1 – BASIC PROPERTIES OF GAS, SOLID AND LIQUID PHASES OF SOIL

Main parameters of the soil: Liquid Limit

The Liquid limit (LL) is conceptually defined as the water content at which the behavior of clayey soil changes from plastic to liquid. However, the transition from plastic to liquid behavior is gradual over a range of water contents, and the shear strength of the soil is not actually zero at the liquid limit.

A more precise definition of the liquid limit is based on the Casagrande cup [Fig.1] which is a standard test procedures described below:

Fig.1 Casagrande Cup

Soil is placed into the metal cup portion of the device and a groove is made down its center with a standardized tool of 13.5 millimeters (0.53 in) width. The cup is repeatedly dropped 10 mm onto a hard rubber base at a rate of 120 blows per minute, during which the groove closes up gradually as a result of the impact. The number of blows for the groove to close is recorded.

The moisture content at which it takes 25 drops of the cup to cause the groove to close over a distance of 13.5 millimeters is defined as the liquid limit. The run is normally run at several moisture contents, and the moisture content which requires 25 blows to close the groove is interpolated from the test results. The Liquid Limit test is defined by ASTM standard test method D 4318.The test method also allows running the test at one moisture content where 20 to 30 blows are required to close the groove; then a correction factor is applied to obtain the liquid limit from the moisture content.

In case it may be interesting for the course please see Atterberg’s limits too.

Reference:

- *Wikipedia*
- *Geotechnical Materials from geotechnical course in Rome*

2 – SOIL WATER CONTENT

Measurements of the water contents in the soil

NEUTRON PROBE : //

ELECTROMAGNETIC METHODS :
TDR **(Time Domain Reflectometry)** - The formula mentioned to compute the water content is the Topp equation; however this equation fails to describe adequately cases for water contents exceeding 0.5, and for organic soils or mineral soils high in organic matter or clay content. In its simplest form the dielectric mixing approach uses dielectric constants and volume fractions for each of the soil constituents (e.g. solid, water, air) to derive a relationship describing the composite (bulk) dielectric constant. Such a physically based approach was adopted by Birchak et al. (1974), Dobson et al. (1985), Roth et al. (1990), and Friedman (1998). According to Roth et al. (1990), the bulk dielectric though there is another one which is commonly used to estimate it. It's the so-called CRIM equation (Complex Refractive Index Model)

$$\theta = \frac{\sqrt{\varepsilon} - \emptyset\sqrt{\varepsilon_{air}} - (1-\emptyset)\sqrt{\varepsilon_{solid}}}{\sqrt{\varepsilon_{water}} - \sqrt{\varepsilon_{air}}}$$

For the common case of ε_{solid}= 4 and with ε_{air}=1 and ε_{water}=81 we therefore have:

$$\theta = \frac{\sqrt{\varepsilon} - (2-\emptyset)}{8}$$

Note that the soil's porosity must be known or estimated when using the mixing model approach. Soils having high clay or organic matter content often require soil-specific calibration. The presence of high porosity combined with large amounts of 'bound' water fraction produces substantial differences between the dielectric signatures of typical mineral versus organic soils. This is illustrated the following figure [Fig.2] by a comparison of the Topp and the a calibration curve based on the CRIM's equation with Ø=0.5.

