Infiltration process in terraced slopes: monitoring and numerical modeling

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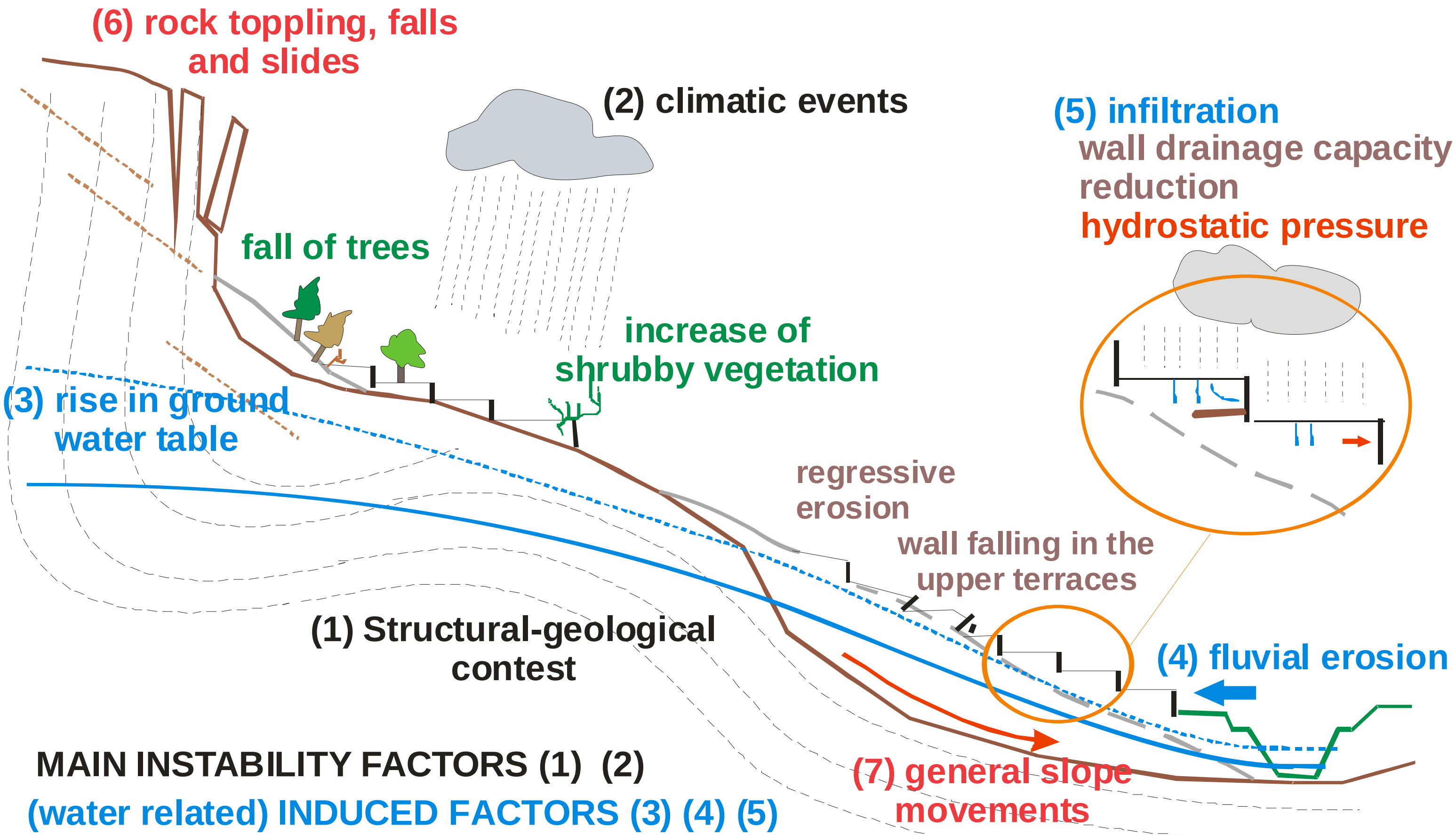
AIM: to study the modalities with which flow develops and evolves in terraced slope, characterized by dry stone retaining wall and its effects on the slope instability.

NATURAL CAUSES OF TERRACED SLOPE INSTABILITY



(6) rock toppling, falls and slides

(2) climatic events

(5) infiltration

wall drainage capacity reduction

hydrostatic pressure

fall of trees

increase of shrubby vegetation

(3) rise in ground water table

regressive erosion

wall falling in the upper terraces

(4) fluvial erosion

(1) Structural-geological contest

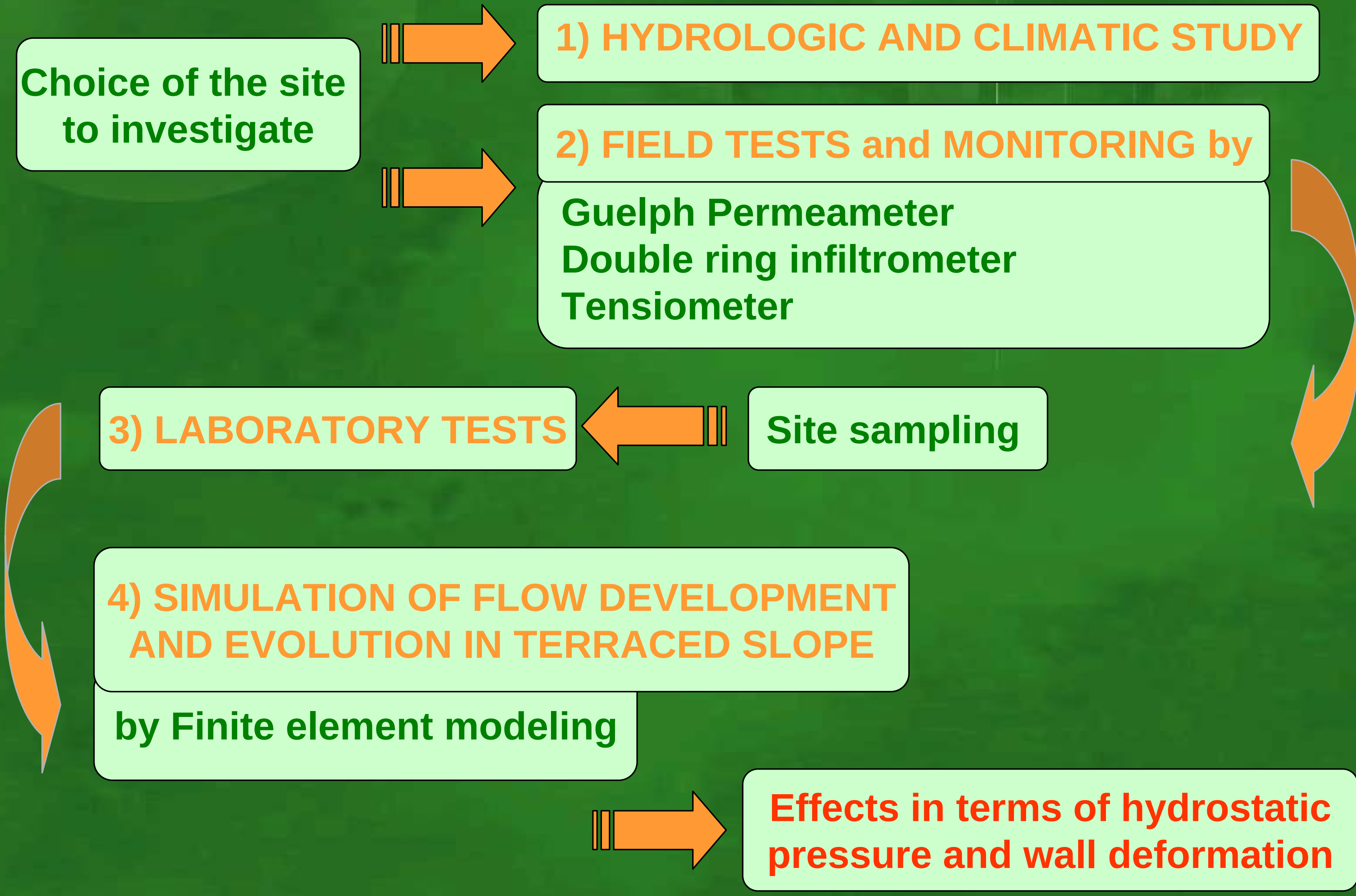
(7) general slope movements

MAIN INSTABILITY FACTORS (1) (2)

(water related) INDUCED FACTORS (3) (4) (5)

(gravitational) INDUCED FACTORS (6) (7)

Research flow chart



Choice of the site to investigate

1) HYDROLOGIC AND CLIMATIC STUDY

2) FIELD TESTS and MONITORING by

Guelph Permeameter
Double ring infiltrometer
Tensiometer

Site sampling

3) LABORATORY TESTS

4) SIMULATION OF FLOW DEVELOPMENT AND EVOLUTION IN TERRACED SLOPE

by Finite element modeling

Effects in terms of hydrostatic pressure and wall deformation

1)

Hydrologic study

Calculation of the **Depth-Duration-Frequency curves (DDFC)** on the base of historical precipitation data.

