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QUANTIFICATION OF PINHOLE TEST EQUIPMENT HYDRAULIC CHARACTERISTICS

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16. ABSTRACT

A modified pinhole test procedure for identifying dispersive clays has been developed by the Bureau of Reclamation. Changes to the original test equipment and test procedure developed by Dr. James L. Sherard include: (1) increased emphasis on the use of system flow rates in the classification of dispersive soil grades, (2) reduced emphasis on the qualitative test evaluation criteria such as final eroded pinhole size and discharge effluent turbidity in the final dispersive grade classification, and (3) designing the equipment to assure atmospheric pressure at the pinhole discharge and to assure verification of the actual hydraulic head on the system.

Laboratory soil test data to substantiate the proposed changes were obtained through routine testing and an analysis of Sherard's original data. An extremely high degree of correlation was found between soils originally classified as dispersive by Sherard on the basis of effluent turbidity and subsequently reclassified as dispersive on the basis of system flow rates. The quantitative method of evaluating pinhole test results on the basis of flow rates represents a considerable improvement over the qualitative methods originally used because subjective criteria and operator bias are eliminated.

17. KEY WORDS AND DOCUMENT ANALYSIS

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QUANTIFICATION OF PINHOLE TEST EQUIPMENT HYDRAULIC CHARACTERISTICS

by

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September 1982

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Denver, Colorado

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UNITED STATES DEPARTMENT OF THE INTERIOR • BUREAU OF RECLAMATION

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INTRODUCTION

In 1977, the Bureau of Reclamation began a laboratory testing program for the identification of dispersive clays. It had been previously recognized that dispersive clays naturally deflocculate or disperse readily in the presence of relativity pure water; however, laboratory tests had not been standardized for dispersive clay identification. These clays are highly susceptible to erosion and could therefore represent unsuitable materials for earthwork construction. The deflocculation of a dispersive clay occurs when the repulsive (electrical surface charge) forces exceed the attractive (Van Der Walls) forces on the individual clay particles. Changes in the clay particle physiochemical force system occur when absorbed metallic cations are exchanged with cations and anions available in a water solution.

The work of Dr. James L. Sherard, during the 1970's, has resulted in an increased awareness of dispersive clays in the Geotechnical engineering community. Sherard, et al., reported in 1976 [1][1] a high correlation between the concentration of Na^+, K^+, Ca^{++}, and Mg^{++} cations for soil-pore water samples from field sites of observed erodible or erosion resistant clays. His study also showed that soil-pore water extracts from dispersive clays would generally contain a high percentage of Na^+ as a function of the total concentration of cations. In addition, the study showed that dispersive clays could be identified by a physical test in which distilled water was percolated through a 1.0-mm-diameter pinhole in a 25-mm-long compacted soil specimen. This test, called the pinhole test [2], identified dispersive soils by a colored discharge water, erosion and enlargement of the pinhole, and a rapid increase in flow rate during the first 5 minutes of percolation under a 50-mm hydrostatic head. Two other tests, the Crumb test and the double hydrometer or SCS laboratory dispersion test, to evaluate soil dispersibility are also described in reference [1].

The pinhole test, developed by Sherard in cooperation with the SCS (Soil Conservation Service), was adopted by the Bureau in 1977 as the physical test to be used in conjunction with the double hydrometer test, the modified crumb test, and soil-pore water chemistry tests to form the dispersive clay identification test series. A detailed description of the test procedures used by the Bureau for dispersive clay identification is given by James L. Kinney in reference [3].

[1] Numbers in brackets refer to entries in Bibliography.

DESCRIPTION

The pinhole apparatus used in the original research test program conducted by Sherard, et al. [2], was a modified Harvard Miniature Permeameter manufactured by Soiltest, Inc. The general schematic diagram of this apparatus was used as a guide to construct and fabricate the Bureau's pinhole equipment. Figures 1 and 2 are engineering drawings of the Bureau's and SCS's pinhole test equipment, respectively. Both of these drawings show a truncated brass cone with a 1.5-mm-diameter center hole. This cone is used as a centering guide to punch the 1.0-mm-diameter pinhole into the soil specimen. The cone or "nipple" remains inserted in the soil specimen during the test.

The quantity of flow in the pinhole test apparatus, under constant hydrostatic head conditions, is a function of the minimum cross-sectional area and length of the cylinder with that cross section. For nondispersive or intermediate soils, the flow is controlled by the soil specimen pinhole diameter, initially 1.0 mm in diameter. For dispersive soils, the pinhole erodes to a diameter greater than the hole in the nipple and, consequently, the flow is then controlled by the 1.5-mm-diameter hole in the nipple.

Table 1 shows the different categories of dispersive soil classification, and table 2 is a summary of the criteria for evaluating the pinhole test results. Both of these tables are reproduced directly from reference [2].

As part of the initial calibration process for the Bureau's pinhole apparatus, flow rates were determined under hydrostatic heads of 50, 180, 380, and 1020 mm through a 1.5-mm-diameter hole in the nipple. The flow rate determinations revealed that the maximum flow rates shown in [2] could not be reached. The Bureau equipment produced a maximum flow rate of 1.2 to 1.3 mL/s under a hydrostatic head of 50 mm, whereas the SCS equipment produced flows in excess of 1.5 mL/s, which allowed a D1 classification (table 2). The reduced flow rate by the Bureau equipment was unexpected because the similarity in design and construction to the SCS equipment should have resulted in similar hydraulic characteristics. Although the cause of the discrepancy in flow rates was not technically identified, the symptoms of the problem were resolved when the Bureau modified its equipment design by enlarging the hole diameter through the nipple from 1.5 to 2.2 mm. This modification increased the hydraulic capacity of the equipment to a degree necessary to achieve flow rates in excess of 1.5 mL/s and therefore, a D1 (dispersive) soil classification. No further technical concerns were raised

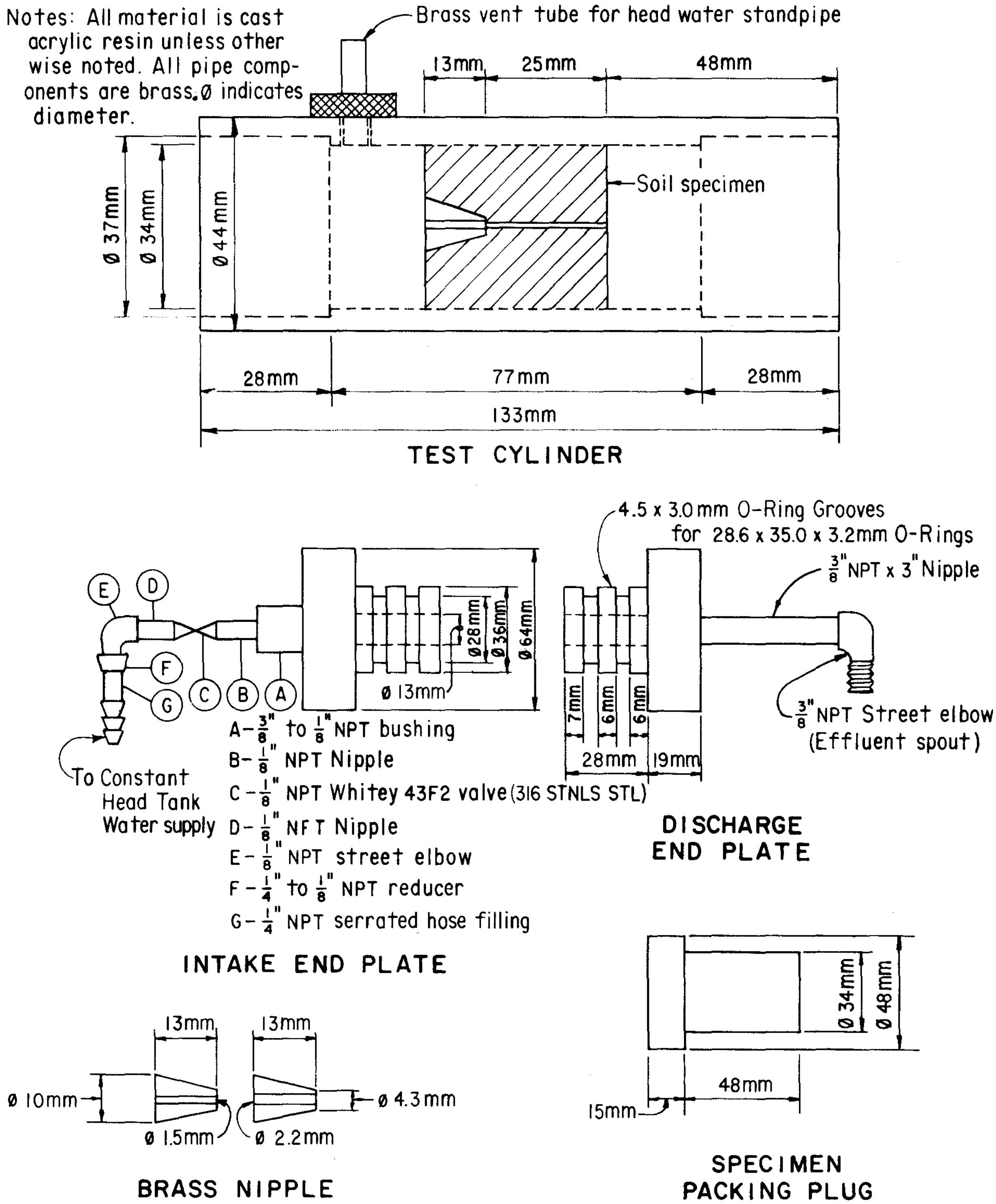


Figure 1.–Bureau of Reclamation pinhole test apparatus.

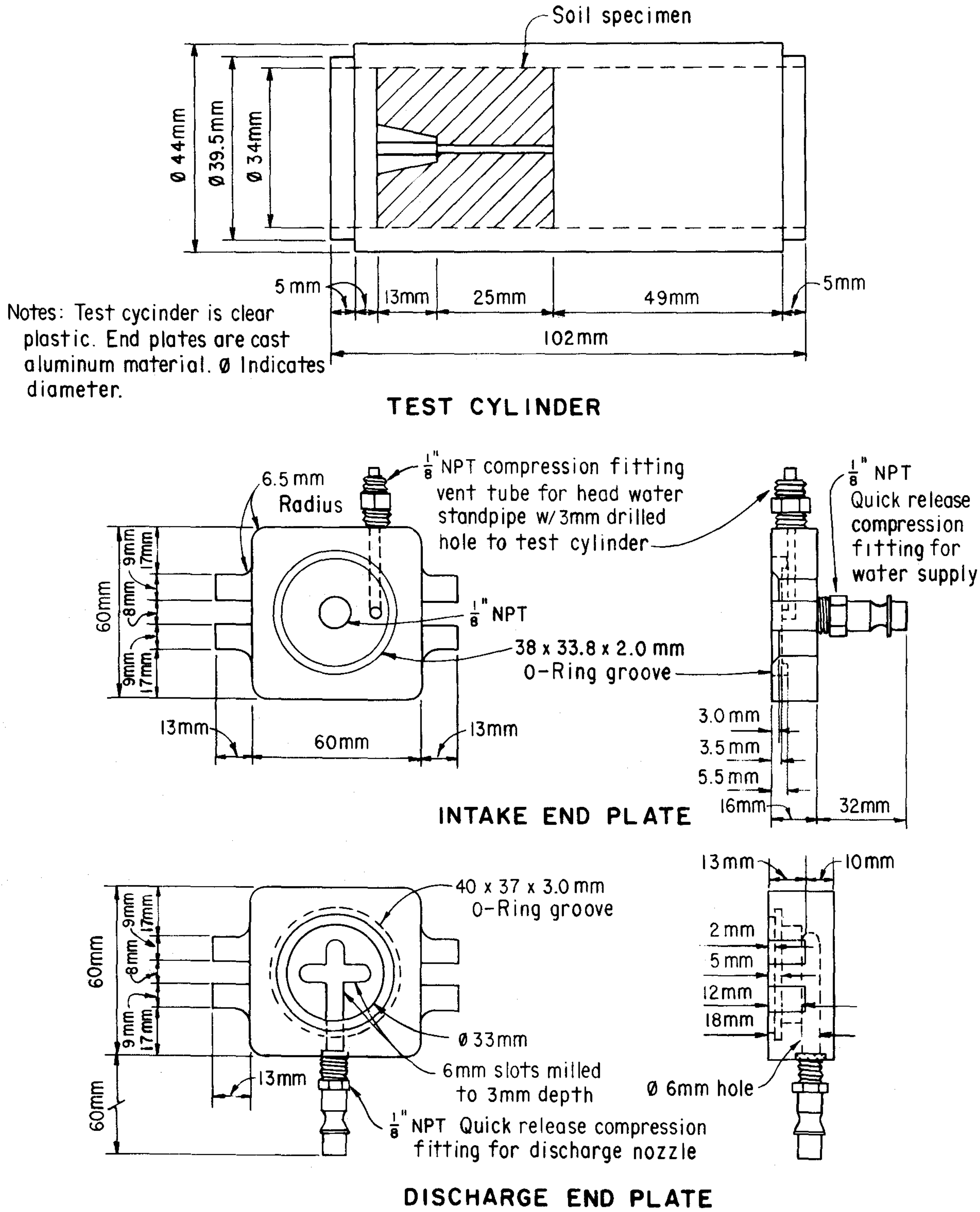


Figure 2.–Soil Conservation Service pinhole test apparatus.

Table 1.—*Categories of test results*

Classification of individual test results	Classification of soil
D1 and D2	Dispersive soils: fail rapidly under a 50-mm head.
ND4 and ND3	Intermediate soils: erode slowly under a 50- or 180-mm head.
ND2 and ND1	Nondispersive soil: no colloidal erosion under a 380- or 1020-mm head.

Table 2.—*Summary of criteria for evaluating results*

Classification	Head, mm	Test time for given head, min	Visual final flow through specimen, mL/s	Color of flow at end of test (cloudy or color)	Hole size after test (needle diameter)
D1	50	5	>1.5	Very distinct	>2X
D2	50	10	>1.0	Distinct to slight	2X
ND4	50	10	<0.8	Slight but easily visible	1.5X
ND3	180-380	5	>2.5	Slight but easily visible	2X
ND2	1020	5	>3.5	Clear or barely visible	2X
ND1	1020	5	<5.0	Crystal clear	no erosion

over the fact that flow rates were being developed which allowed the utilization of the soil dispersive grade classification scheme even though the equipment had been significantly altered. With no further research or investigation of this hydraulic anomaly, the 2.2-mm-diameter hole in the nipple was adopted as part of the Bureau's standard pinhole test in March 1977 [3].

From March 1977 to July 1981, the Bureau evaluated pinhole test results using table 2. Problems were experienced in applying Sherard's qualitative effluent turbidity criteria without introducing operator bias in the process of evaluating test results. Four distinct problem areas developed during these test years in evaluating turbidity of the colloidal discharge effluent:

1. It was difficult to visually classify the different degrees of "cloudiness" in the collected effluent. Different operators develop different perceptions of dark, cloudy, or slightly cloudy colloidal suspensions. Also, different soil colors produce different levels of turbidity with the same concentration of colloids. Evaluation of effluent that "clears," has "slight color," or a "slight trace of color" is extremely subject to operator interpretation.

2. In many cases, eroded soil particles and aggregates were observed to collect in the gravel pack downstream of the test specimen. When this occurs, the collected particles do not contribute to the visual turbidity of the effluent, resulting in a lighter colored effluent.

3. The observed effluent turbidity is affected by the diameter and wall thickness of the graduated cylinders or flasks used to collect the discharge. Two identical colloidal suspensions have different visual turbidity when viewed through different types of collection flasks.

4. If the erosion rate exceeds the expansion rate, expansive soils may be classified as dispersive early in the pinhole test. Evaluating these soils as dispersive only on the basis of the effluent turbidity ignores the soils' tendency to swell and seal the pinhole, and therefore reduce flow rates. Evaluation of changes in flow rates would detect the soils' swelling potential as a function of time and would provide useful information on the soil behavior.

From the preceding discussion, two basic problem areas are identified:

1. Evaluation of effluent turbidity to interpret pinhole test results is extremely subject to operator bias and therefore represents a qualitative evaluation criterion.

2. Evaluation of flow rate, a measurable quantity not subject to operator bias, appears to be a more precise technical approach for evaluating pinhole test results. However, preliminary investigations revealed significant discrepancies in hydraulic characteristics between the Bureau and SCS equipment.

The remainder of this report describes the testing and analysis performed to resolve the hydraulic discrepancies between the equipment of the two agencies. The report provides a new pinhole test procedure that incorporates flow rates as a quantitative primary test evaluation criterion, and recommendations on equipment modifications to assure the verification of proper hydrostatic head.

CONCLUSIONS AND RECOMMENDATIONS

The original scope of the pinhole test [2] was to provide a qualitative physical test for observing the turbidity of water from dispersive clay erosion under low hydraulic gradients. The qualitative evaluation of discharge effluent turbidity has been shown to present several problems as a result of operator bias with subjective interpretation of test results. Using the original test data generated by Sherard, et al. [2], their basic test procedures, and the results of data presented in this report, a new quantitative method for evaluating pinhole test results has been developed. This new test procedure reduces the emphasis on qualitative evaluation and increases the emphasis on using the quantitative measured flow rate of discharge effluent to determine soil dispersibility.

The data presented in this report indicate:

- Pinhole equipment developed by different manufacturers have extremely high levels of reproducibility, accuracy, and precision with respect to system hydraulic characteristics.

- The Harvard Miniature Permeameter, manufactured by Soiltest, Inc., requires a vent in the test cylinder or end plate downstream of the test specimen. This vent assures atmospheric pressure at the discharge end of the specimen pinhole and, therefore, assures accurate measurement of the total hydraulic head on the system.

- The hydraulic capacity of pinhole test equipment is a valid test evaluation criterion for the critical cases of flow constricted by the specimen pinhole or nipple.

- A high degree of correlation exists between the physical test results and the analytical results predicted from conventional fluid mechanics for laminar flow through a pinhole and nipple system.

The test procedure and evaluation criteria proposed herein have been adopted as the Bureau of Reclamation Standard Pinhole Test as of January 1982. It is recommended that laboratories using the original or any modified form of the pinhole test consider:

- Incorporating a "breather hole" in the equipment test cylinder or discharge end plate to assure atmospheric pressure at the discharge end of the specimen pinhole.

- Using the quantitative flow rates as the primary pinhole test evaluation criterion, and reducing the emphasis on qualitative information such as degree of effluent turbidity, turbidity rate of change, and final eroded hole size as the test evaluation criteria.

TEST PROCEDURES

Review

Early in 1981, the Bureau renewed investigation of the pinhole test during the early phases of research studies for establishing filter design criteria for dispersive clays. Review of the existing Bureau pinhole test [3] and the SCS pinhole test [2] occurred concurrent with reviews of the COE (Corps of Engineers) Pinhole Erosion Test [4], the Physical Erosion Test developed by T. A. Haliburton [5], and the TVA (Tennessee Valley Authority) Pinhole Test [2]. These reviews indicated that several of the major Government agencies and geotechnical consultants involved with the physical testing for identifying dispersive clays had adopted the original or some modified form of the pinhole test as initially documented by Sherard [2]. Table 3 identifies the major differences that existed between the four Government agencies as of June 1981.

All of the different pinhole test procedures require observing erosion of the soil specimen pinhole as a common evaluation criterion for soil dispersibility. However, the COE pinhole test evaluation [4], relates flow rates generated during soil testing to flow rates previously obtained through aluminum cylinders with uniform holes of 1.59, 3.18, 6.35, and 12.7 mm in diameter. This test assumes that a dispersive soil would tend to erode uniformly about the pinhole surface in the presence of flow under low hydraulic gradients. Increasing flow rates associated with erosion and enlargement of the pinhole are related to the flow rate values previously obtained on the uniform aluminum cylinders. Using the approach of modeling the erosion of the soil specimen pinhole diameter, a detailed review of the hydraulic characteristics of Bureau pinhole equipment was then undertaken, and is discussed in the next subsection.

Hydraulic Model Analysis

A hydraulic model analysis of the nipple and pinhole was used to determine water velocities, flow rates, and shear stresses developed along the pinhole surface. The following conventional fluid mechanics formulas were used for analyzing laminar pipe flows through the 2.2- and 1.5-mm nipples and using uniform pinhole diameters of 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 mm [6,7,8]:

Head loss:

$$H_L = \frac{V_n^2}{2g}\left(0.5 + \frac{f_n L_n}{d_n}\right) + \frac{V_p^2}{2g}\left(K + \frac{f_p L_p}{d_p} + 1.0\right) \quad (1)$$

Friction factor:

$$f_{n,p} = \frac{64\nu}{V_{n,p} d_{n,p}} \text{ ; for Reynolds numbers less than 2000} \quad (2)$$

Shear stress:

$$\tau = \frac{8.0\, V_p \mu}{d_p} \quad (3)$$

where H_L = head loss, mm
$V_{n,p}$ = water velocity in nipple and pinhole, respectively, mm/s
$f_{n,p}$ = friction factor of nipple and pinhole, respectively
$L_{n,p}$ = length of nipple and pinhole, respectively, mm
$d_{n,p}$ = diameter of nipple and pinhole, respectively, mm
K = contraction/divergence coefficient
ν = kinematic viscosity of water, mm^2/s
μ = dynamic viscosity of water, kg/m·s
τ = shear stress, Pa
g = acceleration of gravity, mm/s^2

Appendix A shows the method used for calculating the values of water velocities and shear stresses defined by equations (1), (2), and (3). It is recognized that equations (1), (2), and (3) apply to the limited conditions of laminar flow with a fully developed boundary layer on the pinhole surface. In the tables and figures in this report, the transition from laminar to turbulent flow was taken at a Reynolds number equal to 2000. Although equations (1) and (3) do not properly model turbulent flow with a partially developed boundary layer, the boundary shear stress can still be qualitatively determined. Using a conservative approach, the boundary shear stress in a partially developed boundary layer can be assumed to be at least the magnitude that exists in a fully developed boundary layer. Turbulence and drag forces in the developing boundary layer zone (25 to 50 pipe diameters) would cause the boundary shear stress in that zone to exceed the values shown in table 4 and on figure 5. Table 4 summarizes the calculated values of water velocities, shear stresses, and flow rates for laminar flows through the 1.5- and 2.2-mm-diameter nipple hole configurations through uniform pinhole diameters of 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 mm. Flow rates determined from the following test procedure are also included in table 4 for comparison.

Flow Rate Test Procedure

The brass nipples (fig. 1) are inserted in brass cylinders that are used as simulated pinhole specimens. The brass cylinders, hereinafter referred to as brass specimens, are machined with pinhole diameters ranging from 1.0 to 3.5 mm in 0.5-mm increments. The interface between the brass specimen, nipple, and inner wall of the test cylinder is sealed with plasticene modeling clay to assure waterflow only through the nipple and pinhole. A fine gravel pack and 2-mm (No. 10) U.S. Standard mesh screens are placed upstream and downstream of the specimen to help provide uniform flow at the entrance and exit of the specimen. Flow rates, in mL/s, are determined by measuring the volume of water collected during a specified time interval while the system is subjected to constant hydrostatic heads of 50, 180, and 380 mm. Flow rate measurements are recorded at 15-, 30-, or 60-second intervals for 3 to 5 minutes at each head.