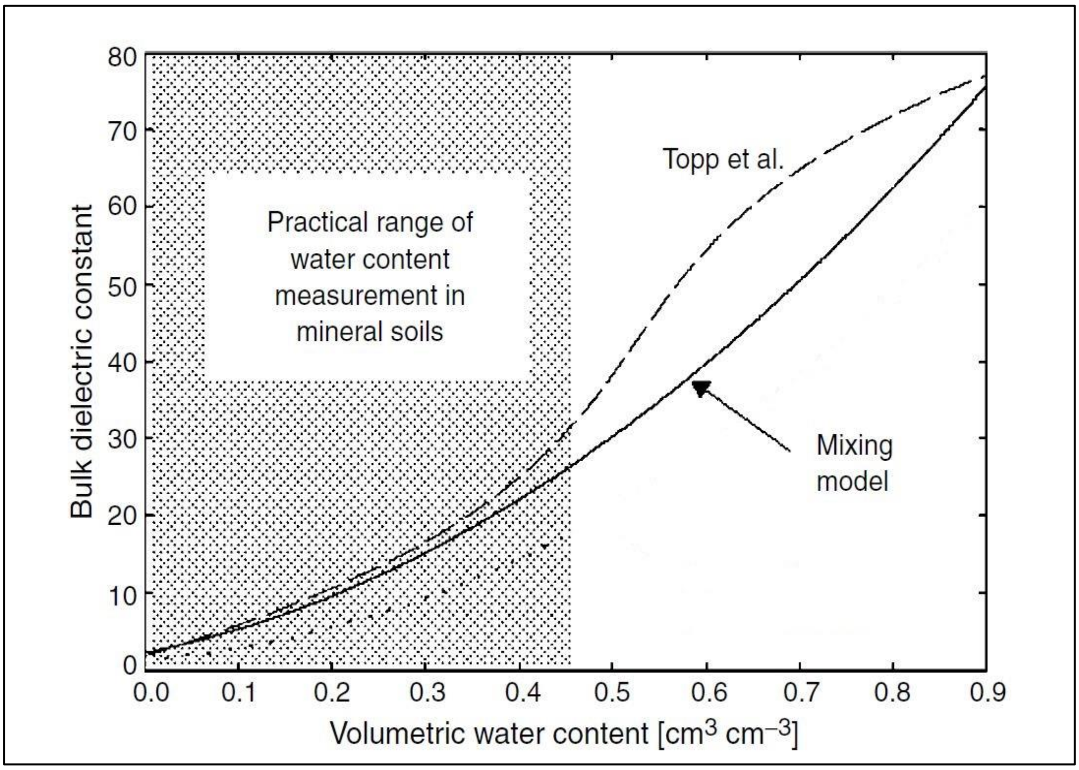


Fig.2 Comparison between Topp and CRIM

Alternative frequency domain analyses

FDR (Frequency Domain Reflectometry): Although TDR offers simultaneous and accurate water content and electrical conductivity determination in soils and other porous media, waveform reflections necessary for dielectric constant measurements can be totally attenuated in lossy materials. Factors such as soil texture, salinity, cable length, probe geometry and water content all influence signal attenuation.
FDR also uses an oscillator to propagate an electromagnetic signal through a metal tine or other wave guide, but with this method, the difference between the output wave and the return wave frequency is measured to determine soil moisture.
Frequency Domain Reflectometry (FDR) probes are considered accurate but must be calibrated for the type of soil they will be buried in. They offer a faster response time compared to Time Domain Reflectometer (TDR) probes and can be connected to a standard data logger to collect readings.
While frequency capacitance types soils sensors are call “FDR” sensors, this is somewhat of a misnomer because many of these probes only use a single frequency and not a “domain” of many frequencies.
Despite the laborious nature of this approach, including fast Fourier transformation of the waveform and fitting of an appropriate model to the transformed scatter function, the procedure has the potential to be automated to make it more amenable to real-time measurements.

Outlook: The TDR method is maturing, as evidenced by the introduction of devices specifically designed for hydrological applications. Moreover, the application of alternative methods of analysis, such as frequency domain techniques, provides a means to extend the useful range of utility as well as a potential for extraction of supplementary information concerning water and its interactions with porous media. Some potentially useful applications derived directly from the TDR method include measurement of specific surface area, and in situ determination of water retention properties of field soils.

References:

- *Scitentific Briefing –Time domain reflectometry measurement principles and applications - Scott B. Jones,1* Jon M. Wraith2 and Dani Or1- Hydrological Processes - 16, 141–153 (2002) DOI: 10.1002/hyp.513*
- *Hydrogeophysics materials, EPFL – Master Course Environmental Engineering*
- *Hydrology Course Material, University of Rome, La Sapienza*
- *http://www.soilsensor.com/soilsensors.aspx*
- *Wikipedia*

Latest technologies: Wi-Fi sensors

A promising new technology for monitoring soil water content dynamics at multiple depths is the wireless sensor network. Wireless environmental sensor networks enable the observation of soil water content variability in space and time in near real time previously impossible. They will play an important role in the emerging terrestrial environmental observatories because they are able to bridge the gap between local- (e.g., lysimeter) and regional-scale measurements (e.g., remote sensing).

Remote sensing technologies, such as passive or active microwave radiometry, can avoid direct measurements by providing area wide estimates of surface; however, the received signal is strongly influenced by vegetation and surface roughness, and the sampling depth is restricted to the uppermost soil (2–5 cm) (Walker et al., 2004).

Consequently, direct measurements are still indispensable in areas with significant vegetation and litter cover. Typically, the footprint scale ranges from about 100 m for an airborne radiometer (e.g., a polarimetric L-band multibeam radiometer), to about 50 km for a space-borne radiometer (e.g., the Soil Moisture and Ocean Salinity satellite). Given the high variability of soil water content, a large number of ground measurements are needed to estimate the mean soil water content within a remotely sensed footprint for validation purposes.

