RTH 381-80

SUGGESTED METHOD FOR IN SITU DETERMINATION OF ROCK MASS PERMEABILITY USING WATER PRESSURE TESTS

1. Introduction

1.1 The water pressure test consists of the injection of water into a borehole at a constant flow rate and pressure. Water enters the rock mass along the entire length of borehole or along an interval of the borehole (test section) which has been sealed off by one or more packers (Fig. 1). Water pressure tests can be conducted in media above or below the groundwater table and anisotropic permeability can be estimated by orienting test boreholes in different directions. Permeability can be computed by assuming a continuous porous medium, or individual fissures and fissure sets within the rock mass can be considered.

2. Test Procedures and Interpretation

2.1 Test Layout and Setup - In many cases, initial exploration boreholes are routinely pressure tested prior to determining location and orientation of predominant fissure sets. Some boreholes should be specifically located for pressure testing as information concerning fissure networks is obtained. A pressure test affects a region, possibly within only a few feet of the borehole. Consequently, test boreholes should be as closely spaced as practicable. Extrapolation of test data between boreholes can be aided by determination of fissure continuity through examination of core logs or visual inspection of borehole walls with a borehole television or conventional type camera. Fault zones should be located and tested separately as they may be zones of exceptionally high or low permeability with respect to the surrounding region.

2.1.1 Where the scope of the exploration program will allow it, predominant fissure sets should be tested individually by orienting boreholes to intersect only the fissure set under investigation. Permeabilities of fissure sets can be combined to obtain overall directional permeabilities. Where fissures are numerous and randomly oriented, the borehole orientation should be perpendicular to the plane in which permeability is to be measured. The majority of pressure tests will be conducted in vertical boreholes; however, some test boreholes in other orientations are needed to estimate the anisotropy of the rock mass. In rock exploration programs, groups of inclined boreholes are generally needed to determine reliable estimates of joint set orientations. These boreholes could be pressure tested to aid in estimating anisotropic permeability.

2.1.2 Generally, a borehole should be tested at intervals along its length to determine a permeability profile. A knowledge of the characteristics and location of intersected fissures is desirable in choosing test section lengths. Such information can be obtained from core examination (Note 1). When possible, test section lengths should be chosen to isolate fissure sets. Where fissures are numerous, test lengths can be limited to 5 or 10 ft (1.5 or 3 m). Where fissures are infrequent, a longer test length may be utilized. In many cases, fissure networks may be considered too complex to require special care in selecting test section lengths. However, it is good practice to test in 5- to 10-ft (1.5- to 3-m) intervals to allow detection of localized high- or low-permeability zones.

NOTE 1--Visual inspection with a borehole television camera or film camera would be beneficial and should be used where economically feasible.

2.1.3 Intervals along the borehole length should be tested using either the single or double packer method. The single packer setup shown in Fig. 1 is used when testing as drilling progresses. This technique is advantageous because it reduces the amount of drill cuttings available for clogging fissures since each section is tested before being exposed to the cuttings produced by further drilling. Also, errors due to packer leakage are minimized since only one packer is used. The double packer method (Fig. 1) can be used to test or retest sections of previously drilled boreholes.

