University of Siegen - School of Science and Technology
Dept. of Civil Engineering – Chair of Geotechnical Engineering at the Research Institute for Water and Environment
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Climate change and the influence on structural stability

Prof. Dr.-Ing. habil. Kerstin Lesny

DAAD Seminar, Panama, October 25-29, 2021

UNIVERSITÄT SIEGEN

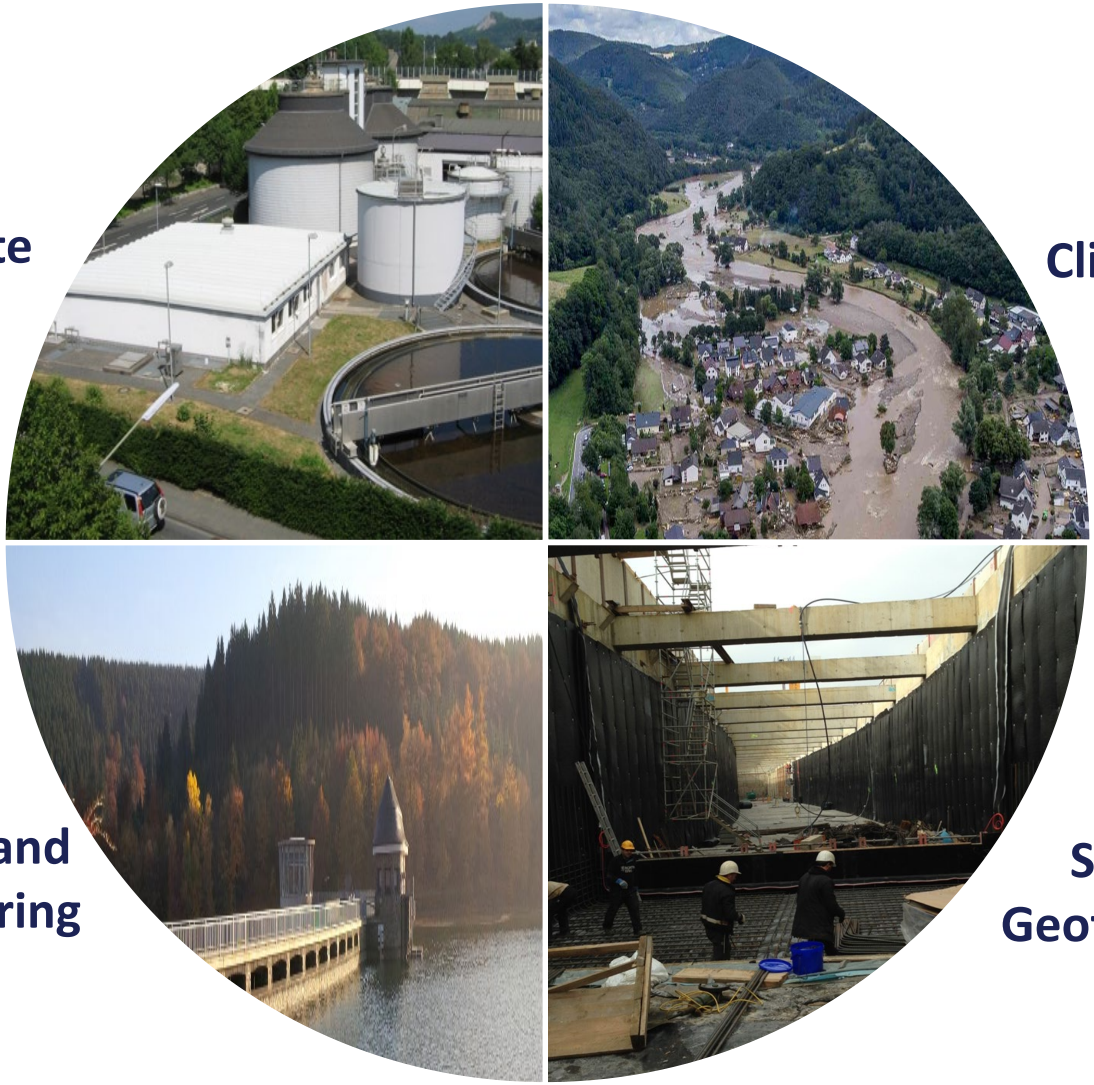
Short Introduction

- Civil Engineer, Geotechnical Engineering
- Graduation as Dipl.-Ing. Civil Engineering in 1996 with in-depth studies on geotechnical Engineering, environmental Engineering and transportation
- Graduation as Dr.-Ing. in 2001 about a consistent failure model for the verification of shallow foundation stability
- Habilitation in 2008 about Foundations for Offshore Wind Energy Converters – Tools for Planning and Design; Venia Legendi in Soil Mechanics and Foundation Engineering
- 2015-2020 Professor for Geotechnical Engineering, HafenCity University Hamburg
- since 2020 Professor for Geotechnical Engineering, University of Siegen
- Research interests:
  foundations for on-/offshore wind energy converters, floating offshore structures, behaviour of shallow and pile foundations under combined loading, environmental geotechnics, safety and reliability of geotechnical structures

Research Institute for Water and Environment (fwu)

Sewage and Waste Technology

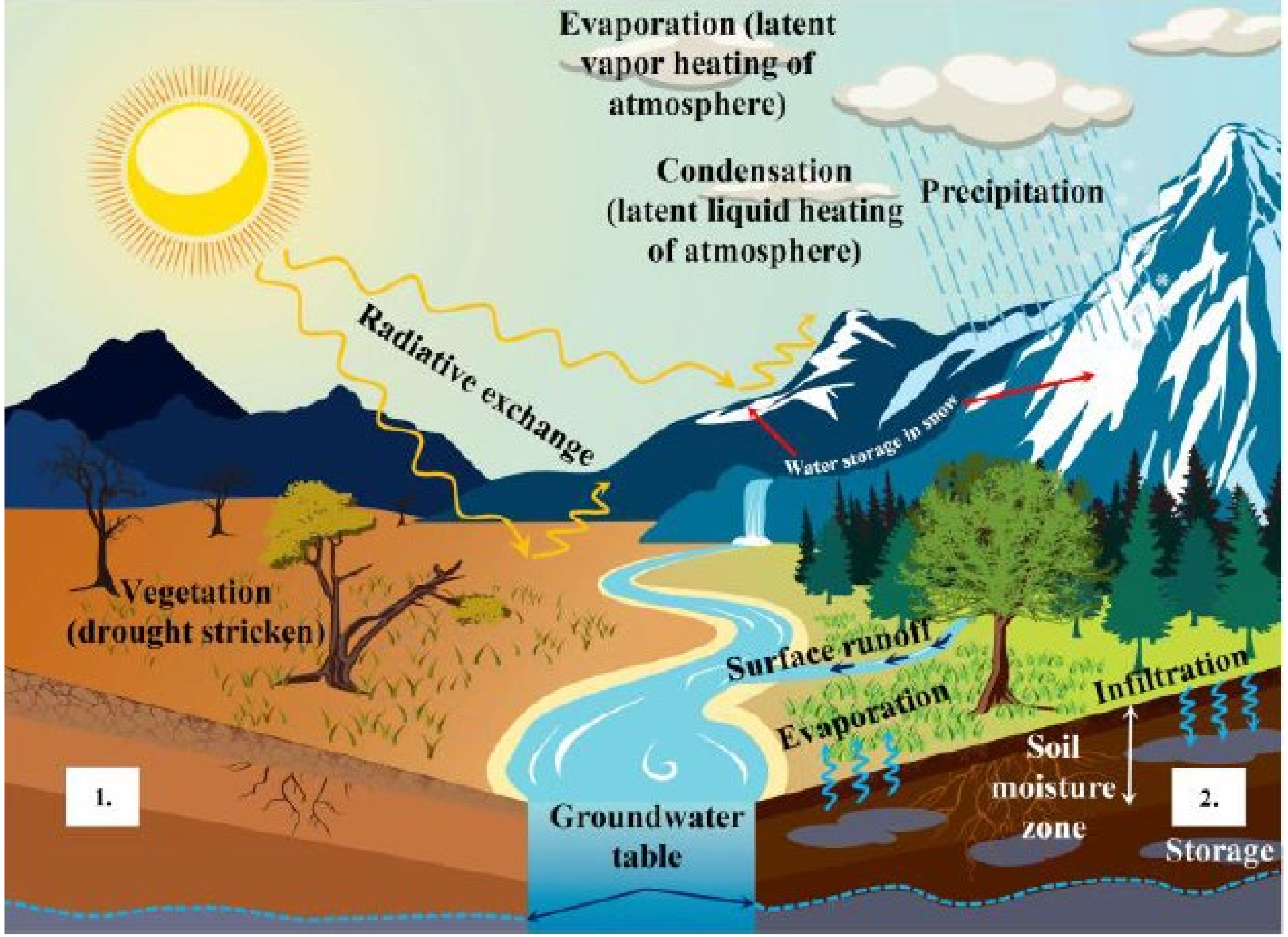
Water Resources Management and Climate Impact Research



Hydromechanics and Hydraulic Engineering

Soil Mechanics and Geotechnical Engineering

Challenges of Climate Change in relation to Soil-Structure-Interaction



(Vahedifard et al., 2018)

Anticipated effects of climate change:

- sea level rise
- more and heavier flood events
- more and heavier rainfall events
- more and longer drought periods, heatwaves
- …

Ground and atmosphere are interrelated!

Challenges of Climate Change in relation to Soil-Structure-Interaction

others

Consequences for Structural Integrity:

- Alteration of **soil properties** of the foundation ground
- Change of **loading conditions** on the structure
- Change of **performance** of the structure deviating from the anticipated design performance

Sustainablity but also **resiliance** of structures against climate impacts becomes more and more important, though not yet in the focus of structural design processes!

Next version of Eurocode 7 will include the principle of robustness and the explicit requirement to consider effects of climate change!

Extract from draft EN 1997-1 (Eurocode 7):

4.1.4 Robustness

NOTE 1 See EN 1990-1, 4.4

NOTE 2 For most geotechnical structures, design in accordance with the Eurocodes provides an adequate level of robustness without the need for any additional measures to enhance robustness.

