

Figure 2.1 Experimental apparatus for the illustration of Darcy's law.

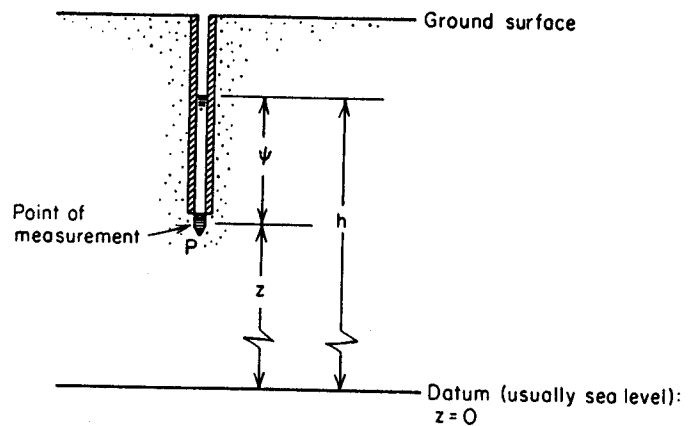


Figure 2.5 Hydraulic head  $h$ , pressure head  $\psi$ , and elevation head  $z$  for a field piezometer.

Since  $z + h_p = h$ , the hydraulic head

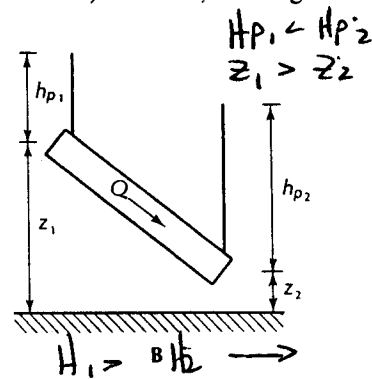
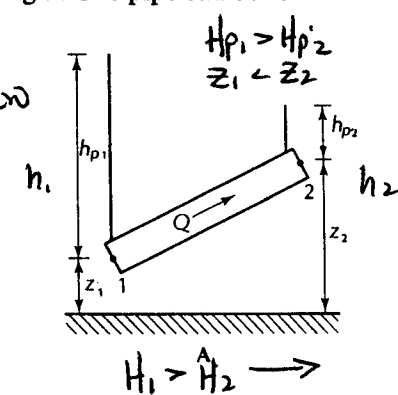
$$\Phi = gh \quad (5-17)$$

The force potential is the driving impetus behind ground-water flow and is equal to the product of hydraulic head and the acceleration of gravity. Both force potential and hydraulic head are potentials. Hydraulic head is energy per unit weight and force potential is energy per unit mass.

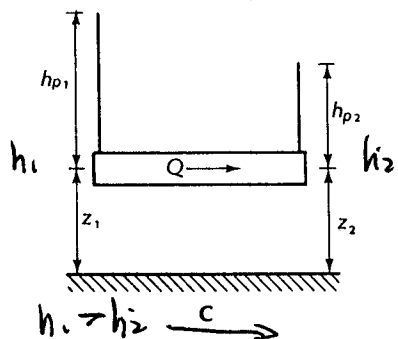
Figure 5.5 shows a pipe filled with sand with water flowing through it from left to right. The pipe can be rotated to any inclination, with the discharge of water

$Q =$  DISCHARGE  
 $\rightarrow$  FLOW DIRECTION

UNSATURATED BED



$h_{p1} > h_{p2}$   
 $z_1 = z_2$



$h_{p1} = h_{p2}$   
 $z_1 > z_2$

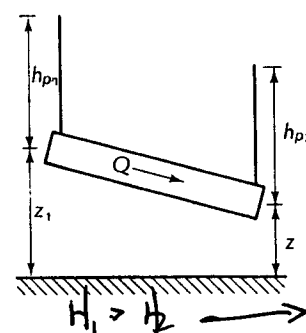


FIGURE 5.5 Apparatus to demonstrate how changing the slope of a pipe packed with sand will change the components of elevation,  $z$ , and pressure,  $h_p$ , heads. The direction of flow,  $Q$ , is indicated by the arrow. IN ALL CASES Flow from High  $h$  to Low  $h$ .