The 1981 testing confirmed the discrepancies in flow rates that had previously been recognized in 1977 (app. I [3]). Figure 3 shows curves that compare the flow rates obtained through the Bureau's pinhole equipment using 1.5- and 2.2-mm-diameter nipple holes in brass specimens with pinhole diameters of 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 mm. Figure 4 shows the hydraulic capacity of

Table 3.—*Pinhole test procedure comparisons for four Government agencies (June 1981)*

Feature	Bureau of Reclamation[1]	SCS and TVA[2]	COE[3]
Test heads	50, 180, and 380 mm	50, 180, 380, and 1020 mm	50, 180, and 380 mm
Pinhole diameter	1.0 mm	1.0 mm	1.59 mm
Nipple hole diameter	2.2 mm	1.5 mm	No nipple used
Specimen size	340 X 38 mm	340 X 38 mm	(a) 340 X 38 mm (b) 1020 X 117 mm (c) 790 X 117 mm
Specimen preparation	Mechanical tamping to specified moisture and density	Harvard miniature spring tamping	(a) Harvard miniature (b) 0.033-ft^3 mold (c) Undisturbed Shelby tube
Data analysis	Modified Sherard's D1-ND1 criteria	Original Sherard's D1-ND1 criteria	Modified Sherard's D1-ND1 criteria
	(D1, D2), 10 min, 50 mm	(D1), 5 min, 50 mm	(D1, D2, ND4), 10 min, 50 mm
	(ND3, ND4), 5 min, 180 mm	(D2, ND4), 5 min, 50 mm	(ND3), 10 min, 180 mm
	(ND1, ND2), 5 min, 380 mm	(ND3), 5 min, 180 mm (ND3), 5 min, 380 mm	(ND1, ND2), 10 min 380 mm
		(ND1, ND2), 5 min, 1020 mm	See footnote No. 4:

[1] See [3] for detailed test procedure.
[2] See [2] for detailed test procedure.
[3] See [4] for detailed test procedure.
[4] Flow rates to suit the final classification are dependent on results of calibration using aluminum cylinders with holes.

the Bureau's equipment using nipples with hole diameters of 1.5 and 2.2 mm. Of particular interest is the considerable increase in hydraulic capacity of the system when using the 2.2-mm-diameter nipple hole. The shear stress developed along the assumed cylindrical surface of the eroded pinhole varies considerably as a function of the hole diameter through the nipple as shown in table 4 and on figure 5.

The pinhole test, as originally developed in [2], was not intended to provide precise, quantitative data on soil erosion rates with respect to applied shear stress. However, the fact that the Bureau and SCS equipment produced considerably different system flow rates and shear stresses along the soil specimen pinhole, has caused renewed interest in the hydraulic characteristic anomaly of apparently identical test equipment. Technical concerns have also developed because the Bureau had been identifying dispersive soils using pinhole equipment with a 2.2-mm nipple hole diameter, which subjected the soil specimen to significantly higher water velocities, shear stresses, and flow rates than those produced by Sherard's original pinhole equipment. Considerable cost impact could result on any earthwork project where the Bureau pinhole test identified a nondispersive soil as dispersive if the tested soil deflocculated from higher applied external erosive forces versus internal ionic repulsive forces.

Bureau and SCS Comparative Testing Program

In July 1981, a testing program was conducted at the SCS Soil Mechanics Laboratory in Lincoln, Nebr., to compare the test equipment used by both agencies. This program was developed specifically to identify the anomaly or anomalies responsible for the significant and critical differences in hydraulic characteristics between the equipment. The following

Table 4.—*Summary of pinhole equipment hydraulic characteristics*

d_n, mm	d_p, mm	K	H_L, mm	V_n, mm/s	V_p, mm/s	Q, mL/s	Q_{TEST}, mL/s	T, Pa
1.50	1.00	0.66	50	179	403	0.316	0.30	3.2
2.20	1.00	0.63	50	88	426	0.334	0.36	3.4
1.50	1.50	1.00	50	450	450	0.794	0.84	2.4
2.20	1.50	0.67	50	259	556	0.983	1.00	3.0
1.50	2.00	1.12	50	700	394	1.236	1.22	1.6
2.20	2.00	0.83	50	464	561	1.762	1.55	2.3
1.50	2.50	1.12	50	871	313	1.538	1.33	1.0 *
2.20	2.50	1.17	50	645	499	2.449	2.02	1.6 *
1.50	3.00	1.12	50	965	241	1.705	1.30	0.64 *
2.20	3.00	1.16	50	825	444	3.135	2.66	1.2 *
1.50	3.50	1.11	50	1016	187	1.794	1.32	0.43 *
2.20	3.50	1.13	50	963	380	3.658	2.74	0.90 *
1.50	1.00	0.66	180	448	1009	0.792	0.67	8.1
2.20	1.00	0.63	180	218	1056	0.829	0.89	8.5
1.50	1.50	1.00	180	996	996	1.759	1.88	5.3
2.20	1.50	0.67	180	562	1209	2.135	1.88	6.4
1.50	2.00	1.12	180	1507	847	2.661	2.53	3.4
2.20	2.00	0.83	180	958	1160	3.641	3.42	4.7
1.50	2.50	1.12	180	1864	671	3.293	2.79	2.1 *
2.20	2.50	1.17	180	1304	1010	4.955	4.61	3.2 *
1.50	3.00	1.12	180	2065	516	3.648	2.69	1.4 *
2.20	3.00	1.16	180	1661	893	6.310	6.22	2.4 *
1.50	3.50	1.11	180	2174	399	.3.839	2.44	0.9 *
2.20	3.50	1.13	180	1934	764	7.349	6.36	1.7 *
1.50	1.00	0.66	380	723	1626	1.276	1.15	13.0
2.20	1.00	0.63	380	350	1675	1.331	1.41	13.5
1.50	1.50	1.00	380	1529	1529	2.701	2.91	8.2
2.20	1.50	0.67	380	857	1842	3.254	2.72	9.9
1.50	2.00	1.12	380	2289	1287	4.042	3.81	5.1
2.20	2.00	0.83	380	1435	1736	5.451	5.35	6.9 *
1.50	2.50	1.12	380	2826	1017	4.992	4.20	3.3 *
2.20	2.50	1.17	380	1938	1501	7.363	7.21	4.9 *
1.50	3.00	1.12	380	3131	783	5.529	4.05	2.1 *
2.20	3.00	1.16	380	2463	1325	9.359	6.87	3.6 *
1.50	3.50	1.11	380	3295	605	5.819	3.52	1.4 *
2.20	3.50	1.13	380	2867	1133	–	9.51	2.6 *

* Turbulent flow

$d_{n,p}$ = diameter of nipple and pinhole, respectively, mm

K = contraction/divergence coefficient

H_L = head loss, mm

$V_{n,p}$ = water velocity in nipple and pinhole, respectively, mm/s

Q = calculated flow rate, mL/s

Q_{TEST} = measured flow rate, mL/s

τ = shear stress, Pa

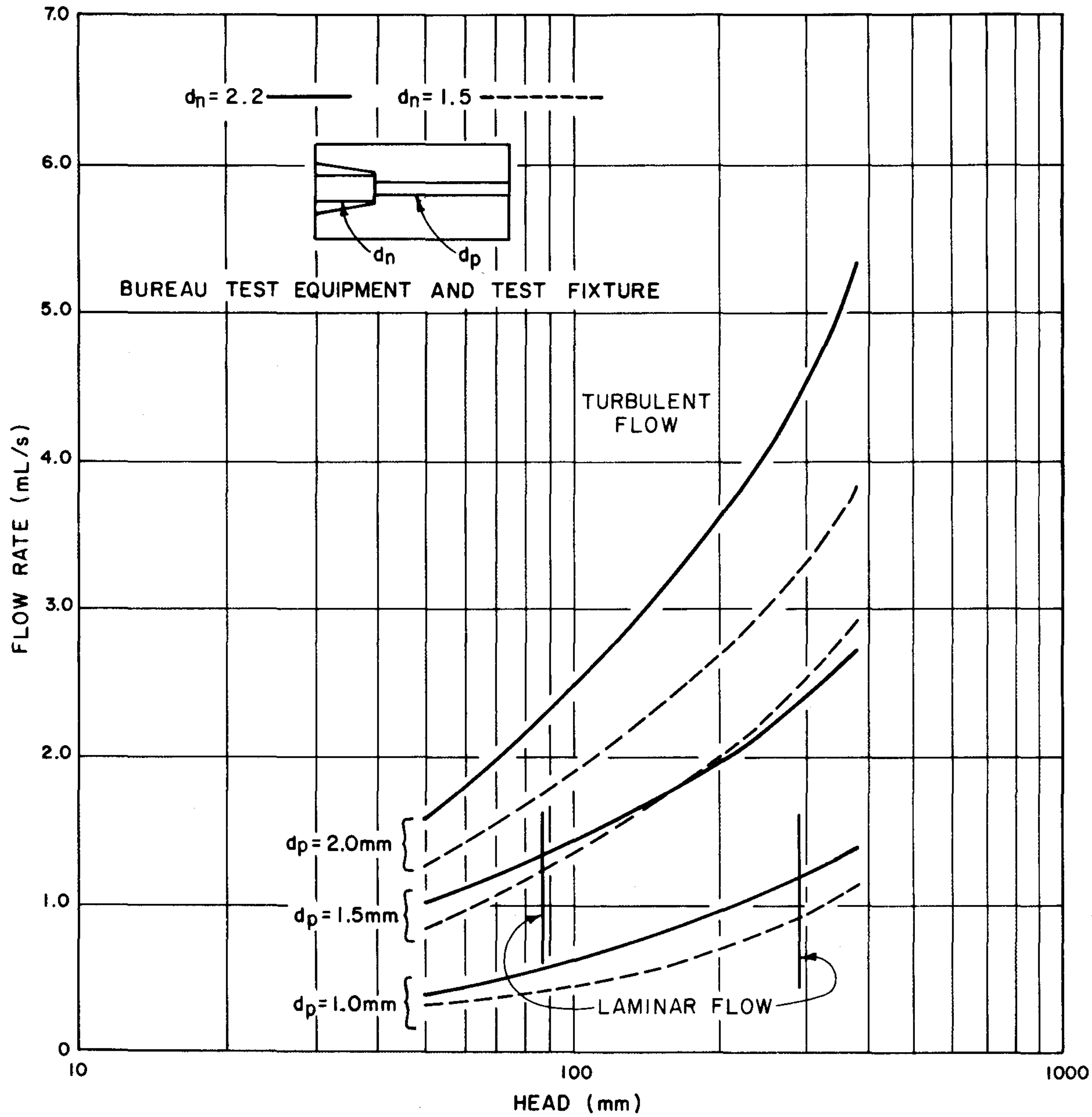


Figure 3.–Flow rates determined from tests of brass specimens (sheet 1 of 2).

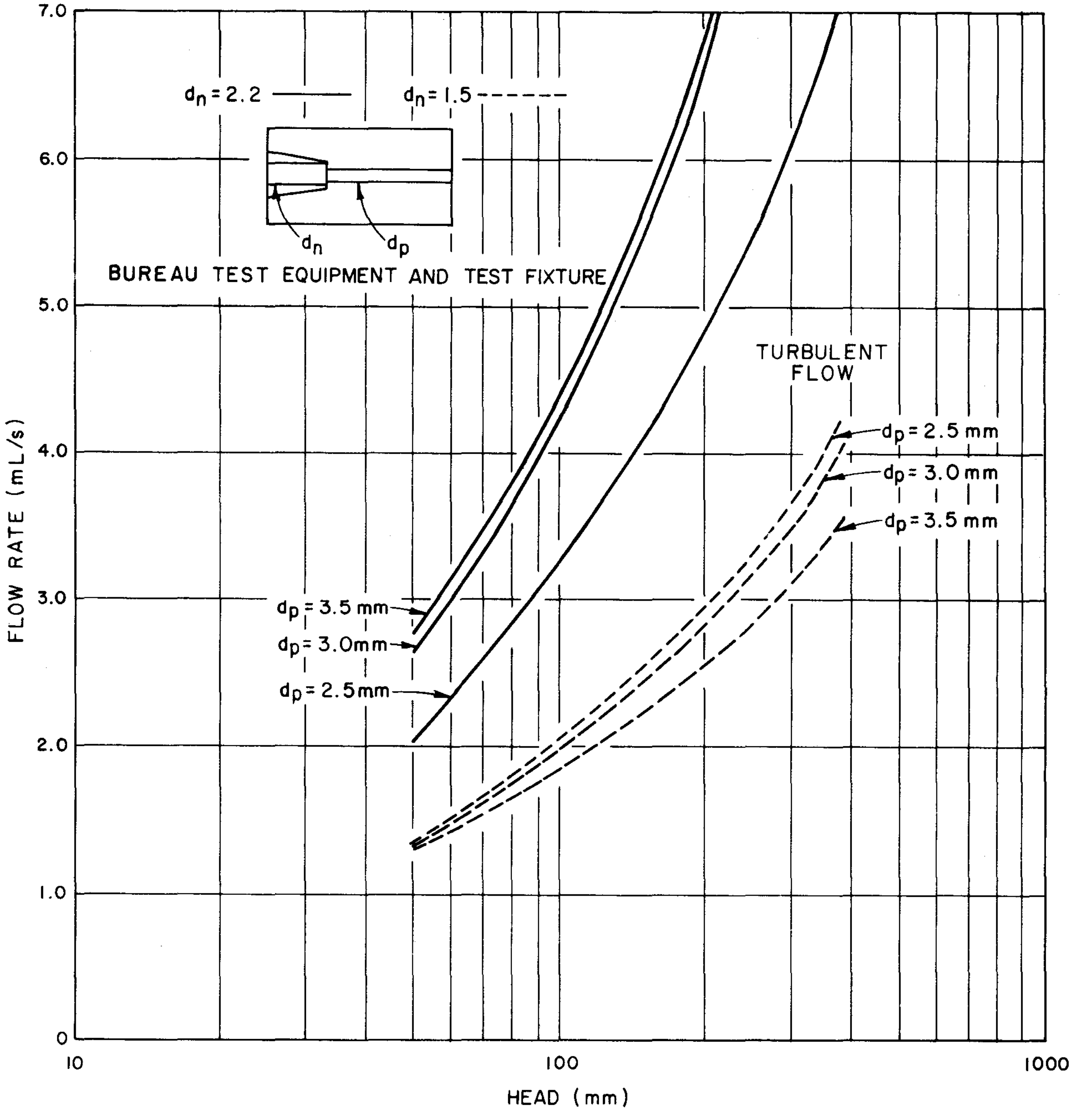


Figure 3.–Flow rates determined from tests of brass specimens (sheet 2 of 2).

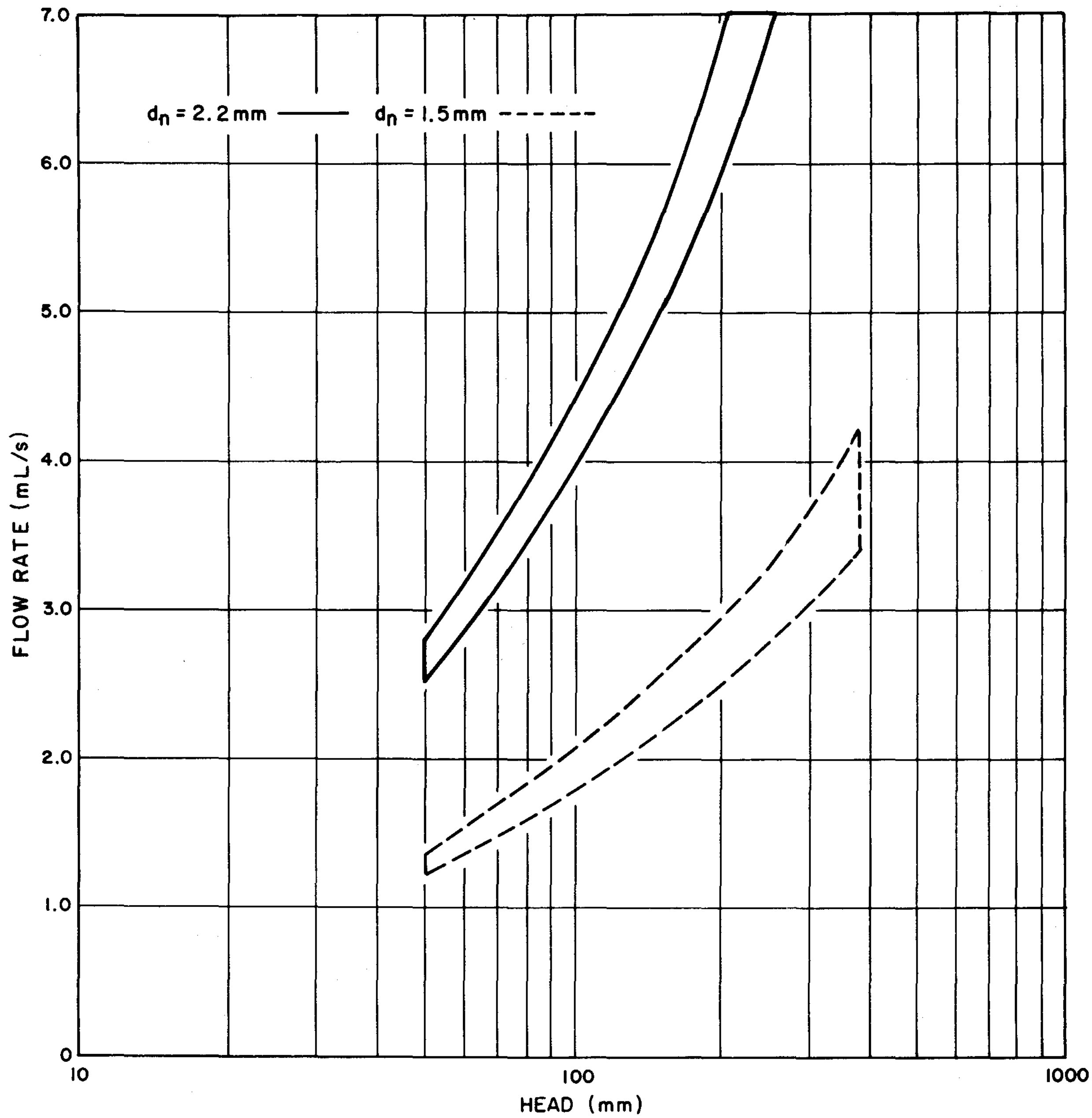


Figure 4.–Hydraulic capacity of Bureau pinhole equipment.

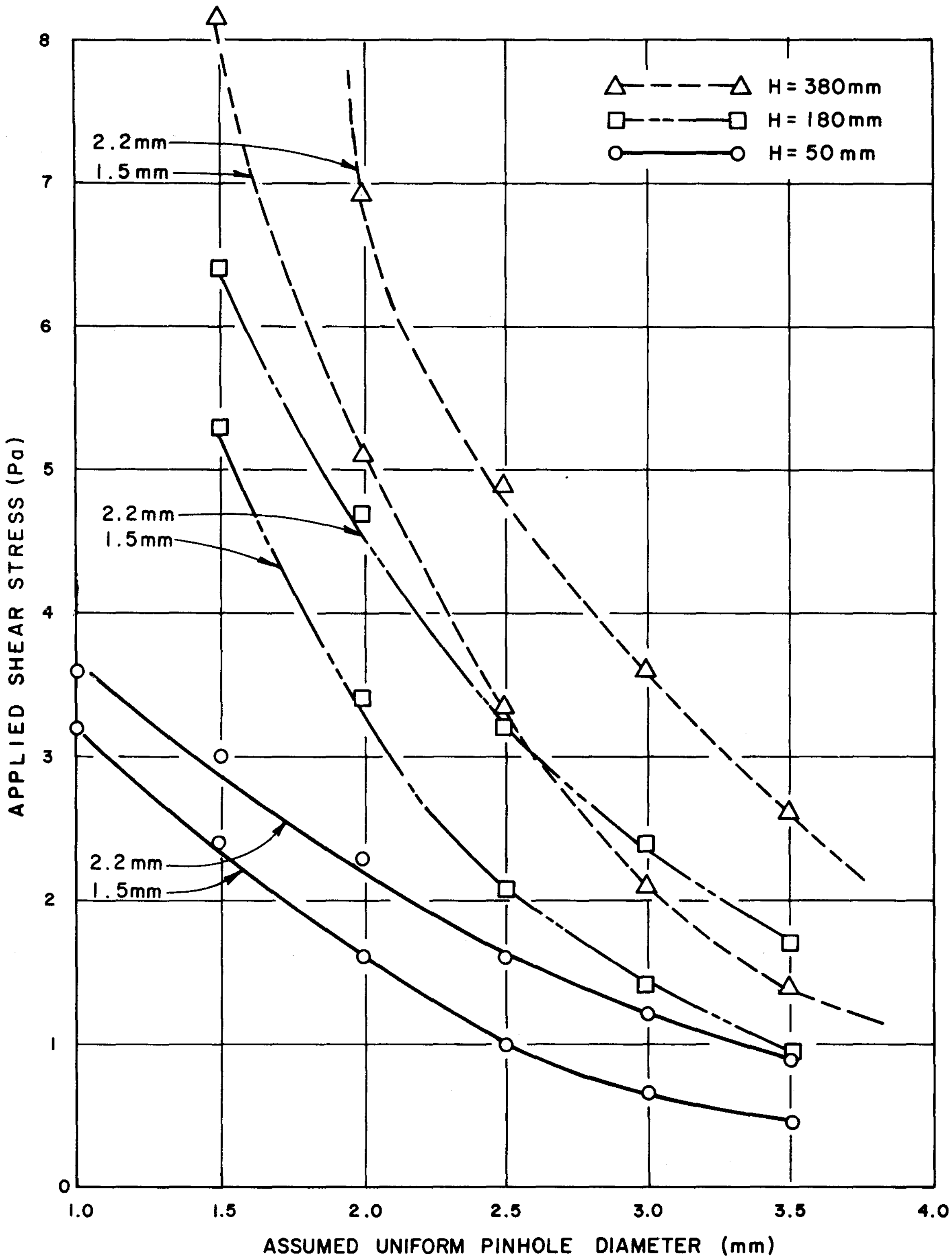


Figure 5.–Applied shear stress versus uniform pinhole diameter.

items were investigated as equipment design differences that could potentially be responsible for the hydraulic characteristic anomaly of lower flow rates at the 50-mm head using Bureau equipment:

- Bureau head tank and water supply system
- Bureau piping system components upstream of test cylinder
- Bureau brass nipple versus SCS plastic nipple friction
- Changes in inlet turbulence conditions due to different specimen locations within the test cylinder
- Differences in test cylinder design and configuration
- Differences in discharge end plate design and configuration

Bureau Head Tank and Water Supply System.–The flow rate curves on figure 3 were developed from test data generated at the Bureau's research laboratory in Denver, Colo. The same set of brass specimens and the brass nipple with the 1.5-mm-diameter hole, originally used at the Bureau's laboratory, were used for the investigation at the SCS laboratory. The Bureau test cylinder and end plates were connected to the SCS head tank and test fixture, and the flow rates obtained were nearly identical to the flows obtained at the Bureau laboratory. This test confirmed that the head tank and water supply tubing of the two agencies, although slightly different, did not affect the hydraulic capacity of either system.

Bureau Piping System Components Upstream of Test Cylinder.–The Bureau's test cylinder had several piping system components upstream of the test cylinder intake end plate (fig. 1). To determine if significant head loss was occurring due to these piping system components, a series of flow rate tests was conducted with successive elimination of each individual component. The 3.0-mm-diameter brass specimen and the brass nipple with the 1.5-mm-diameter hole were installed in the test cylinder during testing. The test results, summarized in table 5, showed that no measurable head loss occurred due to the extra piping system components. The flow rates determined during this testing were again very similar to those originally generated at the Bureau laboratory.

Nipple Friction, Inlet Turbulance, and Cylinder Design.–The following items were investigated essentially simultaneously for increased testing efficiency:

- Bureau brass nipple versus SCS plastic nipple friction
- Changes in inlet turbulence conditions due to different specimen locations within the test cylinder
- Differences in test cylinder design and configuration

For this series of tests, the brass specimens with 1.0-, 2.0-, and 3.0-mm-diameter holes were alternately installed in the SCS test cylinder. As shown on figures 1 and 2, there is a difference in the location of the test specimen with respect to the inlet water intake portion of the test apparatus for the two agencies. To determine if inlet turbulence conditions affected the system flow rates, the location of the simulated specimen was varied within the test cylinder. The specimen was located 5, 25, and 45 mm from the water inlet end plate. At each location, flow

Table 5.–*Flow rates in mL/s using Bureau's piping system components*

Components tested	Head (mm)		
	50	180	380
A B C D E	1.1	2.4	3.8
A B C D	1.2	2.4	3.8
A B	1.1	2.5	3.9
A	1.2	2.5	3.9
Hose inserted directly into end plate	1.2	2.5	3.8

rates were determined with the head tank positioned to provide 50, 180, and 380 mm of headwater with respect to the pinhole elevation. A duplicate series of tests was conducted using the SCS plastic nipple and the Bureau brass nipple installed in the same brass specimen. The test results, summarized in table 6, show that no trend could be identified for variance in flow rate as a function of specimen location within the test cylinder.

The results of the testing summarized in table 6 indicated:

1. No significant difference was observed in flows through either the brass or plastic nipples.

2. The slight difference in flow rates as a function of specimen location within the test cylinder was within the reproducibility limits of the test.

