CHAPTER 4

PRINCIPLES OF SOIL DRAINAGE

4-1. Flow of water through soils. The flow of water through soils is estimated by Darcy's Law which can be expressed as

$$Q = kiAt$$

where:

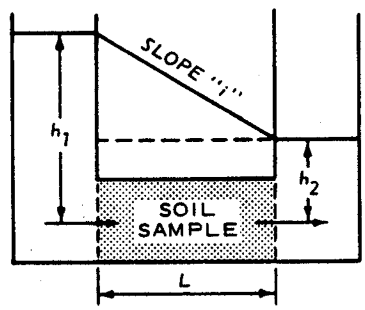
Q = Quantity of seepage
k = Coefficient of permeability
$i = \frac{h_i - h_2}{L}$ (see figure 4-1) = hydraulic gradient
(k x i = discharge velocity)
A = cross-sectional area of sample
t = time

The meaning of Darcy's Law is simply illustrated in figure 4-1. The velocity of flow and the quantity of discharge through a porous media are directly proportional to the hydraulic gradient. For this condition to be true, flow must be laminar or nonturbulent. In most soils, the permeability varies depending on the direction in which the water is moving. The permeability in the direction parallel to the bedding plane or planes of stratification can be several times that in the direction perpendicular to the bedding. In soil deposits with erratic lenses of either coarse, pervious materials or fine, impervious materials, the permeability varies greatly from point to point and is very difficult to determine accurately. The value of permeability which has the units of velocity depends primarily on the characteristics of the permeable materials, but it is also a function of the properties of the fluid. The permeability of a soil can be estimated by the following equation:

$$k = D_s^2 \frac{\gamma}{\mu} \frac{e^3}{(1 + e)} C \qquad \text{(eq 4-1)}$$

where:

k = the coefficient of permeability
D_s = some effective particle diameter
γ = unit weight of water
μ = viscosity of water
e = void ratio
C = shape factor



QUANTITY OF SEEPAGE	$Q = k \times i \times A \times t$
DISCHARGE VELOCITY	$v = k \times i$
HYDRAULIC GRADIENT	$i = \frac{h_1 - h_2}{L}$
CROSS SECTIONAL AREA OF SAMPLE	A
TIME	t
COEFFICIENT OF PERMEABILITY	k

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FIGURE 4-1. DARCY'S LAW FOR FLOW-THROUGH SOILS

This equation aids considerably in the examination of the factors affecting permeability. The following factors influence the permeability of soils.

a. Effect of pore fluid and temperature. The above equation indicates that the permeability is directly proportional to the unit weight of water γ and inversely proportional to the viscosity, μ. Values of γ are essentially constant, but values of μ vary considerably with temperature. The effect of fluid properties on the value of the permeability when other factors are constant is shown in the following equation:

$$k_1 : k_2 = \mu_2 : \mu_1$$

b. Effect of void ratio. The void ratio or porosity of soils, though less important than grain size and soil structure, often has a substantial influence on permeability. The more dense a soil, i.e., the smaller the pores, the lower the soil permeability. From the loosest to the densest condition, permeability may vary 1 to 20 times. As a general rule, the more narrow the range of particle sizes of granular materials, the less the permeability is influenced by density.

c. Effect of average grain size. Equation 4-1 suggests that permeability varies with the square of some particle diameter. It is logical that the smaller the particles, the smaller the voids that constitute the flow channels, and hence the lower the permeability. Also, the shape of the void spaces has a marked influence on the permeability.

d. Effect of structure and stratification. Generally, in situ soils, water deposited soils, and windblown sand and silts present variations in structure and stratification. Therefore, an understanding of the methods of formation of soils aids in evaluating their engineering properties.

e. Effect of discontinuities. The permeability of many formations is established almost entirely by the discontinuities and in such formations tests on individual samples may be very misleading. The presence of holes, fissures, and voids due to frost action, alternate wetting and drying, and the effects of vegetation and small organisms may change even the most impervious clay into a porous material. While this does not affect most problems in the field of earthwork and foundation engineering, it is of importance in soil studies for drainage purposes.

f. Effect of entrapped air in water or voids. Small quantities of entrapped gas have a marked effect on the coefficient of permeability. Therefore, for correct test data the gas content during the tests should be equal to the gas content that occurs in the natural soil or is likely to occur in the future in the natural soil.

g. Effect of saturation. The degree of saturation of a soil has an important influence on its permeability. The higher the degree of saturation, the higher the permeability.

h. Effect of the fine soil fraction. The finer particles in a soil have the most influence on permeability. The coefficient of permeability of sand and gravel materials, graded between limits usually specified for stabilized materials, depends principally upon the percentage by weight of particles passing the No. 100 sieve. The permeability is reduced more than three orders of magnitude as the percentage by weight of fine particles smaller than the No. 100 sieve is varied from 0 to 7 percent.