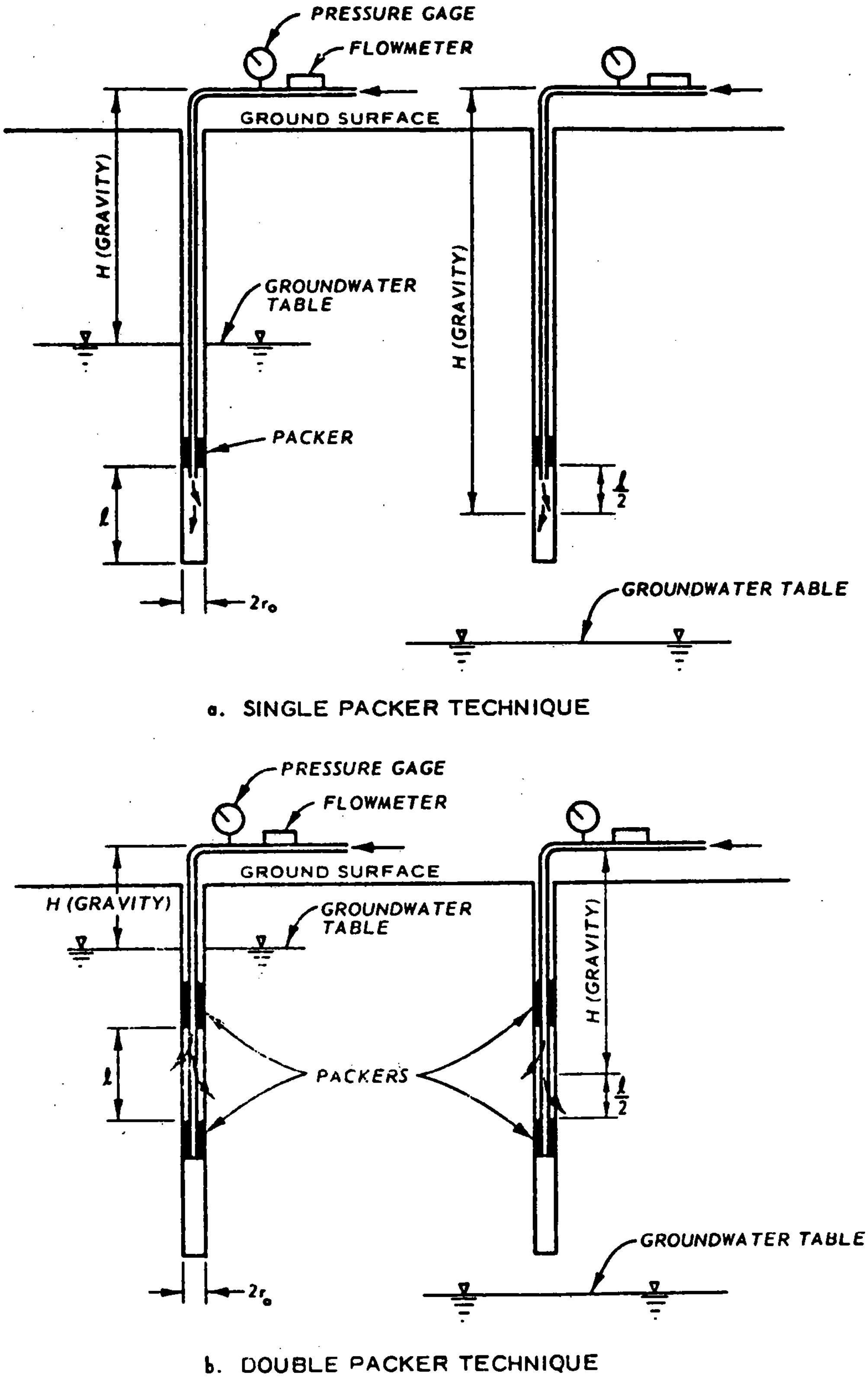


Fig. 1. Pressure test setups--pressure measured at the ground surface.

2.2 Drilling Operations - Prior to pressure testing, the borehole should be surged with water in an effort to remove some of the cuttings and dust. Reverse rotary drilling should be considered for use in boreholes drilled specifically for pressure testing. The removal of cuttings through the drill stem will minimize the clogging of rock fissures.

2.3 Test Equipment - The basic equipment consists of a water supply, pump, packers, flow pipe, and measuring devices. A pump with a minimum capacity of 50 gpm (3150 cu cm/sec) against a pressure of 100 psi (689.5 kPa) is recommended, and only clean water should be used. A progressing cavity-type positive displacement pump is recommended for pressure testing since it maintains a uniform pressure. The type and length of packer needed are dependent on the character of the rock mass to be tested. In most cases, the pneumatic packer will suffice; however, if problems arise, the cup leather or mechanical packers may be substituted. All packers should be at least 18 in. (450 mm) in length. The flow pipe should have a diameter as large as possible to reduce pressure losses between the ground surface and the test section.

2.3.1 Measuring devices are required for determination of volume flow rate and pressure. Flow rate is conveniently measured at the surface, and it is preferred that flow rate be measured continuously rather than averaged by measuring the volume of flow over a known period of time. Multiple gages may be required to measure flow rates ranging from less than 1 gpm (63 cu cm/sec) to as much as 50 gpm (3150 cu cm/sec).

2.3.2 It is recommended that pressure be measured directly within the test section by, for example, installation of an electric transducer. The transducer will also provide a measurement of the existing groundwater pressure at the level of testing. The transducer can be connected to a chart recorder and the initial groundwater pressure indicated as zero. Pressure changes recorded during testing would then be a direct measurement of the excess pressure which is needed in permeability calculations. In most cases, transducer systems will not be readily available. Consequently, pressure will be measured with surface gages. In these instances, pressure loss between the surface and test section must be considered.

2.3.3 When excess pressures are to be determined from surface gage readings, pressure loss between surface and test section must be estimated. Head loss during flow is generally caused by (a) friction, bends, constrictions, and enlargements along the flow pipe; and (b) exit from the flow pipe into the test section. The majority of pressure loss will be caused by friction. Friction losses are dependent on pipe roughness and diameter, and are directly proportional to the square of the flow velocity. Friction losses can be determined experimentally by laying the flow pipe on level ground and pumping water through it at several different velocities while measuring the gage pressure at two points along the pipe. The difference in the gage pressures is the friction loss over the distance between the gages. A plot of friction loss per unit length versus velocity can be obtained from the results. Friction losses can also be estimated from elementary fluid mechanics formulas, tables, and charts.

2.3.4 In most tests, pressure losses caused by pipe bends, constrictions, and enlargements will be insignificant; however, such losses can be checked from relationships given in elementary fluid mechanics textbooks or determined experimentally by pumping on the ground surface and measuring the pressure drop across critical portions of the flow pipe. The pressure loss at the exit from the flow pipe into the test section can be ignored since it is offset by the addition of a velocity head at the surface pressure gage (see paragraph 2.4.3).

2.4 Test Program - The general sequence of operations for using the single packer technique as the borehole progresses is listed below. Changes in the sequence applying to the double packer test are noted.

