LA CONGÉLATION _

ARTIFICIAL FREEZING OF SOILS IN CIVIL ENGINEERING

Sven Kessler

Geotechnical parameters and Laboratory tests

Paramètres géotechniques et Essais Laboratoires

CFMS SCIENTIFIC AND TECHNICAL DAY _ NOVEMBER 17TH 2023

COMITÉ FRANÇAIS DE MÉCANIQUE DES SOLS ET DE GÉOTECHNIQUE

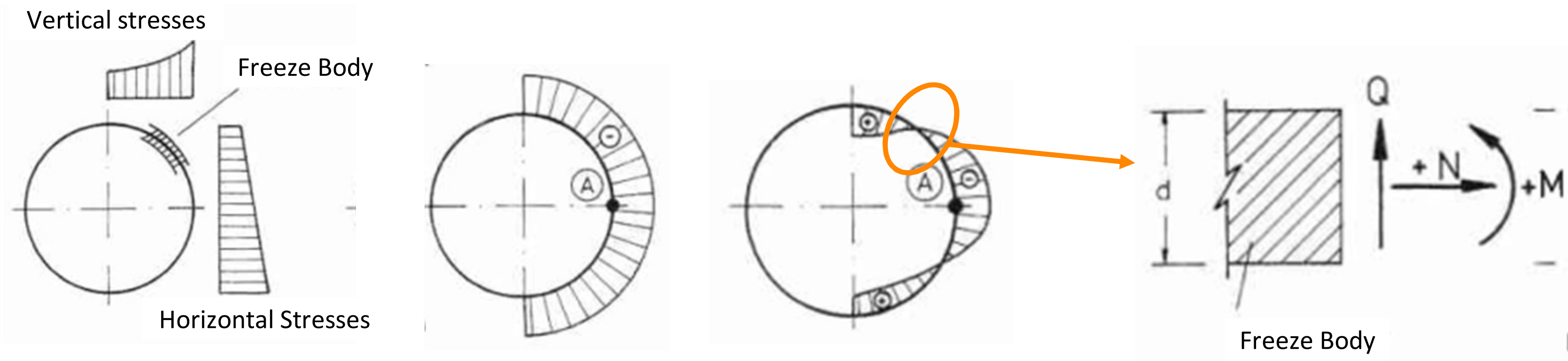
Excurses:
Design of a Freeze Body

Excursus: Design of a Freeze Body

Design Approach

Basic procedure

- Determination of the earth and water pressures acting on the system
- Determination of the internal forces



- Determination of the stress distribution across the frost body cross-section /FE element assuming the relationship: $\sigma = \frac{N}{A} \pm \frac{M}{W}$

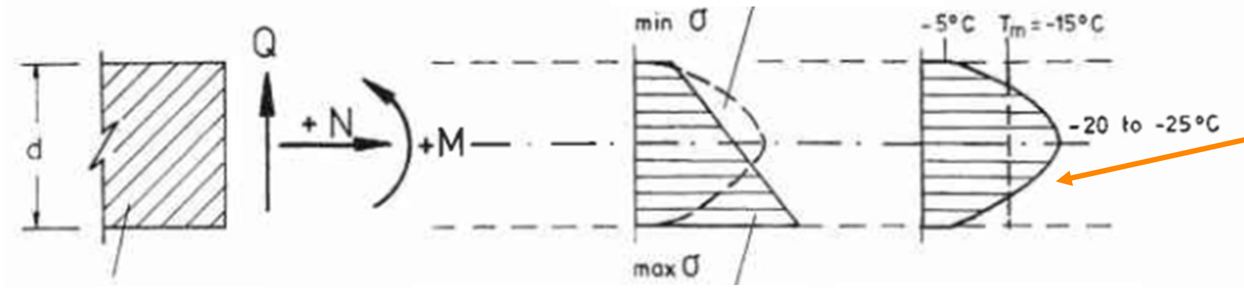
Design Approach

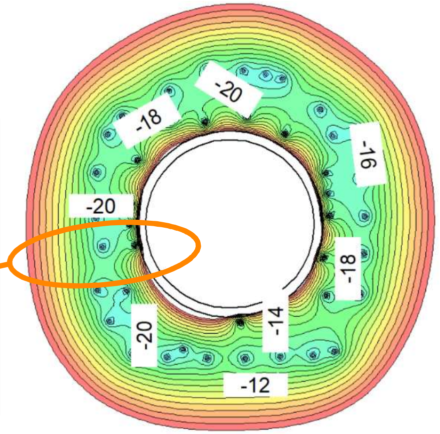
Basic procedure

Note: Temperature curve over cross-section not constant!

