CHAPTER 3
DETERMINATION OF PERMEABILITY OF ROCK

3-1. Permeabilities of Rock Masses. Permeability of rock, as with soil, is a measure of the ease-with which fluids may travel through a medium under the influence of a driving force. The term "permeability," however, has several definitions for describing the flow of water in rock masses.

a. Coefficient of Permeability. The engineer's coefficient, or Darcy's coefficient, is normally referred to as simply the "coefficient of permeability." It is defined as the discharge velocity through a unit area under a unit hydraulic gradient and is dependent upon the properties of the medium, as well as the viscosity and density of the fluid (Section 2-3.a.).

b. Intrinsic Permeability. The physicist's coefficient, or the intrinsic permeability, is occasionally used in the determination of the hydraulic conductivity of a rock mass. It is defined as the volume of a fluid of unit viscosity passing through a unit cross section of a medium in unit time under the action of a unit pressure gradient (Section 2-3.b.). The intrinsic permeability thus varies with the porosity of the medium and is independent of both the viscosity and the density of the fluid.

c. Equivalent Permeability. The complex system of interconnected void space in a rock mass may be described in terms of an equivalent porous continuum, and the flow assumed to occur uniformly throughout the mass rather than within individual passageways. Under these assumptions the term equivalent permeability is used to describe the permeability of a rock mass.

d. Parallel Plate Permeability. The permeability of a fissure or a fissure set is occasionally determined by modeling the rock mass conditions with parallel plates. The parallel plate permeability can be computed from the value of the aperture between the plates (Ziegler 1976) and this permeability provides inferences for use in the modeled rock mass. The accuracy of computed parallel plate permeabilities has been verified consistently with laboratory tests (Snow 1965).

e. Fissure Permeability. Fissure permability is the permeability of an individual fissure or a set of fissures and, whether measured in the laboratory or in the field, is determined using the parallel plate permeability theory. Fissure permeability is determined using an equivalent parallel plate aperture, rather than the actual fissure aperture. This in effect incorporates roughness into the parallel plate law.

3-2. Flow Characteristics in Rock Masses. The determination of the permeability of a rock mass, whether it be a rock slope, dam foundation, or dam abutment, can only be accomplished after certain criteria are defined or specified.

a. Continuum Approximations. From an overall regional point of view, most rock masses may be treated as continua, for all practical purposes. One of the primary considerations in selecting the continuum approach,-for evaluating the permeability of a rock mass, is the relative size, frequency, and orientation of the inherent discontinuities in the rock mass, compared with the size of the area of interest or area under study. If the flow characteristics of a rock mass are to be treated as those of continua, the net variation in flow over the study area should be relatively small, and the frequency and orientation of the discontinuities should be such that they provide an overall averaging effect on the flow with respect to the area of interest.

b. Discontinuum Approximations. As areas of investigation become smaller and smaller, i.e. more specific, the inherent discontinuities in rock masses start to play larger and larger roles in the interpretation of ground-water flow and its path of movement. The permeabilities or relative permeabilities of individual fissures and fissure systems are important for estimating the amount of seepage into various sections of underground excavations such as powerhouse tunnels or diversions, or through specific strata in a dam foundation or abutment. Discontinuum approximations of permeability are normally used when the flow in the area of investigation is governed either by a single fissure or by a fissure system.

(1) Single Fissure Flow. The permeability of single fissures can be very important in karstic terrains, basalt, or rhyolite flows, or in areas where tunnels are driven through faulted zones. The flow through a single fissure, under certain geologic conditions, can be the key to estimating the seepage through a dam foundation or abutment, or for determining the best route for a proposed tunnel.

