Previous Lecture

- **organisational aspects**
- **What is hydrogeology?**
- **groundwater as part of the global water cycle**
- **volume and mass budgets**

questions?

Today

- **structure of the subsurface**
- **grain size distribution of unconsolidated porous media**
- **subterranean water**

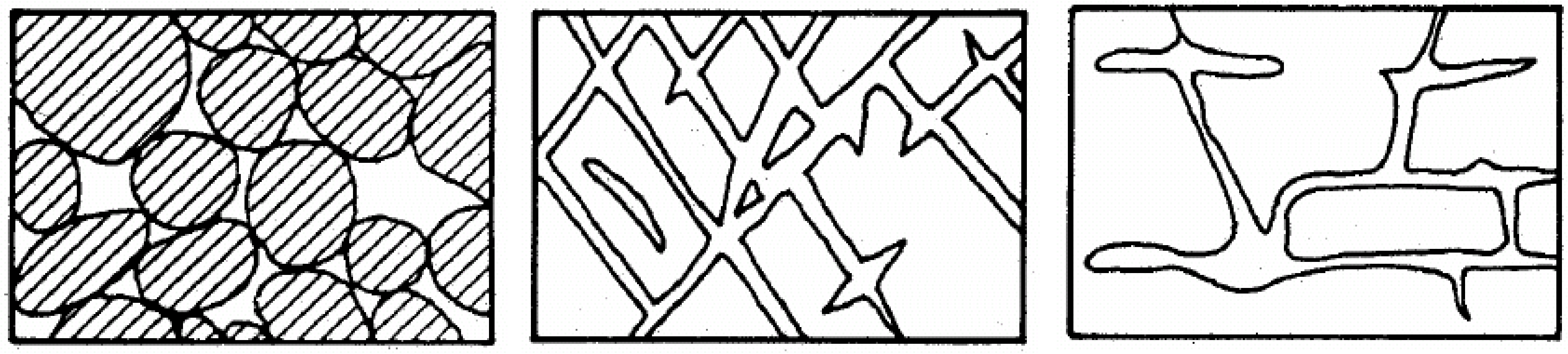
Structure of the Subsurface

Porous Medium

- **A porous medium or a porous body is a solid containing voids (or holes).**
- **The subsurface can be regarded a porous medium.**
- **Voids may have very different shapes (interstitial between ball-like grains, planar crack-like fractures, cylindrically shaped tubes or conduits etc.)**
- **Voids may be connected to or disconnected from each other.**
- **Voids may contain fluids (mostly air and / or water).**
- **Size, shape and connectivity of voids are influential for the ability of the porous medium**
  – to store water
  – to transmit water

Types of Porous Media in the Subsurface

sediments | **rocks**

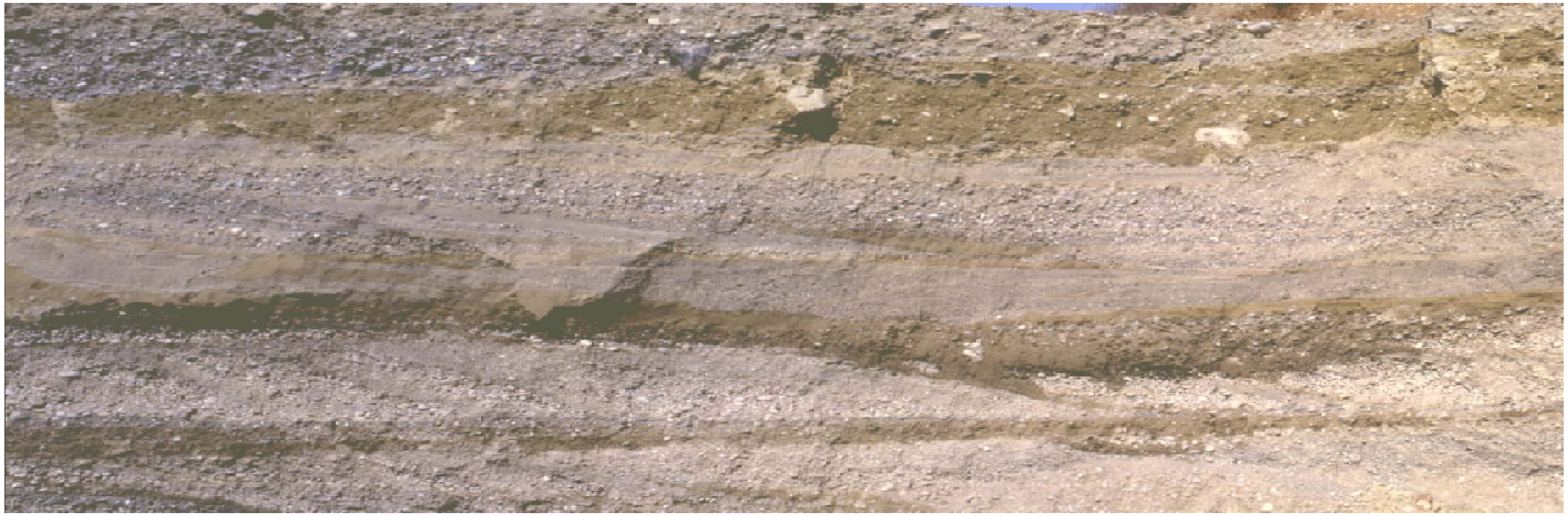


fractured | **karstified**

unconsolidated porous medium (formation due to deposition of solid material mostly by water)

consolidated porous medium (formation of rocks due to increased pressure acting together with thermal and chemical processes)

