V. Favero (2017)

Geomechanics

LECTURE 2

BASIC CONCEPTS, STRESS PATHS AND STRESS-STRAIN BEHAVIOUR

DR. ALESSIO FERRARI

Laboratory of soil mechanics – Fall 2024

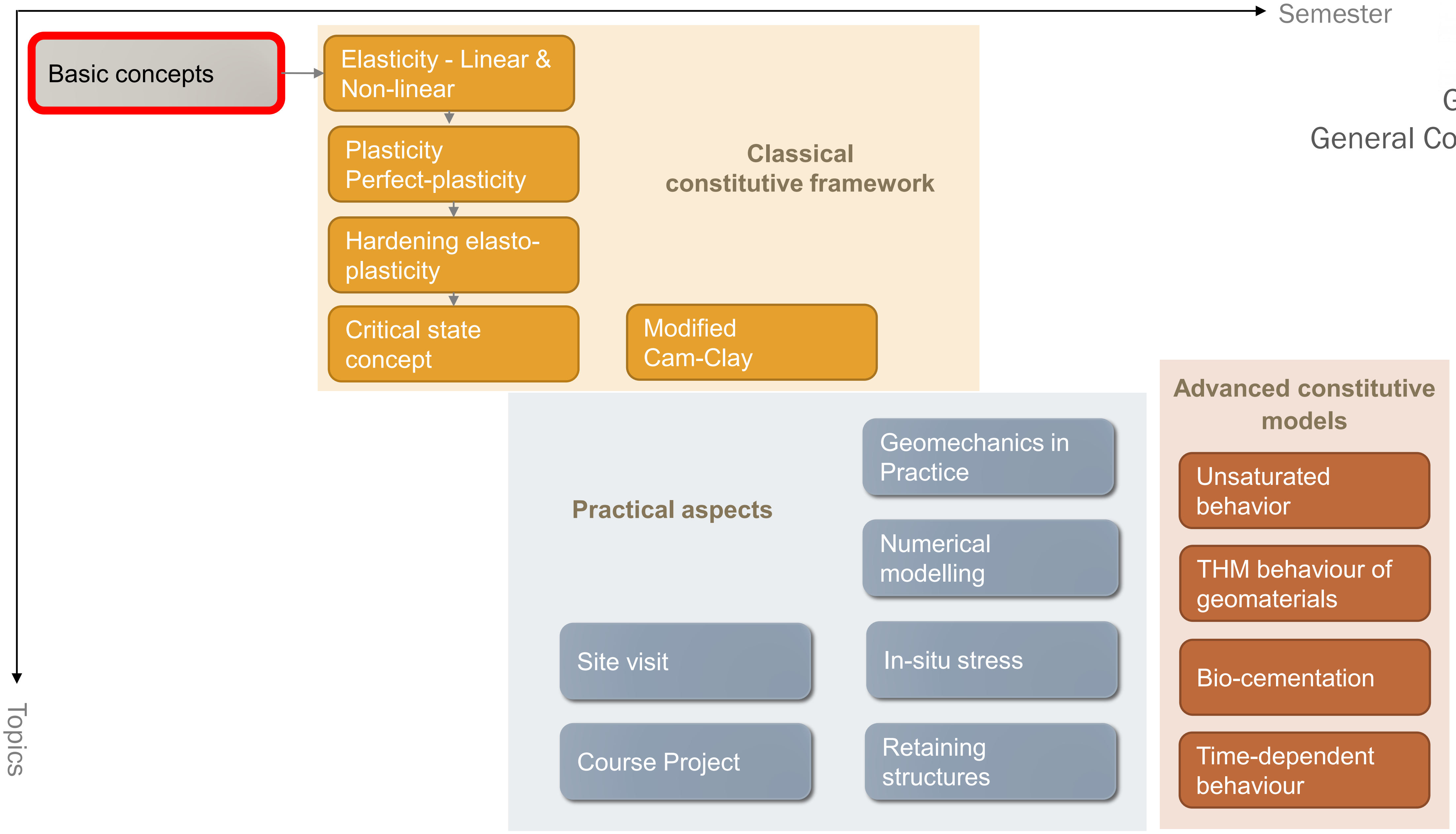
09.09.2024

How much do you remember from soil mechanics?

Access the QUIZZ

https://etc.ch/Hone

Geomechanics
General Course overview



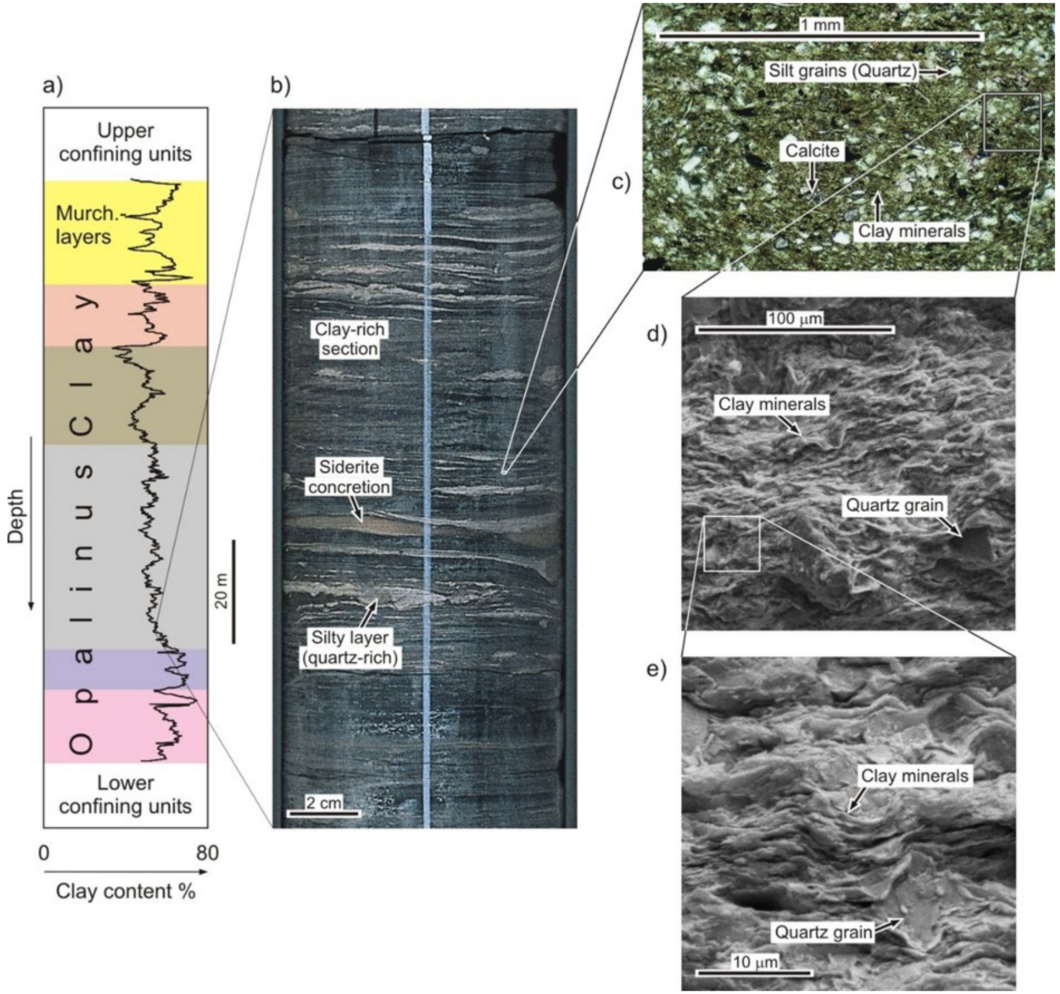
Content

- Basic concepts of continuum mechanics: REV
- Stress and strain tensors, effective stress concept
- Stress paths
- Laboratory testing: Triaxial tests

Basic concepts of continuum mechanics

REV: REPRESENTATIVE ELEMENTARY VOLUME

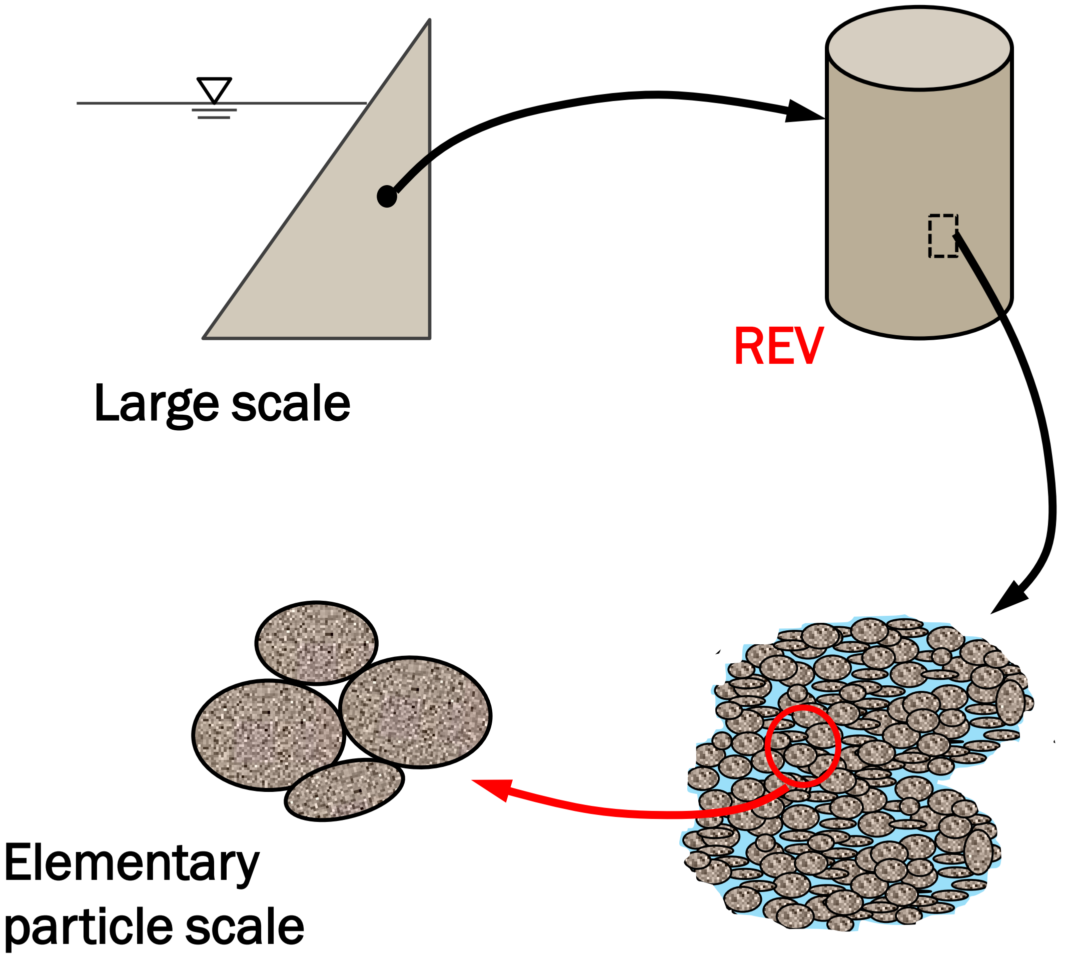
Basic concepts of Continuum mechanics



Opalinus Clay at different scales (Nagra 2002b)

- **Heterogeneity** of porous media at different scales
- Interpretation of the mechanics of porous media at **macroscopic scale**
- **REV: Representative Elementary Volume**
  - Smallest volume over which the value measured of a certain property is considered as representative of the whole

Basic concepts of Continuum mechanics



- Macroscopic homogeneity

  vs.

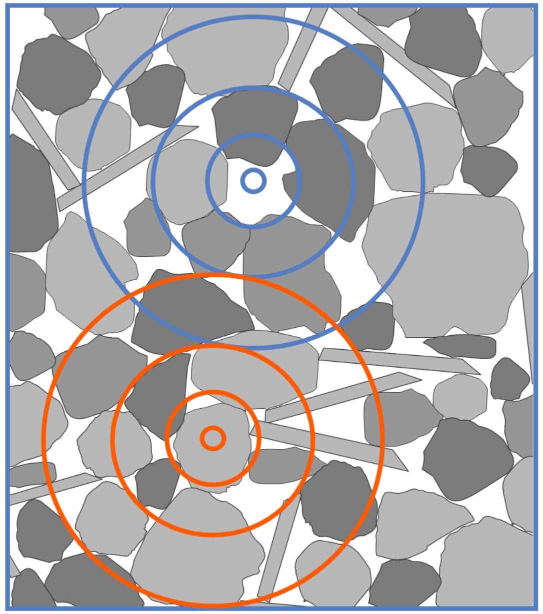
  Microscopic heterogeneity

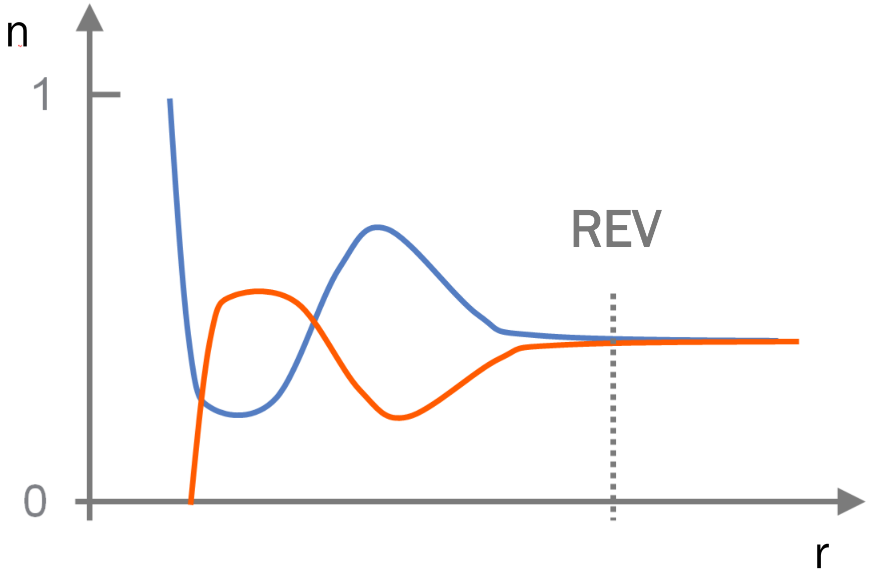
- REV: **R**epresentative **E**lementary **V**olume

  Sample dimensions **>** 10 x largest particles

Basic concepts of Continuum mechanics

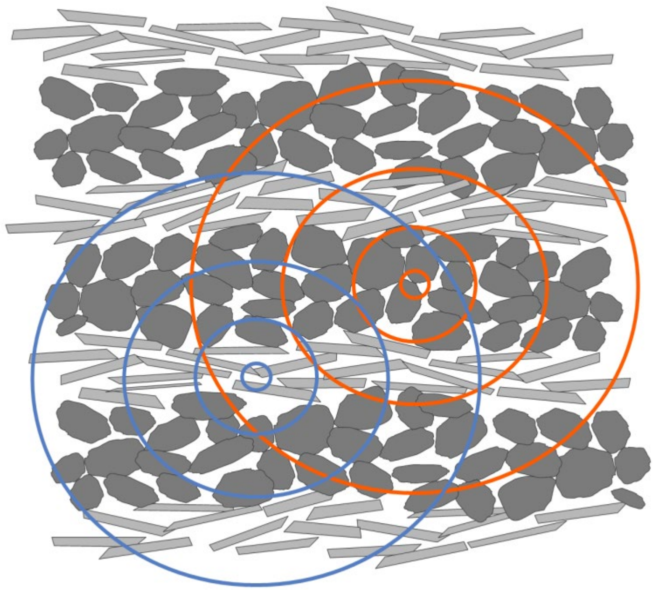
- Microscopic heterogeneity is neglected in the Representative Elementary Volume (REV)
- Size of REV depends on the material and on the considered problem.

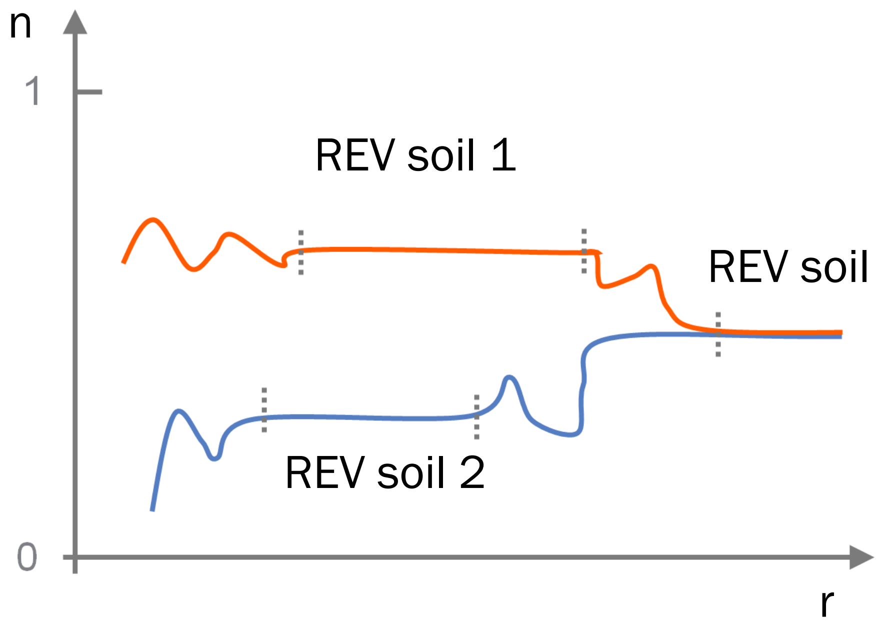




Basic concepts of Continuum mechanics

- REV allows to use Continuum Mechanics for geomaterials
- Geomechanical properties (stiffness, strength, permeability, ...) depend on the REV size.