NOTE 3 Appropriate prognosis of climate change affecting the geotechnical structure during its design service life is considered in 4.3.1.5.

(1) <RCM> Measures to enhance robustness of a geotechnical structure should take into account:

- interaction between different structures or parts of structures;
- interaction between different failure modes affecting the geotechnical structure;
- potential progressive failures in the ground;
- ground conditions with specific issues that are not fully covered by normal design;
- impact on the geotechnical structure due to potential adverse events in the surroundings of the structure;
- erosive influence of running water.

NOTE 1 Ground conditions with specific issues refer to local ground conditions known by comparable experience, to be difficult to handle and with huge consequences e.g. quick clay, swelling ground, liquefiable soils.

NOTE 2 Specification of criteria for application of measures to enhance robustness of geotechnical structure, in addition to design according to Eurocode, can be given in the National Annex.

(2) <RCM> Strategies for designing geotechnical structures for robustness should include providing:

- enough ductility and deformation capacity;
- redistribution of load within the geotechnical structure to avoid sudden collapse;
- increased resistance of identified critical elements within the geotechnical structure;
- larger acceptable excavation tolerances;
- extra drainage capacity by appropriate design of drainage systems;
- measures to prevent scour leading to erosion of soil under and around a geotechnical structure;
- restriction on future loads on the ground surface or the structure.

Extract from draft EN 1997-1 (Eurocode 7):

4.3.1.5 Environmental influences

NOTE See EN 1990-1, 6.1.4.

(1) <REQ> The adverse effects on actions of the following environmental influences shall be considered:

– existing and future climate conditions such as precipitation, temperature and wind;
– freezing and/or thawing of groundwater and surface water;
– mass displacement due to ground improvement, piling, or other installation in the ground;
– increase in groundwater pressure due to construction work or other activities;
– biological activity.

(2) <REQ> In addition to (1), the adverse effects on the design situation of the following environmental influences shall be considered:

– natural and man-made cavities and underground spaces;
– pre-existing activities at regional scale (dewatering, oil or gas extraction, mining);
– climate change effects such as sea level rise;
– natural dissolution features.

(3) <REQ>The adverse effects on the durability of the structure, of the following environmental influences on degradation, corrosion, leaching and erosion shall be considered:

– existing and future climate conditions due to precipitation, temperature and wind;
– freezing and/or thawing of groundwater and surface water;
– electro-chemical composition of ground, groundwater, surface water and any fill;
– salinity of ground, groundwater and surface water;
– mineralogical composition of the ground;
– change of physical, chemical and/or mineralogical composition in the ground;
– evaporation;
– any electrical current flowing in the ground;
– biological activity;
– existing or potential contaminated ground, groundwater, or surface water.

(4) <REQ> The adverse effects on strength and stiffness properties of ground and construction material of the following environmental influences shall be considered:

– existing and future climate conditions due to precipitation, temperature and wind;
– evaporation;
– biological activity;
– freezing and/or thawing of groundwater and surface water.

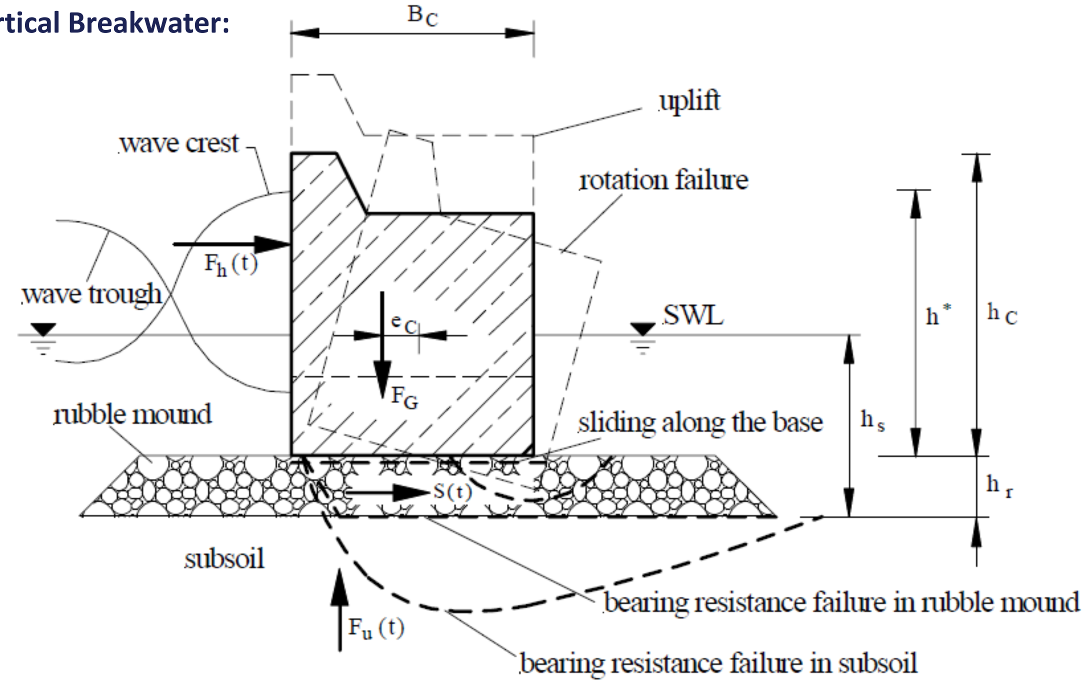
(5) <RCM> The adverse effects of environmental influences other than those given in (2), (3), (4) and (5) should be considered where present.

Concept of Limit State Design

Identify possible limit states:

- Failure modes
- Allowable values of material strength
- Allowable deformation limits
- Other conditions leading to an unwanted state

Vertical Breakwater:



(Lesny & Kisse, 2004)

Define limit state equation: $g(X_i) = 0$

X_i = variable influencing the occurence of the limit state (e.g. geometry, loading, material properties)

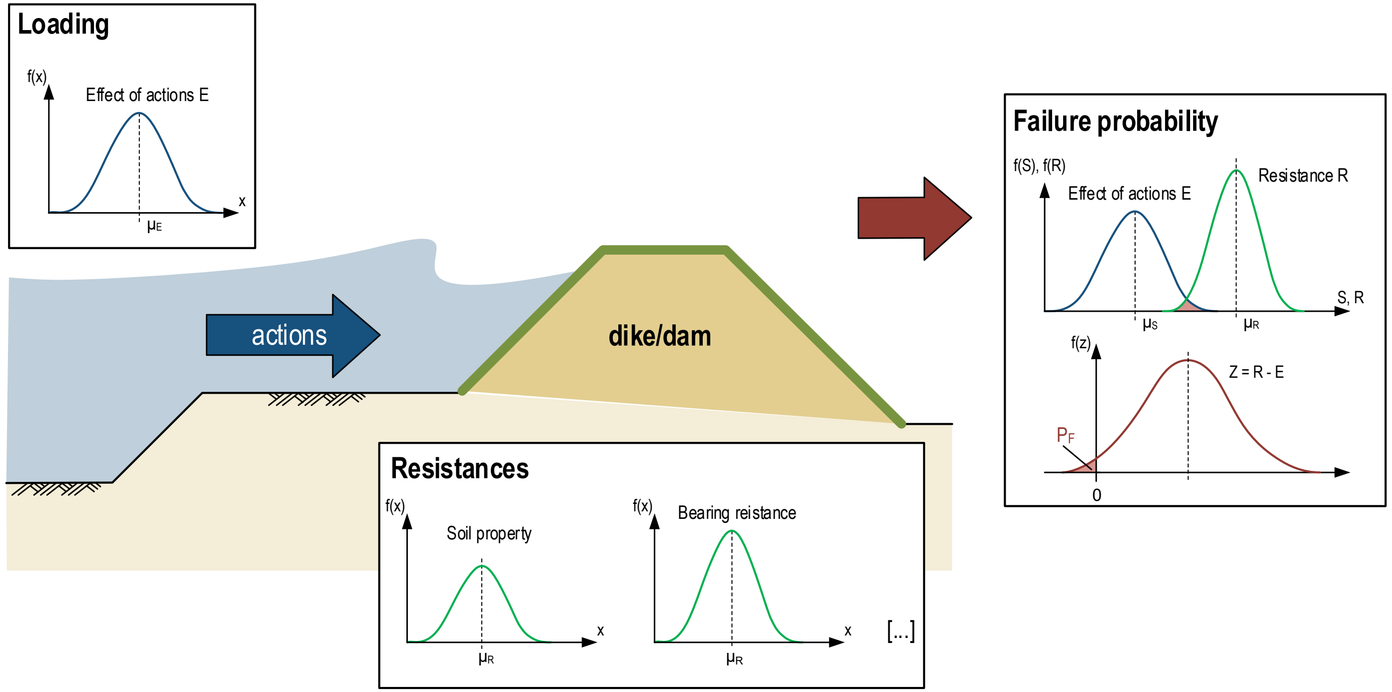
Concept of Limit State Design

If resultant loading = effect of action E and resultant resistance R of the system can be separated, the limit state equation simplifies to:

$$\mathbf{g = R - E}$$

Considerung the probability distributions of R and E the failure probability P_f can be defined:

Note:
- limit state equations are often implicit
- uncertainties related to E and R need to be adequately considered



