The title of the presentation is "Artificial Freezing of Soils in Civil Engineering." The speaker is Sven Kessler, and the presentation covers geotechnical parameters and laboratory tests."Paramètres géotechniques et Essais Laboratoires."
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

\[ \sigma = \frac{N}{A} \pm \frac{M}{W} \]

Freeze Body

Vertical stresses

Horizontal Stresses

Freeze Body

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")

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

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**Excursus: Design of a Freeze Body**

**LA CONGÉLATION _ ARTIFICIAL FREEZING OF SOILS IN CIVIL ENGINEERING**

**SVEN KESSLER - GEOTECHNICAL PARAMETERS AND LABORATORY TESTS _ NOVEMBER 17TH, 2023**

**Freeze Body**

**Linear stress distribution according elasticity theory**

**Stress distribution after plasticize of the frozen soil**

**Temperature Field**
Excursus: Design of a Freeze Body

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")

**Required Parameters for design**

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

**Tolerable stresses at the edge can be exceeded**

→ Plasticizing → Stress redistribution → Stress distribution → Temperature distribution
Excursus: Soil as a 3 Phase Medium

Mineralogical view

- Soil as a 3-phase medium
- 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
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 $\varepsilon_{in}$ then:
    - decreasing deformation rate $\dot{\varepsilon}$
    - Blocking of movement in the crystals

- **Stage 2:** actual creep: constant deformation rate

- **Stage 3:** softening: Deformation rate increases until fracture
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**

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- General: Compressive strength $q$
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  - Shear Strength $\varphi$
  - Cohesion $c$
- Creep Tests
- All parameters temperature depended
Lab Tests on Frozen Soils
Lab Tests on Frozen Soils

Overview

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

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

- Shear Strength $\varphi_s, c_s$
  → Triaxial Compressive Test (TCT)
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

Tests carried out according to ISGF recommendations:
- Uniaxial compressive strength: $\varepsilon_1^\prime = 1\%/\text{min}$ ("short-term strength")
- Triaxial compression tests: $\varepsilon_1^\prime = 0.1\%/\text{min}$
- Long-term strength including creep parameters

The following material-specific properties have a significant influence on the test results:
- Water content
- Density
- Grain 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: $\varepsilon'_1 = 1\%$/min
- Measurement of feed rate and force over time
- $\Rightarrow$ Stress-strain curve
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:

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

Uniaxial Compressive Test (UCT)

<table>
<thead>
<tr>
<th>Date</th>
<th>06.07.18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>394,7 kg</td>
</tr>
<tr>
<td>Height</td>
<td>10,05 cm</td>
</tr>
<tr>
<td>Diameter</td>
<td>5,13 cm</td>
</tr>
<tr>
<td>Ratio</td>
<td>1,96</td>
</tr>
<tr>
<td>Area</td>
<td>20,67 cm²</td>
</tr>
<tr>
<td>Volume</td>
<td>207,73 cm³</td>
</tr>
<tr>
<td>Density</td>
<td>1,90 g/cm³</td>
</tr>
<tr>
<td>Moisture content</td>
<td>21,2 %</td>
</tr>
<tr>
<td>Dry density</td>
<td>1,57 g/cm³</td>
</tr>
<tr>
<td>Constant strain rate</td>
<td>1,005 [mm/min]</td>
</tr>
<tr>
<td>Temperature</td>
<td>-10 °C</td>
</tr>
</tbody>
</table>

**Uniaxial Compressive Strength**

| UCS (MN/m²)  | 8,4 |
| Deformation at failure (%) | 10,1 |
| Tangent Modulus (MN/m²) | 280 |

$4,25 / (0,025-0,01) = 283$ MN/m²
Like uniaxial compressive test (UCS), but under triaxial conditions, at least 3 tests at three different stress stages:

- Deformation rate $\varepsilon_1' = 0.1\%/\text{min}$
- Measurement of displacement (deformation) and force over time
- $\rightarrow$ stress-strain-curve
Lab Tests on Frozen Soils