$$H_d = a \cdot (1 + V \cdot KT) \cdot d^n$$

KT: function of recurrence time

V: variation coefficient

T: recurrence time

$$KT = -\frac{\sqrt{6}}{\pi} \cdot \left(0.5772 + \ln \left(-\ln \left(\frac{T-1}{T} \right) \right) \right)$$

$$V = \sqrt{\frac{s_x^2}{m_x^2}}$$

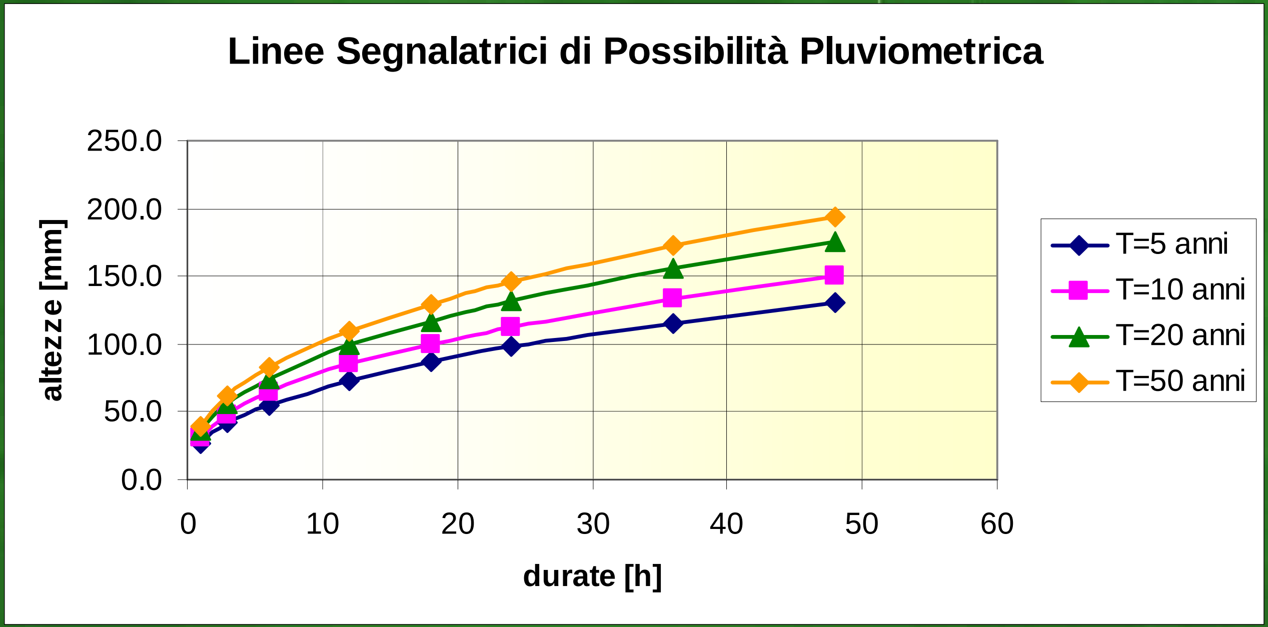
⇨ Determination of the duration and intensity of the critical rainfall event

Hydrologic study DDFC

Rainfall intensity

$i = H_d / d$ *[mm/h]*

represents an input simulation data



$$h = 21.598 \cdot (1 + 0.3244 \cdot KT) \cdot d^{0.4093}$$

Ground water flow

In SATURATED SOIL:

k= hydraulic conductivity

∂h/∂x = hydraulic gradient

$$V_x = k_x \cdot \frac{\partial h}{\partial x}$$

Darcy's law

In UNSATURATED SOIL:

$$v_i = -k(\theta)\left(\frac{\partial z_w}{\partial x_i} + \frac{\partial z}{\partial x_i}\right)$$

Darcy-Buckingham's law

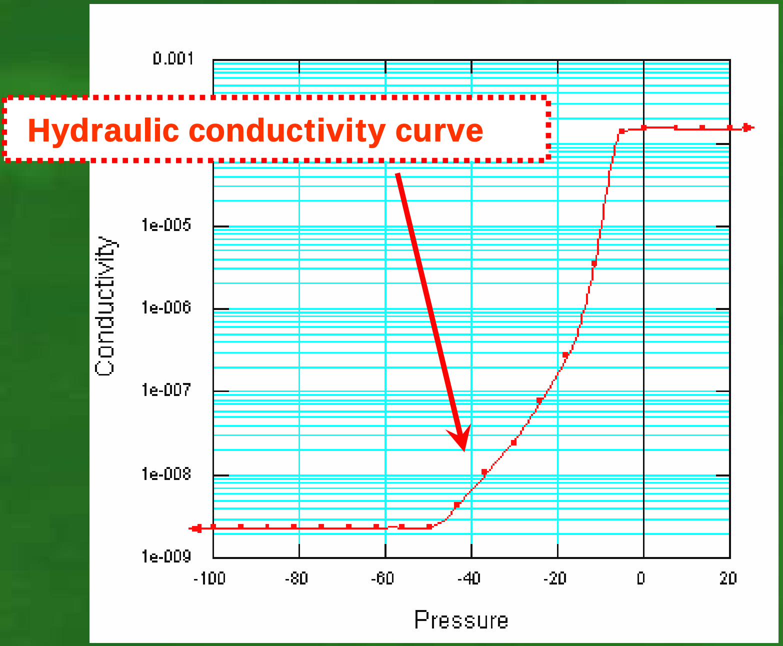
θ : soil water content

z_w: pressure head (m)

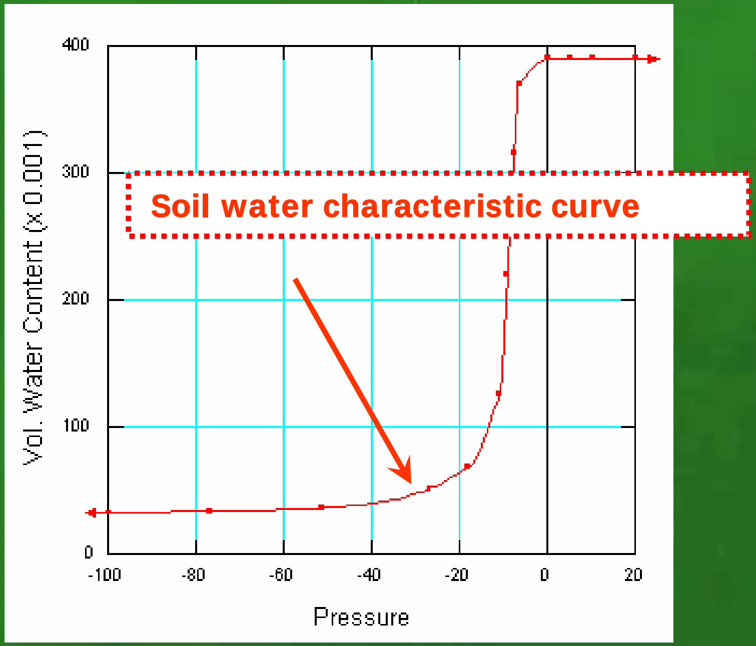
z : elevation head (m)

