DOI 10.7343/as-2025-817

ACQUE SOTTERRANEE
Italian Journal of Groundwater
journal homepage: https://www.acquesotterranee.net/

2025-AS53-817

Ranking multiple infiltration formulas to determine their match to trustable hydrogeological parameters obtained under highly controlled conditions. Santiuste basin, Los Arenales Living Lab, Spain

Classificazione di molteplici formule di infiltrazione per determinarne la corrispondenza con parametri idrogeologici affidabili ottenuti in condizioni fortemente controllate. Bacino di Santiuste, Los Arenales Living Lab, Spagna

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Supplementary file - *File supplementare*

Annex 1 - *Appendice 1*

Necessary data and template design

In order to apply all of the selected equations, the system must allow the collection of, at least, the following data and parameters:

– Water table evolution along the time.
– Exact time at the beginning and end of each test.
– Flow rate introduced over time.
– Total volume introduced into the borehole.
– Length of the tested section (if not the total length).
– Diameter / radius of the percolation well, piezometers (internal and external) and pipelines.
– Length and diameter of the pipes used, both hydraulic and pneumatic.
– Water level, in case of working, at least some stretch, in saturated conditions.
– Detailed characterization of the construction works with their respective geometric measurements.
– Contact surface between the civil work and the receiving medium.
– Height of the pipeline above ground.
– Exact elevation of the levelling point of the civil work.
– Exact unsaturated zone thickness.
– Hydraulic load.
– Atmospheric pressure during the execution of the test (probe with atmospheric pressure correction in-corporated type HYDROS 21 sensor, and recording of its evolution in the data logger.
– Water level evolution over time (the data logger is programmed to measure every minute).
– Water level during slug tests.
– Exact distance between the percolation well and the observation piezometers.
– Slotted and blank surface in the cased piezometers (including the bottom surface of the column).
– Time-descent chart obtained automatically in the field, to check the veracity of the data obtained during capture.
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Hydraulic properties. Interpretation methods

Four infiltration test groups have been established by the authors:

1. Infiltration test based on the elaboration of a drawdown-time log taken from an excavation of known dimensions, keeping the level constant (a), or variable (b).
2. Infiltration test based on the production of a drawdown-time log inside a borehole or well of known dimensions, either open (a) or closed (b).
3. Slug tests. Filling the excavation or borehole almost instantaneously, and recording the lowering of the created (artificial) water level over time. The permeability obtained will be mainly vertical, weighted by the water column, under semi-saturated or desaturated conditions (dry environment with natural field capacity).
4. Pumping tests in wells or boreholes, preferably with an observation piezometer within its radius of influence.

The 20 selected interpretation methods are listed in Table 1-1.

Tab. 1 - Methods and equations used to calculate hydraulic conductivities from in-field data classified by type of test and in alphabetical order. Not comprehensive.

Method	Equation	Theoretical type of essay / source
Gilg-Gavard (constant level)	$K = \frac{Q}{600 \cdot A \cdot h_m}$	Infiltration test (1a) (Custodio & Llamas, 1983)
Gilg-Gavard (variable level)	$K = \frac{1{,}308 d^2}{A \cdot h_m} \cdot \frac{\Delta h}{\Delta t}$	Infiltration test (1b) (Custodio & Llamas, 1983)
Double ring test	ASTM D3385-18	Infiltration test (1 a-b) (ASTM, 2018)
Darcy	$K = Q / A \cdot I$	Infiltration test (1b) (Darcy, 1856)
Ernst	$h = s\frac{D_v}{K_l} + \frac{sL^2}{8KD} + sLW_r$	Infiltration test (1b) (Ernst, 1950)
Green & Ampt	$f = -K_s \frac{dh}{dz}\frac{dh}{dz} = \text{hydraulic gradient}\left[\text{cm}^3\text{s}^{-1}\text{cm}^{-2}\right]$ $f = -K_s \frac{h_f - h_o}{Z_f}\left[\text{cm}^3\text{s}^{-1}\text{cm}^{-2}\right]$	Infiltration test (1b) (Green & Ampt, 1911)
Kostiakov	$T = L / b \cdot m$	Infiltration test (1b) (Kostiakov, 1932)
Kraijenhoff van de Leur	$h' = \frac{\pi}{2\mu\alpha} s_0 e^{-ct}$ $\alpha = \frac{\pi KD}{\mu L_0^2}$	Infiltration test (1b) (Kraijenhoff van de Leur, 1958)
Lewis	$l = kt^n$	Infiltration test (1b) (Lewis, 1937)
Matsuo-Akai	$K = \frac{-C}{60 \cdot t} \cdot \ln\left(\frac{h + C}{H_0 + C}\right)$ $C = \frac{L \cdot l}{2 \cdot (L + l)}$	Infiltration test (1b) (Matsuo-Akai, 1952)
Lefranc (ISO, 2012) (with FF)	$K = \frac{Q}{C \cdot h}$ $C = \frac{2\pi L}{\ln(L/d)} + \sqrt{(L/d)^2 + 1}$	Infiltration test. Open circuit (2a) (UNE, 2012)
Lefranc (ISO, 2012) (without FF, variable load)	$k = \frac{(de)^2 \ln\left(\frac{2h}{d}\right)}{8ht} \cdot \ln\frac{H_1}{H_2}$	Infiltration test. Open (2a) (ISO, 2012)
Cooper, Bredehoeft & Papadapulos (1967)	$\frac{h_t}{H_0} = F(\alpha,\beta)$ $F(\alpha,\beta) = \frac{8\alpha}{(\pi)^2}\int_0^\infty e \frac{\left(-\frac{\beta u^2}{\alpha}\right)}{u^2 \Delta u} du$ $a = \frac{R_w^2 S}{R_c^2}$ $\beta = \frac{Tt}{R_c^2}$	Slug test (3) (Cooper et al., 1967)
Bouwer & Rice (1976)	$\frac{h_t}{H_0} = \exp\frac{-kt}{\pi R_c^2} F$ $F = \frac{2\pi L_i}{\text{Ln}\left[\frac{R_i}{R_w}\right]}$	Slug test (3) (Bouwer & Rice, 1976; Bouwer, 1989)
Hvorslev (1951)	$\frac{h_t}{H_0} = \exp\left(\frac{-kt}{\pi R_c^2} F\right)$	Slug test (3) (Hvorslev, 1951)
Hantush (1959)	$s = \frac{Q}{2\pi T}\ln\left(\frac{1{,}12 \cdot B}{r}\right)$ $\text{B} = \sqrt{\frac{Tb'}{K'}}$	Pumping tests (4) (Hantush, 1959)
Jacob (1946)	$s = 0{,}183\frac{Q}{T}\log\frac{2{,}25 \cdot T \cdot t}{r^2 \cdot S}$	Pumping tests (4) (Cooper & Jacob, 1946)
Newman (1975)	$s = \frac{Q}{4\pi T} W(u_s, u_s, \beta)$ $\beta = \frac{r^2 K_x}{b^2 K}$; $\text{u}_A = \frac{r^2 S}{4/T}$; $\text{u}_s = \frac{r^2 S_r}{4/T}$	Pumping tests (4) (Newman, 1975)
Theis (1935)	$s = \frac{Q}{4\pi T} W(u)$ $\text{u} = \frac{r^2 S}{4Tt}$	Pumping tests (4) (Theis, 1935)
Thiem (1906)	$s_1 - s_2 = \frac{Q}{2\pi T}\ln\frac{r_2}{r_1}$	Pumping tests (4) (Thiem, 1906)