**EXAMPLE  
PROBLEM**

The following data were collected at a nest of piezometers (several piezometers of different depths located within a few feet (1 to 2 m) of each other):

	A	B	C
Elevation at surface (m a.s.l.)	225	225	225
Depth of piezometer (m)	150	100	75
Depth to water (m below surface)	80	77	60

**Part A:** What is the hydraulic head at each of A, B, and C?

Hydraulic head is elevation of the water in the piezometer. It is found by subtracting the depth to water from the surface elevation.

A: 145 m    B: 148 m    C: 165 m

**Part B:** What is the pressure head at each of A, B, and C?

Pressure head is the height of the water in the wall above the depth of the piezometer. It is found by subtracting the depth to water from the depth of the piezometer from the surface.

A: 70 m    B: 33 m    C: 15 m

**Part C:** What is the elevation head in each well?

Elevation head is the height of the measuring point above the datum. In this case the datum is mean sea level and the elevation head is found by subtracting the depth of the piezometer from the surface elevation.

A: 75 m    B: 125 m    C: 150 m

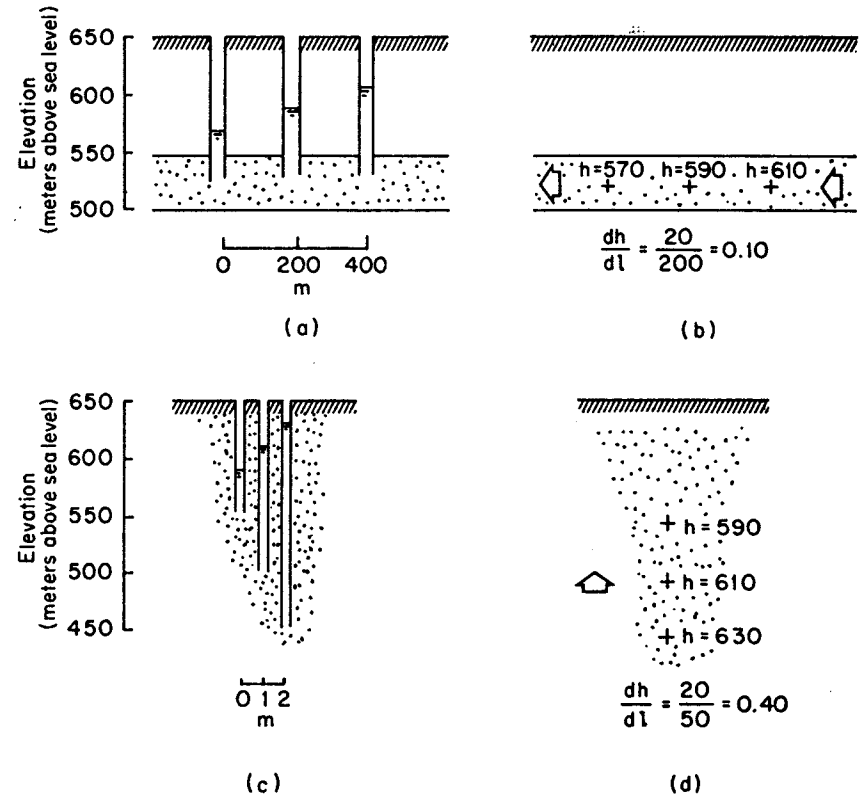
Notice that the total head found in part A is the sum of the pressure head found in part B and the elevation head found in part C.

**Part D:** What is the vertical hydraulic gradient between the piezometers?

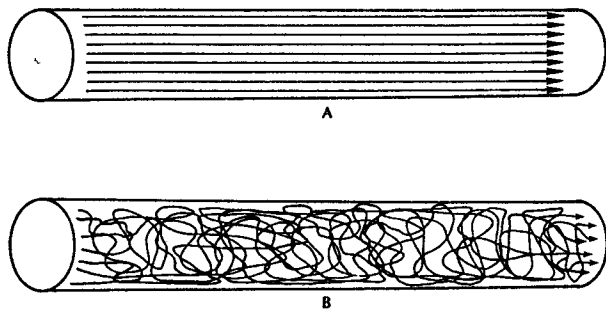
The hydraulic gradient is the difference in total head divided by the vertical distance between the two piezometers.