The basic structure of a wireless network is presented in [Fig. 3].

Typically, three different components are present in a wireless network application. The coordinator is the top of the network tree. It stores information about the network and it can provide a link to other networks. Each network has only a single coordinator.

An important task of the coordinator is to initiate the wireless links within the network. The second component is the router, which acts as a relay station that passes data from other devices. The third component is the sensor, which should have just enough functionality to communicate with its parent node (either the coordinator or a router). This allows the sensor to be asleep a significant amount of the time to save energy.

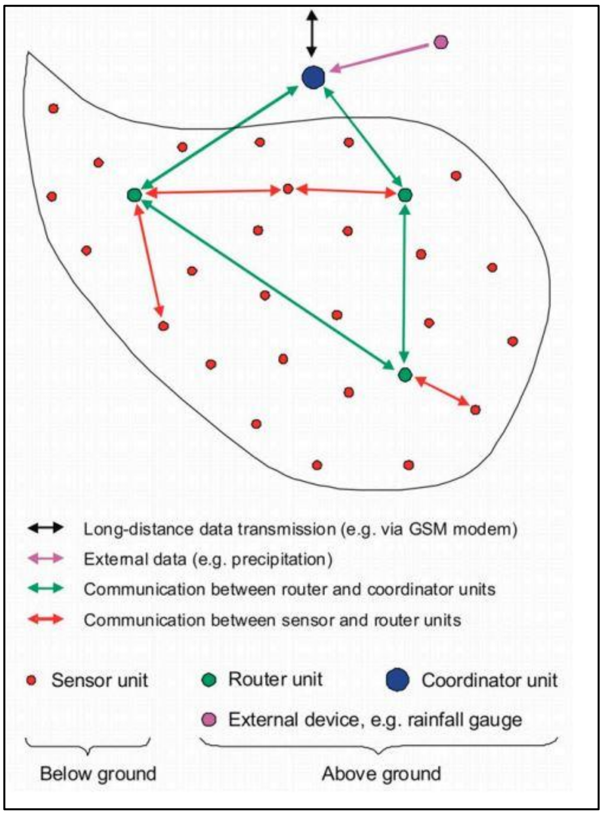


Fig.3 Wireless network schema

A well-designed wireless sensor network can be infinitely expanded and can be dynamically adapted. In addition, it can react to external influences. For example, a soil water content sensor network can be linked to an automated rain gauge and the sampling frequency could be increased during rainfall events to allow the investigation of highly dynamic processes.

Besides these advantages of wireless sensor networks, a considerable disadvantage is their strong reliance on batteries. Even for sensors with low power consumption, the batteries have to be changed after several years. This will lead to additional maintenance costs and should be considered when using sensors in the subsurface. Therefore, sensor selection should also consider energy consumption to ensure a long battery life.
Finally, wireless transmission may be more prone to signal transmission failures (e.g., attenuation, radio interference, dead battery), which implies a risk of data loss. This can largely be avoided with appropriate communication protocols, but it cannot be completely excluded. A solution to this problem would be to store data locally on each sensor unit so that data could still be recovered in the case of transmission failure.

References:

- *Wireless Sensor Networks for Soil Science - Andreas Terzis∗ Razvan Musaloiu-E.∗ Joshua Cogan‡ Katalin Szlavecz† Alex Szalay‡ Jim Gray+ Stuart Ozer+ Chieh-Jan Mike Liang∗ Jayant Gupchup∗ Randal Burns∗ / Inderscience Enterprises Ltd*
- *Hydrogeophysics materials, EPFL – Master Course Environmental Engineering*
- *Potential of Wireless Sensor Networks for Measuring Soil Water Content Variability, H.R. Bogena [*], M. Herbst, J.A. Huisman, U. Rosenbaum, A. Weuthen and H. Vereecken – Vadose Zone Journal - Vol. 9 No. 4, p. 1002-1013*
- *Walker, J.P., P.R. Houser, and G.R. Willgoose. 2004. Active microwave remote sensing for soil moisture measurement: A field evaluation using ERS-2. Hydrol. Processes 1811:1975–1997*