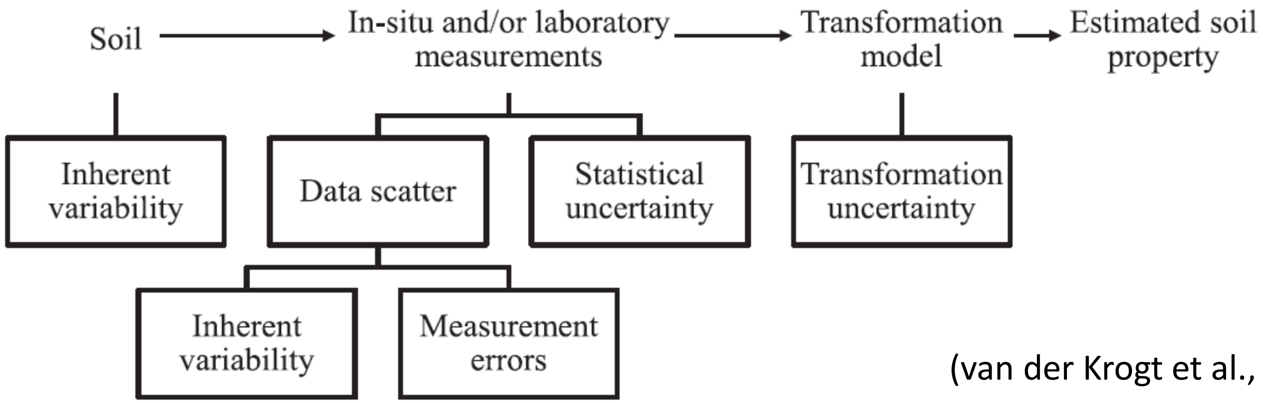
In structural design codes such as the Eurocodes the **partial factor concept** with **fixed safety factors** γ_i on actions or effects of actions and material strength parameters or resistances is applied. It must be therefore verified for each limit state:

$$E_d(\gamma_F \cdot F_k, X_k, a_d) \le R_d(X_k/\gamma_M, F_k, a_d)$$

Sources of uncertainties

in geotechnical design:

- uncertainties in loads/actions
- inherent uncertainty (spatial variability)
- measurement errors
- statistical uncertainty
- transformation uncertainty (deriving soil paramaters from field or lab tests by using correlation equations)
- model uncertainty (models for calculation of loads and resistances)

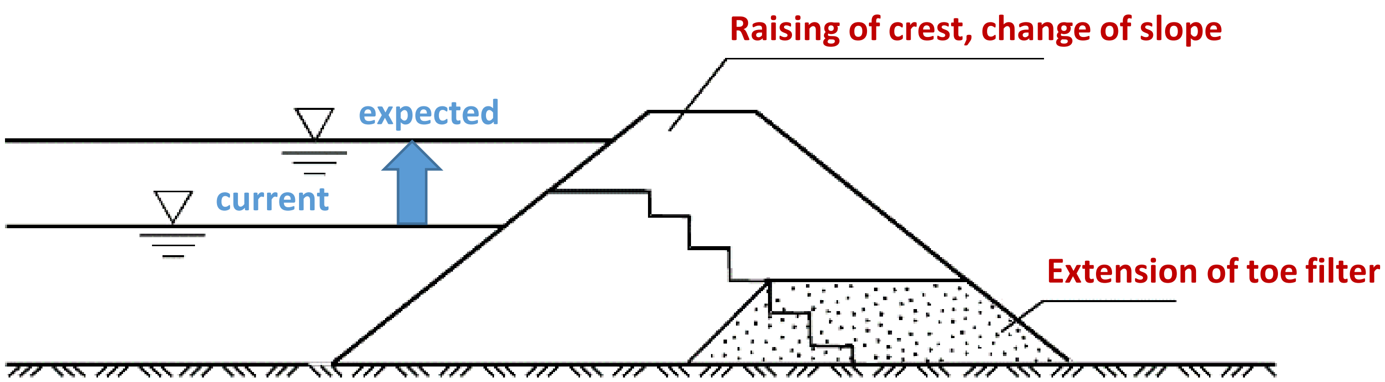


(van der Krogt et al., 2019)

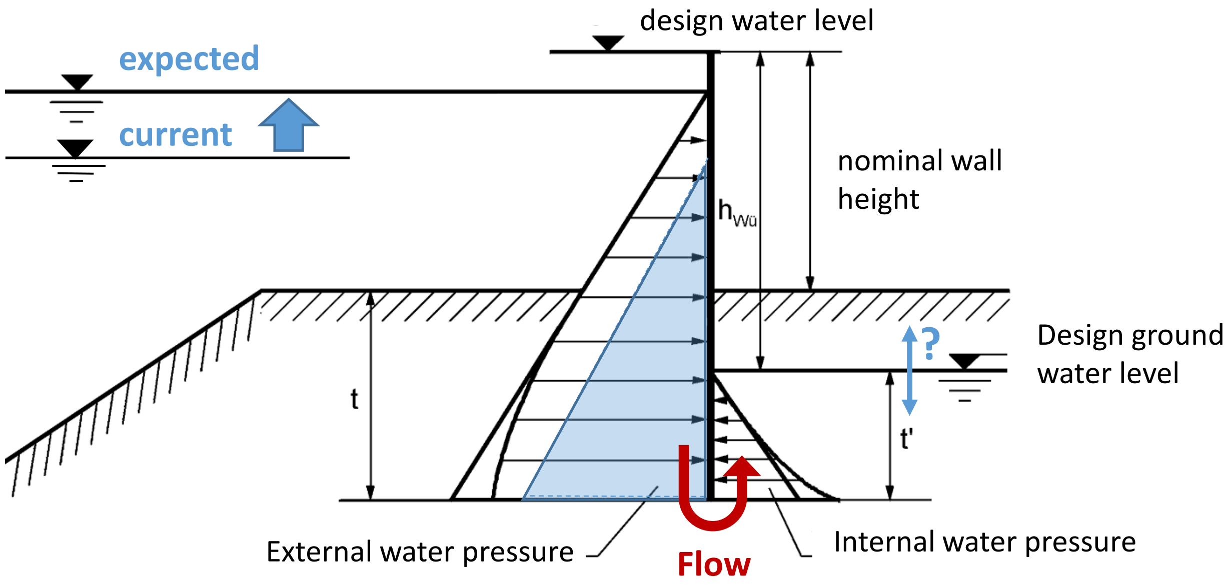
These uncertainties exist without considering effects of climate change!

The challenge is to assess, how these uncertainties will change <u>over time</u>.

Example 1: Dike



Example 2: Flood wall



Change of loading conditions means:

- Adjustment of **geometry** and/or
- Adjustment of **material strength and stiffness** of structure or of ground (e.g. soil improvement)

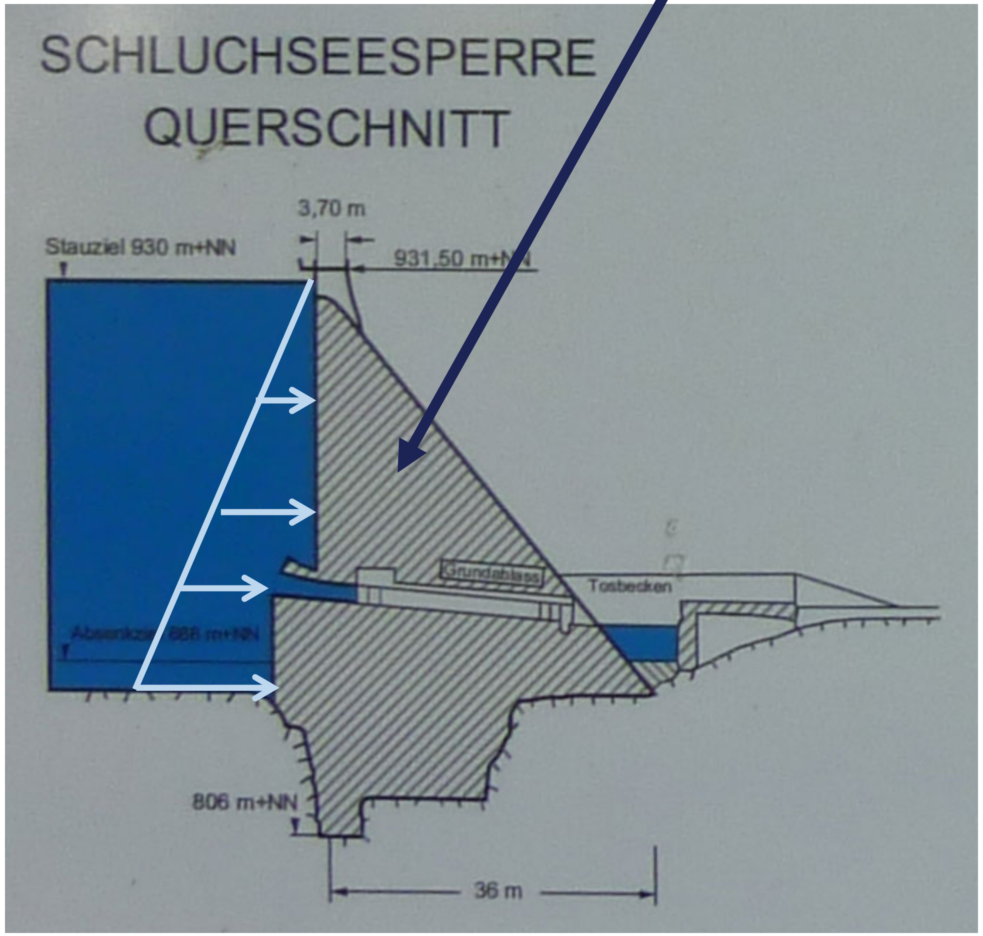
Example: Increase of design water level

- Increase of hydrostatic pressures on walls (e.g. flood walls, quay walls, basement walls) → greater embedment depths and/or larger cross-sections
- Increase of hydrostatic water pressures on horizontal surfaces, e.g. base slabs, caissons → heavier structures and/or additional anchors
- Increase of hydraulic gradients, i.e. increase of flow velocities leading to more internal and external erosion up to hydraulic failure → increase of flow path (e.g. via greater embedment depth)

Example 3: Concrete dam

geometry of structure adjusted to water pressure distribution

Reservoir Schluchsee (picture: Volatus)