From piezometer A to piezometer B the difference in the total head is 148 m - 145 m and the vertical distance is 50 m. The hydraulic gradient is (3 m)/(50 m), or 0.06, and the direction is downward as the head in B, the shallower piezometer, is greater.

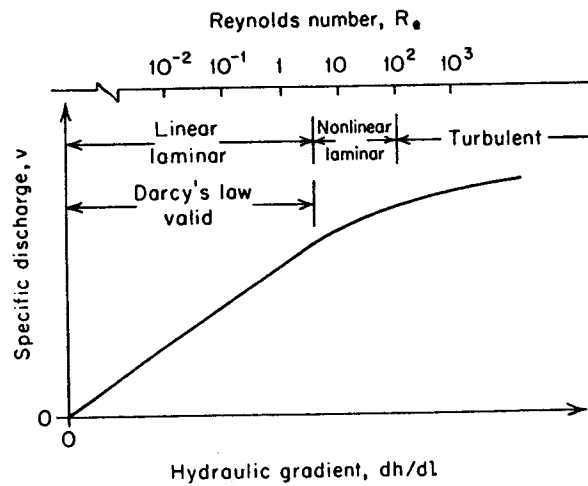
From piezometer B to piezometer C the difference in total head is 165 m - 148 m and the vertical distance is 25 m. The hydraulic gradient is (17 m)/(25 m) or 0.68. This gradient is also downward.



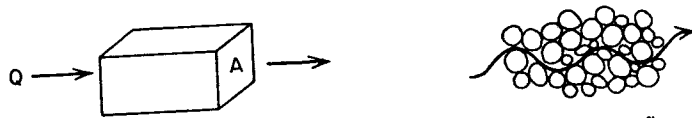
**Figure 2.6** Determination of hydraulic gradients from piezometer installations.



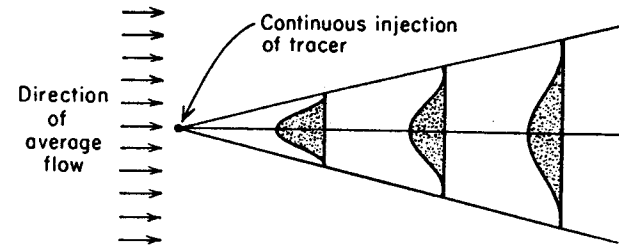
**FIGURE 5.6** A. Flow paths of molecules of water in laminar flow. B. Flow paths of molecules of water in turbulent flow.



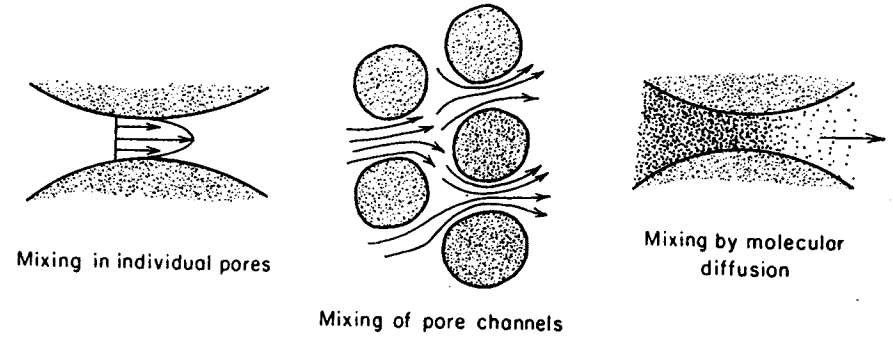
**Figure 2.28** Range of validity of Darcy's law.