GYPSIUM BLOCKS

Gypsum blocks measure soil water tension, a reflection of the force that a plant must overcome to extract water from the soil. Gypsum blocks measure tension in dry soil. Tensiometers similarly measure soil water tension but in wet and moist soil.
Gypsum blocks use two electrodes placed into a small block of gypsum to measure soil water tension. Wires connected to the electrodes are connected to either a portable hand-held reader or a data logger. The gypsum blocks are permanently buried in the soil at the desired depth. Once buried there the blocks have a life of 3 to 5 years (depending on the type of soil).
The resistance between the two electrodes varies with the water content in the gypsum block, which will depend directly on the soil water tension. As the soil dries out water is extracted from the gypsum block and the resistance between the electrodes increases. Conversely as the soil wets, water is drawn back into the gypsum block and the resistance decreases. While gypsum blocks can be relatively inexpensive and easy to install compared to other types of soil sensors, they have to be replaced periodically as the gypsum disintegrates. Gypsum blocks are also more sensitive to having readings throwing off by soil with high salinity (salt content).
However, because naturally occurring gypsum doesn’t have a consistent pore size distribution and it degrades over time, the instrument was not very accurate.
The following figures [Fig.4] and [Fig.5] show the gypsum technology sensors.

Fig.4

Fig.5

References:

- *eg.ictinternational.com/products/5201/gypsum-block-g-block/?from=/products/soils/water-potential-field/*
- *en.eijkelkamp.com/products/field-measurement-equipment/soil-moisture-measuring-system-with-gypsum-blocks.html*
- *depi.vic.gov.au/agriculture-and-food/farm-management/soil-and-water/soils/gypsum-blocks-for-measuring-the-dryness-of-soil*

Hydraulic head

PEZIOMETERS

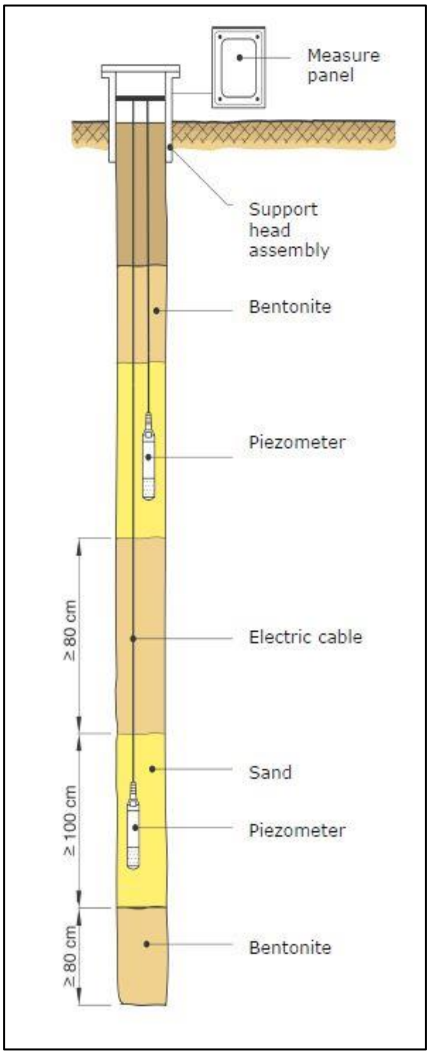
Two main types of piezometer:

Open wells or standpipe piezometers:

- Simple piezometer
- Casagrande's piezometer

The standpipe piezometer is used to monitor piezometric water levels. It consists of a filter tip joined to a riser pipe. Readings are obtained with a water level indicator.
Standpipe piezometers are simple, reliable and relatively inexpensive. The accuracy depends on the skill of an operator. They can be very slow to respond to changes in porewater pressure since large fluid volumes are required to change the level in the standpipe. It is not usually possible to monitor these instruments remotely.

Closed circuit type piezometers: Piezometers in durable casings can be buried or pushed into the ground to measure the groundwater pressure at the point of installation. Generally used for low permittivity grounds or in presence of groundwater acquirer.



The pressure gauges (transducer) can be vibrating-wire, pneumatic, or strain-gauge in operation, converting pressure into an electrical signal. These piezometers are cabled to the surface where they can be read by data loggers or portable readout units, allowing faster or more frequent reading than is possible with open standpipe piezometers.

Electrical piezometers are largely used in civil and foundations engineering, to monitor groundwater level and to measure pore water pressure. They can be installed in borehole, embankments or directly by drive-in if the ground features allow the operation.

How it works: the membrane deforms due to water pressure, causing the variation of an electric signal, measured with a measuring device.

Fig.5 Electrical Piezometer components

There are two kinds of sensors: -Vibrating wire -Resistive

In the *vibrating wire piezometers (VW)* the membrane deformation causes the tension variation of a steel wire stretched between the membrane and the instrument body. The vibration frequency is collected from a measuring device. This instrument, moreover, includes a thermistor to measure the temperature.