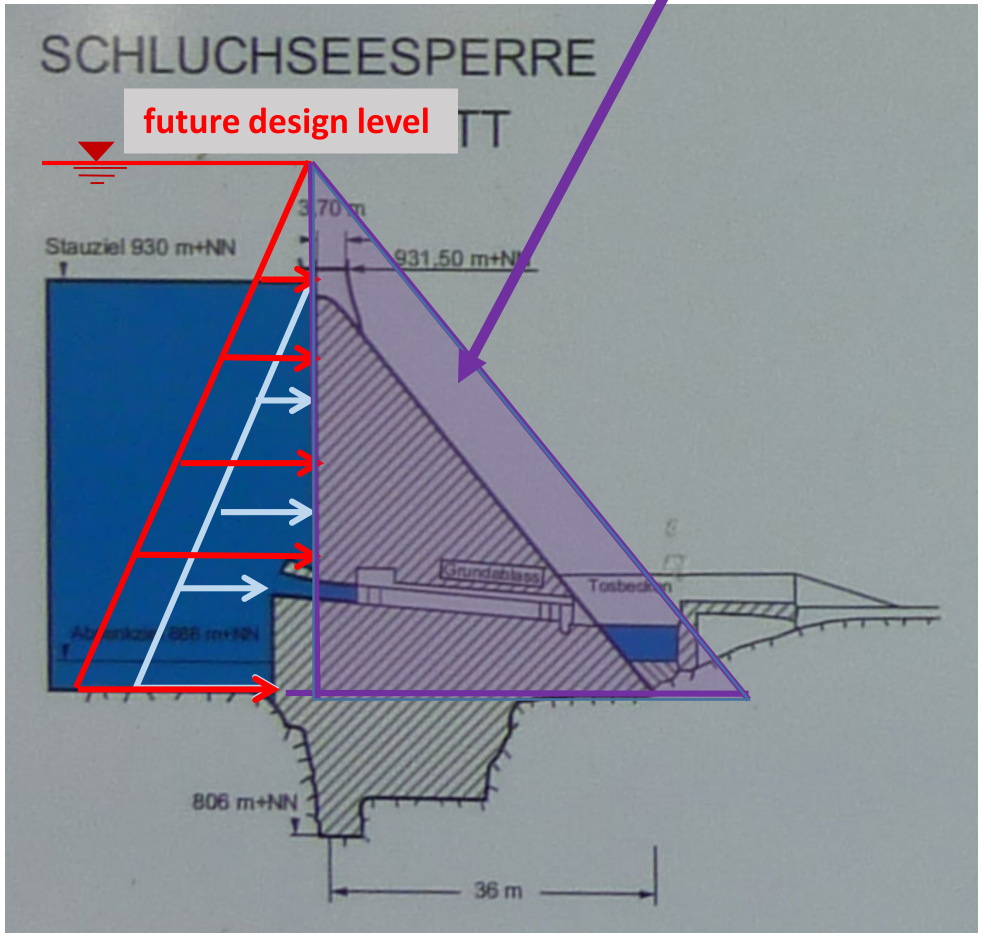
Hydrostatic water pressure on dam (sketch: www.stauanlage.de)

Change of loading conditions

Example 3: Concrete dam

Increase in design reservoir level directly leads to a volume increase

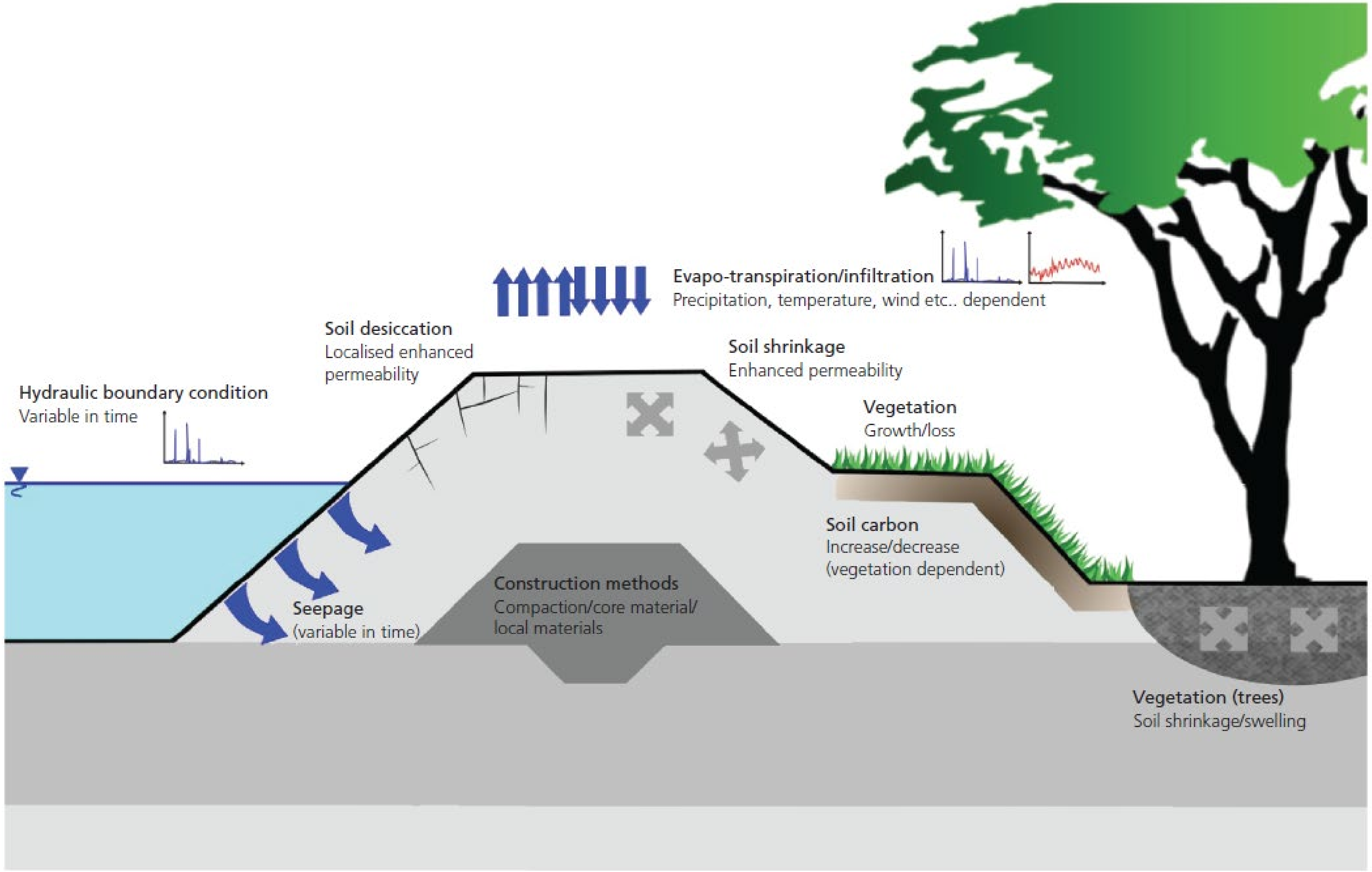
Reservoir Schluchsee (picture: Volatus)



Hydrostatic water pressure on dam (sketch: www.stauanlage.de)

Increased water levels result in bigger structures!

Example of a river dike as an earth structure:



(Vardon, 2015)

Droughts:
Soil desiccation
Soil shrinkage, soil cracking
land subsidence

Floods/rainfalls:
Fluctuation of groundwater table
Seepage through soil
Soil softening due to increased water content
Erosion (internal/external)

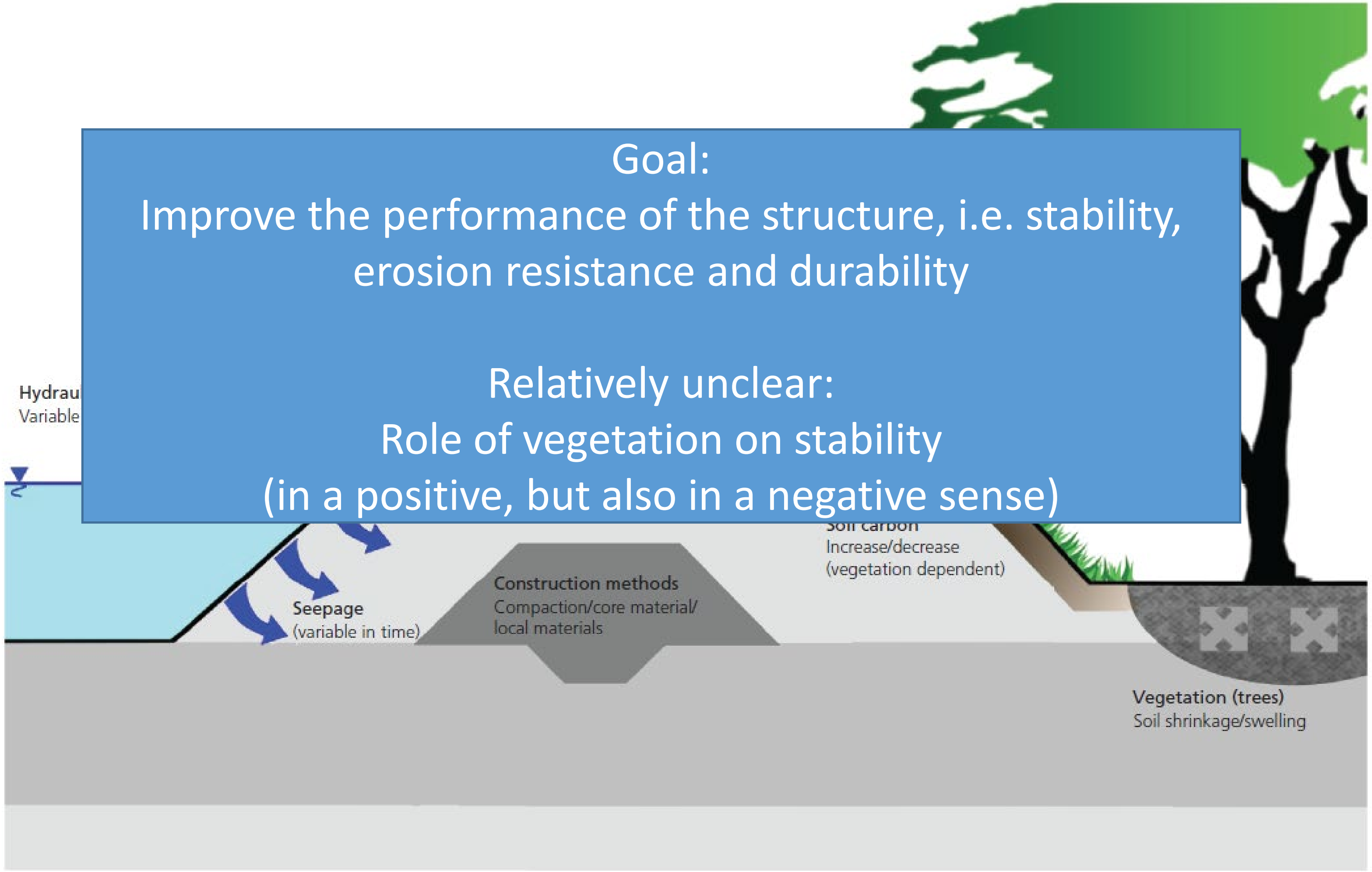
Further:
Change of soil carbon content
Microbiological oxidation of organic matter
Growth or loss of vegetation