- High strength in the centre of the frost body (cold)
- Strength at the edge low ("warm")

Stress distribution after plasticize of the frozen soil





Freeze Body

Linear stress distribution according elasticity theory

Temperature Field

- Tolerable stresses at the edge can be exceeded
  → Plasticizing → Stress redistribution → Stress distribution → Temperature distribution

Excursus: Design of a Freeze Body

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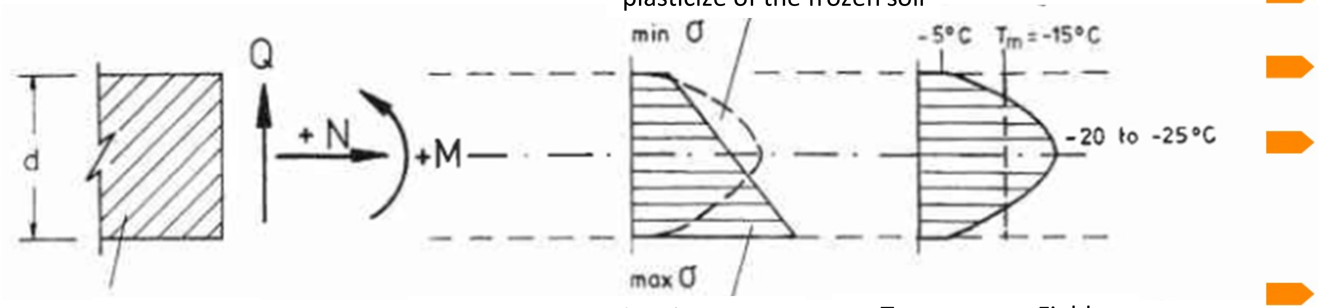

Freeze Body

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- Tolerable stresses at the edge can be exceeded
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Required Parameters for design

- **General: Compressive strength q**
- **Deformation: Modulus of Elasticity E**
- **Plasticization (Mohr-Coulomb):**
  - Shear Strength φ
  - Cohesion c
- **All parameters temperature depended**

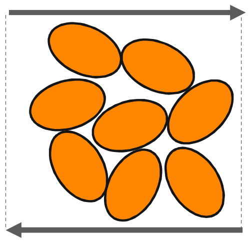
Excursus: Soil as a 3 Phase Medium

Mineralogical view

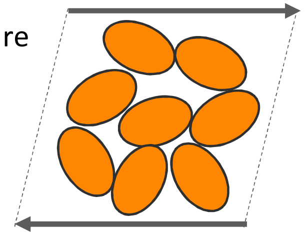
- Soil as a 3-phase medium

Soil Particles (solid) — air (gas); water (fluid) — water / ice — Temp. — saturation / water content

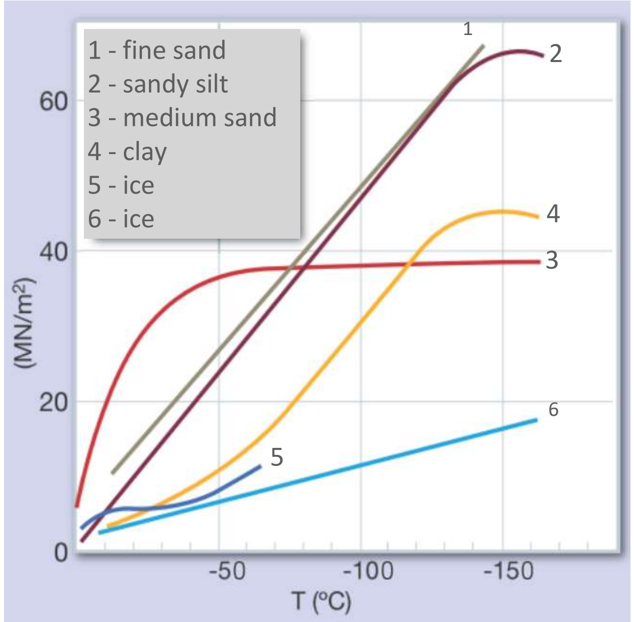
Pore volume / soil density



- Pore ice cements the soil and prevents deformation of the grain structure



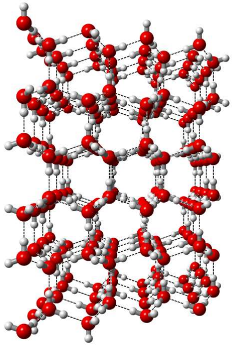
- Soil particles are stiffer than ice
  - distortions are concentrated on the ice
  - deformations in the ice are greater than the mean deformations of the soil mixture

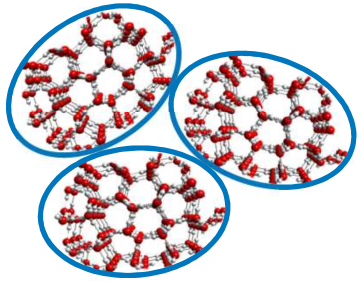


Excursus: Soil as a 3 Phase Medium

Role of ice in the soil matrix

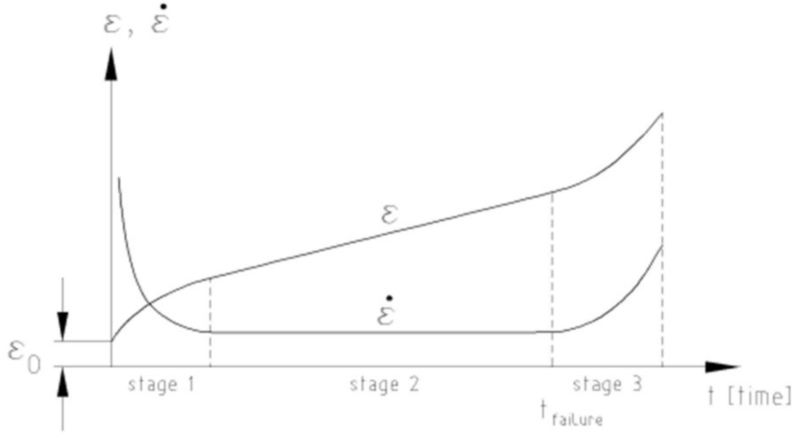
- Pore ice is poly-crystalline: Crystal bodies with individual, homogeneous crystalline bodies (crystallites)
- Crystallites are crystals that do not or only partially show the actual crystal form. Crystallites can be deformed in certain temperature and speed ranges without destroying the crystal lattice.





