Chapter 72
Soil Water Desorption and Imbibition: Tension and Pressure Techniques

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72.1 INTRODUCTION

Soil water desorption refers to the decrease in soil volumetric water content with decreasing pore water matric head (drainage), while imbibition refers to the increase in volumetric water content with increasing matric head (wetting). A discussion of the principles and parameters associated with the determination of desorption and imbibition curves is given in Chapter 69. This chapter describes the tension table, tension plate, and pressure extractor methods for measuring soil water desorption and imbibition curves, while Chapter 73 describes the long column method, and Chapter 74 describes the dew point psychrometer method.
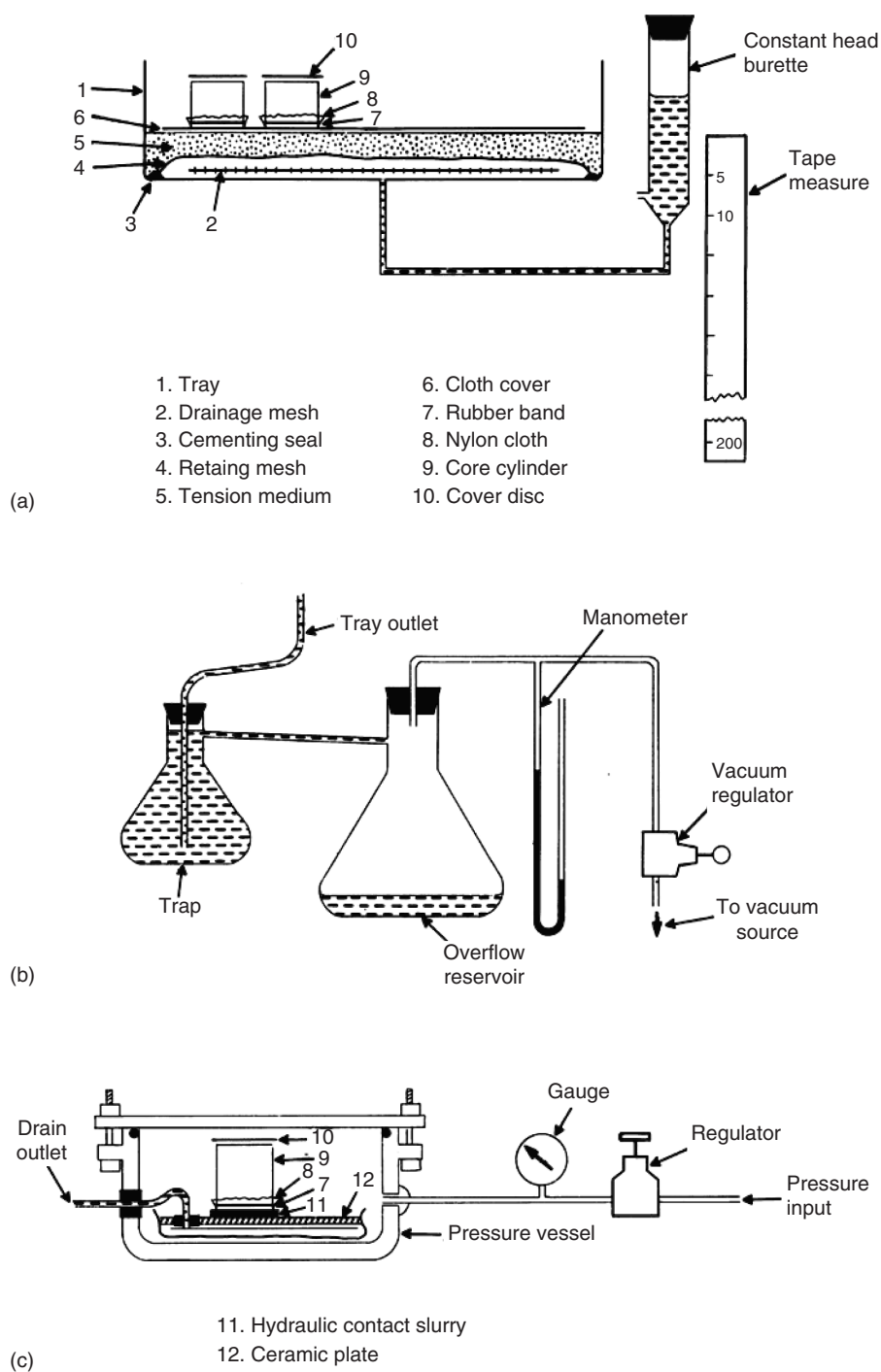
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72.2 TENSION TABLE AND TENSION PLATE

The tension table and tension plate methods are used primarily for soil cores that are less than 20 cm diameter by 20 cm long, although larger samples can be used. These methods involve establishing a continuous hydraulic connection between the sample and the tension medium or plate, and then sequentially equilibrating the sample to a series of preselected matric heads set on the table or plate. The water content of the sample after equilibration represents one point on the desorption or imbibition curve. If the soil sample is initially saturated and the preselected matric heads are set in a descending sequence (i.e., successively more negative), a desorption curve is obtained. If the soil sample is initially dry and the preselected matric heads are set in an ascending sequence (successively less negative), an imbibition curve is obtained. Scanning curves are obtained by reversing the sequence of matric heads (i.e., from

ascending to descending or vice versa) at some intermediate point along the desorption or imbibition curves (see Chapter 69 for details).