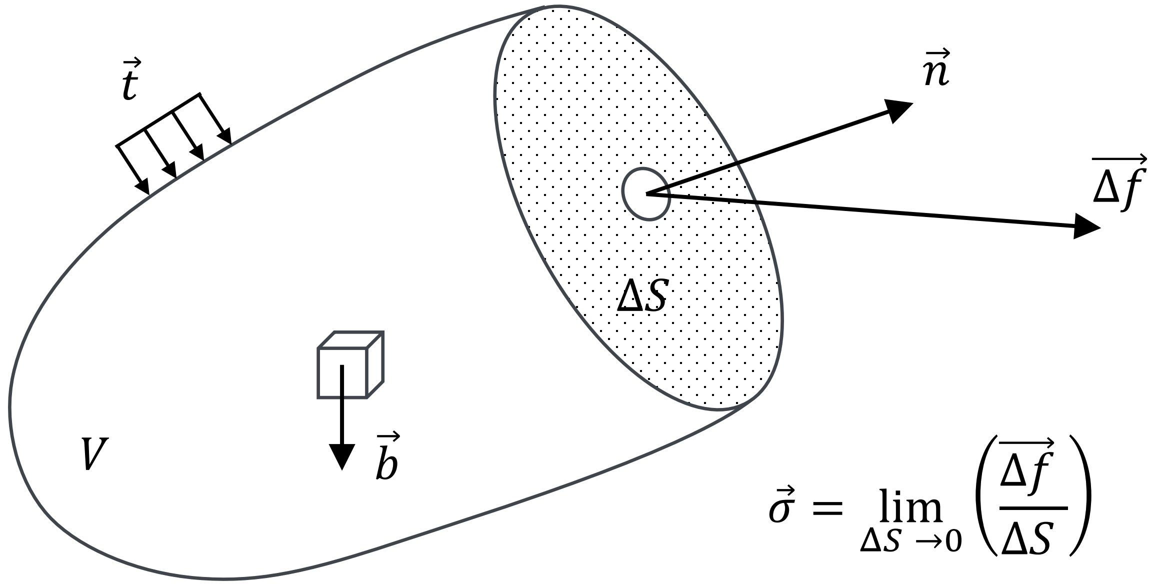


Stress and strain tensors

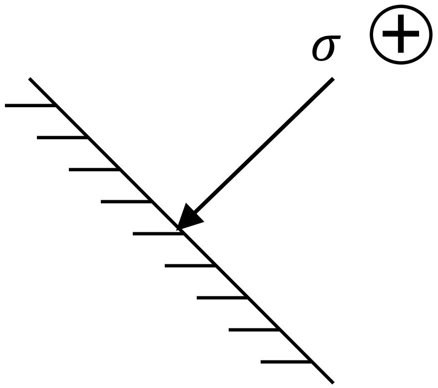
STRESS AND STRAIN VARIABLES, INVARIANTS AND TENSORS

EFFECTIVE STRESS CONCEPT

Stress



$$\vec{\sigma} = \lim_{\Delta S \to 0}\left(\frac{\overrightarrow{\Delta f}}{\Delta S}\right)$$



Sign convention: Compressive stress is positive

Tensor definitions

- **Tensor:** mathematical entities in the form of ordered arrays or matrices.

- Tensor of rank n in a m dimensional space has m^n components.

- Here, we are dealing with Cartesian coordinates therefore m=3
  - Tensors of zero rank: Scalars 1 component
  - Tensors of first rank: Vectors 3 components
  - Tensors of second rank: 9 components

- Among other uses, tensors of second rank serve to describe properties of materials that differ from one direction to another, called anisotropic.

- **Invariant of a Tensor** is a quantity that does not change with coordinate system.

Stress tensor

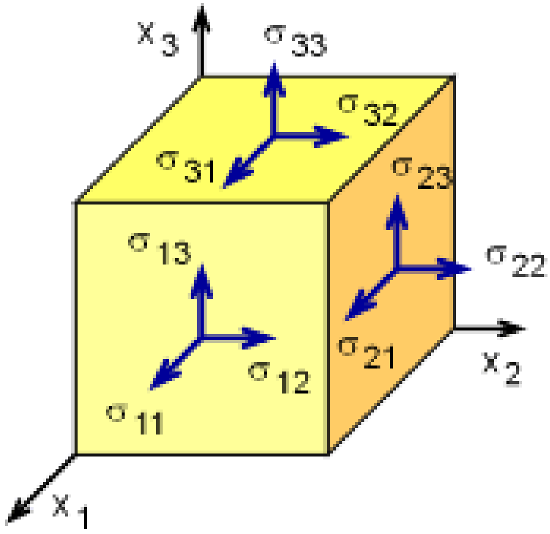
- Stress tensor is a second order tensor with a matrix representation

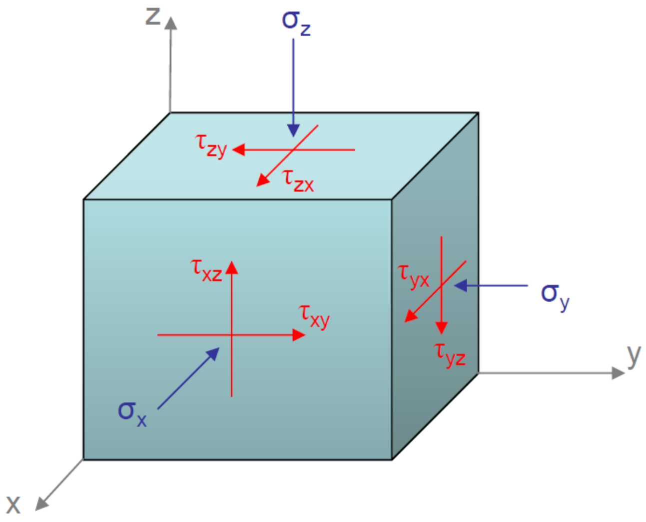
$$[\sigma]=\begin{bmatrix}\sigma_{11} & \sigma_{12} & \sigma_{13}\\ \sigma_{21} & \sigma_{22} & \sigma_{23}\\ \sigma_{31} & \sigma_{23} & \sigma_{33}\end{bmatrix}=\begin{bmatrix}\sigma_{x} & \tau_{xy} & \tau_{xz}\\ \tau_{yx} & \sigma_{y} & \tau_{yz}\\ \tau_{zx} & \tau_{zy} & \sigma_{z}\end{bmatrix}$$

σ_{ij} : Stress on i plane along j direction

Direction of stress component

Direction of the surface normal upon which the stress acts





Stress tensor

- Stress tensor is **symmetric** due to balance of angular momentum.

$$\sigma_{ij} = \sigma_{ji}$$

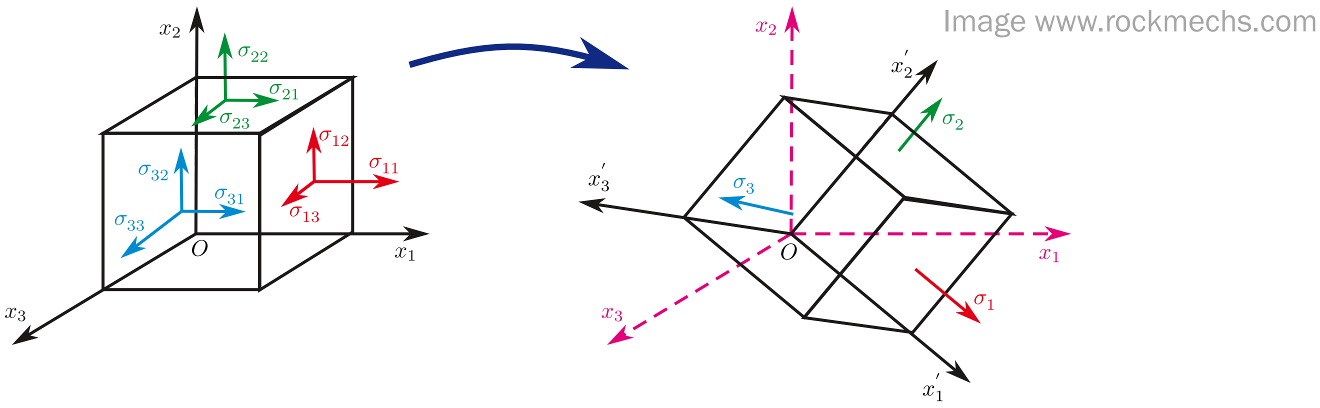
- The diagonal stresses are referred to as the ***normal stresses*** whereas the off-diagonal stresses are referred to as the ***shear stresses***

$$[\sigma] = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ & \sigma_{22} & \sigma_{23} \\ (\text{sym}) & & \sigma_{33} \end{bmatrix} = \begin{bmatrix} \sigma_{x} & \tau_{xy} & \tau_{xz} \\ & \sigma_{y} & \tau_{yz} \\ (\text{sym}) & & \sigma_{z} \end{bmatrix}$$

Principal stresses

- For a given stress tensor, there is a set of planes on which the stress vectors are normal to them. On these planes, the shear stresses are zero. These are principal planes and stresses normal to them are **principal stresses**.

$$[\sigma] = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix}$$

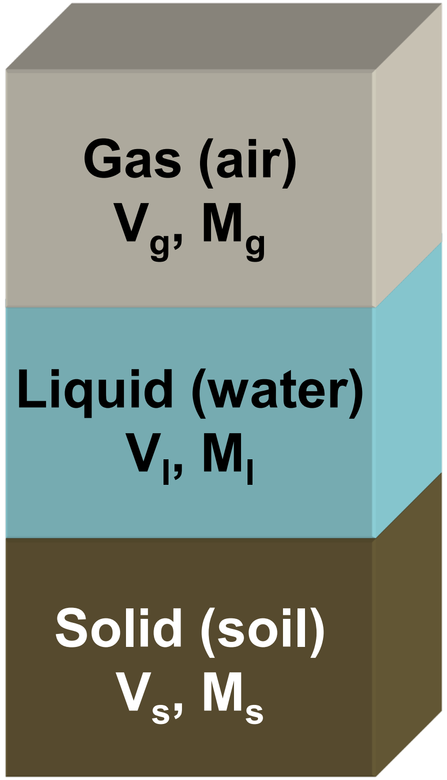


- It can be shown that the three principal stresses are the characteristic values of stress tensor obtained from **characteristic equation**:

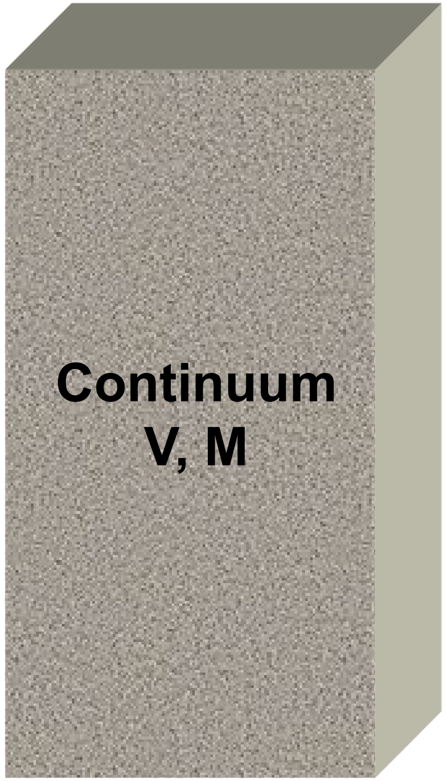
$$\begin{vmatrix} \sigma_{11} - \lambda & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & \sigma_{22} - \lambda & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} - \lambda \end{vmatrix} = 0$$

The effective stress concept

- The REV includes a **solid**, a **liquid** and a **gas** phase

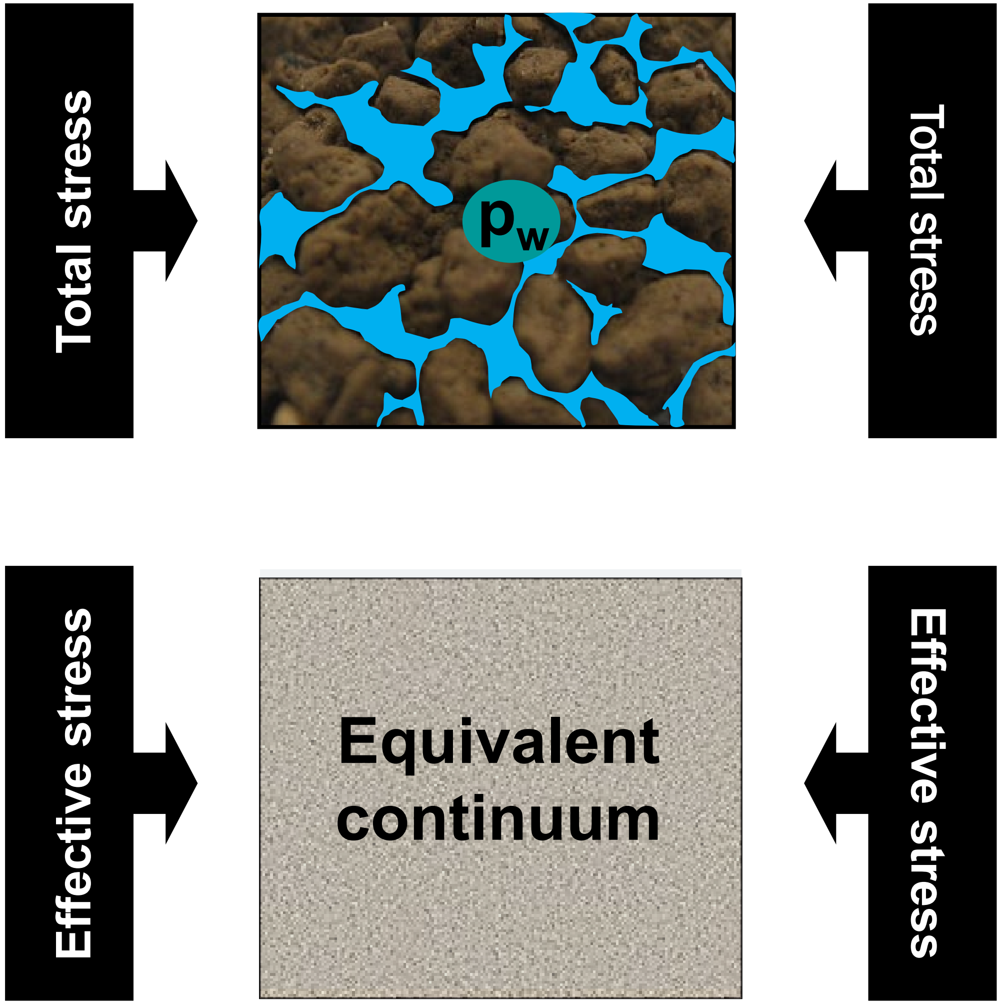


Multi-phase description



Single-phase description

Effective stress for saturated media



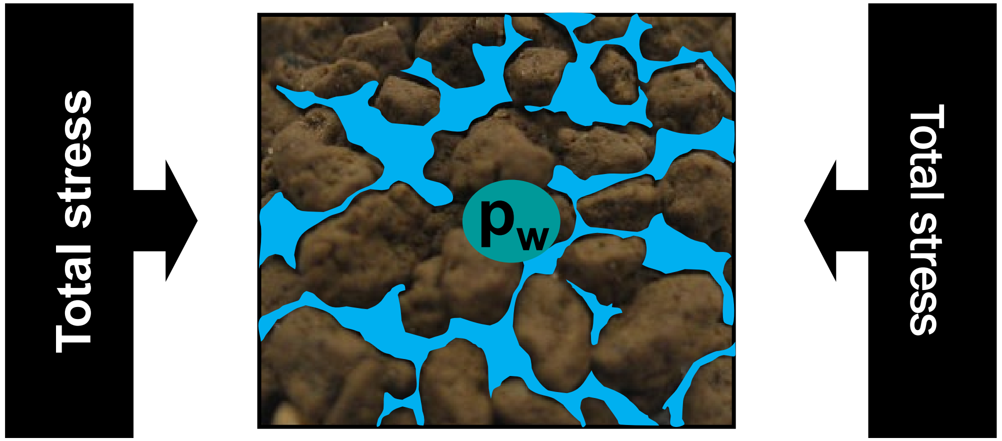
- **Terzaghi's effective stress** (1936)

$$\sigma'_{ij} = \underbrace{\sigma_{ij}}_{\text{Total stress}} - \underbrace{p_w \delta_{ij}}_{\text{Pore water pressure}}$$

- **Assumptions**
  - ➢ Fully saturated granular material
  - ➢ Incompressible fluid and grains

- **All measurable effects produced by a change in the state of stress are due to a change in the effective stress** (Terzaghi, 1936)