** Moench method was not essayed due to it es for double porosity in fractured aquifers, dissimilar to the environmental conditions of this spot (Šejna et al., 2011).*

The interpretation of the data can be developed using the methodologies set out above. A detailed explanation of each is extended next.

 DOI 10.7343/as-2025-817

SURFACE INFILTRATION TESTS (1A)

GILG-GAVARD (Custodio, 1983)
Interpretation test equivalent to Lefranc with different formulae:

Constant level (for not-spot piezometers)

$$K = \frac{Q}{600 \cdot A \cdot h_m}$$

Where:
- K = Permeability (in m/s or m/d) [L/T].
- Q = Flow rate introduced to achieve the constant level (usually in l/min o m^3/s) [L^3/T].
- A = Contact area between pipeline and receiving medium [L^2].
- h_m = Dynamic level above the initial water level [L].

Variable level

$$K = \frac{1{,}308 d^2}{A \cdot h_m} \cdot \frac{\Delta h}{\Delta t}$$

Where:
- K = Permeability (in m/s or m/d) [L/T].
- D = Diameter of the borehole in the tested stretch [L].
- A = Contact area between pipeline and receiving medium [L^2].
- h_m = Water table variation above the initial level [L].
- h = Length of the tested stretch [L].
- T = Drawdown time [T].

DOUBLE RING TEST (SURFACE TESTING) (ASTM, 2018)

It is a "generally accepted method", consisting on monitoring the evolution of the water level confined inside a cilinder recipient stuck on the soil surface during several time intervals. Another wider cilinder is maintained flooded during the whole test. Ring dimensions are normalized by USDA (USTM, 2018).The test can be conducted maintaining a constant water level, or variable level.

The double ring infiltrometer is a simple tool but allows obtaining accurate soil infiltration rates, from observing the amount of water infiltrated through a known surface and time slot. Interpretation is based on darcy´s Law whilst the receiving medium is partially saturated (Figure 1-1).

Fig. 1-1 - Double ring infiltration tests in a biofilter surface under semisaturated conditions. Measures are registered thanks to a CTD sensor placed just on the soil surface. Photos of the first author.

Measures are registered in specific templates, charged in a calculus sheet for automatic interpretation and calculation of the infiltration rate. The most usual template to gather field observations contains, at least, the ater table variation, the accumulated variation along the whole test, amount of water poured into the external cilinder, partial and total time during the test. An example is displayed in Figure 1-2.

Date:			Type of soil:				
Site:			Crop:				
Coordinates X/Y:			Soil Moisture				

Hour	Value from zero (cm)	Refill to zero (outer ring)	Water sheet (cm)	Time (min)	Infiltration (cm/hour)	Accumulated water sheet (cm)	Accumulated time (min)

Fig. 1-2 - Example for a double ring test template.

Graphical interpretation is made obtaining the equation of the interpolated curve for partial drawdowns, and the accumulated drawdown along time, using a software. Extrapolating the intersection point where both curves cross is obtained an average infiltration rate along the test (Figure 1-3).