(2) Flow Through Fissure Systems. Fissure systems such as joints, fractures, and bedding planes can yield, or contribute to, unpredictable flow paths, seepage patterns, and uplift pressures. The permeability of fissure systems should be evaluated by a discontinuum method of analysis when the size, frequency, and orientation of such systems make a continuum approach to the area under investigation unrealistic.

c. Ground-water Velocity. Flow of water in rock masses is generally considered to be governed by one of two laws. Under conditions of laminar flow, Darcy's law, previously presented as equation 2-1 in Chapter 2 is assumed to govern the flow. For turbulent flow conditions in rock there is a nonlinear flow velocity versus hydraulic gradient relationship and equations presented by Forchheimer (1914) and Missbach (1937) are assumed to govern the flow. The Missbach law is the most convenient to analyze and it takes either of two forms,

$$v^m = k'i \qquad (3\text{-}1)$$

or

$$v = B'i^\alpha \qquad (3\text{-}2)$$

where

m and α = degrees of nonlinearity

k' and B' = turbulent coefficients of permeability

Since the two equations are identical, resolving them indicates that $m = \frac{1}{\alpha}$ and $k' = B'^{1/\alpha}$. The use of the above laws, however, is usually restricted to a homogeneous, isotropic, porous continuum. Since in soil and rock masses there are complex systems of interconnected void spaces, an equivalent rather than an absolute permeability should be determined. The coefficient of equivalent permeability from the continuum approach assumes that flow occurs uniformly throughout the mass rather than within individual passageways. Therefore, for equivalent permeability, Darcy's law and Missbach's law are written, respectively,

$$v = k_e i \tag{3-3}$$

and

$$v^m = k'_e i \tag{3-4}$$

where

k_e = laminar equivalent permeability

k'_e = turbulent equivalent permeability

The continuum approach, in some cases, is not applicable and therefore, the discontinuum method of analysis for evaluating an equivalent permeability should be used. Formulae for the discontinuum analysis for equivalent permeability are presented later with various other methods of analysis.

3-3. <u>Methods for Determining Rock Mass Permeability</u>. Numerous methods have been developed for determining or estimating rock mass permeabilities. All of the available testing, as well as analytical techniques should be considered and evaluated for each individual study, in order to optimize the advantages and minimize the disadvantages inherent within each method for determining the permeability of a rock mass.

a. <u>Laboratory Permeability Tests</u>. Laboratory permeability tests are used for evaluating the permeability of rock cores or samples, determining the flow characteristics of rock fissures, and performing parametric studies of the factors affecting the permeability of rock masses. Laboratory test methods for permeability provide a convenient research and evaluation tool because a variety of parameters may be controlled and varied to yield a broad spectrum of conditions which may be encountered in a rock mass.

(1) Model Tests. Model tests are conducted by constructing parallel plate models to simulate given geologic information. The tests generally tend to be a parametric evaluation, but have been used extensively in evaluating both theoretical and empirical rock mass permeability formulae. To model fissures as equivalent parallel plate conductors, the flow between parallel plates must be defined (Snow 1965 and Wilson and Witherspoon 1970). Laminar flow of an incompressible viscous fluid between smooth, parallel plates can be expressed as

$$v = \frac{\gamma_w}{12\mu_w} d^2 i \qquad (3\text{-}5)$$

where

γ_w = unit weight of water

μ_w = dynamic viscosity of water

d = aperture between smooth parallel plates

The volume flow rate per unit width, q , becomes

$$q = \frac{\gamma_w}{12\mu_w} d^3 i \qquad (3\text{-}6)$$

Comparison of the flow velocity equation with Darcy's law indicates that the parallel plate permeability, k_p , can be expressed by

$$v = k_p i \qquad (3\text{-}7)$$

where $k_p = \dfrac{\gamma_w d^2}{12\mu_w}$.

(2) Individual Fissure Tests. The majority of the laboratory tests which have been conducted, to date, have been on individual fissures. Tests on individual fissures are perhaps the most flexible of the laboratory tests for rock mass permeability. The tests are generally conducted at various flow rates within the individual fissure and at various normal loads to simulate the in situ effective stress flow conditions. The data are used to develop

correlations for predicting the permeability under the anticipated in situ stress and hydraulic gradient conditions. The permeability measured from individual fissures provides direct input into discontinuum analyses and may be applied to continuum analyses under certain conditions. Before fissure permeability, k_j , can be determined, however, the fissure roughness must be incorporated into the equation for the parallel plate permeability, k_p . To accommodate the roughness, the aperture between smooth, parallel plates, d , is replaced with an equivalent parallel plate aperture, e . Thus, the fissure permeability is expressed by