Unconsolidated Porous Medium

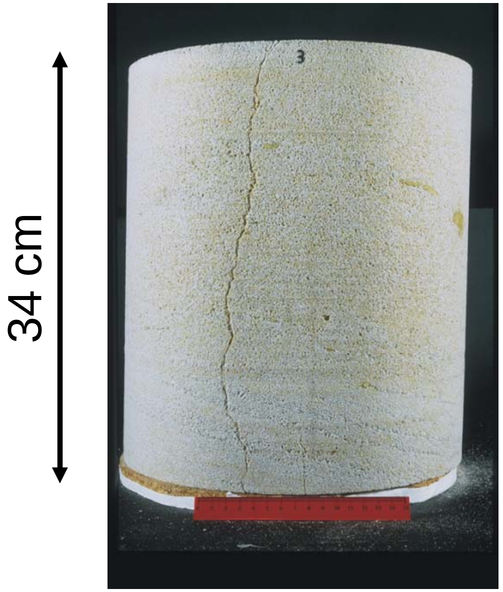


(Klingbeil, 1998)

sediments consisting of fluvial deposits of sands and gravels (Rhine Basin – Southwest Germany / Northern Switzerland)

Consolidated Porous Media

Sandstone (South Germany)



Gypsum (Western Ukraine)

Fractured porous medium:
Genesis of fractures or cracks due to mechanical or thermal processes (stress / strain or cooling / warming)

Karstified porous medium:
Genesis of fractures or tubes (conduits) due to chemical processes (i.e. dissolution of rock by water)

Porosity

- **Porosity (or more precise: total porosity) is defined as the volumetric share of voids in a porous medium:**

$$n = \frac{V_v}{V_T}$$

void volume [L³]

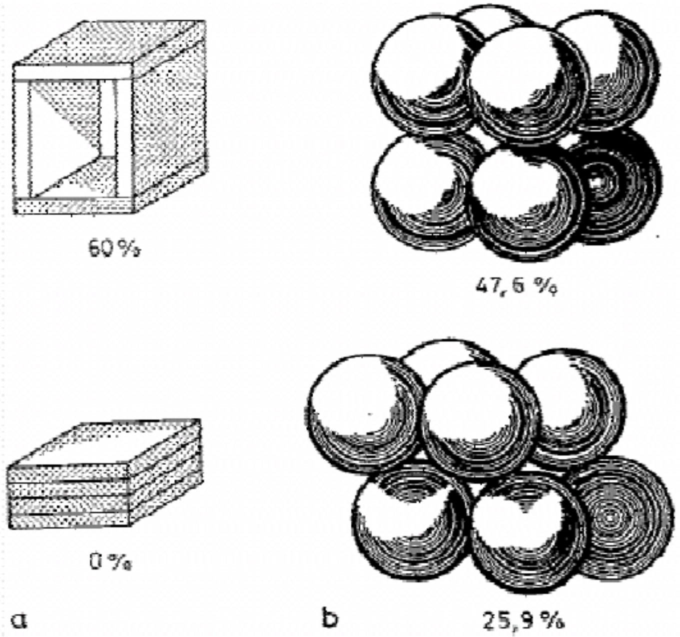
total porosity [-]

total volume [L³]

- **Total porosities can be given either as numbers between 0 and 1 or as percentages between 0 % and 100 %.**

Total Porosity of Artificial Porous Media

If „grains" have identical shape and are regularly arranged, it is possible to exactly compute total porosity, e.g. for packed spheres of same size.

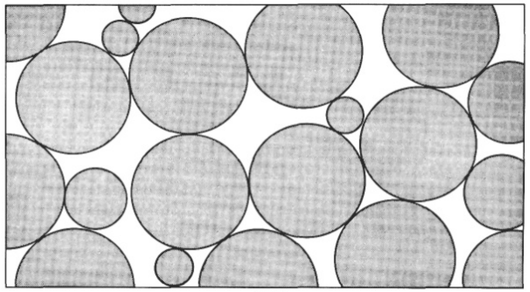


"loose packing"

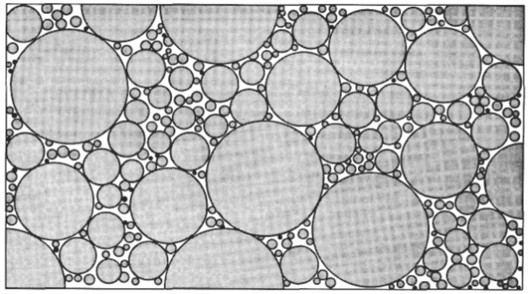
"dense packing"