Effective stress for saturated media



- **Extended effective stress**

$$\sigma'_{ij} = \sigma_{ij} - \alpha\, p_w \delta_{ij}$$

$$\alpha = 1 - \frac{K_{SK}}{K_S}$$ Biot's coefficient

$\boldsymbol{K_{SK}}$: bulk modulus of the dry material

$\boldsymbol{K_S}$: bulk modulus of the solid particles

Soils: $\boldsymbol{K_{SK}} \ll \mathbf{K_S}$ and $\boldsymbol{\alpha = 1}$

- **Terzaghi's effective stress** (1936)

$$\boxed{\sigma'_{ij} = \sigma_{ij} - p_w \delta_{ij}}$$

Tensorial form of effective stress

- Terzaghi's effective stress: $\sigma' = \sigma - p_w$
- And in tensorial form $\sigma'_{ij} = \sigma_{ij} - p_w \delta_{ij}$

Kronecker Delta $\delta_{ij} = \begin{cases} 0 & i \neq j \\ 1 & i = j \end{cases}$

$$\begin{bmatrix} \sigma'_{11} & \sigma'_{12} & \sigma'_{13} \\ \sigma'_{12} & \sigma'_{22} & \sigma'_{23} \\ \sigma'_{13} & \sigma'_{23} & \sigma'_{33} \end{bmatrix} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & \sigma_{22} & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} \end{bmatrix} - \begin{bmatrix} p_w & 0 & 0 \\ 0 & p_w & 0 \\ 0 & 0 & p_w \end{bmatrix}$$

Stress variables

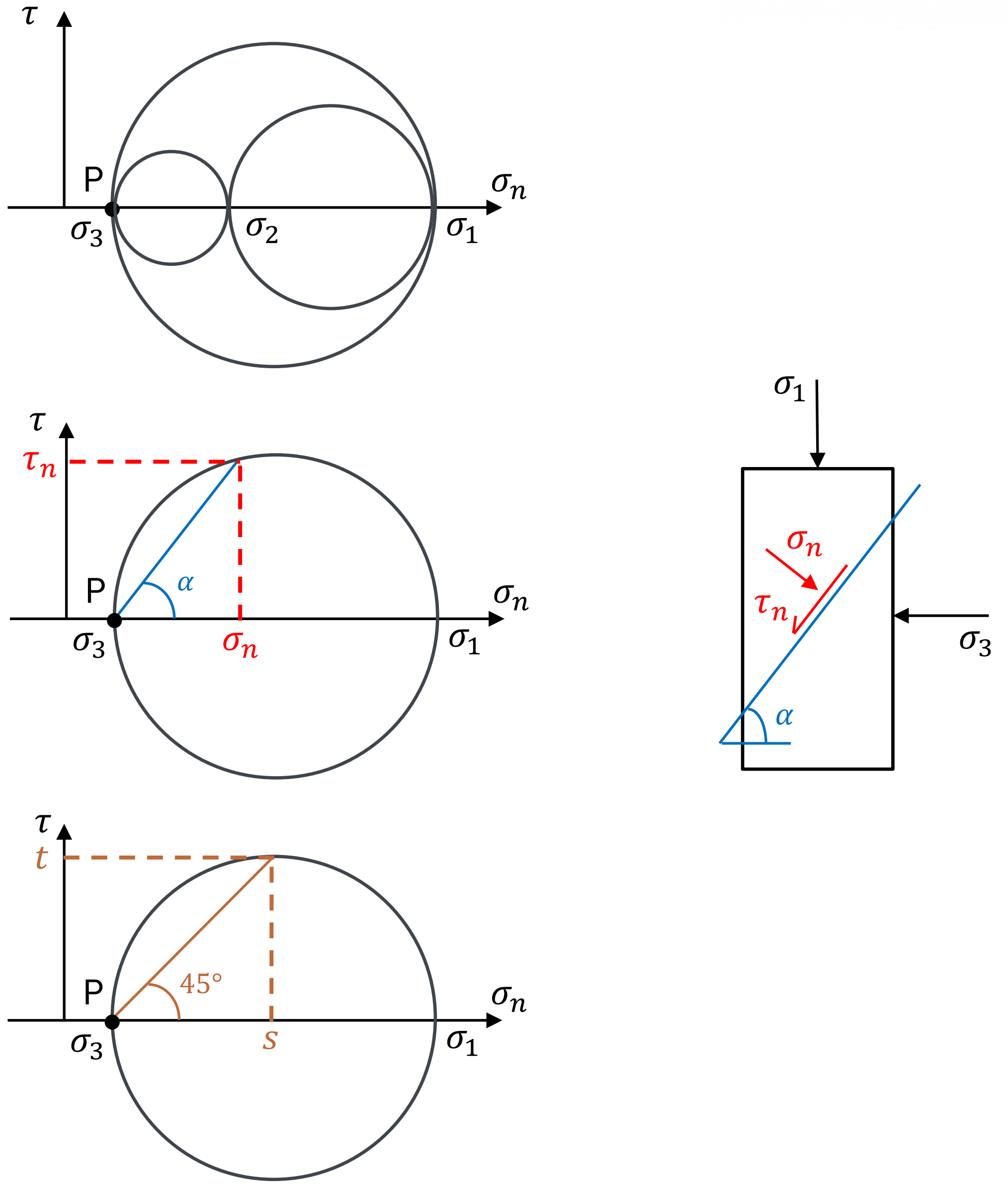
Mean total stress $p = \frac{\sigma_1+\sigma_2+\sigma_3}{3}$

Mean effective stress $p' = \frac{\sigma_1'+\sigma_2'+\sigma_3'}{3}$

Deviatoric stress $q = \sigma_1 - \sigma_3$

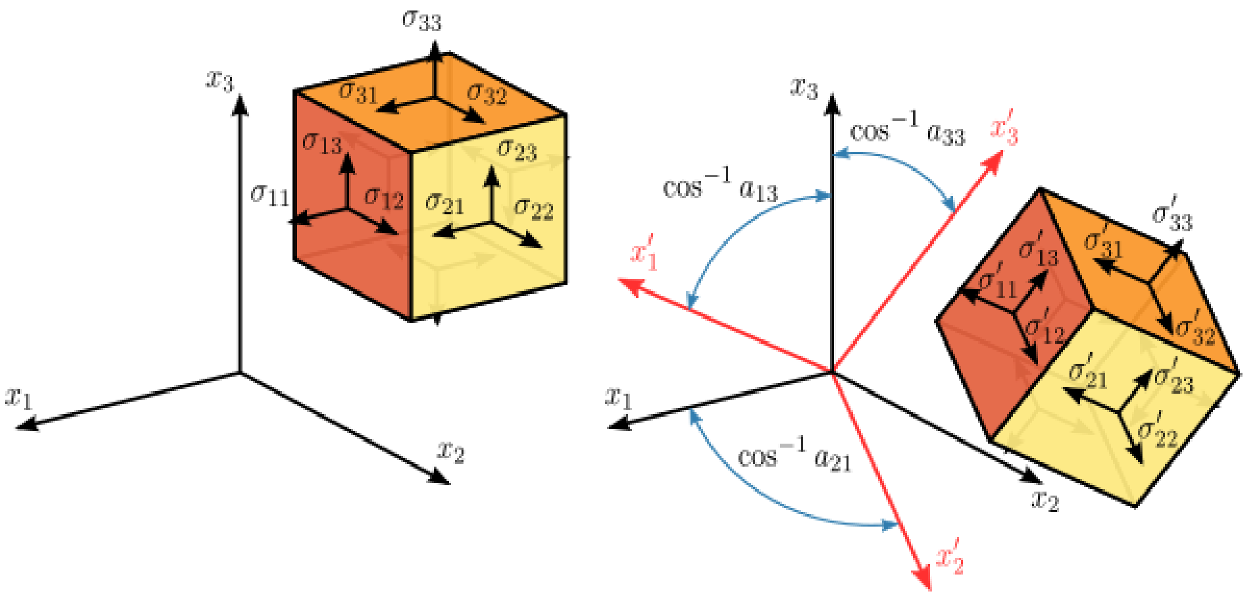
Mean stress $s = \frac{\sigma_1+\sigma_3}{2}$

Maximum shear stress $t = \frac{\sigma_1-\sigma_3}{2}$



Stress invariants

- The stress tensor matrix representation depends on the system of coordinates we choose, while the tensor itself does not change.
- When studying deformations, we typically change the system of coordinates.
- We need to find some functions of stress tensor that do not change with the choice of coordinate: invariants of stress tensor.



Stress invariants

- $\boldsymbol{J_1}$: First invariant of the principal stress tensor σ_{ij} (its trace)

$$J_1 = tr(\sigma_{ij}) = \sigma_1 + \sigma_2 + \sigma_3$$

- $\boldsymbol{J_{2D}}$: Second invariant of the deviatoric stress tensor s_{ij}

$$J_{2D} = \frac{1}{2} tr(s_{ij}^2) = \frac{1}{6}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2]$$

- $\boldsymbol{J_3}$: Third invariant of the principal stress tensor σ_{ij} (its determinant)

$$J_3 = det(\sigma_{ij}) = \sigma_1 \sigma_2 \sigma_3$$

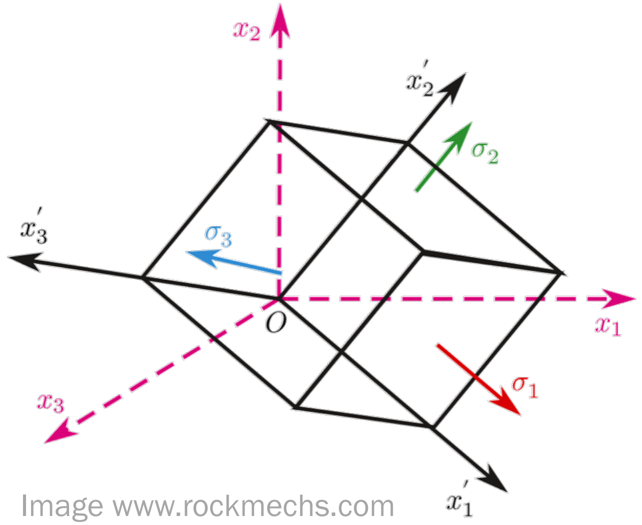


Image www.rockmechs.com

Isotropic stress tensor

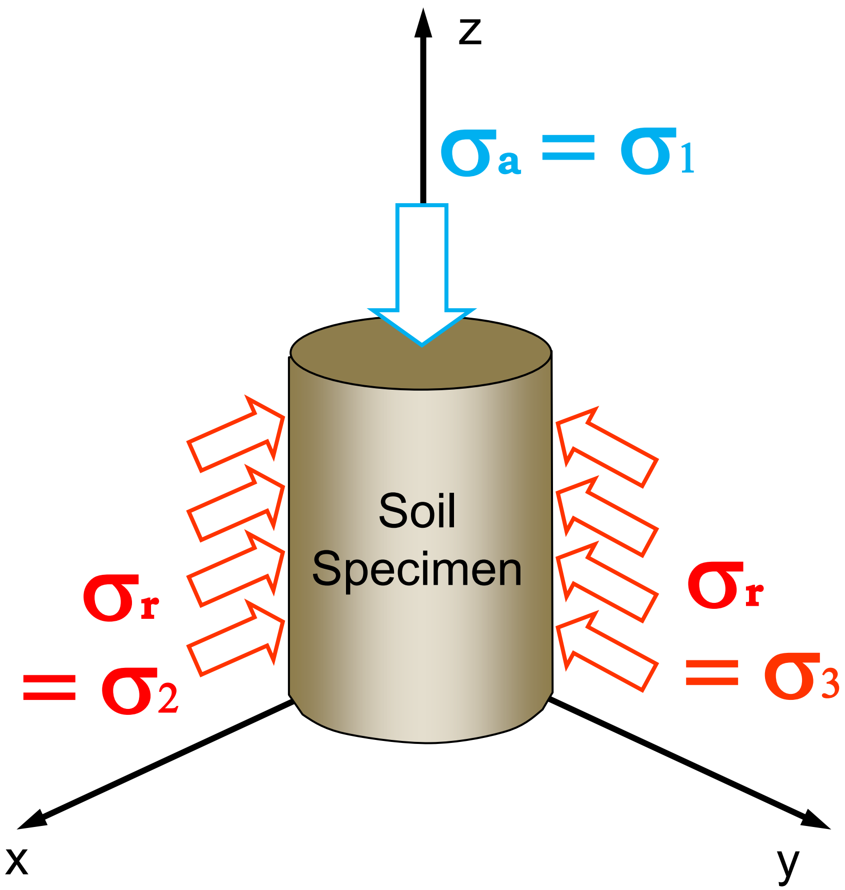
Deviatoric stress tensor

$$\sigma_{ij} = p\delta_{ij} + s_{ij}$$

$$p\,I = \begin{bmatrix} p & 0 & 0 \\ 0 & p & 0 \\ 0 & 0 & p \end{bmatrix}$$

$$s = \begin{bmatrix} \sigma_{11} - p & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} - p & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} - p \end{bmatrix}$$

Triaxial stress conditions



Cylindrical tested specimen: h/d=2

Applied stresses

σ_1: Maximum principal stress

σ_2: Intermediate principal stress

σ_3: Minimum principal stress

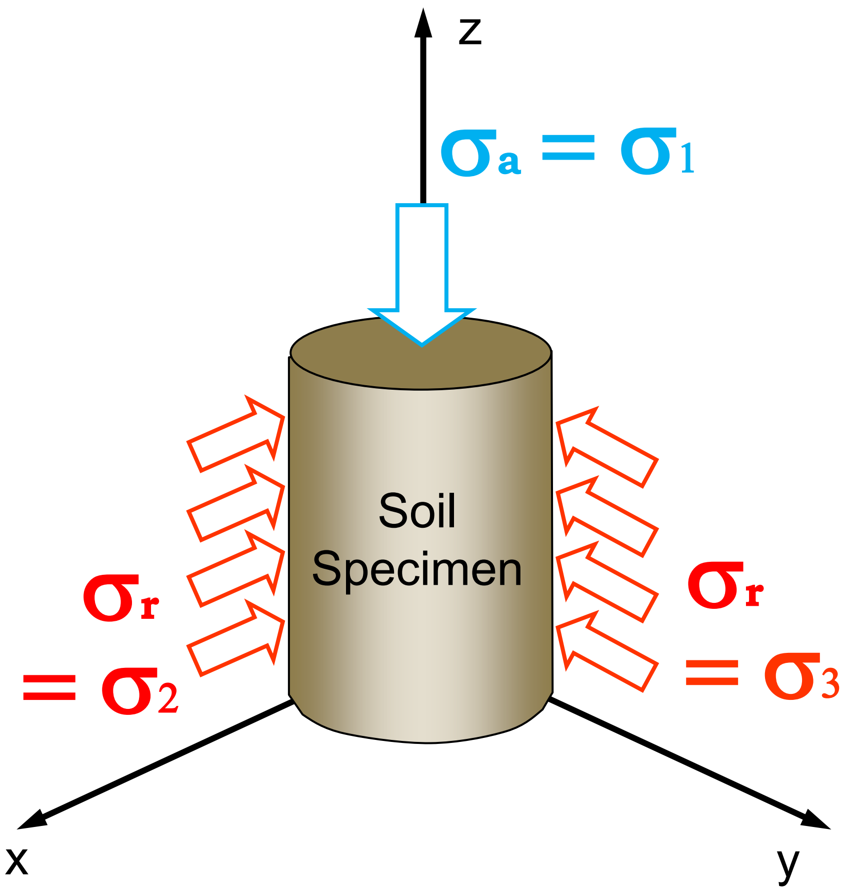
Axisymmetric conditions

$\sigma_1 = \sigma_a$ Axial stress

$\sigma_2 = \sigma_3 = \sigma_r$ Radial stress

(confining stress or cell pressure)

Triaxial stress conditions



Mean (total) stress

$$p = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} = \frac{\sigma_a + 2\sigma_r}{3} = \frac{J_1}{3}$$

Mean effective stress

$$p' = \frac{\sigma_1' + \sigma_2' + \sigma_3'}{3} = \frac{\sigma'_a + 2\sigma'_r}{3} = \frac{J_1'}{3}$$

Deviatoric stress:

$$q = \sigma_1 - \sigma_3 = \sigma_a - \sigma_r = \sqrt{3J_{2D}}$$

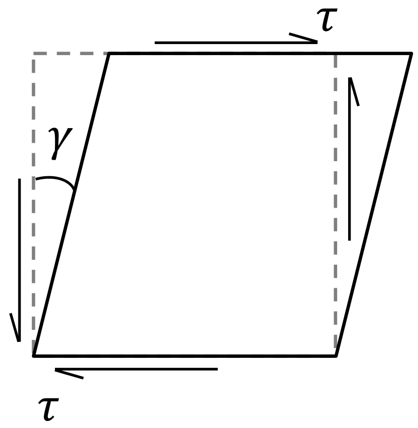
Maximum shear stress:

$$\tau = \frac{\sigma_a - \sigma_r}{2}$$

Strain tensor

- The strain tensor is a symmetric tensor used to quantify the strain of an object undergoing a small 3-dimensional deformation

