Groundwater Hydrology

SECOND EDITION

David Keith Todd
UNIVERSITY OF CALIFORNIA, BERKELEY
and
DAVID KEITH TODD,
CONSULTING ENGINEERS, INC.

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Note that the tabulated values cover the following conditions below the hole: a shallow impermeable layer, an infinite homogeneous stratum, and a shallow, highly permeable (gravel) layer. The value y should correspond to that when dy/dt is measured.

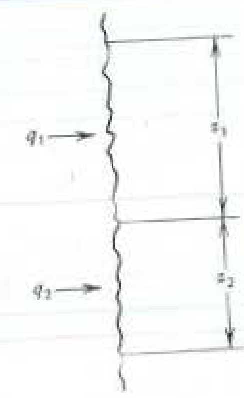
Several other techniques similar to the auger hole test have been developed in which water level changes are measured after an essentially instantaneous removal or addition of a volume of water. With a small-diameter pipe driven into the ground, K can be found by the piezometer, or tube, method.[65] For wells in confined aquifers, the slug method can be employed.[12,41] Here a known volume of water is suddenly injected or removed from a well after which the decline or recovery of the water level is measured in the ensuing minutes. Where a pump is not available to conduct a pumping test on a well, the slug method serves as an alternative approach.

Pumping Tests of Wells. The most reliable method for estimating aquifer hydraulic conductivity is by pumping tests of wells. Based on observations of water levels near pumping wells, an integrated K value over a sizable aquifer section can be obtained. Then, too, because the aquifer is not disturbed, the reliability of such determinations is superior to laboratory methods. Pump test methods and computations are described in Chapter 4.

Anisotropic Aquifers

The discussion of hydraulic conductivity heretofore assumed that the geologic material was homogeneous and isotropic, implying that the value of K was the same in all directions. In fact, however, this is rarely the case, particularly for undisturbed unconsolidated alluvial materials. Instead, *anisotropy* is the rule where directional properties of hydraulic conductivity exist. In alluvium this results from two conditions. One is that individual particles are seldom spherical so that when deposited underwater they tend to rest with their flat sides down. The second is that alluvium typically consists of layers of different materials, each possessing a unique value of K. If the layers are horizontal, any single layer with a relatively low hydraulic conductivity causes vertical flow to be retarded, but horizontal flow can occur easily through any stratum of relatively high hydraulic conductivity. Thus, the typical field situation in alluvial deposits is to find a hydraulic conductivity K_x in the horizontal direction that will be greater than a value K_z in a vertical direction.

Consider an aquifer consisting of two horizontal layers, each individually isotropic, with different thicknesses and hydraulic con-



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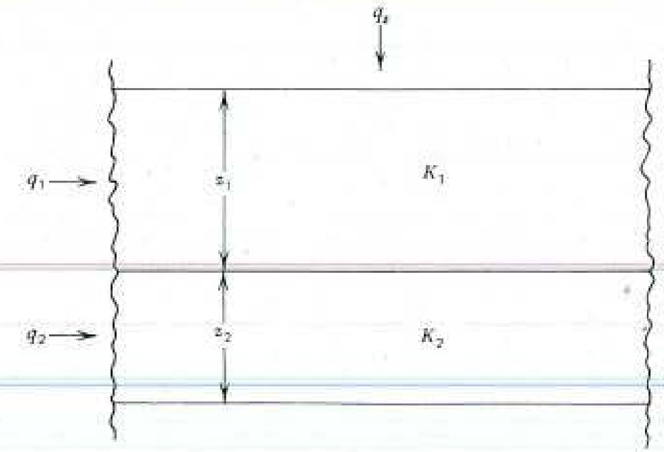

Fig. 3.7 Diagram of two horizontal strata, each isotropic, with different thicknesses and hydraulic conductivities.

ductivities, as shown in Fig. 3.7. For horizontal flow parallel to the layers, the flow q_1 in the upper layer per unit width is

$$q_1 = K_1 i z_1 \tag{3.25}$$

where i is the hydraulic gradient and K_1 and z_1 are as indicated in Fig. 3.7. Because i must be the same in each layer for horizontal flow, if follows that the total horizontal flow q_x is

$$q_x = q_1 + q_2 = i(K_1 z_1 + K_2 z_2) \tag{3.26}$$

For a homogeneous system this would be expressed as

$$q_x = K_x i(z_1 + z_2) \tag{3.27}$$

where K_x is the horizontal hydraulic conductivity for the entire system. Equating these and solving for K_x yields

$$K_x = \frac{K_1 z_1 + K_2 z_2}{z_1 + z_2} \tag{3.28}$$

which can be generalized for n layers as

$$K_x = \frac{K_1 z_1 + K_2 z_2 + \ldots + K_n z_n}{z_1 + z_2 + \ldots + z_n} \tag{3.29}$$

This defines the equivalent horizontal hydraulic conductivity for a stratified material.