Total Porosity of Natural (Unconsolidated) Porous Media

- **Natural unconsolidated porous media consist of grains of different size.**
- **Total porosity depends on the grain size distribution.**



"well sorted"
(= grain diameters cover a small range)



"poorly sorted"
(= grain diameters cover a large range)

- **In general, well sorted unconsolidated porous media exhibit larger total porosities than poorly sorted unconsolidated porous media (in the above example: 32 % vs. 17 %)**

Typical Porosity Values

unconsolidated porous media

	grain diameter (mm)	total porosity (%)
coarse gravel	20 – 60	24 – 36
fine gravel	2 – 6	25 – 38
coarse sand	0.6 – 2	31 – 46
fine sand	0.06 – 0.02	26 – 53
silt	0.002 – 0.06	34 – 61
clay	< 0.002	34 – 60

consolidated porous media

	total porosity (%)
siltstone	21 – 41
sandstone	5 – 30
basalt	3 – 35
claystone	1 – 10
limestone	1 – 10
shale	< 10
granite	< 1

- **Total porosity of consolidated porous media (rocks) is usually smaller than total porosity of unconsolidated porous media. However, weathering effects may lead to increased values.**
- **For *unconsolidated* porous media, total porosity tends to increase with decreasing grain size.**

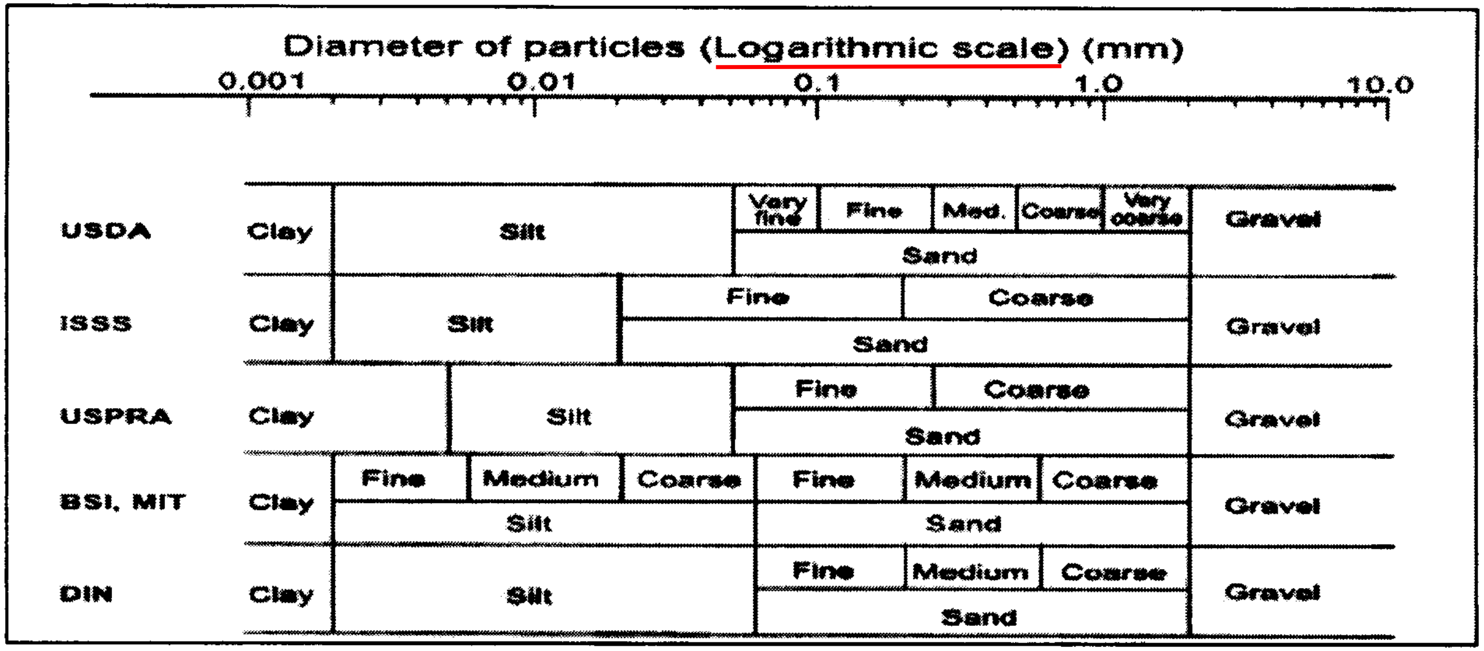
Grain Size Distribution of Unconsolidated Porous Media

Introductory Remarks

- **The ability of unconsolidated porous media to transmit water is highly dependent on the grain size distribution.**
- **The grain size distribution is therefore frequently determined in laboratory experiments in order to deduce important flow properties.**
- **There are five major grain size classes (ordered by increasing diameter): clay, silt, sand, gravel, cobbles (or debris)**
- **The classes for silt, sand and gravel are usually subdivided by "fine", "medium", and "coarse" (or "very fine", "fine", "medium", „coarse", and "very coarse").**
- **Different ranges for individual grain size classes have been defined by different authorities or regulators!**
- **The standard method to determine the grain size distribution of a sample is sieve analysis.**

Classification Schemes

The diagram below includes a couple of classification schemes to define ranges of grain diameters for clay, silt, sand, and gravel.