(a) Step 1 - Drill the desired length of test section, ℓ, (usually 5 or 10 ft (1.5 or 3 m)) and remove the drill equipment. Where the double packer method is to be used, the borehole is drilled to any desired depth.

(b) Step 2 - Study the core to determine the location, number, and characteristics of fissures intersecting the proposed test interval. If only equivalent permeability is to be computed based on test section length, ℓ, fissure information is not needed. However, such information, when correlated with measured permeability, is helpful in understanding the influence of various fissures or fissure sets on the overall permeability of the mass.

(c) Step 3 - Insert the flow pipe and packer, and seal the packer against the borehole wall. To ensure the best possible seal, additional inflation (or tightening) of packers should be accomplished under each test pressure. When tightening packers, a significant and lasting increase in test pressure accompanied by a decrease in flow rate is an indication that the seal has been improved.

(d) Step 4 - Conduct tests using a series of test pressure.

(e) Step 5 - Remove the packer and flow pipe, and begin drilling as in Step 1. In the double packer test, packers are moved to a new test zone; removal of test equipment will be required to alter the test section length as necessary.

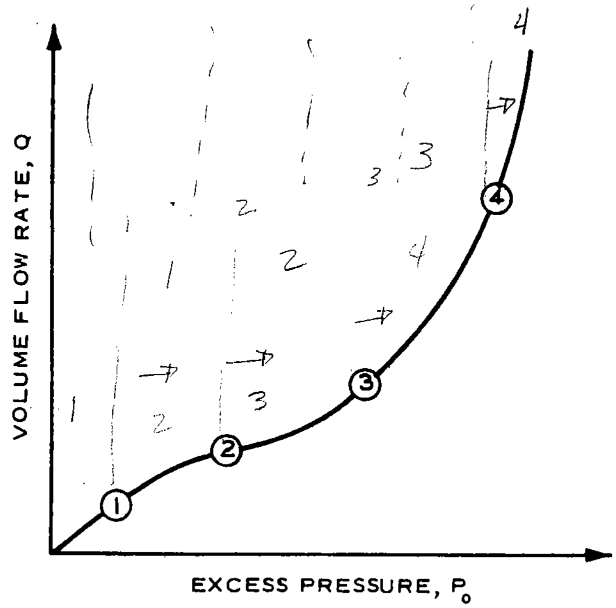
2.4.1 The actual pressure testing is conducted in Step 4. The recommended test procedures are:

(a) Inject water into the borehole and establish a constant pressure.

(b) Take readings of pressure and flow rate over a 3- to 5-min period to ensure that steady-state conditions have been attained. If volume of flow rather than volume flow rate is measured, the average volume flow rate should be checked at 30-sec to 1-min intervals and compared with the overall average volume flow rate for the 3- to 5-min period. At the end of the test, conduct a pressure drop test. This is done simply by shutting off the pump and recording the drop in pressure with time.

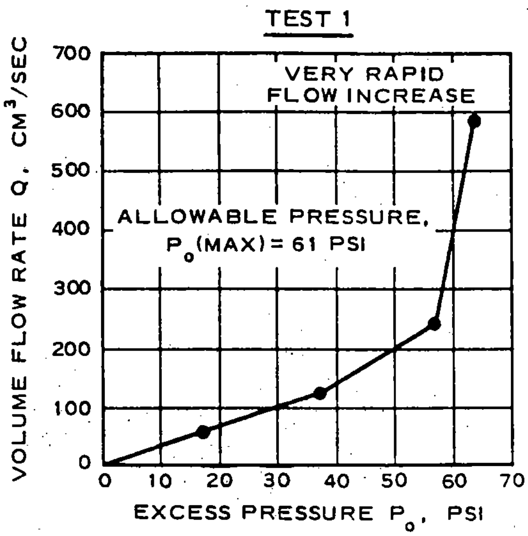
(c) Increase or decrease the flow rate (and pressure) and conduct the next test.

2.4.2 The test program should be designed to check for turbulent flow and the effects of fissure widening. This requires that in a selected number of test sections, a series of tests be conducted at different pressures. A minimum of three tests, each at an increased pressure, are required to detect the nonlinear flow rate versus pressure relationship characteristic of turbulent flow. However, more tests should be conducted as necessary to completely describe any nonlinear behavior. Typical flow rate versus pressure curves are shown in Figs. 2-6. Consistency of results should also be checked by repeating the tests in the same sequence. A significant increase in permeability under the lower pressures would indicate the possibility of permanent fissure expansion.