Typical creep behavior of frozen soils

- Stage 1: Solidification
  - Initial deformation ε_0, then:
  - decreasing deformation rate ε'
  - Blocking of movement in the crystals
- Stage 2: actual creep: constant deformation rate
- Stage 3: softening: Deformation rate increases until fracture



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  - Shear Strength φ
  - Cohesion c
- **Creep Tests**
- All parameters temperature depended

Lab Tests on Frozen Soils

Lab Tests on Frozen Soils

Overview

- Compressive strength q_g and Moduls of Elasticity
  → Uniaxial Compressive Test (UCS)

- Creep Parameters A, B, C
  → Uniaxial Creep Test (UCT)

- Shear Strength φ_g, c_g
  → Triaxial Compressive Test (TCT)

Lab Tests on Frozen Soils

Execution of Lab Tests on Frozen Soil

→ Recommendations of the ISGF
(International Society for Ground Freezing)

- Consideration of the specific task
(temperature and stress conditions)
- Carrying out the uniaxial creep tests at -10°C
- Depending on requirements, also -20°C or lower (e.g. nitrogen freezing, salt water)
- Freezing the soil samples under laboratory conditions
- Consider the characteristics of the core and sample material, e.g.
  - Layer and fissure surfaces
  - Harness surfaces
  - Other inhomogeneities
  - Chemical conditions (impurities, salt water)

Lab Tests on Frozen Soils

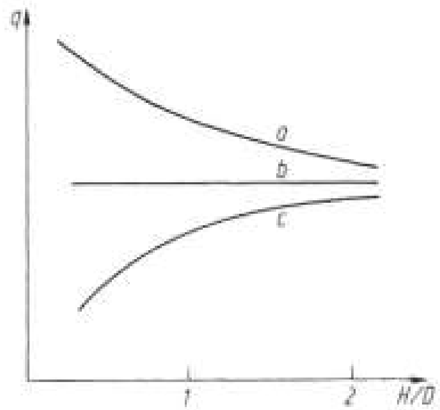
Determination of strength and deformation properties

Effects on the results of laboratory tests to determine strength

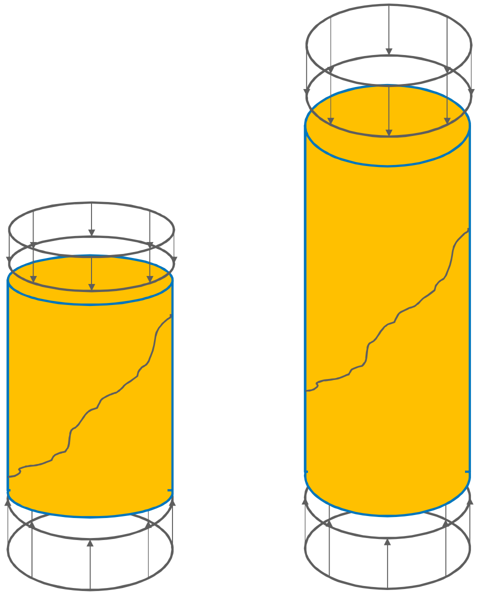
- Sample Diameter:
  - 5 cm for fine-grained material without stratification
  - 10 cm for inhomogeneities or undisturbed samples

- Slimness (height-to-diameter ratio)
  - usually between 1.0 and 2.5
  - Close to 1: better reproducible test results, as buckling is less likely
  - But: careful end face lubrication to eliminate shear stresses at the edge (otherwise no homogeneous stress state)

- Experience:
  H/D = 2 with lubricated end caps



Influence of the end face design and slimness of the specimen on the uniaxial compressive strength (according to Baker)
a) Rigid end plate with high friction
b) End plates behave like specimen
c) Soft end plates, lubricated



Lab Tests on Frozen Soils

Determination of strength and deformation properties

Test procedure

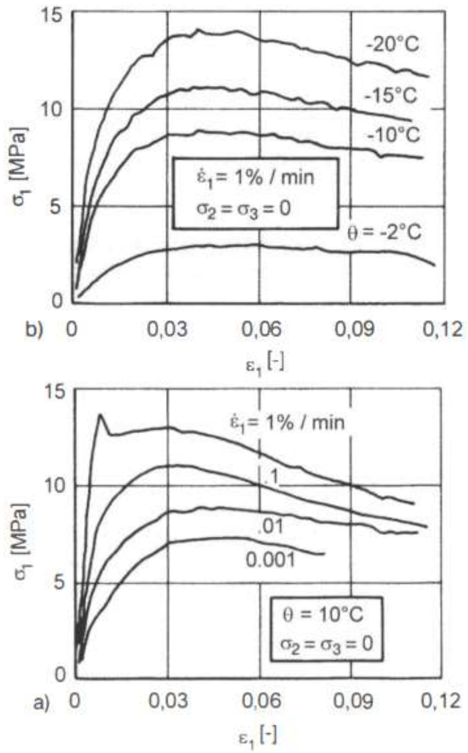
- Modulus of elasticity and breaking stress: strain-controlled
- Creep tests: constant stress