72.2.1 MATERIALS AND SUPPLIES

1   *Tension table*: A tension table (Figure 72.1a) consists of a circular or rectangular tank containing a saturated layer of tension medium, a port for allowing water inflow and outflow, and an apparatus for changing and controlling the matric head, ψ_m, of the pore water in the tension medium (Stakman et al. 1969). The tension medium has an air-entry value, ψ_a (see Chapter 69), that is lower (more negative) than the minimum matric head set on the medium, plus a high-saturated hydraulic conductivity to minimize sample equilibration time (Topp and Zebchuk 1979). For convenience and improved equilibration times, ''low-tension'' and ''high-tension'' tables are often set up, with low-tension tables operating in the range of $-1\ \mathrm{m} \leq \psi_m \leq 0\ \mathrm{m}$, and high-tension tables operating in the $-5\ \mathrm{m} \leq \psi_m \leq -1\ \mathrm{m}$ range (Topp and Zebchuk 1979). The tension medium in low-tension tables is usually natural fine sand ($< 50\ \mu\mathrm{m}$ particle diameter), fine glass beads (42 $\mu\mathrm{m}$ mean particle diameter), or silica flour ($10-50\ \mu\mathrm{m}$ particle diameter), while the high-tension tables generally use glass bead powder (25 $\mu\mathrm{m}$ mean particle diameter) or aluminum oxide powder (9 $\mu\mathrm{m}$ mean particle diameter) (see also Table 72.1). Beneath the tension medium is a water inflow–outflow port that is connected to the apparatus for setting and maintaining matric head, a drainage system to facilitate water movement into or out of the tension medium, and a fine mesh retaining screen to prevent loss of tension medium through the inflow–outflow port. The top of the tension medium may be protected by a cloth cover (nylon mesh) to prevent the tension medium from adhering to the soil core samples. Two main tension table designs are currently in use: (i) a rectangular perspex (acrylic) tank with a drainage system comprised of a glass microfiber retaining screen overlying a network of channels cut into the tank bottom (Ball and Hunter 1988) and (ii) a cylindrical polyethylene or PVC tank (Figure 72.1a) with a drainage system comprised of a retaining screen made of fine-grade nylon mesh ($6-20\ \mu\mathrm{m}$ openings depending on fineness of tension medium) overlying a coarse mesh woven stainless steel screen (≈ 3 mm openings) placed on the tank bottom (Topp and Zebchuk 1979). Both designs should have loose-fitting, opaque lids for the following reasons: (i) to allow easy air exchange, and thereby prevent possible buildup of vacuum or pressure when the matric head is changed; (ii) to prevent evaporative water loss from the sample surfaces during the course of the measurements; and (iii) to omit light to inhibit fungal/algal/microbial growth on and in the samples during the course of the measurements.

The tank needs to be stiff enough to resist flexing over the applied matric head range, as this can result in air entry due to cracking of the tension medium or breaking of the seal between the tension medium and tank wall (for cylindrical polyethylene or PVC tanks, a wall and base thickness of at least 0.5 cm is recommended for the low-tension system, and at least 1.5 cm for the high-tension system). A 60 cm diameter tension tank can accommodate up to 30 cores with a 7.6 cm diameter, and up to 12–15 cores with a 10 cm diameter. Although tension tables are relatively easy and inexpensive to construct, they can require frequent maintenance as a result of algal growth and periodic plugging of the retaining

Soil Water Desorption and Imbibition: Tension and Pressure Techniques   **985**

1. Tray   6. Cloth cover
2. Drainage mesh   7. Rubber band
3. Cementing seal   8. Nylon cloth
4. Retaing mesh   9. Core cylinder
5. Tension medium   10. Cover disc

(a)

(b)

11. Hydraulic contact slurry
12. Ceramic plate

(c)

FIGURE 72.1. Schematic of tension table/plate and pressure extractor systems: (a) a low-tension table with matric head control by constant head burette; (b) a controlled vacuum system for use with high-tension tables or plates; and (c) a pressure extractor system. Note that the burette reservoir and trap (storage) flask are the water sources for the imbibition curve.

TABLE 72.1 Approximate Equilibration Times (Days) for Desorption from Saturation. The Tension Table and Tension Plate Times Apply to 7.6 cm Long Intact (Undisturbed) Soil Cores, or 10 cm Long Intact Cores (Bracketed Values). The Pressure Extractor Times Refer to 7.6 cm Long Intact Cores (First Column) or 1.0 cm Thick Samples that Have Been Granulated to ≤2 mm (Second Column)

| | Tension table or tension plate with corresponding tension medium or contact material | | | | | |
Matric head, ψ_m (m)	Glass beads (42 µm mean particle diameter)	Glass beads (25 µm mean particle diameter)	Aluminum oxide (9 µm mean particle diameter)	Silica flour (10−50 µm particle diameter)	Pressure extractor (intact core)	Pressure extractor (granulated sample)
0	0.5 (1)	—	—	—	—	—
−0.05	1 (2)	—	—	—	—	—
−0.1	1 (2)	—	—	4 (5)	—	—
−0.2	1 (2)	—	—	5 (6)	—	—
−0.3	2 (3)	—	—	6 (7)	—	—
−0.4	3 (4)	—	—	7 (8)	—	—
−0.5	3 (4)	—	—	8 (9)	—	—
−0.6	3 (4)	—	—	9 (10)	—	—
−0.75	4 (5)	—	—	9 (10)	—	—
−0.8	4 (5)	—	—	9 (10)	—	—
−1.0	6 (7)	—	—	10 (11)	—	—
−1.5	—	8 (9)	—	11 (12)	—	—
−2.0	—	10 (11)	—	12 (13)	—	—
−3.3	—	12 (13)	12 (13)	14 (15)	≥10[a]	—
−5.0	—	—	14 (15)	—	≥11[a]	—
−10	—	—	—	—	≥12[a]	≥3[a]
−40	—	—	—	—	≥15[a]	≥7[a]
−150	—	—	—	—	≥20[a]	≥10[a]

[a] Equilibration times for pressure extractors are very sensitive to sample and plate hydraulic characteristics, and to the degree of hydraulic connection between sample and plate. Hence, determination of equilibration is best achieved by monitoring plate outflow (e.g., Figure 72.3).

screen or tension medium with silt and clay; and they can also be unreliable at matric heads < −1 m due to air entry and air accumulation problems (Topp and Zebchuk 1979; Townend et al. 2001).