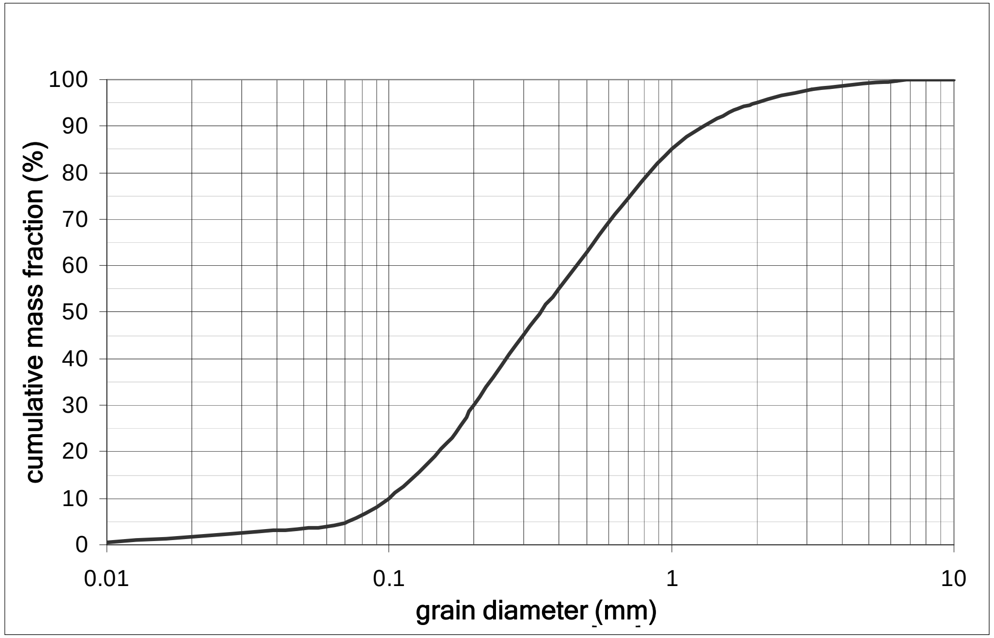


U.S. Department of Agriculture (USDA); International Soil Science Society (ISSS); U.S. Public Roads Administration (USPRA); British Standards Institute (BSI); Massachusetts Institute of Technology (MIT); German Standards (DIN).