  - Diagonal components: relative change in length in *i* direction
  - Other components: shear strains, i.e., half the variation of the right angle



$$\varepsilon_{ij} = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ & \varepsilon_{22} & \varepsilon_{23} \\ \text{(sym)} & & \varepsilon_{33} \end{bmatrix} = \begin{bmatrix} \varepsilon_x & \frac{1}{2}\cdot\gamma_{xy} & \frac{1}{2}\cdot\gamma_{xz} \\ & \varepsilon_y & \frac{1}{2}\cdot\gamma_{yz} \\ \text{(sym)} & & \varepsilon_z \end{bmatrix}$$

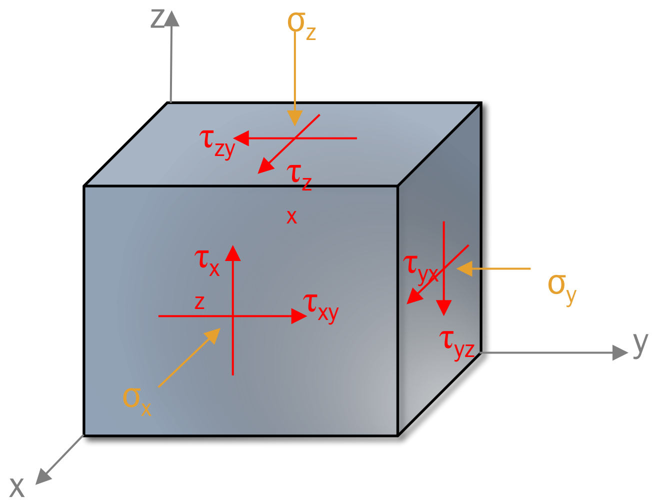
The strain variables and the sign convention

Strain variables

Volumetric strain $\varepsilon_v = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$

Sign convention in geomechanics

- **Compressive** forces and **compressive** stresses are **positive**



- **Compressive** strains are **positive**

$$\Delta L = L_f - L_i \qquad \varepsilon_i = -\frac{\Delta L}{L_i}$$

$$\Delta V = V_f - V_i \qquad \varepsilon_v = -\frac{\Delta V}{V_i}$$

Example:

$V_f < V_i$

$\Delta V = V_f - V_i < 0$ $\Rightarrow$ $\boxed{\varepsilon_v = -\frac{\Delta V}{V_i} > 0}$

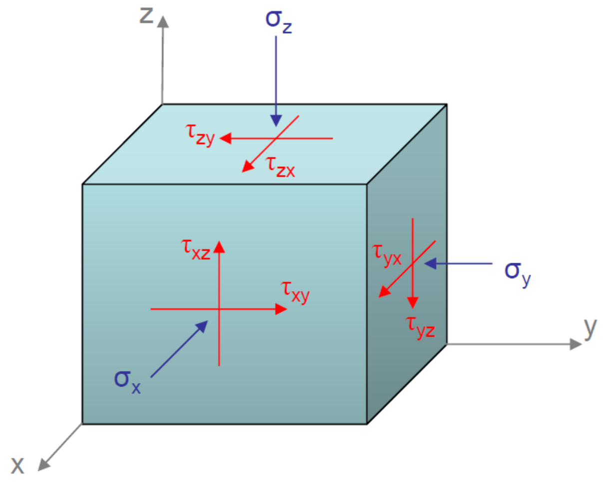
Stress-strain conjugate pairs

- Work input per unit volume of element

$$\delta W = \sigma'_{xx}\delta\varepsilon_{xx} + \sigma'_{yy}\delta\varepsilon_{yy} + \sigma'_{zz}\delta\varepsilon_{zz} + \tau_{yz}\delta\gamma_{yz} + \tau_{zx}\delta\gamma_{zx} + \tau_{xy}\delta\gamma_{xy}$$

- In term of principal stresses

$$\delta W = \sigma'_1\delta\varepsilon_1 + \sigma'_2\delta\varepsilon_2 + \sigma'_3\delta\varepsilon_3$$



- In term of triaxial stresses

$$\delta W = \sigma'_a\delta\varepsilon_a + 2\sigma'_r\delta\varepsilon_r$$

Triaxial stress-strain conjugate pairs

$$\delta W = \sigma'_a \delta\varepsilon_a + 2\sigma'_r \delta\varepsilon_r$$

$$\delta W = \underbrace{\delta W_v}_{\text{Change in volume}} + \underbrace{\delta W_q}_{\text{Change in shape}}$$

$$\Rightarrow \quad \delta W = p'\,\delta\varepsilon_v + q\,\delta\varepsilon_d$$

$$\Downarrow$$

$$\delta W = \frac{(\sigma'_a + 2\sigma'_r)(\delta\varepsilon_a + 2\delta\varepsilon_r)}{3} + \frac{(\sigma'_a - \sigma'_r)2(\delta\varepsilon_a - \delta\varepsilon_r)}{3}$$

Mean effective stress

$$p' = \frac{\sigma'_1 + \sigma'_2 + \sigma'_3}{3} = \frac{\sigma'_a + 2\sigma'_r}{3}$$

Volumetric strain:

$$\varepsilon_V = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 = \varepsilon_a + 2\varepsilon_r$$

Deviatoric stress:

$$q = q' = \sigma_1 - \sigma_3 = \sigma_a - \sigma_r$$

Deviatoric strain:

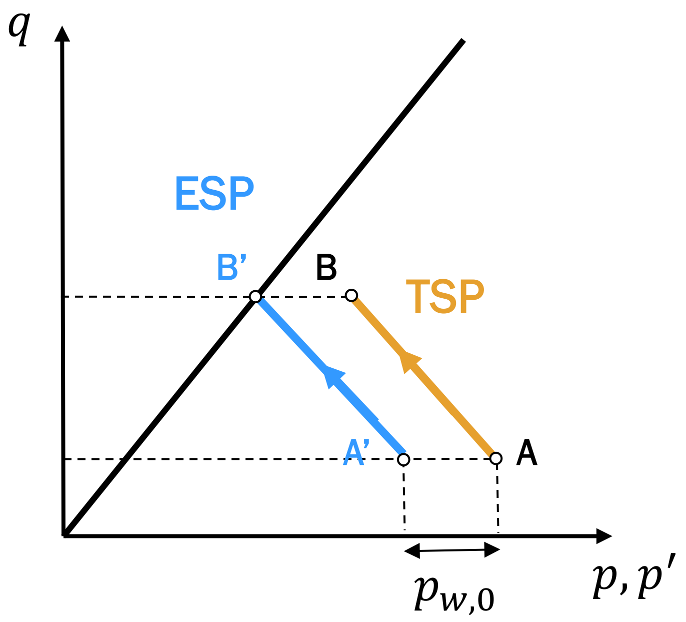
$$\varepsilon_d = \frac{2}{3}(\varepsilon_1 - \varepsilon_3) = \frac{2}{3}(\varepsilon_a - \varepsilon_r)$$

Stress paths

STRESS PATHS OF GEOMECHANICS PROBLEMS

Stress paths

- The behaviour of an element of soil to a change in the stress state depends on:
  Stress path = Successive states of stress to which the soil is subjected



Examples

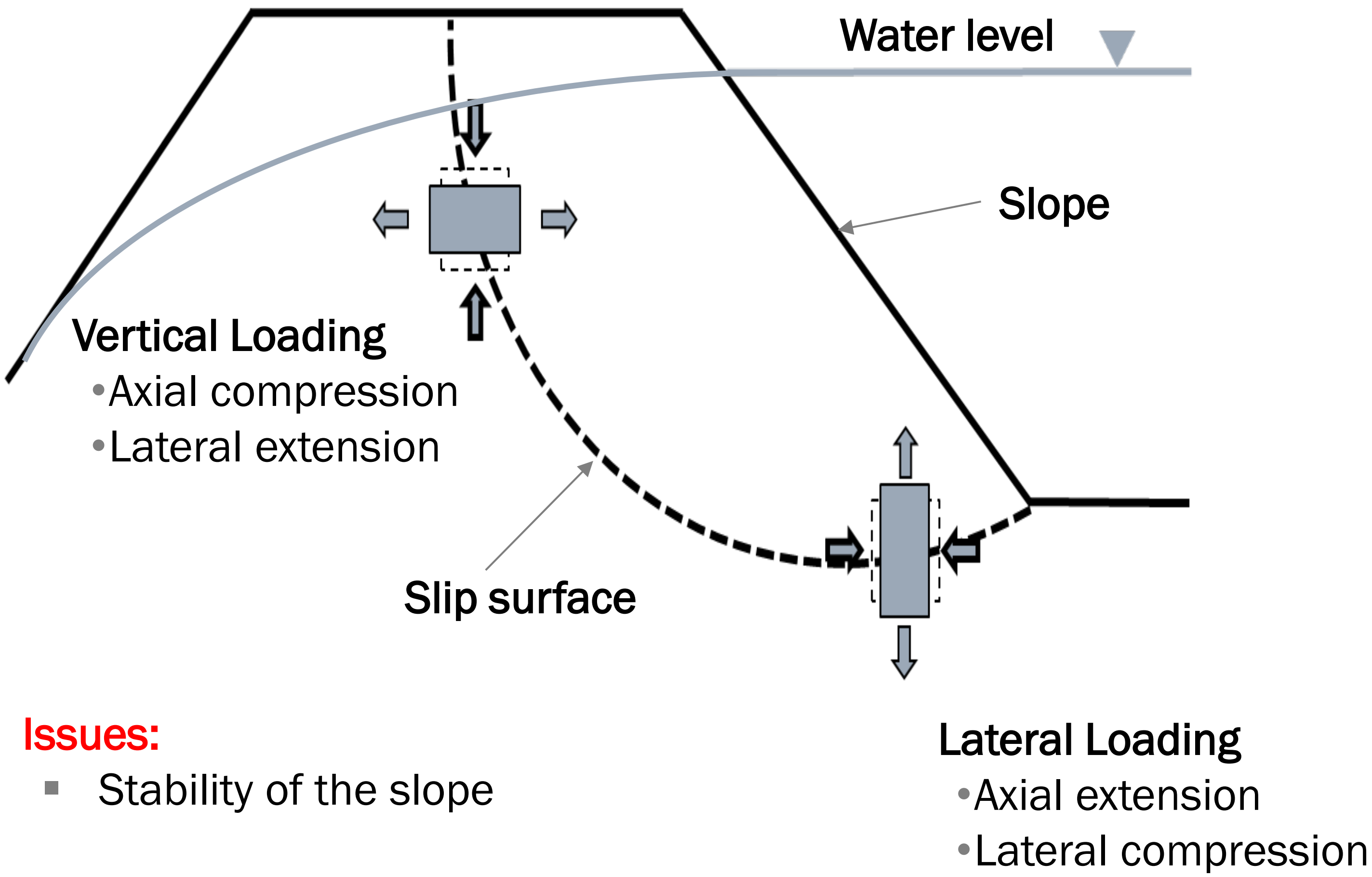
ESP (effective stress path): stress path expressed in terms of **effective** stress

TSP (total stress path): stress path expressed in terms of **total** stress

Drained stress path: $\Delta p_w = 0$ at the end of the stress change, any variation of pore water pressure with respect to the initial value takes place;

Stress paths

Slopes



Issues:

- Stability of the slope

General procedure:

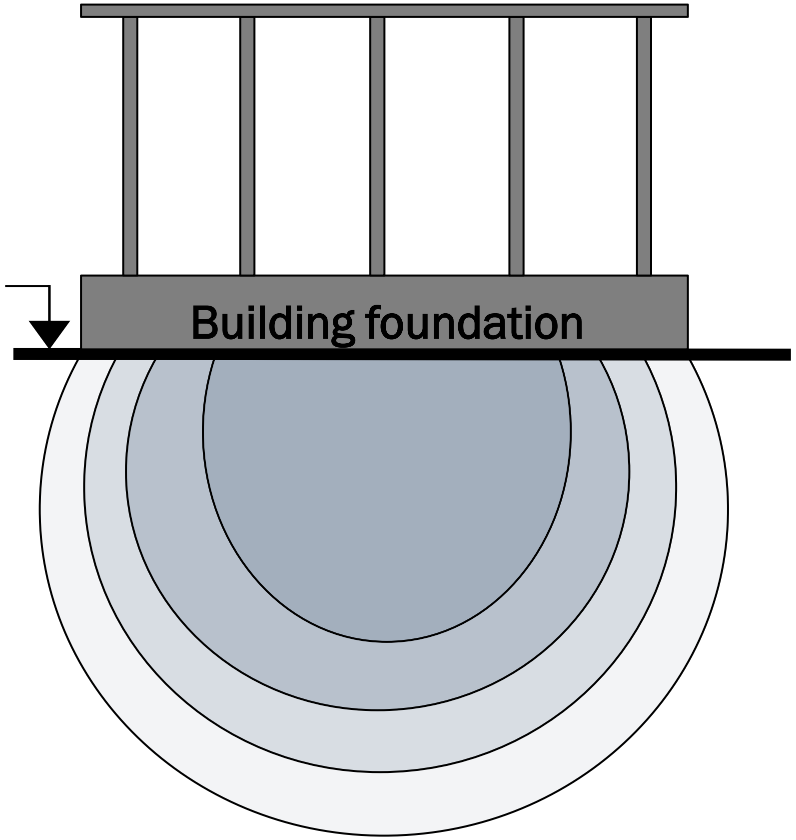
i. selection of some soil elements representative for the problem of interest

ii. identification of the stress path(s) followed by such element(s) in the phase of interest

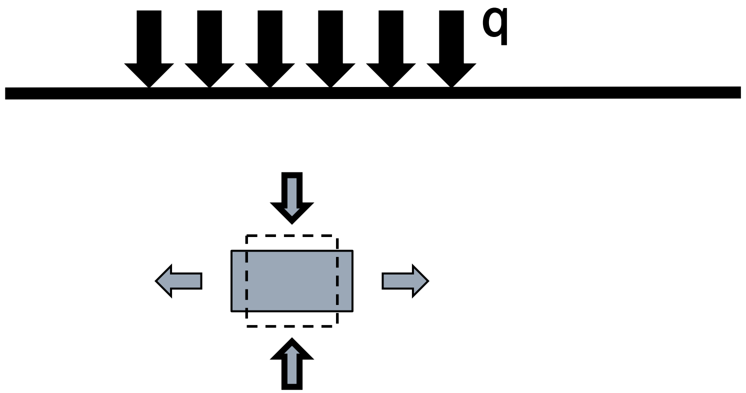
iii. carrying out of laboratory tests to reproduce these stress path(s).

Stress paths

Shallow foundations



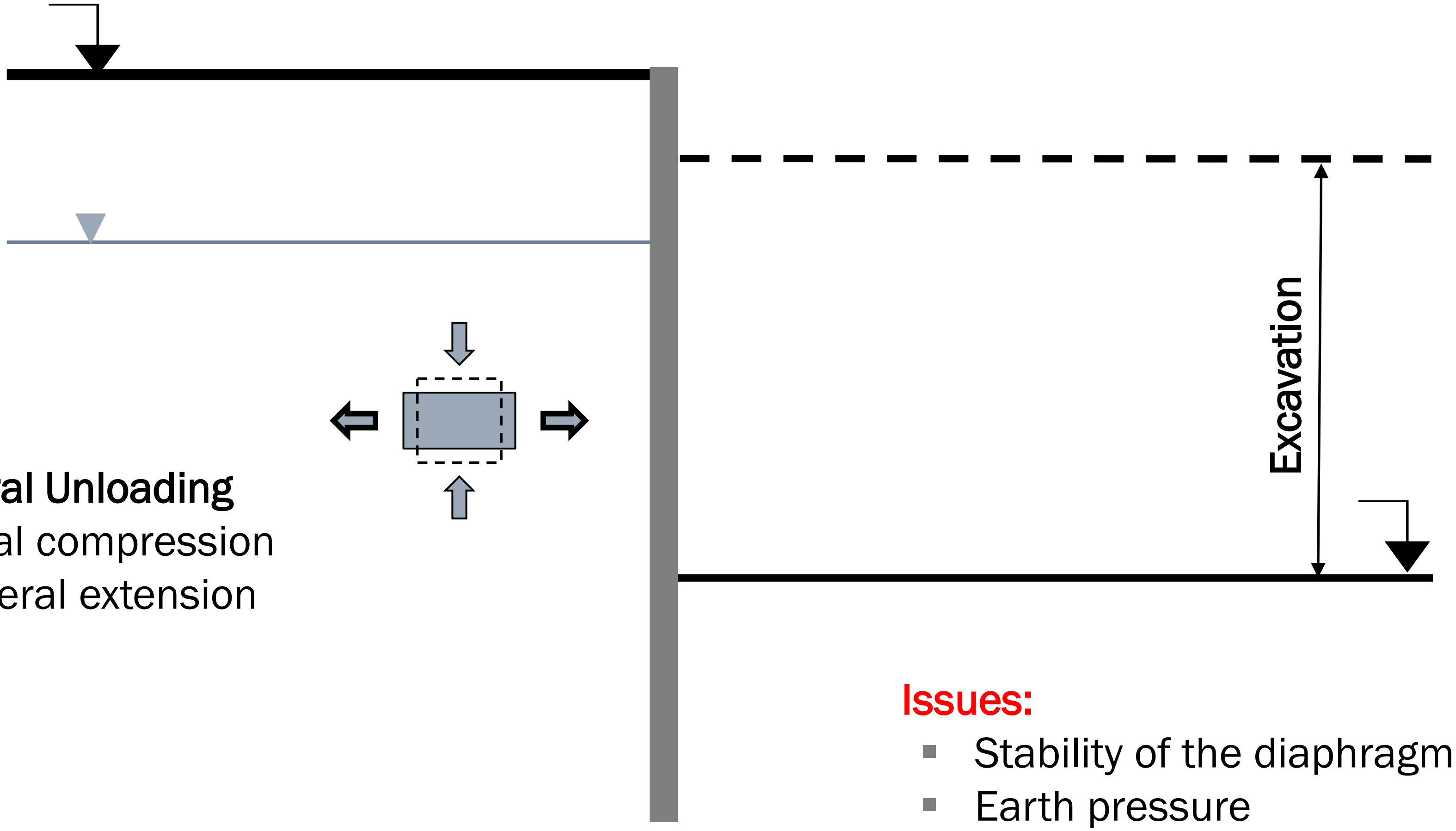
Issues:
- Settlements (differential)
- Bearing capacity