- unsaturated soil behaviour
- thermal effects at high temperatures
- thermal effects at low temperatures
- chemical effects

Coupled THM problem

Soil mechanical aspects causing structural instability

Example of a river dike as an earth structure:



Goal:
Improve the performance of the structure, i.e. stability, erosion resistance and durability

Relatively unclear:
Role of vegetation on stability
(in a positive, but also in a negative sense)

(Vardon, 2015)

Droughts:
Soil desiccation
Soil shrinkage, soil cracking
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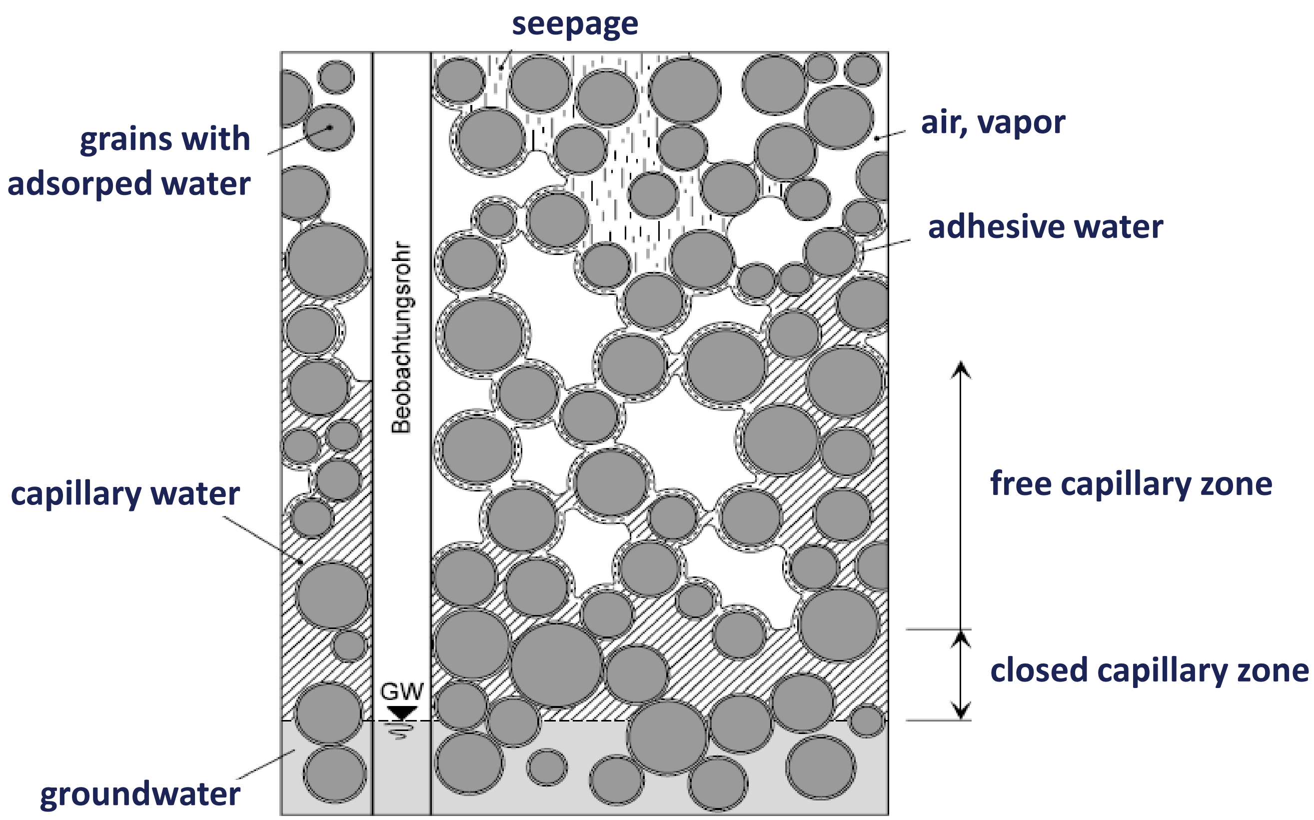
Coupled THM problem

Soil mechanical aspects causing structural instability

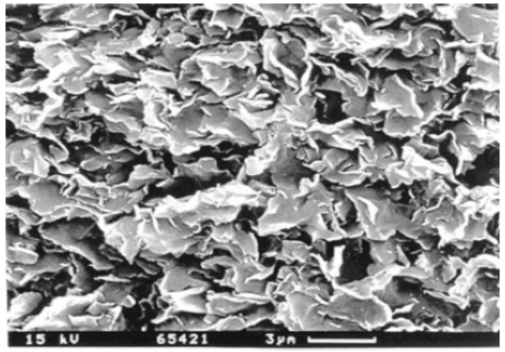
Soil as a multiphase porous medium:



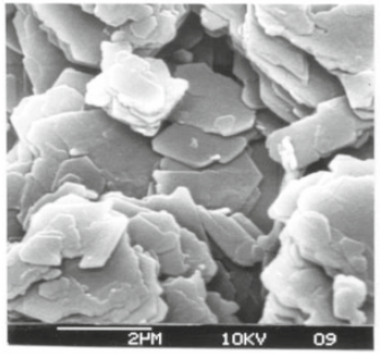
(adapted from Möller, 2013)

Important features:

- non-cohesive soils (sand, gravel) vs. cohesive soils (clay, silt)
- Structure of clay minerals:



Montmorillonit



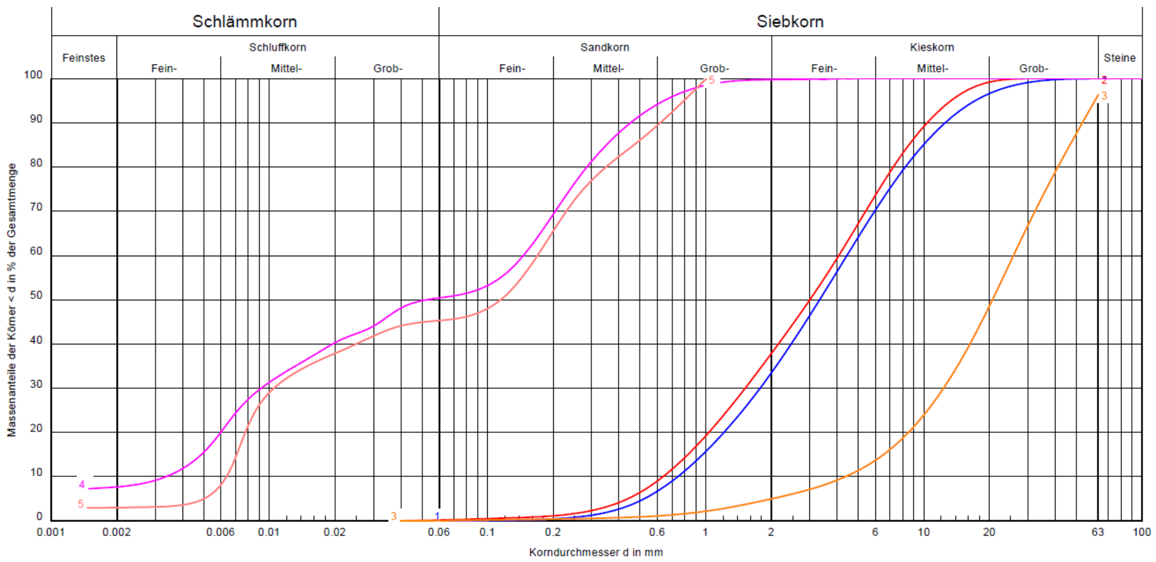
Kaolinit

→ significantly adsorb water

- Grain size and degree of uniformity of non-cohesive soils → erosion/scour
- Carbon content, organic content → compressibility and strength