The compressive strength is higher

- the faster the sample is deformed
- the lower the temperature is ⍰ Micromechanics

Tests carried out according to ISGF recommendations:

- Uniaxial compressive strength: ε_1‘ = 1%/min ("short-term strength")
- Triaxial compression tests: ε_1‘ = 0,1%/min
- Long-term strength including creep parameters



The following material-specific properties have a significant influence on the test results:

- Water content
- DensityGrain size distribution
- salt content
- Contaminant content
- Preload and solidification
- Disturbances and inhomogeneities

Lab Tests on Frozen Soils

Uniaxial Compressive Test (UCT)

Test procedure

- Preparation of the test specimens
- Freezing the samples to the target temperature (usually -10°C)
- Temperature monitoring on parallel sample
- Carrying out the test in the test stand in the cooling chamber
- Constant Deformation rate: $\varepsilon_1' = 1\%/\text{min}$
- Measurement of feed rate and force over time
- → Stress-strain curve

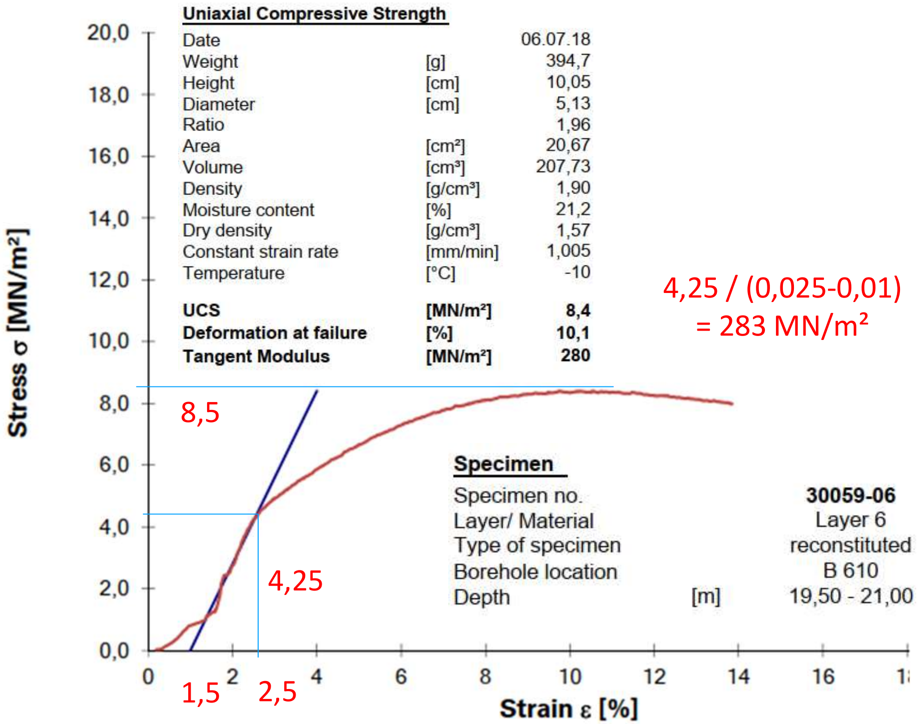
Lab Tests on Frozen Soils

Uniaxial Compressive Test (UCT)

- Stress at failure q_g
- Note: Stress at failure in the strain-controlled test for deformations that are too high in construction practice

  → heuristic reduction, usually 2
- Modulus of Elasticity E at 50% of the stress at failure:

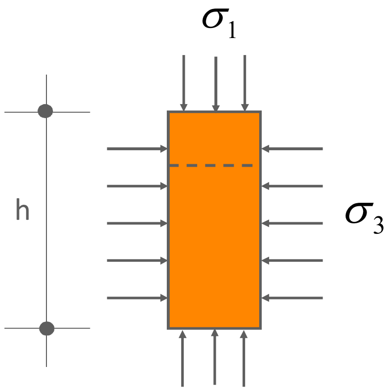
$$E_{50} = \frac{q_{g50}}{\varepsilon_{g50}}$$



Lab Tests on Frozen Soils

Triaxial Compressive Strength (TCT)