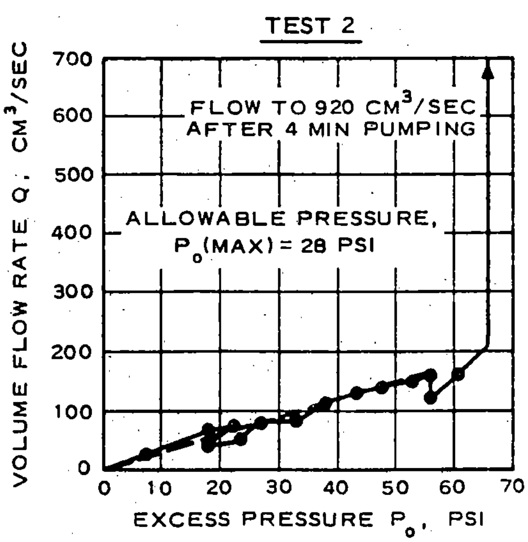


ZONE 1 - LINEAR LAMINAR REGIME
ZONE 2 - TURBULENCE EFFECTS
ZONE 3 - TURBULENCE OFFSET BY FISSURE EXPANSION, OR PACKER LEAKAGE
ZONE 4 - PREDOMINANCE OF FISSURE EXPANSION OR PACKER LEAKAGE

Fig. 2. Typical result of water pressure tests conducted at a series of increasing pressures (after Louis and Maini, 1970; Zeigler, 1975).



a. TEST CONDUCTED IN A VERTICAL BOREHOLE BETWEEN DEPTHS OF 97 AND 102 FT; GROUND-WATER TABLE AT A DEPTH OF 10 FT



b. TEST CONDUCTED IN A VERTICAL BOREHOLE BETWEEN DEPTHS OF 40 AND 45 FT; GROUND-WATER TABLE AT A DEPTH OF 10 FT

Fig. 3. Results of pressure tests in horizontally bedded sedimentary rock (after Morgenstern and Vaughan, 1963; Zeigler, 1975).

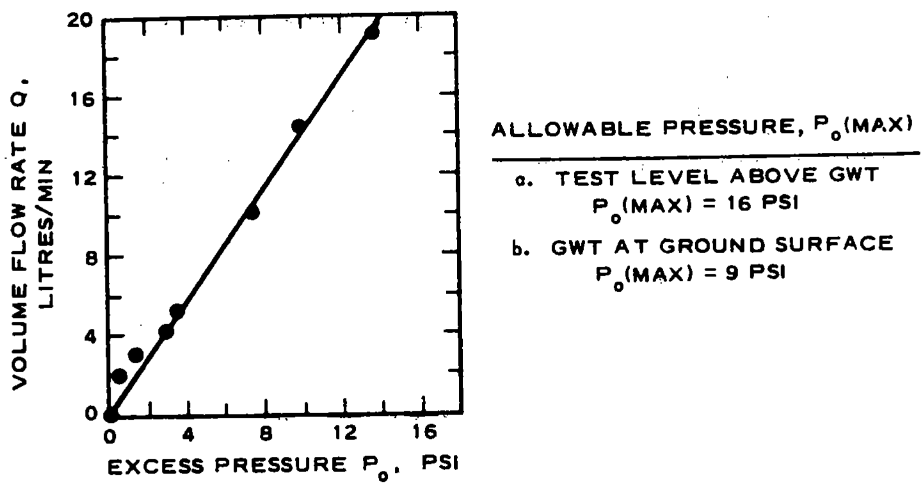


Fig. 4. Pressure test in a vertical borehole between depths of 13.3 and 18.8 ft (after Maini, 1971; Zeigler, 1975).