3. The difference in test cylinder lengths did not affect system flow rates.

The results of all the preceding tests and evaluations indicated that all equipment differences upstream of the simulated specimen and nipple did not account for the flow rate anomaly. This finding isolated the anomaly in hydraulic characteristics to a difference in the design of the test cylinder and the end plates of the equipment.

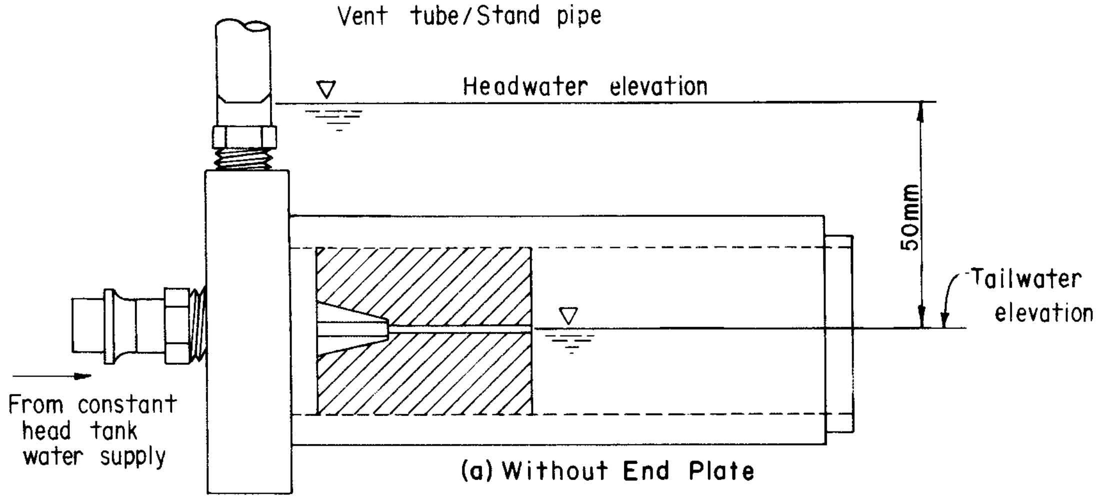
Discharge End Plate Design.–To investigate the effect of the discharge end plates of both the SCS and Bureau equipment, the brass nipple with the 1.5-mm-diameter hole was inserted into the brass specimen with the 3.0-mm-diameter hole. This assembly was then tested in the test cylinders of both agencies, with their respective end plates. Flow rates under the same headwater conditions (50 mm difference in elevation between the headwater and pinhole) were once again found to be 1.2 to 1.3 mL/s (Bureau) and 1.9 to 2.0 mL/s (SCS). The end plates of both cylinders were then removed, and flow rates were determined to be 1.2 to 1.3 mL/s through both agency's equipment. Equalization of the flow rates occurred with atmospheric pressure at the discharge end of the simulated pinhole specimen in the SCS test cylinders. When the SCS end plate was reattached to the SCS cylinder, the flow rate increased to the 1.9 to 2.0 mL/s previously determined under the same hydrostatic headwater condition. Therefore, the flow rate increase occurred as a result of the head increase on the system when the tailwater elevation was lowered by reattaching the discharge end plate to the SCS test cylinder (fig. 6).

The end plate and water discharge nozzle of the SCS equipment were responsible for creating a vacuum downstream of the specimen when the outlet nozzle became totally submerged and subject to full pipe-flow conditions. This caused the tailwater elevation of the system to lower from the elevation of the pinhole to the elevation of the bottom of the discharge nozzle (fig. 6). This phenomenon was visually investigated by conducting tests without a gravel pack downstream of the specimen to allow observation of the discharge water level in the test cylinder. It was observed that flow rates increased when the water outlet end plate was systematically rotated. This procedure allowed the water level in the test cylinder stilling basin downstream of the specimen to collect and raise high enough to submerge the outlet nozzle. When the discharge end plate was returned to the original position, without interrupting flow, the flow rate was maintained at the higher rates of 1.9 to 2.0 mL/s. The inability of the system to discharge the water accumulated in the stilling basin indicated the presence of a vacuum in the test cylinder downstream of the simulated specimen. The flow rates that were obtained by systematically rotating the position of the discharge end plate are shown on figure 7. Rotating the end plate allowed the flow to occur under partially or totally submerged outlet nozzle conditions.

Table 6.–*Flow rates in mL/s with specimen at different locations within test cylinder*

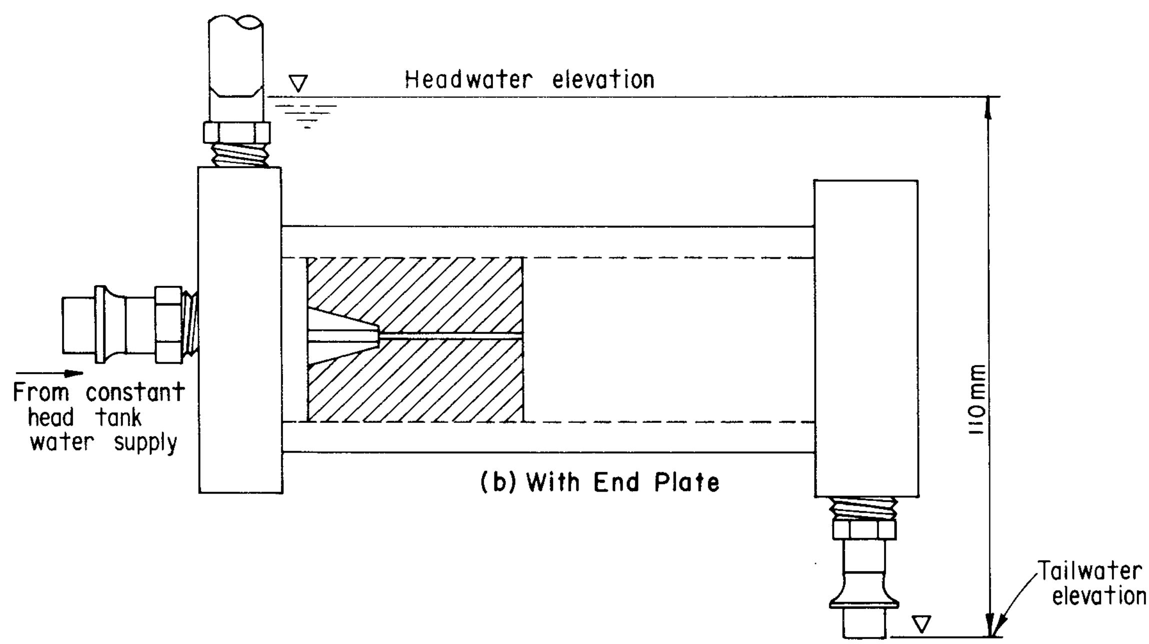
Nipple, 1.5-mm-diameter hole	Pinhole diameter, mm	Distance from water inlet to specimen, mm								
		5	25	45	5	25	45	5	25	45
			50 mm*			180 mm*			380 mm*	
SCS (plastic)	1.0	0.31	0.37	0.36	0.71	0.83	0.76	1.3	1.3	1.2
Bureau (brass)	1.0	0.37	0.38	0.37	0.85	0.82	0.78	1.4	1.3	1.3
SCS (plastic)	2.0	1.4	1.5	1.5	2.5	2.7	2.6	3.9	4.1	3.7
Bureau (brass)	2.0	1.8	1.7	1.8	2.9	2.5	2.9	4.2	3.8	4.1
SCS (plastic)	3.0	1.9	1.8	1.8	2.8	2.8	3.0	4.1	4.2	4.3
Bureau (brass)	3.0	1.9	2.2	2.0	3.0	3.6	3.2	4.1	5.3	4.8

* Difference in elevation between headwater and centerline of pinhole specimen.



(a) Without End Plate

Flow rates through the brass nipple with 1.5-mm-diameter hole inserted in the brass simulated specimen with 3.0-mm-diameter hole, without the discharge end plate, were determined to be 1.2 - 1.3 mL/s. Head on system is 50mm, calculated as distance from headwater elevation to centerline of pinhole.



(b) With End Plate

When the discharge end plate was attached to the equipment configuration shown in (a), the flow rates increased to 1.9-2.0 mL/s. Head on system is 110mm, calculated as distance from headwater elevation to bottom of discharge end plate water nozzle.

Figure 6.–Flow rate with atmospheric pressure and vacuum conditions.

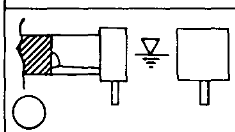
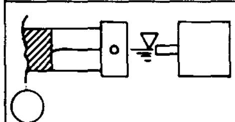
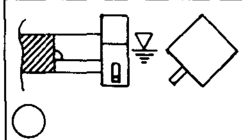
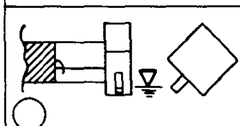
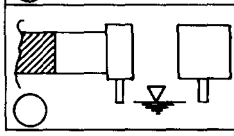
ATMOSPHERIC CONDITIONS - OUTLET NOZZLE OPEN				
SKETCH	HEADWATER TANK LEVEL (mm)	TOTAL HEAD (mm)	NOZZLE POSITION	FLOW RATE, Q (mL/s)
	50	50	OPENING DOWN VERTICAL	1.2
	50	50	OPENING HORIZONTAL	1.0
	50	50	OPENING AT 45° FROM VERTICAL	1.2
VACUUM CONDITIONS - OUTLET NOZZLE SUBMERGED				
SKETCH	HEADWATER TANK LEVEL (mm)	TOTAL HEAD (mm)	NOZZLE POSITION	FLOW RATE, Q (mL/s)
	50	90	OPENING AT 45° FROM VERTICAL	1.7
	50	110	OPENING DOWN VERTICAL	1.9

Figure 7.–Position of discharge end plate and outlet nozzle.

In summary, two distinctly different flow rates were achieved through the SCS pinhole test apparatus while the headwater elevation remained at the level required for 50 mm of head with respect to the elevation of the pinhole. The reason for the two different flow rates involves the discharge end plate. When the end plate was either completely removed or attached to allow atmospheric pressure in the test cylinder downstream of the simulated specimen, the flow rates were 1.2 to 1.3 mL/s with a 50-mm head. When the end plate was attached with the water outlet nozzle submerged, the flow rates increased to 1.9 to 2.0 mL/s under the same 50-mm headwater level. This higher flow rate corresponds to a total head value of 100 to 110 mm on the calibration curves originally obtained from the Bureau apparatus (fig. 4). The geometry of the SCS pinhole apparatus (fig. 6) indicates how the additional 60 mm of elevation difference exists between the level of the pinhole and the bottom of the discharge nozzle. This observation fully explains why the SCS equipment produced higher flow rates than the Bureau equipment at the "apparent" 50-mm head.

Additional Quantitative Data.–To conduct additional tests, the SCS pinhole test apparatus was moved to the Bureau's laboratory in Denver and fitted with a U-tube manometer positioned at the top of the discharge end plate with valves to control atmospheric pressure in the test cylinder and U-tube (fig 8). This modification allowed measurement of the vacuum created in the test cylinder downstream of the specimen as the outlet nozzle became submerged and subject to full pipe-flow conditions.

A series of flow rate tests were conducted by inserting the brass nipple with the 1.5-mm-diameter hole and brass specimen with the 3.0-mm-diameter hole into the SCS test cylinder with no gravel pack installed downstream of the specimen. Flow rates were determined under both atmospheric and vacuum conditions in the test cylinder downstream of the brass specimen. The headwater elevation was set 50 mm above the brass specimen pinhole elevation for all tests. Figure 9 shows the relationship between the water levels in the U-tube due to vacuum conditions with a 60-mm drop in tailwater (fig. 6). During the remainder of the vacuum portion of the testing, the tailwater elevation of the system was successively lowered in about 50-mm increments by attaching various lengths of plastic tubing to the discharge nozzle. Figure 10 shows the relationship between the water levels in the U-tube and a typical length of plastic tubing added to the discharge nozzle. The data obtained is given in table 7, and also shown on figure 11 to show the correlation with the Bureau calibration curve (fig. 3).

The results of this testing confirmed that flow rates increased when the nozzle outlet became submerged, and continued to increase with successive lowering of the system's tailwater. From the analysis and test evaluation of the original SCS pinhole test equipment, the conclusion became apparent that the initial development of the pinhole test was done using equipment that created higher hydrostatic heads during testing when the water outlet nozzle became submerged. This phenomenon becomes extremely important because the basis for determining clay dispersibility occurs at very low hydraulic heads, about 50 mm. Sherard, et al. [1], reported that dispersive clays erode rapidly, within 5 minutes after the start of flow, under a 50-mm head. Also, final flow rates through the specimen at the 50-mm head must be greater than 1.5 mL/s, which is dictated by the hydraulic capacity of the equipment. The previous discussions have shown that flow rates greater than 1.2 to 1.3 mL/s cannot occur at a 50-mm head. Paragraph 10, appendix I of Sherard's paper [2] notes that the hydraulic capacity of the SCS pinhole test equipment is 1.5 to 2.0 mL/s at a 50-mm head, but the test data summarized in this report indicate that flow rates of that magnitude exist only at about a 100- to 110-mm head.

A comparison of the flow rates versus the difference in elevation between the headwater and pinhole of the SCS and Bureau equipment, using the same brass specimen and brass nipple configuration, is given on figure 12, and figure 13 compares the hydraulic capacities of the equipment.

The flow rate bands on figure 13 exist because of the limits of reproducibility of the pinhole test (app. D). The SCS curve on figure 13 can be made to "match" the Bureau curve by shifting each boundary of the SCS curve about 50 to 60 mm to the right. This distance corresponds to the difference in elevation of the water nozzle with respect to the pinhole in the test specimen.

From the previous presentation of test data and mathematical analysis, it has been shown that:

1. At a 50-mm head, and with atmospheric pressure in the test cylinder downstream of the test specimen, the hydraulic capacities of the SCS and Bureau pinhole test equipment are virtually identical; i.e., 1.2 to 1.3 mL/s.

2. A flow rate greater than 1.5 mL/s cannot be achieved at a 50-mm hydrostatic head through the pinhole equipment using a nipple with a 1.5-mm-diameter hole.

3. The hydraulic capacity of both the Bureau and SCS test equipment is governed by the nipple with the 1.5-mm-diameter hole.

Table 7.—*SCS vacuum system—hydraulic head and flow rates with successively lowered tailwater*

Tailwater position No.	Tube length[1], mm	U-tube reading, mm			Tube head loss[2] mm	Total system head, mm	Flow rate, mL/s
		Vacuum	Left	Right			
1	0	0	1783	2385	0	50	1.2
2	60	49	1808	2361	11	99	1.7
3	116	88	1827	2341	18	138	2.2
4	165	121	1844	2325	54	171	2.4
5	225	163	1865	2304	62	213	2.9
6	267	194	1880	2288	83	244	3.1
7	320	229	1898	2271	91	279	3.4
8	370	259	1912	2255	111	309	3.6
9	415	285	1928	2245	130	335	3.6

[1] Length of tube attached to discharge water outlet nozzle.
[2] Additional head loss from flow through discharge tubing.

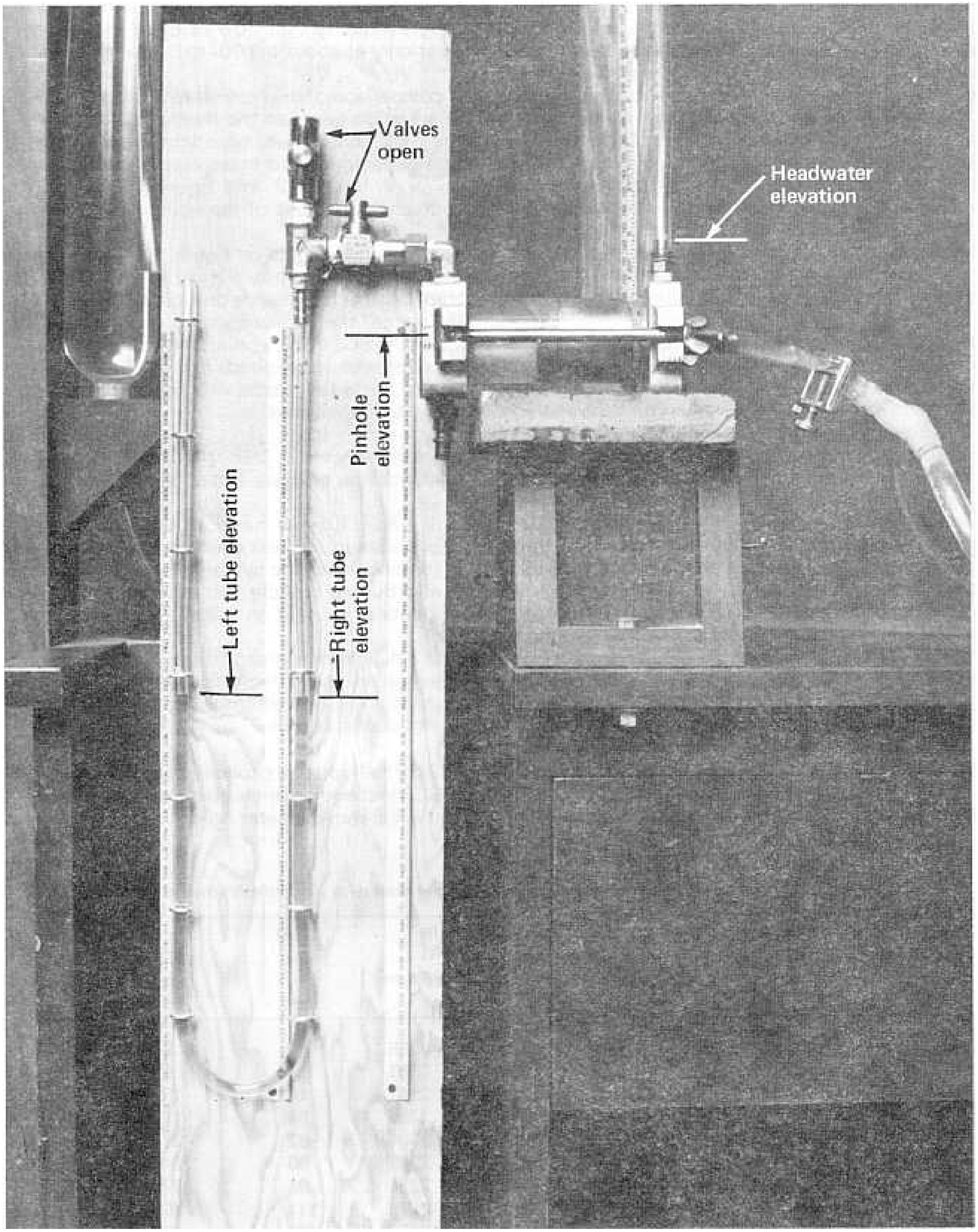
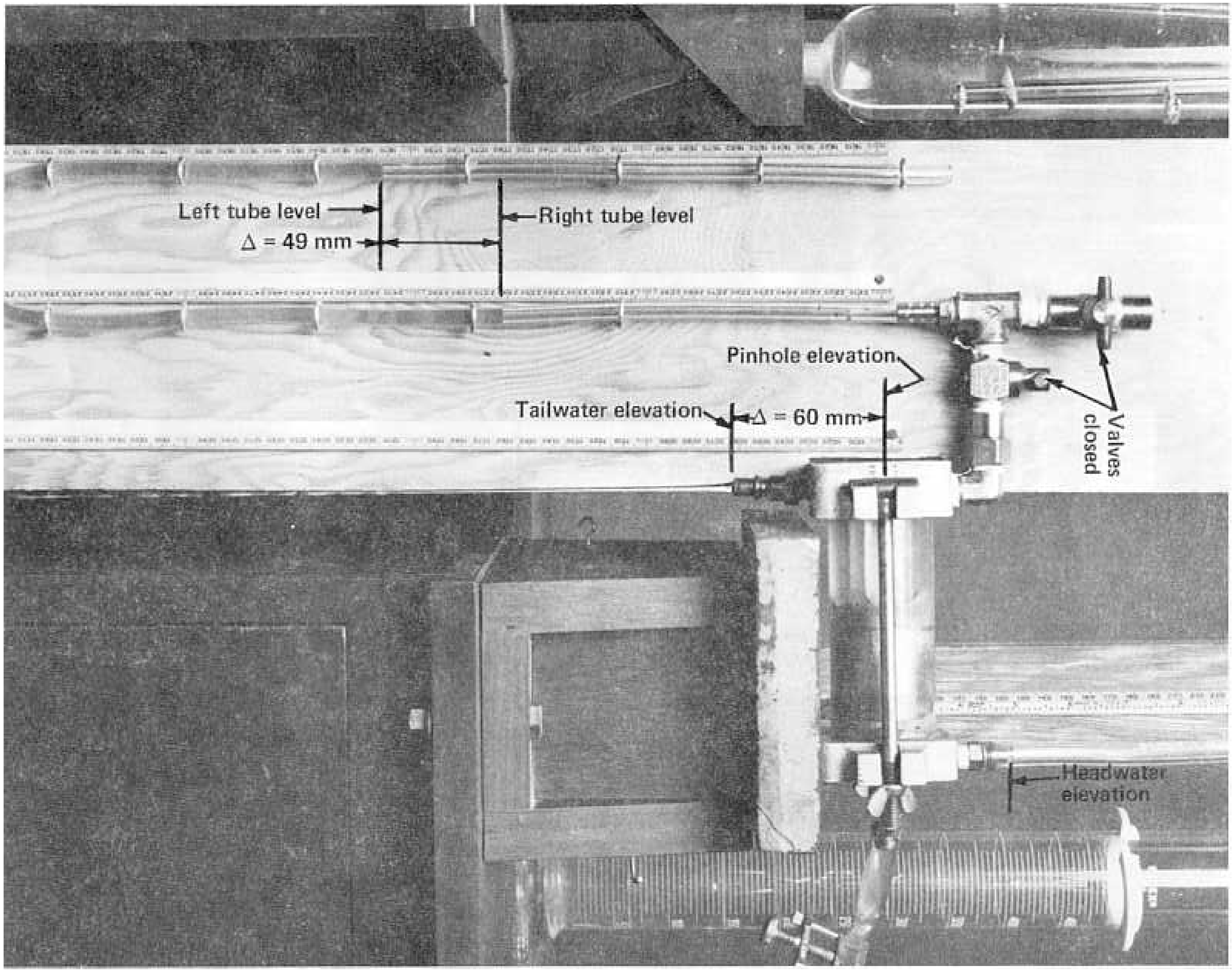
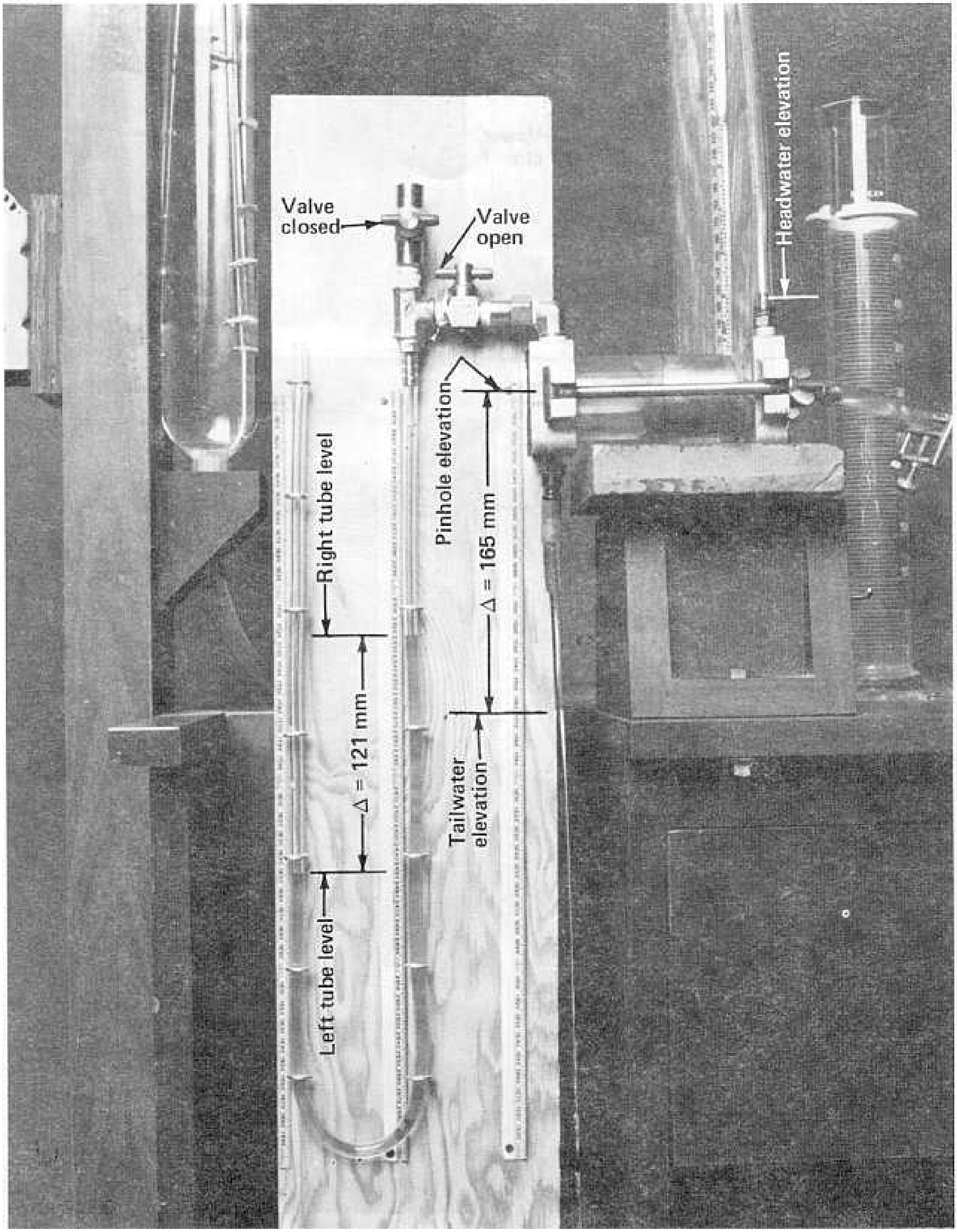


Figure 8.–Manometer and valve installation on SCS apparatus.