Flow in vadose zone

To analyze ground water flow, for Sr<1, two functions must be known

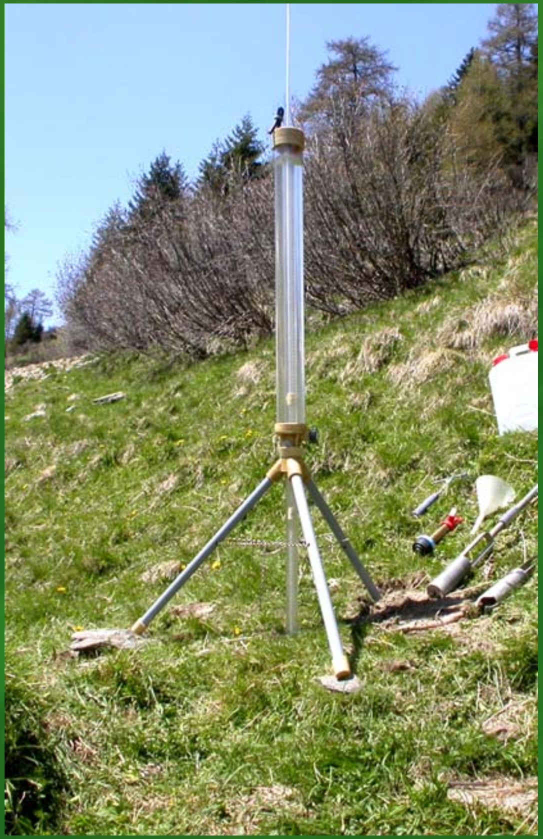


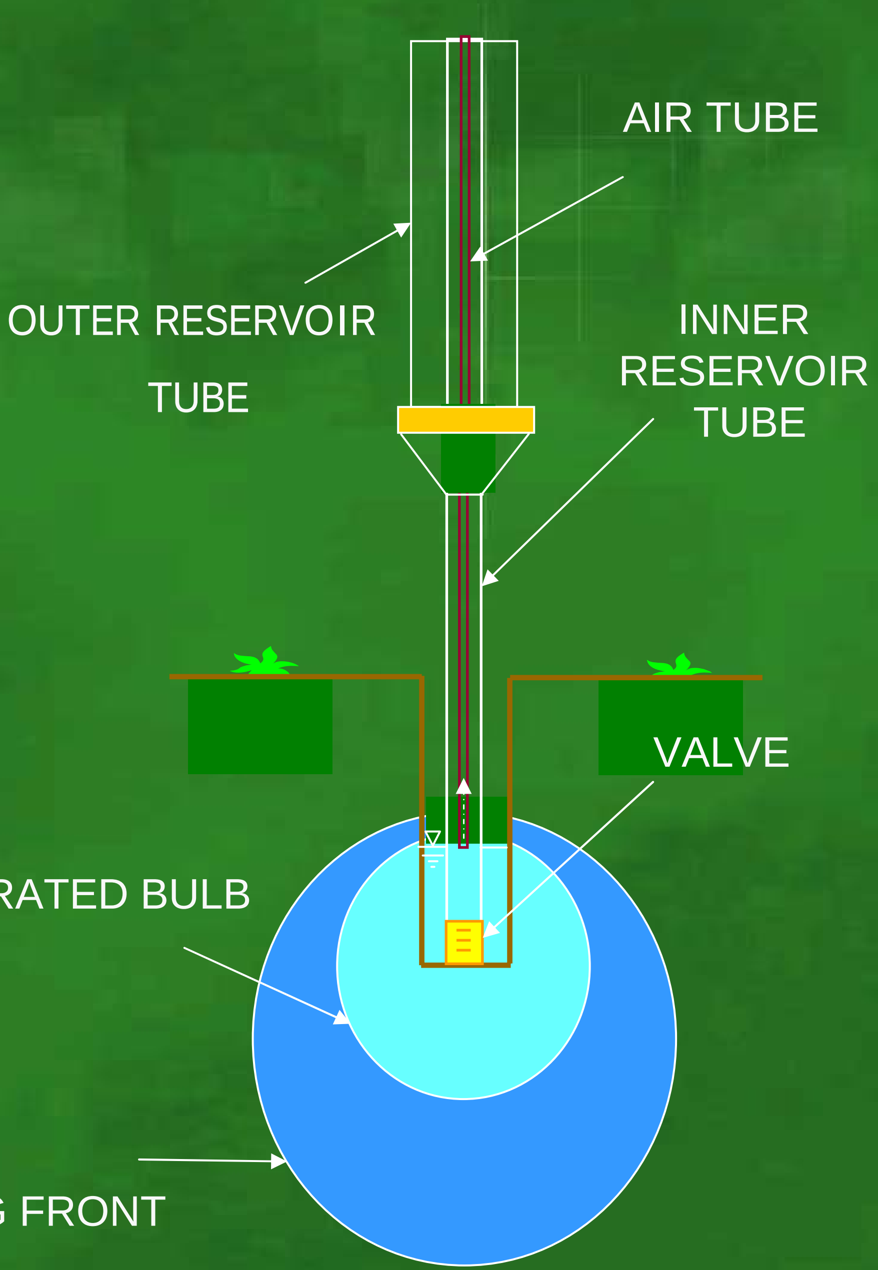
Hydraulic conductivity curve



Soil water characteristic curve

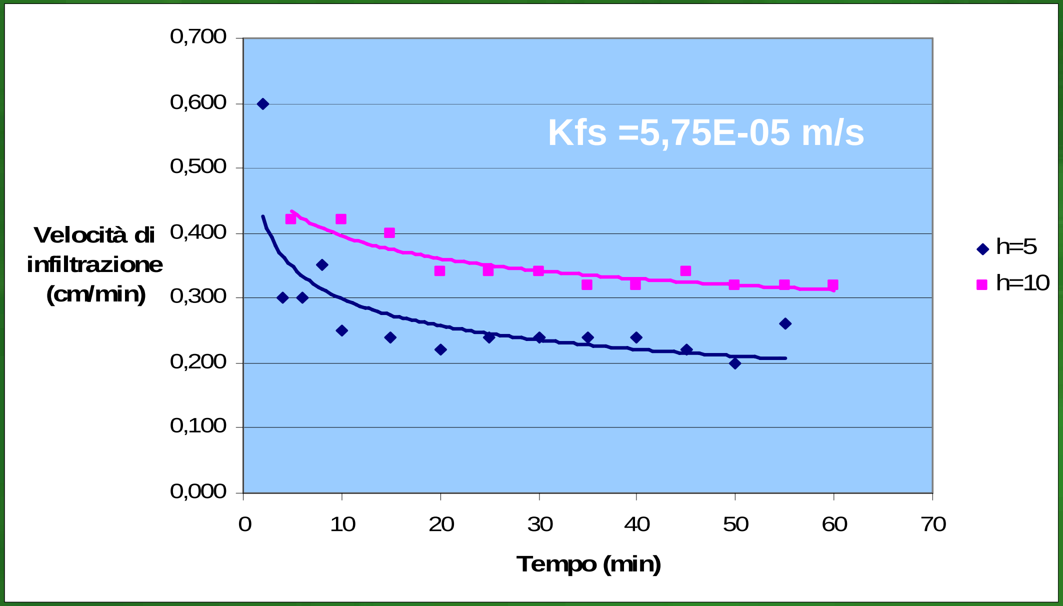
2) field tests: Guelph Permeameter





The GP method measures the **steady-state rate Q** (m^3/s) necessary to maintain a **constant depth of water H** (m) in an uncased cylindrical well of radius a (m), above the water table.

Guelph Permeameter



The **field saturated hydraulic conductivity Kfs** (m/s), and the **matric flux fm** (m^2/s) are calculated from Q (steady-state rate) and H.

Using a dual (or two ponded) height analysis:

$$k_{fs} = [(0{,}0041)(X)(\overline{R_2})] - [(0{,}0054)(X)(\overline{R_1})]$$

Where:

X= 35,22 cm^2 reservoir constant

0,0041 e 0,0054

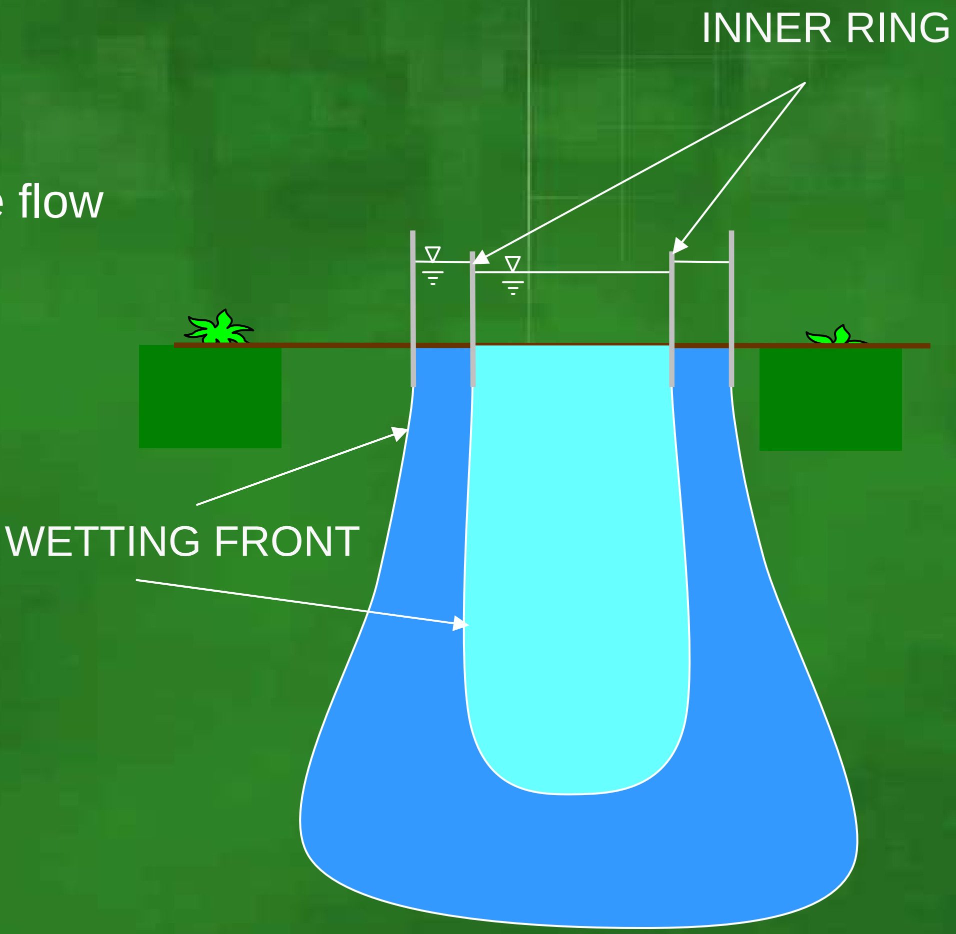
$\overline{R_1}$ and $\overline{R_2}$ = steady-state drop in water level during the first and second test (5cm - 10cm)

Field tests: double ring infiltrometer

The instrument investigates the soil down to the depth of about 1-2 m.

Average test duration: 4-6 hours.

The external ring vertically confines the flow created from the inner ring.



double ring infiltrometer

field hydraulic conductivity :

$$k_{fs} = \frac{QL}{AH}$$

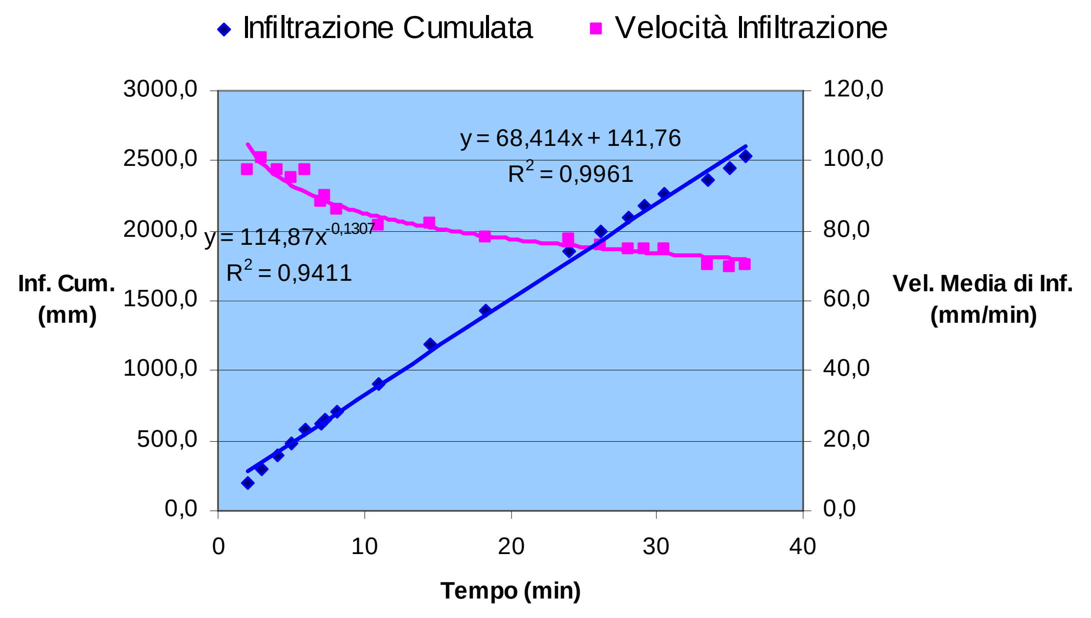
where

Q= steady-state rate,

L= depth of ring driven into the ground

A= inner ring surface

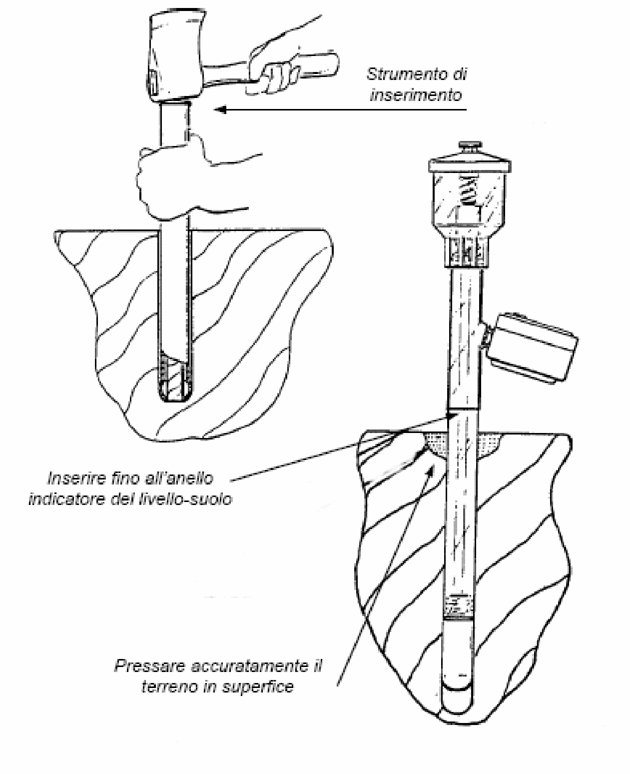
H= hydraulic head



Hydraulic conductivity (m/s)	**3,287E-04**
Infiltration velocity (m/s)	**1,171E-03**

