Soil Suction

- Total Suction

Total soil suction is defined in terms of the free energy or the relative vapor pressure (relative humidity) of the soil moisture.

\[ \Psi = - \frac{RT}{v_{w0} \omega_v} \ln \left( \frac{u_v}{u_{v0}} \right) \]

- \( u_v \) = partial vapor pressure of pore water vapor
- \( u_{v0} \) = saturation vapor pressure of water vapor over flat surface of pure water

For pure water at 20°C:

\[ \Psi = - 135022 \ln \left( \frac{u_v}{u_{v0}} \right) \]

where \( \Psi \) is in kPa.

The total suction consists of two components, matric suction \((u_a - u_W)\) and osmotic suction \((\pi)\).

\[ \Psi = (u_a - u_W) + \pi \]

Both components are due to differences in relative humidity of the soil vapor.
• **Matric Suction**

A meniscus forms at the soil-air interface, due to the surface tension, resulting in reduced vapor pressure in the water.

The vapor pressure decreases, becomes more negative, and the matric suction pressure increases as the radius of curvature of the meniscus decreases.

The size of the soil pores decreases with a decrease in soil particle size which then affects the size of the radius of curvature and consequently the matric suction pressure.

The vapor pressure decreases as the degree of saturation decreases.

• **Osmotic Suction**

The presence of dissolved ions in water decreases the soil vapor pressures, relative humidity, which then increases the total soil suction.

Osmotic suction can be a significant portion of the total soil suction.
The following figure can be used to illustrate osmotic suction.

![Diagram of osmotic suction]

a) Waters flow through the membrane into the solution due to the osmotic suction in the solution.

b) Water flows through the membrane into the pure water due to the application of pressure on the solution.

The pressure on the solution required in order to equalize the flow of water from the solution to the pure water is equal to the osmotic pressure of the solution.

Capillary Model

Soil matric suction is described in terms of capillary forces, i.e., capillary rise, acting in soil.

Capillary rise is caused by surface tension and the attractive forces between the soil ions and the water molecules in the adsorbed water.

The rise in a capillary tube is computed by setting the total upward forces due to surface tension equal to the downward force due to the weight of the water in a tube.

\[ 2 \pi r T_s \cos \alpha = \pi r^2 h_c \rho_w g \]

The height of capillary rise, \( h_c \), is obtained by assuming \( \alpha = 0 \).

\[ h_c = \frac{2 T_s}{\rho_w g R_s} = \frac{2 T_s}{\rho_w g r} \]
The matric suction pressure can then be given as

\[(u_a - u_w) = \rho_w g h_c = \frac{2T_s}{R_s} \approx \frac{2T_s}{r}\]

The pores sizes in soil (comparable to \(r\)) are indeterminate so it is not possible to calculate pore water pressure directly.

In a soil, the surface tension can have component forces perpendicular and parallel to the surface which results in compressive forces acting on the soil particles.

The variation of pore sizes and particle orientation within soil results in variation in soil properties.

The angle \(\alpha\) varies depends on conditions, e.g., during wetting and drying of the soil, which results in hysteresis effects (soil properties depend on soil history) in soil.
Total Soil Suction Measurements

- **Psychrometers**

  **Basic Principle:**

  The temperature difference between an evaporating and nonevaporating surface is dependent on the relative humidity.

  **Description:**

  A thermocouple (electrical circuit with two dissimilar conductors) is used to determine the relative humidity.

  **Methodology:**

  A very small current causes the temperature to increase and decrease at the junctions of a thermocouple (Peltier Effects).

  Condensation and subsequent evaporation will occur at the junction that is cooled to the dew point.

  The evaporation will cause a cooling of the junction.

  An electromotive force is induced by the temperature difference at the two junctions (Seebeck Effects). The measured voltage (micro volts) is a function of the temperature difference which is a function of the relative humidity.
Calibration Procedure:

Calibrated using known osmotic suction pressures of solutions and the sensor output.

Sensor Capabilities:

Can be used to measure total suctions between 100 and 8000 kPa.

Sensor Limitations:

Response times for sensors may provide limitations.

Since relative humidity is dependent on temperature, use requires constant temperature (i.e., laboratory conditions) during measurements, or a temperature-compensated sensor.

• Filter Papers

Basic Principle:

The moisture in a filter material will reach equilibrium with the surrounding environment.
Description:

Initially dry filter paper of prescribed mass (and size) is calibrated to give matric or total suction.

Methodology:

Dry filter paper is placed in contact with soil (matric suction) or suspended above soil (total suction) in a closed container and allowed to come to equilibrium with the soil water or the vapor pressure.

The water content of the filter paper at equilibrium (7 days) is an indication of the suction pressure.

Calibration Procedure:

The water contents of filter paper specimens at equilibrium are calibrated (bilinear) against known suction pressures of solutions.

Sensor Capabilities:

Used to measure high suction pressures, $10^4$ or $10^5$ kPa.

Sensor Limitations:

Response times (7 days) may provide limitations.

Filter does not make good contact with soil.
Matric Suction Measurements

- High Air Entry Materials

A ceramic material (typically) with uniform openings will act as a capillary medium when in contact with moisture according to Kelvin's equation.

\[
(u_a - u_w) = \frac{2T_s}{R_s} = \text{Air entry value.}
\]

The air entry value is inversely proportional to the radius of the openings.

As long as the air pressure does not exceed the air entry value, the surface tension acting at the air-water interface will prevent air from entering.

Thus the material acts as an interface between the soil air and water.

The high entry values, materials with small radii, reduce the permeability of the materials which affects the rate that water can interact with sensors.
Direct Measurement of Matric Suction

By using high air entry materials it is possible to directly measure the water pressure (less than atmospheric) using a pressure gage or transducer.