2 *Tension plate*: An alternative to the tension table is the so-called ''tension plate'' (Figure 72.2). The essential difference between a tension plate and a tension table is that the tension plate uses a large-diameter ceramic disc or ''plate'' (e.g., ≥50 cm diameter) instead of tension medium. The ceramic plate is usually designed to have a relatively high-saturated hydraulic conductivity and a minimum operating matric heads of −5 to −10 m. Although tension plates are more expensive than tension tables and must usually be purchased from a commercial supplier (e.g., Soilmoisture Equipment Corp., California), they are very reliable and much easier to operate and maintain. Good hydraulic connection between the plate and the core samples is established and maintained using a thin layer (≈0.5 cm) of saturated ''contact material'' made of fine-grade glass beads (42 µm

Soil Water Desorption and Imbibition: Tension and Pressure Techniques   **987**

FIGURE 72.2. Example of tension plate apparatus (high-tension system) loaded with 10 cm inside diameter by 11 cm long intact soil cores. The cores are resting on a nylon cloth (15 μm pore size), which overlies a 0.5 cm thick layer of glass bead tension medium (25 μm mean particle diameter), which in turn overlies a 53 cm diameter ceramic disk (-10 m bubbling pressure) sealed within a PVC backing plate. To minimize biological growth and evaporative water loss, the cores are loosely capped with opaque plastic lids and the entire tension plate is covered with an acrylic lid. The trap (small flask) and overflow reservoir (large flask) for the vacuum system (Figure 72.1b) can be seen below the plates. Tygon tubing (1/4-in. i.d. by 1/8-in. wall) connects the trap to the inflow–outflow port of the tension plate via a hole drilled through the bench top.

mean particle diameter for the ''low-tension'' system; 25 μm mean particle diameter for the ''high-tension'' system) topped with fine-mesh nylon cloth (15 μm openings) to prevent the contact material from adhering to the samples. To minimize biological growth and evaporative water loss, the samples are loosely capped with opaque plastic lids and the entire tension plate is covered with an acrylic lid (Figure 72.2). A 50 cm diameter tension plate can accommodate up to 20–22 cores of 7.6 cm diameter, and up to 10–11 cores of 10 cm diameter.

3   *Matric head control*: Control of the matric head (ψ_m) applied to the water saturating the tension medium/plate and the coincident drainage/uptake of water by the samples is achieved using a hanging water column–constant head burette system (Figure 72.1a), or a regulated vacuum—manometer/transducer system (Figure 72.1b). The constant head burette system is recommended for low-tension tables/plates (-1 m $\leq \psi_m \leq 0$), while the vacuum system is recommended for high-tension tables/plates (-5 m $\leq \psi_m \leq -1$ m). For desorption

curve measurements, water removed from the samples drains out the burette outflow or into the overflow flask; and for imbibition curve measurements, water taken up by the samples is extracted from the burette reservoir or trap (storage) flask. Both systems are fitted with shutoff valves so that water flow can be stopped when needed (see Section 72.3.1). The matric head datum can be set at the top, bottom, or mid height position on the soil cores; however, the mid height position is most logical as it locates the average matric head in the core once equilibrium is established. For the constant head burette system, the mid-core datum position is most easily established by simply setting the zero point of the measuring scale (i.e., the top of the tape measure in Figure 72.1a) at the height, $L/2$, above the tension medium or contact sand surface, where L is the length of the soil core.

4 *Appropriately collected and prepared soil cores*: Collect soil cores (as recommended in Chapter 69), then trim the soil flush with the bottom end of the sampling cylinder using a sharp, thin-bladed knife or hacksaw blade to prevent smearing and loss of material. If there are gaps or holes at the bottom of the soil sample, fill them with fine-grade sand or glass beads (e.g., $25-42$ μm mean particle diameter) so that hydraulic contact between the sample and the tension medium or plate is maximized. Place a piece of nylon cloth (53 μm openings) over the bottom end of the core and hold in place with a stout, elastic band. The upper end of the core is covered with a loose-fitting disc to prevent losses or gains of soil and water.

5 *Rake (tension table) or putty knife (tension plate)*: Use a small handheld rake or similar implement suitable for raking and leveling the tension medium surface. Use a wide plastic putty knife or similar implement for scraping contact material off the tension plate. Do not use metal implements to scrape the tension plate, as they may damage the ceramic surface.

6 *Balance*: A weigh balance with the appropriate range (usually 0–3 kg) and sensitivity (usually 0.1–0.01 g).

7 *Controlled temperature*: Temperature controlled room (20°C $\pm$ 1°C) for housing the tension tables or plates, sample preparation, and sample weighing.

8 *Drying oven*: Forced air or convection oven for drying soil cores at 105°C $\pm$ 5°C.

9 *Cooling box*: Box with water vapor-tight seal suitable for cooling soil cores and other samples from oven temperature to room temperature in the presence of a desiccant.

72.2.2 PROCEDURE

72.2.2.1 DESORPTION CURVE

(i) Saturate the soil cores at room pressure and temperature (20°C $\pm$ 1°C) using deaired, temperature equilibrated water. Convenient procedures for deairing water include the following: (a) boiling or autoclaving in large-vacuum flasks (4 L),

Soil Water Desorption and Imbibition: Tension and Pressure Techniques **989**

then applying airtight seals to the flasks and cooling, (b) filling a vacuum desiccator with water and applying a 65 kPa vacuum for 45 min, and (c) direct application of vacuum (via vacuum pump or tap aspirator) to water in large-vacuum flasks. An advantage of autoclaving is that the water is also sterilized, which helps to reduce biological growth in the samples and in the tension medium or plate. Water used for saturation should have similar major ion speciation and concentrations as the native soil water to prevent aggregate slaking and dispersion/aggregation of silt and clay. Local tap water is often adequate, but this should always be checked. Saturate the cores by placing them in an empty ''wetting tank'' (Chapter 75), and submerge one-third and subsequent thirds of the core length each 24 h period, so that the ponded water is at the top of the core by the third day. This promotes more complete saturation of the sample (e.g., reduces air entrapment within the sample), and allows time for fine-textured soils to swell completely. Leave the cores in the wetting tank until free water appears on the core surface. Weigh the saturated core by (a) weighing it under water (using a cradle) or (b) quickly removing the core from the wetting tank and placing it in a tared weigh boat so that the weight of rapidly drained macropore water is included in the total core weight. Record the saturated core weight, $M_c(\psi_1)$, where $\psi_1 = 0$ is the first (and largest) ψ_m value on the desorption curve, which yields the saturated water content value, θ_s.