Tensiometer

Allowed to measure soil moisture and **negative pore water pressure**



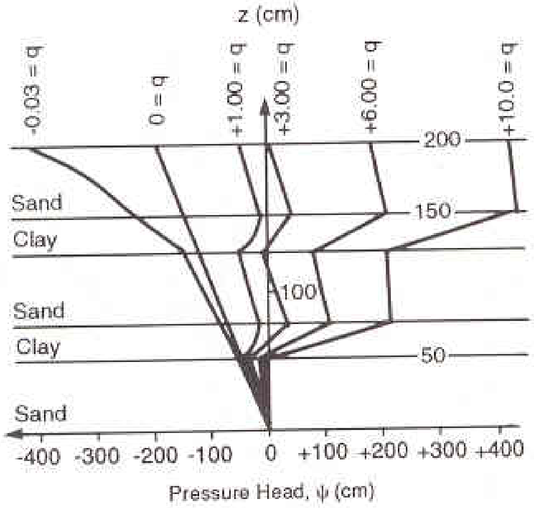
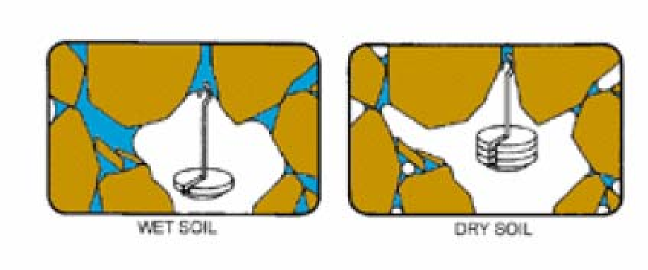


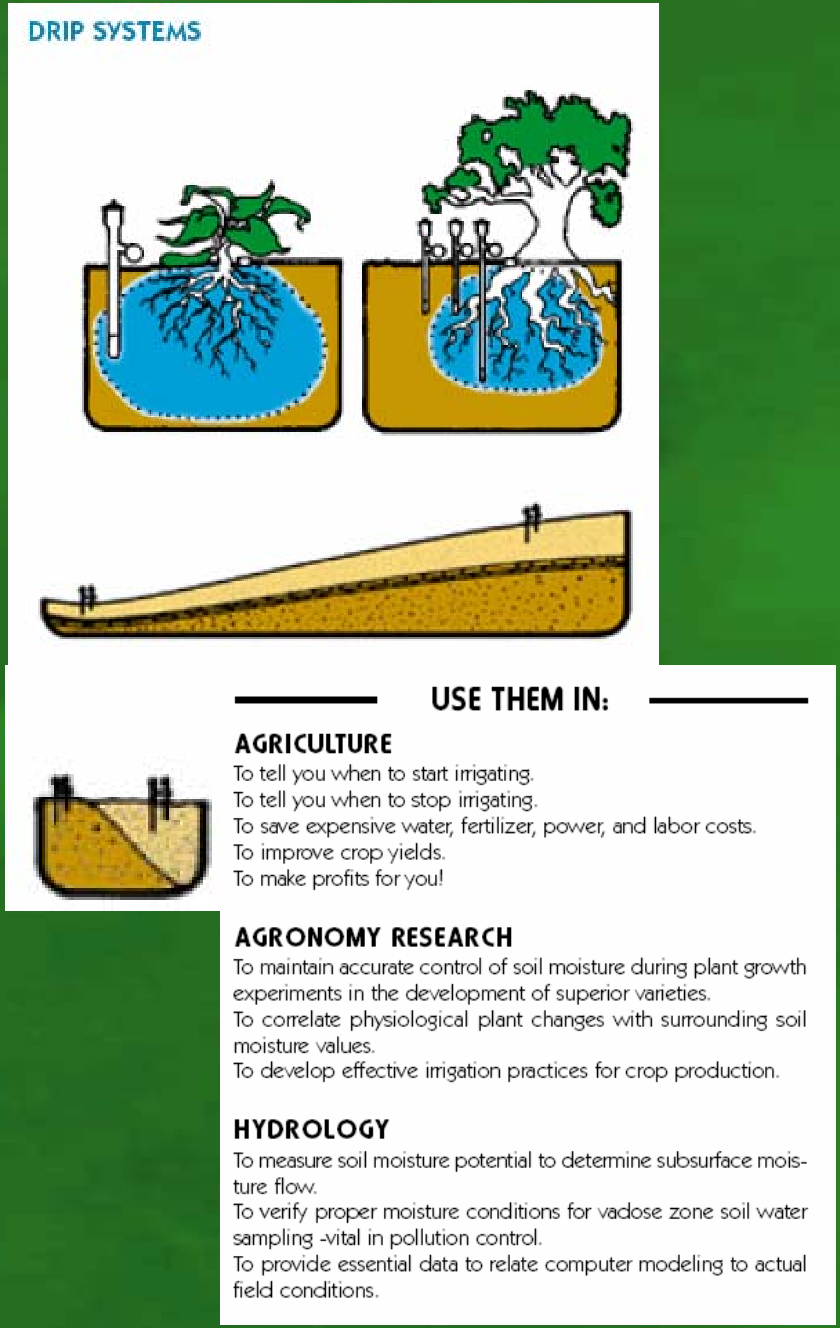
Figure 8 Steady-state pressure head profiles in a layered soil for different values of the specific discharge, *q* (cm/d). (From Bear, 1972. With permission.)

The tensiometer allowed a direct measure of the “soil suction”, the force required to remove water from the soil.

This parameter controls the water flow in vadose zone.



Tensiometer



DRIP SYSTEMS

USE THEM IN:

AGRICULTURE

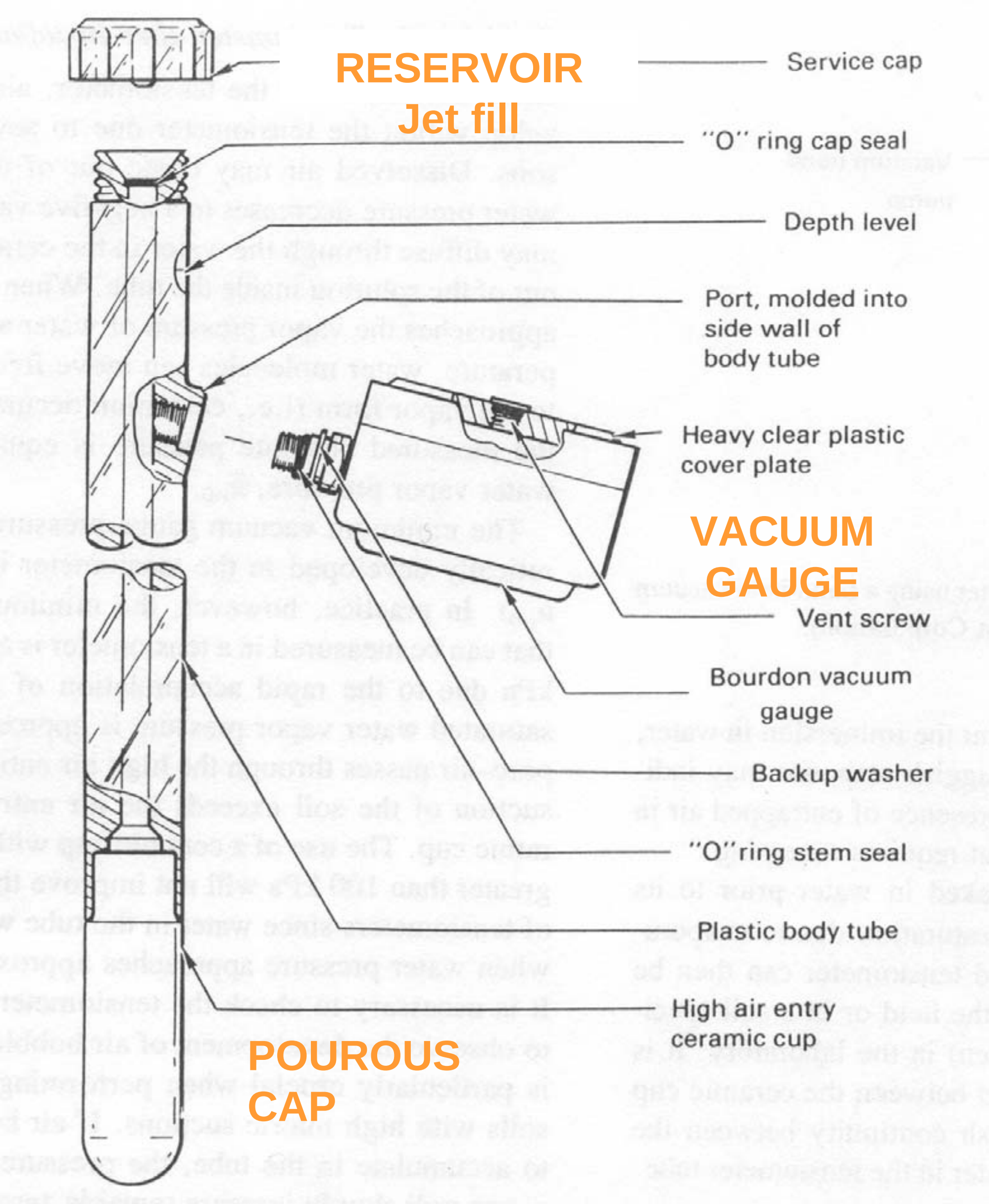
To tell you when to start irrigating.
To tell you when to stop irrigating.
To save expensive water, fertilizer, power, and labor costs.
To improve crop yields.
To make profits for you!