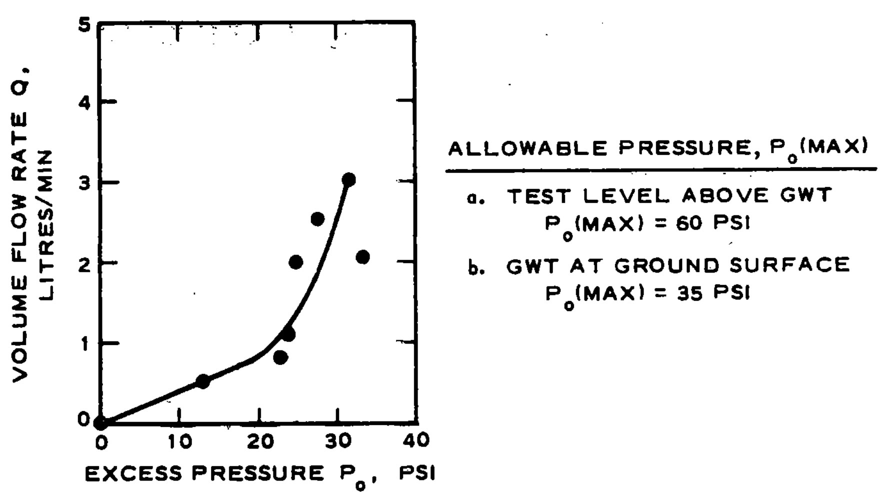
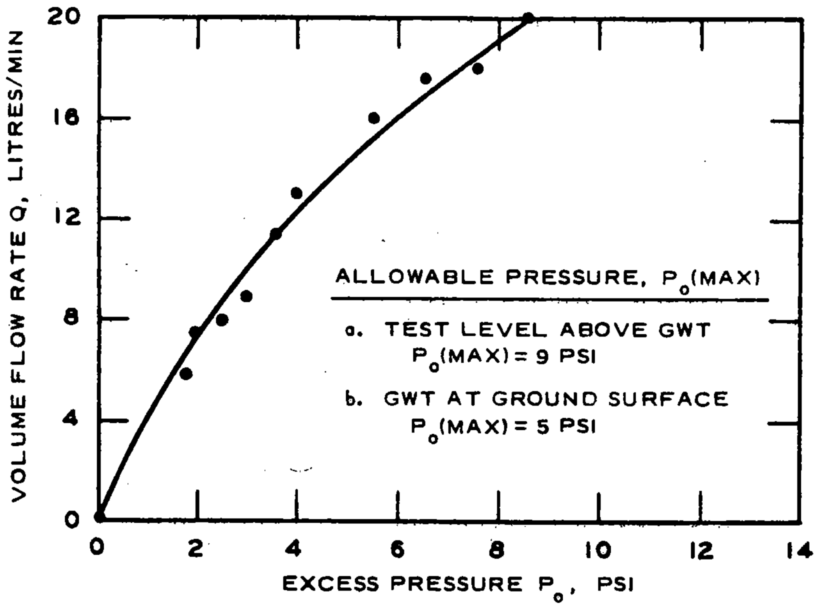
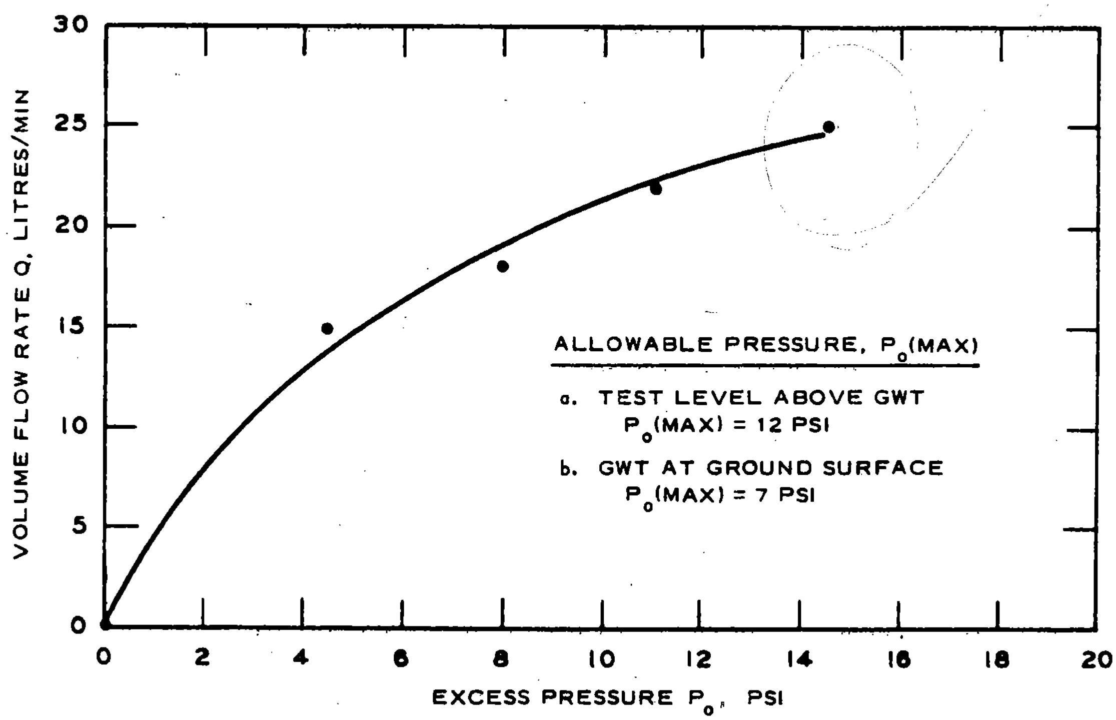


Fig. 5. Pressure test in a vertical borehole between depths of 58.3 and 63.8 ft (after Maini, 1971; Zeigler, 1975).



a. TEST CONDUCTED IN A VERTICAL BOREHOLE BETWEEN DEPTHS OF 6.0 AND 11.5 FT



b. TEST CONDUCTED IN A VERTICAL BOREHOLE BETWEEN DEPTHS OF 10.0 AND 15.5 FT

Fig. 6. Results of pressure tests (after Maini, 1971; Zeigler, 1975).

2.4.3 A typical test sequence using five separate pressures is as follows:

Test No.	Excess Pressure at Center of Test Section, P_o
1	1/5 P_o (MAX)
2	2/5 P_o (MAX)
3	3/5 P_o (MAX)
4	4/5 P_o (MAX)
5	P_o (MAX)
6	1/5 P_o (MAX)
7	3/5 P_o (MAX)
8	P_o (MAX)

The range of pressures over which tests should be conducted can be estimated by choosing P_o(MAX) to equal 1 psi/ft (22.62 kPa/m) of depth above the water table and 0.57 psi/ft (12.89 kPa/m) of depth below the water table. It is not intended that the computed P_o(MAX) be interpreted as a limit below which only laminar flow will occur; it should be used only as a guide in selecting a series of test pressures. Test results should be plotted as they are obtained to determine if further testing of the interval at other pressures is necessary to completely describe any nonlinear behavior.

2.5 Test Data Reduction - The quantities required for use in computing permeability parameters are:

(a) Length of the test section, ℓ (L).

(b) Radius of borehole, r_o (L).

(c) Number, n, and location of fissures intersecting the borehole test section.