4-2. Drainage of water from soils. The quantity of water removed by a drain varies depending on the type of soil and location of the drain with respect to the ground water table. All of the water in soil cannot be removed by gravity drainage methods.

a. Effective porosity. The permeability of a specimen gives no indication of the total volume of water that can be drained from the material. Not all of the water contained in a given specimen can be removed by gravity flow since water retained as thin films adhering to the soil particles and held in the voids by capillarity will not drain. Consequently, to determine the volume of water that can be removed from a soil in a given time, the effective porosity (n_e), as well as the permeability, must be known. The effective porosity is defined as the ratio of the volume of the voids that can be drained under gravity flow to the total volume of soil and can be expressed mathematically as in the following equation:

$$n_e = 1 - \frac{\gamma_d}{G_s \gamma_w}(1 + G_s w_e)$$

where:

γ_d = dry density of the specimen
G_s = specific gravity of solids
γ_w = unit weight of water
w_e = effective water content (after the specimen has drained water to a constant weight) expressed as a decimal fraction relative to dry weight

Limited effective porosity test data for well-graded base-course materials, such as bank-run sands and gravels, indicate a value for effective porosity of not more than 0.15. Uniformly graded soils such as medium or coarse sands may have an effective porosity of not more than 0.25.

b. Coefficient of permeability of base and subbase materials. Base and subbase materials used immediately beneath pavements generally consist of sand and gravel, sand, crushed rock, and partially crushed gravel and sand, but may consist of slag, cinders, natural subgrade, etc. In many cases, the base and subbase will consist of several layers, each of different material. The coefficient of permeability of sand and gravel courses, graded between limits usually specified for base and subbase materials, depends principally upon the percentage by weight of sizes passing the No. 200 mesh sieve. The following tabulation may be used for preliminary estimates of average coefficients of permeability for remolded samples of these materials:

Coefficient of permeability for remolded samples

Percent by weight Passing 200-mesh sieve	cm/sec	fpm
3	0.51×10^{-1}	10^{-1}
5	0.51×10^{-2}	10^{-2}
10	0.51×10^{-3}	10^{-3}
15	0.51×10^{-4}	10^{-4}
25	0.51×10^{-5}	10^{-5}

The coefficient of permeability of crushed rock and slag, each without many fines, is generally greater than 0.5 cm/seconds. The coefficient of permeability of sands and sand and gravel mixtures may be approximated from figure 4-2.

c. Horizontal permeability. The coefficient of permeability of a base course in a horizontal direction (parallel to compaction planes) may be 10 times greater than the average value tabulated above. For uniformly graded sand bases, the coefficient of permeability in a horizontal direction may be about 4 times greater than the value determined by tests on remolded samples. Very pervious base materials, such as crushed rock or slag with few fines, have essentially the same permeability in the vertical and horizontal directions. When more than one material is used for the base and subbase, the weighted coefficient of horizontal permeability, determined in accordance with the following equation:

$$k = \frac{k_1 d_1 + k_2 d_2 + k_3 d_3 + \ldots}{d_1 + d_2 + d_3 \ldots}$$

where:

k = weighted coefficient of horizontal permeability
k_1, k_2, k_3 . . . = coefficients of horizontal permeability on individual base materials
d_1, d_2, d_3 . . . = thickness of the individual layers

