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1-1.2.3 Capillary phenomena in soils

The description of capillary pressure curves in Chapter 1-1.2 implicitly concerns the aquifer or petroleum reservoir rocks, but this property can be generalised to all porous media. The purpose of this paragraph is to demonstrate the similarities, not always obvious at first sight, between the approaches adopted in petroleum and soil science techniques.

The soils, in the pedological sense and the geological sense, are worthy of special attention since capillary phenomena in soils are extremely important for all aspects of hydrology, agronomy and civil engineering. These disciplines have their own methods and terminology and readers interested either one can refer to the corresponding literature [e.g. Brady and Weil, 1999; Maidment, 1993].

A) Soil specificity

a) Specificity concerning the physical processes

Regarding the physical process, soil specificity is fundamental since the total volume of a soil sample may vary depending on the water content. This is not the case for reservoir rocks, which contain water and/or hydrocarbons and whose total volume (and *a fortiori* the volume of the solid phase) is considered as invariant: any loss of liquid in terms of volume leads to desaturation, and vice versa.

In a soil, loss of water first results in a reduction in total volume, the saturation index remaining equal to 100%. Then, beyond a water content limit known as the “shrinkage limit”, the soil behaves as a rigid rock and loss of water leads to desaturation of the porous space (see Fig. 1-1.5, p. 15).

In practice therefore, the water volume is either compared with the solid volume or to the dry mass in order to obtain an invariant. This leads to an abundance of definitions, sometimes a source of confusion, which will be summarised below, using the volume and mass parameters described in § 1-1.1.2 (p. 5): V_V , V_S , V_T , V_W respectively the void, solid and total volumes ($V_T = V_V + V_S$) and the water volume contained in the porous medium; W_S the dry mass and W_W the water mass:

- Porosity: $\phi = V_V/V_T$ The letter “n” is used in soil physics and soil mechanics (and sometimes “f” in hydrogeology, instead of “ ϕ ”).
- Void ratio: $\bar{E} = V_V/V_S$ where $\bar{E} = \phi/(1 - \phi)$, often written “e”.
- Saturation index $S_W = V_W/V_V$ (“saturation” in petroleum terminology). In soil physics and soil mechanics, S_R is often used instead of S_W .
- Soil moisture: $\theta_W = W_W/W_S$. The term “water content” is frequently employed instead of “soil moisture” and written “w” or “ ω ”
- Volume water content: $\theta_V = W_W/V_T$ This term is often confused with the expression V_W/V_T since these notions are used in soil mechanics and in soil physics where the assumption is made that $\rho_w = 1000 \text{ kg/m}^3$ (freshwater).

b) Specificity concerning the methodological approach

There are a certain number of specificities in the study of soil capillarity which correspond to methodological differences:

- In petroleum petrophysics, due to the specialisation of the technical teams, petrophysicists mostly disregard fluid movement related to capillary forces. These studies belong to the field of reservoir modelling. Consequently, it is the capillary pressure curve as such which is studied. In soil sciences however, this specialisation is less obvious and the movement of fluids (water in fact) is an integral part of the studies on capillarity. This leads to the definition of potentials (moisture, gravity, etc.). Since our objective is primarily to highlight the similarities between petroleum methods and soil sciences, independently of terminology differences, we will first describe the equivalent of the capillary pressure curve. We will then briefly discuss the movements of water in soil.
- One of the main applications of soil science is agronomy. It is not surprising that plants (especially their roots) play a major role, extending as far as the definition of

capillary properties. The maximum capillary pressure that can be “overcome” by the roots to extract water from the soil is one of the major parameters of the capillary pressure curve (wilting point).

B) Curve of capillary pressure in soils

a) Matrix potential curve

Figure 1-1.35, found in various forms in hydrogeology or pedology books [e.g. de Marsily, 1986] is the equivalent of the capillary pressure curve described in the previous paragraphs. The terminology differences must nevertheless be taken into account.

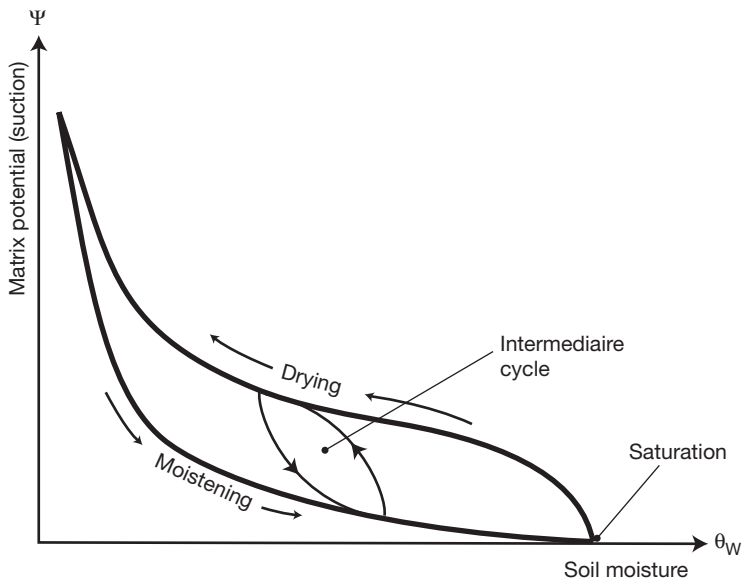


Figure 1-1.35 Curve of suction matrix potential against water content (equivalent, in soil science, of the capillary pressure curve)

