地下水水文学

Groundwater Hydrology

讲 授：肖长来

吉林大学环境与资源学院

水文水资源系

2004年9月

第四章 地下水运动的基本规律

提 要

●要求掌握重力水运动的基本规律，能熟练写出Darcy定律的数学表达方式及各项符号的意义，掌握渗透流速、水力梯度、渗透系数等基本概念；

●理解流网的概念，掌握均质各向同性介质中的流网特点，能绘制流网并能熟练应用流网进行水文地质分析；

●了解层状非均质介质中的流网特点；

●了解饱水粘性土中水的运动规律，理解起始水力梯度的涵义。

第四章 地下水运动的基本规律

第四章 地下水运动的基本规律

4 .0 基本概念

Flow is the rate of water discharged from a source expressed in volume with respect to time. GW

（1）渗流（seepage）是指地下水在岩石空隙中的运动。

The interstitial movement of water that may take place in rocks or soils. 渗流场（seepage field）是指发生渗流的区域。Seepage is spot where water contained in the ground oozes slowly to the surface and often forms a pool; a small spring. GW

（2）层流运动（laminar flow）是指在岩石空隙中渗流时水的质点作有秩序的、互不混杂的流动。

The flow of fluid in which the flow paths are in smooth, parallel lines, with essentially no mixing and no turbulence.

4 .0 基本概念

紊流运动（turbulent flow）指在岩石空隙中渗流时水的质点作无秩序的、互相混杂的流动。

（3）稳定流（steady flow）是指水在渗流场内运动过程中各个运动要素（水位、流速、流向等）不随时间改变的水流运动。

Steady flow is the flow that occurs when, at any point in the flow field, the magnitude, and direction of the specific discharge are constant in time. HG

非稳定流（unsteady flow）是指水在渗流场内运动过程中各个运动要素（水位、流速、流向等）随时间变化的水流运动。

Unsteady flow is the flow that occurs when, at any point in the flow field, the magnitude or direction of the specific discharge changes with time. Also called transient flow or nonsteady flow. HG

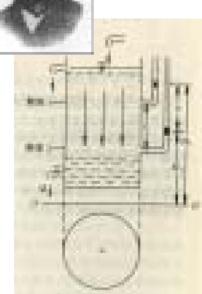
4.1 重力水运动的基本规律

4.1.1达西定律（Darcy's law）

又称为线性渗透定律

是指流体在多孔介质中遵循渗透速度（v）与水力梯度（I）呈线性关系的运动规律，是法国H. Darcy于1856年通过砂柱渗透实验而得到的线性渗透定律。

Darcy's law is an equation that can be used to compute the quantity of water flowing through an aquifer HG



4 .1 重力水运动的基本规律

Darcy's Law

In 1856, a French hydraulic engineer named Henry Darcy (1803-1858) published a report on the water supply of the city of Dijon, France. In that report, Darcy described the results of an experiment designed to study the flow of water through a porous medium (Freeze, 1994). Darcy's experiment resulted in the formulation of a mathematical law that describes fluid motion in porous media.

Darcy's Law is the fundamental constitutive relationship that we use to understand the movement of fluids in the Earth's crust. Darcy's Law states that the rate of fluid flow through a porous medium is proportional to the potential energy gradient within that fluid. The constant of proportionality is the hydraulic conductivity; the hydraulic conductivity is a property of both the porous medium and the fluid moving through the porous medium.

4 .1 重力水运动的基本规律

During his lifetime, Darcy was most noted for his design and construction of a water-supply system for his native town of Dijon. In the first half of the nineteenth century, most large cities had no central water-supply or sewage systems. Water was supplied by a few inadequate wells or drawn from a contaminated stream. There were no water-supply or drain pipes, and water was delivered daily to residences on carts.

Darcy drew upon a nearby spring for a supply of fresh and pure water and designed a network of supply and drainage pipes. The entire system was constructed in 18 months. Although a relatively small and provincial town, thanks to Darcy, Dijon enjoyed the benefits of a modern water-supply system 20 years earlier than Paris.

4 .1 重力水运动的基本规律

Darcy's efforts were so appreciated by his fellow townsmen, they renamed the main square in the town "Place Darcy" following his death in 1858. Notably, Darcy not only refused payment for his work in the construction of this water system, but even declined renumeration of his personal expenses. Philip (1995) noted that under the laws of the time, Darcy rightfully had a claim to the 1995 equivalent of $1.5 million US dollars. The only compensation Darcy would accept was free water for his family and household during his lifetime.

4.1 重力水运动的基本规律

达西定律的数学表达式为

$$Q = K\omega \frac{h}{L} = K\omega I \qquad Q = -KA\frac{dh}{dl}$$

其中Q-----为渗透流量（出口处流量），亦即通过过水断面（砂柱各断面）A的流量(m³/d)；volumetric flow rate.