(d) Elevation of groundwater table (L).

(e) Volume flow rate, Q (L^3/T).

(f) Excess pressure head at the center of the test section, H_o(L).

2.5.1 The test section length, ℓ, is simply the distance between the packer and borehole bottom (single packer test) or between the two packers (double packer test) as shown in Fig. 1. The radius of the borehole, r_o, is determined from the drill equipment. The number, n, and location of fissures intersecting the borehole test section are obtained from study of the core or a borehole camera survey. The fissure data are not needed if only equivalent permeability is computed based on the assumption that the tested medium is homogeneous and isotropic. The elevation of the groundwater table is determined before testing and assumed to remain constant during testing.

2.5.2 The volume flow rate, Q, will have been continuously recorded or determined by averaging the volume of flow over known time periods. The excess pressure head at the center of the test section, H_o, is a measure of pressure in height of water and is determined from

$$H_o = \frac{P_o}{\gamma_w} \qquad (1)$$

where

P_o = excess pressure at center of test section (F/L^2)

γ_w = unit weight of water (F/L^3)

If total pressure in the test section is measured during the test with, for example, an electric transducer, the excess pressure head, H_o, is given by

$$H_o = \frac{P_t}{\gamma_w} - \frac{P_{t_i}}{\gamma_w} \qquad (2)$$

where

P_t = total pressure at the center of the test section (F/L^2)

P_{t_i} = pretest (or natural) groundwater pressure at the center of the test section (F/L^2)

The pressure head (P_{t_i}/γ_w) will generally be equivalent to the height of the groundwater table above the center of the test section. In tests above the groundwater table, P_{t_i}/γ_w will be zero. If a natural groundwater pressure exists and is set equal to zero on the recording device, the excess pressure, P_o, and not total pressure will be recorded during testing and H_o would be determined from Equation 1.

2.5.3 The excess pressure head, H_o, can also be determined from gage pressure measured at the ground surface. The following relationship is derived by application of Bernoulli's equation

$$H_o = \frac{P_g}{\gamma_w} + \frac{v_g^2}{2g} + H(\text{gravity}) - h_t \tag{3}$$

where

P_g = pressure measured at the surface gage (F/L^2)
V_g = flow velocity at the surface gage (L/T)
g = acceleration due to gravity (L/T^2)
H(gravity) = excess pressure head due to the height of the water in the flow pipe (Fig. 1) (L)
h_t = sum of all the head losses between the surface gage and the test section (L)

By assuming the test section and surrounding medium to behave as a large reservoir, the head loss at the exit from the flow pipe to the test section can be approximated as $v_e^2/2g$, where v_e is the flow velocity at the exit point as noted by Vennard.[3.6] Equation 3 can be revised to

$$H_o = \frac{P_g}{\gamma_w} + \frac{v_g^2}{2g} + H(\text{gravity}) - h_L - \frac{v_e^2}{2g} \tag{4a}$$

where h_L = friction head loss plus minor losses due to pipe bends, constrictions, and enlargements (L). Pipe diameters at the surface and test section are usually equal, such that $v_g = v_e$. Also, the minor pressure losses due to pipe bends, constrictions, and enlargements can normally be ignored. Consequently, the pressure head, H_o, can be expressed as

$$H_o = \frac{P_g}{\gamma_w} + H(\text{gravity}) - h_f \tag{4b}$$

where h_f = friction head loss (L).

2.6 Equivalent Permeability - An equivalent permeability should be computed for each test section. Equivalent permeability is computed based on the assumption that the tested medium is homogeneous and isotropic. An equivalent permeability can be computed for laminar or turbulent flow, whichever is indicated by the test data. Radial flow will be assumed since the geometry of the test section (in particular, the high borehole length to diameter ratio) tends to dictate radial flow in a zone near the borehole which is most affected by the pressure test:

(a) Laminar flow governed by Darcy's law ($v = k_e i$, where v = discharge velocity (L/T), k_e = laminar equivalent permeability (L/T), and i = hydraulic gradient (L/C):

$$k_e = \frac{Q}{\ell H_o} \frac{1}{2\pi} \ln (R/r_o) \tag{5}$$

The radius of influence, R, can be estimated from $\ell/2$ to ℓ. To compute k_e, a value of volume flow rate, Q, and corresponding excess pressure head, H_o, are chosen from a straight-line approximation of a plot of Q versus H_o. The straight line must pass through the origin as shown in Fig. 4.

(b) Turbulent flow governed by the Missbach law ($v^m = k_e'i$, where k_e' = turbulent equivalent permeability $(L/T)^m$, and m = degree of nonlinearity):

$$k_e' = \frac{Q^m(R^{1-m} - r_o^{\ 1-m})}{(2\pi\ell)^m\ H_o(1 - m)} \tag{6}$$

The radius of influence, R, can be estimated from $\ell/2$ to ℓ. The degree of nonlinearity, m, is determined as the arithmetic slope of a straight-line approximation to a plot of log H_o versus log Q. The log-log plot may involve all or only a portion of the test data. The value of m should be between 1 and 2. To compute k_e', values of flow rate, Q, and corresponding excess pressure head, H_o, are chosen from the approximated straight-line log-log plot.