The y-axis does not strictly correspond to a pressure (P_c) but to a moisture potential (Ψ_m), (also called “suction matrix potential”, “matrix potential” or “capillary potential”. It corresponds to the energy required to “extract” a unit mass of water fixed by the capillary forces. Note that:

- this physical quantity is expressed in practice as equivalent water height. We therefore obtain the same hydrostatic formula $P_c = \Delta\rho\gamma h$ as that used in § 1-1.2.6 (p. 102) to explain the saturation profiles in hydrocarbon reservoirs;
- in soil science applications, the air is virtually always at atmospheric pressure, which is taken as zero for pressure difference measurements. Since the capillary pressure is equal to the pressure difference between the non-wetting fluid (air, reference pressure

zero) and the wetting fluid -water), the pressures in water are negative. This explains why we speak of “suction”;

- For historical reasons (in reference to the former CGS system of units), these heights are converted into centimetres. Since the range encountered extends over several orders of magnitude, the heights are expressed in logarithmic form. The moisture potential “pF” is therefore equal to the decimal logarithm of the capillary suction expressed in centimetres of water, taking into account the sign inversion inherent to the use of the term “suction”.

Other sources of terminology confusion are given below: In the field of petroleum, and in the case of water-wet media, we have defined the two hysteresis branches:

- *drainage*: branch describing the decrease in water saturation;
 - *imbibition*: branch describing the increase in water saturation;
- In soil science, the term “drainage” is reserved for the water evacuation process during consolidation (water-saturated soils).
- the branch describing the decrease in water saturation is often called *drying*;
 - the branch describing the increase in water saturation is called *humidification, moistening or rewetting*.

b) Order of magnitude of moisture potentials

We have defined the potential “pF” as the decimal logarithm of the capillary suction expressed in centimetres of water. The orders of magnitude observed in soils are listed in Table 1-1.8. Note that the range of values is much broader than that generally considered for reservoir rocks.

c) Specific retention, Wilting point

By convention, pedologists identify two singular points on the pF curve:

- A point corresponding to $pF = 2$ (100 cm of water) corresponding to the “specific retention” of the soil expressed in volume content, equivalent to the hydrogeological notion of field capacity (weight content): if the pF is less, the soil is assumed to dry spontaneously (i.e. allow the water to flow by gravity).
- A wilting point corresponding to the energy beyond which plants cannot extract water from the soil, and set by convention at $pF = 4.2$ (16 000 cm of water, i.e. 1.57 MPa).

d) Soil water reserve

The difference between the volume water content at $pF = 2$ (“specific retention” or “field capacity”) and the volume water content at $pF = 4.2$ (wilting point) defines the soil “Available Storage” (**AS**) (or available reserve). The “Field capacity” is also called the “Water Storage Capacity” (**WSC**). We sometimes even speak of an “Available Moisture” (**AM**) limited by the water content to $pF = 3$. Some authors define it even more empirically: 1/3 or 2/3 of the **AS**, or 1/3 of the “Water Storage Capacity” (**WSC**).

These characteristics are schematised on Figure 1-1.36. We observe a certain similarity with the distinctions made by petroleum petrophysicists (Fig. 1-1.10, p. 20). The most

Table 1-1.8 Order of magnitude of moisture potentials “pF” and pore throat equivalent radii (data from Baize [2004, in French] and Banton and Bangoy [1999, in French])

Suction (Equivalent negative pressure)		Hydraulic head		Pore throat equivalent radius	Remarks
kPa (10 ⁻² Bar)	atm	Water column (cm)	pF		
0.1	≈ 0.001	1	0	1.5 mm	Pedologist’s macroporosity
1	≈ 0.01	10.2	1.1	0.15 mm	
10	≈ 0.1	102	2	0.015 mm	Specific retention
98	0.967	1 000	3	1.5 μm	Limit of classical tensiometers <i>in situ</i>
1 000	≈ 10	10 200	4.0	0.15 μm	<i>In situ</i> measurements: – limit of new-generation tensiometers – start of the field of psychrometric measurements
1 569	15.48	16 000	4.2	0.094 μm	Wilting point
7 000	69	71 400	4.85	0.021 μm	Limit of psychrometric measurements <i>in situ</i> (95% humidity)
9 804	100	100 000	5	0.015 μm	Air-dried soil (relative moisture 92%)
98 039	1 000	1 000 000	6	0.0015 μm	Air-dried soil (relative moisture 48%)

interesting similarity is that between the notion of “wilting point” used in soil physics and that of “irreducible water saturation” used in petroleum petrophysics. This similarity will also apply below, when we examine polyphase flows.