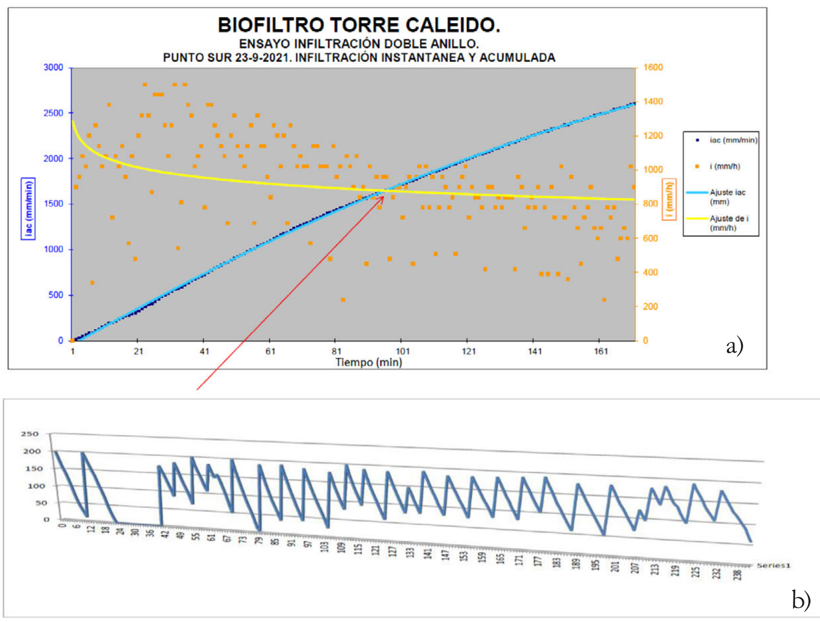


Fig. 1-3 - Example for a double ring test interpretation (a), chart of water level reposition (b).

The most usual interpretation is applying the Kostiakov equation (Kostiakov , 1932), improved by Philip (1957).

$$I_{ac}=K{\cdot}t^{N}$$

Where:

- I_{ac} = Accumulated infiltration [L/T].
- T = time (independent variable) [T].
- K and N correspond to: log K is the ordenate in the origin of the chart; and N is the slope of the interpolated segment (soil constant) [1/L].

Resolution by minmimum squares provides an infiltration formula in function of time.

The metholology is defined in the Norma ASTM D3385-18.

SURFACE INFILTRATION TESTING (1B)

DARCY (Darcy, 1856)

Darcy Law is the basal formulation of the general flow equation in its most simple expression.

$$Q=A{\cdot}K{\cdot}i$$

Where:

- Q= Water flow [L^3].
- A= Area [L^2].
- K= Permeability [L^3/T].
- i= Hydraulic gradient (Δh/ ΔL) [L/L].

ERNST (Ernst, 1950)

Ernst equation is specific for permanents flow regimes is layer soils in which the upper layer has a smaller permeabvility than the underlying layer. It considers four flow vectors: vertical, horizontal, radial, and an additional flow attributable to artificial recharge.

The radial component is the most assimilable to the humidification bulb expansion at the bottom of the channels, what is directly proportional to load losses, and inversely to the radial resistance, calculated from templates or formula-based from semi-empirical constants (Muñoz-Carpena & Gowdish, 2005).

Equating the radial flow region to the humidification bulb, the inflow through the unsaturated zone results from applying equation:

$$h = s\frac{D_v}{K_l} + \frac{sL^2}{8KD} + sLW_r$$

Where:

- h: ZNS inflow from the recharge channel [L^3/T].
- s: Specific discharge [L^3].
- D_v / D: Thickness of the lower / higher permeability region [L].
- K_l / K: Hydraulic conductivity of the least permeable / most permeable stratum [L/T].
- L: Horizontal flow distance [L].
- W_r: Radial resistance [T/L].

The degree of certainty is questioned for the environmental circumstances of each experience.

GREEN Y AMPT (1911)

Infiltration through a saturated soil is determined by the equation of Green and Ampt, formulated for unsaturated media:

$$f = -K_s\frac{dh}{dz}\frac{dh}{dz} = \text{hydraulic gradient}\left[\text{cm}^3\text{s}^{-1}\text{cm}^{-2}\right]$$

$$f = -K_s\frac{h_f - h_o}{Z_f}\left[\text{cm}^3\text{s}^{-1}\text{cm}^{-2}\right]$$

In case of no waterlogging (h_0=0):

$$f = \frac{K_s\left|\Psi_f\right| + Z_f}{Z_f}\left[\text{cm}^3\text{s}^{-1}\text{cm}^{-2}\right]$$

Where:

- f: Infiltration rate [L/T].
- $K_{s:}$ Hydraulic conductivity (L/T].
- h_f: Hydraulic potential at the water table wetting front from the ground surface (L].
- h_0: Hydraulic potential at the surface (L].
- Zf: Total cumulative decline (L].
- Ψ_f: Capillary suction capacity, metric pressure or negative pressure around the humidification bulb. It ranges from 0 to -102 (Morel-Seytoux and Kanghi, 1974), although values outside this range are obtained in practice (L].

The equation does not take dissolved air into account, so the result is underestimated. The parameter Ψ_f: must be calculated for realistic conditions.

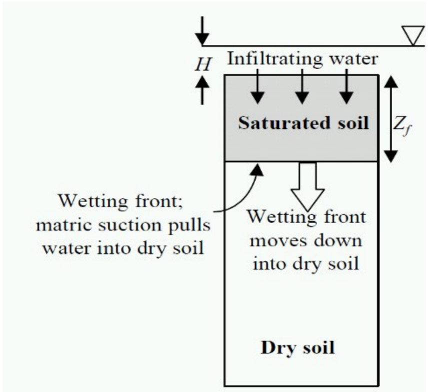


Fig. 1-4 - Schematic representation of the components of Green's and Ampt's formula (1911), taken from BEE 3710 (2018).