2.6.1 In computing equivalent permeability of particular fissure systems, test section length, ℓ, should be replaced by the term nb_{avg} where n is the number of fissures intersecting the test section, and b_{avg} is the average spacing between fissures intersecting the test section. Substitution of nb_{avg} for ℓ is important where fissures are clustered over a small portion of the test interval. A fairly even distribution of fissures along the test length will normally yield ℓnb_{avg}.

2.7 <u>Permeability of Individual Fissures</u> - Laminar or turbulent permeabilities are estimated for individual fissures by assuming the test section to be intersected by a group of parallel and identical fissures. Each fissure is assumed to be an equivalent parallel plate. Flow is assumed to be radial and to occur only within the fissures. The material between fissures is assumed impermeable. The following equations are applicable:

(a) Laminar flow governed by Darcy's law ($v = k_j$ (where k_j = laminar fissure permeability (L/T))). The equivalent parallel plate aperture, e, is computed from Equation 7 below and used to compute the permeability of each fissure, k_j, from Equation 8:

$$e = \left[\frac{Q \ \ln \ (R/r_o)}{2\pi n H_o} \ \frac{12\mu_w}{\gamma_w} \right]^{1/3} \qquad (7)$$

where μ_w = dynamic viscosity of water $(F\text{-}T/L^2)$

and

$$k_j = \frac{e^2 \gamma_w}{12\mu_w} \qquad (8)$$

To compute e, corresponding values of Q and H_o are chosen from a straight-line approximation of Q versus H_o, which must pass through the origin as shown in Fig. 4. The radius of influence, R, can be estimated between $\ell/2$ and ℓ.

(b) Turbulent flow governed by Missbach's law ($v^m = k'_j i$, where k'_j = turbulent fissure permeability $(L/T)^m$):

$$k'_j = \frac{Q^m (R^{1-m} - r_o^{\ 1-m})}{(2\pi n e)^m \ H_o (1 - m)} \qquad (9)$$

To apply Equation 9, an equivalent parallel plate aperture, e, must first be estimated from the linear portion of the flow rate, Q, versus pressure, H_o, curve (i.e., zone 1, Fig. 2) as given by Equation 7. The degree of nonlinearity, m, is the slope of a straight-line approximation to a log-log plot of H_o versus Q. The log-log plot may involve all or only a portion of the test data. Corresponding values of Q and H_o can be chosen from the straight-line log-log plot for substitution in Equation 9. The radius of influence, R, can be chosen between $\ell/2$ and ℓ.

2.8 <u>Directional Permeability</u> - Equivalent permeabilities computed for fissure sets must be interrelated to obtain overall directional permeabilities which are needed in continuum seepage analyses. Directional permeabilities can be obtained by adding the equivalent permeabilities of fissure sets (computed via Equation 5 or 6) oriented in the same direction. This procedure is illustrated for an assumed laminar flow in the three cases shown in Fig. 7. In case (a), the zone tested contains one set of horizontal fissures (fissure set 1). The vertical borehole in case (a) will give a measure of the laminar equivalent permeability, k_{e_1}, of fissure set 1. Permeability in the vertical direction, $k_e(V)$, would be that of the intact rock since there are no vertical fissures. Permeabilities in a direction contained within the horizontal plane (such as $k_e(H1)$ and $k_e(H2)$ in Fig. 7) would be interpreted as k_{e_1}, since k_{e_1} is based on a radial flow.

2.8.1 In case (b) there are two intersecting fissure sets: the horizontal fissures (fissure set 1) and a series of vertical fissures (fissure set 2). The pressure test boreholes are oriented so that each intersects only one of the fissure sets. It is assumed that each test measures only the permeability of the intersected fissure set. In computing directional permeabilities both fissure sets 1 and 2 can transmit flow in the horizontal direction, H2; consequently, their equivalent permeabilities are summed ($k_e(H2) = k_{e_1} + k_{e_2}$). In the vertical direction, V, and horizontal direction, H1, the equivalent permeability of each fissure set is considered separately ($k_e(V) = k_{e_2}$, $k_e(H1) = k_{e_1}$).

2.8.2 In case (c) there are three intersecting fissure sets. Three boreholes are each oriented to intersect only one of the fissure sets. The directional permeabilities are each the sum of equivalent permeabilities corresponding to two fissure sets ($k_e(V) = k_{e_2} + k_{e_3}$; $k_e(H1) = k_{e_1}$; $k_e(H2) = k_e + k_{e_2}$).