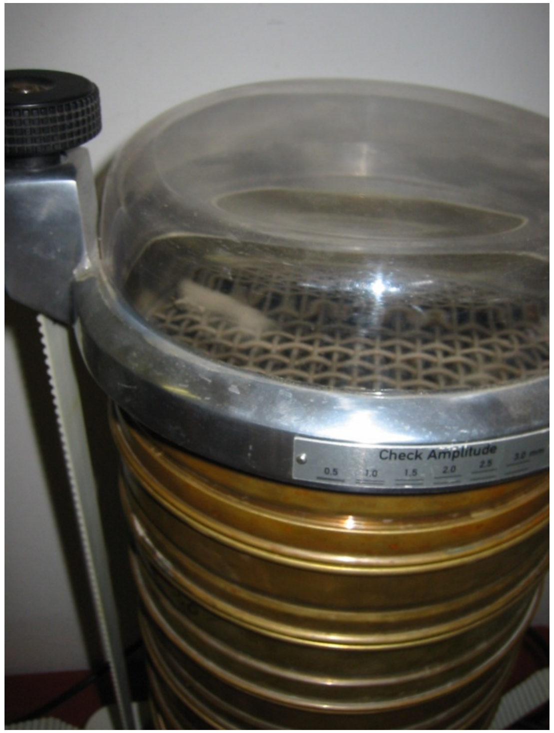
Sieve Analysis

Sample consists of different grain size fractions

granulometric curve

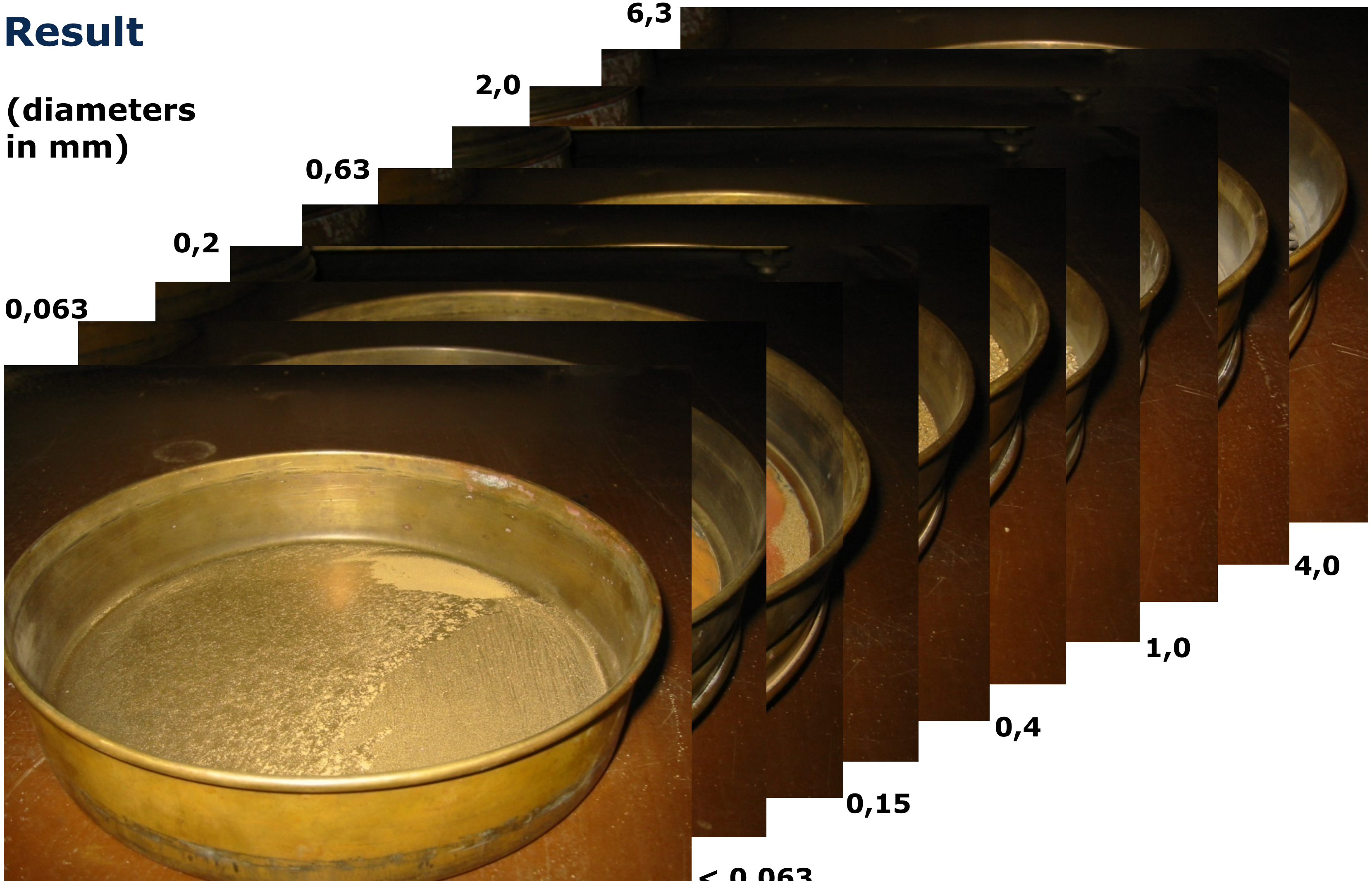


Sieving Machine



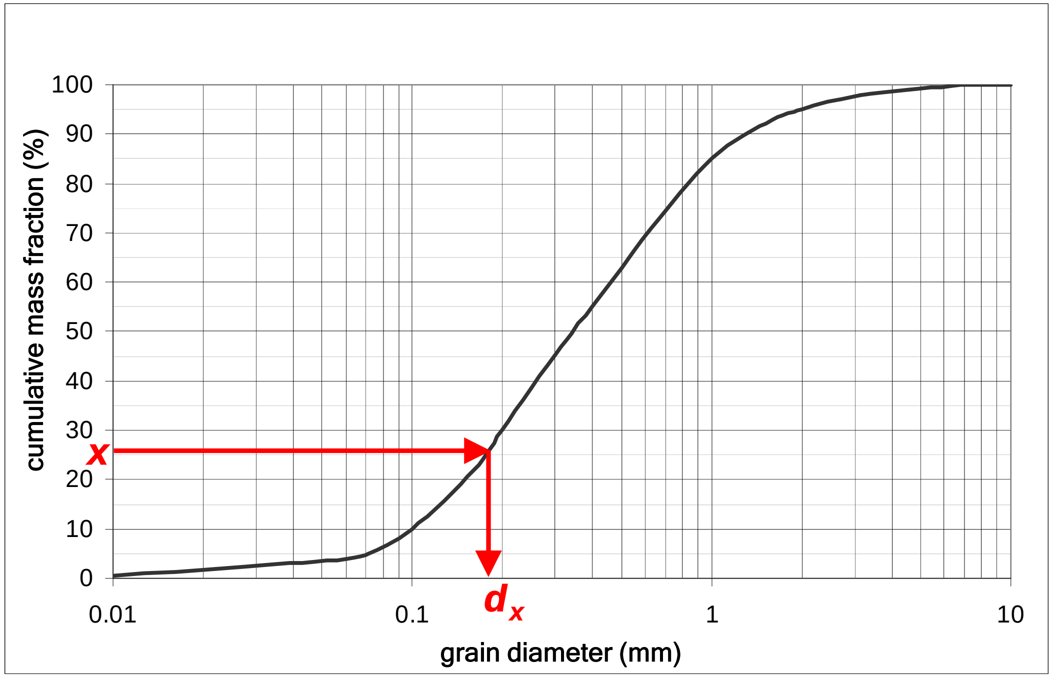
Result

(diameters in mm)



d_x and U

d_x denotes the grain diameter for which x % (in mass or weight, not volume!) of the sieved material is smaller than this diameter.