(ii) Place the saturated cores on the presaturated tension table or plate with the constant head burette set to yield $\psi_m = 0$ m at the tension medium surface (tension table) or contact material surface (tension plate). Close the burette inflow–outflow valve to prevent water flow. Establish good hydraulic connection between the bottom of the cores and the tension medium or contact material by pushing and twisting the cores slightly to deform the material to the shape of the core base. Open the burette valve and allow the cores to equilibrate, then remove and weigh to obtain core weight, $M_c(\psi_2)$, where $\psi_2 = -L/2$ is the second ψ_m value on the desorption curve and L is the core length. The time required for equilibration (equilibration time) depends on the matric head (equilibration time increases with decreasing head due to decreasing soil core hydraulic conductivity); the height of the soil core (equilibration time increases roughly as the square of the core length because of increased flow path); the quality of the hydraulic connection between soil core and tension medium or contact material (equilibration time increases as the contact area between core and medium decreases); and the saturated hydraulic conductivity of the tension medium/contact material (equilibration time may be somewhat greater for high-tension media relative to low-tension media). Approximate equilibration times for 7.6 cm long soil cores are given in Table 72.1, and 1–2 days are generally added to these times for 10 cm long cores. Note that the times are approximate only, and individual equilibration time tests are recommended for accurate work with any particular soil.

72.2.2.2 IMBIBITION CURVE

(i) Weigh the unsaturated soil cores to obtain, $M_c(\psi_i)$, where ψ_i is the initial ψ_m value of the samples. This weight will be used later to determine the initial soil water content of the cores.

(ii) Presaturate the tension table (or tension plate and contact material) using deaired, temperature-equilibrated water (see desorption curve procedures for details), and set the constant head burette or vacuum to produce the desired minimum (most negative) matric head relative to the chosen datum (e.g., mid-core height), and close the water inflow–outflow valve. Establish contact between the soil cores and the tension table or plate by wetting the bottom of the cores, then firmly placing the cores on the tension medium or contact material with a slight push and twist to establish a good hydraulic connection. Open the inflow–outflow valve and allow the cores to equilibrate (imbibe water), then remove and weigh to obtain core weight, $M_c(\psi_1)$, where ψ_1 is the first (and most negative) ψ_m value on the imbibition curve. Equilibration times for imbibition are generally longer than those for desorption because rewet soil hydraulic conductivity is usually less than drainage hydraulic conductivity due to hysteretic and air entrapment effects. Unfortunately, equilibration time guidelines for imbibition curves are not yet established, hence preliminary equilibration tests are required.

72.2.2.3 DESORPTION AND IMBIBITION CURVES

(i) *Next matric head $(\psi_m) \geq -1$ m (low-tension system)*: After $M_c(\psi_1)$ is measured, close the water inflow–outflow valve. To reestablish hydraulic connection between the cores and the tension table or plate, dampen the tension medium or contact material surface using a spray bottle (desorption curve), or wet the bottom of the cores (imbibition curve), and then return the cores to the same locations used for the previous head using a slight push and twist to ensure good core contact. Set the next desired head (i.e., ψ_2) by adjusting the height of the constant head burette, and then open the water inflow–outflow valve. Allow the soil cores to equilibrate, then remove and weigh to obtain, $M_c(\psi_2)$.

Low-tension tables and plates usually do not accumulate significant exsolved air (within and under the tension medium or plate) for matric heads ≥ -1 m. It is always advisable, however, to flush low-tension systems periodically to prevent possible buildup of exsolved air overtime. This is most conveniently accomplished by closing the inflow–outflow valve, setting the matric head at -1 m, ponding 3–6 L of deaired temperature-equilibrated water on the surface, opening the inflow–outflow valve to allow the water to drain through, and then resetting the matric head to zero at the surface. At the end of a sequence of low-tension measurements on a batch of soil cores (e.g., cores successively equilibrated to $\psi_m = 0, -0.05, -0.1, -0.3, -0.5, -0.75, -1$ m), it is advisable to ''purge'' the low-tension table or plate using the procedures given below for the high-tension system. It is also advisable to replace the contact material at the end of each sequence of low-tension measurements to prevent potential plugging of the ceramic plate by silt and clay; and to replace the tension medium when the tank drainage rate starts to decline, which usually signals incipient plugging of the medium by silt and clay. Idle tanks and plates should always be left with a small amount of ponded water on the surface, the matric head set to near-zero, and the inflow–outflow valve closed.

(ii) *Next matric head $(\psi_m) < -1$ m (high-tension system)*: Tension table: close the water inflow–outflow valve; add 1–2 cm depth of deaired, temperature-equilibrated water onto the tension medium surface; rake and level the top 1–2 cm of the

medium (to produce a soft, smooth, and flat surface for easier establishment of good hydraulic connection between core and medium); then purge exsolved air that usually accumulates within and under the tension medium (procedure given below). Tension plate: scrape the contact material off the plate; purge exsolved air that usually accumulates within and under the plate (procedure given below); pond 1–2 cm of deaired, temperature-equilibrated water on the plate surface; then replace and level the contact material (≈ 0.5 cm depth).