2.8.3 When only vertical boreholes are tested, but structures such as in case (b) and case (c) of Fig. 7 are known to exist, the additional permeability added by the other fissure sets must be estimated. This

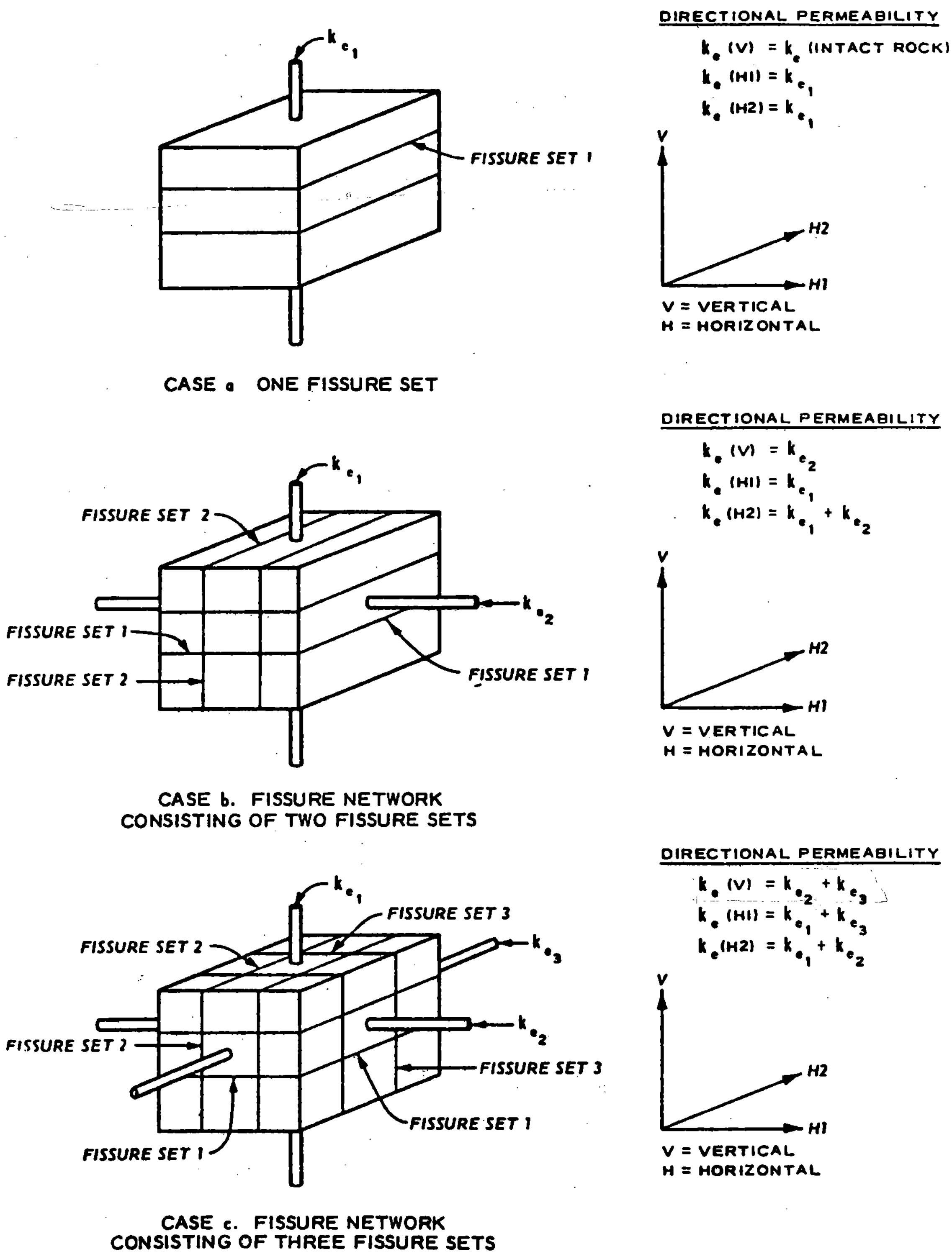


Fig. 7. Directional permeability from superposition of laminar equivalent permeabilities of fissure sets.

can be done based on the assumption that fissures not tested have the same equivalent parallel plate aperture as the tested fissures. Any difference in equivalent permeability between the fissure sets would be a function of the difference in fissure frequency. For example, in case (b) in Fig. 7 under conditions of laminar flow,

$$k_{e_2} = k_{e_1} \frac{b_{avg_1}}{b_{avg_2}} \qquad (10)$$

where

b_{avg_1} = average fissure spacing of tested fissure set 1

b_{avg_2} = average fissure spacing of untested fissure set 2

2.8.4 The procedure of adding permeabilities of separate fissure sets relies heavily on the assumption that pressure tests reflect only the permeability of the fissure sets intersecting the test section. This assumption is based on the theoretical rapid loss in pressure away from the borehole. The assumption is likely to become less accurate as average fissure spacing within secondary fissure sets (i.e., fissures tending to parallel the borehole) is decreased. In complex fissure networks with fissure spacings less than 1 ft, it is recommended that the method of Snow,[3.4, 3.5] based on the assumption of a homogeneous anisotropic continuum, be used in computing directional permeabilities.

2.8.5 The problem of combining fissure set permeabilities is avoided by using discontinuum rather than continuum seepage analyses. In the discontinuum analyses, fissures can be oriented to correspond to the field geologic structure and assigned individual permeabilities and/or equivalent parallel plate openings as determined from pressure tests. However, a three-dimensional analysis such as that presented by Wittke et al.[3.7] would be required in many situations. In structures similar to case (c) in Fig. 7, a two-dimensional seepage analysis in any of the indicated directions would consider only two of the three fissure sets. For example, in direction H1, fissure set 3 would be ignored, although it may be a major contributor to seepage in direction H1.

3. References

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