Soil mechanical aspects causing structural instability

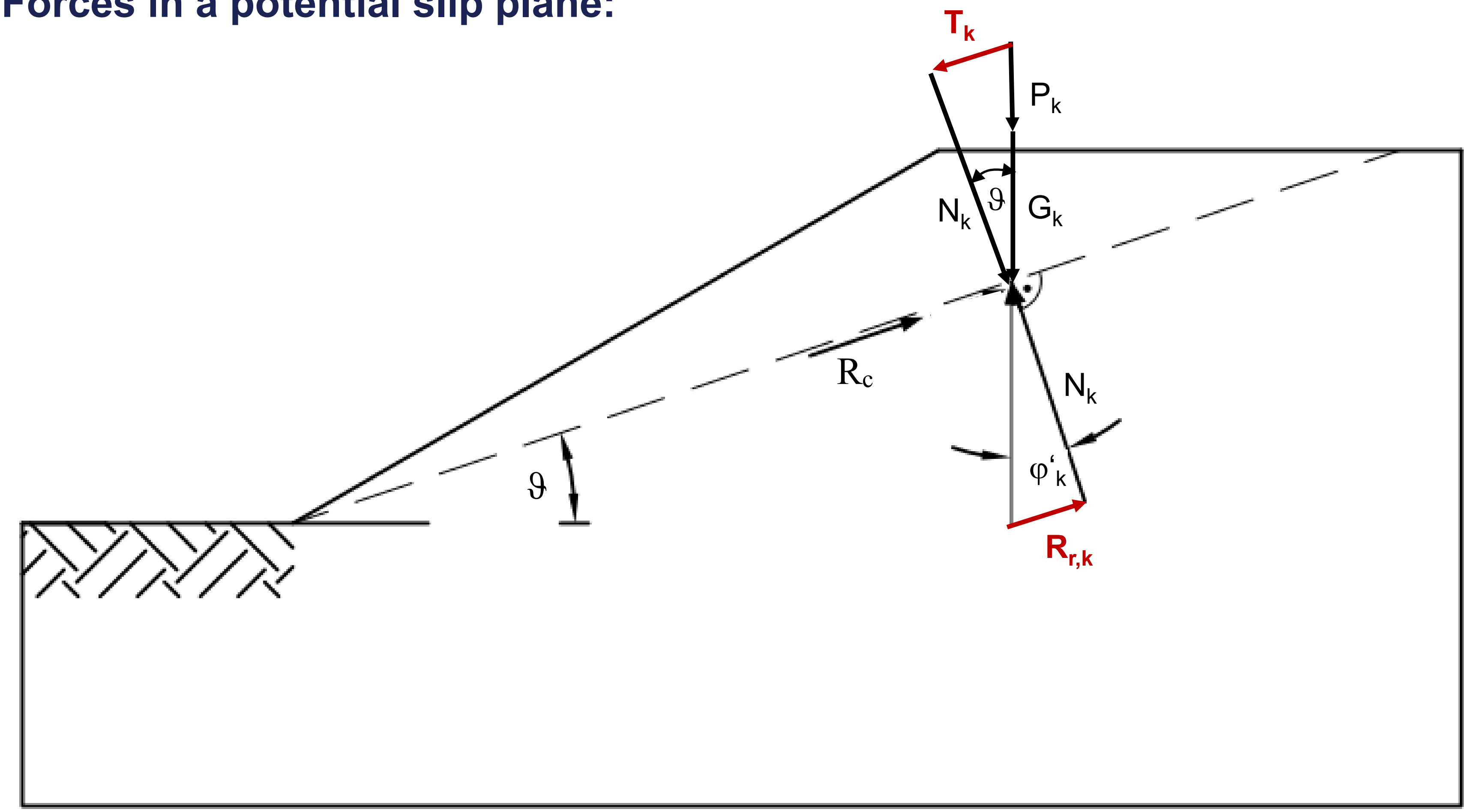
Soil as a multiphase porous medium:



Important features:

- Stresses induced by the structure are transfered in the ground via **grain-to-grain contacts** (effective stresses)
- Dependent on the density of non-cohesive materials and the consistency of cohesive materials
- **Density** determined by the **grain size distribution, degree of uniformity**
- **Consistency** determined by the **natural water content**; it changes over a more or less broad range (plasiticity index PI) from the liquid limit LL to the plastic limit PL
- Density and consistency directly influence strength and stiffness of the soil
- **Partially saturated soils** experience **suction** in the unsaturated soil matrix depending on the **degree of saturation**

Forces in a potential slip plane:



Driving force: $\boxed{T_k = (G_k + P_k) \cdot \sin\vartheta}$

Resisting forces:

- **Due to effective friction:**

$$\boxed{R_{r,k} = N_k \cdot \tan\varphi'_k = (G_k + P_k) \cdot \cos\vartheta \cdot \tan\varphi'_k}$$

- **Due to effective cohesion:**

$$\boxed{R_{c,k} = c'_k \cdot l_c}$$

(drained case only)

Based on Coloumbs failure criterion for shear strength in the slip plane: $\tau_f = \sigma' \cdot \tan\varphi' + c'$

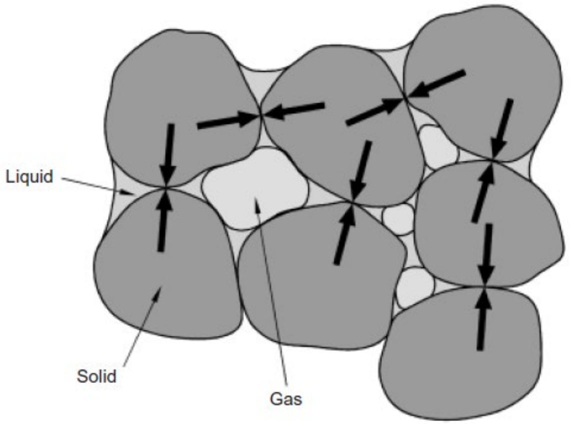
Effects on slope stability

- In the fully saturated soil zone (below groundwater table) σ‘ is the effectice stress according to Terzaghi:

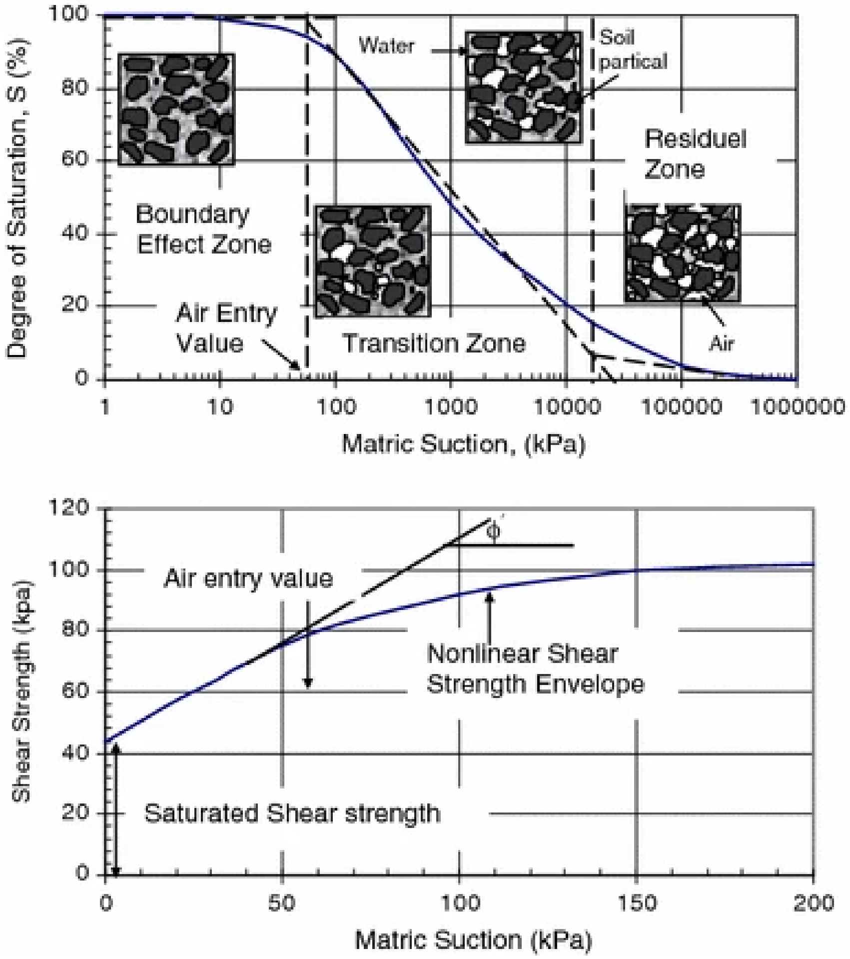
  $\sigma' = \sigma - u$ (σ: total stress and u: pore water pressure)

- In partially saturated soils the shear strength τ_f is increased due to suction which depends on the degree of saturation S_r:

  Example formulation: $\tau_f = (\sigma - u_a) \tan \varphi' + \underbrace{\mathbf{(u_a - u_w)\, S_r \cdot tan\, \varphi'}}_{\textbf{suction strength}} + c'$



(Gens, 2010)



(Vanapelli et al., 1996)

In conventional design this effect is often neglected!

Effects on slope stability

- Shear strength in the saturated zone depends on groundwater level and its fluctuations which lead to changes in the pore water pressures
- Shear strength in the partially saturated zone depends on the degree of saturation and is therefore directly linked to infiltration or desiccation processes
- Wetting of the soil in this zone may lead to a loss of the suction strength and can therefore be a trigger for rainfall induced landslides:

(Gariano et al., 2015)

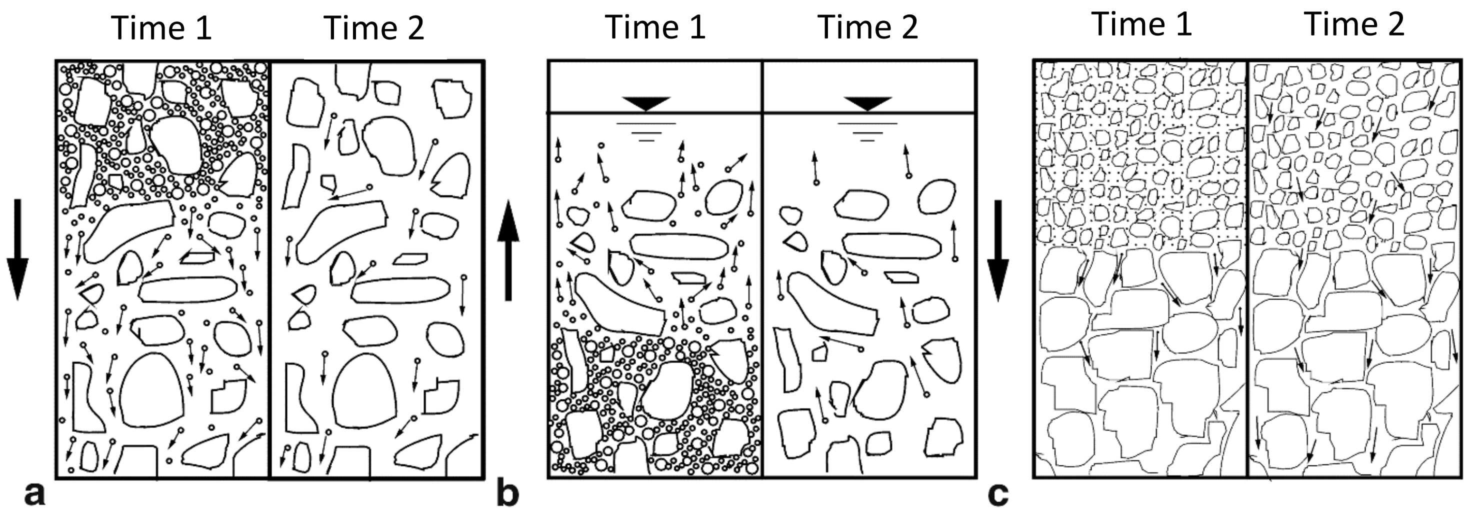
(Filho & Fernandes, 2019)