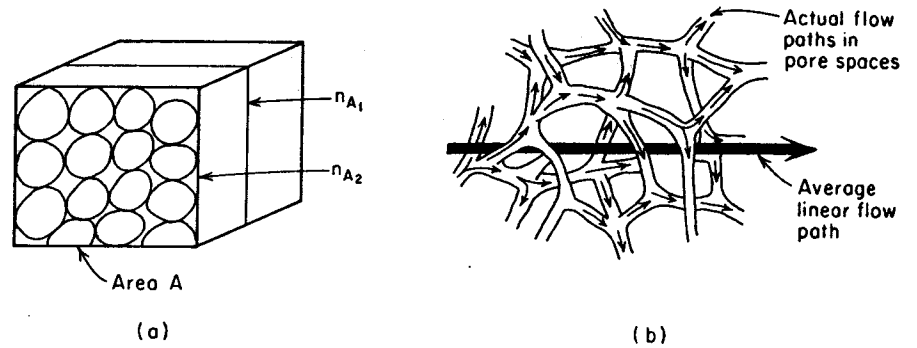
**Figure 2.2** Macroscopic and microscopic concepts of groundwater flow.



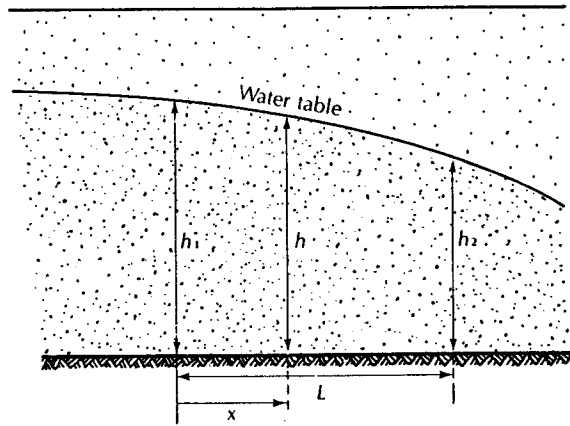
**Figure 2.29** Schematic representation of the dilution process caused by mechanical dispersion in granular porous media.



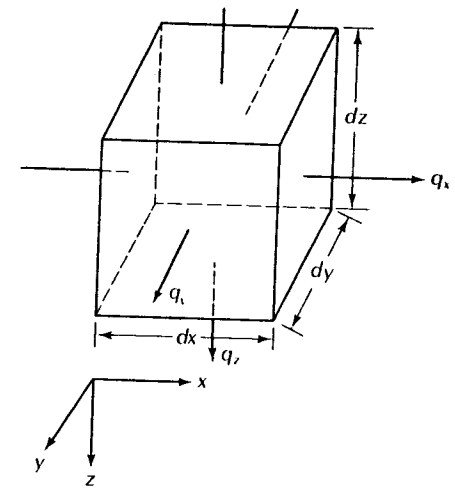
**Figure 2.30** Processes of dispersion on a microscopic scale.



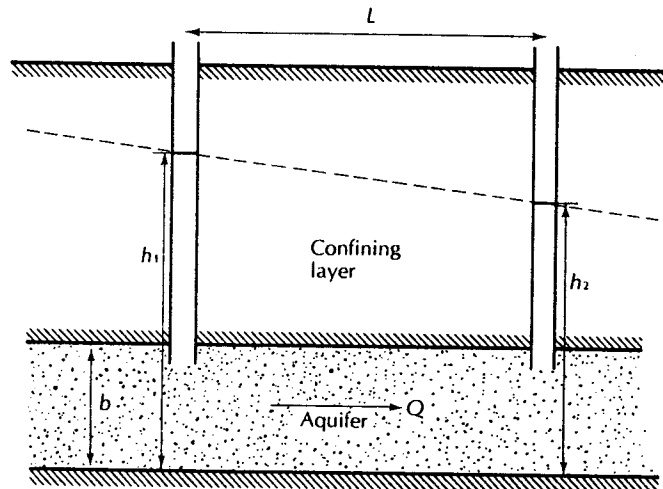
**Figure 2.27** Concepts of (a) areal porosity and (b) average linear velocity.