Left tube level
Δ = 49 mm
Right tube level
Pinhole elevation
Tailwater elevation
Δ = 60 mm
Valves closed
Headwater elevation

SC



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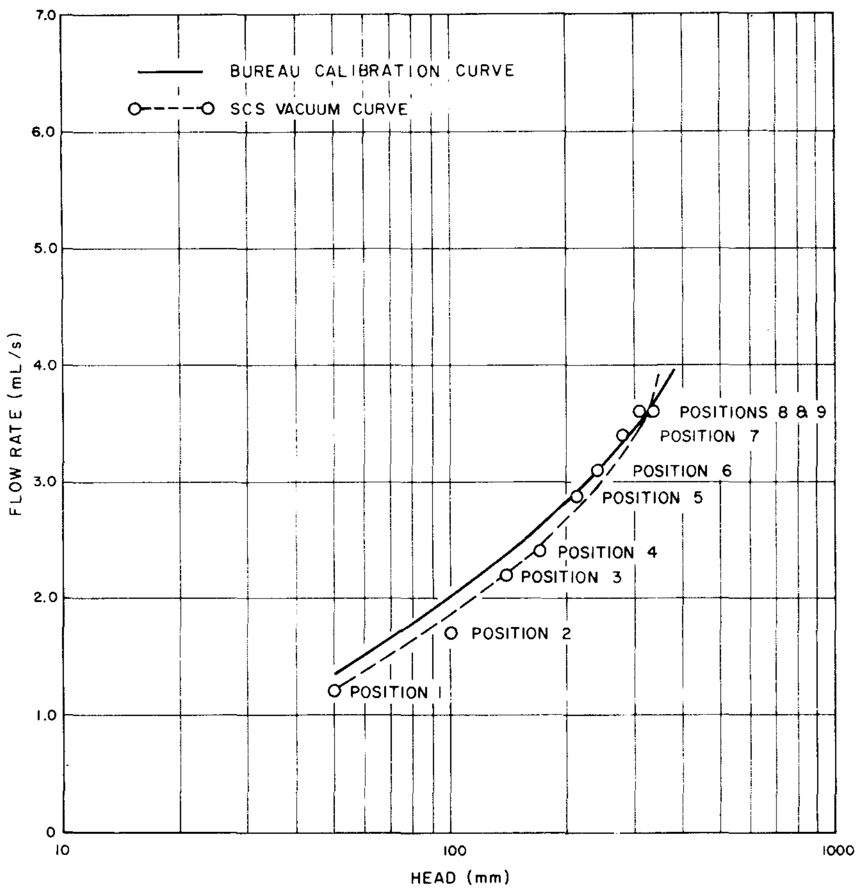

Figure 11.–Bureau calibration curve versus SCS vacuum curve.

4. The hydraulic characteristics of both the Bureau and SCS pinhole equipment are reproducible to two significant digits with an accuracy of plus or minus 15 percent.

Data Base for Developing a Quantitative Method for Evaluating Pinhole Test Results

A major objective of the Bureau's efforts in identification of dispersive clays has been to develop a test method with a quantitative basis for evaluating clay dispersibility. Sherard's work [2] was "... not intended to be used as a quantitative test for measuring rates of erosion as a function of the velocity of flowing water." In fact, the statement is made in [2] that "... the main indicator or failure is the colloidal color of the water (flowing through the test specimen under a 50-mm hydrostatic head)."

During November 1981, a return visit was made to the SCS laboratory in Lincoln, Nebr., to review data from more than 1200 original pinhole tests used in compiling data to support Sherard's paper [2]. During that visit, discussions with the original authors revealed that system flow rates were intended to be included in the paper as informative comments, not as exclusive evaluation criteria. However, that fact was regrettably insufficiently emphasized in the text, tables, and appendix I of the paper. Several Government agencies including the Bureau of Reclamation and Corps of Engineers, the Soil Bureau of New Zealand, various geotechnical engineering consultants, and other users/operators have concluded that flow rate observations can provide meaningful, objective, measurable data for dispersive clay evaluation. With the intent of categorizing the original pinhole test data with respect to measured flow rates as opposed to effluent turbidity, flow rate data from about 950 pinhole tests were reviewed. Of these data, 318 tests were from soil specimens that demonstrated a dispersive reaction (D1 or D2) in the pinhole test. The test data were reviewed for two specific features:

(1) Initial, final, and rate of increase in system flow rates under the "apparent" 50-mm head; and

(2) Observation of the time required to reach the hydraulic capacity of the system using the 1.5-mm-diameter nipple hole at the initial 50-mm hydraulic head.

Appendix B contains a detailed summary of test data from SCS pinhole tests No. 270 through 1200. A brief summary of the data is given in table 8.

Of the tests reviewed, 84 percent indicated pinhole erosion to a diameter greater than 1.5 mm within 5 minutes of testing under an initial hydrostatic head of 50 mm. Concurrent with, or subsequent to, erosion of the pinhole, the flow rate increased to a constant value greater than 1.5 mL/s as the submergence of the outlet nozzle increased the hydraulic head to 110 mm. Some 43 percent of the specimens were originally classified dispersive (table 1) even though the flow rates were less than the 1.5 mL/s value. In all cases, the discharge effluent of these dispersive soils had been visually classified as either slightly cloudy, cloudy, or dark.

Additional Interpretation of Original SCS Test Data

As stated earlier in this report, the quantity of flow in the pinhole test apparatus, under a constant hydrostatic head, is a function of the minimum cross-sectional area and the length of the cylinder with that cross section. For soils that erode rapidly (dispersive), the 1.5-mm-diameter nipple hole controls the flow rate. For soils that do not erode or erode slowly (nondispersive to intermediate), the soil specimen pinhole diameter controls the flow rate. The hydraulic capacities for a 1.5-mm-diameter nipple hole and a 1.0-mm-diameter pinhole for hydrostatic heads of 50, 180, and 380 mm are given on figure 14. The data as presented are the ranges obtained from testing the brass specimens and nipples with an additional plus or minus 15 percent included for operator and equipment variance. Figure 14 was developed directly from figure 13 and by using data from Sherard's original paper [2], table 8, and the interpretation of Bureau flow rate data generated using brass specimens.

Figure 15 was constructed so that a dispersive grade could be assigned to a soil specimen based on flow rates from various hydraulic restrictions:

- Nondispersive (ND1, ND2) – Flows restricted by the soil specimen 1.0-mm-diameter pinhole.
- Dispersive (D1, D2) – Flows restricted by the 1.5-mm-diameter nipple hole (subsequent to enlargement of the pinhole from 1.0 mm to plus 1.5 mm diameter).
- Intermediate (ND3, ND4) – Flows restricted by soil specimen pinhole diameters between 1.0 and 1.5 mm.

Plots of several pinhole tests conducted by the Bureau using figure 15 are given in appendix C.

The flows from the new flow rate criteria developed in this investigation do not match the flows presented by Sherard in table 2 because:

1. Sherard did not intend to use flow rates as the primary criterion for assigning the D1-ND1 dispersive grades.

2. The flow rate ranges shown in appendix I and table 2 of reference [2] were originally developed from Sherard's general interpretation of flow rate data collected during the original specimen testing program. The flow rate investigations that form the basis of this report were conducted with considerable emphasis on reproducibility, accuracy, and precision limits of measuring flow quantities, and time collection intervals. Appendix D gives an analysis of the limits of precision, accuracy, and reproducibility of pinhole equipment.

3. The flow rates originally reported were higher due to the difference between actual and nominal hydraulic head as a result of submerging the SCS pinhole equipment outlet nozzle.

Table 8.—*Dispersive grade versus final system flow rates*

Dispersive grade	Number of pinhole tests			
	Q>1.5 mL/s	Q>1.0 mL/s Q<1.5 mL/s	Q<1.0 mL/s	Total
D1	173	68	43	284
D2	7	18	9	34
Total	180 (57%)	86 (27%)	52 (16%)	318 (100%)

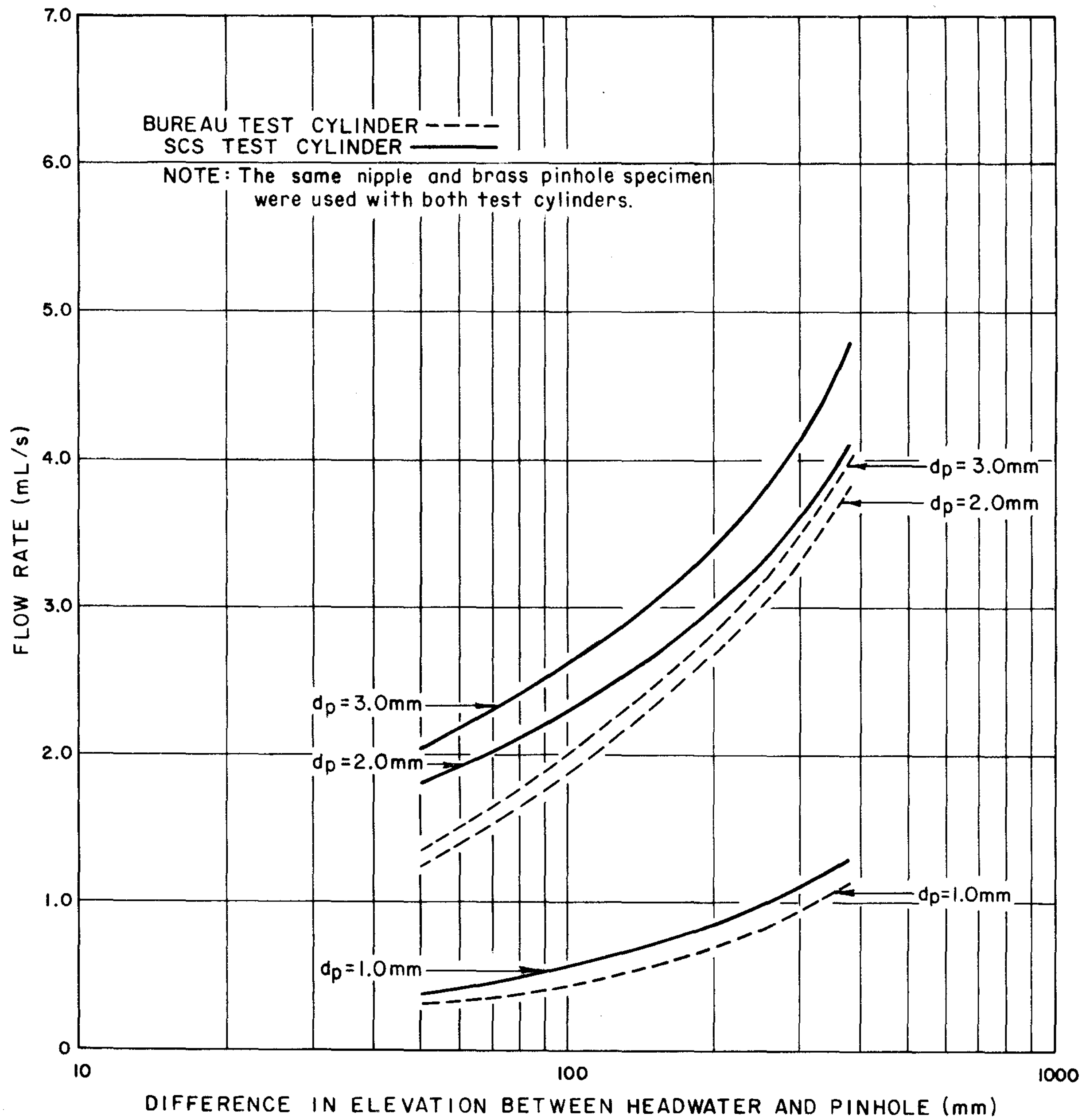

Figure 12.–Flow rate comparison between Bureau and SCS test cylinders.

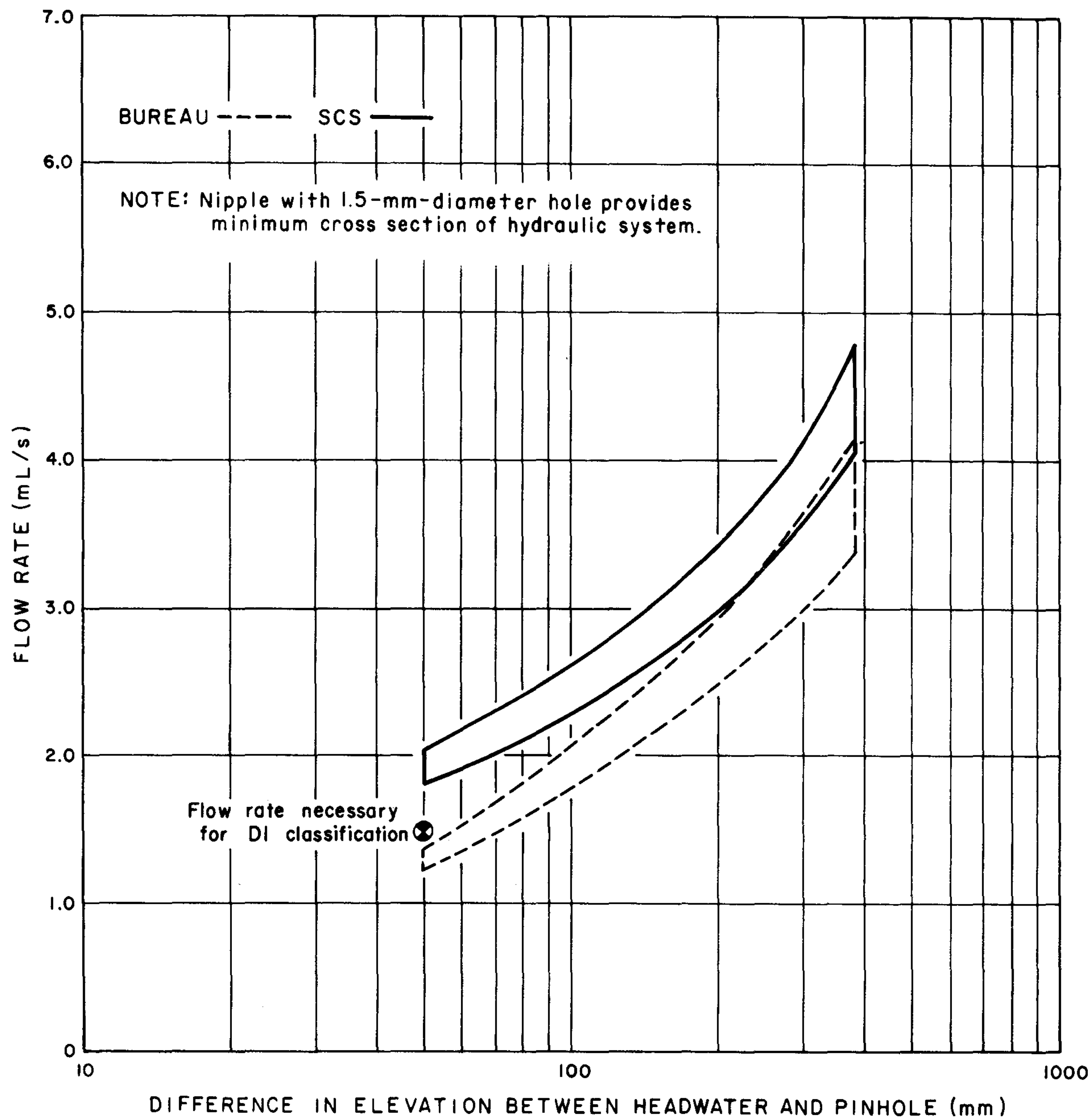

Figure 13.–Hydraulic capacity comparison between Bureau and SCS pinhole equipment.

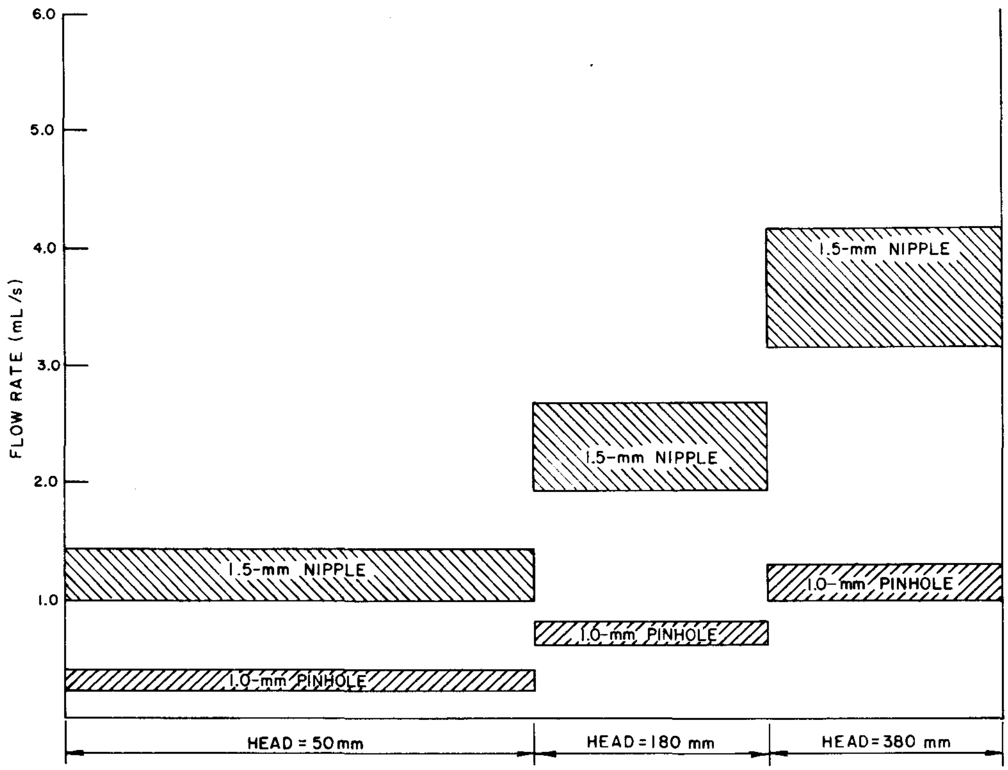

Figure 14.–Hydraulic capacity of pinhole equipment with nipple and pinhole restrictions.

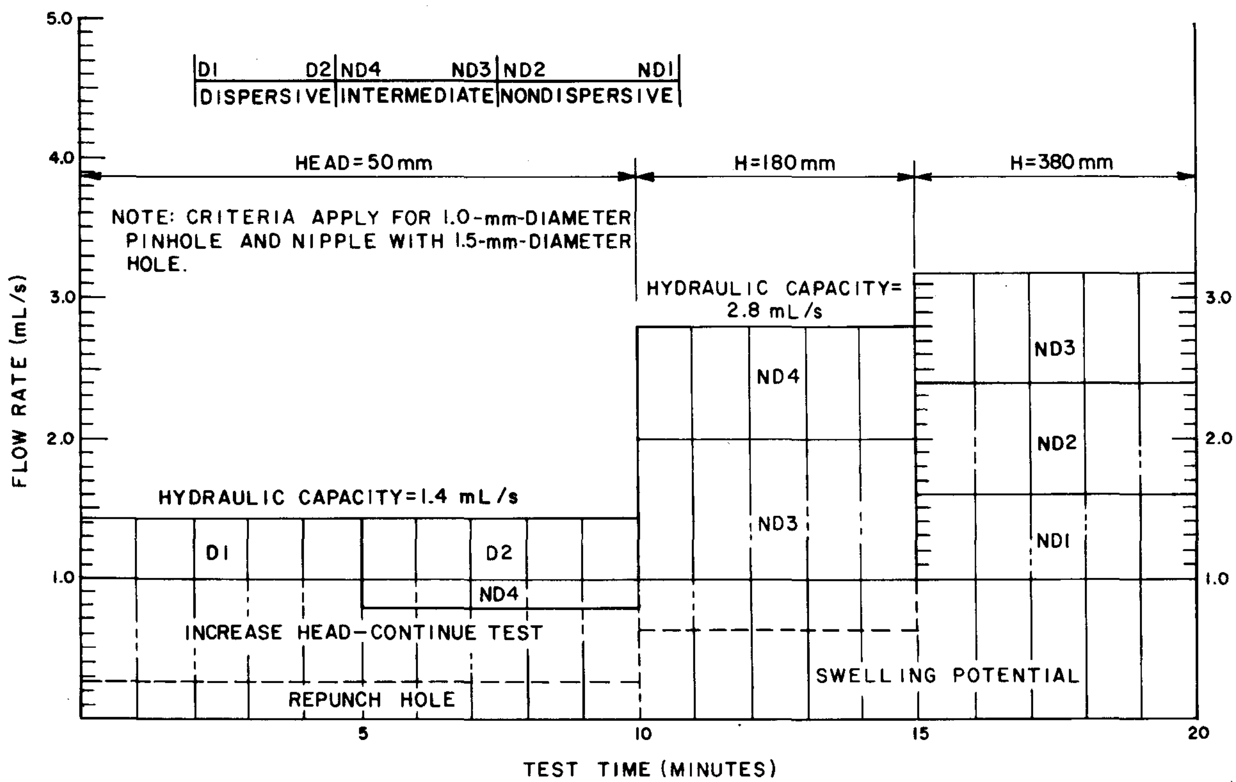

Figure 15.–Dispersive grade versus flow rate.

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APPENDIX A

HYDRAULIC ANALYSIS OF LAMINAR FLOWS THROUGH PINHOLE EQUIPMENT

Calculations shown in this appendix were used to determine flow rates, water velocities, and shear stresses associated with laminar flows through the pinhole equipment. A set of brass specimens and truncated cone nipples was fabricated to validate the analytical models with the physical testing. The intention of this appendix is to provide analytical support for evaluating pinhole test results on the basis of quantitative flow rate measurements; that is, eliminate or replace the subjective portions of the pinhole test as originally developed in reference [2]. When the Soil Testing Section of the Bureau began developing a test data base in 1977, the flow rates as presented in [2] were not reproducible. To validate the published flow rates, the hole in the brass nipple was enlarged from 1.5 to 2.2 mm in diameter. Additional investigations on the flow rates were pursued by testing new sets of brass specimens and nipples.

Figure A-1 show the hydraulic restrictions on the nipple hole and pinhole. Figure A-2 is a representation of the contraction and divergence between the nipple and pinhole, and also shows the coefficients of the contraction and divergence. Assumptions used throughout this analysis are:

1. Laminar flow conditions exist at heads up to 380 mm [2].

2. Total head loss is due to friction loss along the nipple and pinhole specimen.

3. Brass specimens and cohesive, smooth soil specimens have similar surface roughness over the ranges of laminar flows considered.

