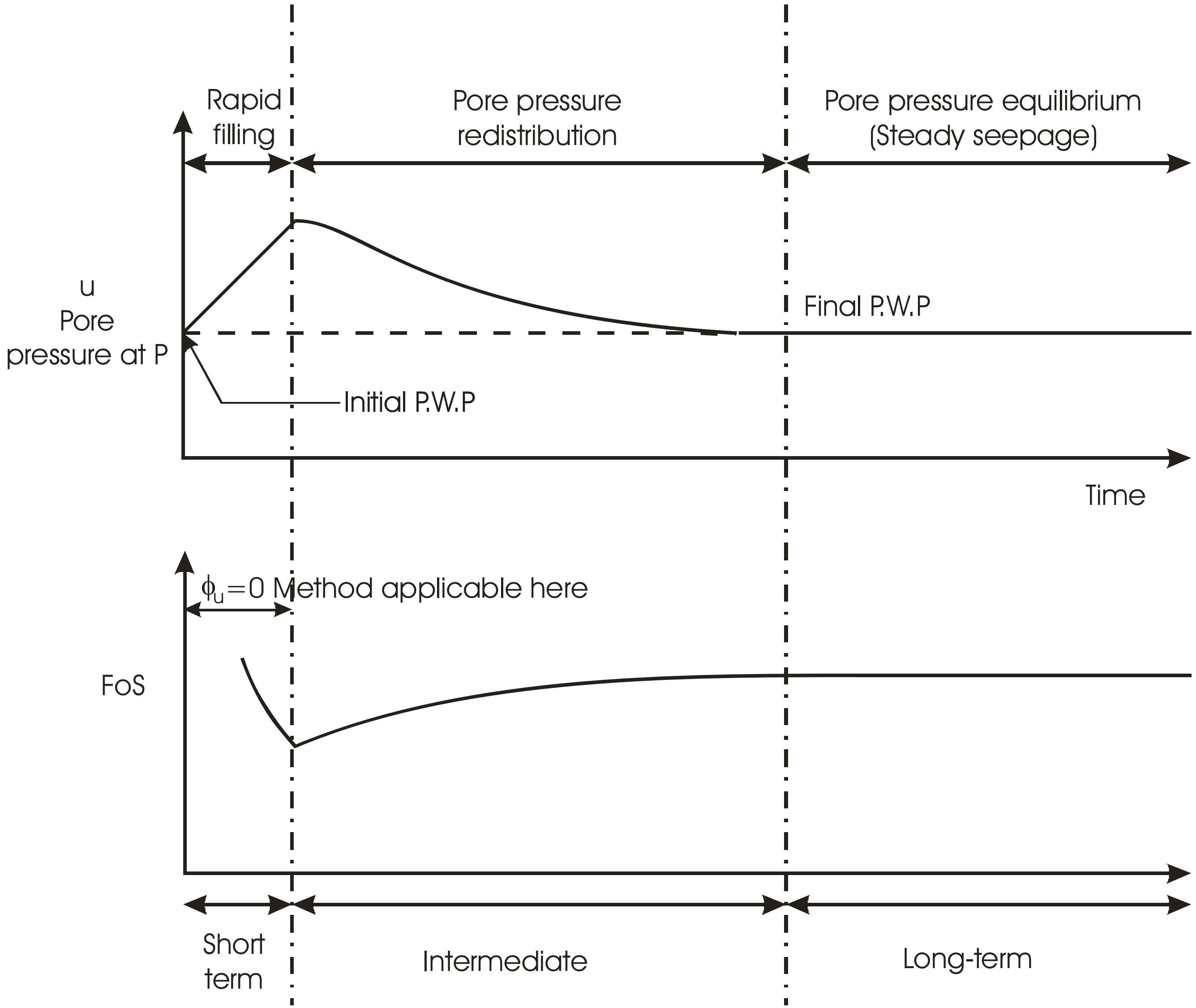


Examples: Embankment

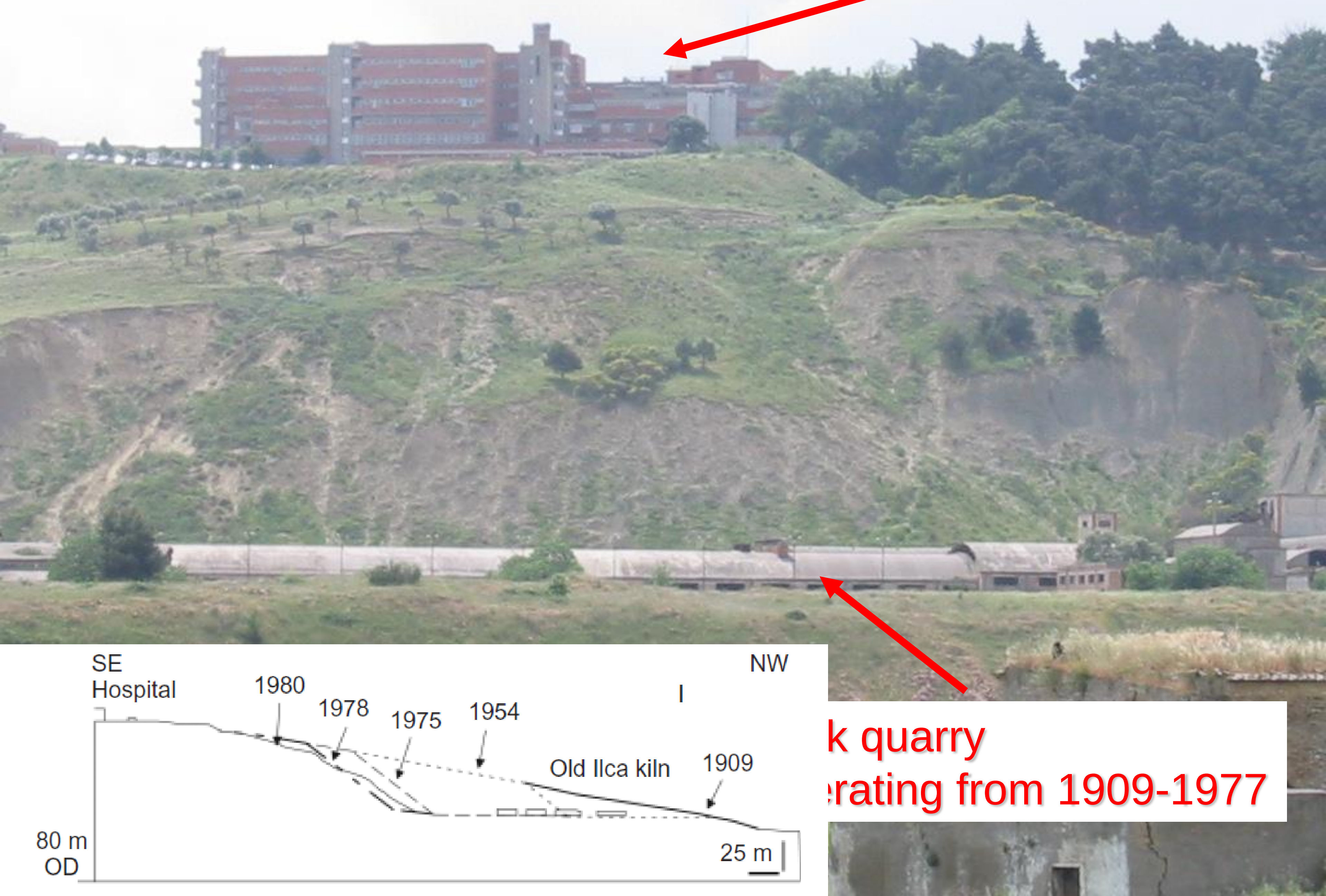


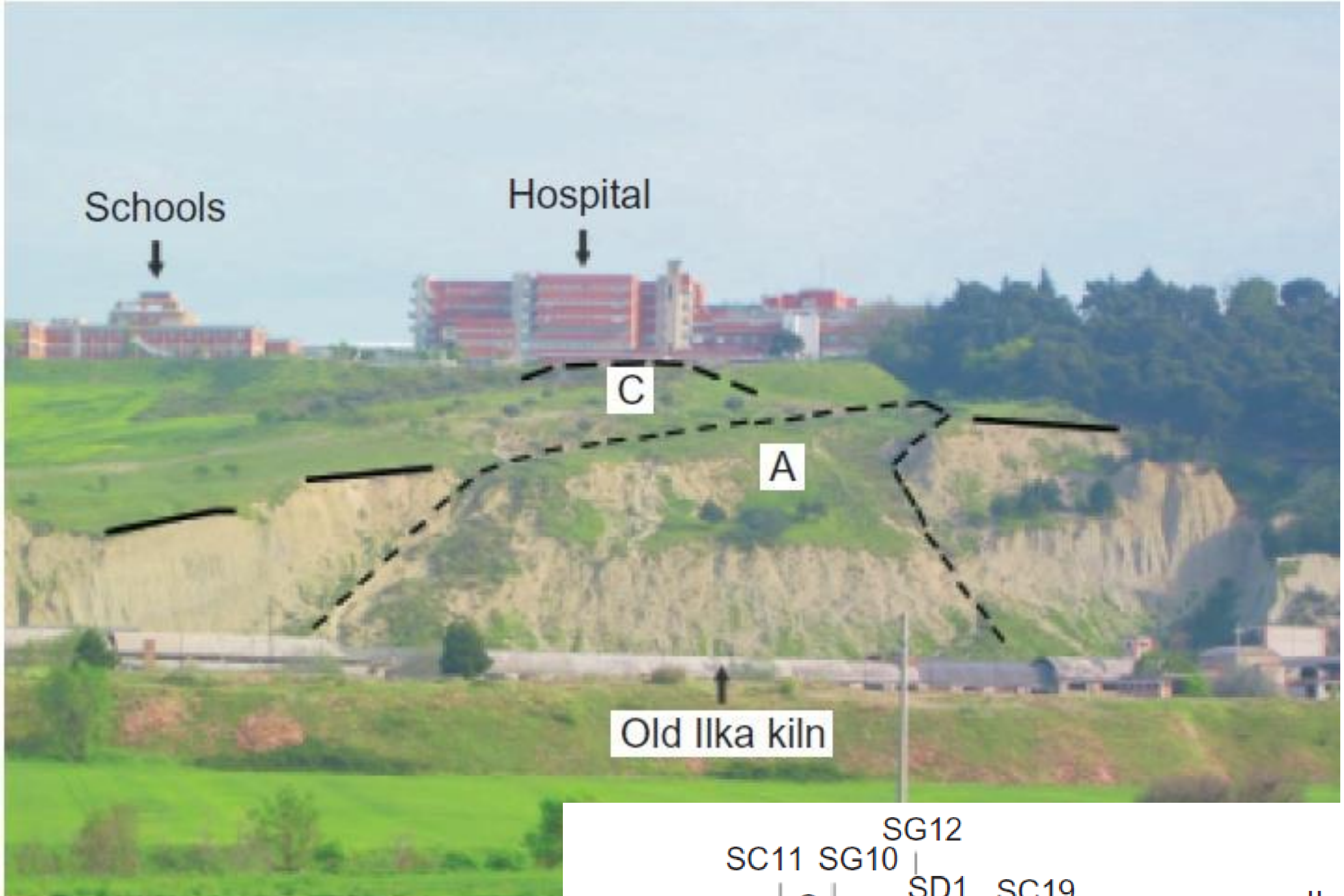
Increase in mean stress	**Δu(p) is +ve**
For dilatant soils	**Δu(q) is -ve**
For contractant soils	**Δu(q) is +ve**
Clearly for contractant soils	**Δu is +ve**

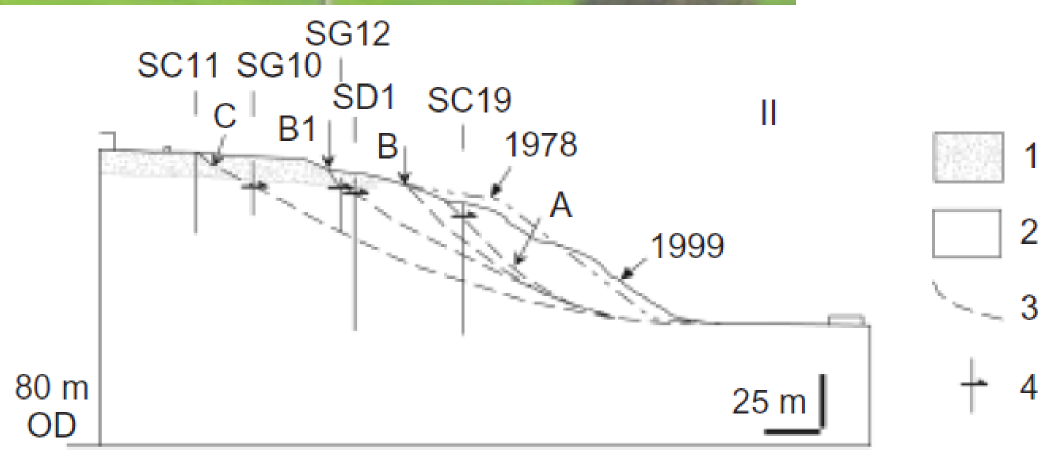
Examples: Embankment



Lucera landslide, Italy







Lollino et al 2011

Retrogression of the rear scrap reached the parking area of the hospital in 1998

Stiff, Highly O-C Clay

Learning Objectives

1. Appreciate the differences between “first time” and reactivation slides, understanding what soil strength is associated with “first time” slides and what with slides which occur on pre-existing shear surfaces.
2. Understand the concept of progressive failure.
3. Distinguish between short term, intermediate term and long term failures.
4. Understand how the pore water pressures in the soil below a cut slope are likely to change with time during excavation and subsequently.
5. Understand how the pore water pressures in a clay foundation beneath an embankment are likely to change with time during construction and subsequently