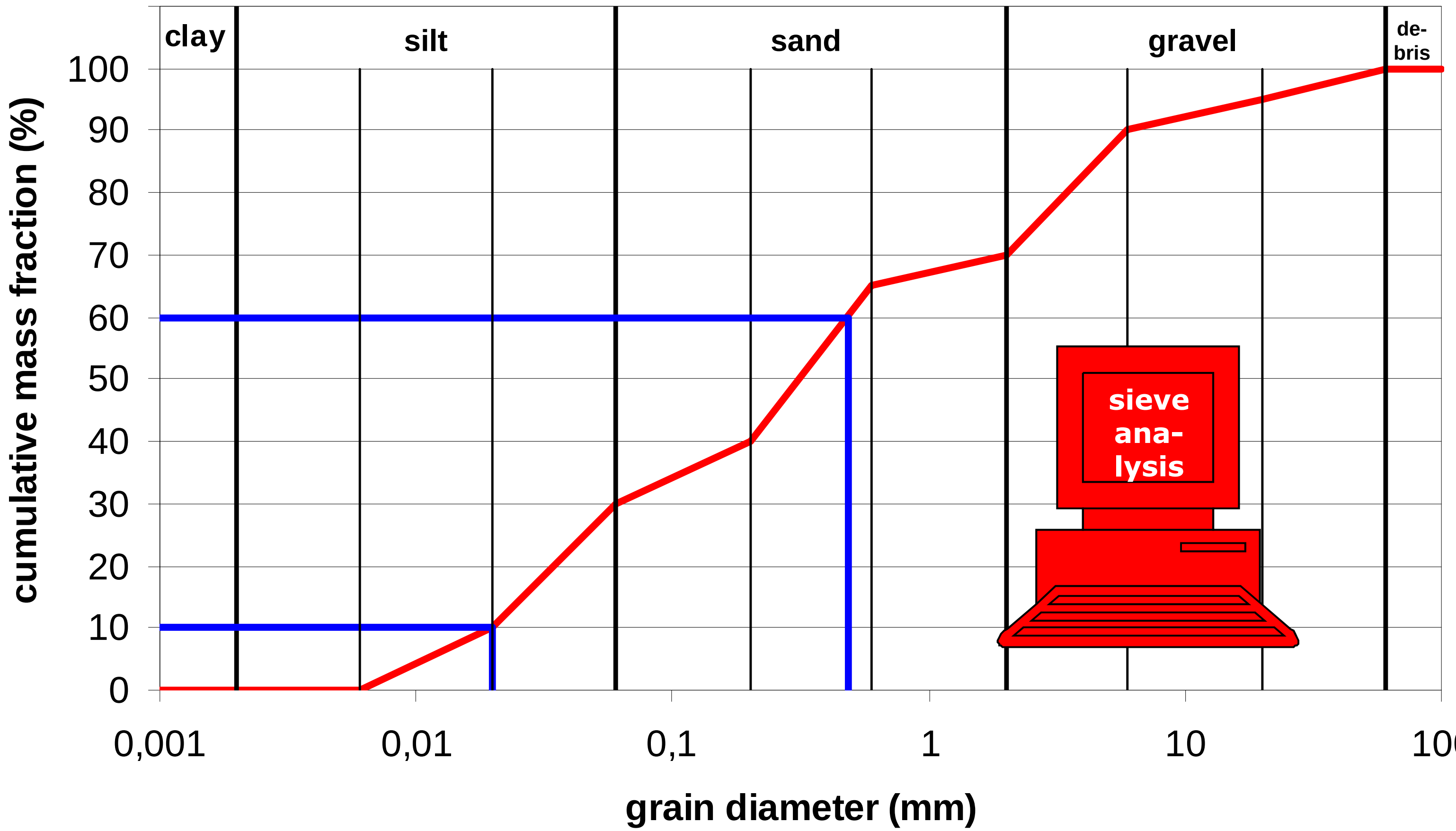


- **Grain diameters d_{10}, d_{60} and d_{75} are of practical importance with regard to groundwater flow properties.**
- **The ratio of d_{60} and d_{10} is called coefficient of uniformity U :**