4. Final eroded shapes of the pinholes will be cylindrical, or the eroded volumes will match those of the cylinders used.

5. The soil-water "mud" slurry that is created adjacent to the eroded pinhope surface has no significant shear strength (i.e., Bingham Yield Strength).

From [2], the flow through the nipple and pinhole system can be calculated from:

$$H_L = \frac{V_n^2}{2g}\left(0.5 + \frac{f_n L_n}{d_n}\right) + \frac{V_p^2}{2g}\left(K + \frac{f_p L_p}{d_p} + 1.0\right) \qquad (1)$$

$$f_{n,p} = \frac{64}{R_e} = \frac{64\nu}{V_{n,p} d_{n,p}} \qquad (2)$$

where H_L = head loss, mm
$V_{n,p}$ = water velocity in nipple and pinhole, respectively, mm/s
$f_{n,p}$ = friction factor of nipple and pinhole, respectively
$L_{n,p}$ = length of nipple and pinhole, respectively, mm
$d_{n,p}$ = diameter of nipple and pinhole, respectively, mm
R_e = Reynolds number
ν = kinematic viscosity of water, mm^2/s
g = acceleration of gravity, mm/s^2
K = contraction or divergence coefficient from nipple to pinhole

Use equation (2) for the friction factor of the cylinder walls of the nipple and pinhole.

Laminar flow conditions were assumed through the nipple and pinhole where the pipe lengths are extremely long in relation to the diameter, allowing the assumptions of constant flow rate and constant velocity throughout the entire lengths; i.e., ignore the effect of vena contracta:

$$Q_p = Q_n$$
$$V_pA_p = V_nA_n$$
$$V_p = V_n(A_n/A_p)$$

where $Q_{n,p}$ = flow rate through nipple and pinhole, respectively, mL/s
$A_{n,p}$ = area of nipple and pinhole, respectively, mm^2
$V_{n,p}$ = (as previously defined)

Equation (2) can then be written:

$$f_p = \frac{64\,\nu}{V_n\left(A_n/A_p\right)d_p} = \frac{64\,\nu\,A_p}{V_nA_nd_p} \tag{2}$$

To obtain the head loss H_L as a function of V_n, equation (1) can be written:

$$H_L = \frac{V_n^2}{2g}\left(0.5 + \frac{64\nu L_n}{V_nd_n^2}\right) + \frac{V_n^2\ (A_n/A_p)^2}{2g}\left(K + \frac{64\nu L_pA_p}{V_nA_nd_p^2} + 1.0\right) \tag{1}$$

For ν = 0.984 mm^2/s (water at 21 °C)
g = 9820 mm/s^2
L_n = 13 mm, and L_p = 25 mm (from fig. 1)

$$H_L = \frac{V_n^2}{2(9820)}\left(0.5 + \frac{(64)(0.984)(13)}{V_nd_n^2}\right) + \frac{V_n^2\ (A_n/A_p)^2}{2(9820)}\left(K + \frac{(64)(0.984)(25)A_p}{V_nA_nd_p^2} + 1.0\right)$$

$$= 5.09 \times 10^{-5}\ V_n^2\,(0.5 + 819/V_nd_n^2) + [5.09 \times 10^{-5}\ V_n^2(A_n^2/A_p^2)][K + 1570\,A_p/V_nA_nd_p^2 + 1.0]$$

$$= 2.54 \times 10^{-5}\ V_n^2 + 4.17 \times 10^{-2}\ V_n/d_n^2 + [5.09 \times 10^{-5}\ V_n^2(A_n/A_p)^2]\ [K+1] + 7.99 \times 10^{-2}\ V_nA_n/A_pd_p^2$$

$$= V_n^2\ \left\{2.54 \times 10^{-5} + [5.09 \times 10^{-5}\,(A_n^2/A_p^2)]\ [K+1]\right\} + V_n\ (4.17 \times 10^{-2}\ /d_n^2 + 7.99 \times 10^{-2}\ A_n/A_pd_p^2)$$

Since $A_{n,p} = \pi d^2_{n,p}/4$, then $A_n/A_p = d_n^2/d_p^2$, and

$$H_L = V_n^2\ \left\{2.54 \times 10^{-5} + [5.09 \times 10^{-5}(d_n^4/d_p^4)][K+1]\right\} + V_n\ [4.17 \times 10^{-2}\ /d_n^2 + 7.99 \times 10^{-2}\ (d_n^2/d_p^4)]$$

Setting up as a quadratic equation of the form $AV_n^2 + BV_n + C = 0$,

$$\left\{2.54 \times 10^{-5} + [5.09 \times 10^{-5}\,(d_n^4/d_p^4)]\ [K+1]\right\}\ V_n^2 + [4.17 \times 10^{-2}/d_n^2 + 7.99 \times 10^{-2}\,(d_n^2/d_p^4)]\ V_n - H_L = 0$$

Let $AA = 5.09 \times 10^{-5}\ d_n^4/d_p^4$, and $AB = K + 1$

Then $A = 2.54 \times 10^{-5} + AA(AB)$

Let $BB = 8.01 \times 10^{-2}\,(d_n^2/d_p^4)$, and

$BC = 4.17 \times 10^{-2}/d_n^2$

Then $B = BC + BB$, and $C = -H_L$

$$AV_n^2 + BV_n + C = 0$$

Solution for this quadratic equation is:

$$V_n = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}$$

Computer solution follows:

PROGRAM FILE

```
      PROGRAM UNIPIN (INPUT,OUTPUT,TAPE1,TAPE2)
      WRITE(2,1100)
      WRITE(2,1200)
   10 C=0.-50.
      GO TO 40
   20 C=0.-180.
      GO TO 35
   30 C=0.-380.
   35 REWIND1
   40 READ(1,*)DN,DP,XK
      IF(EOF(1))2000,50
   50 AA=(.0000509*DN**2./DP**4.)
      AB=(XK+1.)
      A=.0000254+(AA*AB)
      BB=(.0799*DN**2./DP**4.)
      BC=.0417/DN**2.
      B=BB+BC
      BNEG=0.-B
      CNEG=0.-C
      BSQ=B*B
      RAD=(BSQ-(4.*A*C))**.5
      VN=(BNEG+RAD)/2.*A
      VP=VN*DN**2./DP**2.
      Q=VN*3.14*(DN**2.)*.001/4.
      WRITE (2,1300)DN,DP,XK,CNEG,VN,VP,Q
      GOTO40
 2000 L=L+1
      IF(L.EQ.1)20,2100
 2100 IF(L.EQ.2)30,2200
 1100 FORMAT (' DN   DP    K  HEAD   VN    VP   Q ')
 1200 FORMAT ('----------------------------------')
 1300 FORMAT (3(F4.2,1X),F4.0,1X,2(F5.0,1X),F5.3)
 2200 STOP
      END
```

INPUT FILE (d_p, d_n, k)

```
1.5,1.,.66
2.2,1.,.63
1.5,1.5,1.
2.2,1.5,.67
1.5,2.5,1.12
2.2,2.,.83
1.5,,2.5,1.12
2.2,2.5,1.17
1.5,3.,1.12
2.2,3.,1.16
1.5,3.5,1.109
2.2,3.5,1.13
```

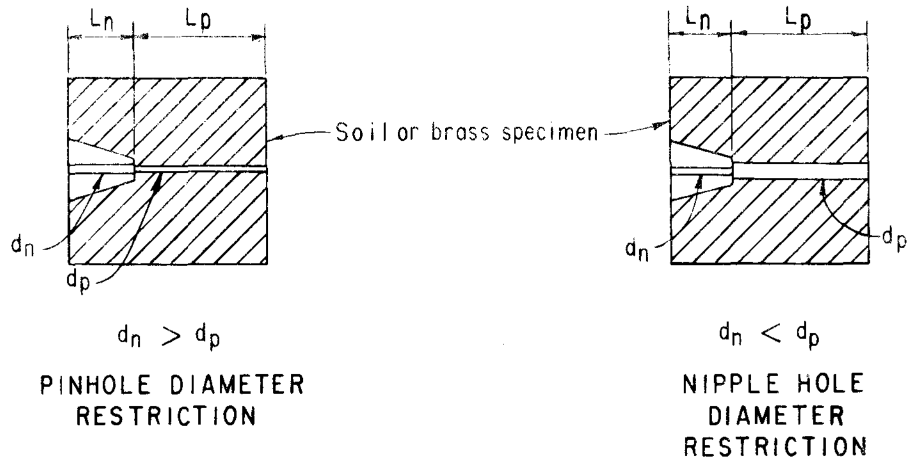
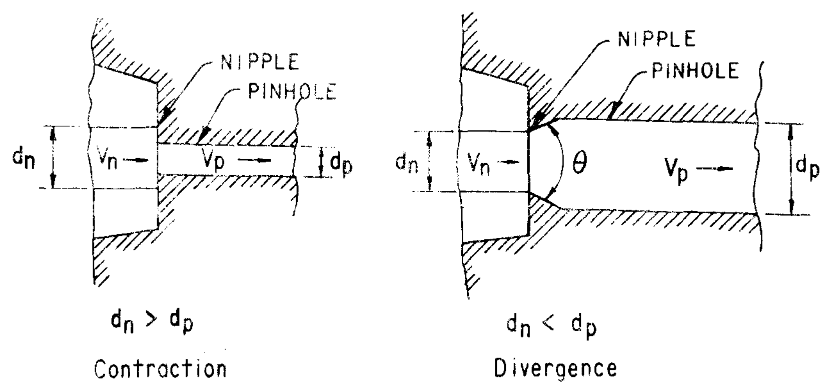


Figure A-1.–Hydraulic restrictions on pinhole and nipple hole.



(a) Representation of contraction and divergence between nipple and pinhole.

d_n NIPPLE HOLE (mm)	d_p SPECIMEN PINHOLE (mm)	AREA RATIOS $\frac{d_p^2}{d_n^2}$	θ ASSUMED WALL DIVERGENCE	INTERFACE COEFFICIENTS [1] CONTRACTION	DIVERGENCE
1.5	1.0	0.444	–	0.66	–
2.2	1.0	0.207	–	0.63	–
2.2	1.5	0.465	–	0.67	–
2.2	2.0	0.826	–	0.83	–
2.2	2.5	–	90°	–	1.17
2.2	3.0	–	90°	–	1.16
2.2	3.5	–	90°	–	1.13

[1] SEE REFERENCES [6, 7, 8]

(b) Coefficients of contractions and divergence.

Figure A-2.–Contraction and divergence data on nipple and pinhole.

FLOW RATE DATA OF 318 RANDOMLY SELECTED DISPERSIVE SOIL SAMPLES FROM SCS PINHOLE TESTS

Table B-1.—*Pinhole test specimen flow rates from original SCS data base generated from February 1974 to January 1975*

SCS pinhole test number	Test date	Dispersive grade	System flow rate (mL/s)		
			Initial[1]	Intermediate[2]	Final[3]
270	2-74	D1	0.19	0.67	1.4
271	2-74	D1	0.56	1.1	1.1
272	2-74	D1	0.59	1.1	1.2
273	2-74	D1	0.76	1.0	1.7
274	2-74	D1	0.42	0.50	0.77
275	2-74	D1	0.36	0.53	1.0
306	2-74	D1	0.71	1.1	1.5
309	2-74	D1	0.42	0.70	0.91
311	2-74	D1	0.40	0.96	1.1
313	3-74	D1	0.28	1.1	1.8
314	3-74	D1	0.46	0.93	1.4
315	3-74	D1	0.35	0.97	1.9
316	3-74	D1	0.63	1.1	2.0
317	3-74	D1	0.50	0.59	0.83
319	3-74	D1	0.63	0.83	1.4
320	3-74	D1	0.59	1.1	1.5
322	3-74	D1	0.40	0.59	0.59
324	3-74	D1	0.40	0.42	0.45
367	3-74	D1	0.83	1.0	1.5
370	3-74	D1	1.3	1.7	1.8
371	3-74	D1	0.40	0.83	1.4
374	3-74	D1	0.56	0.77	0.74
375	3-74	D1	0.42	1.3	1.4
402	3-74	D1	0.46	1.8	1.9
403	3-74	D1	0.28	0.40	0.63
404	3-74	D1	1.1	2.3	2.3
406	3-74	D1	0.27	0.4	1.0
414	3-74	D1	0.53	1.1	1.9
415	3-74	D1	0.71	1.0	1.8
416	3-74	D1	0.59	0.77	1.7
435	3-74	D2	1.4	1.4	1.4
436	4-74	D1	0.67	1.3	1.4
437	4-74	D2	0.67	0.91	1.3
438	4-74	D2	0.42	0.71	1.0
445	4-74	D1	1.4	1.7	1.6
455	4-74	D2	0.67	0.91	0.77
459	4-74	D2	0.33	0.40	0.63
460	4-74	D2	0.59	1.0	1.2
463	4-74	D1	0.77	1.4	1.8
470	4-74	D1	0.83	1.0	1.2
474	4-74	D1	0.77	1.0	1.0
479	4-74	D1	1.4	1.7	1.7
486	4-74	D1	0.53	0.77	0.74
491	4-74	D2	1.4	1.9	2.0
492	4-74	D1	0.62	0.77	1.5
500	4-74	D1	0.59	0.70	1.4
509	4-74	D1	0.48	0.62	0.83
512	4-74	D2	0.71	0.77	0.77
518	4-74	D1	0.56	1.1	1.1

Table B-1.—*Pinhole test specimen flow rates from original SCS data base generated from February 1974 to January 1975*—Continued

SCS pinhole test number	Test date	Dispersive grade	System flow rate (mL/s)		
			Initial[1]	Intermediate[2]	Final[3]
520	4-74	D1	0.48	1.0	2.8
522	4-74	D1	0.29	1.2	2.5
538	4-74	D1	0.40	0.70	0.70
539	4-74	D2	0.56	1.2	1.2
540	4-74	D1	0.67	1.0	1.3
541	4-74	D1	0.30	0.62	0.91
543	4-74	D1	0.50	1.4	1.8
544	4-74	D1	1.0	2.0	2.5
545	4-74	D1	2.0	2.0	2.0
546	4-74	D1	0.20	1.0	1.7
553	4-74	D1	0.33	1.0	1.9
556	4-74	D2	0.50	1.0	1.0
559	4-74	D1	0.59	1.0	1.7
561	5-74	D2	0.52	0.46	1.5
564	5-74	D2	0.35	0.52	1.3
567	5-74	D2	0.56	0.62	0.30
568	5-74	D1	0.77	1.5	2.0
569	5-74	D1	0.67	1.0	1.2
570	5-74	D2	0.71	1.0	1.5
571	5-74	D1	0.36	0.83	1.1
572	5-74	D1	0.53	1.2	1.9
574	5-74	D1	0.50	0.77	1.8
580	5-74	D2	1.0	1.2	1.5
583	5-74	D2	0.90	0.9	1.2
590	5-74	D1	0.40	0.83	1.2
592	5-74	D1	0.59	0.83	1.0
593	5-74	D2	0.50	0.70	1.9
597	5-74	D1	0.40	0.60	1.0
600	5-74	D1	0.40	0.75	1.0
601	5-74	D1	0.90	0.90	1.0
604	5-74	D1	0.40	0.40	0.35
605	5-74	D2	0.50	0.50	0.32
606	5-74	D1	0.56	1.6	2.1
607	5-74	D1	0.63	0.8	0.9
608	5-74	D1	0.30	0.5	0.5
612	5-74	D1	1.2	1.6	1.6
616	5-74	D1	0.21	1.0	2.5
617	5-74	D1	1.4	1.5	1.5
618	5-74	D1	0.30	0.71	1.9
621	5-74	D1	0.63	1.1	1.8
643	5-74	D1	0.27	0.71	1.1
644	5-74	D1	0.50	0.77	1.5
645	5-74	D1	0.36	1.0	1.2
646	5-74	D1	0.40	0.80	1.2
647	5-74	D1	0.30	0.25	0.25
648	5-74	D1	0.28	0.71	1.7
649	5-74	D1	0.25	0.60	1.7
650	5-74	D1	0.28	1.0	1.6
651	5-74	D1	0.35	0.59	1.7
652	5-74	D1	0.33	1.1	1.3

Table B-1.—*Pinhole test specimen flow rates from original SCS data base generated from February 1974 to January 1975*—Continued

SCS pinhole test number	Test date	Dispersive grade	System flow rate (mL/s)		
			Initial[1]	Intermediate[2]	Final[3]
653	5-74	D1	0.62	1.0	1.7
664	5-74	D2	0.29	0.90	1.3
671	6-74	D1	0.71	1.1	1.1
675	6-74	D2	0.59	0.83	0.83
677	6-74	D1	0.90	0.83	0.59
695	6-74	D1	0.42	0.68	0.68
698	6-74	D2	0.67	1.7	1.7
708	6-74	D1	0.26	1.1	1.8
709	6-74	D1	0.36	1.2	2.4
712	6-74	D2	0.46	0.90	1.9
716	6-74	D2	0.29	0.60	2.5
721	6-74	D1	0.40	0.90	1.0
736	6-74	D1	0.30	0.85	1.2
737	6-74	D1	0.35	0.80	1.5
738	6-74	D1	0.48	1.1	2.1
739	6-74	D1	0.56	1.1	1.5
740	6-74	D1	0.44	1.5	2.5
741	6-74	D1	0.90	1.5	2.4
742	6-74	D1	0.50	1.1	2.0
743	6-74	D1	0.55	1.2	1.9
745	6-74	D2	0.62	0.90	1.8
749	6-74	D1	0.56	0.56	0.56
750	6-74	D1	1.2	1.5	1.5
753	6-74	D1	0.59	0.83	1.0
754	6-74	D1	0.56	1.2	1.4
755	6-74	D1	0.56	0.71	0.86
756	6-74	D2	0.53	0.71	1.4
757	6-74	D2	0.83	0.83	0.67
759	6-74	D1	0.43	0.59	0.43
763	6-74	D1	0.56	0.67	1.0
764	6-74	D1	0.50	1.5	2.5
765	6-74	D1	0.59	1.1	1.7
766	6-74	D1	0.50	1.1	1.5
772	6-74	D1	0.20	1.7	2.5
773	6-74	D1	0.40	1.0	2.2
774	6-74	D1	0.25	1.0	1.1
775	6-74	D1	0.67	2.0	2.5
776	6-74	D1	0.59	1.1	1.7
777	6-74	D1	0.42	0.8	1.0
783	7-74	D1	0.37	1.0	2.5
784	7-74	D1	0.59	0.91	1.8
786	7-74	D2	0.37	1.0	1.3
787	7-74	D1	0.77	1.0	1.7
788	7-74	D1	0.56	1.3	1.7
794	7-74	D1	0.50	0.85	1.3
797	7-74	D1	1.2	1.5	1.5
798	7-74	D2	0.91	0.89	0.89
804	7-74	D1	0.77	0.80	0.80
806	7-74	D1	0.59	0.83	0.83

Table B-1.—*Pinhole test specimen flow rates from original SCS data base generated from February 1974 to January 1975*—Continued

SCS pinhole test number	Test date	Dispersive grade	System flow rate (mL/s)		
			Initial[1]	Intermediate[2]	Final[3]
807	7-74	D1	0.71	1.25	1.9
808	7-74	D1	0.77	0.90	1.8
809	7-74	D1	0.67	1.7	2.3
810	7-74	D1	0.71	1.1	1.9
811	7-74	D1	0.59	1.1	1.7
812	7-74	D1	0.42	1.1	1.3
814	7-74	D1	0.56	0.67	0.76
820	7-74	D2	0.34	0.44	0.93
824	7-74	D1	0.77	1.5	1.7
829	7-74	D1	0.56	1.0	1.5
830	7-74	D1	0.59	0.91	1.5
832	7-74	D1	0.42	0.40	0.40
836	7-74	D1	0.83	1.8	2.5
837	7-74	D1	1.0	1.6	1.7
845	7-74	D1	1.7	1.7	1.8
850	7-74	D1	0.59	1.2	1.5
860	7-74	D1	0.71	0.62	0.67
867	7-74	D1	0.59	0.67	0.92
870	7-74	D1	0.91	1.2	1.5
877	7-74	D1	0.77	1.2	1.6
879	7-74	D1	0.40	1.5	1.6
882	7-74	D1	1.0	1.7	2.1
889	7-74	D2	0.32	0.60	1.9
892	7-74	D1	1.2	2.0	2.0
896	7-74	D1	0.51	1.1	1.1
897	7-74	D1	0.56	1.0	2.0
898	7-74	D1	0.77	1.8	1.9
899	7-74	D1	0.42	1.0	1.8
902	7-74	D1	0.57	1.0	1.6
906	7-74	D1	0.67	1.6	1.9
907	7-74	D1	0.50	0.9	1.0
910	7-74	D1	0.59	0.83	0.83
915	8-74	D1	0.91	1.0	1.2
916	8-74	D1	1.0	1.7	2.0
917	8-74	D1	0.48	1.0	2.5
918	8-74	D1	0.55	1.1	2.3
919	8-74	D1	0.70	1.1	1.7
923	8-74	D1	0.56	2.5	2.7
924	8-74	D1	0.50	0.62	1.4
927	8-74	D1	0.59	0.64	0.62
928	8-74	D1	0.33	0.91	1.5
929	8-74	D1	0.50	1.0	2.5
930	8-74	D1	0.67	1.3	2.1
935	8-74	D1	1.0	1.3	1.7
937	8-74	D1	0.62	1.2	2.2
938	8-74	D1	0.42	1.0	2.5
939	8-74	D1	0.50	0.70	0.91
943	8-74	D1	0.71	1.1	2.9
944	8-74	D1	1.4	1.4	1.9

Table B-1.—*Pinhole test specimen flow rates from original SCS data base generated from February 1974 to January 1975*—Continued

SCS pinhole test number	Test date	Dispersive grade	System flow rate (mL/s) Initial[1]	Intermediate[2]	Final[3]
947	8-74	D1	0.83	1.2	1.7
948	8-74	D1	0.77	1.4	1.4
949	8-74	D1	0.43	1.1	1.2
950	8-74	D1	1.2	1.8	2.2
955	8-74	D1	0.77	1.1	1.6
957	8-74	D1	1.0	1.7	2.8
959	8-74	D1	1.1	1.5	2.8
963	8-74	D1	0.77	1.5	2.1
964	8-74	D1	0.56	1.2	2.1
968	8-74	D1	0.80	1.4	2.3
969	8-74	D1	0.57	0.91	1.5
970	8-74	D1	0.36	1.0	2.8
971	8-74	D1	0.62	1.1	1.7
972	8-74	D1	0.37	0.91	1.4
973	8-74	D1	0.50	1.4	2.5
974	8-74	D1	1.1	2.0	1.9
986	8-74	D1	0.57	1.1	2.1
988	8-74	D1	1.2	1.5	2.1
994	8-74	D1	1.1	2.1	2.4
995	8-74	D1	0.83	1.5	1.7
996	8-74	D1	0.50	1.0	2.1
997	8-74	D1	0.37	0.67	1.8
998	8-74	D1	0.91	2.0	2.1
1002	8-74	D1	0.77	1.8	2.0
1003	8-74	D1	0.62	0.77	2.3
1006	8-74	D1	0.59	0.67	0.71
1007	8-74	D1	1.7	2.0	2.5
1008	8-74	D1	0.33	0.45	0.50
1009	8-74	D1	0.18	1.0	1.4
1015	8-74	D2	0.62	1.0	1.2
1019	8-74	D2	0.30	0.91	1.2
1020	8-74	D1	0.45	0.60	2.5
1021	8-74	D1	0.23	0.60	2.3
1022	8-74	D1	0.71	1.2	2.1
1026	8-74	D1	0.59	0.91	0.90
1027	8-74	D1	0.41	1.0	2.5
1031	8-74	D1	0.59	1.2	1.8
1032	8-74	D1	0.28	0.91	0.91
1033	8-74	D1	0.38	0.91	2.5
1038	8-74	D1	0.44	1.0	1.6
1040	8-74	D1	0.48	1.1	2.1
1041	8-74	D1	0.31	1.1	1.9
1042	8-74	D1	0.51	1.1	2.1
1046	8.74	D1	0.50	0.67	0.60
1047	8-74	D1	0.60	1.0	1.9
1050	8-74	D1	0.57	0.67	0.67
1051	8-74	D1	0.77	1.2	2.3
1052	8-74	D1	0.36	0.59	0.62
1053	8-74	D1	0.35	1.0	2.5
1054	8-74	D1	0.50	1.5	1.9