Bouwer et al. propose the following parameters for different lithologies, according to experiments carried out in infiltration meters. The *hwe* or capillary suction capacity (Ψ) (Bouwer et al, 2001), for the front of the humidification bulb, is:

- Coarse-grained sands: -5
- Medium-grained sands: -10
- Medium fine-grained sands: -15
- Sands and silts - sandy silts: -25
- Sands: -35
- Stratified clays: -35
- Dispersed clays: -100

KOSTIAKOV (1932)

Calculation of the infiltration rate from the evolution of the water layer thickness. The test is usually done without addition of water during the infiltration test. Its formulation is:

$$\mathbf{L=b \cdot T \cdot m}$$

Where:

- L= Infiltration rate due to the variation in the height of the surface water sheet (total infiltration over time). (cm/min) [L/T].
- T= Time during which the water remains inside the infiltration basin or channel (min) [T].
- b and m = Empirical parameters (calculated from the representation of the data in a descent-time plot).

The derivative with respect to time has velocity dimensions. Infiltration rate (I):

$$\mathbf{I= m \cdot b \cdot T^{m-1}\ [cm/min\ or\ mm/min]}$$

For one hour: $\mathbf{I= 60 \cdot m \cdot b.T^{m-1}}$ (cm/hour o mm/hour) [L/T].

Simplifying: $\mathbf{B = 60 \cdot m \cdot b}$, if $\mathbf{-n = m-1}$, then $\mathbf{I = B \cdot T^{-n}}$ (cm or mm/hour) [L/T].

Ib can be used to calculate the replenishment volumes within the infiltration basin (in case of full infiltration).

$$\mathbf{I_b = B \times T\ b^{\ m-1}}$$

Infiltration tests using a Haefeli cube, which dimensions are 1.5 x 1.5 m^2 (surface), 0.5 x 0.5 m^2 at the base, with a depth of 0.5 m, have given very reliable results, according to real tests in hyper-controlled conditions carried out in the Los Arenales Aquifer, Castile and Leon, Spain (MARSOL, 2016a).

KRAIJENHOFF VAN DE LEUR (1958)

Kraijenhoff van de Leur equation, deduced for variable regime contemplates the recharge attributable to irrigation and rainwater, and allows predicting the oscillation and position of the water table as a function of the rainfall pattern, hydraulic parameters of the aquifer, and the drainage system (Djurovic and Stricevic, 2003).

It is applied in more homogeneous soils and deep aquifers, so, for sandy aquifers, it is necessary to introduce Dupuit's simplifications for horizontal flow (Dupuit, 1857).

The equation considers constant precipitation (assimilable to artificial recharge) and that the aquifer has reached steady-percolation, so, it is necessary to introduce the De Zeeuw modification for a variable rainfall regime (as are the recharge flows), which entails introducing "completing factors". The expression of the equation is simplified as follows:

$$h' = \frac{\pi}{2\mu\alpha} s_0 e^{-ct}$$

Where:

- h´: Residual hydraulic charge (m/day) [L/T].
- μ: Volume-fraction of pores drained at a falling watertable, or volume-fraction of poras filled at a rising water-table %[L^3].
- α: system reaction factor, dependent of the mean depth of the impermeable layer below the groundwater table.
- S_0: rate of groundwater flow per unit lenght of out-flow-channel passing through a vertical plane at a distance x from the origin (maximum discharge to the highest water table) [L^3/T].
- αt: completing function, or "reservoir-coefficient" determinin g the amount of water that will be stored if steady percolation continues infinitely [L^3].

The reservoir-coefficient factor is equal to:

$$\alpha = \frac{\pi^2 KD}{\mu L_0^2}$$

Where:

- K: Hydraulic condiuctivity as influenced by the permeability of the soil and the viscosity of the groundwater [L^3/T].
- D: Mean depth of the impermeable layer below the groundwater table [L].
- L_0: distance between two outflow channels [L].

Given the origin of the water, this equation is not, *a priori*, the most appropriate for the interpretation of vertical permeability results in an heterogeneous and anisotropic media.

LEWIS (1979)

Lewis modification of the Kostiakov formula (1979). It has the following expression:

I=k x tn

Where:

- I: infiltration rate (cm/h) [L/T].
- K: Dimensionless numerical factor representing the infiltration rate during the initial interval obtained analytically or graphically. It is equivalent to the fit parameter of the model data. 0.99
- N: Exponent between 0 and -1. It represents the rate of change of infiltration over time. It is equivalent to the slope of the graphical curve of adjustment. -0.029
- T: Infiltration time, in minutes [T].

There are other "indirect" methods for the calculation of hydraulic conductivity such as the measurement of the water table with tidal oscillation, the measurement by means of presiometric tests in boreholes, and by geophysical prospecting, more specifically with electrical resistivity, although the effectiveness is very variable.

MATSUO – AKAI (1952)

The Matsuo or Matsuo-Akai test (depending on the source) is performed inside excavations in dry or semi-saturated soils, or in a bedrock. The permeability coefficient is determined from the flow rate infiltrated in a pit or trench-shaped excavation (Figure 1-5). The equation used for this test is:

$$K = \frac{-C}{60 \cdot t} \cdot \ln\left(\frac{h + C}{H_0 + C}\right)$$

Parameter C is calculated:

$$C = \frac{L \cdot l}{2 \cdot (L + l)}$$

Where.

- K: Permeability (m/s) [L/T].
- C: Coefficient -0.33
- L: Test pit depth in m 2 [L].
- P: Depth of the water-filled pit or gutter 1 [L].
- H0: Initial height of the water sheet (t=0) 0.90 [L].
- h: Measured height of the water sheet 0.415 [L].
- t: Time of each measurement in minutes 279 [T].