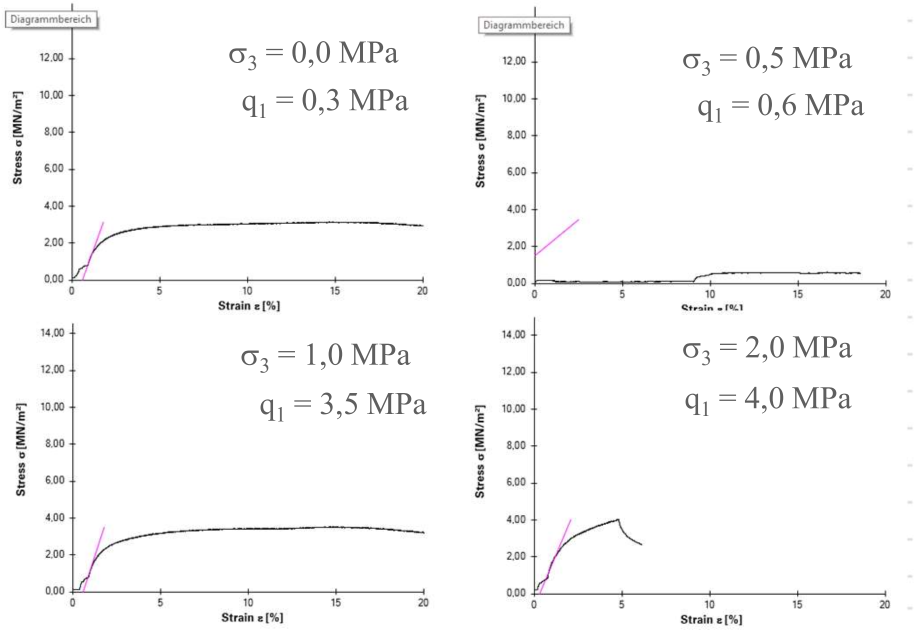
- Like uniaxial compressive test (UCS), but under triaxial conditions, at least 3 tests at three different stress stages:

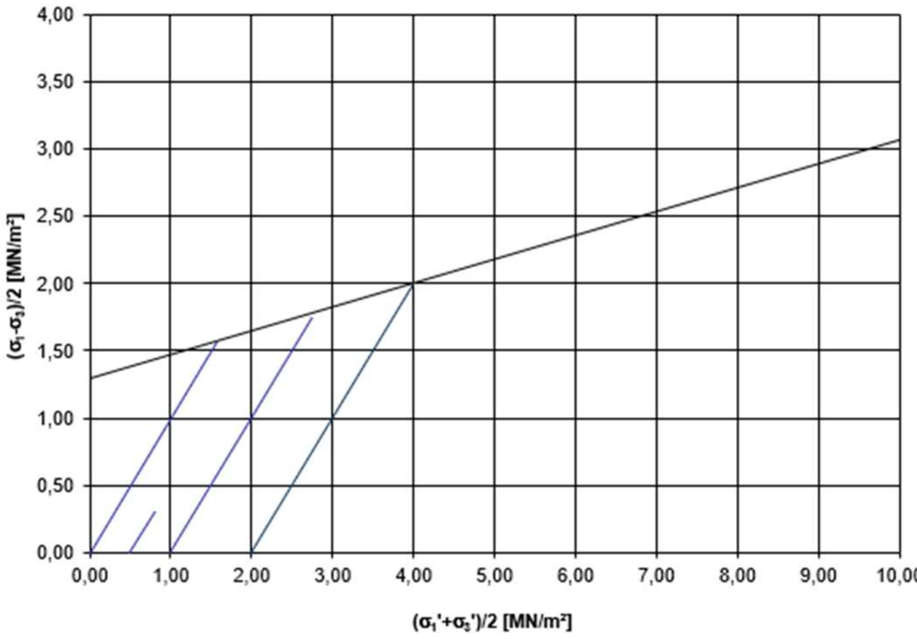


- Deformation rate ε_1' = 0,1%/min
- Measurement of displacement (deformation) and force over time
- → stress-strain-curve

Lab Tests on Frozen Soils

Triaxial Compressive Strength (TCT)





Lab Tests on Frozen Soils

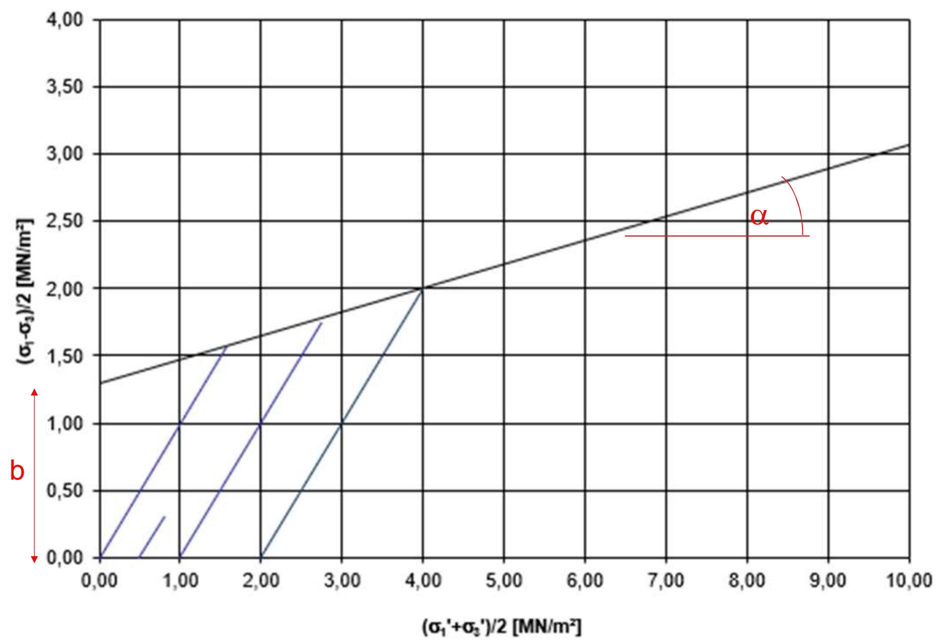
Triaxial Compressive Strength (TCT)