In these notions of soil water reserves, we find ambiguities similar to those observed in the definition of petroleum reserves. Initially, these concepts were determined to quantify the water available in the soil for vegetation. The capacity of plants to extract water obviously varies from one species to another. In addition, the limit defining the “field capacity” is purely empirical. Determination of “AS” or “AM” based on a range of pF values is therefore conventional and corresponds to a usual value, obtained by observation and experiment and mainly involving crops.

We must also mention two other sources of ambiguity:

- Soil physicists working in the field of pedology generally express volumes in water height by analogy with pluviometries and in order to make comparisons. The difficulty arises not so much in the conversion of volume into height per unit area, but in the determination of the depth of soil concerned. Strictly speaking, it can only be the

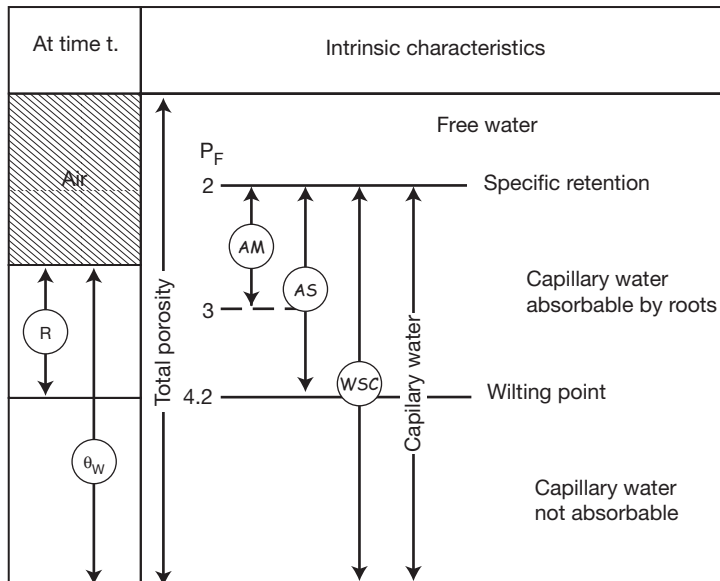


Figure 1-1.36 Occupation of soil porosity by water. Diagrammatic representation of various types of reserve

depth reached by the roots of the plants (cereals, trees, etc.) concerned and not the total thickness of the pedological soil or the geological surface formation considered.

- This leads to the other conceptual difficulty: a difference must be made between the potential total volume of a pedological horizon and the water actually available at a given time. This explains why modern agronomist make a clear distinction between the notion of *storage* (AS) and the notion of *reserve* (R).

It is interesting to point out the analogy with a notion also sometimes unclear in oil exploration, but which the petroleum engineers have had to strictly define by rigorously identifying the notion of hydrocarbon accumulation and the notion of reserves.

C) Total soil water potential and water movement in soils

The study of water movements in soils is clearly fundamental for soil science specialists and hydrogeologists. However, petrographers studying diagenesis (cementation, compaction) of sediments in the vadose zone, i.e. the zone very close to the surface in two-phase water/air saturation, also require a knowledge of these movements. Vadose diagenesis is of paramount importance in the study of numerous carbonate rocks, for example.

The generalised notion of total soil water potential is used to describe these movements. It is a physical quantity expressing the potential energy of water per unit mass, volume or weight of soil considered. Its dimensions vary depending on the definition used.

We will continue using the unit equivalent water height, as we did for capillary pressures.

The potential (Φ) is divided into three main potentials:

$$\Phi = \psi_z + \psi_m + \psi_o$$

where: ψ_z = gravity potential

ψ_m = moisture potential (or capillary potential, matrix potential) described above

ψ_o = osmotic potential

The osmotic potential is induced by the difference in salt concentration across a membrane, whether biological (plants) or mineral (clay).

Strictly speaking, an external potential (related to atmospheric pressure) and a kinetic energy term related to the fluid speed should be added to the previous potential energies. Since the flow speeds in porous media are generally very slow, however, this term is negligible.

Note that ψ_m changes sign and becomes a pressure potential (ψ_p) under the level of the aquifer piezometric surface.

The notion of total soil water potential is a very useful concept, since it provides an overall picture of the system, considering the soil-plant-atmosphere continuum as a single entity.

The possible water movements in the soil can therefore be identified. At a given time, the water profile of a soil is imposed by the equilibrium between the influxes (precipitation)/outfluxes (evaporation) on the soil surface and the capillary supply by the water table (in the broad sense).