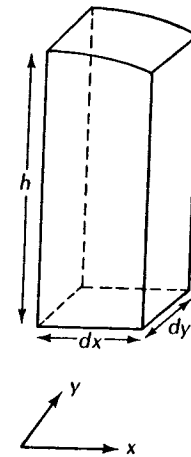
**FIGURE 5.17** Steady flow through an unconfined aquifer resting on a horizontal impervious surface.



**FIGURE 5.7** Control volume for flow through a confined aquifer.



**FIGURE 5.16** Steady flow through a confined aquifer of uniform thickness.



**FIGURE 5.18** Control volume for flow through a prism of an unconfined aquifer with the bottom resting on a horizontal impervious surface and the top coinciding with the water table.

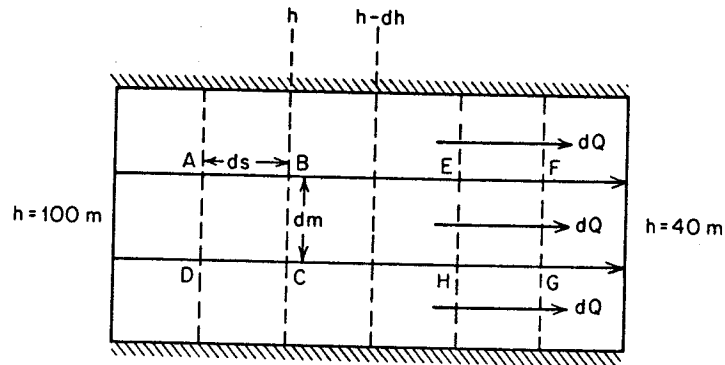


Figure 5.2 Quantitative flow net for a very simple flow system.

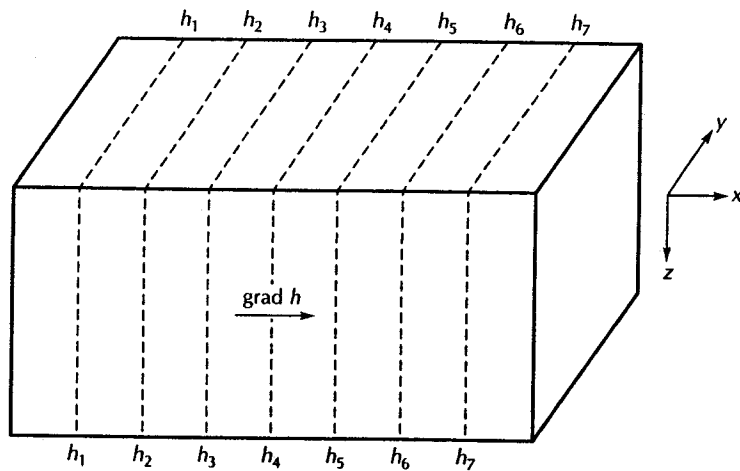


FIGURE 5.8. Equipotential lines in a three-dimensional flow field and the gradient of  $h$ .

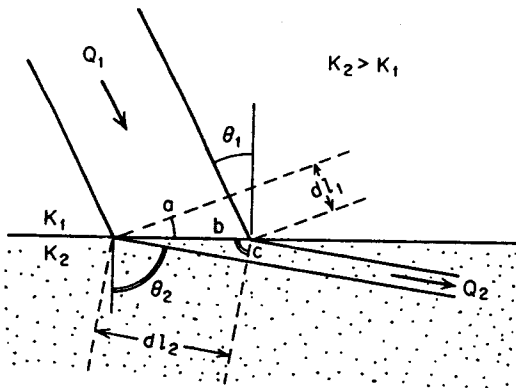


Figure 5.4 Refraction of flowlines at a geologic boundary.