Evaluation

- EvaluationStress path for 3 tests
- Shear parameters according to the following relationship:

$$\sin\varphi = \tan\alpha$$
$$c = \frac{b}{\cos\phi}$$

- Usually friction angle temperature-dependent (→ cohesion)
- The results may be influenced by whether the soil sample is disturbed or whether there are fissures / disturbances



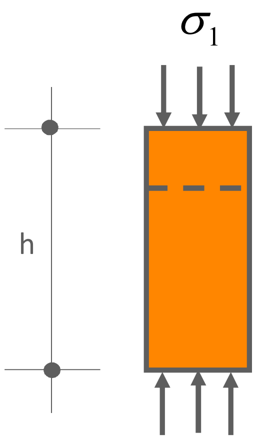
Lab Tests on Frozen Soils

Uniaxial Creep Tests (UCT)

Test procedere

- Determination of creep parameters by uniaxial creep tests in a cooling chamber (usually -10°C)
- Creep loads according to ISGF recommendations :

  70%, 50%, 30%, 10%
  of the short-term strength
  (other sources: 70%, 50%, 40%, 30%)
- Diagram of the time-depended deformation
  ε_1‘ vs. time

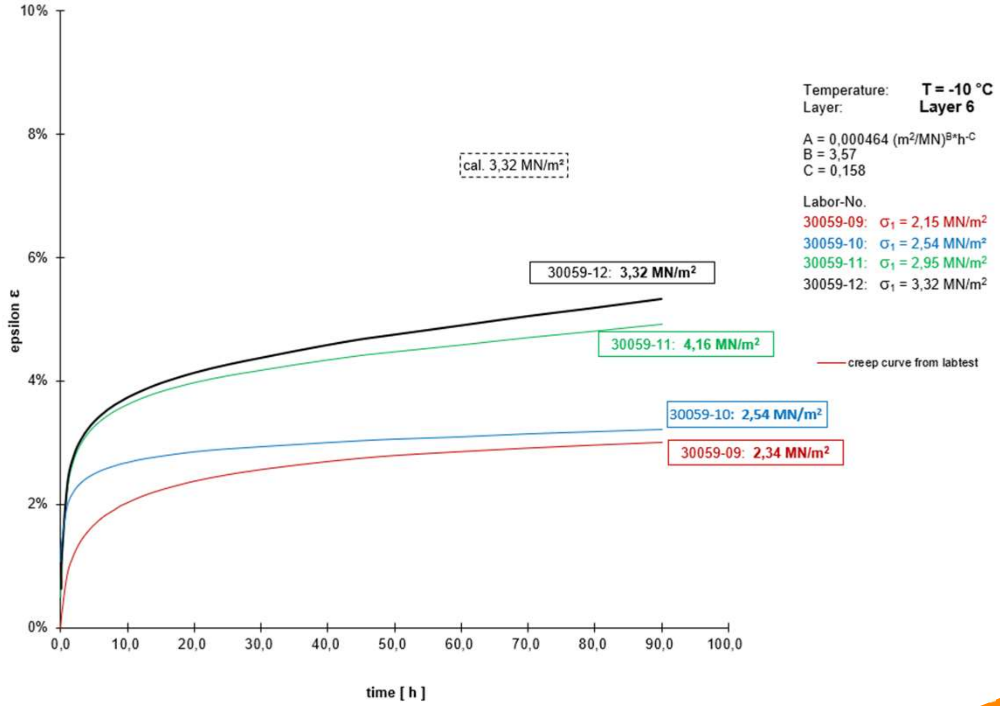


Lab Tests on Frozen Soils

Uniaxial Creep Tests (UCT)

Tonprobe vor dem Versuch

Tonprobe nach dem Versuch



Lab Tests on Frozen Soils

Uniaxial Creep Tests (UCT)

Evaluation

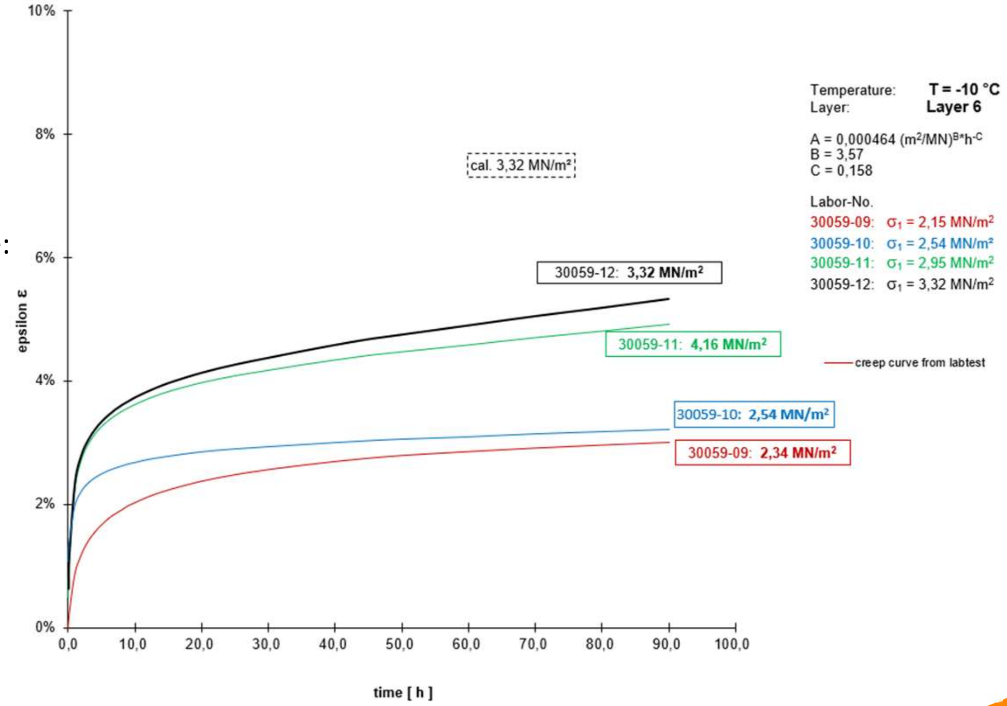
- Non-linear stress-deformation behaviour of frozen soils can be expressed by a formula
- Ladanyi: constitutive relationship for creep behaviour in which the first two stages are approximated by a straight line:

$$\varepsilon = \underbrace{\frac{\sigma}{E} + \varepsilon_k \cdot \left(\frac{\sigma}{\sigma_k}\right)^k}_{\text{stadium 1 (elast.)}} + \underbrace{\dot{\varepsilon}_c \cdot \left(\frac{\sigma}{\sigma_c}\right)^n \cdot t}_{\text{stadium 2 (plast.)}}$$

- Creep behaviour according to Klein:

$$\varepsilon = \frac{\sigma_1}{E_0} + A \cdot \sigma_1^B \cdot t^C$$

with: A, B, C = test constants
E_0 = initial elastic modulus
σ_1 = constant axial stress
t = time



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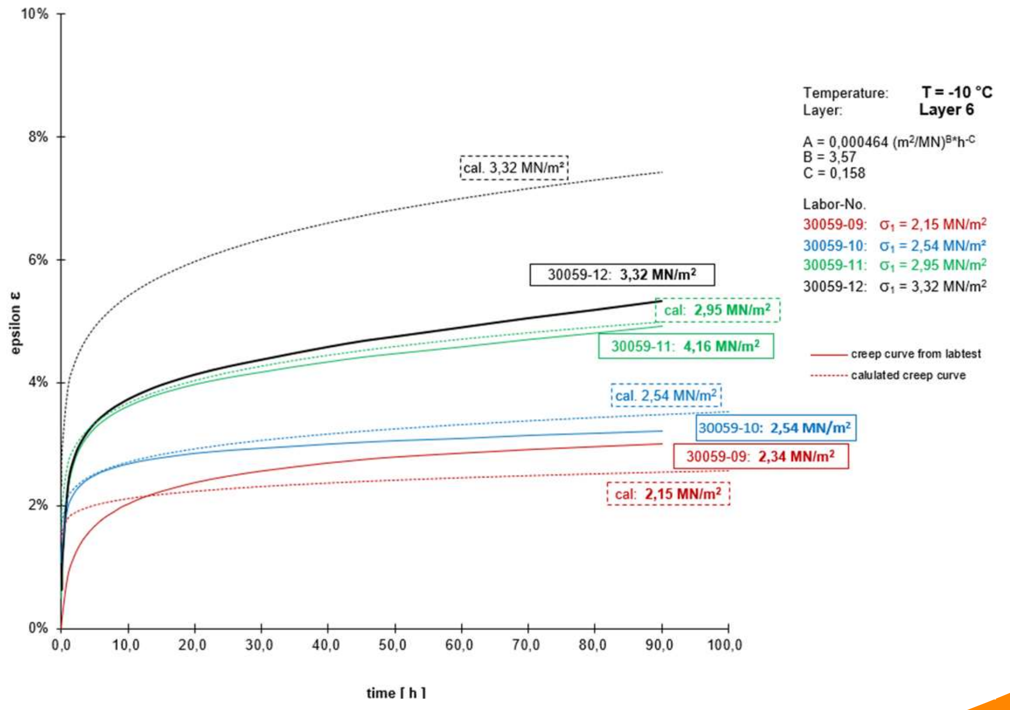
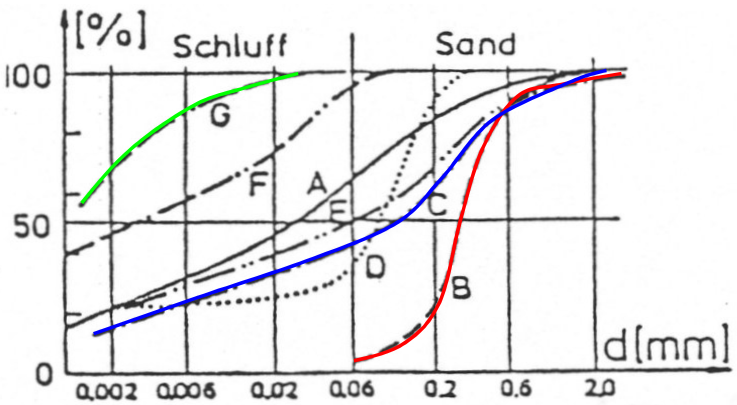