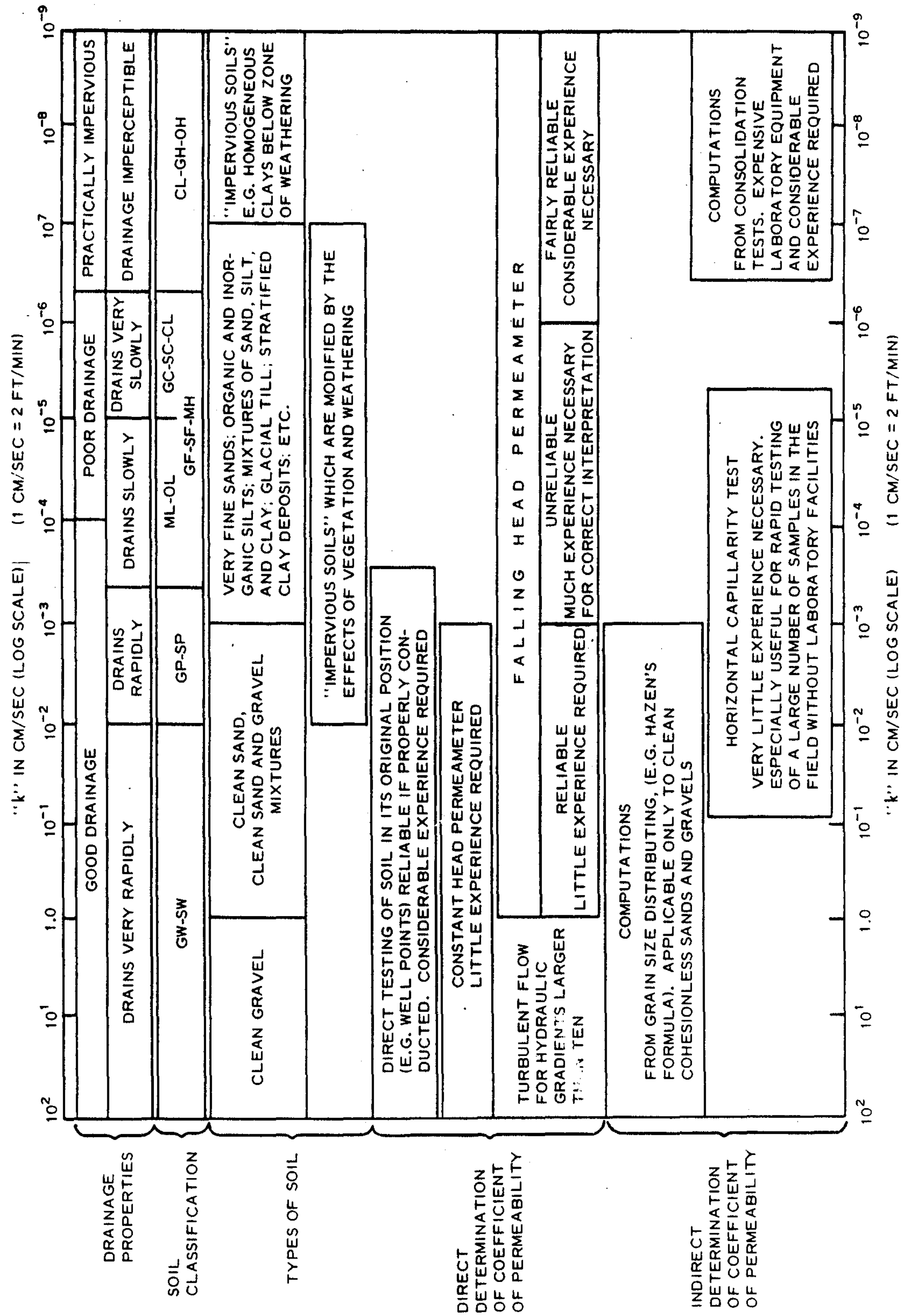

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FIGURE 4-2. PERMEABILITY CHART

d. Time for drainage. It is desirable that the moisture be drained from the base and subbase layers as rapidly as possible. Base- and subbase-course design should be based on the criterion that a degree of drainage of 50 percent in the base course should be obtained in not more than 10 days. Degree of drainage is defined as the ratio, expressed as a percent, of the amount of water drained in a given time to the total amount of water that is possible to drain from the given material. The following equation may be used to determine the time required for a saturated base course to reach a degree of drainage of 50 percent:

$$t = \frac{n_e D^2}{2880\ kH_o}$$

where:

t = time in days for 50 percent drainage
n_e = effective porosity of the soil
k = coefficient of permeability of the soil parallel to direction of seepage flow, fpm
D and H_o = base- and subbase-course geometry dimensions (illustrated in fig 4-3), feet

Since the time required to drain horizontal layers is a function of the square of the length of the flow path, it is important that the flow paths be kept as short as possible.

e. Continuity. If accumulations of water within pavement structural sections and in all parts of the drainage systems are to be prevented, the potential for drainage should increase in the direction of flow from points of entry through base drainage layers and through collector pipes and outlet pipes. This principle, which may be called a condition of continuity, insures the free discharge of water through all component parts of a subsurface drainage system.

f. Drainage boundaries. Pavements are wide flat areas with large flat expanses exposed to surface infiltration. When flow is vertical, as it is through upper surfaces of pavements, the hydraulic gradient is essentially 100 percent or 1.0, and the entire surface area is a potential source of inflow. So, inflow potentials are relatively large. But when flow is horizontal through base courses or drainage layers, the area available to drain the water is quite small and limited to the thickness of the layer, and the hydraulic gradients are limited to small values. As a consequence, to maintain continuity of drainage, basecourse layers need to be considerably more permeable than the surfaces through which water is permitted to enter.

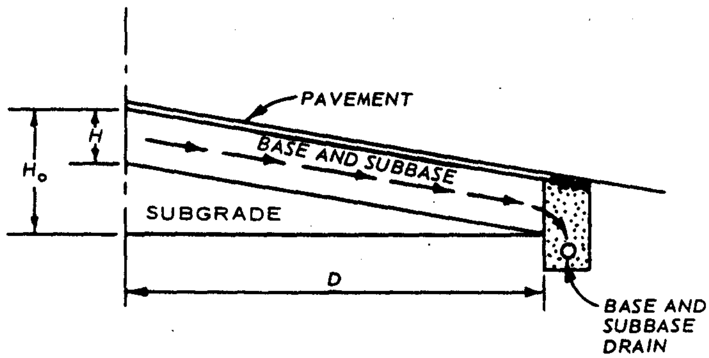

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FIGURE 4-3. DESIGN OF BASE- AND SUBBASE-COURSE DRAINAGE