The resistive piezometers have a ceramic membrane with molded staring-gauge that changes their resistance and the electric signal according to membrane deformations due to water pressure. Generally the vibrating wire piezometers assure a high reliability for long term measures; the resistive allow high insulation (for example in industrial plants) and possibility to take dynamic measures.

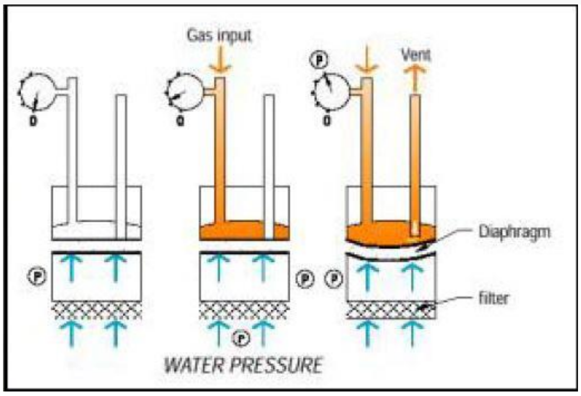
One of the most important elements of the piezometer is the conical filter tip; its choice depends on the ground type. The sintered stainless steel or vjon filters have a porosity of ca. 40 µm, are called “low air entry” (LAE) and are used for most standard applications. Ceramic filters have a low porosity and shall keep the saturation of the hydraulic chamber also if submitted to negative pressures (suction). The ceramic filters are called “High Air Entry” (HAE).

Filters Saturation

The purpose of filters saturation is to remove the air in filters pores and replace it with water in order to have a faster answer to pressure variations and more accurate measures; moreover it prevents grounds particles to obstruct filter pores.

The air entry is the pressure necessary to force the air through a porous filter completely saturated. Typical values of “low air entry” are the ones between 3 and 30 KPa while typical values of “high air entry” are the ones higher than 100KPa.

Pneumatic Piezometer



In this type of piezometer on the front side of the diaphragm there is force due to the air pressure that opposes the water pressure on the other side.

When the two pressure values equal, an equilibrium point is reached. In that moment the pressure of the air correspond to the pressure of the water aimed to be measured.

Fig.6 Pneumatic Piezometer

References:

- *Ing. Quintilio Napoleoni – Geotecnical Course Material, La saPienza University of Rome, 2013/2014*
- *www.geokon.com/content/datasheets/4590_Casagrande_Standpipe_Piezometer.pdf*
- *SPECTO TECHNOLOGY - www.spectotechnology.com/wp-content/downloads/products/water%20and%20piezometers/piezometers/piezometer%20-%20manual%20(sisgeo).pdf*
- *Wikipedia*

TENSIOMETERS

Tensiometers are among the oldest water potential instruments in soil physics (first used by Willard Gardner and his students almost 100 years ago), but they are still the most accurate instruments available for measuring soil matric potential.

The tensiometer's range is limited by the ability of water inside the tube to withstand tension. Although water itself has been shown to withstand tensions as high as 28000 kPa before cavitating, and water in the xylem of plants routinely sustains tensions beyond 3000 kPa, tensiometers have a much more limited range. Discontinuities in the water surface such as edges or grit provide nucleation points where water's strong bonds are disrupted and cavitation (low-pressure boiling) occurs. Most tensiometers cavitate around -80 kPa.

Fig.7 Tensiometer

The Evolution of Ceramic Discs

We learned with the gypsum blocks that one of the challenges in solid matrix water potential measurement is finding a material that will create the same water retention curve every time. In quest of this goal, the ceramic discs in sensors have taken years of development. Because of the limited range of the tensiometer, we wanted to develop a water potential sensor that could measure over a larger range. The hardest part about developing that ceramic was getting a variety of pore sizes so the instrument could read said wide range of water potentials. This started years ago in the lab of Dr. Gaylon Campbell at Washington State University where his technician, Kees Calisendorf, experimented over a long period of time to come up with the perfect recipe.

Fig.8

One of the first ceramic sensor released It allowed for long-term monitoring in the field because, unlike gypsum, the ceramic did not degrade over time.

What's Next?

Testing different ceramics, or other porous media, may hold the key to a solid equilibrium technique sensor reading all the way to 0 kPa, eventually replacing the need for tensiometers in the field.

