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GROUNDWATER HYDROLOGY

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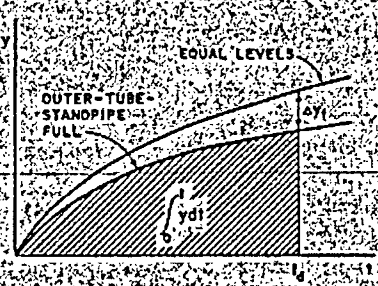

Figure 5.18 Curves of water-level drop versus time in standpipe on inner tube when water level in outer-tube standpipe was held at top of pipe (lower curve) and when allowed to fall at same rate as water level in inner-tube standpipe (upper curve).

measurements (equal levels in standpipes) will be above that for the first set (outer-tube standpipe kept full), as shown in Figure 5.18. The K value is calculated from these curves as

$$K = \frac{r_r^2}{F_f r_c} \frac{\Delta y_t}{\int_0^t y\, dt} \qquad (5.48)$$

where r_r = radius of standpipe on inner tube
r_c = radius of inner tube
Δy_t = vertical difference between curves in Figure 5.18 at time t_d
F_f = dimensionless factor
$\int_0^t y\, dt$ = area under lower y-vs.-t curve between $t = 0$ and $t = t_d$

The time t_d for which Δy_t is read from the graph and for which the area under the lower curve is evaluated should be selected as small as possible while still yielding a sufficiently accurate value of Δy_t. The factor F_f is dependent on the geometry of the system, and it was evaluated with a resistance network analog as a function of r_c/d (Figure 5.19), where d is the penetration of the inner tube into the hole bottom. The curve in this figure applies to soil that is uniform to great depth,

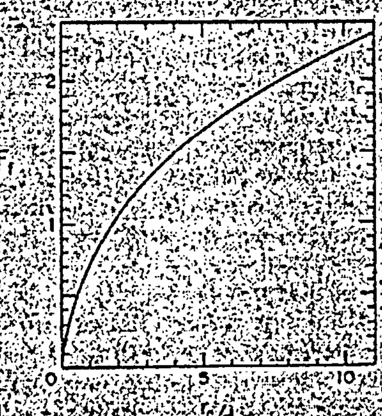

Figure 5.19 Plot of F_f in relation to r_c/d for double-tube method if soil is uniform to a depth of at least $2r_c$ below hole bottom.

which in practice means a depth of at least $2r_c$ below the hole bottom. Values of F_f were also determined for the case where impermeable or infinitely permeable material occurs at depths less than $2r_c$ below the hole bottom (Bouwer, 1961; Bouwer and Jackson, 1974). A simplified procedure for calculating K, based on replacing the y-vs.-t curves as in Figure 5.18 by straight lines to eliminate the integral, was developed by Bouwer and Rice (1964).

The K value obtained with the double-tube method is affected by K in both horizontal and vertical direction, but it is closest to K in vertical direction. The soil region sampled for K is approximately a cylinder with a radius somewhat larger than r_c and a height of about $2r_c$. Tests usually take 3 to 6 h to complete, and several hundred liters of water may be required per test.

5.5.4 Well Pump-in Technique

With the well pump-in technique, which is also called the *reverse auger-hole* method, a well or auger hole is dug and filled with water to a certain depth L_w, which should not be less than 10 times the hole radius r_w (Figure 5.20). Water is added to the hole to maintain this water depth until the outflow Q from the hole into the soil has become essentially constant. If the depth S_i of the impermeable layer below the hole bottom is greater than $2L_w$, K of the wetted zone can be calculated as

$$K = \frac{Q}{2\pi L_w^2}\left\{\ln\left[\frac{L_w}{r_w} + \sqrt{\left(\frac{L_w^2}{r_w^2} - 1\right)}\right] - 1\right\} \qquad (5.49)$$

If $S_i < 2L_w$, the equation for K is

$$K = \frac{3Q \ln \dfrac{L_w}{r_w}}{\pi L_w (3L_w + 2S_i)} \qquad (5.50)$$

These equations were developed by Zangar (Bouwer and Jackson, 1974, and references therein).

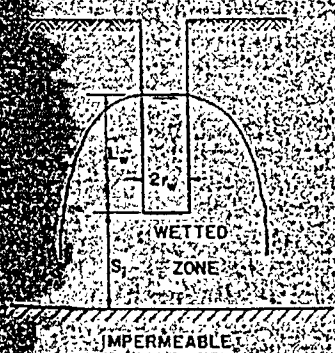

Figure 5.20 Schematic of well pump-in method.