The flux direction will be determined by the potential difference between the two points considered, from the higher to the lower. If, to a first order, the kinetic energy is neglected, considering that the displacements are very slow, the total soil water potential is that defined above: $\Phi = \psi_z + \psi_m + \psi_o$. In addition, the soil surface is usually taken as height reference.

Figure 1-1.37 gives a very simple and highly schematic example of the distribution of these potentials and therefore of the possible water movement, taking into account only the resultant of the moisture potential and the gravity potential. This problem is addressed implicitly when describing capillary drainage (§ 1-1.2.4B, p. 74) and more indirectly when examining the distribution of fluids in hydrocarbon reservoirs (§1-1.2.6, p. 102). In both situations, however, we are dealing with equilibrium profiles, which is not the case here.

We will first consider the examples of saturation profiles (Fig. 1-1.37 a). From an equilibrium profile (1) corresponding to the gravitational equilibrium of § 1-1.2.4B, near the soil surface, we observe variations due to the water influxes by precipitation (2) or water outfluxes due to evaporation (3).

These saturation variations induce correlative variations in moisture potential (Fig. 1-1.37 b). Since we chose the water equivalent height as unit of potential, the capillary equilibrium potential corresponds (by definition) to a straight line of gradient -1 cutting the y-axis at a negative value equal to the depth of the free (piezometric) water table. The influx or outflux profiles correspond to curves tending towards lower values for the outfluxes and higher values for the influxes (obviously, these are not absolute values but negative algebraic values).

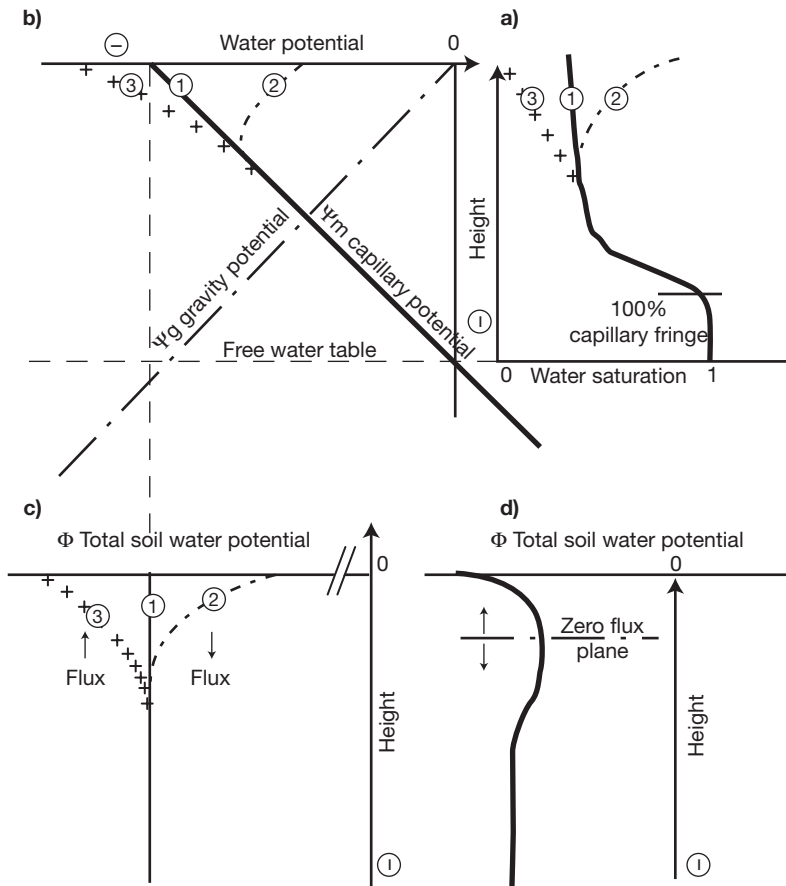


Figure 1-1.37 Highly diagrammatic example of distributions of potentials and saturations in a soil

- Saturation profile and capillary pressure for a gravitational equilibrium state (1); water influx (2) or water outflux (3).
- Potential corresponding to these states.
- resulting total potential.
- Example of zone with influx and outflux resulting in a zero flux plane.

The gravity potential corresponds to a straight line of gradient 1 going through the origin of the graph (soil surface).

In the simple hypothesis chosen, the water potential is equal to the sum of the previous ones. The resulting profile (Fig. 1-1.37 c) corresponds to a vertical line (equipotential) for the case of capillary equilibrium (by definition). In our examples of water influx and outflux, the potentials are locally greater or less than this equipotential, the water fluxes occurring either towards the top or the bottom.

Obviously, however, some saturation profiles may correspond to influxes and outfluxes successively on the same vertical. The resulting potential will be more complicated