Vertical Loading
- Axial compression
- Lateral extension

Stress paths

Earth retaining structure (i.e. diaphragm wall)

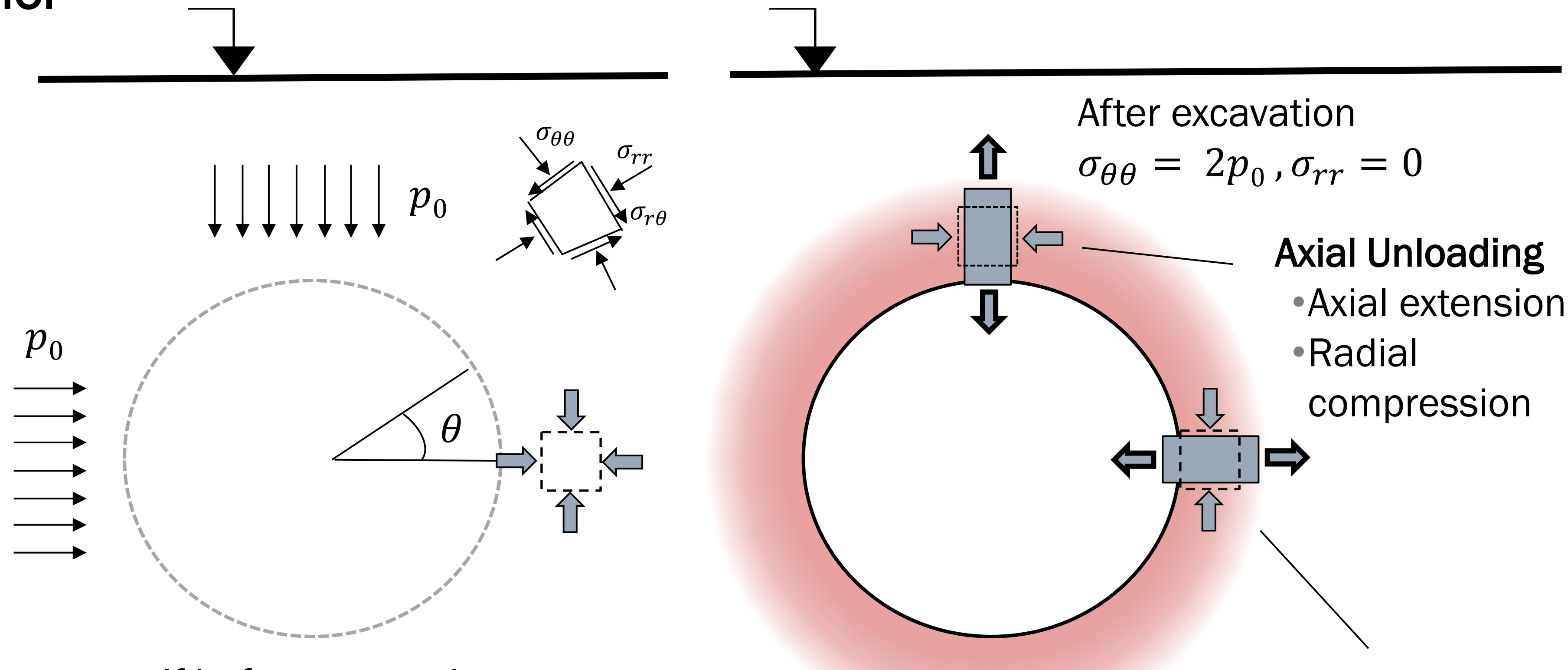


Lateral Unloading
- Axial compression
- Lateral extension

Issues:
- Stability of the diaphragm
- Earth pressure

Stress paths

Tunnel



If before excavation
$\sigma_{\theta\theta} = \sigma_{rr} = p_0$

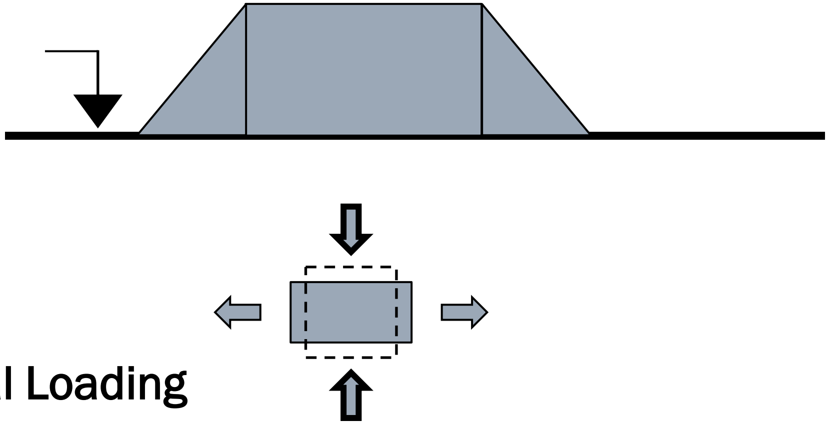
After excavation
$\sigma_{\theta\theta} = 2p_0 , \sigma_{rr} = 0$
(Brady and Brown, 2006)

Radial Unloading
- Axial compression
- Radial extension

Issues:
- Tunnel convergence
- Stability of the excavation face

Stress paths

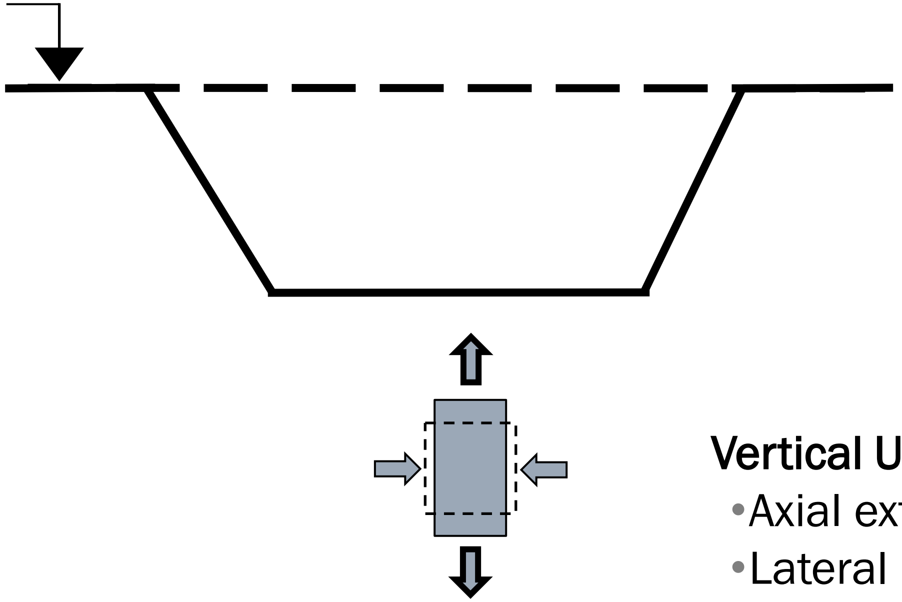
Embankment construction



Vertical Loading
- Axial compression
- Lateral extension

Issues:
- Pore pressure development
- Consolidation (time-dependent settlements)

Trench excavation



Vertical Unloading
- Axial extension
- Lateral compression

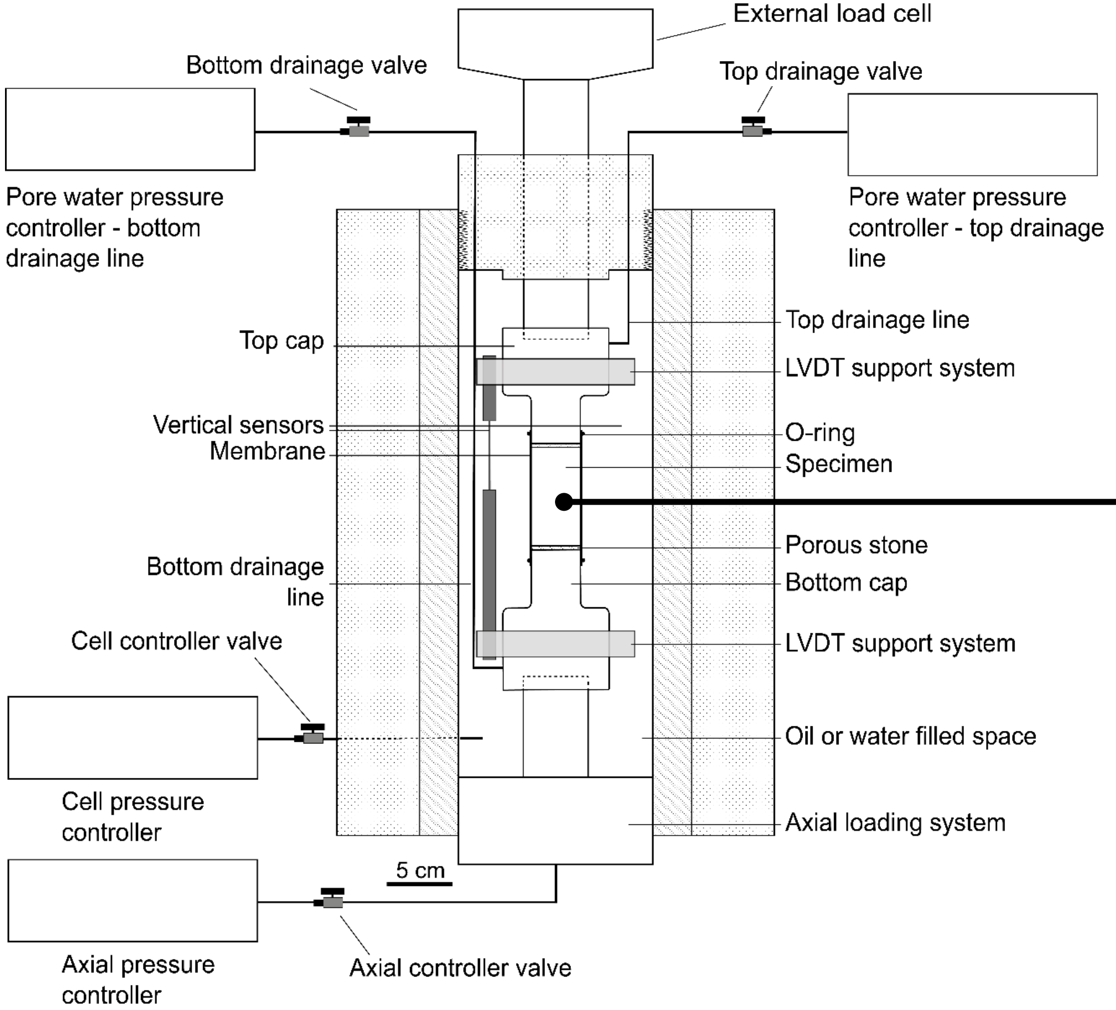
Issues:
- Negative pore pressure development
- Consolidation (time-dependent settlements)

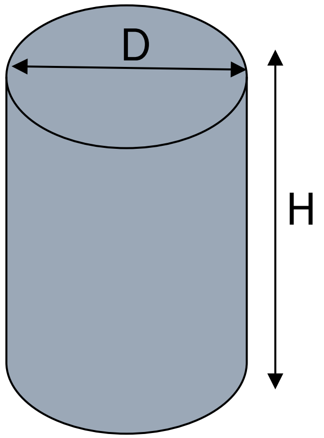
Laboratory testing: Triaxial tests

STRESS-STRAIN BEHAVIOUR

How to reproduce stress paths in laboratory

Triaxial test





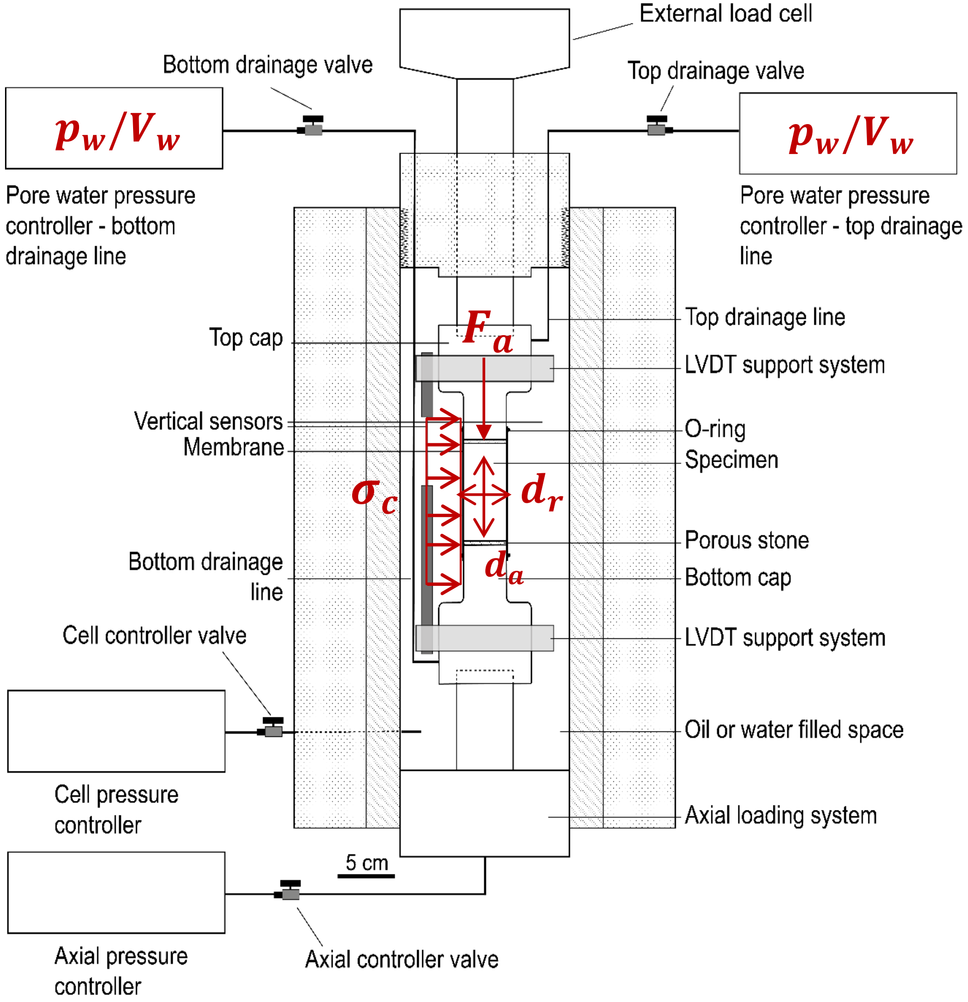
$$H/D \cong \frac{1}{2}$$

Usually:

$$D = 3.8\ cm$$

$$H = 7.6\ cm$$

How to reproduce stress paths in laboratory



Controlled or Measured

- F_a : Axial force
- σ_c : Cell pressure
- d_a : Axial displacement
- d_r : Radial displacement
- p_w : Pore water pressure
- V_w : Pore water volume

Measured

- t : time

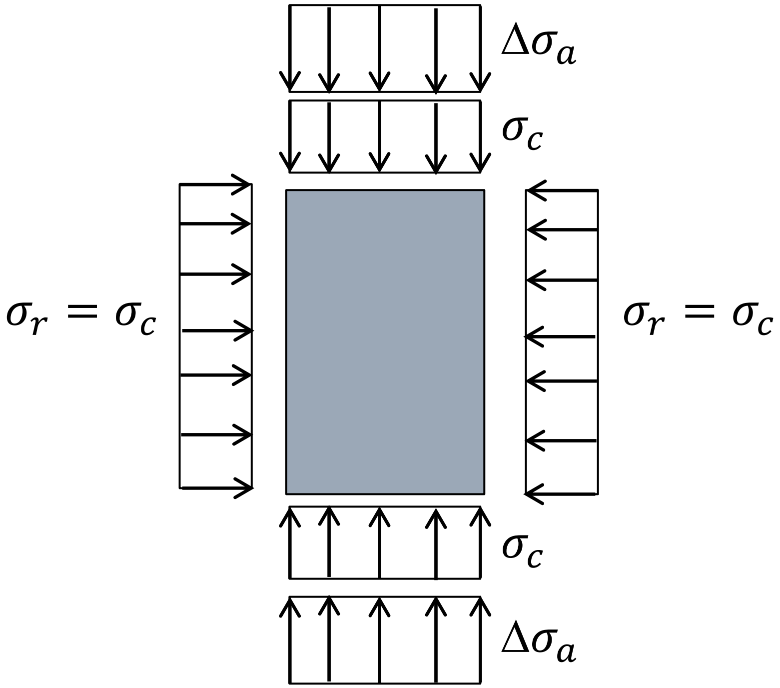
Computed

- σ_a : Axial stress
  - $\longrightarrow$ Axial force F_a
- σ_r : Radial stress
  - $\longrightarrow$ Cell pressure σ_c
- ε_a : Axial strain
  - $\longrightarrow$ Axial displacement d_a
- ε_r : Radial strain
  - $\longrightarrow$ Radial displacement d_a
- ε_v : Volumetric strain
  - $\longrightarrow$ Pore water volume V_w