The high-tension systems usually accumulate exsolved air overtime, which should be "purged" between tensions as air bubbles can impede, or even stop, drainage and imbibition. The following procedure seems effective for purging exsolved air from within and under the tension medium or plate: (a) close the inflow–outflow valve and pond a shallow depth (3–5 cm) of deaired, temperature-equilibrated water on the surface; (b) set a low-matric head (e.g., -3 to -5 m) on the tension table or plate; (c) open the inflow–outflow valve quickly to produce sudden rapid drainage through the tension medium or plate. The hydraulic "shock" produced by rapid opening the valve generally dislodges exsolved air within and under the tension medium or plate, and the ensuing rapid drainage forces the air out the outflow port; and (d) after about 1 min of flow, close the inflow–outflow valve for a few minutes, then repeat step (c). Most, if not all, exsolved air can generally be removed by a few repetitions of steps (c) and (d), as evidenced by few air bubbles coming out the outflow port. During this procedure, care must be taken to maintain ponded water on the surface so the air cannot reenter the tension medium or plate as a result of the low-matric head set in step (b). Idle tanks and plates should always be left with a small amount of ponded water on the surface, the matric head set to near-zero, and the inflow–outflow valve closed.

After removing exsolved air, close the water inflow–outflow valve, install the core samples as done for the low-tension system, set the next desired matric head (i.e., ψ_2) by adjusting the vacuum, and then slowly open the water inflow–outflow valve. Allow the soil cores to equilibrate, then remove and weigh to obtain, $M_c(\psi_2)$.

(iii) Repeat step (i) or (ii) for each desired point on the desorption or imbibition curve (i.e., θ for ψ_3, ψ_4, ψ_5, etc.). The matric head settings depend on the intended use of the data (see comment 1 in Section 72.4). If changing water content causes the soil in intact cores to shrink (desorption curve) or swell (imbibition curve), the soil volume must be determined at a specific matric head, which is usually the field capacity head; e.g., $\psi_{FC} = -1$ m for intact core samples and $\psi_{FC} = -3.3$ m for disturbed samples.

(iv) Proceed to the analysis section if no additional curve points (i.e., $\theta(\psi_m)$ values) are required. If matric heads lower (more negative) than -5 m are required for the desorption curve, proceed to the pressure extractor method. At present, obtaining points on the imbibition curve at matric heads more negative than -5 m is difficult and rare, as it requires specialized materials and equipment.

72.3 PRESSURE EXTRACTOR

The pressure extractor method (Figure 72.1c) can provide points on the soil water desorption curve over the matric head range, -150 m $\leq \psi_m \leq -1$ m. However, the method is most commonly used for the more limited range, -150 m $\leq \psi_m \leq -3.3$ m, as the tension table

and tension plate methods are more efficient for greater heads (i.e., the tension table and plate methods have greater capacity and faster equilibration). The pressure extractor method applies gas pressure (rather than water tension) to push water from the soil sample, and thereby allows matric heads much lower (more negative) than the -5 to -8 m limit of the tension table or plate method. The pressure extractor method includes a ''low-pressure'' (-50 m $\leq \psi_m \leq -1$ m) and a ''high-pressure'' system (-150 m $\leq \psi_m \leq -50$ m), with the main difference being the air-entry pressure head (ψ_a) of the ceramic plate, and the size and strength of the pressure vessel. The use of pressure restricts the size of the extractor vessel, which in turn limits the size and number of intact soil cores that can be processed at one time. Standard commercial extractors can usually desorb no more than six 7.6 cm diameter soil cores at a time, and the cores cannot be longer than about 7.6 cm. Due to the restrictions on sample size/number and the long equilibration times associated with very low-matric heads, pressure extractors are used primarily for desorbing disturbed (granulated) soil samples that are only about 1–3 cm thick (see also comment 2 in Section 72.4).

72.3.1 MATERIALS AND SUPPLIES

1 *Pressure vessels*: The pressure vessels should be designed and built specifically for this application (e.g., Soilmoisture Equipment Corp., California), as the low-pressure vessels must withstand pressures up to 500 kPa ($\approx$73 psi), and the high-pressure vessels must withstand pressures up to 1500 kPa ($\approx$220 psi).

2 *Ceramic plates*: Porous ceramic plates with attached drainage system and three maximum pressure head ratings (10, 50, 150 m) are available commercially (e.g., Soilmoisture Equipment Corp., California).

3 *Pressurized air or nitrogen gas*: Regulated air compressor or commercial compressed gas cylinder containing compressed air or industrial grade nitrogen. Compressed nitrogen gas in a cylinder is often preferred due to the following reasons: (i) nitrogen is less soluble in water than air and thereby produces less gas accumulation under the porous plate and less evaporative water loss from the soil samples; (ii) nitrogen excludes oxygen from the pressure vessel and thereby reduces biological activity in the soil samples; and (iii) a compressed gas cylinder allows a simpler pressure control system than an air compressor, and it is not affected by power outages.

4 *Pressure regulator, pressure hose, gas shutoff valve, needle valve, and pressure gauge*: A bleed-off type regulator should be used if the pressure source is an air compressor; a nonbleeding type regulator should be used if the pressure source is a compressed gas cylinder. Use appropriately rated flexible pressure hose and gas shutoff valves. Plumb an accurate and sufficiently detailed pressure gauge into the line between the pressure source and pressure vessel to allow setting and monitoring the vessel pressure. Connect a needle valve to the pressure vessel exhaust to allow slow release of gas pressure when the soil samples are ready to be removed from the vessel.

5 *Contact material*: Fine particulate material, such as kaolin, is often (but not always) used to establish and maintain a good hydraulic connection between the ceramic plate and intact soil cores or samples of granulated soil. Equilibration times may be increased substantially if contact material is not used.

6   *Appropriately collected and prepared soil cores or granulated soil samples*: Intact soil cores should be collected and prepared as recommended in Chapter 69. Granulated soil samples are prepared by placing ≈ 1 cm depth of air-dried, granulated soil (≤ 2 mm particle size) in preweighed (0.01 g precision) 2.8–4.7 cm diameter by 2.0–4.0 cm long noncorroding rings (e.g., aluminum, brass, acrylonitrile butadiene styrene (ABS) plastic, etc.) which have either high-flow, ashless filter paper (e.g., Whatman no. 42) or nylon cloth (15 μm openings) wrapped over the bottom end and held in place by a stout elastic band. Record the weight of air-dry soil plus ring plus filter paper or cloth plus elastic band (0.01 g precision). Place loose-fitting cover plates on top of the cores or rings to minimize evaporative water loss while equilibrating in the pressure vessel.