AGRONOMY RESEARCH

To maintain accurate control of soil moisture during plant growth experiments in the development of superior varieties.
To correlate physiological plant changes with surrounding soil moisture values.
To develop effective irrigation practices for crop production.

HYDROLOGY

To measure soil moisture potential to determine subsurface moisture flow.
To verify proper moisture conditions for vadose zone soil water sampling -vital in pollution control.
To provide essential data to relate computer modeling to actual field conditions.



RESERVOIR
Jet fill

VACUUM GAUGE

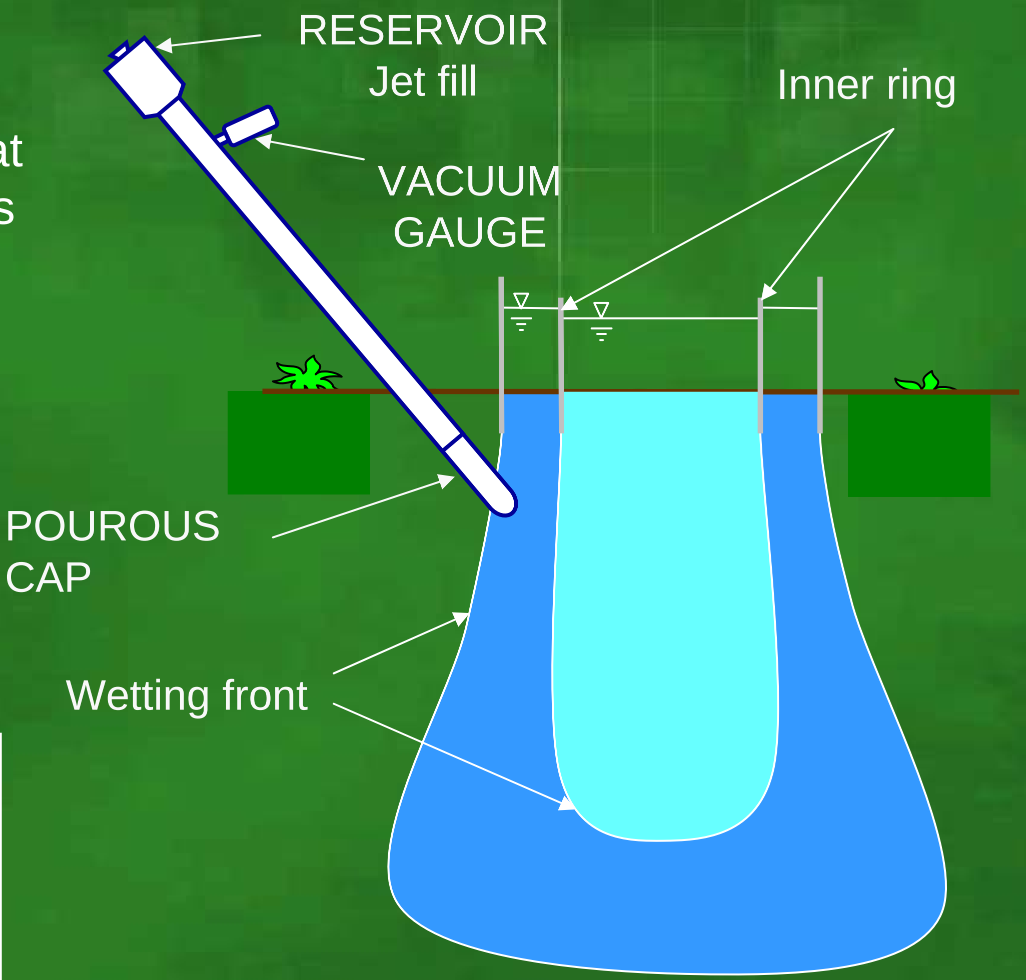
POUROUS CAP

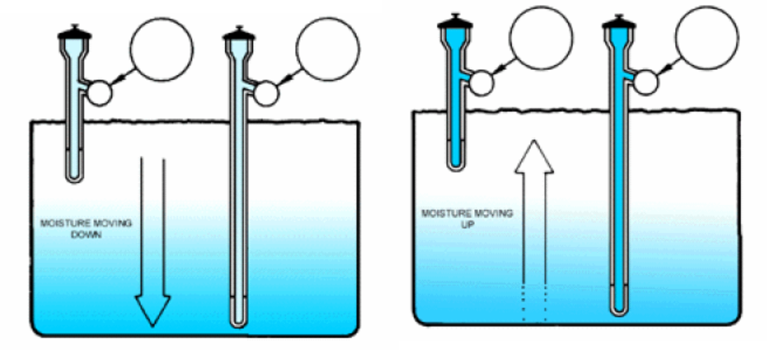
Tensiometer applications

USED

1) to record soil moisture changes at different depth during climatic events (long time measurements in fixed stations)

2) to monitor negative water pressure during permeability tests





In situ density and moisture measurements

$$\gamma_n = \frac{P}{V}$$

3)

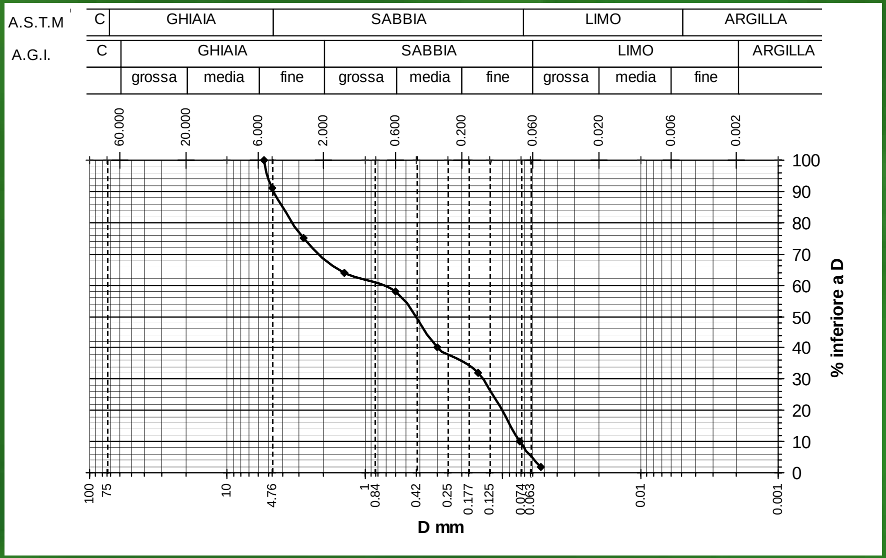
LABORATORY TESTS

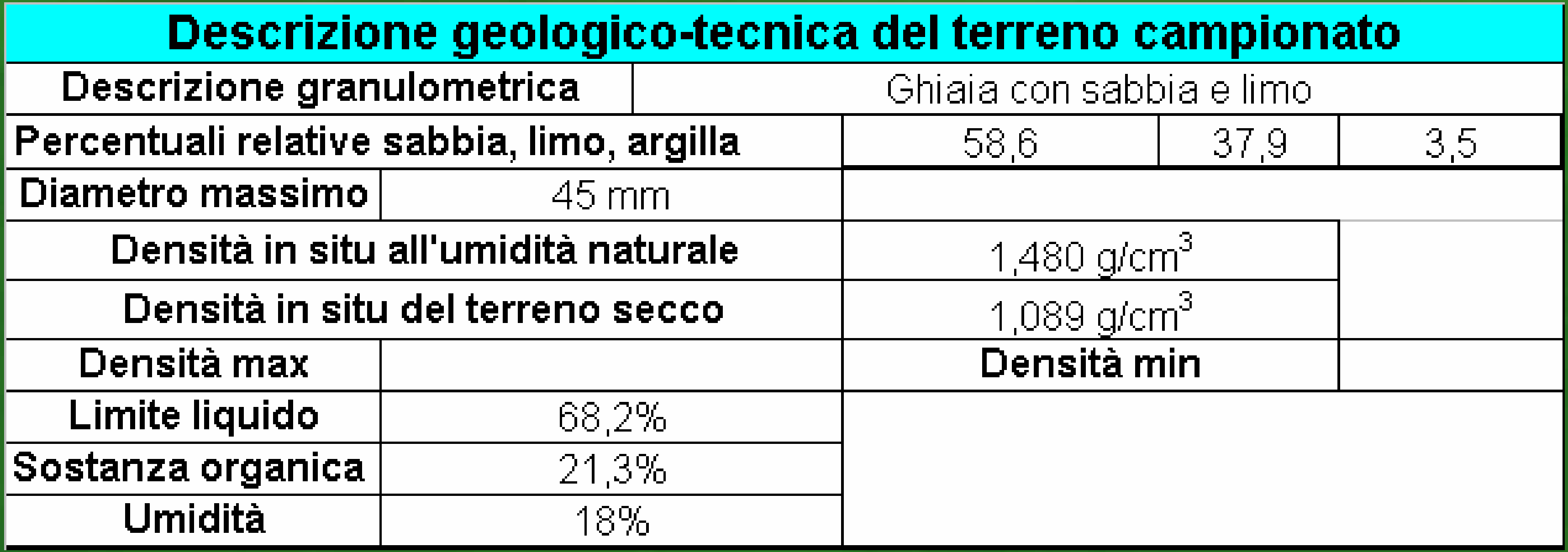
- **Particle size analisis**
- **Atterberg limits, plasticity index**
- **Natural water content**
- **Oraganic content**