References :

- *http://www.environmentalbiophysics.org/*
- *http://www.environmentalbiophysics.org/the-history-and-future-of-water-potential/*

LAB EQUIPEMNT:

-<u>plaque de succion (faibles succions)</u>: ok

-<u>marmite à pression (Richards plates)</u>: The pressure plate doesn't actually measure the water potential of a sample. Instead, it brings the sample to a specific water potential by applying pressure to the sample and allowing the excess water to flow out through a porous ceramic plate. When the sample comes to equilibrium, its water potential will be equivalent to the pressure applied.

Essentially, there are only two highly accurate ways to measure water potential—with a tensiometer or with vapor pressure. The tensiometer works in the wet range of water potential—from 0 to about -0.2 MPa. Vapor pressure methods work in the dry range of water potential—from about -0.1 MPa to -300 MPa (0.1 MPa is 99.93% RH; -300 MPa is 11%). With recent advances in technology, a skilled user with excellent methods and the best equipment can finally measure the full water potential range in the lab.

Thermocouple Psychrometer

The psychrometer is equipped with two identical thermometers. One is kept dry while the other is kept continuously moist. Atmospheric humidity is calculated from the temperature difference between the two thermometers. The psychrometer works well in the atmosphere where the humidity is usually quite low and ventilation can be controlled, but in the soil the humidity is generally above 99% and there can be no ventilation.

Like the psychrometerr, the WP4-C measures the vapor pressure inside a sealed chamber, equilibrated with the soil sample. Unlike the psychrometer, it uses the dew point method to measure the vapor pressure, and also accurately measures the sample temperature. The psychrometer adds water to the air in order to measure its vapor pressure, but in the dew point method, the air is cooled without changing its water content until the air just saturates. The vapor pressure is computed from this dew point temperature. The water potential of the sample is linearly related to the difference between the sample temperature and the dew point temperature.

Fig.9 WP4-C *Dewpoint Potentiometer*

HYPROP is a modular lab instrumen that generates a moisture characteristic curve and determines the unsaturated hydraulic conductivity of soil samples in standard 250 ml soil sampling rings. Hyprop uses two precision mini-tensiometers to measure water potential at different levels within a 250 ml soil sample while the sample rests on a laboratory balance. As the sample dries, changes in water potential are correlated to changes in moisture content using the Wind/Schindler evaporation method.

Fig.10 Hyprop

Fig.11 Hyprop cutout

Scroll down for comparison table and section references.

Water Potential Instrument Ranges – Table 1 [Fig.12]