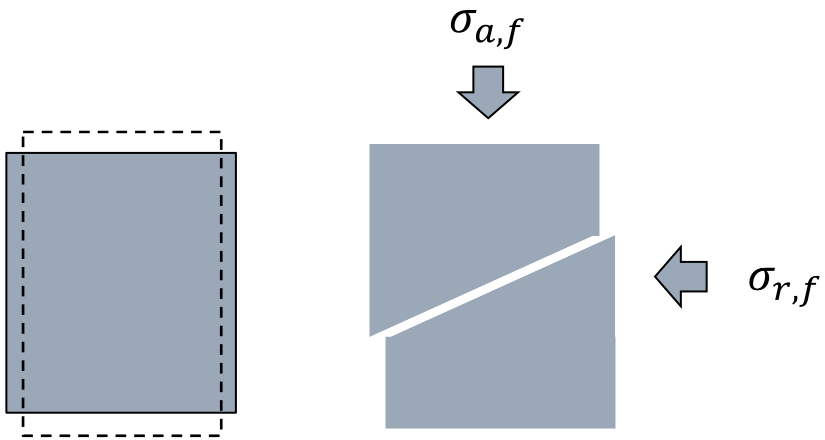
How to reproduce stress paths in laboratory

Triaxial test

The axial and radial stress



Type of strain



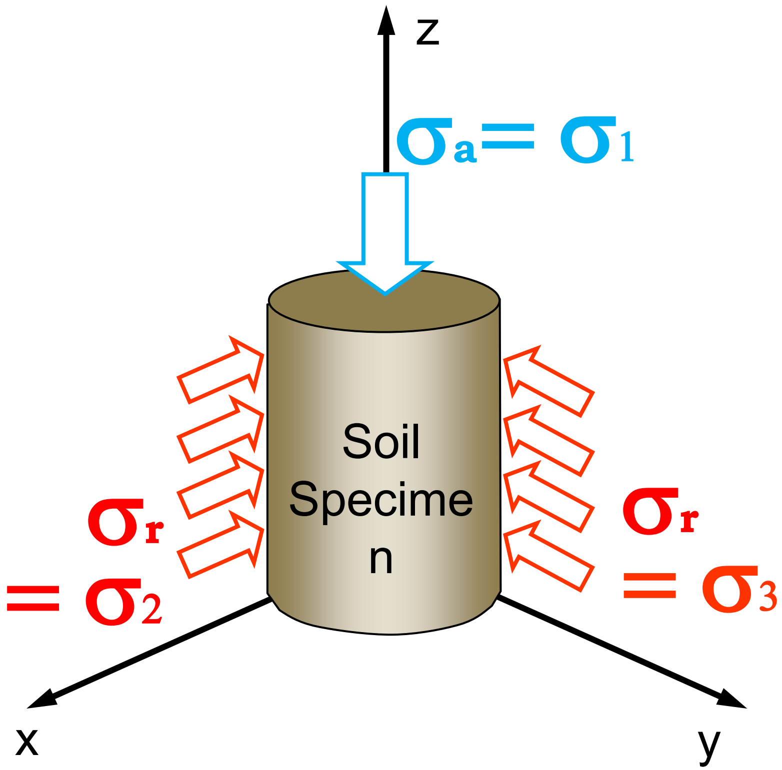
Volumetric + Distorsion

Failure in shear

How to reproduce stress paths in laboratory

Stress and strain variables for triaxial tests

- Axisymmetric stress state
- The principal directions coincide with the axial and the radial ones



Mean total stress $p = \frac{\sigma_1+\sigma_2+\sigma_3}{3} = \frac{\sigma_a+2\sigma_r}{3}$

Mean effective stress $p' = \frac{\sigma'_1+\sigma'_2+\sigma'_3}{3} = \frac{\sigma'_a+2\sigma'_r}{3}$

Deviatoric stress $q = \sigma_a - \sigma_r$

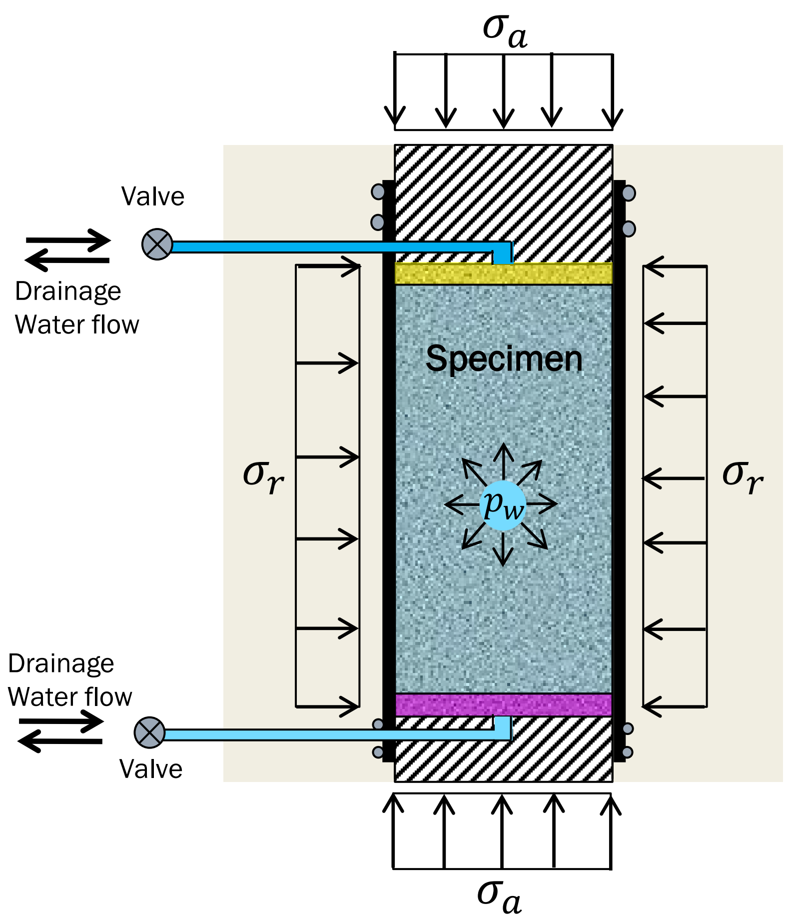
Maximum shear stress $\tau = \frac{\sigma_a-\sigma_r}{2}$

Volumetric strain $\varepsilon_v = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 = \varepsilon_a + 2\varepsilon_r$

Deviatoric strain $\varepsilon_d = \frac{2}{3}(\varepsilon_a - \varepsilon_r)$

How to reproduce stress paths in laboratory

Drained and Undrained conditions



DRAINED CONDITION

- Water Flow **ALLOWED**
- Excess pore water pressure **dissipates**

- Long term analysis in low permeable geomaterials (clays)
- Almost all analyses in high permeable geomaterials (gravels, sands)

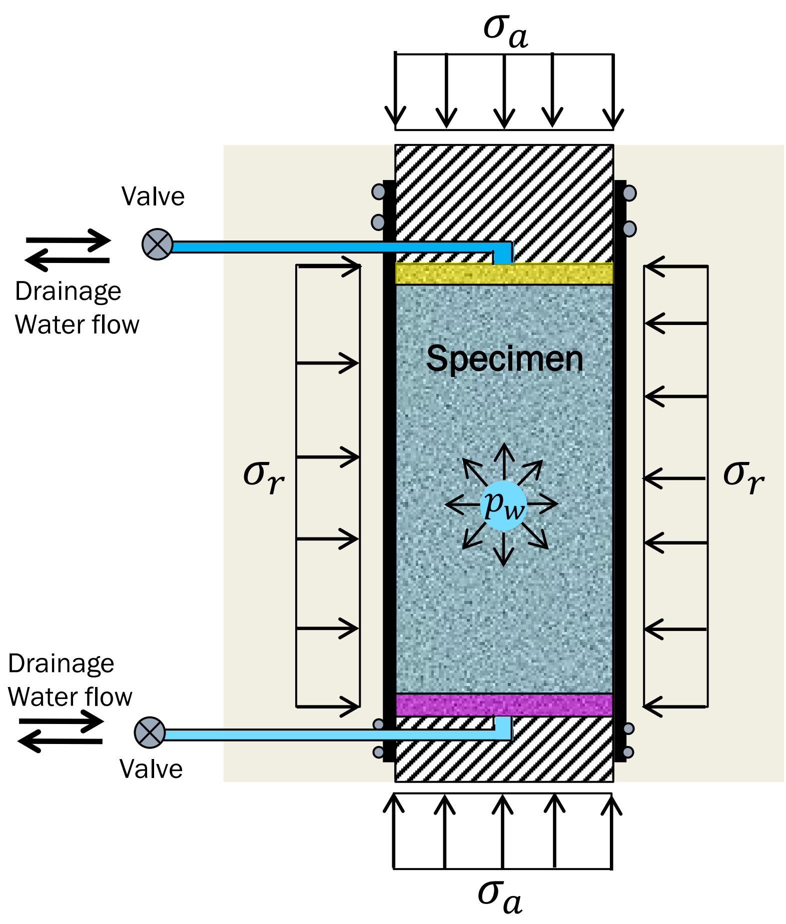
UNDRAINED CONDITION

- Water Flow **NOT allowed**
- Excess pore water pressure **build-up**

- Short term analysis in low permeable geomaterials (clays)

How to reproduce stress paths in laboratory

Drained conditions



- Drainage valves are **open**
- The specimen experiences volume changes $\varepsilon_{vol} \neq 0$

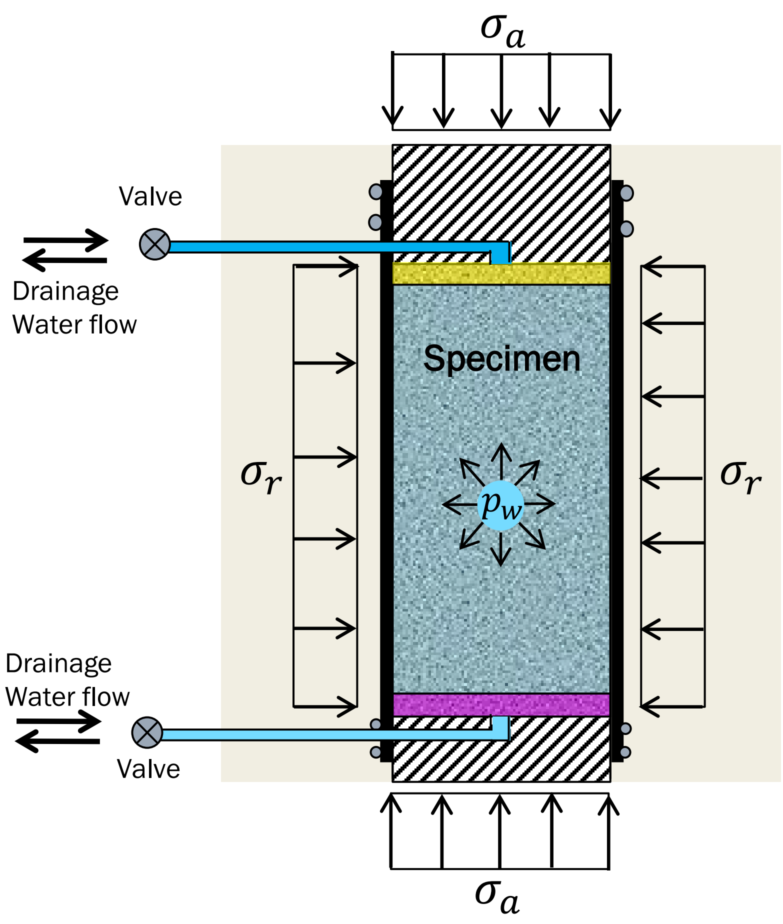
CONTROLLED	MEASURED	COMPUTED
• p_w	• ΔV_w	• ε_{vol} from ΔV_w
• ε_a	• σ_a	• $\varepsilon_r = \frac{(\varepsilon_{vol} - \varepsilon_a)}{2}$
• σ_r		

<u>Effective stress path (ESP) and total stress path (TSP) are parallel (displaced horizontally)</u>

ESP=TSP if $p_{w,0} = 0$

How to reproduce stress paths in laboratory

Undrained conditions



- Drainage valves are **closed**
- The specimen experiences no volume changes in saturated conditions $\varepsilon_{vol} = 0$

CONTROLLED

- ε_a
- σ_r
- $\Delta V_w = 0 \rightarrow \varepsilon_{vol} = 0$

MEASURED

- p_w
- σ_a

COMPUTED

- ESP from p_w and TSP
- $\varepsilon_r = -\frac{\varepsilon_a}{2}$

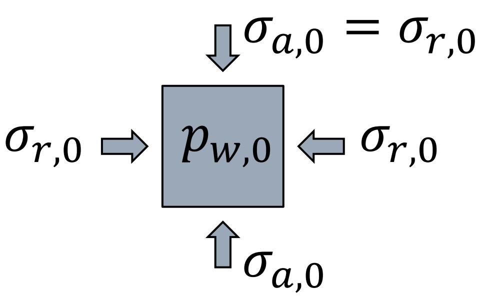
Effective stress path (ESP) and total stress path (TSP) are NOT parallel

How to reproduce stress paths in laboratory

Triaxial test: General procedure

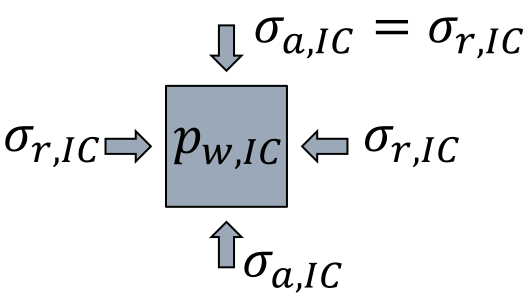
0. Saturation

The pore water pressure is increased to saturate the specimen. Axial and radial stress are increased for ensuring positive effective stress.



1. Isotropic compression (IC)

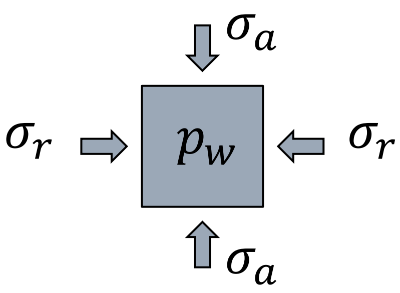
Axial and radial stress are equally increased, the specimen is compressed isotropically.