7   *Balance, controlled temperature room, drying oven, and cooling box*: See Section 72.2.1 for specifications and details.

72.3.2 PROCEDURE

1   Saturate the ceramic plates by immersion in deaired, temperature equilibrated tap water overnight and drain ponded water from the plate before placing the plate into position inside the pressure vessel. A wire or string cradle allows more convenient placement and removal of plates from pressure vessels. Connect the plate drainage outlet to the feed-through of the pressure vessel (Figure 72.1c). Some practitioners place a small volume of water (e.g., 50 mL) at the bottom of the pressure vessel (below the ceramic plate) to maintain high-relative humidity and thereby reduce evaporative water loss from the samples and porous plate.

2   (a) *Intact soil cores*: After completion of the tension table or plate desorption measurements (Section 72.2), spread a 1–3 mm thick layer of saturated contact material (e.g., kaolin) onto the cloth-covered base of the cores and immediately place this end of the cores on the ceramic plate. Place loose-fitting cover plates on top of the cores to reduce evaporative water loss.

(b) *Granulated samples*: Saturate the air-dry samples by placing in 1–2 cm depth of deaired, temperature-equilibrated water for 24 h, so that water infiltrates through the filter paper or cloth and upward into the soil. Spread a 1–3 mm thick layer of saturated contact material (e.g., kaolin) on the ceramic plate, then immediately place the saturated soil samples on the plate. Place loose-fitting cover plates on top of the rings to reduce evaporative water loss.

3   Close the pressure vessel and pressurize slowly (to avoid potential disruption of sample-plate contact) to the desired pressure head, noting that a pressure head of x m is equivalent to a matric head of $-x$ m. Monitor water outflow from the vessel until sample equilibration is achieved, as evidenced by cessation of water flow. Given that water outflow often approaches zero asymptotically (especially for low-matric heads), detection of equilibration (or virtual equilibration) can be assisted by plotting cumulative outflow volume versus inverse time (Figure 72.3). Approximate pressure extractor equilibration times are given in Table 72.1, although it must be recognized that actual times can vary substantially.
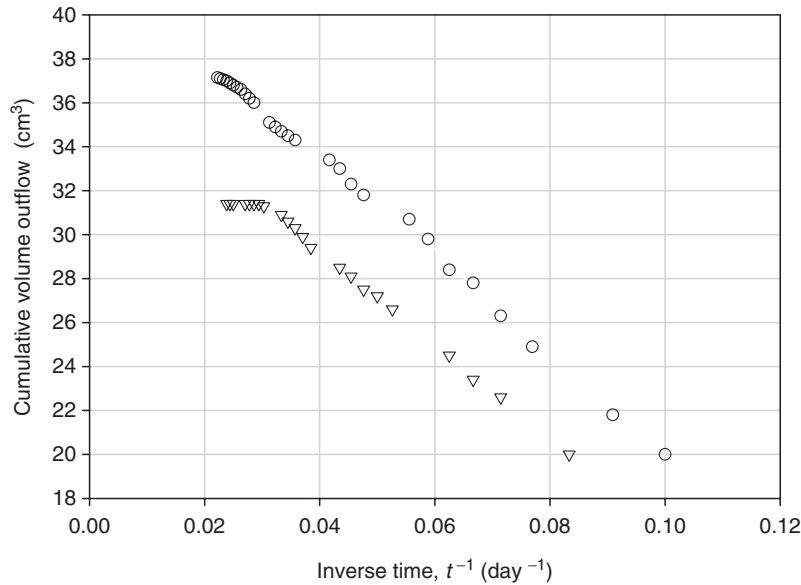
FIGURE 72.3. Cumulative volume outflow versus inverse time (t^{-1}) for equilibration of two sets of granulated clay loam soil samples (1 cm thickness) at $\psi_m = -150$ m using the pressure extractor method. One set of samples reached equilibrium after 34 days (triangles), while the other was still not equilibrated after 40 days (circles).

For example, Gee et al. (2002) found that 1.5 cm thick samples of granulated sandy, silty, and clayey soils pressurized to $\psi_m = -150$ m were still far from equilibrium after 10 days; and one author (W.D. Reynolds) routinely finds that equilibration to $\psi_m = -150$ m of 1.0 cm thick clay loam samples requires 30–60 days (see Comment 3 in Section 72.4).

4   Slowly bleed the pressure from the vessel (by closing the valve to the pressure source and opening the needle valve on the vessel exhaust) and remove the samples once the pressure has reached atmospheric. Remove the cover plate and all contact material adhering to the base of the sample, then weigh immediately (before significant evaporative water loss can occur) to obtain $M_c(\psi_m)$ (intact cores) or $M_s(\psi_m)$ (granulated samples).

5   Repeat steps 2, 3, and 4 for each selected matric head, but do not resaturate granulated samples.

6   After the final matric head and sample weights are attained, place the samples (minus the cover plates) in the drying oven at $105°C \pm 5°C$ until oven-dry (≈ 72 h for 7.6 cm high intact cores; ≈ 96 h for 10 cm high intact cores; ≈ 24 h for 1 cm high granulated samples), then place in the cooling box until equilibrated to room temperature.

7   Weigh the cooled intact cores to a precision of 0.1 g, or the cooled granulated samples to a precision of 0.01 g, to obtain the oven-dry sample weight, M_d [M].