Others

- **max and min density**
- **Permeability laboratory tests**

Geotechnical description





Descrizione geologico-tecnica del terreno campionato			
Descrizione granulometrica	Ghiaia con sabbia e limo		
Percentuali relative sabbia, limo, argilla	58,6	37,9	3,5
Diametro massimo	45 mm		
Densità in situ all'umidità naturale	1,480 g/cm^3		
Densità in situ del terreno secco	1,089 g/cm^3		
Densità max		Densità min	
Limite liquido	68,2%		
Sostanza organica	21,3%		
Umidità	18%		

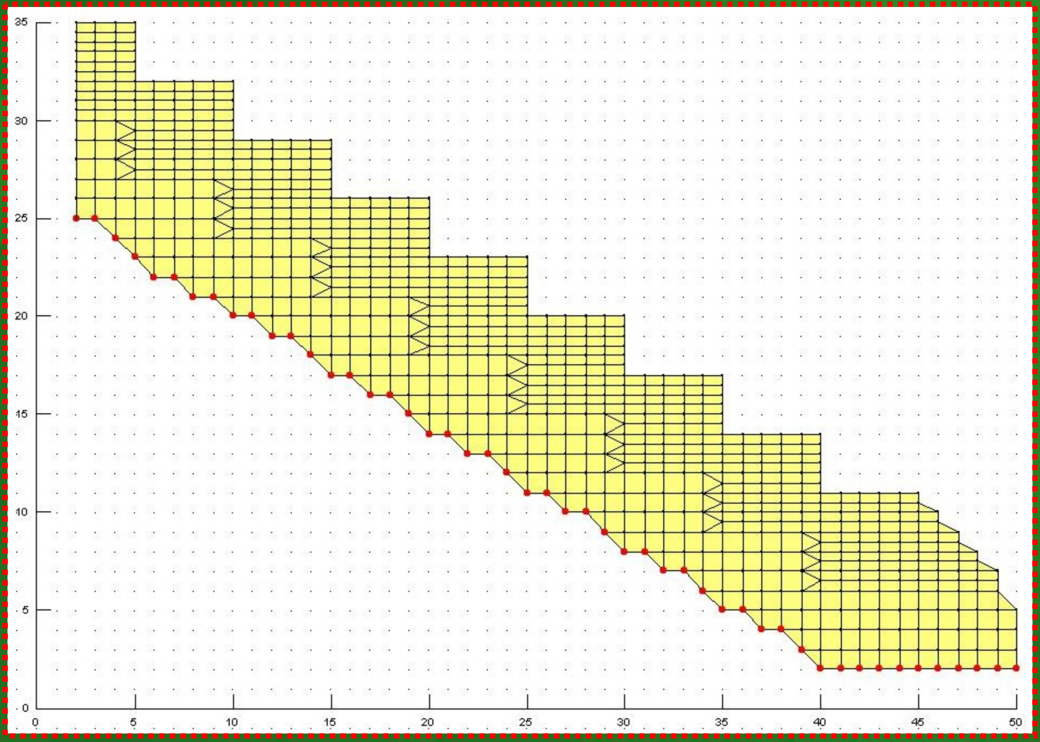
4)

Flow modeling

AIM: to study the modalities with which flow develops and evolves in terraced slope, characterized by dry stone retaining wall.

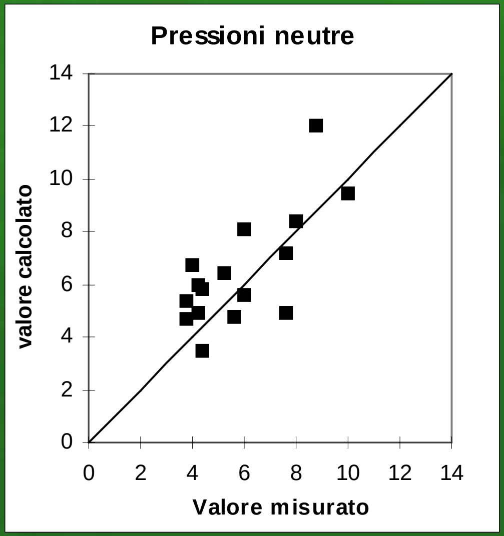
Modeling by **FINITE ELEMENT CODE**

Slope geometry and grid for the modeling



MODEL CALIBRATION

To validate the results of simulations it is necessary the comparison between direct measurements (by tensiometers) and calculated values of pore water pressure.

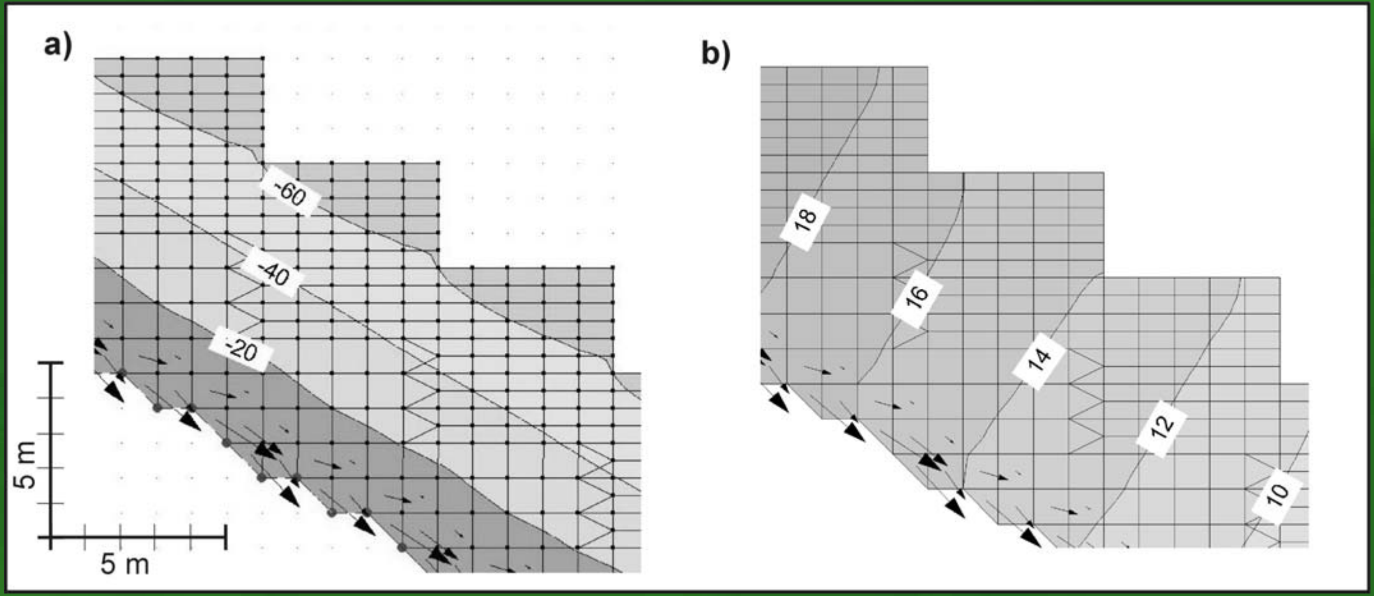


Simulations

SIMULATIONS	Steady state	Transient analysis	Soil anisotropy	Clay layers	Undraining Wall
Simulazione	Stazionario	Transitorio	Anisotropia	Livelli argillosi	Muri non filtranti
Sim. 0	X				
Sim. 1		X			
Sim. 2		X	X		
Sim. 3		X		X	
Sim. 4		X		X	X

Steady state analysis results (Sim.0). a) Pore pressure contour lines (kPa). b) Hydraulic head contour lines (m).

Pore pressure (kPa)

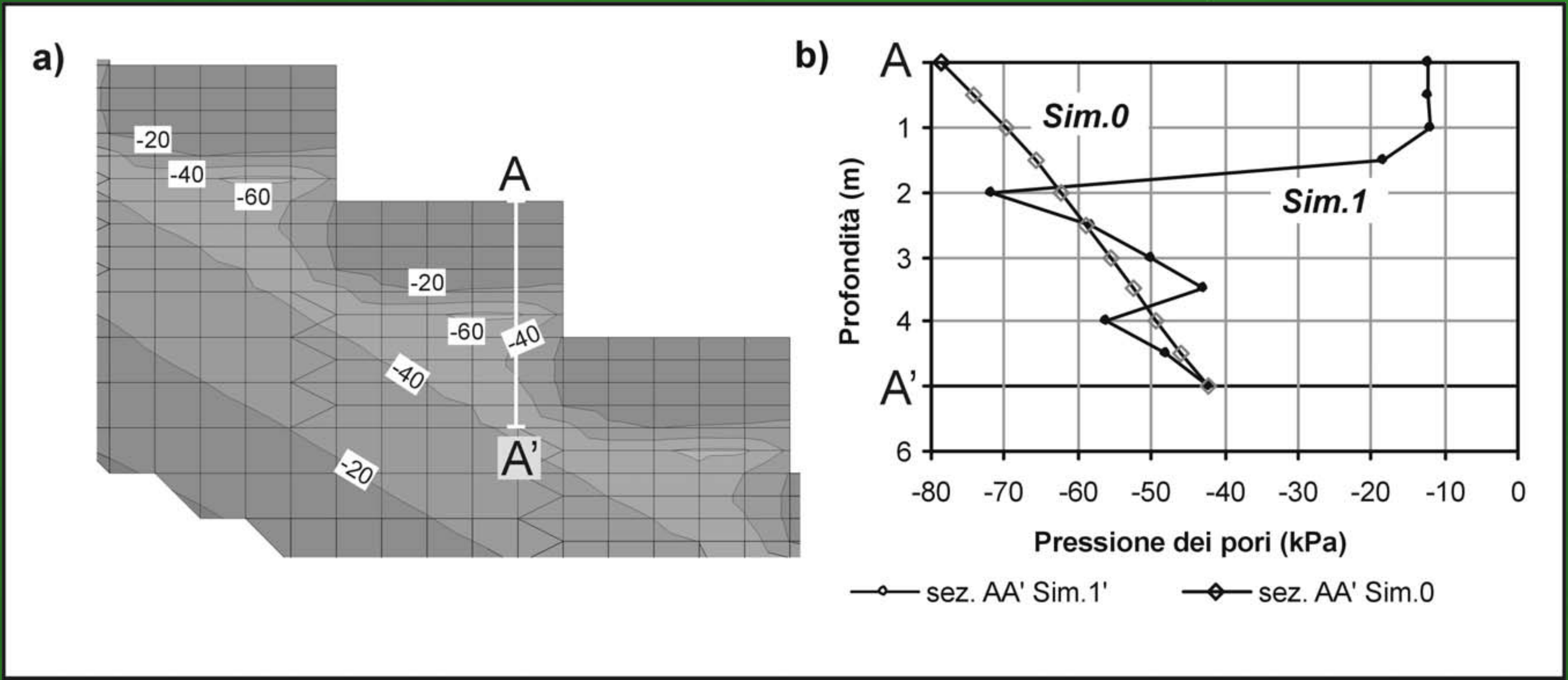


Hydraulic head (m)