The value of K obtained with the well pump-in technique mostly reflects K in horizontal direction. Sealing and other disturbances of the soil at the hole wall may cause underestimation of the true K value. The volume of the soil region sampled for K is approximately the same as that for the auger-hole method, i.e., about $0.4L^3$. Water may have to be added to the hole for several days before Q approaches a constant value. The water requirements are about 1 m³ per test. Lining the hole with perforated casing or filling it with gravel may be necessary in unstable soils. The method can be used in gravelly or stony materials, which normally is not possible for the other techniques for measuring K in the absence of a water table.

5.6 MEASURING ANISOTROPY OF SOILS AND AQUIFERS

Anisotropy of subsurface material can be evaluated by combining techniques that measure K in different directions. In isotropic soils, these methods theoretically yield the same K value. Different K values indicate anisotropy, provided of course that the soil is otherwise homogeneous. To minimize the effect of local nonuniformities, the different techniques should measure K on essentially the same body of soil or aquifer material, so that the predominant flow direction is the only factor that is different.

Measurements of K in predominantly vertical and horizontal directions can be obtained with the piezometer method by first using a cavity of zero height and then deepening the cavity to a depth of about 4 or 5 times the cavity diameter below the piezometer tube (Maasland, 1957). Talsma (1960), however, found that the hydraulic conductivity K_z in a vertical direction showed much greater variation with depth than the hydraulic conductivity K_x in a horizontal direction. Thus, increasing the height of the piezometer cavity could yield a different K value merely by including soil with different K_z values in the flow system around the cavity. This would lead to erroneous conclusions regarding anisotropy.

Measurement of K in different directions but on essentially the same soil region can be accomplished by first measuring K with the double-tube method (yielding a value affected by both K_z and K_x) and then measuring K_z of the same soil by applying the infiltration-gradient technique to the same installation. Based on the theory of flow in anisotropic media, K_x can then be calculated (Bouwer, 1964; Bouwer and Rice, 1967).

Anisotropy in the horizontal plane can be evaluated with the two-well method, which measures mostly K_x in the direction of the line connecting the wells. If a well or auger hole is dug on each corner of a square, K_x in two mutually perpendicular directions can be evaluated by applying the two-well method in succession to each pair of diagonally opposite holes. Estimates of three-dimensional anisotropy can then be obtained by measuring K_z in the same area with, for example, the infiltration-gradient method.

The above methods give directional K values for relatively small volumes of soil or aquifer material ("point" measurements) and at relatively small depths. To obtain K in different directions for aquifers as a whole, some of the recent refinements in analyzing pumping-test data could be used (see references in Section 5.2.6). Other techniques include simulating certain flow systems in a model and varying K_z and K_x in the model until the simulated system produces the same cause-and-effect relations as observed for the actual system. This technique was employed by Bouwer (1970) to evaluate K_z and K_x of an unconfined aquifer from the response of the water levels in two piezometers to infiltration from groundwater recharge basins. Stallman (1963) developed a procedure, based on electric analog analyses, to determine anisotropy of unconfined aquifers from drawdown measurements at five points. Weeks (1969) evaluated K_z and K_x from drawdown measurements around a pumped well in a glacial-outwash aquifer.

5.7 CORE SAMPLING AND PERMEAMETER TECHNIQUE

The oldest technique for measuring K of subsurface materials is to collect a sample, place it in a cylinder or "permeameter" in the laboratory (Klute, 1965; Reeve, 1957), let water flow through the cylinder, and calculate K with Darcy's equation from the observed flow rate and head loss across the sample (see Section 3.2). Needless to say, this disturbed-sample permeameter technique yielded reliable results only for uniform sands or other coarse materials consisting of relatively round particles. Better results are obtained with an "undisturbed" sample, collected by pushing, driving, or drilling (for rock) a metal cylinder into the material (Campbell and Lehr, 1974; Reeve, 1957; see also Section 6.2.2). The cylinder with the sample inside is then taken to the laboratory for determination of K with the permeameter principle. Disadvantages of the technique are disturbance of the material (truly undisturbed samples of unconsolidated materials are almost impossible to obtain, no matter how sophisticated the core sampling technique is), the small size of the sample (the diameter is usually 5 to 10 cm and the height 5 to 50 cm), and the possibility of leakage flow between the sample and the cylinder wall. Core samples are usually taken in vertical bore holes so that the technique yields K_z. Horizontal samples for measuring K_x can be obtained by pushing the sampler horizontally into walls of pits, trenches, etc.

5.8 PLANNING AND INTERPRETING HYDRAULIC-CONDUCTIVITY MEASUREMENTS

Careful planning of hydraulic-conductivity measurements and rational interpretation of the results are needed where the similar-flow-system approach is not possible and "point" measurement techniques must be resorted to. Because of the heterogeneity of soils and aquifers, the locations and depths of K measurements and the number of replications must be carefully selected. This requires detailed knowledge of the various soils, soil layers, and stratigraphy of the area so that each layer or soil type will be adequately covered by the measurements.