K----多孔介质的渗透系数(m/d)；

A,ω----过水断面面积(m²）；cross-sectional area of flow.

h——水头损失（$h=H_1-H_2$，为上下游过水断面的水头差）；

L——渗透途径；

I----为水力梯度（I = h/L），等于两个计算断面之间的水头差除以渗透途径，亦即渗透路径中单位长度上的水头损失。

4.1 重力水运动的基本规律

由水力学知，Q=A V，则V=Q/A，

于是得到达西定律的另一种表达式：

V = K I

其中V ---多孔介质中流体的渗透流速(m/d)。

K--多孔介质的渗透系数(m/d)，是水力梯度等于1时的渗透流速，它是描述含水层介质透水能力的重要水文地质参数。

v--多孔介质中流体的渗透流速(m/d)，它并非真实的流速。

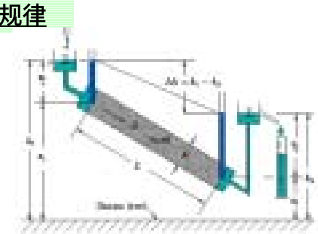
达西定律是定量计算的基础和定性分析的依据。

4.1 重力水运动的基本规律

Darcy's Law

$$Q = KA\frac{h_1 - h_2}{L}$$

$$h = z + \frac{p}{\rho g}$$



K = coefficient of proportionality called hydraulic conductivity.
Q = volume of fluid per unit time passing through a column of constant cross-sectional area, *A* and length *L*.
h_1, h_2 = elevations of inflow and exit reservoirs of the column.
z = elevation of the point at which the piezometric head is measured, above a datum level.
p, ρ = fluid's pressure and mass density.
z = elevation of the point at which the piezometric head is measured.
p, ρ = fluid's pressure and mass density

4.1 重力水运动的基本规律

4.1.2渗透流速（seepage velocity）

有效孔隙度（effective porosity）n_e----重力水流动的空隙体积与岩石体积之比，$n_e<n$，但$n_e>\mu$，一般有$\mu<n_e<n$。

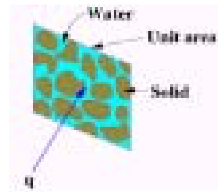
Effective porosity is the portion of pore space in saturated permeable material where the movement of water takes place.   GW

4.1 重力水运动的基本规律

4.1.2渗透流速（seepage velocity）

渗透流速（v）并非真实的流速，而是假设水流通过包括骨架与空隙在内的断面（A）时所具有的一种虚拟流速，等于通过实际过水断面的实际流速u与岩石的有效孔隙度之积。设通过实际过水断面（ω'= ω n）的实际流速为u，则Q= ω'·u，得

$$v = n_e \cdot u$$。



Seepage velocity is the actual rate of movement of fluid particles through porous media. HG

4.1 重力水运动的基本规律

4.1.3水力梯度（hydraulic gradient）

水力梯度（I）是指沿渗透途径水头损失与渗透途径长度的比值，I=h/L；可以理解为水流通过单位长度渗透途径为克服摩擦阻力所耗失的机械能；或为克服摩擦力而使水以一定速度流动的驱动力。

Hydraulic gradient is the change in the total head with a change in distance in a given direction. The direction is that which yields a maximum rate of decrease in head.

4.1 重力水运动的基本规律

4.1.4渗透系数

渗透系数（K）是水力梯度等于1时的渗透流速。单位：m/d,cm/s。 K大，岩石透水能力就强。

Hydraulic conductivity can be defined as specific discharge per unit gradient (in 1-d flow in an isotropic porous medium). The hydraulic conductivity depends of fluid properties and void space configuration (width of passages and tortuosity).

Hydraulic conductivity is a coefficient of proportionality describing the rate at which water can move through a permeable medium. The density and kinematic viscosity of the water must be considered in determining hydraulic conductivity. HG

4.1 重力水运动的基本规律

4.1.4渗透系数

渗透系数/水力传导系数，其英文术语较多.

C.S.Slichter 在1800年最先提倡使用transmission constant，以后出现了

seepage coefficient

permeability coefficient

coefficient of permeability

percolation coefficient

hydraulic permeability

hydraulic conductivity

以往最常用permeability coefficient

近年来则盛行使用hydraulic conductivity

4.1 重力水运动的基本规律

渗透系数（K）的影响因素：

K与岩石空隙性质、水的某些物理性质有关。

（1）孔隙直径大则渗透性强，取决于最小孔隙直径：孔隙直径越小，结合水占据的无效空间越大，透水性就小。孔隙直径越大，结合水占据的无效空间就越小，透水性就大。透水能力很大程度上取决于最小的孔隙直径。