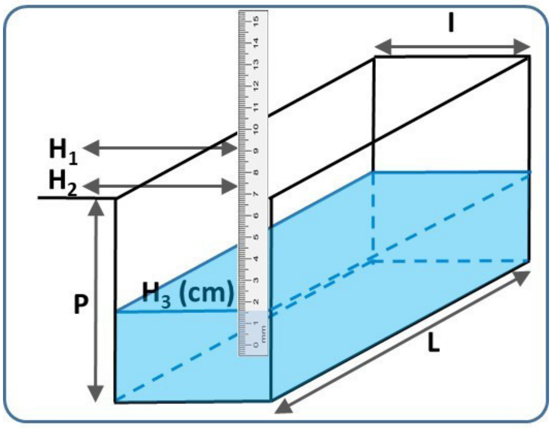


Fig. 1-5: Components of a Matsuo pit or trench P, L, l and h (m); 1 - ruler, 2- support.

INFILTRATION TEST. OPEN CIRCUIT (2A)

LEFRANC

The Lefranc test is used to measure the permeability coefficient in granular soils and in highly fractured rocks. The test consists of filling the borehole with water, and measuring the flow rate necessary to maintain a constant level (permanent regime tests), or measuring the rate at which the water level drops (variable regime test).

The Lefranc test in open section of constant level is described in the standard UNE-EN ISO 22282-2 (ISO, 2012), described as constant piezometric level method and consists of filling a borehole with water to maintain a constant level. The flow rate Q necessary to achieve this objective will be obtained and K is calculated with the expression K=Q/(Cxhm), where hm is the height reached by the water above the piezometric level {L], and C is a coefficient that depends on the geometric characteristics of the filtering zone.

The Lefranc test in open section with variable level consists of suddenly introducing a given flow (Q) {L3/T} of water, and measuring the time it takes to descend versus the descent level. The expression depends on the initial and final heights or levels, the time difference, and the characteristics of the filtering zone.

The Lefranc downhole test (open end gravity test) is performed at the bottom of the borehole and covering the entire length of the borehole. In this case the cavity through which the permeability test is to be performed comprises only the lower circular section of the pipe, and the seepage component is mainly vertical.

<u>Formulation with shape factor</u>

K= (A / C (t2 - t1) (ln (H1/H2))

Where:

- h: Drill pipe depth {L].
- d: Pipe diameter {L].
- D: Borehole diameter {L].
- B: Casing height above ground {L].
- NF: Depth of the phreatic level {L].
- b_0: Initial water level test {L].
- H1: Initial test hydraulic load {M}.
- H2: Final hydraulic load test {M].
- L: Length of test section {L].
- C: Shape Factor C
- t1: Initial time considered {T].
- t2: Final time considered {T].

Shape Factor C:

$$K = \frac{Q}{C \cdot h} \quad C = \frac{2\pi L}{\ln\left(L/d\right)} + \sqrt{\left(L/d\right)^2 + 1}$$

Where:

- K: Permeability, usually in m/sec or m/day {L/T].
- Q: flow rate introduced to achieve the constant level in l/min or m^3/sec {L^3/T].
- L: Length of filtering zone (m) {L].
- d: Diameter of filtering zone (m) {L].
- Hm: Water above initial level (m) {L].

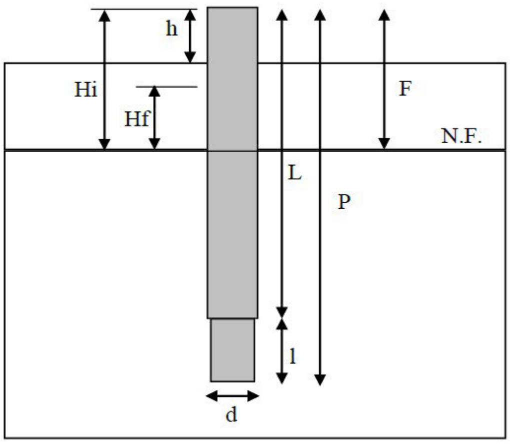


Fig. 1-6: Spatial representation of the components of the Lefranc equation with shape factor.

Formulation without shape factor

After filling the borehole with water, the drawdowns are measured every 1, 2, 3, 5, 5, 10, 15, 15, 20, 25 and 30 minutes. With the variable load results obtained, the permeability (K) is quantified according to the following expressionss (Jiménez Salas, 1981, Cassan, 2000):

$$k = \frac{(de)^2 \ln\left(\frac{2h}{d}\right)}{8ht} \cdot \ln \frac{H_1}{H_2}$$

As a preliminary conclusion: *We can always determine a vertical surface permeability by "sticking a tube".*

INFILTRATION TEST. CLOSED CIRCUIT (2B)

SLUG TEST (3)

The valve tests, also known as "slug tests", are a widely used technique for the "in situ" estimation of the hydraulic properties of aquifers. This type of test is performed by measuring the rise or recovery of the level in a well and/or open borehole in which an instantaneous change of its piezometric level has been generated. They are widely used to obtain hydraulic parameters for subsequent incorporation into flow models at reasonable cost and time (IGME, 2015, Slug-in manual).

In essence, the execution of slug tests consists of causing a rapid perturbation of the piezometric level and measuring its subsequent recovery (drawdown) to the previous conditions. This level perturbation can be done by introducing a solid or liquid body.

Once the data have been obtained by means of a down-hole level sensor, or in logs taken with a probe by the traditional manual procedure. The most common method applied is Hvorslev, 1951 (IGME, 2015).

HVORSLEV (1951). Variable level

- Field of application: Free and confined aquifers.
- Supports Bower correction (free aquifers).
- Supports Chapuis correction (with bottom plug).
- Variables to be calculated: k and b (cut-off point with ordinates).