Transient analysis: Sim – 1

Homogeneous isotropic soil - drained walls

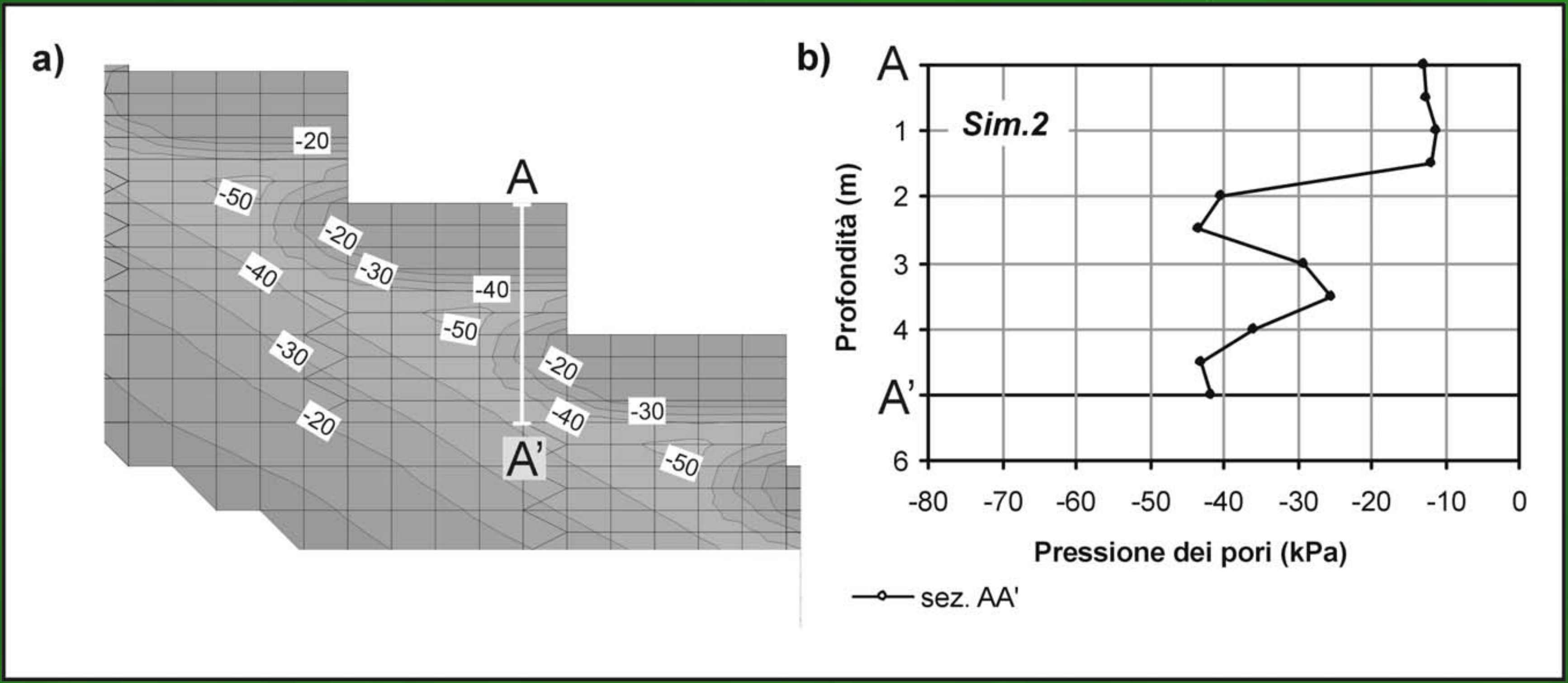
Wetting front advance at the end of Sim.1 event (rainfall duration 12 hours). Pore pressure contour lines (kPa) through the slope (a) and through section AA’, compared with the Sim.0 results (steady state) (b).



Transient analysis: Sim – 2

anisotropic soil - drained walls

Wetting front advance at the end of Sim.2 event (rainfall duration 12 hours; soil anisotropy Kh=3*Kv). Pore pressure contour lines (kPa) through the slope (a) and through section AA' (b).

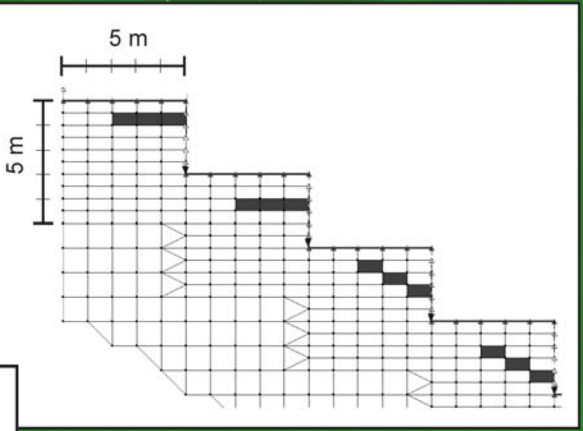


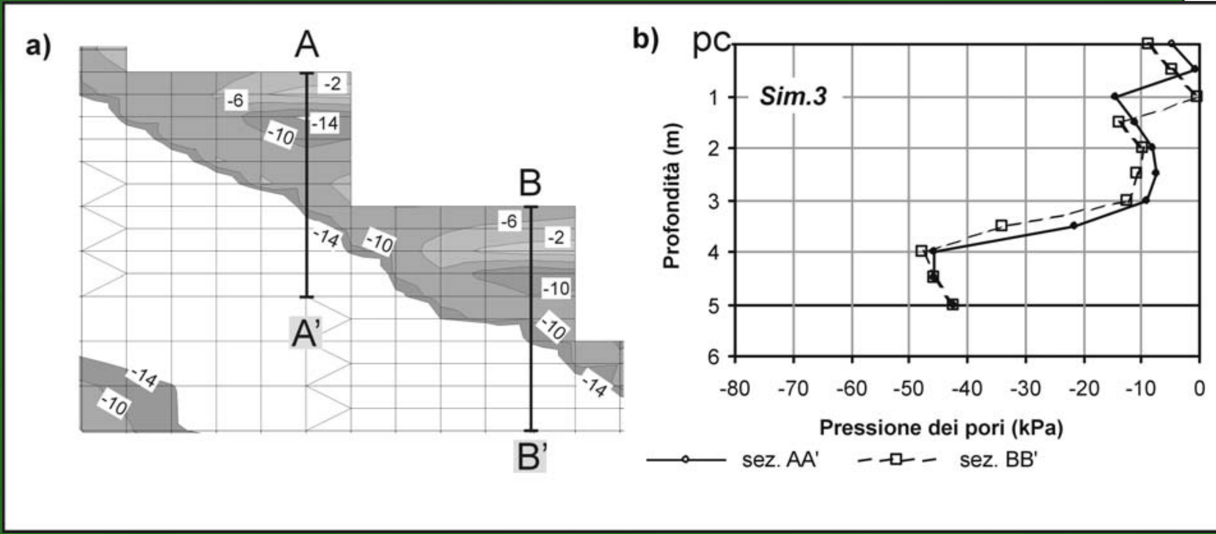
Transient analysis: Sim – 3

low permeability horizontal layers - drained walls

Location and distribution of the low permeability layers, applied to simulation Sim.3.

Kv=Kh=1 10^{-8} m/s.





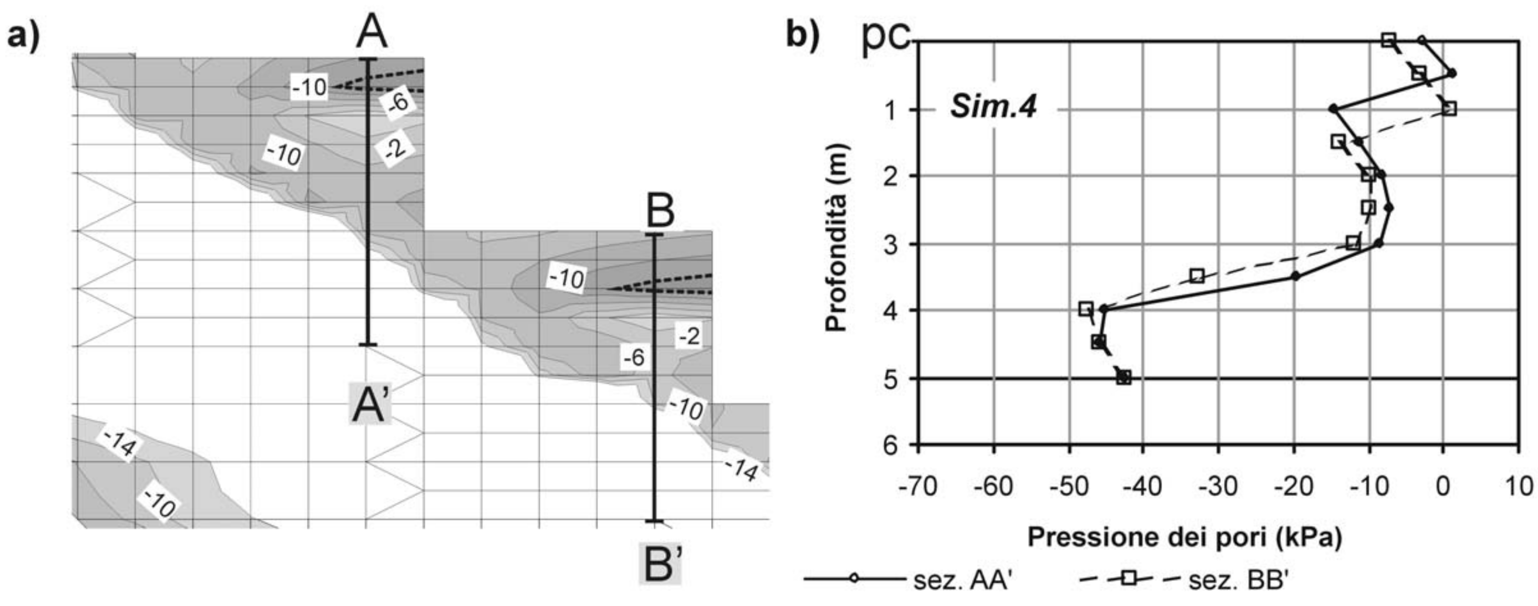
Wetting front advance at the end of Sim.3 event: effect of low permeability horizontal layers. Pore pressure contour lines (kPa) through the slope (a) and through the sections AA' and BB' (b).