Internal/external erosion induced by flow gradients in the ground

a) Movement of smaller grains within soil matrix
b) Movement of smaller grains out of soil matrix at free surfaces
c) Movement of grains from fine-grained soil into coarser soil layer at the contact surface of soils with different grain size distribution

Hydraulic gradient: $\mathrm{i} = \frac{\Delta H}{\Delta L}$

with ΔL: Flow path around structure in the ground

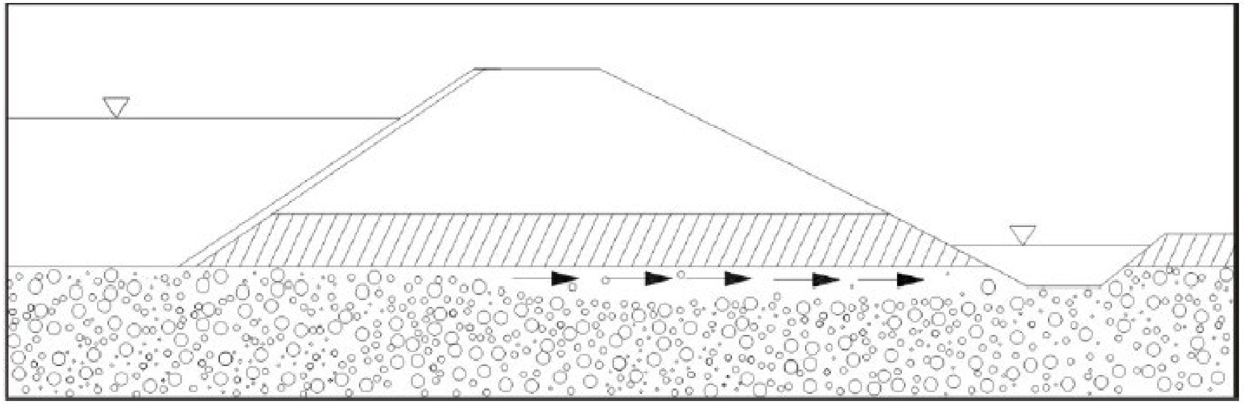


(Busch et al., 1995)

- Matrix of larger grains remains, porosity and permeability increase, density, stiffness and strength decrease (a) and b))
- Especially non-uniform non-cohesive soils are prone to internal erosion (a) and b))
- Smaller soil grains may clog pores of the coarse soil); porosity and permeability decrease, density increases; possible ponding of water (c)

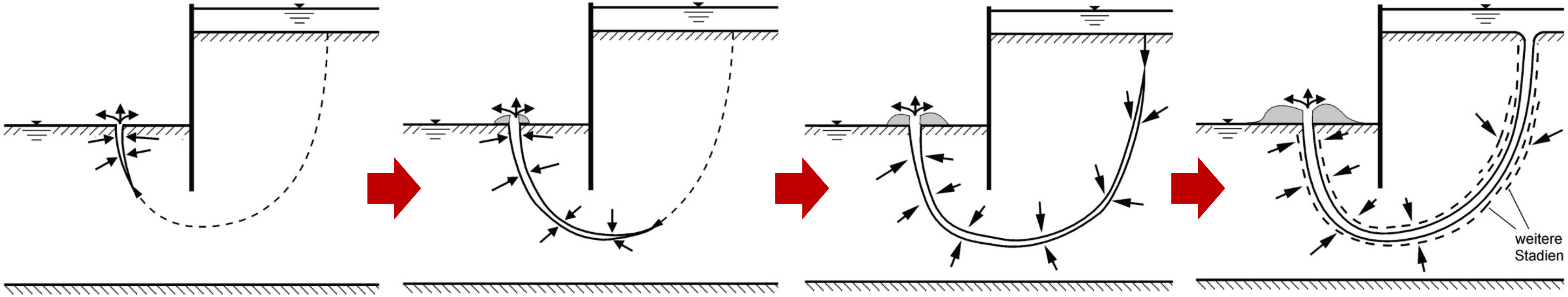
External erosion induced by flow gradients in the ground

- Along impermeable surfaces:



(BAW, 2013)

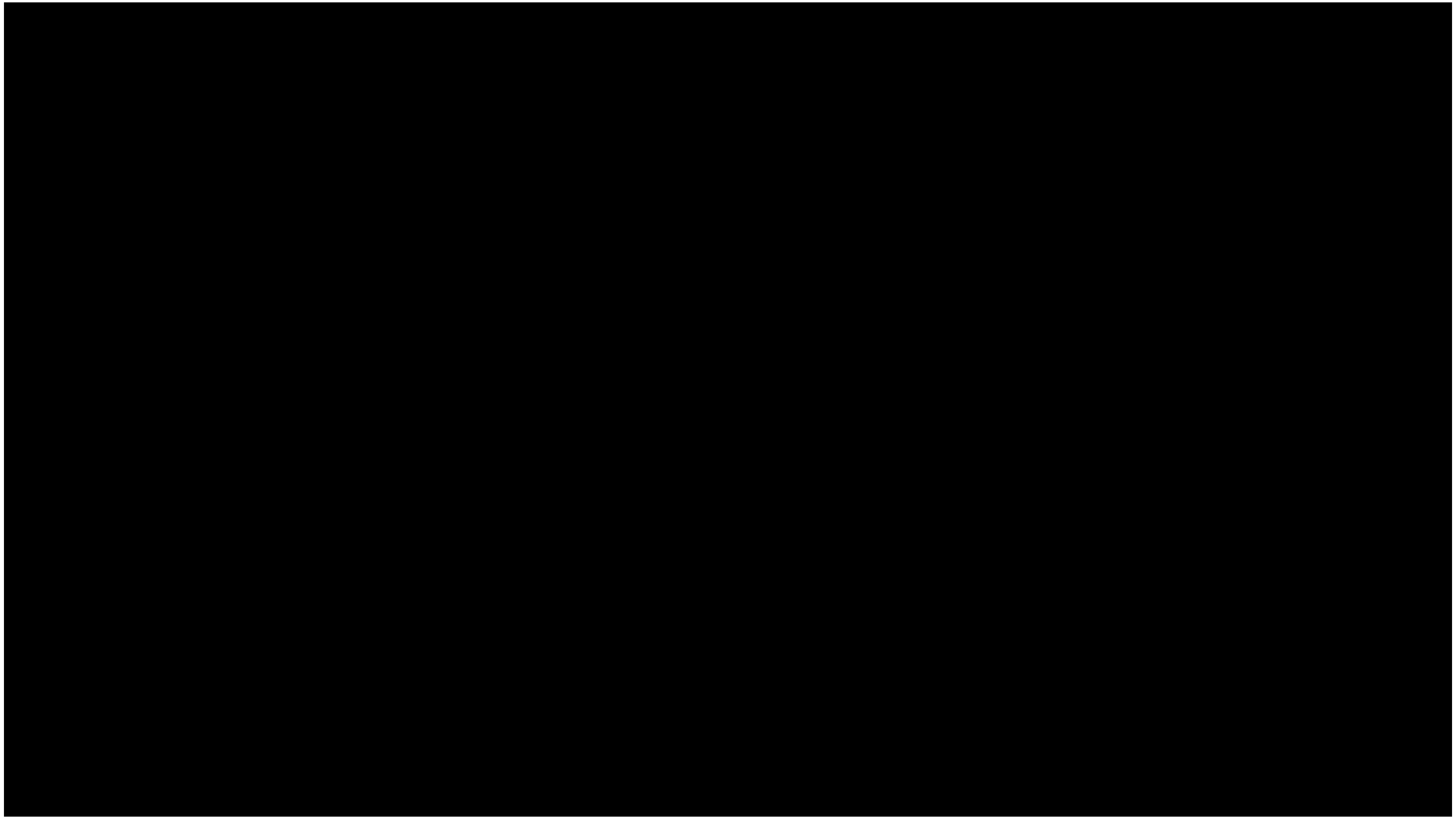
- **Piping:**



(Lesny, 2020)

Erosion and hydraulic failure

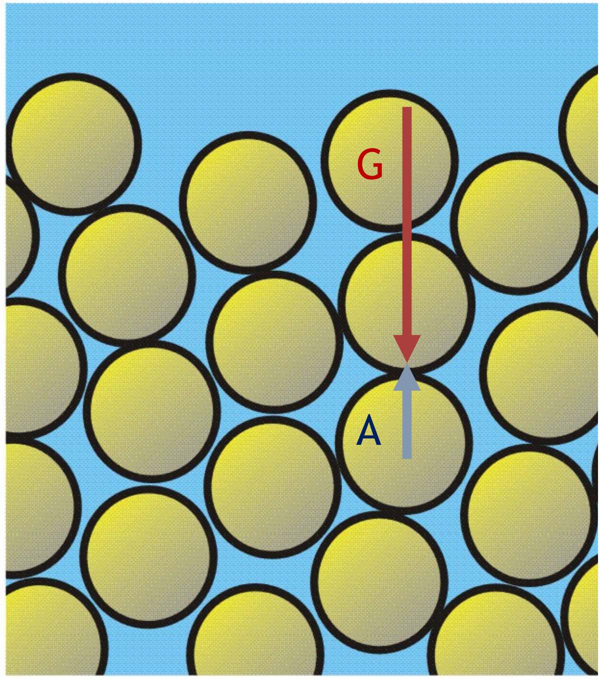
Dam failure caused by piping



(Association of State Dam Safety Officials (ASDSO))