Now, for vertical flow through the two layers in Fig. 3.7, the flow q_z per unit horizontal area in the upper layer is

$$q_z = K_1 \frac{dh_1}{z_1} \tag{3.30}$$

where dh_1 is the head loss within the first layer. Solving for the head loss

$$dh_1 = \frac{z_1}{K_1} q_z \tag{3.31}$$

From continuity q_z must be the same for the other layer so that the total head loss

$$dh_1 + dh_2 = \left[\frac{z_1}{K_1} + \frac{z_2}{K_2}\right] q_z \tag{3.32}$$

In a homogeneous system

$$q_z = K_z \left[\frac{dh_1 + dh_2}{z_1 + z_2}\right] \tag{3.33}$$

where K_z is the vertical hydraulic conductivity for the entire system. Rearranging,

$$dh_1 + dh_2 = \left[\frac{z_1 + z_2}{K_z}\right] q_z \tag{3.34}$$

and equating with Eq. 3.32,

$$K_z = \frac{z_1 + z_2}{\dfrac{z_1}{K_1} + \dfrac{z_2}{K_2}} \tag{3.35}$$

which can be generalized for n layers as

$$K_z = \frac{z_1 + z_2 + \ldots + z_n}{\dfrac{z_1}{K_1} + \dfrac{z_2}{K_2} + \ldots + \dfrac{z_n}{K_n}} \tag{3.36}$$

This defines the equivalent vertical hydraulic conductivity for a stratified material.

As mentioned earlier, the horizontal hydraulic conductivity in alluvium is normally greater than that in the vertical direction. This observation also follows from the above derivations; thus, if

$$K_x > K_z \tag{3.37}$$

then for the two-layer case f

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which reduces to[42]

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then for the two-layer case from Eqs. 3.28 and 3.35,

$$\frac{K_1 z_1 + K_2 z_2}{z_1 + z_2} > \frac{z_1 + z_2}{\dfrac{z_1}{K_1} + \dfrac{z_2}{K_2}} \tag{3.38}$$

which reduces to[42]

$$\frac{z_1}{z_2}(K_1 - K_2)^2 > 0 \tag{3.39}$$

Because the left side is always positive, it must be greater than zero, thereby confirming that

$$\frac{K_x}{K_z} \geq 1 \tag{3.40}$$

Ratios of K_x/K_z usually fall in the range of 2 to 10 for alluvium,[45] but values up to 100 or more occur where clay layers are present. For consolidated geologic materials, anisotropic conditions are governed by the orientation of strata, fractures, solution openings, or other structural conditions, which do not necessarily possess a horizontal alignment.

In applying Darcy's law to two-dimensional flow in anisotropic media, the appropriate value of K must be selected for the direction of flow. For directions other than horizontal (K_x) and vertical (K_z), the K value can be obtained from

$$\frac{1}{K_\beta} = \frac{\cos^2\beta}{K_x} + \frac{\sin^2\beta}{K_z} \tag{3.41}$$

where K_β is the hydraulic conductivity in the direction making an angle β with the horizontal.

Groundwater Flow Rates

From Darcy's law it follows that the rate of groundwater movement is governed by the hydraulic conductivity of an aquifer and the hydraulic gradient. To obtain an idea of the order of magnitude of natural velocities, assume a productive alluvial aquifer with $K = 75$ m/day and a hydraulic gradient $i = 10$ m/1000 m $= 0.01$. Then from Eq. 3.5

$$v = Ki = 75(0.01) = 0.75 \text{ m/day} \tag{3.42}$$

This is approximately equivalent to 0.5 mm/min, which demonstrates the sluggish nature of natural groundwater movement.