$$v = k_j i \tag{3-8}$$

where $k_j = \gamma_w e^2/12\mu_w$. Thus, it follows that the flow rate per unit width becomes

$$q = \frac{\gamma_w}{12\mu_w} e^3 i \tag{3-9}$$

The value of e can be determined from flow experiments by rearranging the above equation to the form

$$e = \left(\frac{12\mu_w q}{\gamma_w i}\right)^{1/3} \tag{3-10}$$

Values for e are determined from laboratory tests on individual fissures, and equations for the laminar equivalent permeability have been developed yielding

$$k_e = \frac{\gamma_w}{12\mu_w} \frac{\left(e_{avg}\right)^3}{\left(b_{avg}\right)} \tag{3-11}$$

where

e_{avg} = average of individual values of e for fissures in the set under consideration

b_{avg} = average of the individual spacing between fissures

Tests of individual fissures can also be analyzed for turbulent flow according to the Missbach law

$$v^m = k_j' i \tag{3-12}$$

where the volume flow rate per unit width can be expressed as

$$q^m = k_j' e^m i \tag{3-13}$$

The turbulent coefficient of permeability thus given by

$$k_j' = \frac{q^m}{e^m i} \tag{3-14}$$

The degree of nonlinearity, m , is determined as the arithmetic slope of log i versus log q (Ziegler 1976). For turbulent flow analysis the equivalent parallel plate aperture, e , is estimated from analysis of the linear portion of the q versus i curve given by

$$e = \left(\frac{12\mu_w q}{\gamma_w i}\right)^{1/3} \tag{3-15}$$

(3) Representative Sample Tests. Another laboratory approach to measuring permeability is to test a representative sample from a rock mass. The obvious difficulty with such tests, however, is the problem of obtaining a representative specimen of reasonable dimensions. The tests may be conducted as standard laboratory permeability tests, but on a larger scale. In addition to the standard permeability tests, small-scale pressure injection tests may be conducted on such specimens, but only a limited amount of success should be expected.

(4) Evaluation of Methods of Analysis. Model tests, as well as the testing of representative samples, have only limited application and the results are frequently subject to much speculation. Measured fissure permeability and computed equivalent permeability can be directly applied to discontinuum and continuum analyses, respectively. In general, laboratory tests are normally representative of only a very small portion of the rock mass under consideration. In addition, the results of such tests can be altered significantly by either the control or the interpretation of the parameters involved in the test. Laboratory tests, therefore, should be used as a supplement to, rather than in lieu of, field tests.

b. Interpretation from Geologic Properties. Theoretical and empirical formulae have been developed which relate permeability to geologic properties. The parameters generally required for interpretation, or computation, are the average fissure aperture, the average surface roughness of the fissures, and the average fissure spacing or number of fissures per given length. The governing assumption for any interpretation by this method is that the rock mass permeability is controlled by fissures and that the fissures may be modeled as equivalent parallel plate conductors. Extensive borehole logging or observation and mapping of exposed surfaces is required for determining the parameters to be used in the analysis.

(1) Analytical Procedures. If no laboratory tests are performed to determine an equivalent parallel plate aperture, an equivalent permeability can be estimated solely from field data. The requirements are core samples for determining surface roughness of fissures and borehole logging to determine the fissure apertures and spacing. To evaluate the surface roughness of fissures, Louis (1969) defined a surface roughness index, S, as

$$S = \frac{y}{a} \qquad (3\text{-}16)$$

where

y = mean height of the asperities on the fissure walls

a = mean fissure aperture

For $S \leq 0.033$ equations for laminar equivalent permeability have been developed which yield

$$k_e = \frac{\gamma_w}{12\mu_w} \frac{(a_{avg})^3}{(b_{avg})} \qquad (3\text{-}17)$$