（2）圆管通道：形状弯曲而变化时，渗透性较差。

（3）颗粒分选性：比对孔隙度的影响要大。

渗透系数与岩性之间的关系

岩性	亚粘土	亚砂土	粉砂	细砂	中砂	粗砂	砾石	卵石	漂石
	Loam	Sandy loam	Silt	F. sand	M. sand	C. sand	Pebbles	Cobbles	Boulder
D(mm)				0.1~0.25	0.25~0.5	0.5~2	2~20	20~60	>60
K(m/d)	0.001~0.10	0.10~0.50	0.5~1.0	1.0~5.0	5.0~20	20~50	50~150	150~500	

4.1 重力水运动的基本规律

$$K = k\frac{\rho g}{\mu} = k\frac{g}{\upsilon}$$

μ = dynamic viscosiy

ν = kinematic viscosity

PERMEABILITY, k (dims. L^2), depends **only** on void space configuration.

UNITS for HYDRAULIC CONDUCTIVITY:

m/d, cm/s, ft/d, gal/d-ft^2, (SI: m/s)

UNITS for PERMEABILITY:

m^2, cm^2, ft^2, (SI: m^2)

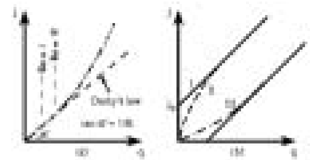
4.1 重力水运动的基本规律

Changes of permeability with time, due to

- Compaction by external load.
- Dissolution of solid.
- Precipitation.
- Clogging by fines,
- Biological activities...
- Shrinkage of clay soil.

RANGE OF VALIDITY OF DARCY's LAW

Experiments:



4.1 重力水运动的基本规律

In petroleum Engineering:

$$1\,\text{darcy} = \frac{1\,\text{cm}^3/\text{s}/\text{cm}^2 \times 1\,\text{centipoise}}{1\,\text{atmosphere}}$$

$$Q = \frac{k\rho g}{\mu}\frac{\Delta h}{L}$$

FORMULAE FOR PERMEABILITY:
Empirical and semi-empirical formulae:

$$k = Cd^2$$ (and many other formulae)

C = dimensionless coefficient.
d = effective grain diameter, say d_{10}.

4.1 重力水运动的基本规律

By analogy, for flow through porous media:

$$\text{Re} = \frac{qd}{\upsilon},$$

Where d = some representative (microscopic) length characterizing void space, e.g. d_{10}.
ν = kinematic viscosity of fluid.

Helps to distinguish between LAMINAR FLOW, at low Re and turbulent flow at higher Re.
Darcy's law is valid as long as the Re, that indicates the magnitude of the inertial forces relative to the viscous drag ones, does not exceed a value of about 1 (but sometimes as high as 10): Re=1~10.

4.2 流 网

流网（flow net）是指在渗流场的某一典型剖面或切面上由一系列等水头线和流线所组成的网络。

Flow net is the set of intersecting equipotential lines and flowlines representing two-dimensional steady flow through porous media. HG

流线（flow line, stream line）是渗流场中某一瞬时的一条线，线上各个水质点在此时刻的流向均与此线相切。

A streamline is a curve that is everywhere tangent to the specific discharge vector. Streamlines indicate the direction of flow at every point in a flow domain.