- **Tensiometers**

Basic Principle:

The pressure of water contained in a high air entry material will come to equilibrium with the soil water pressure making it possible to measure negative soil water pressures.

Description:

A small ceramic cup is attached to a tube filled with deaired water which is connected to a pressure measuring device (pressure gage, transducer, manometer).

Methodology:

Saturate the ceramic cup and tube by filling with water and applying a vacuum to the tubing.
Allow the ceramic tip to dry to reduce the water pressure in the sensor and remove any air bubbles that appear.

Install sensor with ceramic tip in direct contact with soil and remove air bubbles as they appear in the tubing.

Calibration Procedure:

Does not require a calibration as such, except for a transducer calibration, but it is necessary to correct for the difference in elevation head of the pressure gage and the ceramic tip. For $u_a = 0$:

$$(u_a - u_w)_{soil} = -u_w + \gamma_w \times \text{difference in elevation head}$$

where the difference in elevation head is the vertical distance between the gage or transducer and the ceramic tip.

The response time, time to change from negative 80 kPa to atmospheric pressure, can be measured.

Sensor Capabilities:

Used to measure suction pressures to negative 90 kPa.
Sensor Limitations:

Air in the sensor will result in bad (less negative) measurements of the pore water pressure. Air can accumulate because of:

a) air comes out of solution as the water pressures decrease;

b) air in soil can diffuse through the ceramic material;

c) water vaporizes (cavitation) as the soil water pressure approaches the vapor pressure of water at the ambient temperature.
• Pressure Plate Extractor

Basic Principle:

Uses the axis-translation technique which reverses the reference air pressure from atmospheric to above atmospheric causing the pore water pressure to change as it comes to equilibrium with the pore air pressure.

Description:

In a closed system, the air pressure was varied and the soil water pressure varied by the same magnitude so the matric suction remained constant. No water flow occurred. This behavior is used to verify that the axis-translation technique is valid.

In an open system, the high pore air pressure forces the water to flow from the soil to the ceramic disk until the soil pore water pressure, equal to the pressure in the disk, comes to equilibrium with the soil air pressure.

Methodology:

Saturate a ceramic plate and place a soil sample(s) on the ceramic plate and allow the soil to reach a desired state of equilibrium.

Vary the air pressure in the pressure cell until equilibrium is reached again.
The soil matric pressure is the difference between the applied air pressure and the water pressure where the water pressure is usually close to atmospheric.

Determine the soil moisture content by:

a) measuring the volume of flow of water or

b) quickly removing the soil from the cell and conducting a water content test.

Calibration Procedure:

Knowledge of the response time of the ceramic plate is helpful in interpreting the results.

Sensor Capabilities:

Can measure matric suction up to 15 bars and can be used to investigate matric suction-moisture relationships.

Sensor Limitations:

Occluded air bubbles in soil result in overestimation of matric suction (lower measured water pressure).

Air diffusion through the plate can cause underestimation of matric suction if a pressure gauge is used to determine water pressure and erroneous calculation of the volume of the flow of water (air forms bubbles at the bottom of the disk).
Indirect Measurement of Matric Suction

- Moisture Blocks

Basic Principle:

A block of porous material with an electrical sensor is placed in soil and the water pressure of the block is brought to equilibrium with the soil water pressure. The electrical or thermal conductivity properties of the block is dependent on the amount of water in the block.

Description:

For moisture (Watermark™) blocks, measure the electrical resistivity of the soil moisture block.

For thermal conductivity sensors (TCS), the voltage difference across a temperature-sensitive electronic sensor is used to indicate the thermal conductivity of ceramic material that is in equilibrium with the soil water.

Methodology:

Measure electrical output directly from moisture block sensor.

For new types of TCS, the voltage difference across an electrical sensor in the block is obtained immediately before and after applying a prescribed amount of heat.
The difference between the two voltage differences is an indication of the thermal conductivity of the block.

Calibration Procedure:

Calibrate known matric suction versus the electrical output of the sensor.

Can be done using apparatus similar to a pressure plate extractor in order to vary the matric suction.

Calibrations for the TCS, matric suction versus voltage difference, are approximately bilinear for a range of 0 to 375 kPa.

Sensor Capabilities:

TCS, and moisture blocks, can be used to measure matric suction up to 400 kPa or larger.

Sensor Limitations:

Moisture blocks are sensitive to dissolved salts.

TCS devices are not sensitive to dissolved salts and should not be sensitive to temperature.

Cannot measure matric suction of frozen soil because the properties of ice are different than water.
Measurement of Osmotic Suction

- Electrical Conductivity

Both osmotic suction and electrical conductivity are dependent on the ionic concentration of dissolved salts in soil pore water.

Osmotic suction is not a property of the soil water content.

Osmotic suction can be measured by obtaining a sample of pore water, squeezing technique, and measuring the electrical conductivity.

Filter paper can be used to measure total suction (not in contact with soil) and matric suction (paper in contact with soil). The difference is then equal to the osmotic suction.
1) What is an expression for the pressure potential, volume basis (kPa), of water at the meniscus in a capillary tube?

2) A capillary has a diameter 18 µm. Assuming complete wetting (\( \alpha = 0^\circ \)), what is the air entry value in kPa for this capillary?

3) If the relative humidity in a laboratory is kept at 50%, what is the head value measured by a tensiometer in the laboratory? What will happen to the tensiometer under these conditions?

4) It is desired to investigate the seasonal variation of moisture suction at a site with soils that have high shrink/swell potential. The site will be used for slabs on grade construction of light structures and pavements. Recommend a monitoring program that could be used to determine profiles of suction versus depth for the site. It will only be necessary to obtain profiles in the top 2 to 3 meters.