where a_{avg} = average of the individual values of a. For $S > 0.033$ equations for the laminar equivalent permeability have been developed which yield

$$k_e = \frac{\gamma_w}{12\mu_w} \frac{1}{\left(1 + 8.8\, S_{avg}^{\;1.5}\right)} \frac{(a_{avg})^3}{(b_{avg})} \qquad (3\text{-}18)$$

where S_{avg} = average of the individual values of S. The above equations generated by Louis (1969) are empirical and are the result of numerous pipe flow experiments and separate tests of fissures with different roughness, modeled as openings between parallel slabs of concrete. In addition to laminar flow formulae, equations may be developed for turbulent flow for both the hydraulically smooth and the completely rough flow regimes.

(2) Evaluation of Method of Analysis. Comparisons of permeability interpreted from geologic properties with permeability measured by other methods have indicated the potential for large differences between the computed and the actual permeability. Interpretations of permeability from fissure properties are made difficult by obvious problems in measuring fissure apertures and roughness.' Natural fissures can have complex surficial geometries and can only be observed in boreholes or exposed surfaces, which may be disturbed during excavation. Potentially large discrepancies are possible, due to the possibility of many fissures near the borehole being either exaggerated, constricted, or discontinuous, due to the disturbance during drilling. While interpretation of permeability from geologic properties is theoretically possible, the results should be used with caution.

c. Field Measurements. By far the most accurate and most reliable technique for determining the permeability of a rock mass is that of field testing. The use of field tests results in larger volumes of the rock mass being tested and the tests are performed under in situ conditions. Field tests have generally been limited to ground-water velocity measurements, pumping tests, and injection tests.

(1) Ground-water Velocity Measurements. The equivalent permeability can be computed for a rock mass by measuring the ground-water velocity and the hydraulic gradient when certain criteria are met. It must be assumed that steady-state horizontal flow intersects the well and flow is governed by Darcy's law. There are several techniques available for measuring ground-water velocity downhole as discussed below.

(a) Temperature Probes. The velocity of ground water moving through a borehole may be determined with the use of temperature probes or sensors. Such devices consist of a small heater strip or coil mounted beneath a thermistor. The amount of heat dissipated is a function of the ground-water velocity, and properly calibrated, the devices can sense very low velocities (below 1 ft/min). The directional components of flow may be obtained by rotation of the device or by the construction of orthogonal flow channels within the device itself.

(b) Flowmeters. When conditions of high ground-water flow rates are encountered, small horizontally mounted commercial flowmeters may be placed downhole for measuring the velocity. The direction of flow may be determined by varying the orientation of the flowmeter.

(c) Tracer Tests. Tracer tests involve the injection of an inert solution, or tracer, into an existing flow field via a borehole or well. Tracer tests are often desirable because they are passive-type tests and do not place unnatural stress conditions on the flow system. The dilution rate of the tracer at the injection well or its time of travel to another well can be used to calculate the ground-water velocity and ultimately the permeability. Detection of the tracer, or concentration measurements, can be made by either manual or probe sampling. Generally, the probe method of sampling is desirable to avoid any disturbance to the flow system due to sample extraction. The "travel time" tracer tests normally involve large portions of the rock mass, and thus have the advantage of averaging the effects of exceptionally high- or low-permeability zones within the mass. The dilution method of testing is particularly applicable to determining permeability profiles within a single borehole by injection of the tracer into borehole sections isolated by packers. Commonly used tracers are radioisotopes, salt solution, and fluorescent dyes.

