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Steady-State Water Flow in Porous Media

The rate of water flow and the distribution of water potentials in a one-dimensional soil column under steady-state conditions can be obtained by solving the Darcy or Buckingham-Darcy equation. When soils are saturated and homogeneous, the calculation is easy. The problem becomes more difficult when the soil is not homogeneous or when it is unsaturated. This program uses numerical methods to evaluate the flow rate of water, the equivalent conductivity of the soil, and soil-water potentials in a one-dimensional flow system composed of one or two layers of soil. The flow rate, equivalent conductivity, and a graph of total potential, matric potential, gravitational potential, conductivity, driving force, or water content as a function of position along the soil column are then displayed.

Model Description

Darcy's equation is often used to describe water movement in saturated soils. For one-dimensional water flow, it can be written as (Hillel, 1982)

$$q = -K \frac{dH}{dx}$$

where q is the flux density of water passing through the soil, K is the saturated hydraulic conductivity, H is the total potential, and x is the position coordinate.

For unsaturated soils, this equation takes the modified form developed by Buckingham (1907)

$$q = -K(\theta)\frac{dH}{dx} \qquad \text{or} \qquad q = -K(h)\frac{dH}{dx}$$

where K(θ) or K(h) is the unsaturated hydraulic conductivity function (Brooks and Corey, 1964; Gardner, 1958; vanGenuchten, 1980), θ is the volumetric water content and h is the matric potential. The total potential is the sum of the matric potential and gravitational potential.

For uniform saturated soils we can write this equation as

$$q = -K\frac{H_2 - H_1}{L}$$

where H_1 and H_2 are the total potentials at the inlet and outlet of the soil system, respectively. The difference in total potential divided by the length of the system is the driving force causing water to flow. This equation is applicable to layered or unsaturated soils if the hydraulic conductivity, K, in the equation is regarded as the equivalent conductivity of the entire soil system.

When soils are saturated and homogeneous, the flux density can be easily obtained if the conductivity of the soil is known and the total potential or matric potential at the ends of the soil are specified. However, the problem becomes more difficult when the soil is not homogeneous or when it is unsaturated.

This program considers one-dimensional flow in a soil. The soil is assumed to be either homogeneous or composed of two layers. In a homogeneous soil system, the conductivity will be uniform throughout if the matric potentials at both ends are zero or more since that means the soil is saturated. If one or more matric potentials are less than zero, the conductivity and water content can change with position. In a layered soil system, the conductivity will not be uniform throughout even if the soil is saturated.

The program allows a user to select a soil system made up of one or two layers from the drop-down "Preferences" menu. If a two-layer system is selected, the user can specify the length or thickness of each layer in the soil system, the saturated hydraulic conductivity of each layer, the total potential or matric potential at each end of the soil, and the orientation of the soil. The user can also define for each layer the water content and hydraulic conductivity as functions of matric potential that are needed for unsaturated flow. When an one-layer system is selected, the user only needs to specify the thickness and hydraulic parameters for the single layer along with the potentials at the ends of the soil system and its orientation.

The software then solves the equations above for the system and displays graphs of total potential, matric potential, gravitational potential, conductivity, driving force, or water content as a function of position along the soil column. In this way the user can see the impact of changes in matric potential and water content upon the flow rate and equivalent conductivity of the entire soil system.

Assumptions and Simplifications

Simplifications and assumptions on soil media and flow conditions:

1. This software assumes that flow is strictly one-dimensional.

2. Flow-induced deformation in a soil medium affects the shape, size, and connectivity of soil pores, which largely determines the hydraulic properties of a soil system (Buckingham, 1907). In this program, it is assumed that the soil system simulated in this program is rigid, i.e., no flow-induced deformation occurs.
3. Flow through conduits is classified into laminar flow and turbulent flow dependent on the ratio of inertial to viscous forces exerted on the fluids(Bear, 1972). In laminar flow, the relationship between flow rate and gradient in total potential is linear, while in a turbulent flow the relationship is nonlinear. The proportional relationship of Darcy's law is valid in the range of laminar flow only. Hence, an implicit assumption in this program is that flow conditions inside soil pores are laminar.
4. In fine-grained (especially clayey) soils, a minimum potential gradient called threshold gradient may exist. Below this threshold gradient there is very little flow. This non-Darcy behavior(Swartzendruber, 1962) may be due to the effect of stream potential which generates small countercurrents along the pore walls in a direction opposite that of the main flow (Bear, 1972). Another explanation for the non-Darcy behavior is the non-Newtonian liquid viscosity caused by clay-water interaction. In this program, non-Darcy behavior is ignored.

Glossary

Equivalent Conductivity: The equivalent conductivity of a non-homogeneous soil is equal to the flux through that soil divided by the driving force or gradient in total potential across that soil. It could be considered the equivalent or average conductivity for the non-uniform soil.

Flux Density: The flux density of water passing through a soil is the volume of water passing through the soil per unit cross-sectional area (perpendicular to the flow) per unit time. It has units of length per unit time such as mm/sec, mm/hour, or inches/day. Many times flux and flux density are used interchangeably.

Gravitational Potential: The gravitational potential of water is the amount of work required per unit quantity of water to move a very small amount of water reversibly and isothermally from a pool of pure water at atmospheric pressure at a reference level to another pool of pure water at the elevation of interest. This is simply the amount of work required to lift or lower the water from the reference level. (See also Units of Potential).

Hydraulic Conductivity: The hydraulic conductivity of a soil is a measure of the ease at which water moves through the soil. It can be obtained experimentally by measuring the flux density of water passing through a soil, the difference in total potential and the length of the soil. The conductivity is the proportionality constant which when multiplied by the driving force (or gradient in total potential) causing water to move gives the flux density of water. If the potential is defined in terms of a unit weight of water, then the gradient in total head has no dimensions and the conductivity has units of length per unit time just as the flux density does.

Matric Potential: The matric potential of water in a soil is the amount of work required per unit quantity of water to move a very small amount of water reversibly and isothermally from a pool of pure water at the elevation of interest and at atmospheric pressure to the point of interest in the soil. This is the amount of work required to move water into a soil from outside of it. Since the elevations are the same, gravity has no impact upon matric potential. Matric potential is another term for pressure potential or pressure head. (See also Units of Potential)

Total Potential: The total potential of water in a soil is the amount of work required per unit quantity of water to move a very small amount of water reversibly and isothermally from a pool of pure water at atmospheric pressure and at a reference level to the point of interest in the soil. This is the sum of the matric potential and the gravitational potential. (See also Units of Potential)

Units of Potential: All definitions of potential refer to work per unit quantity of water. The final units of potential depend upon the unit quantity of water chosen. It is convenient to define potential per unit weight of water. This means that all types of potential have units of length. This form of potential is often called "head". So we commonly talk of total head, gravitational head, and pressure head or matric head.

Volumetric Water Content: The volume of water in a soil divided by the total volume of the soil (i.e. the sum of the volumes of solids and pores).

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