Hvorslev´s equation (Hvorslev, 1951). is:

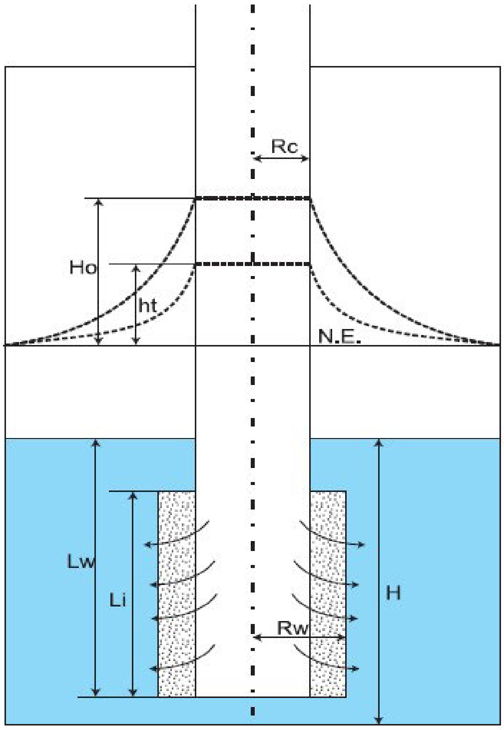
$$\frac{h_t}{H_0} = \exp \frac{-kt}{\pi R_c^2} F$$

Where:

- h_t, residual ascent at time t (m) [L].
- H_0, maximum ascent at time t=0 (m) [L].
- R_c, radius of conduction (m) [L].
- k, hydraulic conductivity (m/s) [L/T].
- F, shape factor (m) [L].

The referenced manual incorporates a summary-table to calculate the shape factor with examples for isotropic and anisotropic mediums.

Depending on the volume of water in the receiving medium, three types of slug test scenarios can be distinguished: dry, partially saturated or fully saturated soil (MARSOLut, 2021).



N.E. static level
$\mathbf{H_0}$ ascent at the start of the test (t=0)
$\mathbf{h_t}$ residual rise over time
$\mathbf{R_c}$ radius of conduction
$\mathbf{R_w}$ radius of filtering zone
$\mathbf{L_i}$ length of filtering zone
$\mathbf{L_w}$ length of the borehole in the saturated zone
H saturated thickness

Fig. 1-7: Slug infiltration tests. Physical meaning of the components of its formulation (taken from the Slug-in software manual, IGME, 2015).

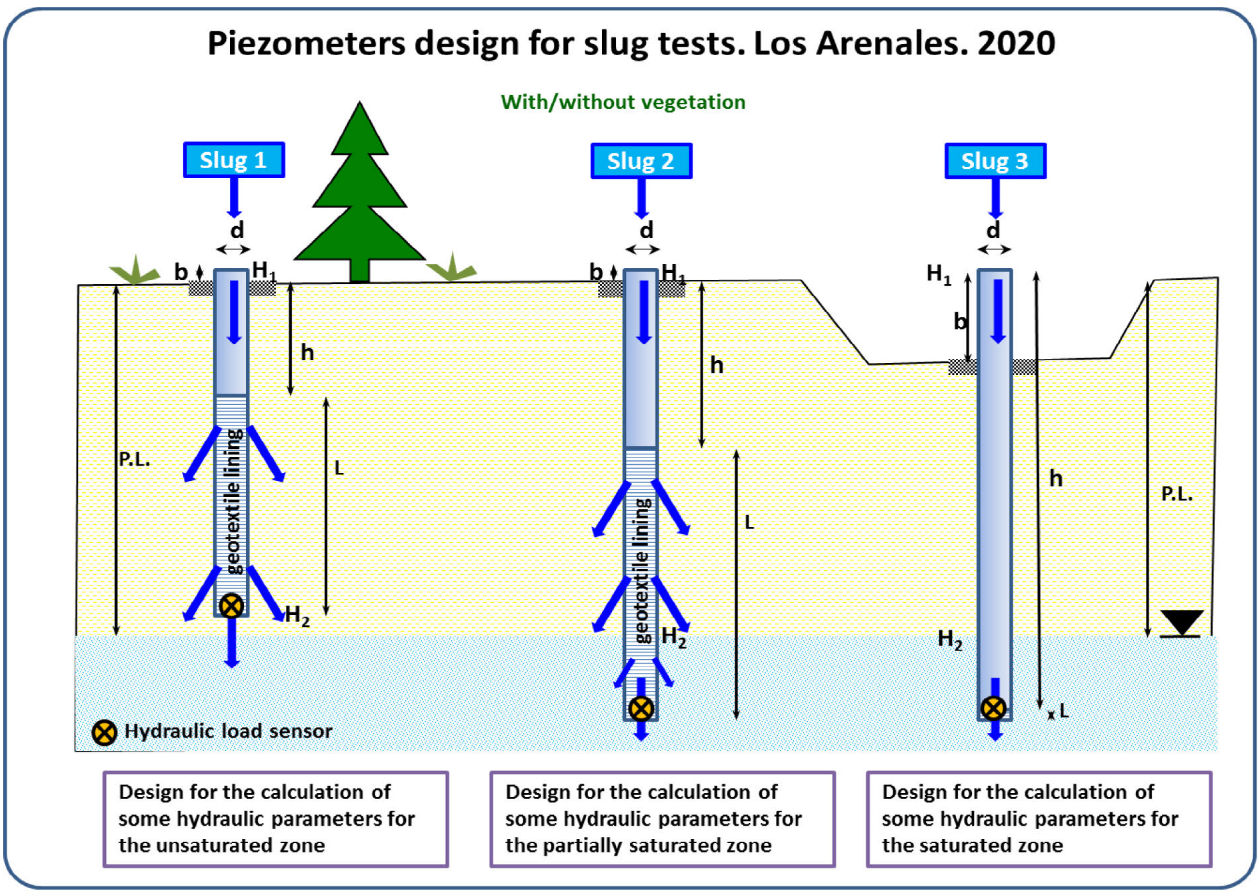


Fig. 1-8: Schemes for slug infiltration tests for desaturated (a), semi-saturated or partially saturated (b), and saturated conditions (c). Taken from MARSOLut, 2021.