$$U = \frac{d_{60}}{d_{10}}$$

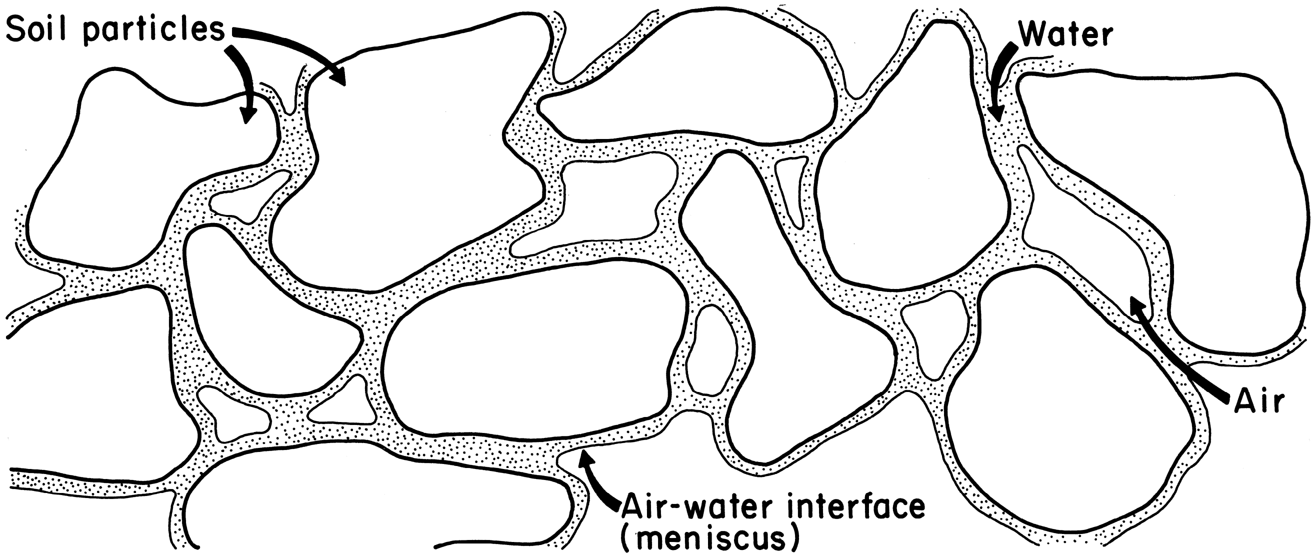
- **d_{75} is specifically used for well construction purpo-ses (not covered by this lecture).**

Example: Sieve Analysis



Subterranean Water

The Subsurface as a Three-Phase System



- **In general, voids in the subsurface are partly occupied by air and water, respectively.**
- **The subsurface can therefore be seen as a three-phase system consisting of a solid phase, a water phase, and a gas phase.**
- **A schematic illustration for voids or <u>pores</u> in an unconsolidated porous medium is given in the figure.**

Some More Volume Ratios

- **The (volumetric) water content is defined as the share of water in the porous medium:**

$$\underbrace{\theta}_{\text{water content [-]}} = \frac{\overbrace{V_w}^{\text{water volume [L}^3\text{]}}}{\underbrace{V_T}_{\text{total volume [L}^3\text{]}}}$$

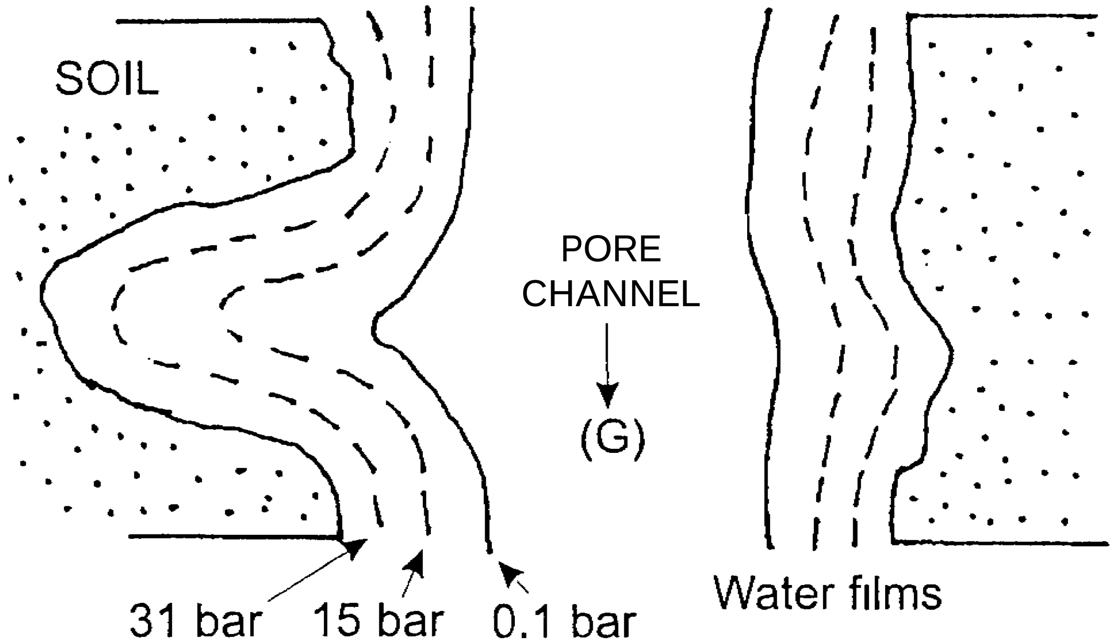
- **The water content cannot exceed total porosity, i.e. $\theta \leq n$.**
- **The degree of saturation is given by the ratio of water volume to void volume:**

$$\underbrace{S}_{\text{degree of saturation [-]}} = \frac{\overbrace{V_w}^{\text{water volume [L}^3\text{]}}}{\underbrace{V_v}_{\text{void volume [L}^3\text{]}}}$$