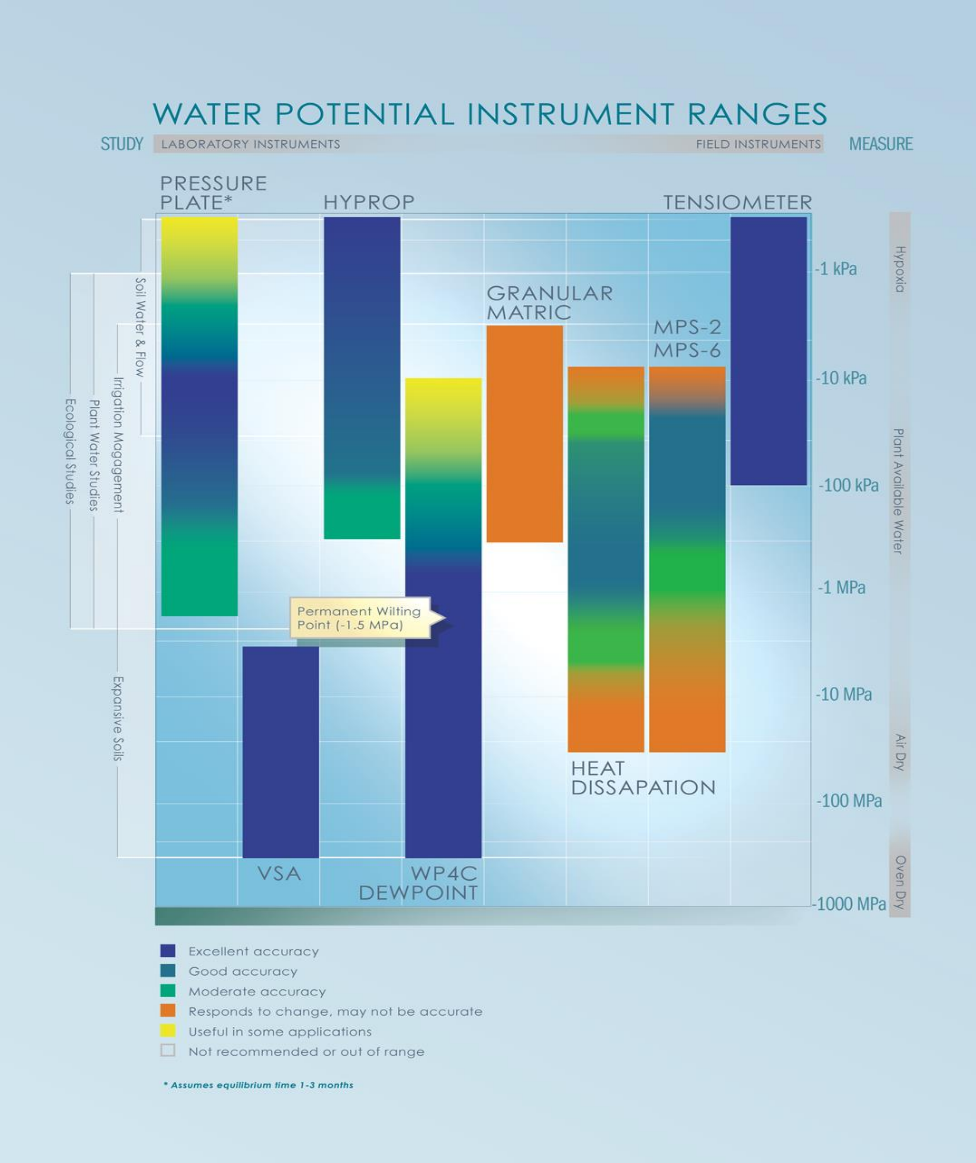


Fig.12 Comparison between the different instruments listed above

http://www.environmentalbiophysics.org/the-history-and-future-of-water-potential/There is not a lot mentioned about the other instruments that compare on the table, though if it may be of your interest please have a look on these pages for further details:

- http://www.decagon.com/products/soils/benchtop-instruments/truedry-cv9/
- http://www.decagon.com/products/soils/benchtop-instruments/vapor-sorption-analyzer/

References:

- *decagon.com/education*
- *http://www.decagon.com/products/soils/benchtop-instruments/*

3 - WATER DYNAMIC IN THE SOIL

Hydraulic Conductivity

Hydraulic conductivity in soils applications is typically used to describe the ease at which water can flow through soil. Saturated hydraulic conductivity (K_s) is used to describe water movement through saturated soils.

Methods for measurements:

LAB : - Permeameter constant Head – Permeameter falling Head – *Indirectly with Edometric test (more used for geotechnical tests, read the following for more details)*

More information about The Edometric test: *Edometric tests try to reproduce the state of tension that develops in ground when it is loaded. The load is applied to a test cylinder contained in a metallic ring and porous stone is placed at its base to allow drainage. The sample is axially loaded with growing increments which are registered as subsidence as a function of time.*
In a saturated clay, as the fluid in the pores is incompressible and permeability is very low, an increase of pressure initially produces only an increase in the pressure of the water (neutral pressure). In the course of time, however, drainage of water allows a reduction in volume which is in effect, consolidation. This phenomenon assumes great importance in forecasting the subsidence over time of clayey ground.
In standard Edometric tests there is one dimensional consolidation and the speed and degree of settlement deriving from variations of volume are measured. The test results are shown as a diagram which relates the index of voids with the pressure for each stage of load increase. From the slope of the curve so derived, one can obtain the Edometric Modulus. The Coefficient of Compressibility mv and the Edometric Modulus Eed which are used in the calculation of subsidence. (Terzaghi's method or the method of Edometric compressibility).

IN SITU : DUALHEAD INFILTROMETER

The DualHead infiltrometer measures soil saturated hydraulic conductivity. It is fully automated and requires no post-processing of data. The Infiltrometer ponds water on top of the soil and use air pressure to create two different pressure heads. It automatically maintains the correct water levels and measures infiltration rates through two complete pressure cycles. The control unit collects all data and performs the calculations to determine field saturated hydraulic conductivity. All data can be downloaded from the control unit for further analysis.

Positive aspects:

- Easy to Carry - Sized for one person to easily carry and install
- Simple Installation - Pound in the ring, connect the hoses, and set the parameters
- Eliminate "Guess Factor" - Measures infiltration at two different pressure heads to find (rather than estimating or guessing) the soil macroscopic capillary length factor (alpha)
- Use Less Water **-** The DualHead uses air pressure to maintain the pressure heads. No need to adjust and measure water levels.
- Proven Method - An automation of the method used by Reynods and Elrick (1990) and others.