Transient analysis: Sim – 4

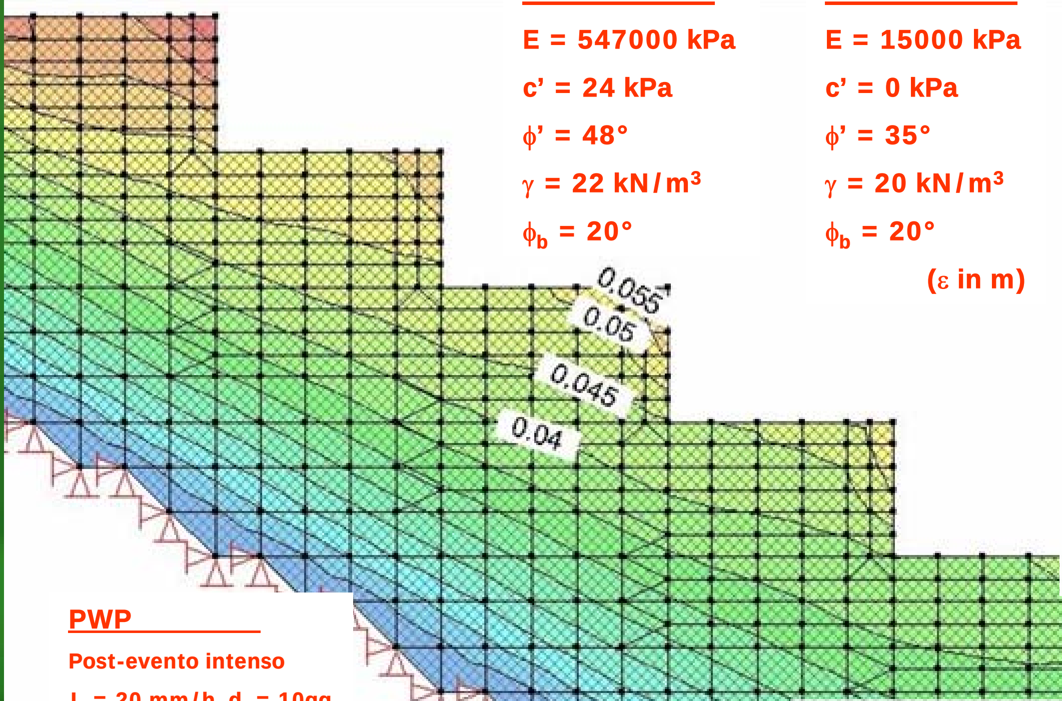
low permeability horizontal layers - undrained walls

$Kv=Kh=1\ 10^{-8}$ m/s.

Wetting front advance at the end of Sim.4 event: effect of low permeability horizontal layers behind the undrained walls. Pore pressure contour lines (kPa) through the slope (a) and through the sections AA’ and BB’ (b).



Stress-strain analysis



Muri

E = 547000 kPa

c’ = 24 kPa

$\phi' = 48°$

$\gamma = 22$ kN/m^3

$\phi_b = 20°$

Terreno

E = 15000 kPa

c’ = 0 kPa

$\phi' = 35°$

$\gamma = 20$ kN/m^3

$\phi_b = 20°$

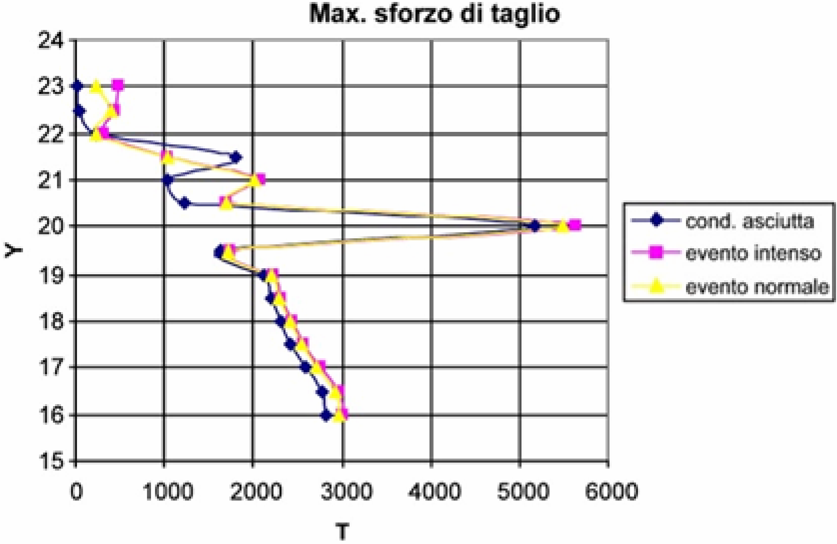
(ε in m)

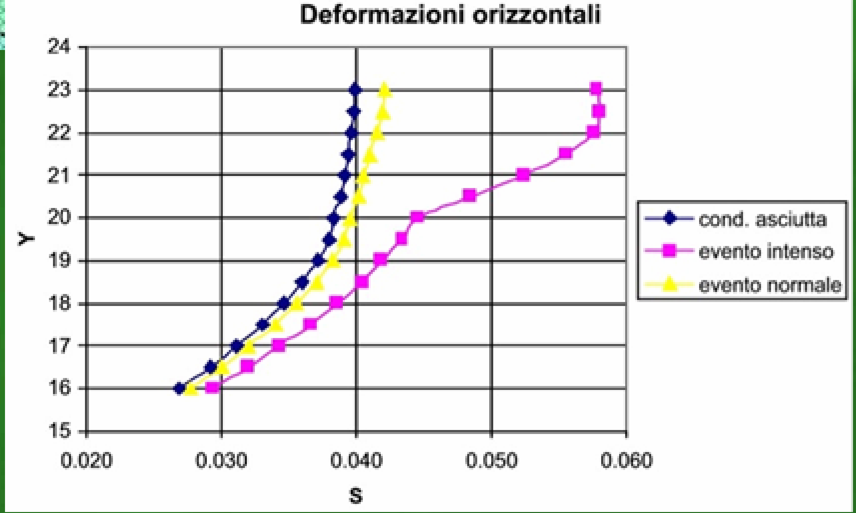
PWP

Post-evento intenso

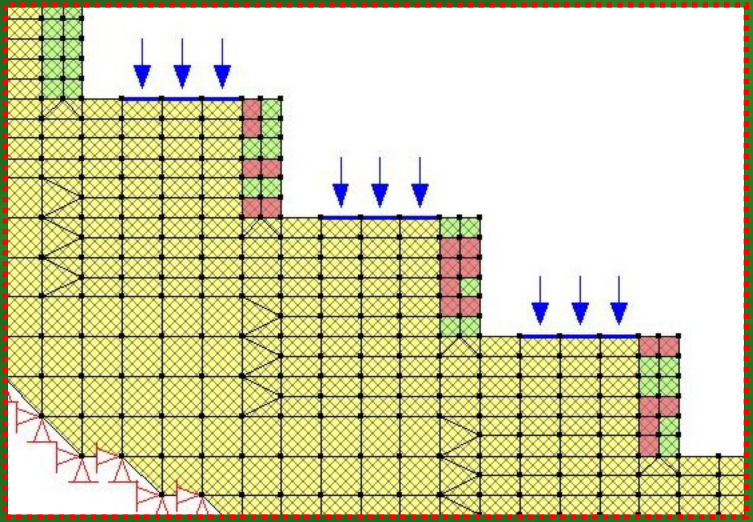
$I_1 = 20$ mm/h, $d_1 = 10$gg

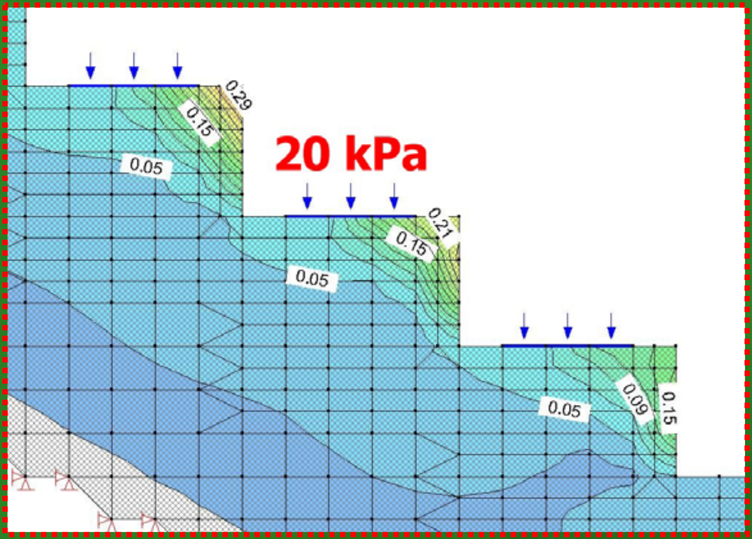
$I_2 = 30$ mm/h, $d_2 = 2$h


Max. sforzo di taglio


Deformazioni orizzontali

Introduction of different perturbing factors into the simulation





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