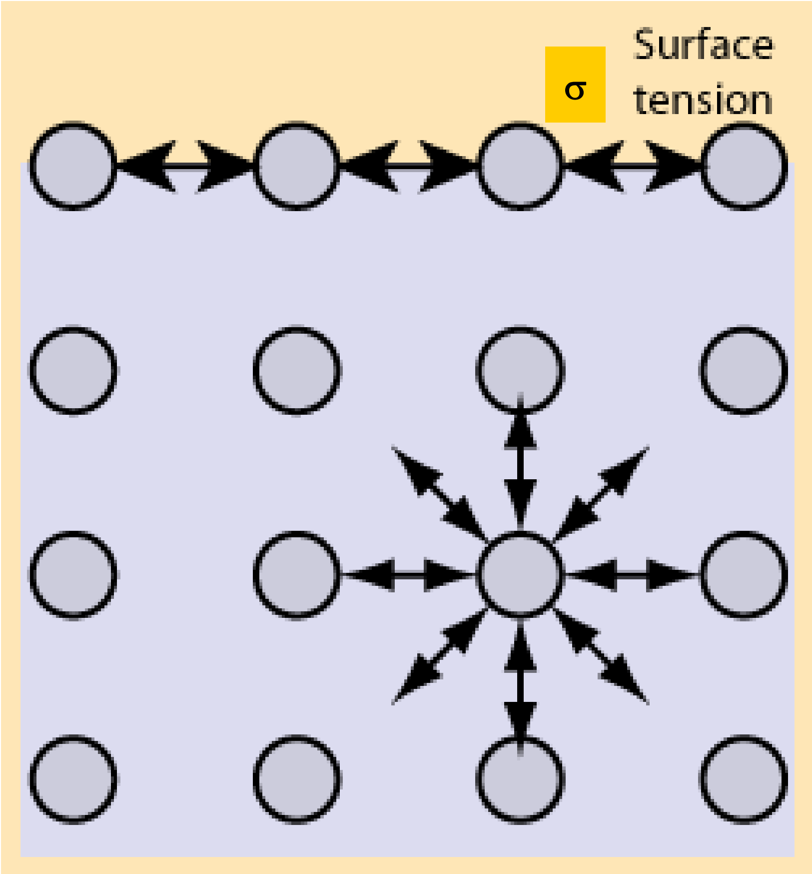
- **The degree of saturation *S* equals θ / n.**
- ***S* may vary between 0 and 1 (or between 0 % and 100 %).**
- ***S* = 0: no water in the voids; *S* = 1: voids are completely filled with water**

Forces Acting on Subterranean Water

- **Subterranean water is subject to several forces.**
- **Most important are**
  – gravity
  – attractive forces between water molecules (cohesion)
  – attractive forces between water and solids (adhesion, see figure).

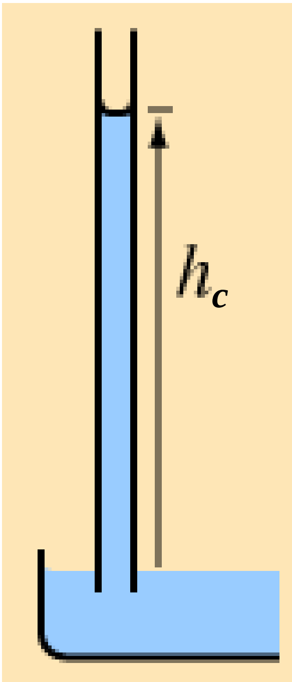


Surface Tension



- **Cohesive forces acting on a water molecule compensate each other if the molecule is not located near the water-air or water-solid interface.**
- **This is no longer true at an interface: cohesive interaction is reduced on one side. The resulting force tends to minimise the interface area.**
- **Macroscopically, this effect is parametrised by the <u>surface tension</u>, which is defined as the energy needed to increase the area of the interface by one unit.**
- **Common units of the surface tension σ are J/m^2 or N/m. (Its dimension is M/T^2.)**
- **The surface tension of water is about $7.5 \cdot 10^{-2}$ N/m at 10 °C.**

Capillary Action



- **Water is subject to capillary action when adhesion is stronger than cohesion.**
- **The capillary rise of water in a tube depends on the surface tension and the tube radius.**
- **The maximum(!) capillary rise is given by:**

$$h_c = \frac{2\sigma_w}{\rho_w g r}$$

surface tension of water [M/T²]

capillary rise [L]

tube radius [L]

density of water [M/L³]

acceleration of gravity [L/T²]

Capillary Action in the Subsurface

- **Capillary action plays a dominant role in the subsurface.**
- **The capillaries are given by the individual pore channels.**
- **Pore channels in poorly sorted material may strongly differ in diameter, such that a certain variability in capillary rise is observed.**