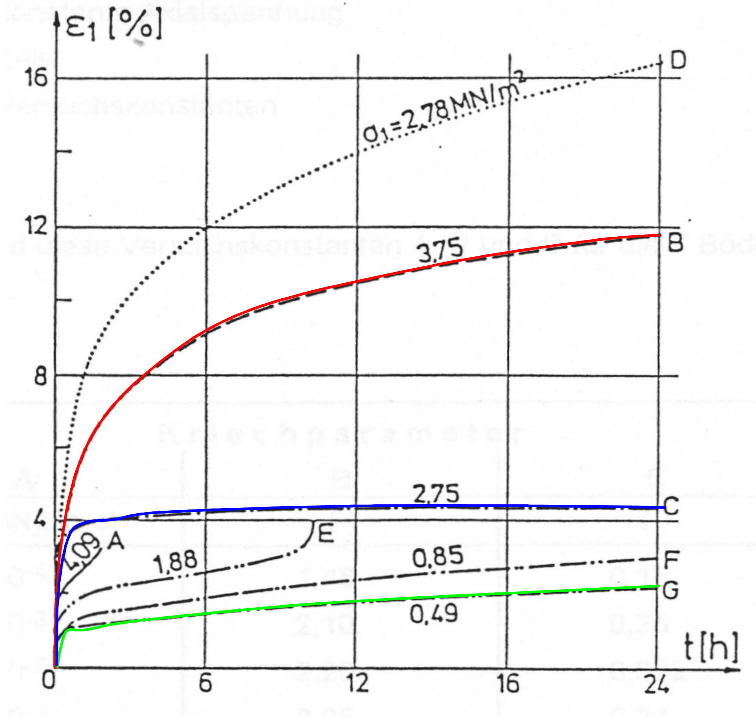
Lab Tests on Frozen Soils

Uniaxial Creep Tests (UCT)

	Kriechparameter		
	A	B	C
	$(m^2/MN)^{B} \cdot h^{-c}$	(-)	(-)
A	$7{,}3 \cdot 10^{-4}$	1,48	0,13
B	$3{,}4 \cdot 10^{-3}$	2,10	0,25
C	$4{,}2 \cdot 10^{-3}$	2,20	0,072
D	$8{,}2 \cdot 10^{-3}$	2,25	0,24
E	$5{,}0 \cdot 10^{-3}$	2,15	0,095
F	$2{,}0 \cdot 10^{-2}$	2,14	0,20
G	$5{,}8 \cdot 10^{-2}$	3,40	0,48

$$\varepsilon = \frac{\sigma_1}{E_0} + A \cdot \sigma_1^{B} \cdot t^{C}$$



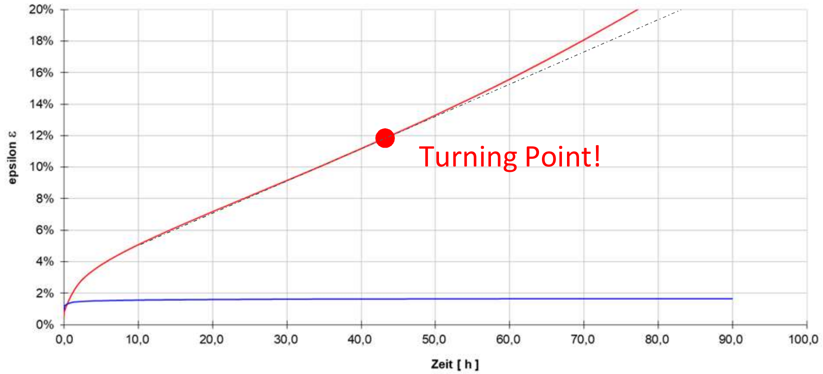


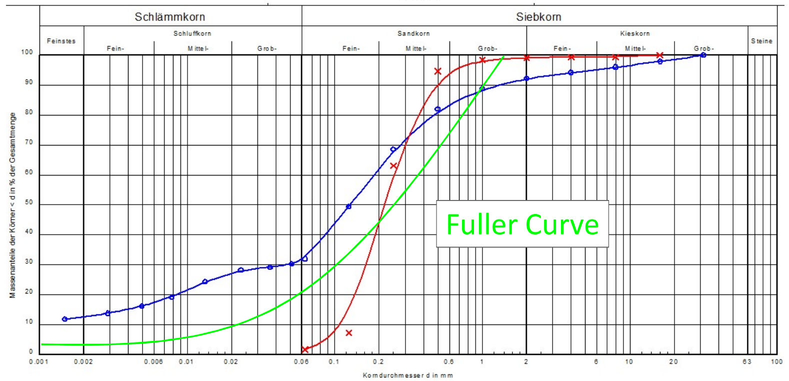
Lab Tests on Frozen Soils

Uniaxial Creep Tests (UCT)

Medium Sand
Saturation: S_r = 0,92
Water content: w = 23,4%
Porosity: n = 0,40
Stress level: s_1=1,89 MN/m²
(45 % q_g)

Wide-graded
silt-sand mixture
Saturation: S_r = 0,83
Water content: w = 7,6%
Porosity: n = 0,20
Stress level: s_1=4,05 MN/m²
(50 % q_g)





Thank You

Questions ?

sven.kessler@cdmsmith.com