Drained (C), or Undrained (U)

2. Shearing

Axial stress and radial stress are changed. The specimen is carried to failure by shearing

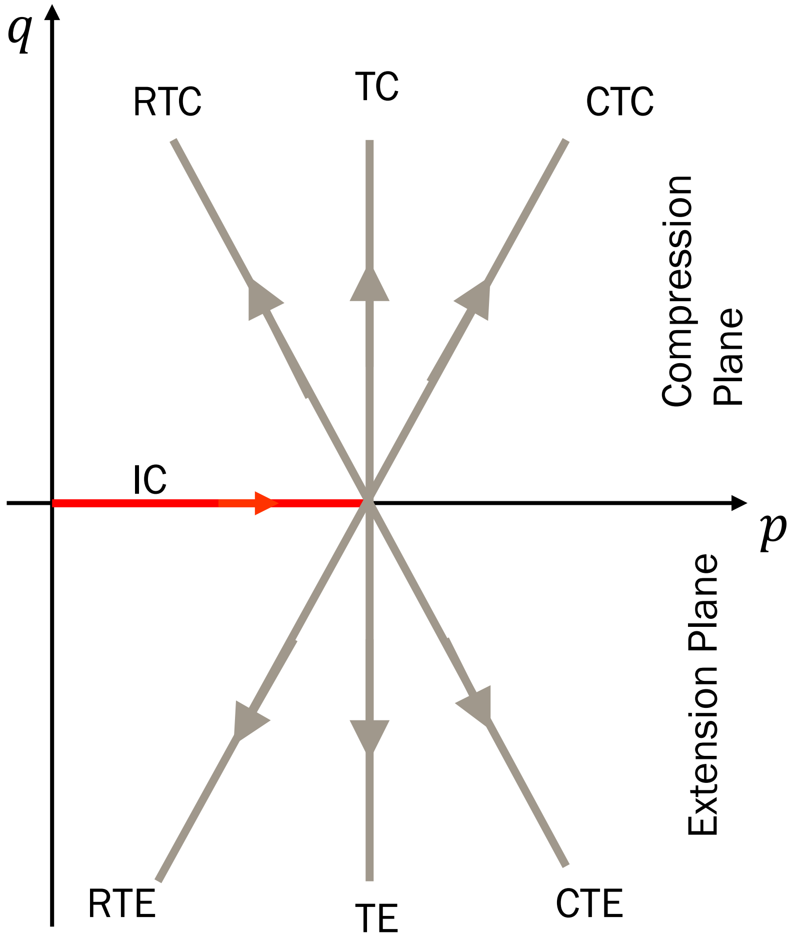


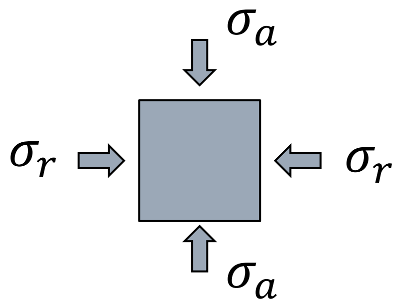
Drained (C), or Undrained (U)

How to reproduce stress paths in laboratory

Stress paths for shearing

Specimen led to failure in different ways

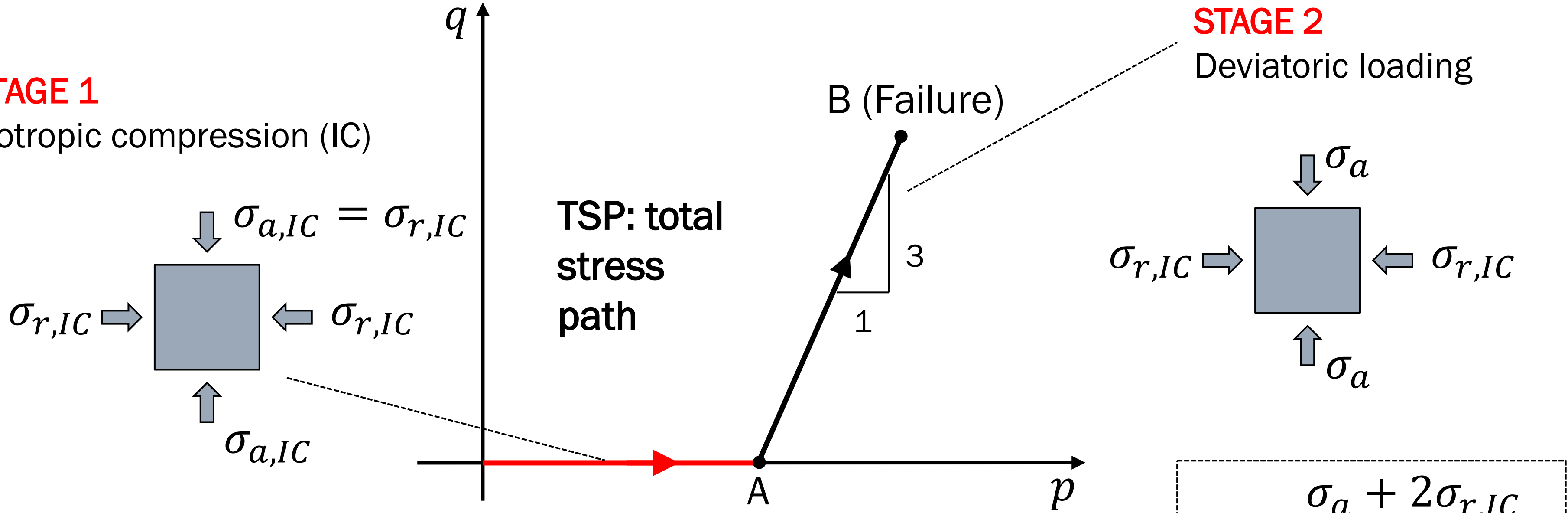




CTC: conventional tx compression	$\sigma_a \uparrow$	σ_r —
RTC: reduced tx compression	σ_a —	$\sigma_r \downarrow$
TC: tx compression	$\sigma_a \uparrow$	$\sigma_r \downarrow$
CTE: conventional tx extension	σ_a —	$\sigma_r \uparrow$
RTE: reduced tx extension	$\sigma_a \downarrow$	σ_r —
TE: tx extension	$\sigma_a \downarrow$	$\sigma_r \uparrow$

How to reproduce stress paths in laboratory

CTC test : shearing with $\boldsymbol{\sigma_a} \uparrow$ and $\boldsymbol{\sigma_r}$ --



$$p = \sigma_{r,IC}$$
$$q = 0$$

$$p = \frac{\sigma_a + 2\sigma_{r,IC}}{3}$$
$$q = \sigma_a - \sigma_{r,IC}$$

How to reproduce stress paths in laboratory

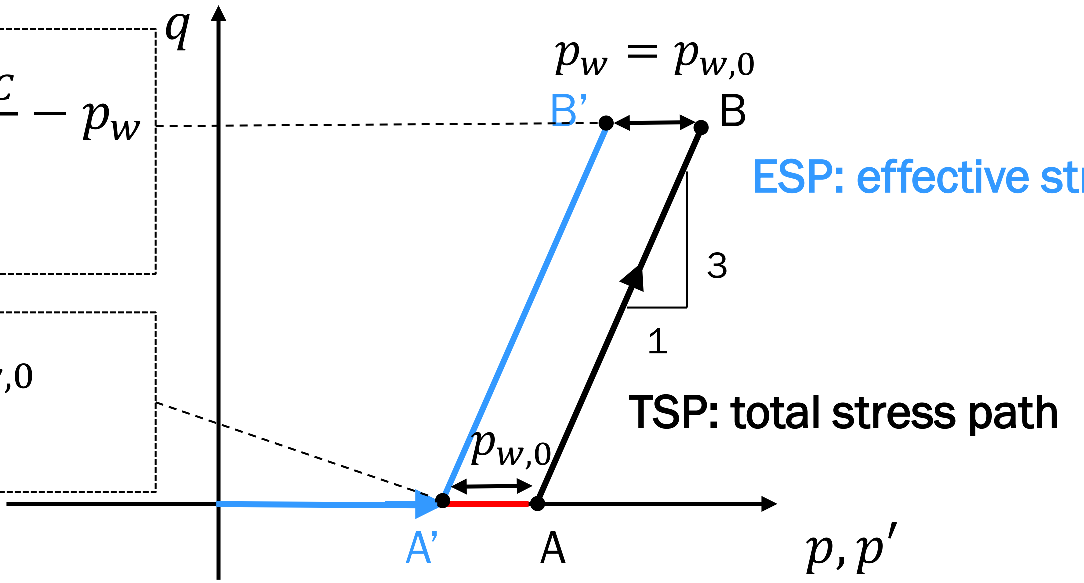
CTC test : shearing in DRAINED CONDITIONS

$$p' = \frac{\sigma_a + 2\sigma_{r,IC}}{3} - p_w$$

$$q = \sigma_a - \sigma_{r,IC}$$

$$p' = \sigma_{r,IC} - p_{w,0}$$

$$q = 0$$



During shearing (stage 2):

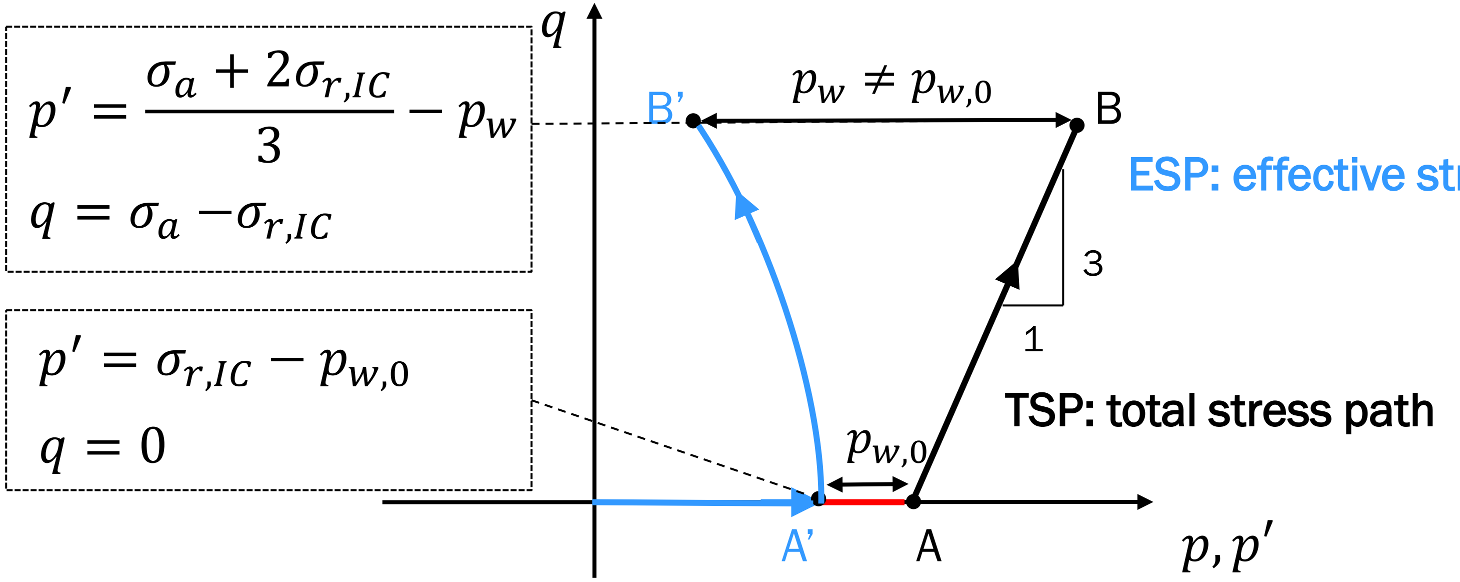
- $p_w = p_{w,0} \rightarrow \Delta p_w = 0$
- $p' = p$ if $p_{w,0} = 0$
- $\varepsilon_{vol} \neq 0$

water flow
$\Delta V = - \Delta V_w$

- the specimen experiences variation in height (H) and diameter (area, A)
- ΔH is measured → ε_a
- $A = \frac{V_0 + \Delta V}{H_0 + \Delta H}$ → σ_a

How to reproduce stress paths in laboratory

CTC test : shearing in UNDRAINED CONDITIONS



During shearing (stage 2):

- $p_w \neq p_{w,0} \rightarrow \Delta p_w \neq 0$
- $p' \neq p$
- $\varepsilon_{vol} = 0$

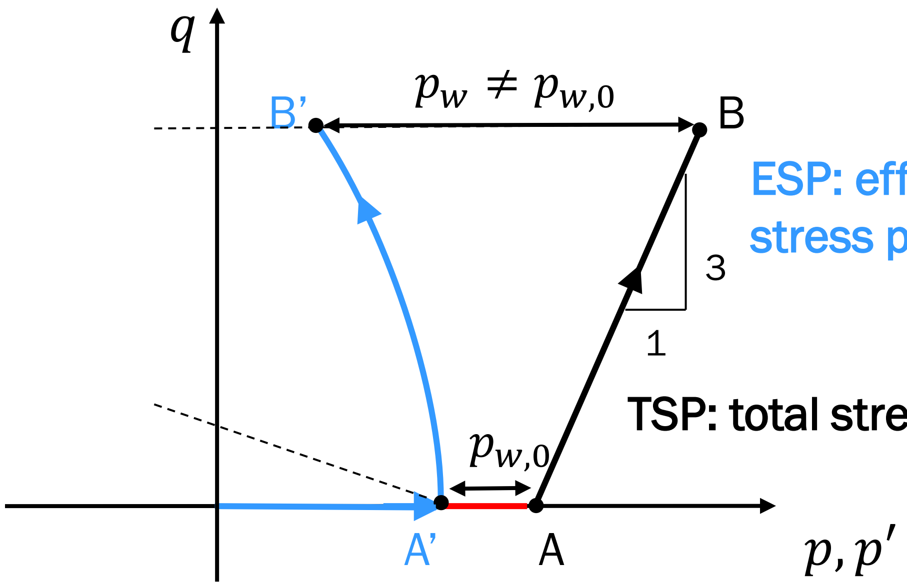
water flow
$\Delta V = - \Delta V_w = 0$

- the specimen experiences variation in height (H) and diameter (area, A) but no volume changes
- ΔH is measured → ε_a
- $A = \frac{V_0 + \Delta V}{H_0 + \Delta H}$ → σ_a

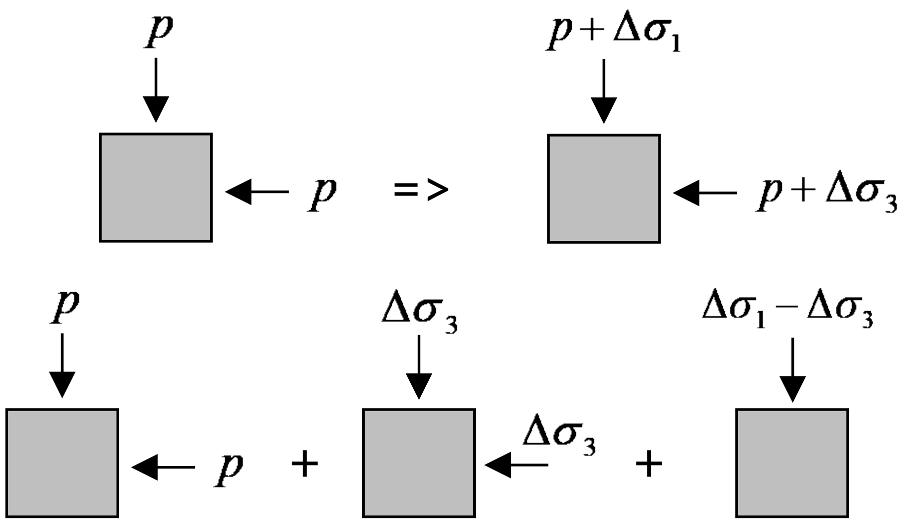
How to reproduce stress paths in laboratory

CTC test : shearing in UNDRAINED CONDITIONS

Δp_w, for a given total stress change, mainly depends on the compressibility of the solid skeleton and of the fluids within the specimen.



The soil element is originally in equilibrium under a stress state (p)



Total stress is modified with changes in principal stresses. The application of the total stresses can be considered as taking place in two stages

How to reproduce stress paths in laboratory

CTC test : shearing in UNDRAINED CONDITIONS

The change in pwp occurring under changes in total stresses must be known in problems involving undrained conditions.
Skempton (1954) derives the following expression:

$$\Delta u_w = B\left[\Delta\sigma_3 + A\left(\Delta\sigma_1 - \Delta\sigma_3\right)\right]$$

A and B are the pore-pressure coefficients, measured in the lab for changes in principal total stresses occurring in the problem under analysis.

B accounts for isotropic stress changes.

A accounts for deviator loadings.

VALUES OF PARAMETER A

Material (S = 100%)	A (at failure)	Reference
Very loose fine sand	2 to 3	Typical values given by Bjerrum
Sensitive clay	1.5 to 2.5	
Normally consolidated clay	0.7 to 1.3	
Lightly overconsolidated clay	0.3 to 0.7	
Heavily overconsolidated clay	−0.5 to 0	

Material (S = 100%)	A (for foundation settlement)	Reference
Very sensitive soft clays	>1	From Skempton and Bjerrum (1957)
Normally consolidated clays	$\frac{1}{2}$ to 1	
Overconsolidated clays	$\frac{1}{4}$ to $\frac{1}{2}$	
Heavily overconsolidated sandy clays	0 to $\frac{1}{4}$	

VALUES OF PARAMETER B

Material	S(%)	B	Reference
Sandstone	100	0.286	Computed from compressibilities given by Skempton (1961)
Granite	100	0.342	
Marble	100	0.550	
Concrete	100	0.582	
Dense sand	100	0.9921	
Loose sand	100	0.9984	
London clay (OC)	100	0.9981	
Gosport clay (NC)	100	0.9998	
Vicksburg buckshot clay	100	0.9990	M.I.T.
Kawasaki clay	100	0.9988 to 0.9996	M.I.T.
Boulder clay	93	0.69	Measured by Skempton (1954)
	87	0.33	
	76	0.10	

Values reported by Lambe and Whitman (1969)