Although Horslev is the most commonly used method, there are other methods for interpreting slug tests at the variable level, such as:

COOPER, BREDEHOEFT & PAPADAPULOS (1967)

- Field of application: Fully penetrating boreholes in confined aquifers.
- Supports Bower correction (unconfined aquifers).
- Supports skin effect correction.
- Variables to be calculated: T and S.

BOUWER & RICE (1976); Bouwer, 1989)

- Field of application: Free aquifers with good results in confined aquifers.
- Total or partially penetrating boreholes.
- It admits Bower correction (free aquifers).
- Supports Chapuis correction (with bottom plug).
- Variable to calculate: k and b (cut-off point with ordinates).***

PUMPING TESTS (4)

HANTUSH (1959)

In semi-confined aquifers, the formula expressing the drawdowns recorded in the aquifer was established by Hantush (with or without storage in the aquitard). Drawdowns will be a function of (simplified equation):

$$s = \frac{Q}{2\pi T} \ln\left(\frac{1{,}12 \cdot B}{r}\right) \qquad \text{B=} \quad Tb$$

Where:

- s: Drawdown [L].
- Q: Constant pumping flow rate [L^3/T].
- T: Transmissivity [L^2/T].
- r: Distance at which drawdown occurs [L].
- B: "Drip factor" [L^2], calculated by (inverse function):

$$\text{B=}\sqrt{\frac{Tb^{'}}{K^{'}}}$$

Where:

- T= Transmissivity [L^2/T].
- b'= Thickness [L].
- K'= Hydraulic conductivity [L/T].

JACOB (Cooper & Jacob, 1946)

This is a simplification of the Theis formula that allows the calculation of variable regime downdrafts without the need to use the W(u) table for small u values. The value of u less than 0.03 is usually adopted for this simplification to be acceptable.

$$s = 0{,}183\frac{Q}{T}\log\frac{2{,}25 \cdot T \cdot t}{r^2 \cdot S}$$

Where:

- s= Drawdown [L].
- Q= Constant pumping flow rate [L/T].
- T= Transmissivity [L^2/T].
- t= Time elapsed since start of pumping [T].
- r= Distance at which drawdown occurs [L].
- S= Aquifer Storage Coefficient

MOENCH (1995)

Moench (1995) proposed a solution for dual-porosity aquifers in fractured media. This author based on Neuman's model with modifications to interpret hydrogeological parameters such as specific yield (Sy) and horizontal (kr) and vertical (kz) hydraulic conductivities (Moench, 1997). It is a variable-regime analytical solution to a finite-diameter, fully penetrating well with storage drilled in a fractured isotropic aquifer, assuming a dual-porosity model. Moench shows how the average values of these hydrogeological parameters can be found in a "more realistic" way than those reported by Neuman by simultaneously interpreting all parameters (Mora et al, 2009).

The initial model was modified in Moench (1997), including partially penetrating wells and anisotropy based on the solution of Dougherty and Babu (1984). Some calculation programs that apply this method allow analyzing data for fully or partially penetrating wells and their delayed effect in an observation piezometer.

Laplace's mathematical solution for the dimensionless drawdown in a pumped well is as follows:

$$\bar{h}_{wD} = \frac{2[K_0(x)+xS_wK_1(x)]}{p\{pW_D[K_0(x)+xS_wK_1(x)]+xK_1(x)\}}$$

$$\bar{h}_D = \frac{2K_0(r_Dx)}{p\{pW_D[K_0(x)+xS_wK_1(x)]+xK_1(x)\}} \quad (2)$$

$$x = \sqrt{p+\bar{q}_D} \quad (3)$$

$$\bar{q}_D = \frac{\gamma^2 m\tanh(m)}{1+S_f m\tanh(m)} \quad \text{slab blocks} \quad (4)$$

$$\bar{q}_D = \frac{3\gamma^2[m\coth(m)-1]}{\{1+S_f[m\coth(m)-1]\}} \quad \text{spherical blocks} \quad (5)$$

$$m = \frac{\sqrt{\sigma p}}{\gamma} \quad (6)$$

$$\gamma = \frac{2r_w}{b'}\sqrt{\frac{K'}{K}} \quad (7)$$

$$\sigma = \frac{S_s'}{S_s} \quad (8)$$

$$r_D = r/r_w \quad (9)$$

$$S_f = \frac{2K'b_s}{K_sb'} \quad (10)$$

$$W_D = \frac{\pi r_c^2}{2\pi r_w^2 S_s b} \quad (11)$$

$$t_D = \frac{Kt}{S_s r_w^2} \quad (12)$$

$$h_D = \frac{4\pi Kb}{Q}(h_0 - h) \quad (13)$$

Where:

- B: Aquifer thickness [L].
- b': Thickness or diameter of the block [L].
- bs: Fracture opening [L].
- h*b*: Water level in the aquifer [L].
- h_0: Static aquifer level [L].
- K_0: Hydraulic conductivity [L].
- K_1: Hydraulic conductivity of the fracture [L/T].
- K': Hydraulic conductivity of the matrix [L/T].
- Ki: Modified Bessel function of the second type, order i [L/T].
- Ks: Hydraulic conductivity across the fracture [L/T].
- p: Laplace transform variable [dimensionless].

