WEEK 14
Further Topics: Soil Behaviour at Unsaturated States, Extreme Temperature, etc.

20. Broader scope: What's left for further study?

For thirteen weeks, we have studied many features of soil behaviour, notably stiffness (including compressibility) and shear strength. There are still lots of other topics to be learnt concerning soil properties. In this lecture series, we have limited the variables mainly just to stresses and strains. However, some geotechnical problems require considerations to other variables, such as pore fluid conditions, temperature and time. As the sphere of geotechnical activity expands, these variables are increasingly coming into mainstream geotechnics from what might perhaps been considered more ‘fringe’ issues. In this last week of the lecture course, we shall have a glimpse of the role that these variables play in geotechnics through their effects on soil behaviour, focusing on three specific topics.

20-1. Soil behaviour at unsaturated states

Unsaturated soil mechanics is a big branch of soil mechanics. The ‘unsaturated’ states normally mean states at which soil pores are filled with fluid (such as water) and gas (such as air). This arrangement makes the mechanics of the system very complicated, because now we have surface tension that works between the fluid and gas phases, in addition to the inter-particle forces (i.e. what we know as effective stress under saturated conditions) and the pore water pressure.

Unsaturated soils are usually encountered at shallower part of ground above the ground water level. In some cases, however, it can exist to a significant depth.

Schematic illustration of unsaturated soil
Unsaturated soils and suction

From equilibrium of force,

\[ u_a - u_w = \frac{T_s}{r} \]

If \( u_a \) is the atmospheric pressure (i.e. zero), \( u_w \) is negative. In unsaturated soils, the water pressure is often negative.

This quantity, \( u_a - u_w \), is called the \textit{(matric) suction}.

In the two-disc analogy (Kelvin’s model), the inter-particle force, \( F \), is expressed as

\[ F = 2(u_a - u_w) \left( r + \frac{D}{2} \right) \cos \theta + r \]

The inter-particle force is proportional to the suction. The suction therefore gives additional stress to the soil’s skeleton (that is, additional to other external forces from the boundaries, such as overburden pressure).

What if the water content increases?

The pore radius \( r \) decreases and eventually \( T_s \) disappears, bringing the suction to zero.

Typical water content – suction relationships

\textit{Water retention curve} or \textit{Soil-water characteristic(s) curve}

(After Fredlund & Xing, 1994)
Shear strength in unsaturated soils

How to express the strength and deformation characteristics of unsaturated soils is still a debated issue and under extensive research. A simple expression for unsaturated soils' strength analogous to the Mohr-Coulomb criterion is:

\[ \tau = (\sigma - u_a) \tan \phi' + c' + c_s \]

Effective stress is no longer useful. Use total stress (minus air pressure).

‘Apparent’ cohesion due to the metric suction

Example of influence of matric suction on ‘suction strength’ in silty soil (After Jotisankasa & Mairaing, 2010)

Rainfall leads to increase in the water content, decrease in suction and then decrease in shear strength.

(Please note: The figures in the text are not formatted as tables or diagrams. The text contains a mathematical expression and a few figures related to soil mechanics and rainfall records.)
Other ways in which unsaturated soils’ properties become relevant to practice: Examples

(i) Changes in permeability (hydraulic conductivity)

Example of how permeability changes with water content:

\[ \theta : \text{Water content} \]
\[ h : \text{Hydraulic head} \]
\[ K_r : \text{Relative permeability} \quad (K_r = 1 \text{ when saturated}) \]

Soil-water characteristic curves (Left) and permeability changes (After van Genuchten, 1980)

(ii) Expansion and collapse

Unsaturated soils exhibit expansive or contractive (collapse) behaviour upon wetting (i.e. increases in water content). These apparently contradictory features are better interpreted and modelled in recent years. Some of the soils are intrinsically expansive (see the photo) due to soil-water interactions at molecular levels. However, many soils can exhibit both phenomena depending on the initial state (e.g. Alonso et al., 1990).

Expansion of bentonite upon wetting (After Komine, 2010)

\[ e : \text{Expansion by wetting} \]
\[ \log p' : \text{Low suction} \]
\[ \text{Collapse by wetting} \]
\[ \text{High suction} \]
20-2. Soil behaviour at extreme temperature

Thermal regime of ground: What’s the temperature underneath?