(d) Methods of Analysis. Downhole ground-water velocity measurement devices such as a temperature probe or flowmeters measure the Darcy velocity or discharge according to his original equation, expressed as

$$v = k_e i \tag{3-19}$$

or

$$v = k_j i \tag{3-20}$$

With the hydraulic gradient determined from observation wells in the area, the permeability can be computed directly. For tracer tests the seepage velocity is determined according to the equation

$$v_s = \frac{d_w}{t_r} \tag{3-21}$$

where

d_w = distance between injection well and observation well

t_r = tracer travel time between wells

Using the relationship

$$v = v_s n \tag{3-22}$$

$$v_s n = k_e i \tag{3-23}$$

$$k_e = \frac{v_s n}{i} = \frac{d_w}{t_r} \frac{n}{i} \tag{3-24}$$

In analyzing a tracer dilution test, the flow velocity, v , is related to the rate at which the tracer concentration diminishes within the test section of the injection well. For an assumed homogeneous isotropic porous medium, the velocity is determined from the following equation given by Lewis, Kriz, and Burgy (1966).

$$v = \frac{\pi w_d \ \ell n \ (C_r)}{8 t_d} \tag{3-25}$$

where

w_d = well diameter

C_r = ratio of the final to the initial tracer concentration

t_d = dilution time period

Analysis of dilution tests in fractured and fissured rock masses is made by applying the parallel plate analogy.

(2) Pumping Tests. Pumping tests have become an established means of determining the permeability of hydraulic characteristics of water bearing materials. In a pumping test, water is pumped from a well normally at a constant rate over a certain time period, and the drawdown of the water table or piezometric head is measured in the well and in piezometers or observation wells in the vicinity. Since pumping tests, as with tracer tests, involve large volumes of the rock mass, they have the advantage of averaging the effects of the inherent discontinuities, such as joints, fissures, fractures, etc. Most classical solutions for pump test data are based on the assumptions that the aquifers are homogeneous and isotropic, and that the flow is governed by Darcy's law. Applications of such solutions to interpretation of pumping tests in rock masses have resulted in varying degrees of success. For cases where the normal solutions have proven to be unsuccessful or inadequate, mathematical models have been developed which are capable of modeling the flow regime in various types of rock masses. With pumping tests, the major disadvantage is the period of time required to perform a test. Test durations of one week or longer are not unusual when attempting to approach steady-state flow conditions. Additionally, large diameter boreholes or wells are required since the majority of the conditions encountered require the use of a downhole pump. The analysis of pumping test results obtained from rock masses is generally completely analogous to the analyses used in classical soil mechanics. Since such analyses are well-documented, they will not be presented here.

(3) Injection Tests. Injection tests, which are the reciprocal of pumping tests, commonly involve the steady-state transmission of a fluid from a borehole into the surrounding medium. The permeability of a rock mass can be related to the relationship between the injection pressure and the flow rate. Equations and techniques have been developed for both the steady-state and the

unsteady-state conditions and for using either air or water for injection. Methods of analysis of pressure injection tests are presented in Appendix C.

(a) Water Pressure Tests. Water pressure tests, also known as packer tests (in Europe they are called Lugeon tests) are normally conducted by pumping water at a constant pressure into a test section of a borehole and measuring the flow rate. Borehole test sections are commonly sealed off by one to four packers, with the use of one or two packers being the most widely used technique. In comparison with a pumping test, a water pressure test affects a relatively small volume of the surrounding medium, because frictional losses in the immediate vicinity of the test section are normally extremely large. The test, however, is rapid and simple to conduct, and by performing tests within intervals along the entire length of a borehole, a permeability profile can be obtained. Additionally, the water pressure test is normally conducted in NX boreholes, and has the advantage of being conducted above or below the ground-water table.

(b) Air Pressure Tests. Air pressure tests are similar to water pressure tests except that air rather than water is used for the testing fluid. The air pressure test was developed for testing above the ground-water table and has predominantly been used for testing areas of high permeability such as those characteristic of rubblelike, fallback material adjacent to explosively excavated craters in rock. In such areas, water pressure tests have been inadequate due to an inability to provide water at a flow rate high enough to pressurize the surrounding media. Air pressure tests have an unlimited supply of testing fluid, as well as the advantage of a wide variety of high capacity air compressors. The disadvantage of such tests is that permeability equations must be modified for application to a compressible fluid and a conversion from the air permeability to a water permeability must be made to obtain usable results.