How to reproduce stress paths in laboratory

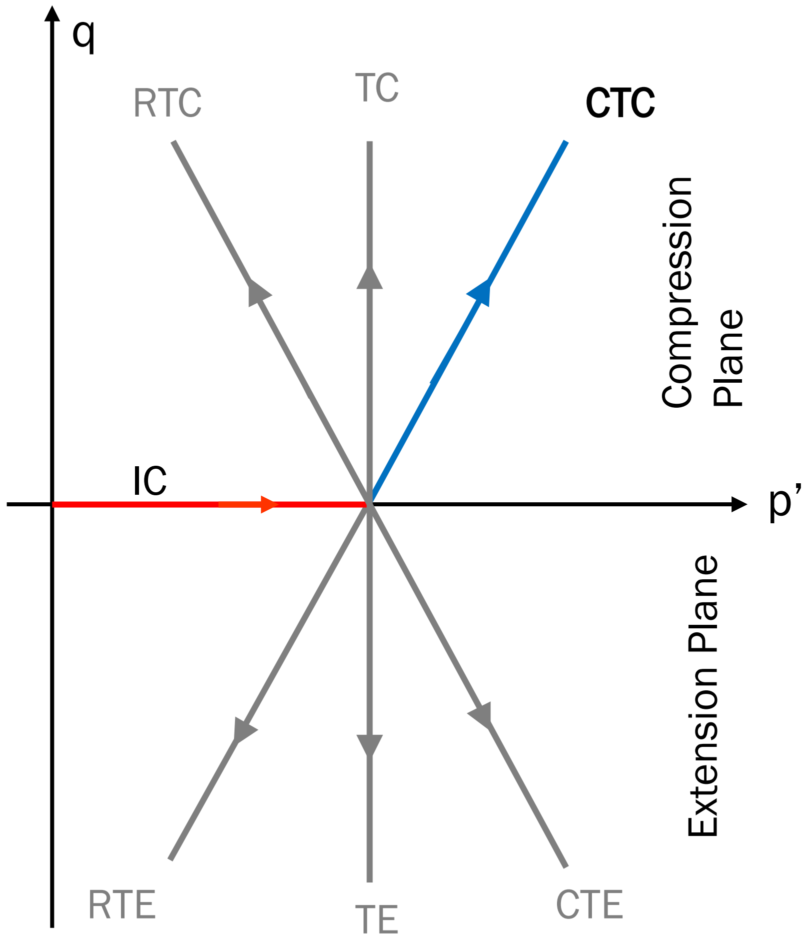
<u>To do @ home</u>

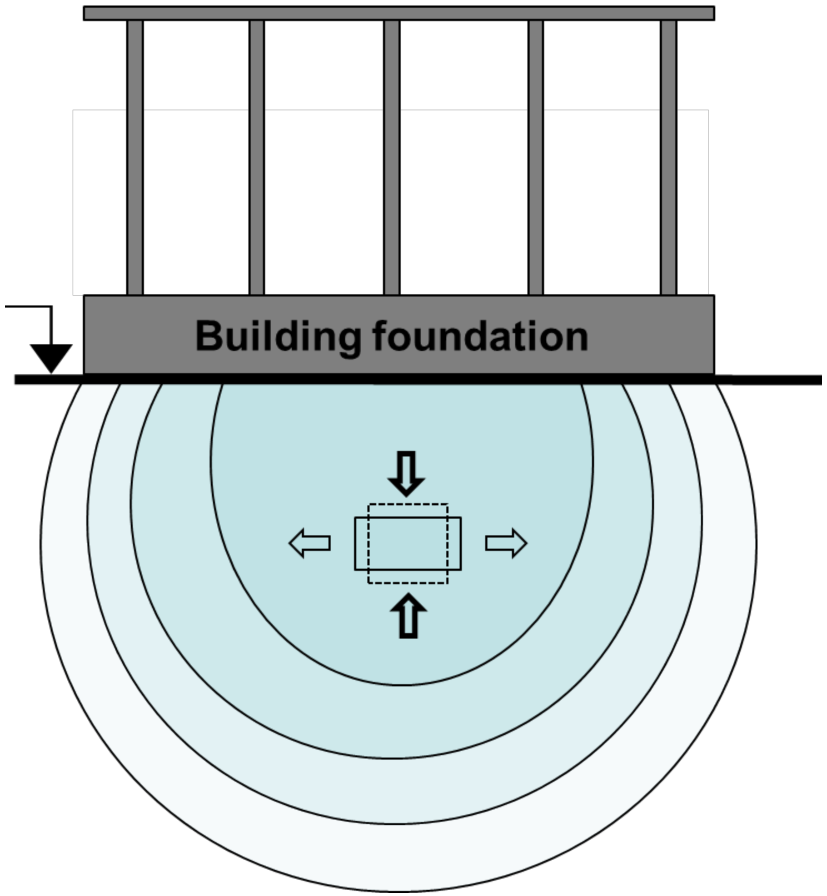
Assume a fully saturated and ideal-elastic geomaterial. During the shearing phase of a CTC triaxial test ($\Delta\sigma_3$ = 0) in undrained conditions, how will evolve the pore pressure (Δp_w) with respect to the axial stress $\Delta\sigma_1$? Illustrate in a *q – p' (p)* plane

Hint: use Skempton's formula

Stress paths

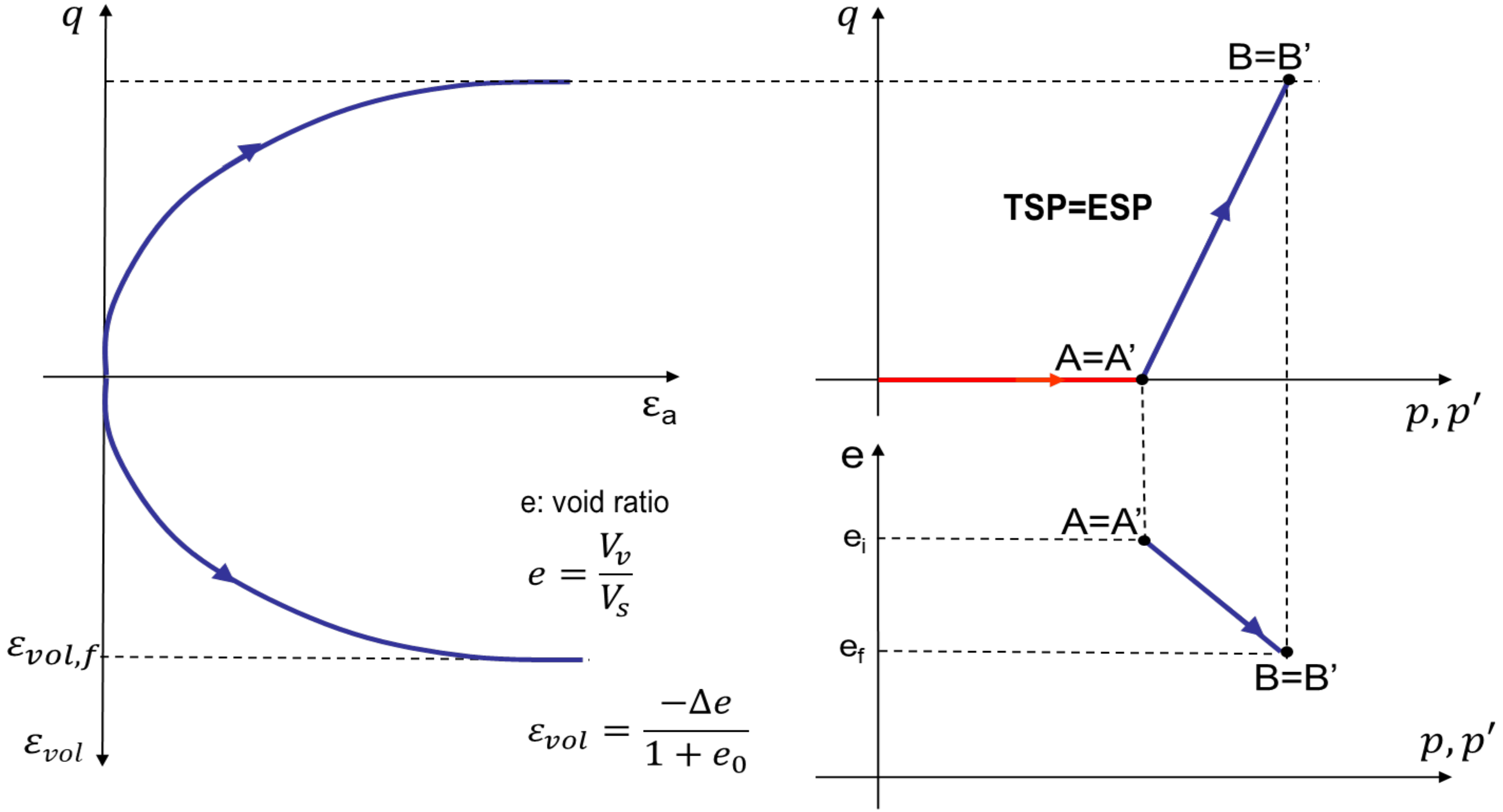
Practical example of the path reproduced by a CTC test





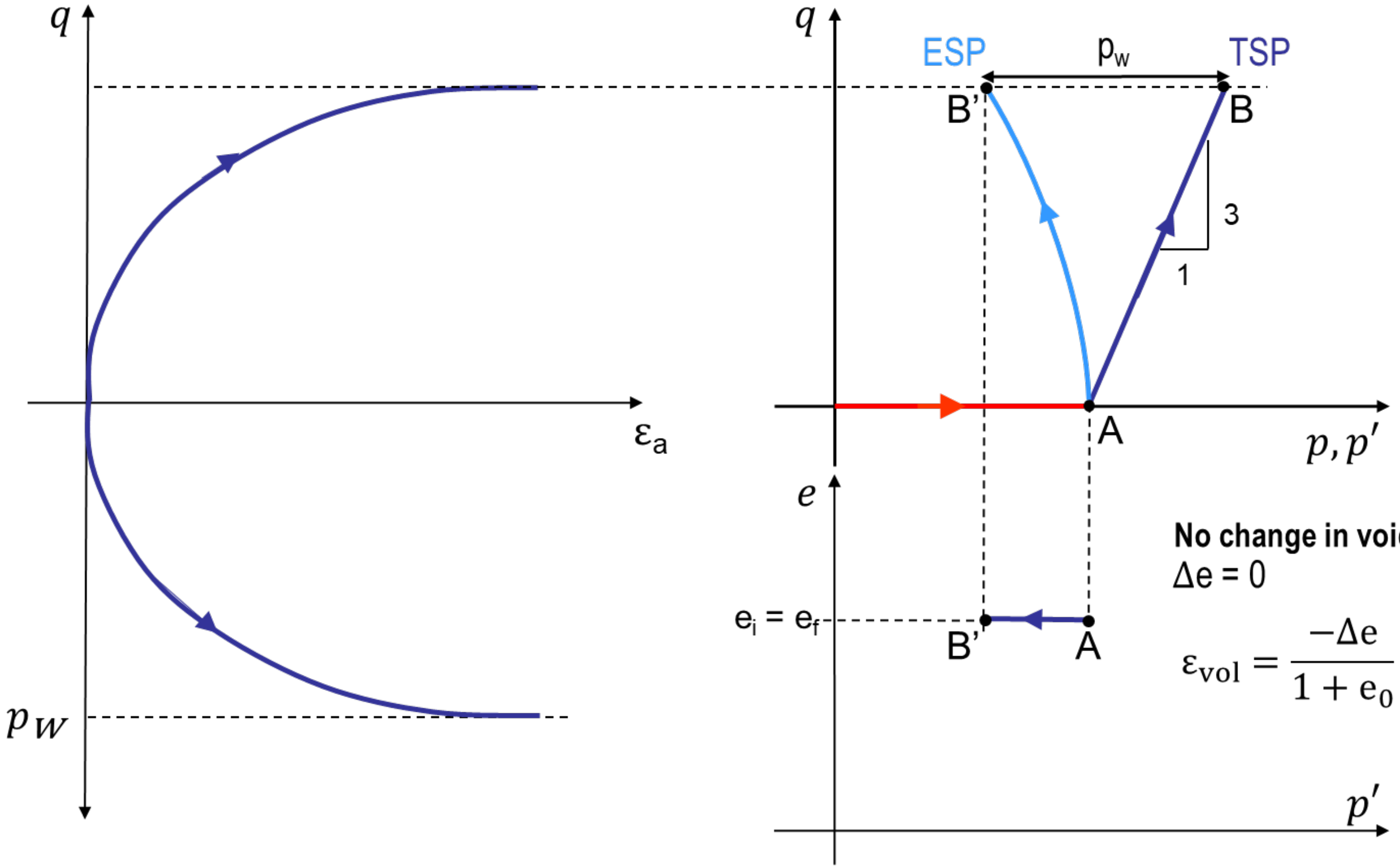
Stress paths

Example of outputs of a CTC test –**DRAINED CONDITION** with $p_{w,0} = 0$



Stress paths

Example of outputs of a CTC test –**UNDRAINED CONDITION** with $p_{w,0} = 0$



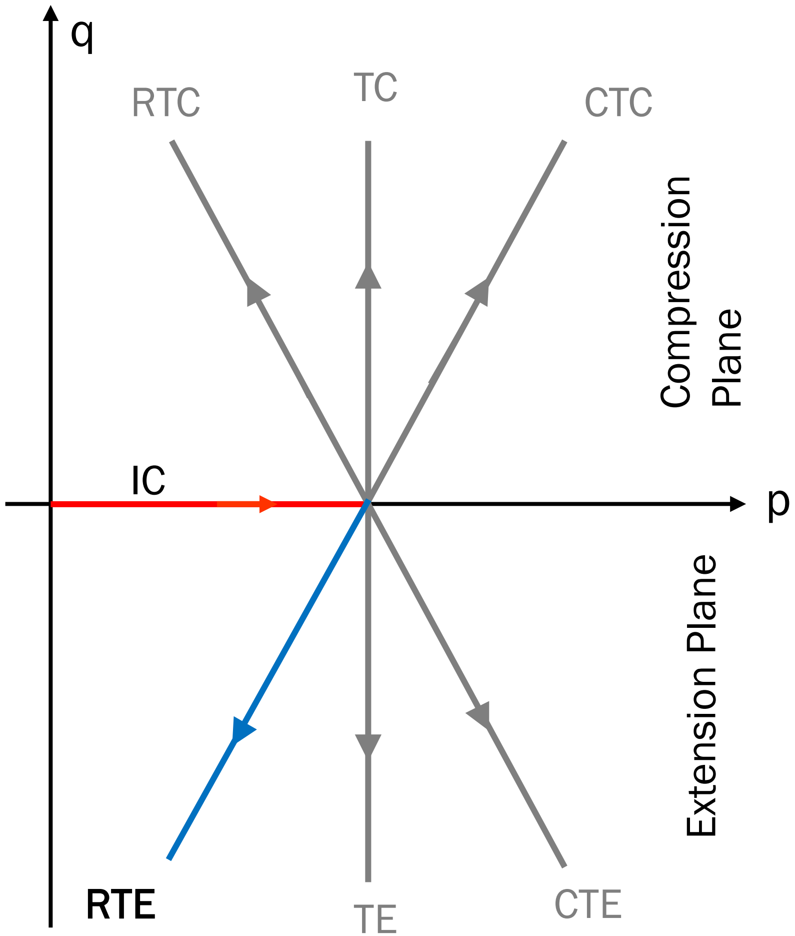
No change in void ratio
$\Delta e = 0$

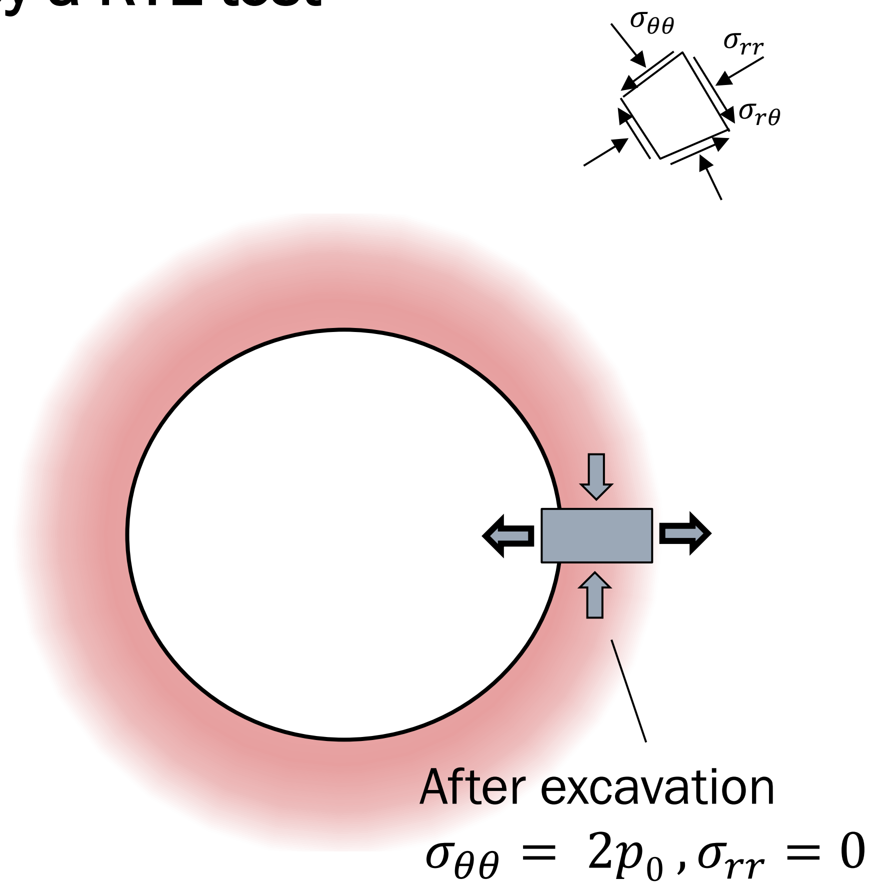
$$\varepsilon_{vol} = \frac{-\Delta e}{1 + e_0} = 0$$

Stress paths

RTE test : shearing with $\boldsymbol{\sigma_a}$ ↓ and $\boldsymbol{\sigma_r}$ --

Practical example of the path reproduced by a RTE test





Conclusions

- Effective stress – a tool to go from multi-phase description to single phase continuum description
- Stress-path strictly depends on the problem under consideration
- Reproduction of stress path using triaxial test as a general framework

Thank you for your attention