迹线（path line）是渗流场中某一时间段内某一水质点的运动轨迹。

流线可看作水质点运动的摄影，迹线则是对水质点运动所拍的电影。在稳定流条件下，两者重合。

4.2 流 网

4.2.1 均质各向同性介质中的流网

均质(homogeneity)，非均质(inhomogeneity)，各向同性(isotropy)，各向异性(anisotropy)。

均质岩层(Homogeneous strata)渗流场中所有点都具有相同参数（K）的岩层。

非均质岩层(inhomogeneous strata)渗流场中所有点不都具有相同参数的岩层，渗透系数K=K(x,y,z)，为坐标的函数。

各向同性岩层(Isotropic strata)渗流场中某一点的渗透系数不取决于方向，即不管渗流方向如何都具有相同渗透系数的岩层。

各向异性岩层(anisotropic strata)渗流场中某一点的渗透系数取决于方向，渗透系数随渗流方向不同而不同的岩层。

4.2 流 网

4.2.1 均质各向同性介质中的流网

边界(boundary)：定水头边界、隔水边界、地下水面边界。

河渠的湿周为等水头线。平行隔水边界为流线，地下水面无补排时为流线。流线由源指向汇。

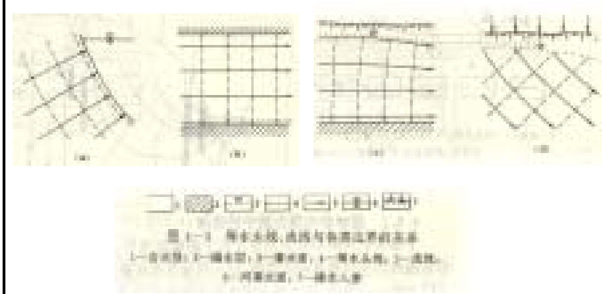
均质各向同性介质中，流线与等水头线构成正交网格。

流网绘制方法：绘制流网时，(1) 先绘制易确定的等水头线、流线，(2) 等水头线与流线正交，插补其余的流线、等水头线。

流网的作用：(1) 分析渗流场的水流特征。(2) 追踪污染物质的运移。

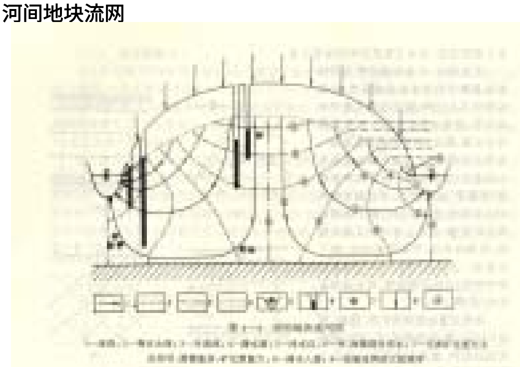
4.2 流 网

等水头线、流线与各类边界的关系



4.2 流 网

河间地块流网



4.2 流 网

4.2.2 层状非均质介质中的流网

层状非均质介质是指介质场内各岩层内部渗透性为均质各向同性，但不同层介质的渗透性不同。

水流折射定律(Refraction law)：

$$\frac{K_1}{K_2} = \frac{\tan\theta_1}{\tan\theta_2}$$

式中K_1-----地下水流入岩层（K_1层）的渗透系数(m/d)；

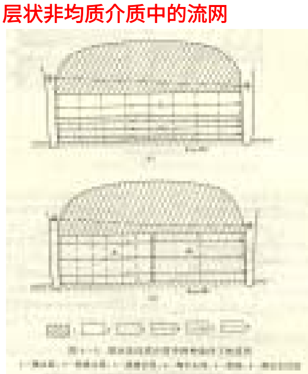
K_2-----地下水流出岩层（K_2层）的渗透系数(m/d)；

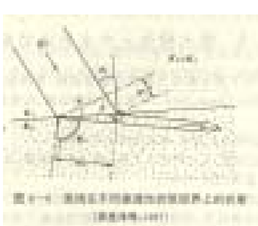
θ_1-----地下水流向与流入岩层（K_1层）层界法线之间的夹角(°)；

θ_1-----地下水流向与流出岩层（K_2层）层界法线之间的夹角(°)。

4.2 流 网

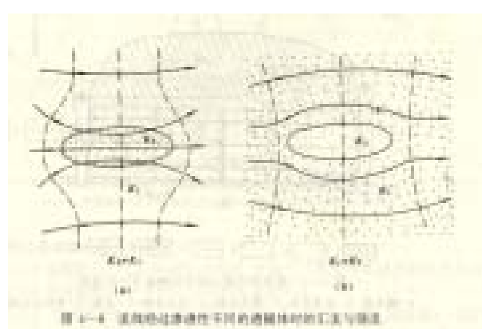
层状非均质介质中的流网





4.2 流 网

渗透性不同的介质中的流网



4.3 饱和粘性土中水的流动

粘性土的渗透流速V与水力梯度I之间有三种关系。

（1）V-I关系为通过原点的直线，服从达西定律。

（2）V-I关系为不通过原点，水力梯度小于某一值I_0时无渗透；大于I_0时，起初为一向I轴凸出的曲线，然后转为直线。

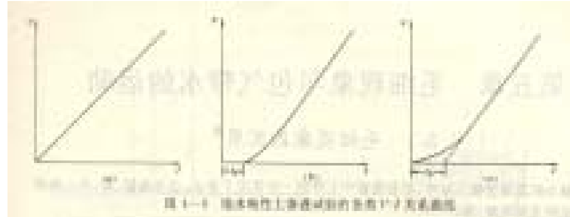
（3）V-I曲线为通过原点的曲线，I小时曲线向I轴凸出，I大时为直线。

偏离达西定律的试验结果可用来分析结合水的运动规律，I小时，结合水也会运动，但此时V很小。I_0称为初始水力梯度。V-I曲线的直线部分可用罗查（1950）公式表示：$V=K(I-I_0)$

结合水是一种非牛顿流体，是性质介于固体与液体之间的异常液体，外力必须克服其抗剪强度方能使其流动。

4.3 饱和粘性土中水的流动

粘性土的渗透流速V与水力梯度I之间有三种关系。



思考题

1.什么是线性渗透规律？公式及各项符号的意义是什么？

2.渗透系数的影响因素有哪些？

3.流网有哪些用途？

4.与饱水带相比，包气带中水的运动特点是什么？