Temperature regime in cold regions (permafrost areas) (Andersland & Ladanyi, 2004)

Temperature regime under seabed: Osaka-bay, 20-m water depth (Terashi et al., 1980)

High-level nuclear waste burial (Gens et al., 2009)

Parts of ground that undergo severe temperature changes are limited in their extent. However, they are often the most vital parts for human activities.
Behaviour of soils at high temperature

Looking through the literature, the following features of soils’ behaviour at elevated temperature are commonly reported:

- Heating normally (but not necessarily always) causes volume decreases (e.g. Campanella & Mitchell, 1968; Mitchell, 1976)

- At elevated temperature, soils have higher shear strength and stiffness (Cekerevac & Laloui, 2004; Abuel-Naga et al., 2006)

- At elevated temperature, permeability increases. But most of the increase can be explained by the lowered water viscosity (Abuel-Naga et al., 2006; Studies at the lecturer’s research group at Hokkaido Univ.)
Behaviour of soils at low temperature (Frozen soils)

As easily imagined, frozen soil (< 0°C) has higher stiffness and shear stiffness, as the pore ice takes part of the load. These advantageous features of frozen soil are exploited for foundation engineering in permafrost areas, and for excavation and sampling work through artificial freezing. As ice’s stiffness and shear strength themselves become higher at lower temperature, so do frozen soil’s.

Unconfined compression strength – temperature relationships (Andersland & Ladanyi, 2004; original data from Sayles, 1968)

Soil-ice composition and unconfined compression strength (Goughnour & Andersland, 1968)

However, there is another important feature to mind; frozen soil’s behaviour is very time-dependent, reflecting ice’s characteristics (remind yourselves of how glaciers flow over very long time). It means that, even if soil can sustain high stress instantaneously, it causes significant deformation over long time (i.e. creep). It therefore requires some caution when exploiting the apparently high stiffness and strength of frozen soils.

Typical creep patterns of frozen soils (Andersland & Ladanyi, 2004)

In addition to how soils behave at frozen states, mass and heat transfer processes during freezing and thawing pose very complex problems. A particular problem among them is frost heave (this topic is planned to be covered in the lecture next term "Disaster Mitigation Geotechnology" by the same lecturer).
20-3. Time effect (Strain rate-effect, or viscosity)

The strain rate-dependent behaviour of soils derives from (at least) two different mechanisms. One of them is related to delayed dissipation of pore water pressure, as typically seen during ‘primary’ consolidation of low-permeability soils. This is fundamentally a soil-water coupled problem. The other kind of mechanism seems to exist, which does not involve pore water pressure as time-dependent variable. This mechanism seems to be more relevant to, for example, creep under sustained loads and the secondary consolidation.

**Creep:** Deformation under constant stress

**Secondary consolidation:** Compression beyond what is expected from time-independent theory

<table>
<thead>
<tr>
<th>Soil group</th>
<th>$C_{aw}/C_c$</th>
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<tbody>
<tr>
<td>Inorganic clays and silts</td>
<td>0.025-0.075</td>
</tr>
<tr>
<td>Organic clays and silts</td>
<td>0.035-0.083</td>
</tr>
<tr>
<td>Peats</td>
<td>0.05-0.085</td>
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(Summary of data reported by Mesri & Godlewski, 1977)

In many types of soil (both sand and clay), Isotach curves of stress-strain relationships can be drawn, which represent relationships for different, fixed strain rates. The isotach model, one of the simplest models to interpret the time-dependent nature of soil’s stress-strain behaviour, assumes that the isotach curves are smoothly transferrable if the strain rate is changed (see the diagram).
Examples: Two natural clays (reproduced from Tsutsumi et al., 2010)

See how the Osaka-Bay Clay obeys the isotach law, while the Louiseville Clay does not.

The effect of strain rates is observed not only for compression behaviour but also for shear behaviour in a wide range of geomaterials (clays, silts, sands, gravels, and indeed many granular substances). Prof. Tatsuoka and his coworkers have been vigorously investigating the strain-rate effects, and categorised them into four patterns (see the diagram).

In many of the existing models, it is often assumed that

- The elastic strain component is independent of the strain rate.
- The plastic strain component is dependent on the strain rate.

This concept is referred to as elasto-viscoplasticity in general.

(After Tatsuoka et al., 2008)