Triaxial Compressive Strength (TCT)

\[
\begin{align*}
\sigma_3 &= 0.0 \text{ MPa} \\
q_1 &= 0.3 \text{ MPa} \\
\sigma_3 &= 1.0 \text{ MPa} \\
q_1 &= 3.5 \text{ MPa} \\
\sigma_3 &= 0.5 \text{ MPa} \\
q_1 &= 0.6 \text{ MPa} \\
\sigma_3 &= 2.0 \text{ MPa} \\
q_1 &= 4.0 \text{ MPa}
\end{align*}
\]
Lab Tests on Frozen Soils

Triaxial Compressive Strength (TCT)

Evaluation

- Evaluation Stress path for 3 tests
- Shear parameters according to the following relationship:
  \[ \sin \varphi = \tan \alpha \]
  \[ c = \frac{b}{\cos \varphi} \]
- Usually friction angle temperature-dependent (\( \Rightarrow \) 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 procedure

- 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-dependent deformation $\varepsilon_1$ vs. time

h

$\sigma_1$
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:
  \[ \varepsilon = \frac{\sigma}{E} + \varepsilon_k \cdot \left( \frac{\sigma}{\sigma_k} \right)^k + \varepsilon_c \cdot \left( \frac{\sigma}{\sigma_c} \right)^n \cdot t \]
  
  stadium 1 (elast.)  
  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  
  \( \sigma_1 = \) constant axial stress  
  \( t = \) time
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:

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  with:  
  \( A, B, C \) = test constants  
  \( E_0 \) = initial elastic modulus  
  \( \sigma_1 \) = constant axial stress  
  \( t \) = time
Lab Tests on Frozen Soils

Uniaxial Creep Tests (UCT)

<table>
<thead>
<tr>
<th>Kriechparameter</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>(MN/m^2 h)</td>
<td>(-)</td>
<td>(-)</td>
<td>(-)</td>
</tr>
<tr>
<td>A</td>
<td>7.3 \times 10^{-4}</td>
<td>1.48</td>
<td>0.13</td>
</tr>
<tr>
<td>B</td>
<td>3.4 \times 10^{-3}</td>
<td>2.10</td>
<td>0.25</td>
</tr>
<tr>
<td>C</td>
<td>4.2 \times 10^{-3}</td>
<td>2.20</td>
<td>0.072</td>
</tr>
<tr>
<td>D</td>
<td>8.2 \times 10^{-3}</td>
<td>2.25</td>
<td>0.24</td>
</tr>
<tr>
<td>E</td>
<td>5.0 \times 10^{-3}</td>
<td>2.15</td>
<td>0.095</td>
</tr>
<tr>
<td>F</td>
<td>2.0 \times 10^{-2}</td>
<td>2.14</td>
<td>0.20</td>
</tr>
<tr>
<td>G</td>
<td>5.8 \times 10^{-2}</td>
<td>3.40</td>
<td>0.48</td>
</tr>
</tbody>
</table>

\[ \varepsilon = \frac{\sigma_1}{E_0} + A \cdot \sigma_{1}^{B} \cdot t^{C} \]

\[ \sigma_1 = 2.78 \text{MN/m}^2 \]

![Graph showing creep strain over time for different materials](image)

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La congélation — Artificial freezing of soils in civil engineering
Sven Kessler — Geotechnical parameters and laboratory tests — November 17th, 2023
Lab Tests on Frozen Soils

Uniaxial Creep Tests (UCT)

**Medium Sand**
- Saturation: $S_i = 0.92$
- Water content: $w = 23.4\%$
- Porosity: $n = 0.40$
- Stress level: $s_1 = 1.89 \text{ MN/m}^2$
  
  (45% $q_g$)

**Wide-graded silt-sand mixture**
- Saturation: $S_i = 0.83$
- Water content: $w = 7.6\%$
- Porosity: $n = 0.20$
- Stress level: $s_1 = 4.05 \text{ MN/m}^2$
  
  (50% $q_g$)
Thank You

Questions?

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