Table B-1.—*Pinhole test specimen flow rates from original SCS data base generated from February 1974 to January 1975*—Continued

SCS pinhole test number	Test date	Dispersive grade	System flow rate (mL/s) Initial[1]	Intermediate[2]	Final[3]
1057	8-74	D1	0.56	1.2	1.9
1058	8-74	D1	0.59	0.91	1.7
1061	8-74	D1	2.0	2.3	2.3
1062	8-74	D1	0.67	1.2	2.5
1063	8-74	D1	0.46	1.3	2.8
1064	8-74	D1	0.29	0.62	1.9
1066	8-74	D1	1.6	2.2	3.1
1067	8-74	D1	0.67	1.8	1.8
1068	8-74	D1	0.62	1.0	1.2
1069	8-74	D1	0.67	1.2	1.6
1072	8-74	D1	1.0	1.2	1.3
1073	8-74	D1	0.59	0.71	0.91
1074	8-74	D1	0.62	1.2	2.3
1075	8-74	D1	0.91	1.8	2.3
1076	8-74	D1	0.83	1.9	1.9
1077	8-74	D1	0.91	1.6	2.2
1078	8-74	D1	1.1	1.4	1.5
1079	8-74	D1	0.91	1.4	1.9
1080	8-74	D1	0.46	0.91	1.0
1081	8-74	D1	0.83	1.0	1.8
1082	8-74	D1	0.67	1.0	2.4
1083	8-74	D1	0.67	1.4	1.7
1086	8-74	D1	2.1	2.5	2.1
1087	8-74	D1	0.53	0.59	0.56
1088	8-74	D1	0.56	1.1	2.5
1089	8-74	D1	0.83	1.0	2.1
1090	8-74	D1	0.40	1.5	2.7
1091	8-74	D1	1.0	1.4	2.5
1092	8-74	D1	0.71	1.7	2.3
1097	8-74	D1	0.53	1.0	1.7
1098	8-74	D2	0.42	1.1	1.2
1099	8-74	D1	0.37	1.0	1.9
1100	8-74	D1	0.36	1.1	2.3
1101	8-74	D1	0.67	0.71	0.91
1105	8-74	D1	0.62	0.67	0.67
1106	8-74	D1	0.46	1.1	1.9
1109	8-74	D1	0.67	0.67	0.67
1110	8-74	D1	1.1	1.5	2.7
1111	8-74	D1	0.53	1.5	2.5
1112	8-74	D1	0.56	1.0	2.4
1117	8-74	D1	0.83	1.5	2.1
1118	9-74	D1	0.44	1.0	1.1
1122	9-74	D1	0.46	0.95	1.9
1123	9-74	D1	0.32	1.4	1.9
1124	9-74	D1	0.42	1.1	2.1
1125	9-74	D1	0.50	0.91	1.5
1130	9-74	D1	0.71	0.91	1.9
1131	9-74	D1	0.40	1.0	2.5
1132	9-74	D1	0.42	1.0	1.9
1133	9-74	D1	0.77	1.0	2.3

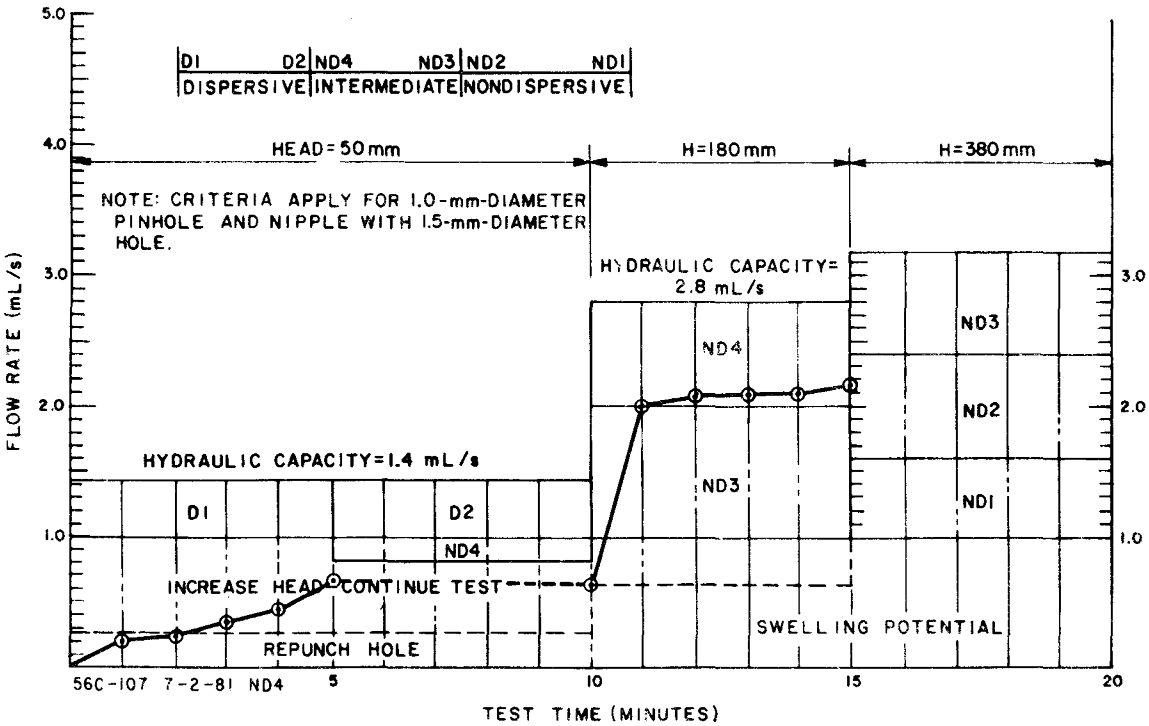
Table B-1.—*Pinhole test specimen flow rates from original SCS data base generated from February 1974 to January 1975*—Continued

SCS pinhole test number	Test date	Dispersive grade	System flow rate (mL/s)		
			Initial[1]	Intermediate[2]	Final[3]
1137	9-74	D1	0.56	1.1	1.4
1140	9-74	D1	0.50	0.50	0.56
1141	9.74	D1	0.59	1.5	2.3
1142	9-74	D1	0.77	1.4	2.1
1143	9-74	D1	0.67	0.91	2.3
1148	9-74	D1	0.53	1.2	2.4
1149	9-74	D1	0.47	1.0	2.3
1152	9-74	D1	0.50	1.0	1.6
1153	9-74	D1	0.56	1.7	1.9
1154	9-74	D1	0.31	1.1	2.1
1155	9-74	D1	0.50	1.3	2.3
1165	9-74	D1	0.37	1.1	1.8
1166	10-74	D1	0.77	1.5	2.5
1167	10-74	D1	0.32	1.0	2.3
1168	10-74	D1	0.77	1.5	1.9
1172	10-74	D1	0.77	1.5	2.3
1175	10-74	D1	0.59	1.4	2.3
1176	10-74	D1	0.34	0.91	0.91
1177	10-74	D1	0.36	1.0	1.7
1201	12-74	D1	0.83	1.1	2.3
1208	1-75	D1	0.53	0.83	1.2

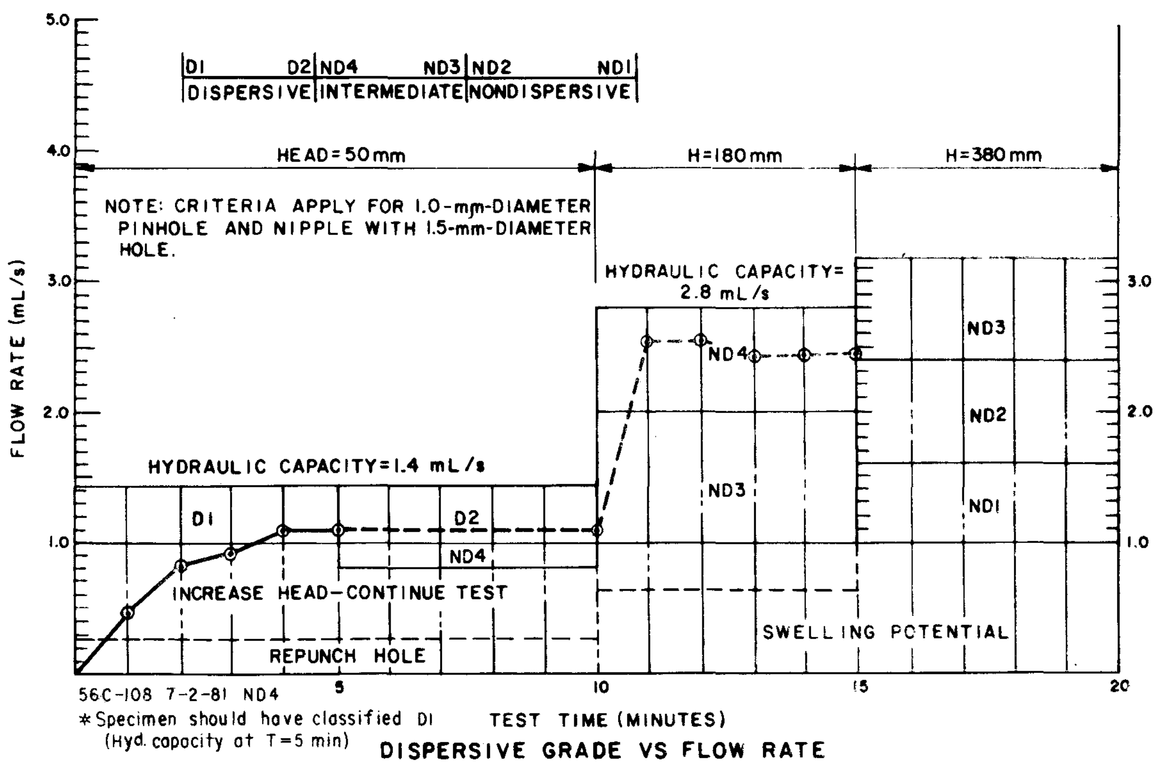
[1] Initial = start of test.
[2] Intermediate = approximately 2 to 4 minutes of elapsed test time is used for this flow rate to show an approximate rate of change of flow. Also, the SCS test uses time as a dependent variable to determine flow rates.
[3] Final = end of test.

APPENDIX C

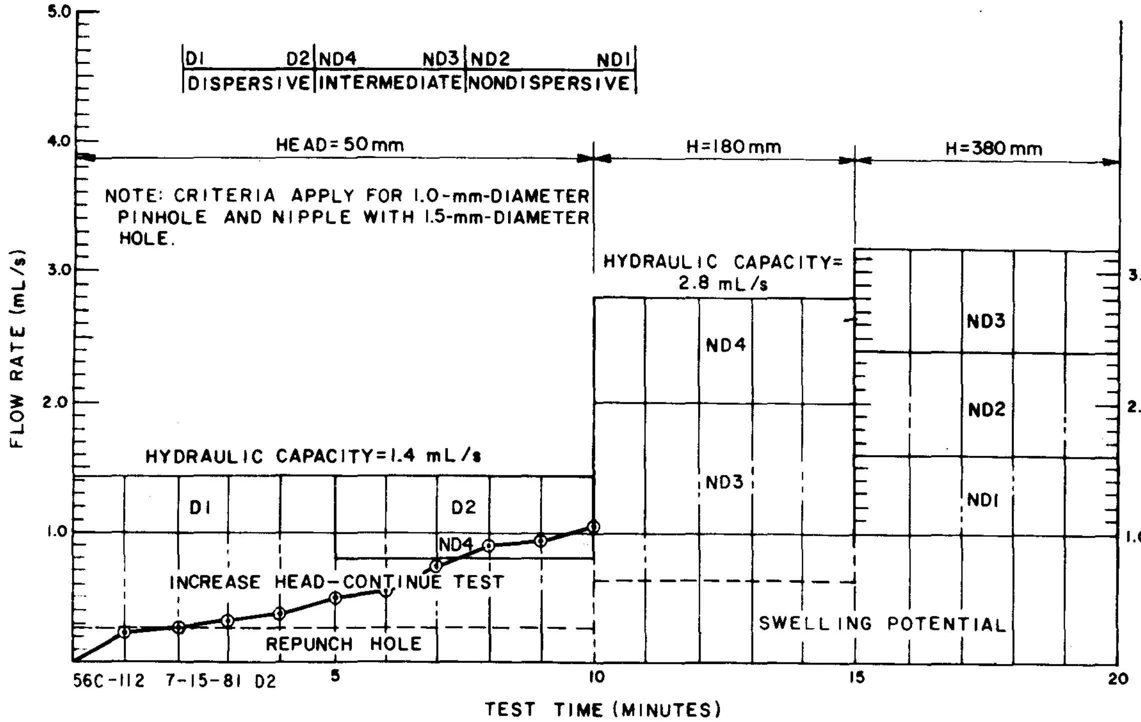
FLOW RATE DATA OF RANDOMLY SELECTED DISPERSIVE AND NONDISPERSIVE BUREAU SOIL SAMPLES