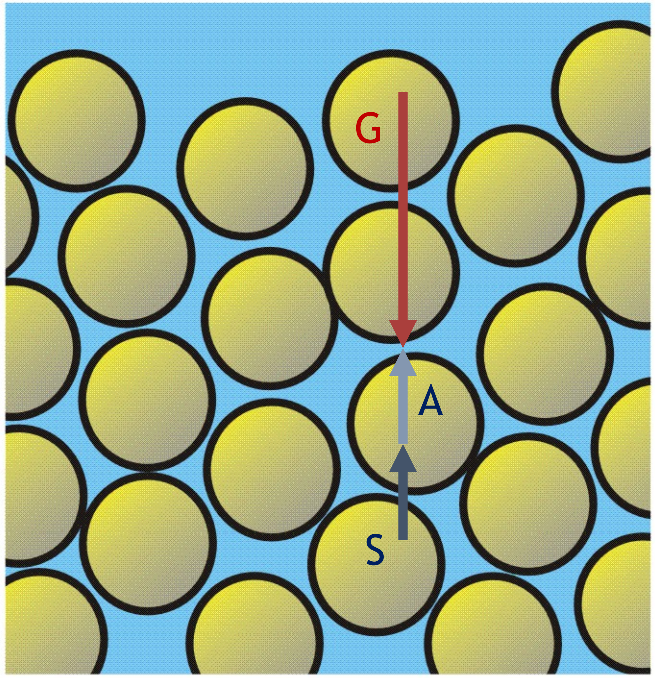
Initiation of erosion in the ground

Phase 1



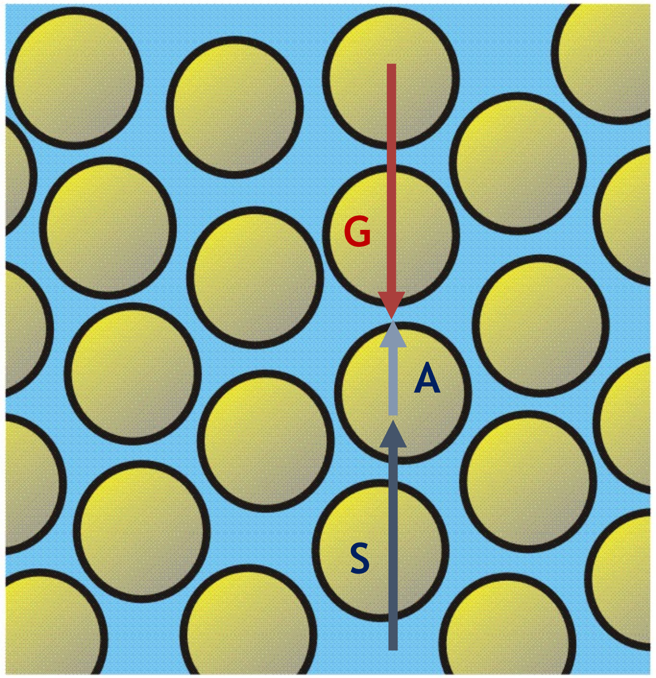
No flow: weight of grains (G) larger than uplift force (A): **stable**

Phase 2



Flow: additional flow force S, grain matrix still intact: **stable**

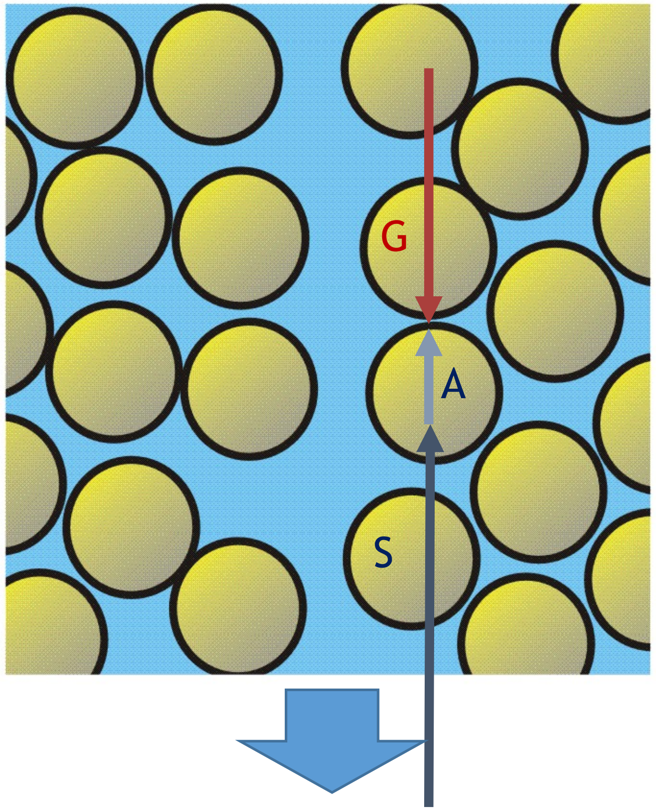
Phase 3



Increasing hydraulic gradients, increasing S: **grains loose contact**

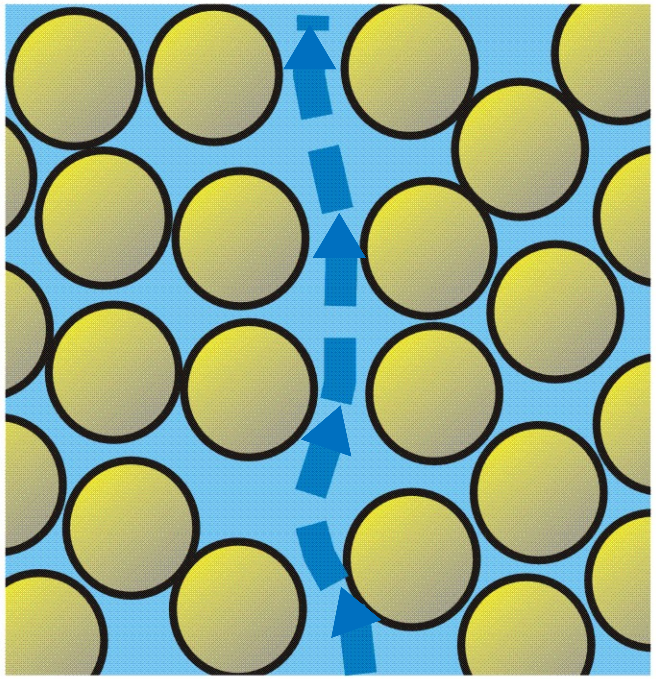
Initiation of erosion in the ground

Phase 4



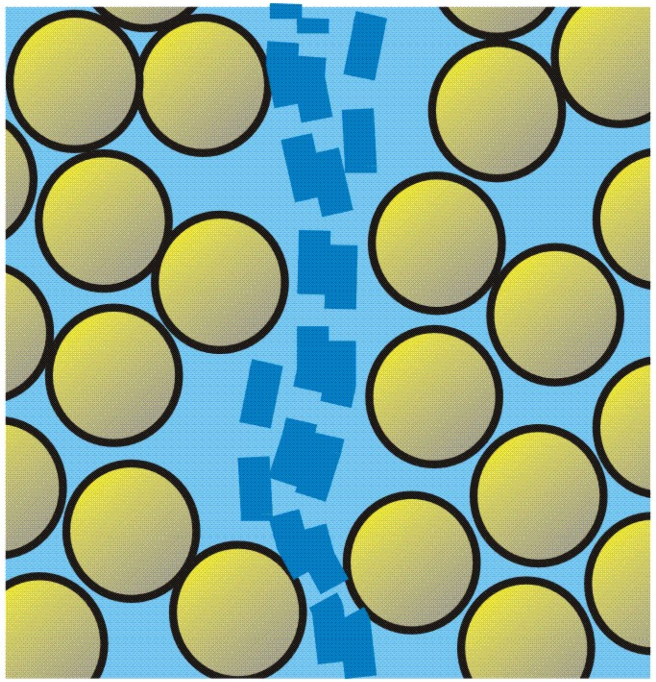
Soil volume increases by increase of pore space; grains can start moving: instable

Phase 5



Erosion channels start to develop; increased flow velocity in channels

Phase 6



Progressive process

Conclusions

- Climate change will have significant effects on the structural stability
- These effects are caused not only by changes of the loading, but especially by changes of the characteristics of the foundation ground!

Existing infrastructure		
Climate change feature	Potential impact on geotechnical infrastructure	Potential failure mode
Increased temperature	Drying	Uplift
Decreased precipitation (drought)	Soil desiccation	Piping, internal erosion, slope stability
	Soil shrinkage	Piping
	Reduction of vegetation/soil erosion	Piping, slope stability
Increased mean precipitation	Some soil erosion/loss of soil quality	Erosion, piping
	Change in water table leading to instability	Slope stability
Intense precipitation	Significant soil erosion	Piping, slope stability
	Rapid soil wetting, highly dynamic pore pressure changes potentially	Slope stability
	Flooding	Piping, internal erosion, slope stability
Freeze/thaw cycles	Loss of soil structure	Slope stability
New infrastructure		
Climate change feature	Potential impact on geotechnical infrastructure	Potential failure mode
Drought	Reduction of moisture content of fill (compaction more difficult) and mixing of fill with water is expensive	Cost, serviceability failure
Increased precipitation/ Intense precipitation	Collapsing of some fill material due to wetting	Slope stability, serviceability failure

(Vardon, 2015)

Conclusions

- Climate change will have significant effects on the structural stability
- These effects are caused not only by changes of the loading, but especially by changes of the characteristics of the foundation ground!

Existing infrastructure		
Climate change feature	Potential impact on geotechnical infrastructure	Potential failure mode
Increased temperature	Drying	Uplift

A risk-based approach is required to adequately tackle the manifold technical but also non-technical effects and their interelations on the structural stability in an interdisciplinary approach.

New infrastructure		
Climate change feature	Potential impact on geotechnical infrastructure	Potential failure mode
Drought	Reduction of moisture content of fill (compaction more difficult) and mixing of fill with water is expensive	Cost, serviceability failure
Increased precipitation/ Intense precipitation	Collapsing of some fill material due to wetting	Slope stability, serviceability failure

(Vardon, 2015)

Thank you very much for your attention!

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