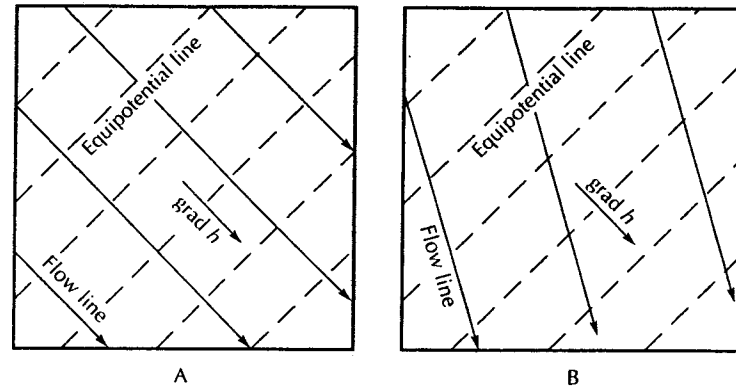


FIGURE 5.10 Relationship of flow lines to equipotential field and  $\text{grad } h$ . A. Isotropic aquifer. B. Anisotropic aquifer.

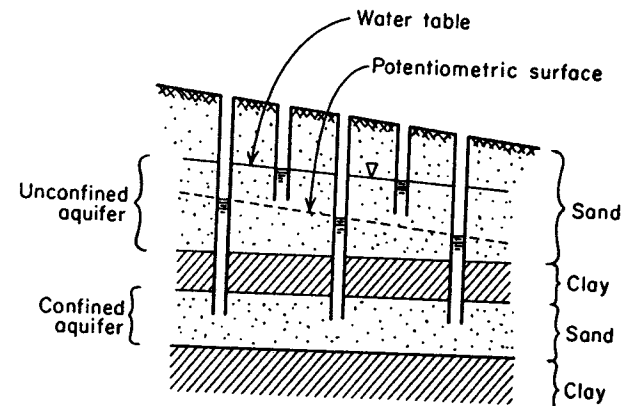


Figure 2.16 Unconfined aquifer and its water table; confined aquifer and its potentiometric surface.

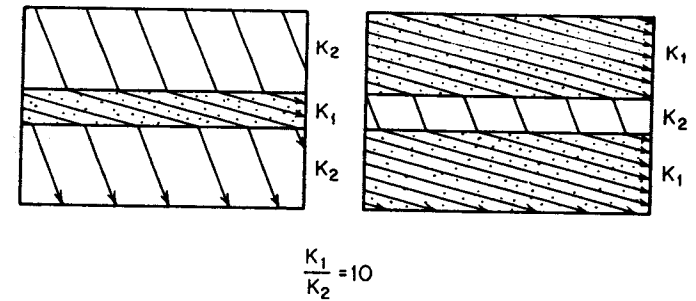
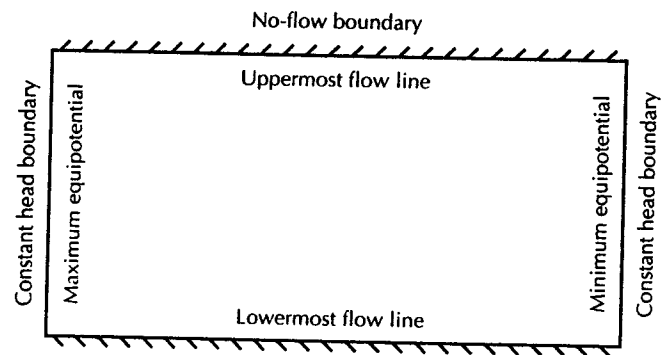
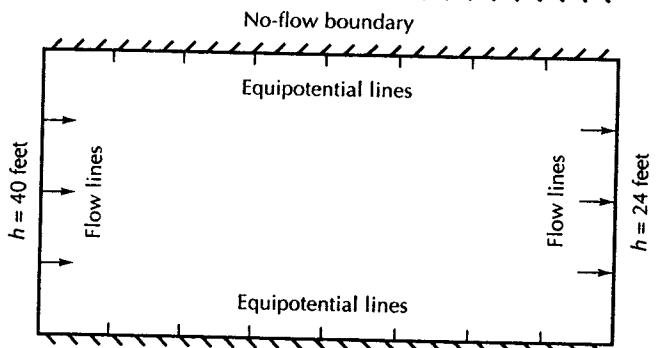