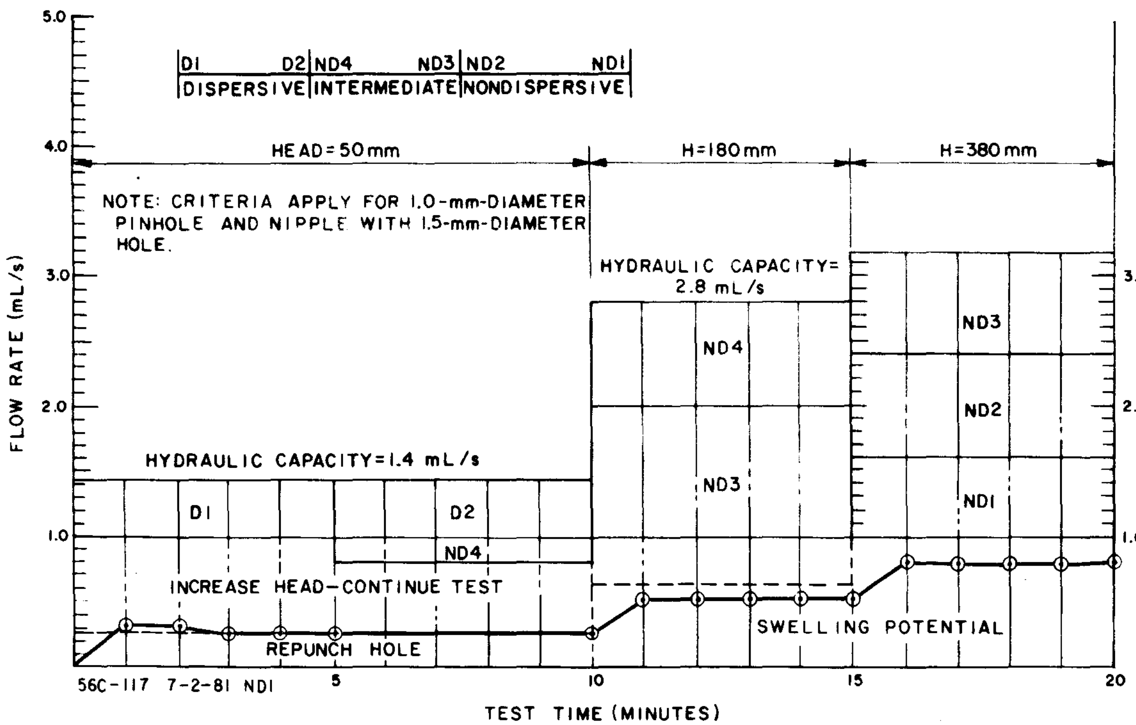
DISPERSIVE GRADE VS FLOW RATE



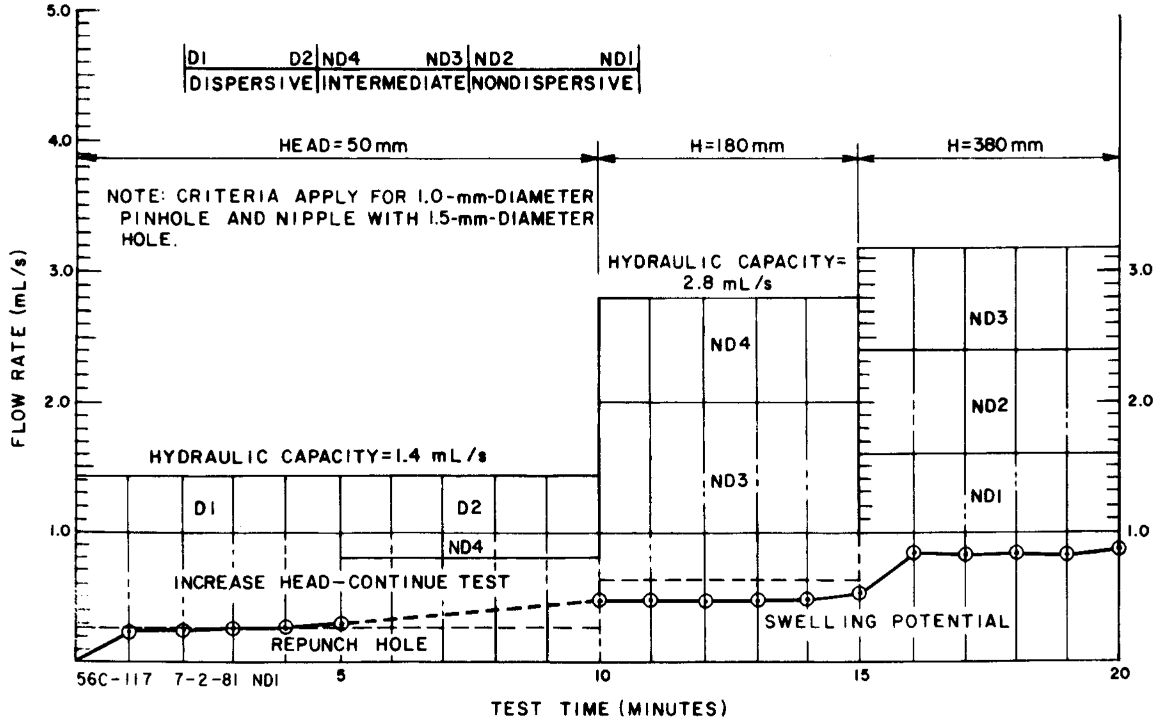
DISPERSIVE GRADE VS FLOW RATE



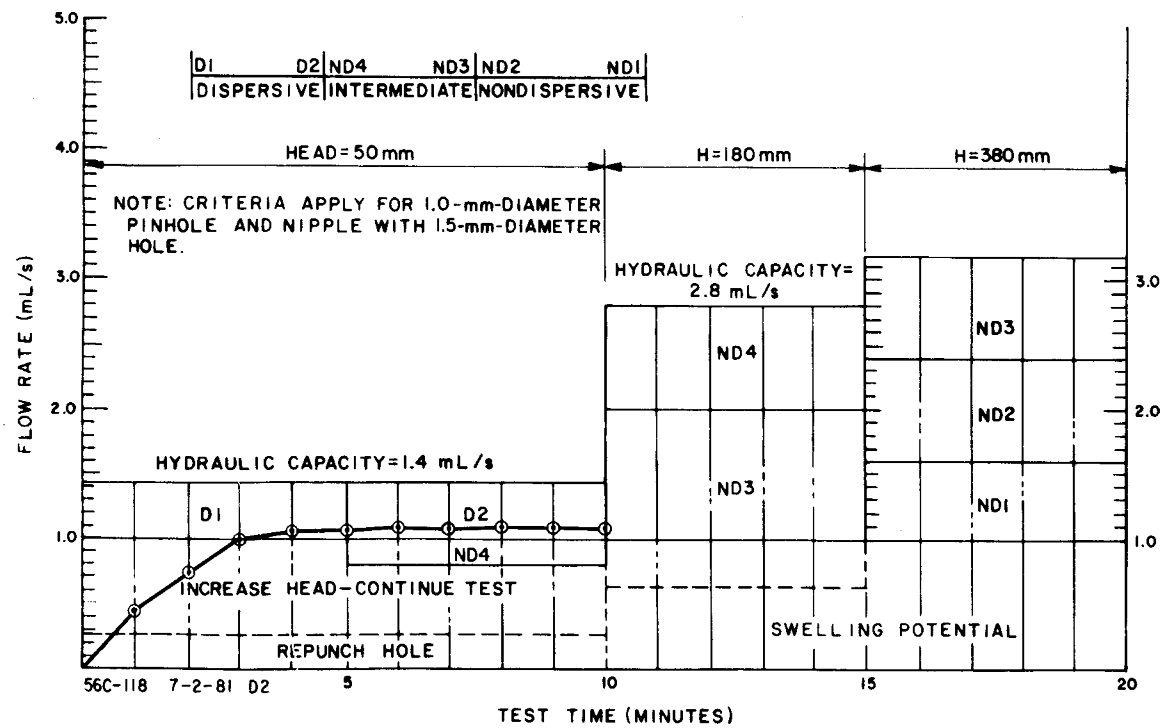
DISPERSIVE GRADE VS FLOW RATE



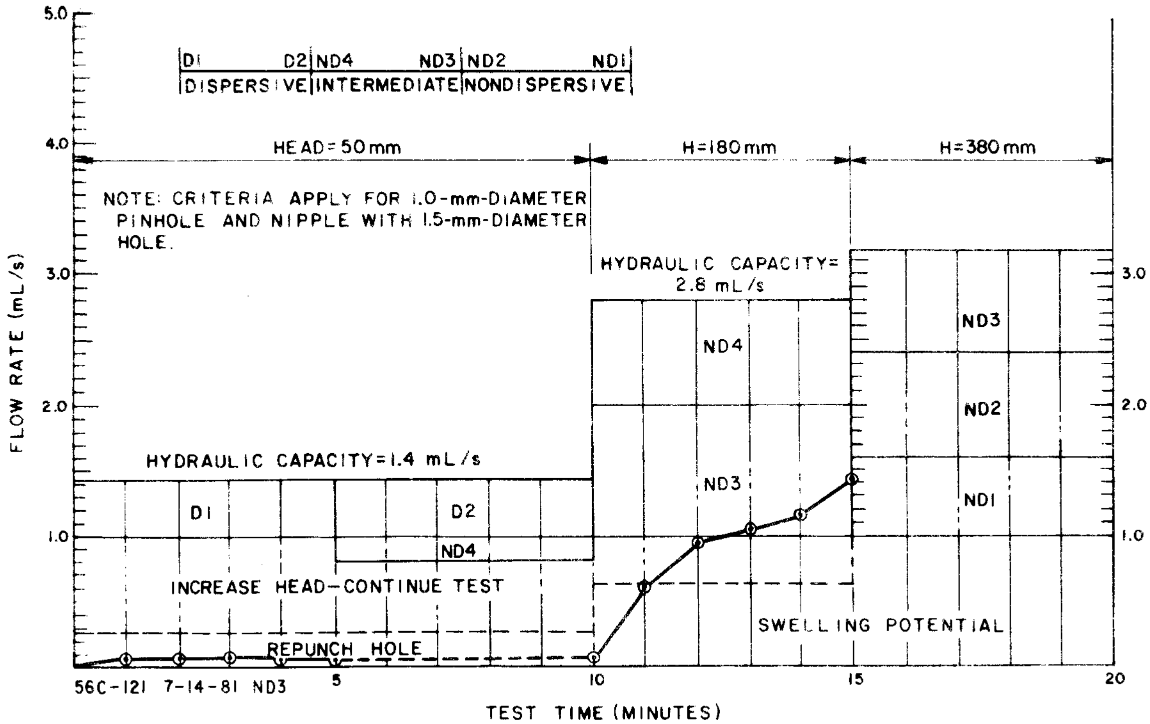
DISPERSIVE GRADE VS FLOW RATE



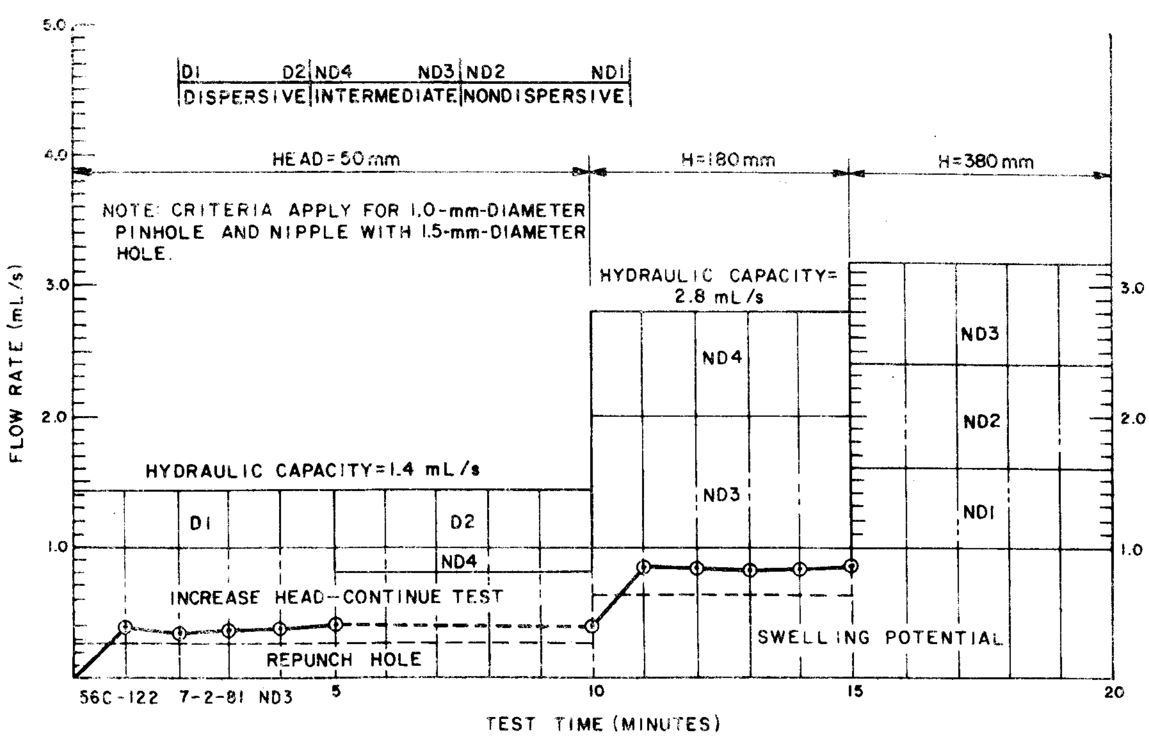
DISPERSIVE GRADE VS FLOW RATE



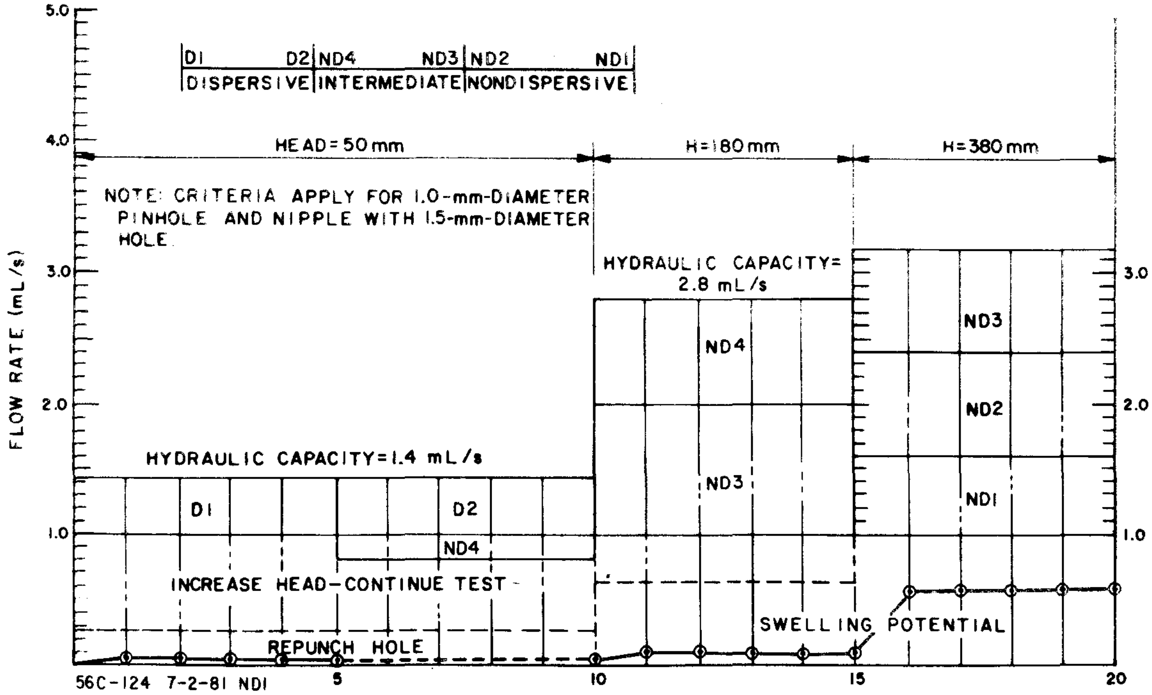
DISPERSIVE GRADE VS FLOW RATE



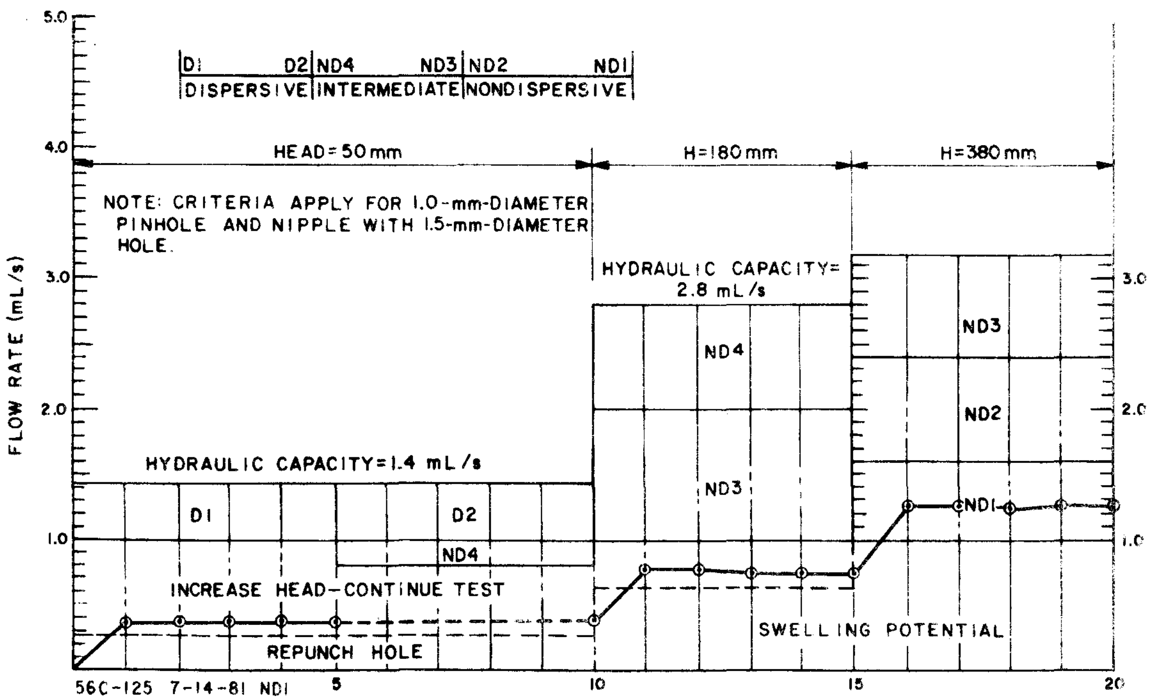
DISPERSIVE GRADE VS FLOW RATE



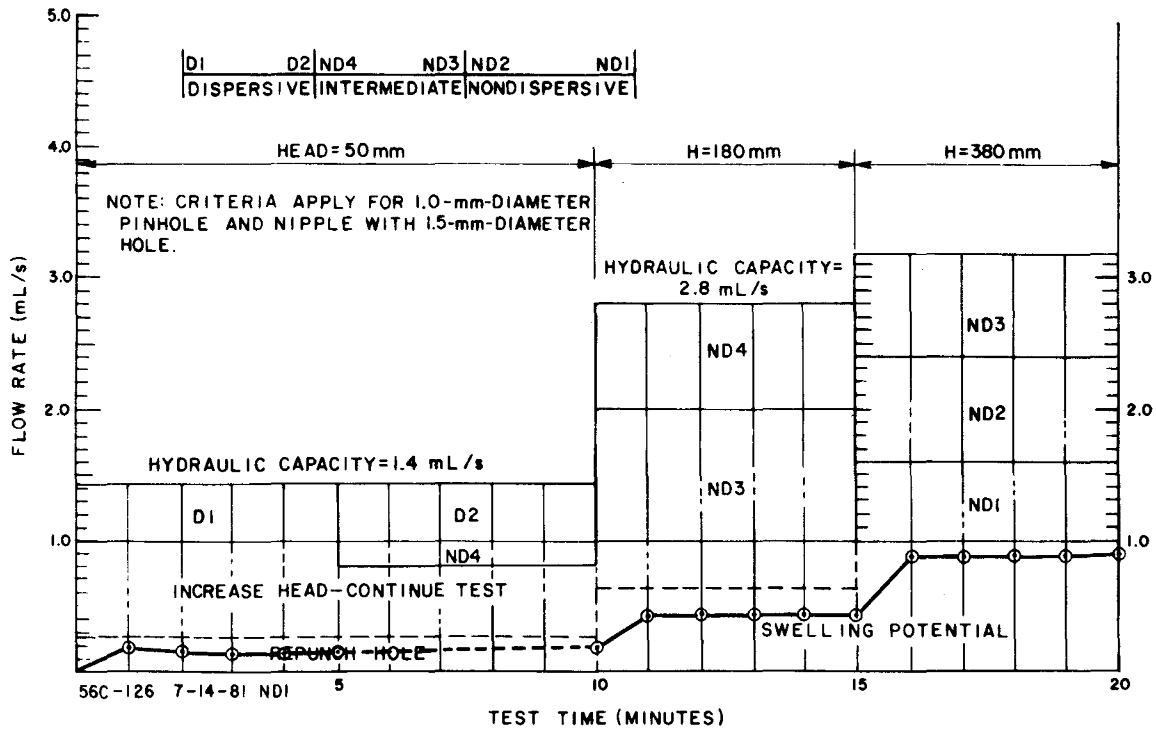
DISPERSIVE GRADE VS FLOW RATE



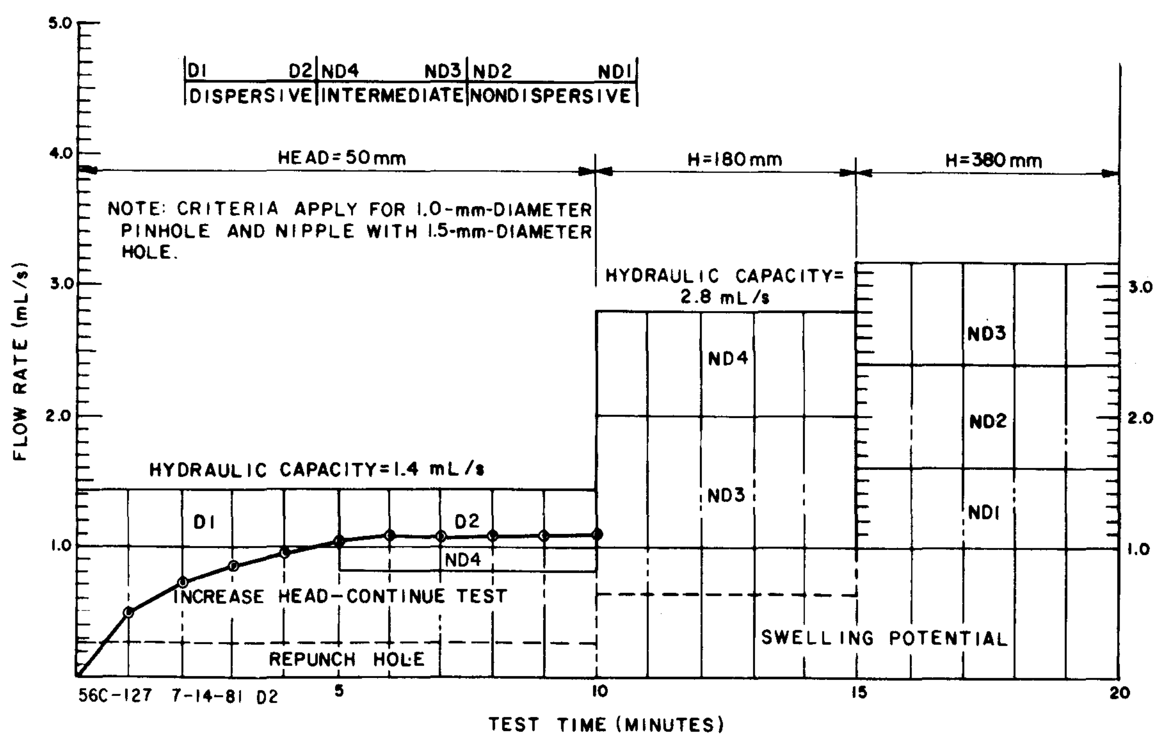
DISPERSIVE GRADE VS FLOW RATE



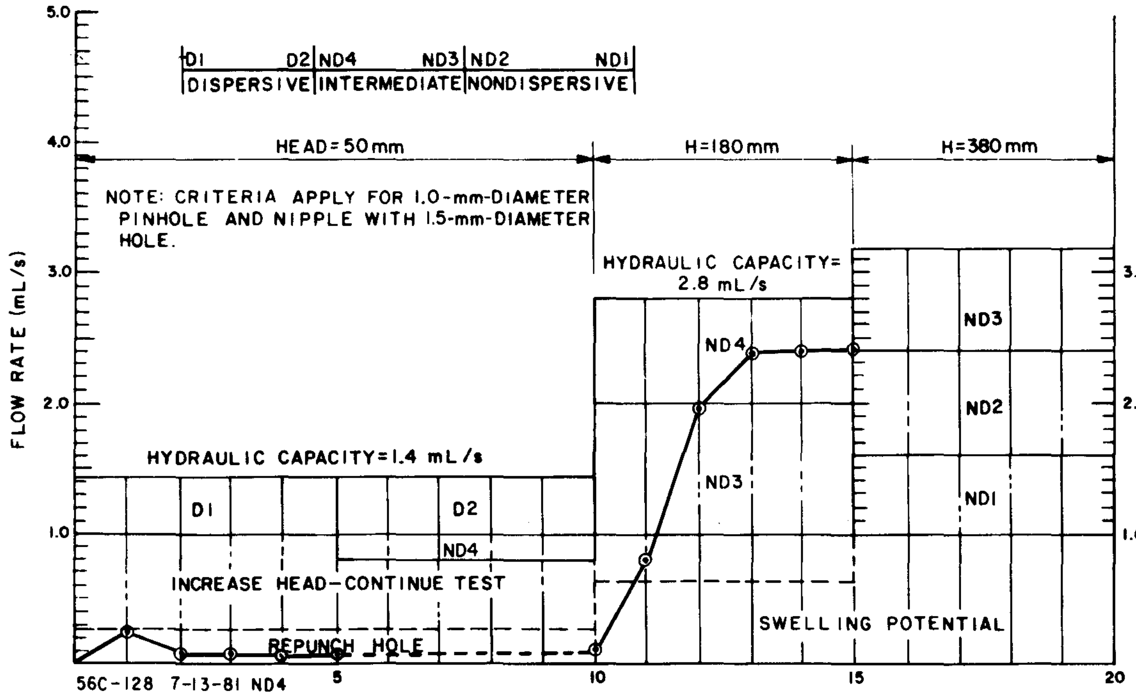
DISPERSIVE GRADE VS FLOW RATE



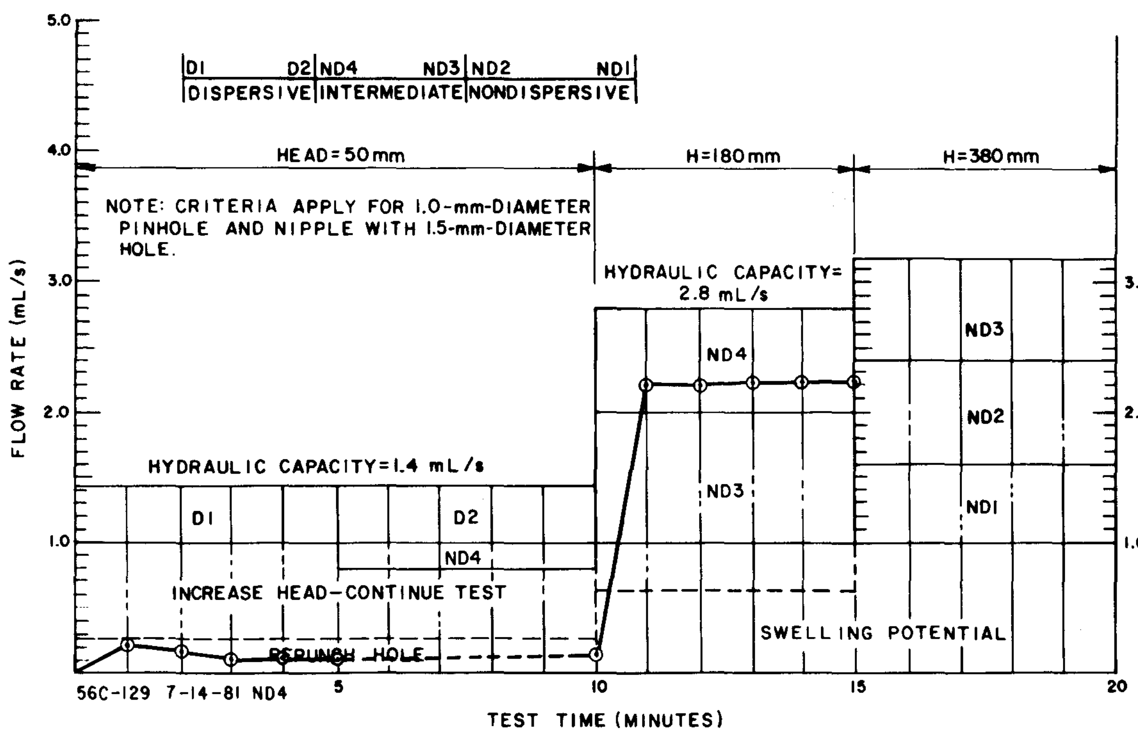
DISPERSIVE GRADE VS FLOW RATE



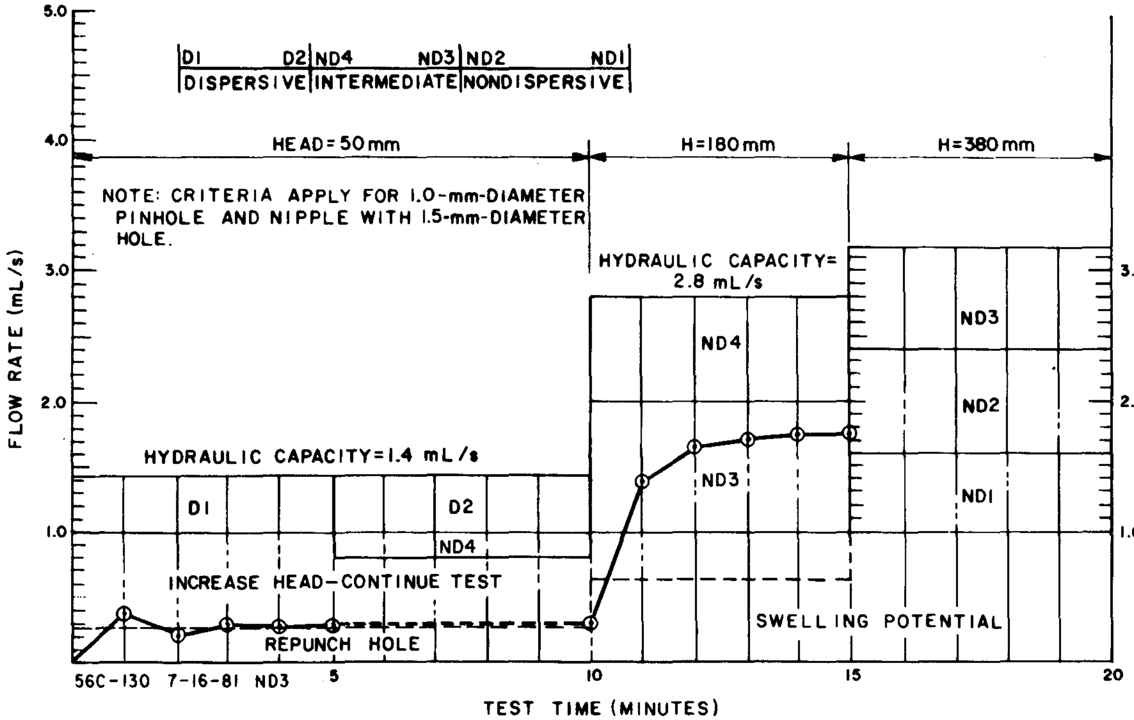
DISPERSIVE GRADE VS FLOW RATE