- Q: Pumping rate {L^3/T}.
- r: Radial distance from the pumping well to the observation piezometer [L].
- rc: Radius of the casing {L].
- rw: Radius of the well [L].
- Ss: Fracture-specific storage {L^{-1}].
- s': Fracture-specific storage {L^{-1}].
- S': Specific storage of the matrix {L^{-1}].
- S_f: Fracture roughness factor {dimensionless].
- S_w: Wellbore roughness factor {dimensionless].
- t: Elapsed time since the start of pumping {T].

The different parameters are represented in the following diagram (Figure 1-9):

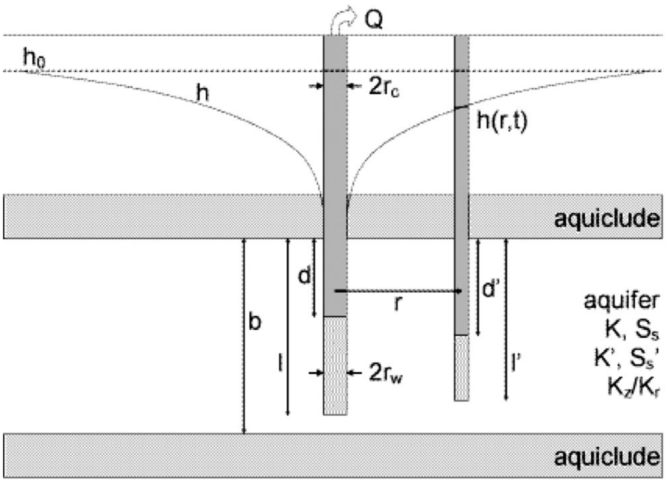


Fig. 1-9: Graphical representation of the parameters used in Moench's numerical solution (Moench, 1988, taken from IGME, 2015).

The required data are:
- Location of pumping and observation wells.
- Pumping flow rate(s).
- Observation piezometer measurements (time and displacement).
- Casing and pumping well radii.
- Downhole radius (optional, if there are drawdowns).
- Aquifer thickness.
- Thickness of blocks or diameter of matrix grains.

Given the complexity of the method and the large number of parameters involved in the calculation, there are specific programs to solve these equations.

In summary, most of these methodologies are for ideal boundary conditions (aquifer of infinite extent and laminar flow), in homogeneous and isotropic media. For heterogeneous and anisotropic media it is convenient to select the equations designed for the specific boundary conditions, such as those common in volcanic zones.

The hydrogeological literature shows that the most commonly used methods are those of Newman and Moench, although due to their complexity, the calculations are usually performed with specific software. As examples, the AQTESOLV software is mentioned, which includes a module called: "Moench Solution for Double-Porosity Fractured Aquifers". (http://www.aqtesolv.com/); and Waterloo software´s Aquifer Test (https://bit.ly/43I01h8).

NEWMAN (1975)

Formula for unconfined aquifers in variable regime, similar to the Theis formulas for confined and semi-confined aquifers, except for the well function (W). Given the complexity of its manual calculation, specific programs are required for its automatic interpretation.

$$s = \frac{Q}{4\pi T} W\left(u_s, u_s, \beta\right)$$

$$\beta = \frac{r^2 K_x}{b^2 K};\ \mathrm{u}_A = \frac{r^2 S}{4/T};\ \ \mathrm{u}_s = \frac{r^2 S_r}{4/T}$$

Where:

- s = descent at a distance r after a time t [L].
- Q = pumping rate [L^3/T].
- T = transmissivity of the aquifer [L^2/T].
- Kv = vertical hydraulic conductivity [L/T].
- Kv = vertical hydraulic conductivity [L/T].
- S = elastic storage coefficient, by decompression
- Sy = effective porosity (Specific Yield)
- W = tabulated function in function of 1/uA and 1/uB
- β = parameter equivalent to the "well function" (Wu) of Theis.

The calculation is reliable if the decreases are small in relation to the initial thickness (Neuman, 1974, in Fetter, 2001).

THEIS (1935)

Mathematical expression reflecting the shape of the downward cone in variable regime. The expression is:

$$s = \frac{Q}{4\pi T} W(u) \quad \text{u=} \frac{r^2 S}{4Tt}$$

Where (parameters similar to those of the Jacob´s formula):

- Q= Constant pumping flow rate [L^3/T].
- T= Transmissivity [L^2/T].
- S= aquifer storage coefficient.
- t= time elapsed since start of pumping [T].
- s= drawdown [L].
- r= distance at which drawdown occurs [L].

W(u) is a complex function for the hydraulic calculation of the downward cone in variable regime and confined aquifer that is called "well function" (W of Well).

THIEM (1906)

Formula for the calculation of drawdowns at a given distance in confined aquifers and permanent regime, and Dupuit correction (Dupuit, 1857) to apply the formula in unconfined aquifers.

The morphology of the downdip cone varies as a function of distance, flow rate and transmissivity. Using this equation, the drawdown can be calculated at any distance from the axis of the pumping well, using an observation point at a known distance (r_2) at which a drawdown (s_1) is measured. Knowing the flow rate, Q, and the transmissivity of the aquifer, T, the drawdown (s_2) at any distance (r_2) can be calculated.

$$s_1 - s_2 = \frac{Q}{2\pi T} \ln \frac{r_2}{r_1}$$

Where the parameters are similar to those of the previous formula.

The Dupuit correction is not necessary when the observed decrease is less than 10 to 15% of the initial saturated thickness (Forchheimer, 1886).

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