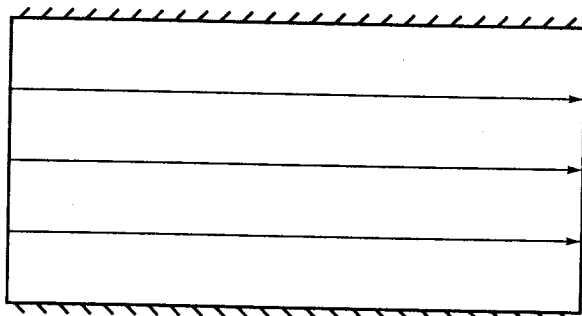
Figure 5.5 Refraction of flowlines in layered systems (after Hubbert, 1940).



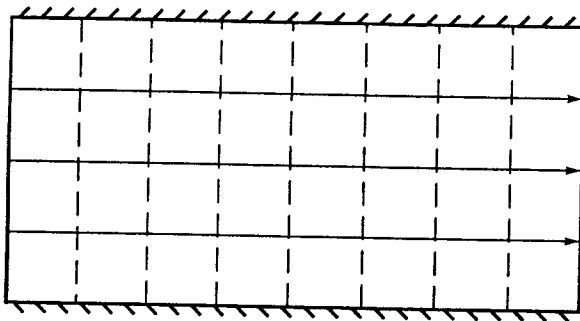
Step 1—Sketch the flow system and identify prefixed flow lines and equipotential lines.



Step 2—Identify prefixed end positions of flow lines and equipotential lines.



Step 3—Draw trial set of flow lines.



Step 4—Draw trial set of equipotential lines orthogonal to flow lines.

FIGURE 5.11 Steps in making a flow net.

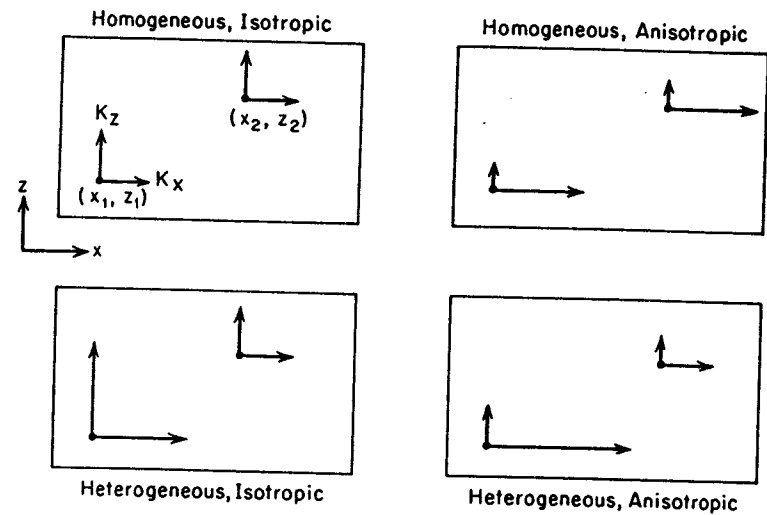


Figure 2.8 Four possible combinations of heterogeneity and anisotropy.

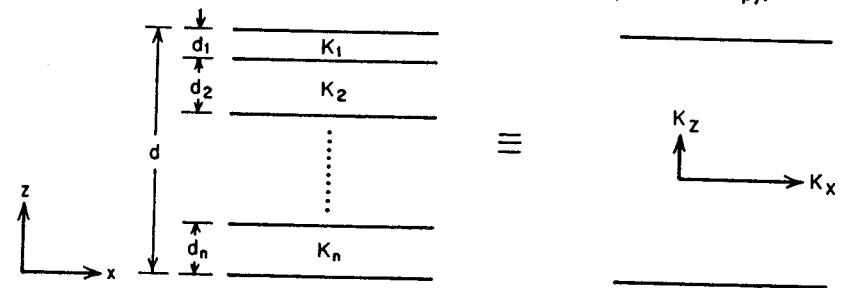


Figure 2.9 Relation between layered heterogeneity and anisotropy.