72.3.3 ANALYSIS AND EXAMPLE CALCULATIONS

72.3.3.1 INTACT SOIL CORES

1. Calculate the mass of water in the soil, M_w [M], at each matric head, ψ_m [L], using

$$M_w(\psi_m) = M_c(\psi_m) - M_d \tag{72.1}$$

2. Calculate the volumetric water content, θ_v [$L^3 L^{-3}$], at each matric head, ψ_m [L], using

$$\theta_v(\psi_m) = \frac{M_w(\psi_m)}{\rho V_b} \tag{72.2}$$

where V_b [L^3] is the bulk volume of the soil, and ρ_w [ML^{-3}] is the pore water density at the temperature of the room (e.g., $\rho_w = 0.9982$ g cm^{-3} at 20°C). The bulk soil volume, V_b, is calculated using

$$V_b = V_c - V_h = \pi a^2 (l_c - \Delta l) \tag{72.3}$$

where V_c [L^3] is the volume of the core sampling cylinder, V_h [L^3] is the "head-space" volume between the top of the soil core and the top of the cylinder, a [L] is the cylinder inside radius, l_c [L] is the length of the sampling cylinder, and Δl [L] is the distance between the soil surface and the top of the sampling cylinder. If changing water content causes the soil in the intact cores to shrink (desorption curve) or swell (imbibition curve), Δl must be measured at a specific head, which is usually the field capacity value, i.e., $\psi_m = \psi_{FC} = -1$ m for intact soil cores, or -3.3 m for disturbed soil cores.

3. For among soil comparisons, the degree of water saturation, $S(\psi_m)$, is often useful

$$S(\psi_m) = \frac{\theta_v(\psi_m)}{\theta_{sat}} \tag{72.4}$$

where θ_{sat} [$L^3 L^{-3}$] is the saturated soil volumetric water content, i.e., θ_v at $\psi_m = 0$.

4. If the mass of oven-dry soil is determined, one can also calculate gravimetric soil water content and soil bulk density. The mass of oven-dry soil, M_{ods} [M], is determined using

$$M_{ods} = M_d - M_{cce} \tag{72.5}$$

where M_{cce} [M] is the weight of the sampling cylinder plus cloth plus elastic band, after the removal of all adhering soil. The gravimetric soil water content, $\theta_g(\psi_m)$ [MM^{-1}], is then determined using

$$\theta_g(\psi_m) = \frac{M_w(\psi_m)}{M_{ods}} \tag{72.6}$$

and bulk density, ρ_b [ML^{-3}], is calculated from

$$\rho_b = \frac{M_{ods}}{V_b} \tag{72.7}$$

72.3.3.2 GRANULATED SAMPLES

1   Calculate the mass of water in the soil, M_w [M], at each matric head, ψ_m [L], using

$$M_w(\psi_m) = M_s(\psi_m) - M_d \tag{72.8}$$

2   Calculate the mass of oven-dry soil, M_{ods} [M], using

$$M_{ods} = M_d - M_{rfe} \tag{72.9}$$

where M_{rfe} [M] is the weight of the ring plus filter paper or cloth plus elastic band, after all adhering soil has been removed.

3   Calculate gravimetric soil water content, $\theta_g(\psi_m)$ [L^{3}L^{-3}], using Equation 72.6.

4   Calculate the volumetric soil water content, θ_v [L^{3}L^{-3}], using

$$\theta_v(\psi_m) = \frac{\theta_g(\psi_m) \times \rho_b}{\rho_w} \tag{72.10}$$

where ρ_b [ML^{-3}] is the soil dry bulk density (Equation 72.7) and ρ_w [ML^{-3}] is the soil water density (e.g., $\rho_w = 0.9982$ g cm^{-3} at 20°C). Note that when granulated soil samples are used, V_b is best obtained as the average value from several replicate intact soil cores collected close to where the granulated samples were obtained.

5   Calculate degree of saturation, $S(\psi_m)$, using Equation 72.4.

Soil water desorption and imbibition curves are often presented as graphical relationships, where the matric head is plotted on a logarithmic x-axis (Figure 72.4). Example calculations for a desorption curve are given in Table 72.2.

72.4 COMMENTS

1   The choice of matric head (ψ_m) settings is best made in relation to the intended use of the data. For example, agronomic surveys may require only the three heads needed to determine soil air capacity and plant-available water capacity (i.e., $\psi_m = 0$, -1, -150 m, see Chapter 69 for details), while highly detailed characterization of management and texture effects on pore size distribution or water relations may require many heads (e.g., $\psi_m = 0$, -0.05, -0.1, -0.3, -0.5, -0.75, -1, -2, -3.3, -15, -50, -150 m). A common selection of heads for characterizing soil structure effects on water transmission and storage is $\psi_m = 0$, -0.05, -0.1, -0.3, -0.5, -1, -3.3 m.
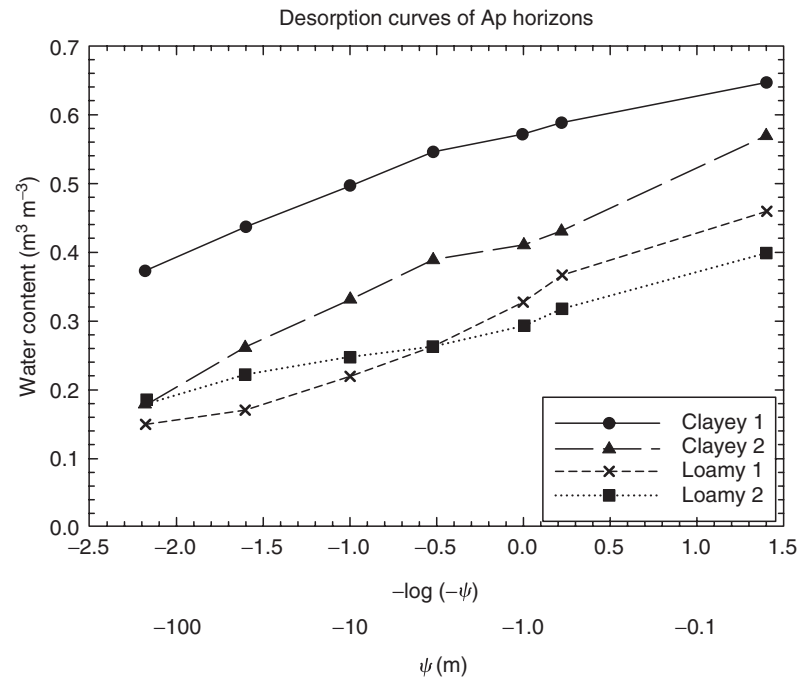
FIGURE 72.4. Example soil water desorption curves for clayey and loamy soils. Note in this example that the first matric head was set at $\psi_m = -0.04$ m, rather than at $\psi_m = 0$.