(c) Pressure Holding Tests. Pressure holding or pressure drop tests are usually conducted in conjunction with water pressure tests. The test is analogous to the falling head test used in soil mechanics; however, in rock the test section is normally pressurized to a value above that of the static head of water between the test zone and the ground surface. The pressures are normally measured in the test section with a transducer, and pressures versus time are recorded. The pressure holding test offers the advantage of being quick and simple to perform, as well as requiring significantly less water than that used in conventional constant pressure tests.

3-4. Applications of Rock Mass Permeability.

a. Assessment of Ground-water Movements. The permeability of a dam's foundation or abutments is one of the controlling factors in the movement of ground water; therefore,. a valid assessment is imperative. The rock mass permeability of the dam foundation or abutment has numerous applications, each having potentially significant impact on the design or safety of the structure.

(1) Seepage Patterns. Seepage patterns which are expected to develop after impoundment of a reservoir should be evaluated during the design phase of

a dam. Seepage patterns which do actually develop after a reservoir is in operation provide valuable data for an evaluation of the as-built performance of any cutoff or relief measures, sources and exits of seepage, and input for planning required remedial measures, such as additional cutoffs, drains, etc. In rock masses, generally, the overall trend of the seepage patterns can be determined by the continuum approach; however, in some cases, a detailed analysis of a specific seepage problem requires the use of a discontinuum approach.

(2) Flow Rates. Given the permeability and gradient, the flow rate across a given area can be computed. With the effective porosity, the rate of advance of a seepage front can be determined. Ground-water flow rates are required for determining construction dewatering requirements for both surface and subsurface excavations, as well as the seepage losses through dam foundations and abutments.

b. <u>Foundation and Abutment Drainage Requirements</u>. The permeability of a dam's foundation and abutments is the major factor involved in evaluating drainage requirements. Accurate and reliable rock mass permeability measurements are required in the design phase for determining the necessity for, and extent of, cutoff, vertical drains, drainage blankets, relief wells, etc. Postconstruction problems with leakage, excessive uplift pressures, etc., also require an in-depth evaluation of the flow of the water in a foundation or abutment. Evaluations of drainage or relief requirements are generally directed toward specific areas and, in most cases, while a continuum approach can give satisfactory approximations, the discontinuum analysis is required for describing the flow characteristics in details.

c. <u>Grouting Requirements and Effectiveness</u>. Consistent with determining the drainage requirements for a structure, the permeability is also useful for estimating the grouting requirements. In the design phase of a dam the requirements for cutoff or grouting, and drainage or relief, compliment each other and are balanced to obtain a desired seepage pattern and uplift pressure distribution beneath or within the structure. In foundations, and particularly in abutments, permeability measurements can indicate possible solution channels, faults, fissures, or other highly permeable zones which require grouting. If permeability tests are conducted at a given location, both before and after a grouting operation, an evaluation of the grouting effectiveness can be made. Such tests should be conducted as a matter of routine since they will either establish a confidence level or indicate the need for additional grouting.

d. <u>General Considerations</u>. The application of rock mass permeability to seepage control methods and evaluations has become increasingly useful as more complex methods of analysis evolve.

(1) Index Tests. The determination of rock mass permeability for dam foundations and abutments has historically been used more as an index test than as an absolute test. As the state of the art advances this trend is gradually changing. While index tests are a valuable tool to the experienced foundation engineer, more complex methods of analysis are becoming available

which allow a complete evaluation of the mechanisms involved as water flows through a fractured or fissured rock mass.

(2) Continuum Analyses. The accuracy of continuum approximations of permeability is dependent upon the geology and the size of the area under consideration. In general, continuum analyses provide average permeabilities or regional permeabilities in which the assumptions of isotropy and homogeneity can be used in a gross sense. From a practical point of view the continuum approach has been and continues to be a useful tool for evaluating rock mass permeability.

(3) Discontinuum Analyses. Recently the discontinuum approach to determining permeability has become more and more promising. As techniques for determining individual fissure permeabilities advance, the availability of better modeling techniques increases, and understanding of the influences of orientation, spacing, apertures, and surficial geometries of fissures and fissure sets increase, the discontinuum approach to determining rock mass permeability becomes more reliable.