Fig.13 DualHead Infiltrometer

Background: Water flows through soil in three dimensions. In the early days of infiltrometers, it was simply impossible to solve two and three dimensional equations, so the dual ring infiltrometer was created to try to physically force water to flow in one dimension.

Now that we can do the math, the single ring infiltrometer is an easier--and better--method. However, if you're using a single head or a changing head, you still need to know--or guess--the "alpha factor" (soil macroscopic capillary length) to solve the equations.

Reynolds and Elrick (1990) showed that by solving the equations at two different pressure heads, alpha drops out, allowing you to determine saturated hydraulic conductivity without making any assumptions.

References:

- *http://www.decagon.com/products/hydrology/hydraulic-conductivity/dualhead-infiltrometer/*
- *http://www.soilmeasurement.com/tension-infiltrometer.html*

5 - INTERACTIONS BETWEEN SOIL – ATMOSPHERE

- ***Disk Infiltrometer*** or Ring Infiltrometer : a quick way to test unsaturated hydraulic conductivity and infiltration rates
- ***Tension Infiltrometer*** : designed to measure the unsaturated hydraulic properties of soils. Water is allowed to infiltrate soil at a rate, which is slower than when water is ponded on the soil surface. This is accomplished by maintaining a small negative pressure on the water as it moves out of the infiltrometer disc into the soil.

Fig.14 Disk Infiltrometer

References:

- *http://www.soilmeasurement.com/tension-infiltrometer.html*
- *Ing. Francesco Napolitano – Hydrology Course Material, La Sapienza University of Rome, 2013/2014*

LYSIMITERS: powerful tools that can help to better understand the water balance, allowing us to measure deep drainage, evapotranspiration, and storage. In addition to the outdoor lysimeters, there is also the possibility to operate lysimeters in column experiments under laboratory conditions. These lysimeters are typically smaller and are used to investigate the behavior of natural soils or vegetation under special environmental conditions, as well as physical/hydrological soil properties of manually imported soils or processes of (contaminant) substance distribution, relocation and leaching. The size of the soil monoliths can vary from very small dimensions (95 cm^2 in area, less than 1 m deep) through to large lysimeters (2 m^2 in area, up to 3.5 m deep).

WEIGHABLE CONTROLLED TENSION LYSIMETER :

Combined with tensiometers, soil moisture sensors, data logger with optional GPRS modem, lightning protection, and powered by solar panels.

Field-Identical Water Conditions

A bi-directional pump is used to maintain the hydraulic boundary condition within the lysimeter. This means the field moisture is measured and transmitted into the lysimeter. If the soil in the lysimeter is drier that the reference field conditions, water will be pumped back into the lysimeter from the drainage reservoir. If the soil in the lysimeter is wetter than the reference field conditions, the pump will pull water out of the lysimeter to match field conditions. This technique ensures true field conditions inside the lysimeter.

Fig.15 Weighable controlled lysimiter in different sizes

Ready-to-go-Lysimeter

The Ready-to-go Lysimeter is a small lysimeter station for soil columns with an area of up to 0.5 m² and a length of up to 1 m. The compact lysimeter station consists of a lysimeter vessel with weighing system and seepage tank with tipping bucket, a weather station, a data logger and a range of soil hydrological sensors. The system operates as plug and play system, so that the entire station can be erected and put into operation without special tools or specialist personnel. The data are displayed on the internet using a data management system. Up to four Ready-to-go Lysimeters can be connected to one data logger. The RTG-Lysimeter is the ideal supplement to an existing weather station for directly calculating evaporation.

Fig.16 Portable Lysimeter

Advantages

- Inexpensive
- Small, and can therefore be handled and exported without large machinery
- Can be installed by the user himself

Fig.17 Installation

References:

- *http://www.decagon.com/products/hydrology/lysimeters/smart-field-lysimeter-weighable-controlled-tension-lysimeter/*
- *http://www.ugt-online.de/en/produkte/lysimetertechnik/ready-to-go-lysimeter.html*
- *Ing. Francesco Napolitano – Hydrology Course Material, La Sapienza University of Rome, 2013/2014*

SOIL SAMPLING

For soil sampling latest equipments: http://www.geotechenv.com/soil_sampling_equip.html

References:

- *decagon.com/education*
- depi.vic.gov.au/agriculture-and-food/farm-management/soil-and-water/soils/gypsum-blocks-for-measuring-the-dryness-of-soil
- *environmentalbiophysics.org/*
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- *Wikipedia*
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