2   The pressure extractor method was originally designed and used for determining the water desorption characteristics of small granulated soil samples (McKeague 1978; Sheldrick 1984; Klute 1986). It is being increasingly used, however, for desorption of intact soil cores to matric heads below the limit of tension tables and tension plates (Section 72.2), thereby providing more complete descriptions of undisturbed pore-size distributions and soil structure, soil water-strength relationships, and water content relations for use in water–solute transport models.

3   Sample equilibration time depends primarily on the unsaturated hydraulic conductivity relationship of the sample, the length of the sample, the set matric head, the hydraulic conductivity of the tension medium or ceramic plate, and the quality of the hydraulic connection between the sample and the tension medium or ceramic plate. Generally speaking, equilibration time increases as the hydraulic conductivity of the sample, tension medium or ceramic plate decreases; as matric head decreases; as the quality of the hydraulic connection between sample and tension medium or ceramic plate decreases; and as sample length increases (equilibration time often increases as the square of the sample length). As a result, fine-textured soils and long samples tend to equilibrate much more slowly than coarse-textured soils and short samples; samples at low (more negative) matric heads equilibrate more slowly than samples at high-matric heads; samples on low-permeability tension media or ceramic plates equilibrate more slowly than those on high-permeability media or plates; and samples with poor hydraulic connection to the tension medium or ceramic plate

TABLE 72.2 Example Calculation of Desorption Curve Water Contents and Degree of Saturation Using the Tension Table/Plate Method and the Pressure Extractor Method

Core or sample number	Matric head, ψ_m (m)	$M_c{}^a$ (g)	$M_w{}^b$ (g)	$\Theta_v{}^c$ (cm^3 cm^{-3})	$\theta_g{}^d$ (g g^{-1})	S^e (%)
280[f]	0	2925.7	460.7	0.520	0.393	100.0
280	−0.05	2869.7	404.7	0.457	0.345	87.8
280	−0.1	2859.6	394.6	0.445	0.336	85.7
280	−0.3	2846.5	381.5	0.431	0.325	82.8
280	−0.5	2841.2	376.2	0.425	0.321	81.7
280	−1	2827.0	362.0	0.409	0.309	78.6
280	−2.25	2805.2	340.2	0.384	0.290	73.8
280	−3.5	2790.5	325.5	0.367	0.277	70.7
25[g]	−150	55.32	2.88	0.220	0.166	42.3

Intact soil core cylinders: 11.0 cm long × 10.4 cm inside diameter.
Granulated sample rings: 4.0 cm long × 4.7 cm inside diameter.
Oven-dry mass of intact soil plus cylinder plus cloth plus elastic band, M_d = 2465.0 g.
Oven-dry mass of granulated sample plus ring plus filter paper plus elastic band, M_d = 52.44 g.
Mass of oven-dry soil, intact core, M_{ods} = 1173.4 g (Equation 72.5).
Mass of oven-dry soil, granulated sample, M_{ods} = 17.35 g (Equation 72.9).
Soil water density, ρ_w = 0.9982 g cm^{-3} (20°C).
Soil core bulk volume, V_b = 887.71 cm^3 (Equation 72.3); soil dry bulk density, ρ_b = 1.32 g cm^{-3} (Equation 72.7).

Note: The θ_v value at ψ_m = 0 gives the saturated volumetric water content, θ_s. For highly accurate work, the amount of water retained in the cloth or filter paper should be measured and subtracted from the M_w determination. This is usually important only for small granulated samples where the mass of water retained by the filter paper or cloth can be large enough to affect the calculated soil water contents.

[a] M_c = Mass of soil plus water plus cylinder/ring plus cloth/filter paper plus elastic band.
[b] M_w = Mass of water in soil (Equation 72.1 or Equation 72.8).
[c] θ_v = Volumetric soil water content (Equation 72.2).
[d] θ_g = Gravimetric soil water content (Equation 72.6).
[e] S = Percent water saturation (Equation 72.4).
[f] 280 = Intact core i.d. number.
[g] 25 = Granulated sample i.d. number.

equilibrate more slowly than samples with good connection. A discussion of the effects of ceramic plate permeability on equilibration time can be found in Gee et al. (2002).

4 The approximate equilibration times given in Table 72.1 for intact soil cores were estimated by extrapolating core drainage rates during the 48–200 h period to the time where drainage was deemed negligible (Topp et al. 1993). This approach was taken because drainage from saturated intact soil cores is usually rapid during the first 24–48 h, and then becomes much slower.

5 Some practitioners (e.g., Klute 1986) recommend ''loading'' the soil samples with lead weights (≈700 g for a 5 cm diameter core sample) to maintain consistent hydraulic connection between the sample and the tension medium and/or porous

plate as the sample desorbs or imbibes water. Breakdown or degradation of the hydraulic connection between the sample and the tension medium or porous plate can greatly increase sample equilibration time, or even entirely prevent equilibration. Topp and Zebchuk (1979) found, however, that the desorption–imbibition curve procedures listed above (i.e., use of appropriate contact media, rewetting base of sample before replacement on contact medium) provided adequate hydraulic connection (and reconnection) without sample loading. On the other hand, loading appears to be necessary for samples of swelling soil collected from the subsurface (as these materials can give unrepresentative desorption and imbibition curves if they are not confined and loaded in a way that mimics their original overburden pressure Collis-George and Bridge 1973).

6   Figure 69.4 (Chapter 69) gives the approximate matric head ranges of the tension table, tension plate, and pressure extractor methods.

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Author Query

AQ1: Please confirm if it is ''pressure extraction methods'' or ''pressure extractor methods'' throughout the text.