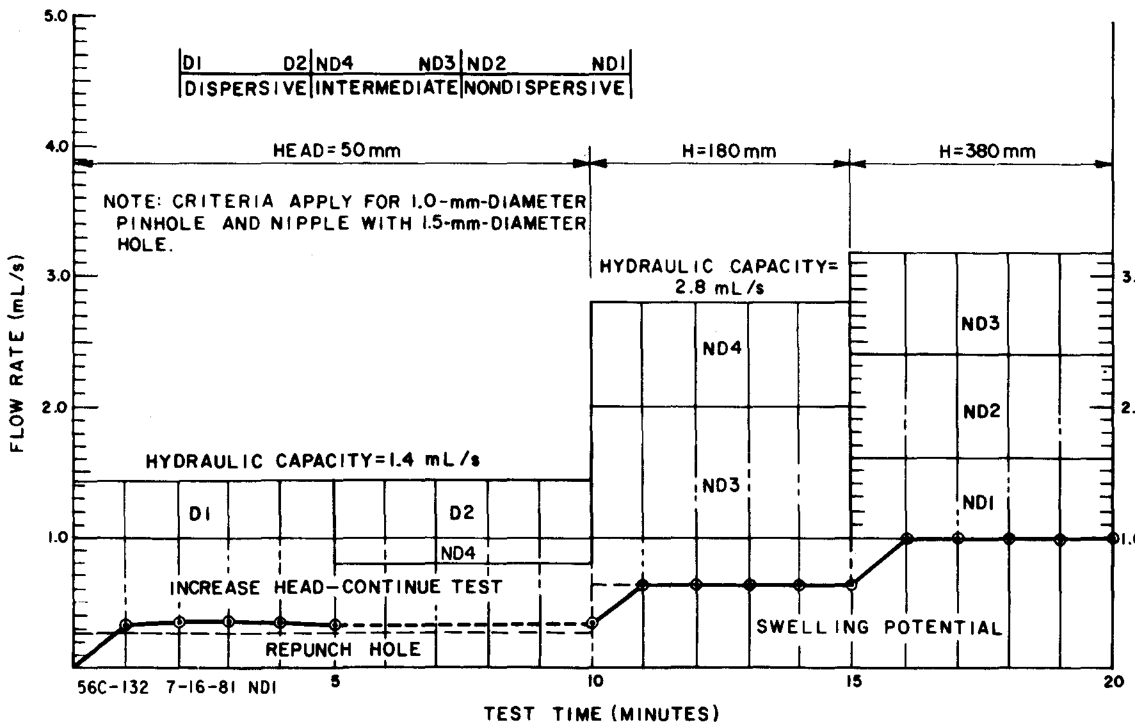
DISPERSIVE GRADE VS FLOW RATE



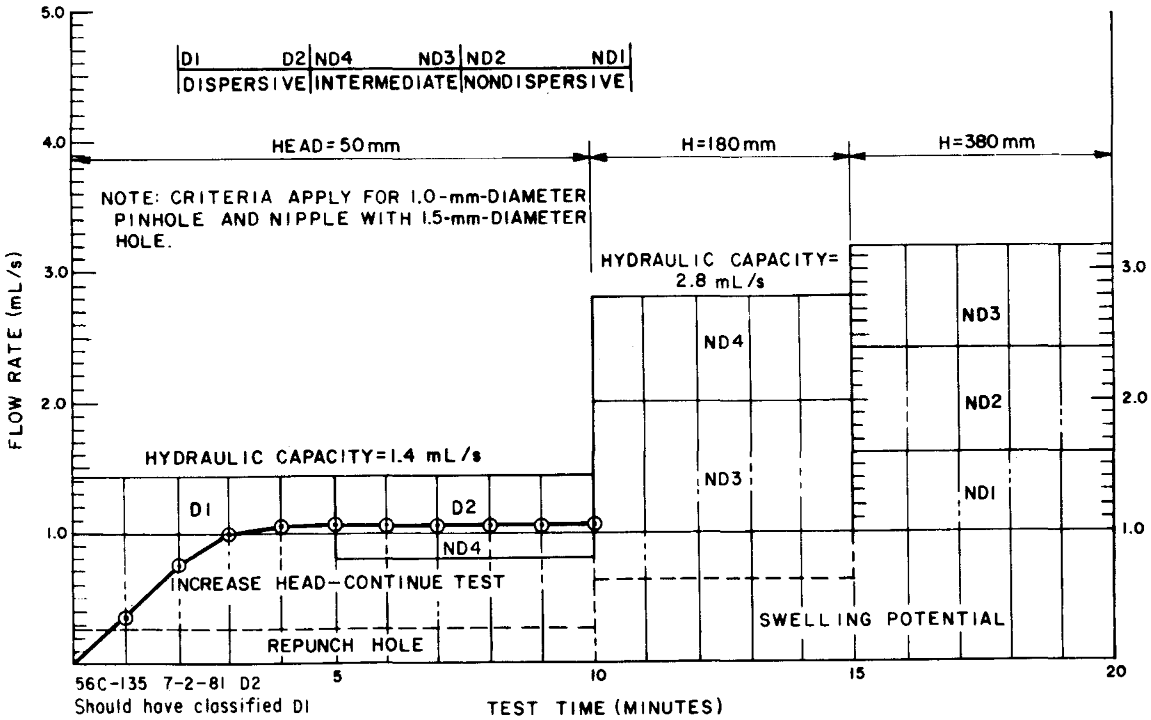
DISPERSIVE GRADE VS FLOW RATE



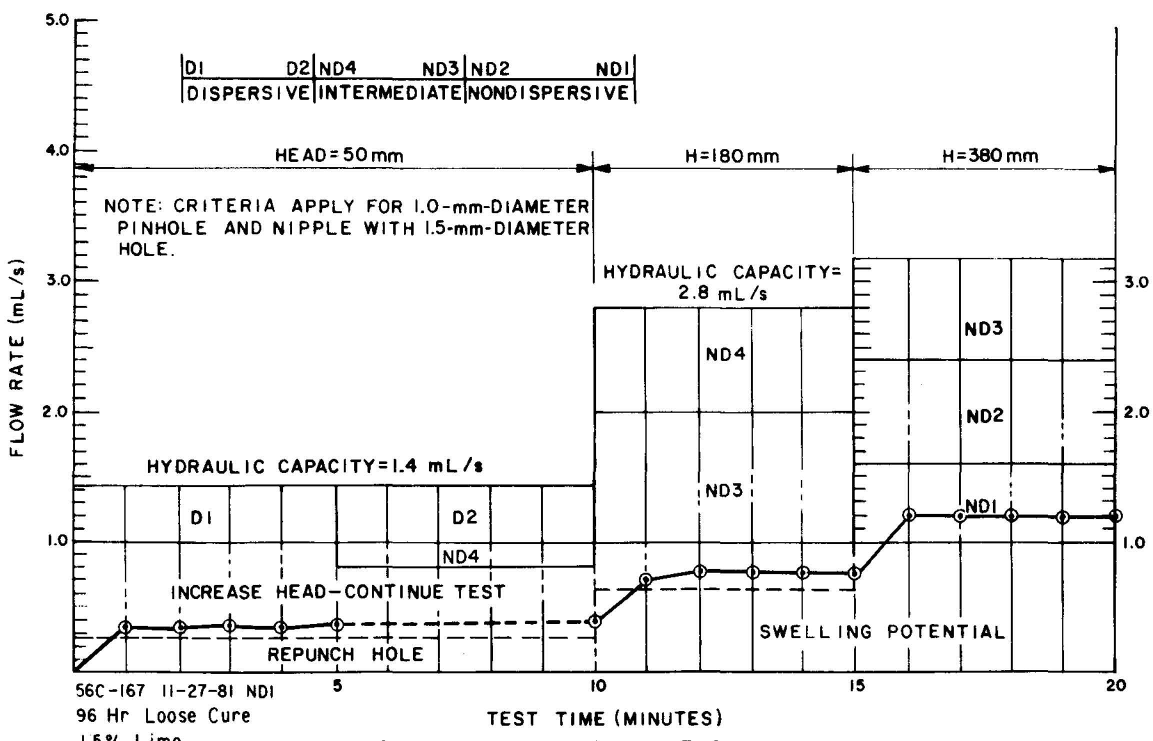
DISPERSIVE GRADE VS FLOW RATE



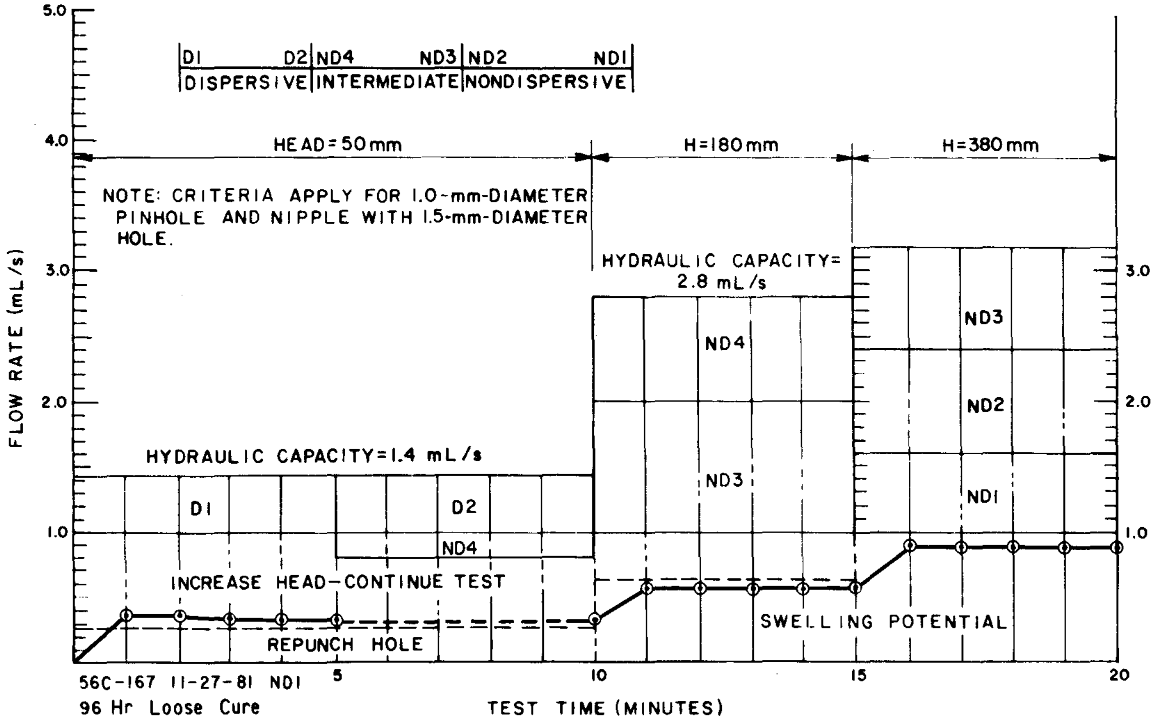
DISPERSIVE GRADE VS FLOW RATE



DISPERSIVE GRADE VS FLOW RATE

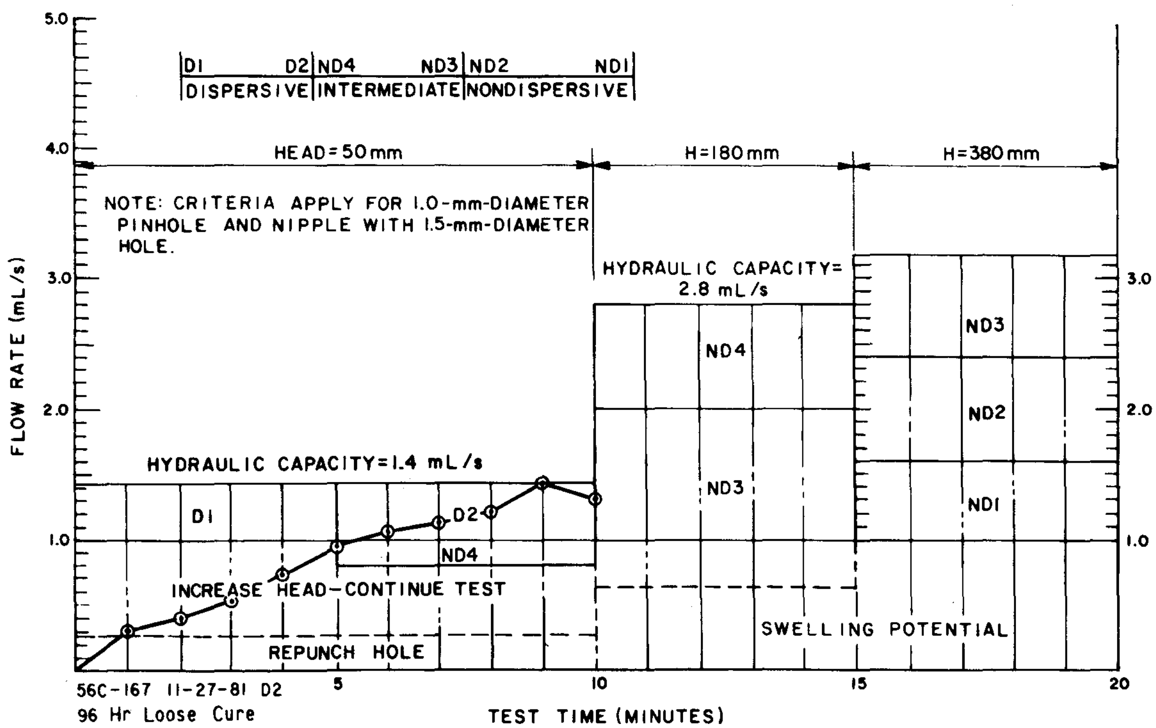


DISPERSIVE GRADE VS FLOW RATE



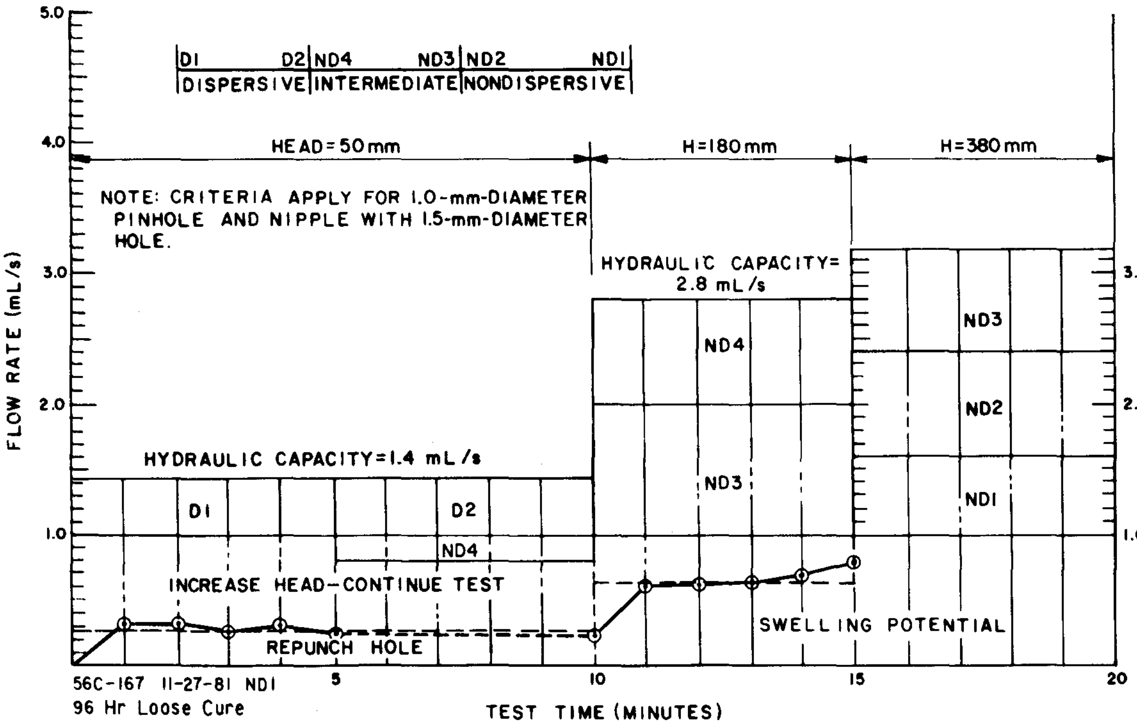
56C-167 11-27-81 ND1
96 Hr Loose Cure
2.0 % Lime

DISPERSIVE GRADE VS FLOW RATE

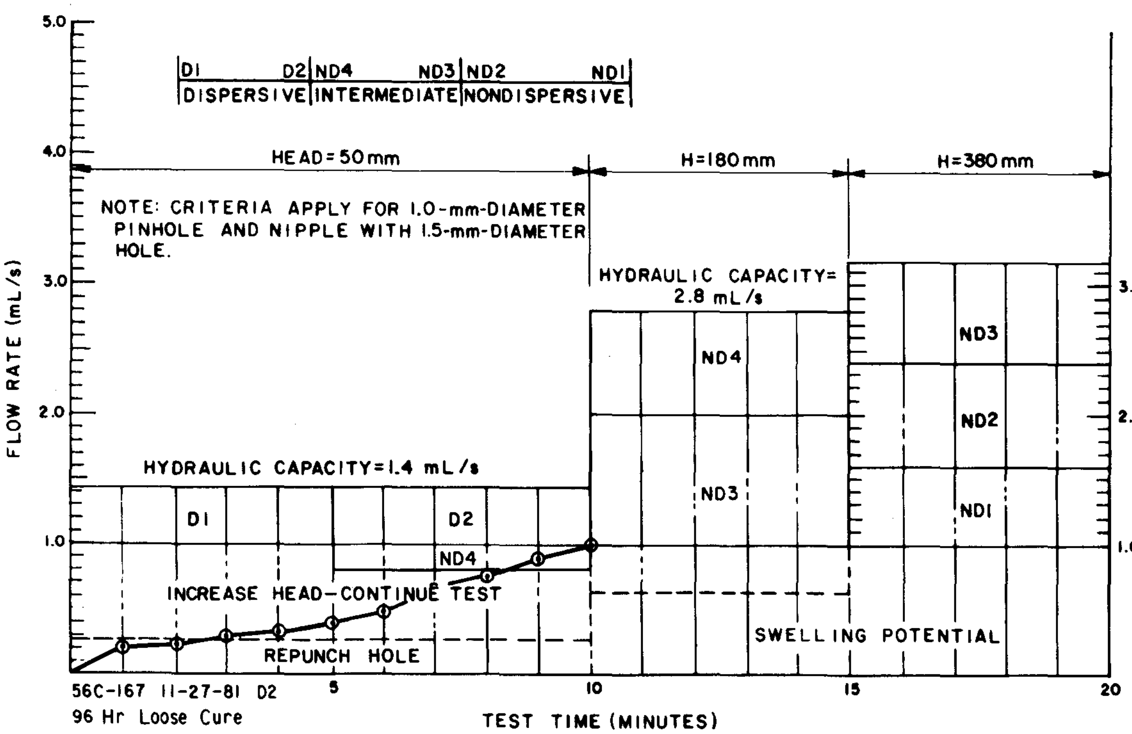


56C-167 11-27-81 D2
96 Hr Loose Cure
0.5 % Lime

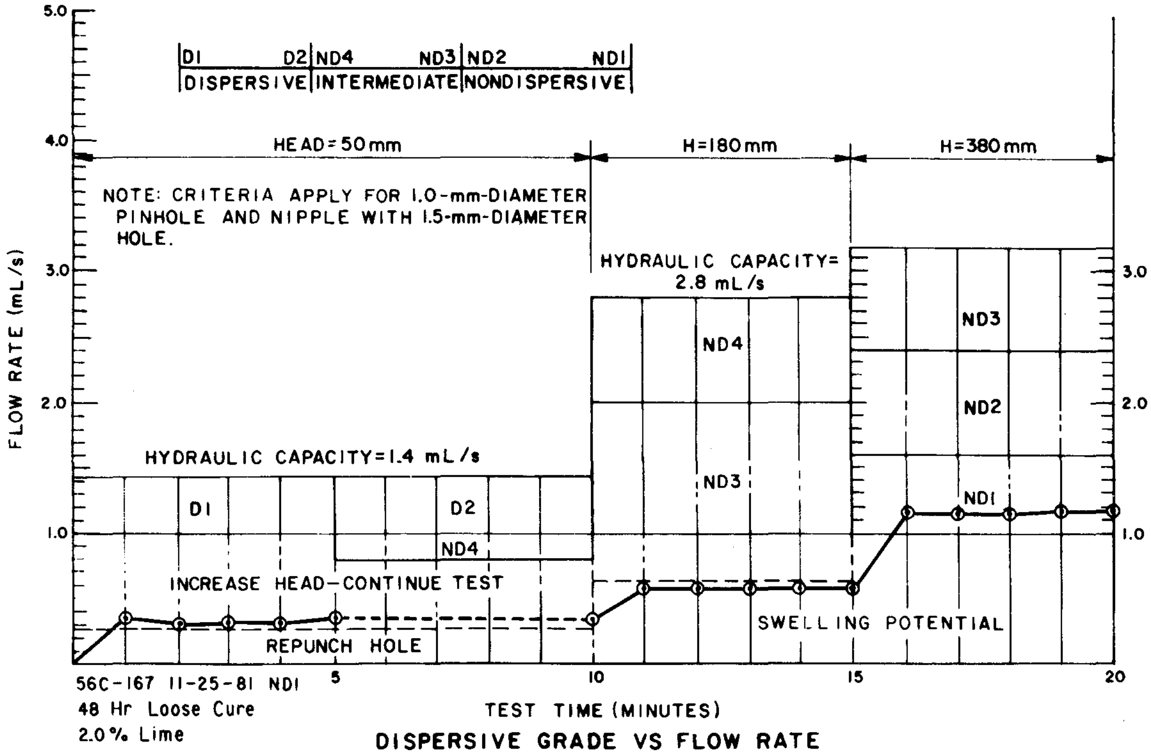
DISPERSIVE GRADE VS FLOW RATE



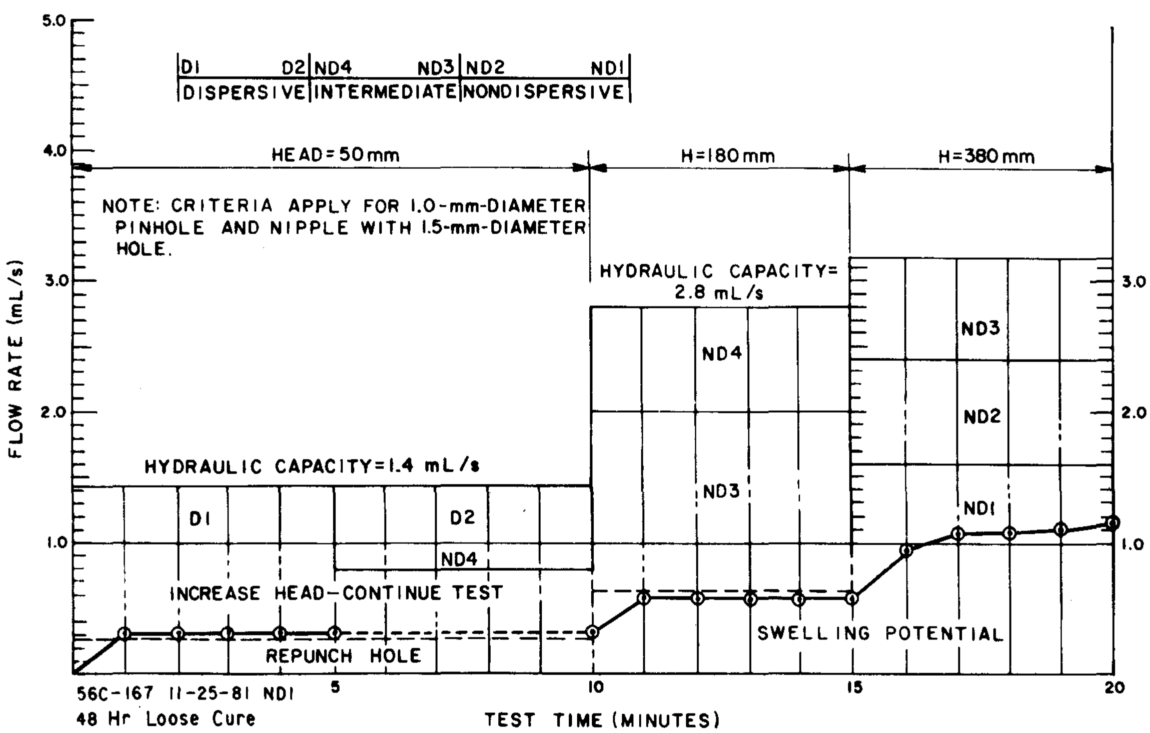
DISPERSIVE GRADE VS FLOW RATE



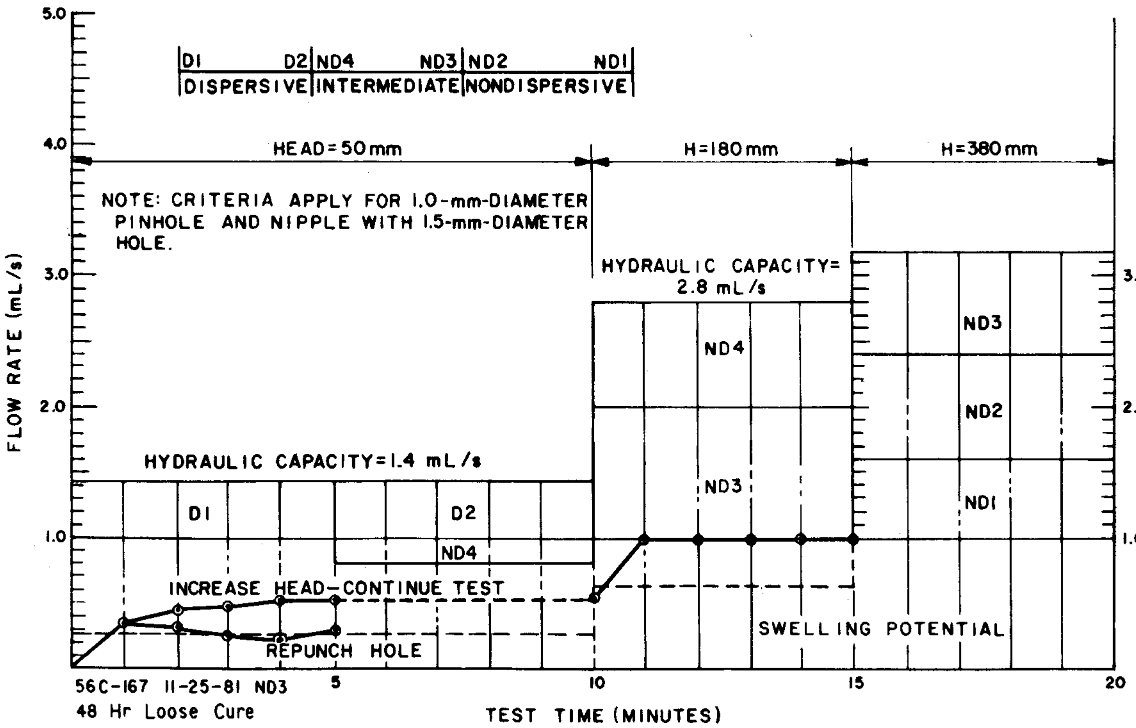
DISPERSIVE GRADE VS FLOW RATE



DISPERSIVE GRADE VS FLOW RATE

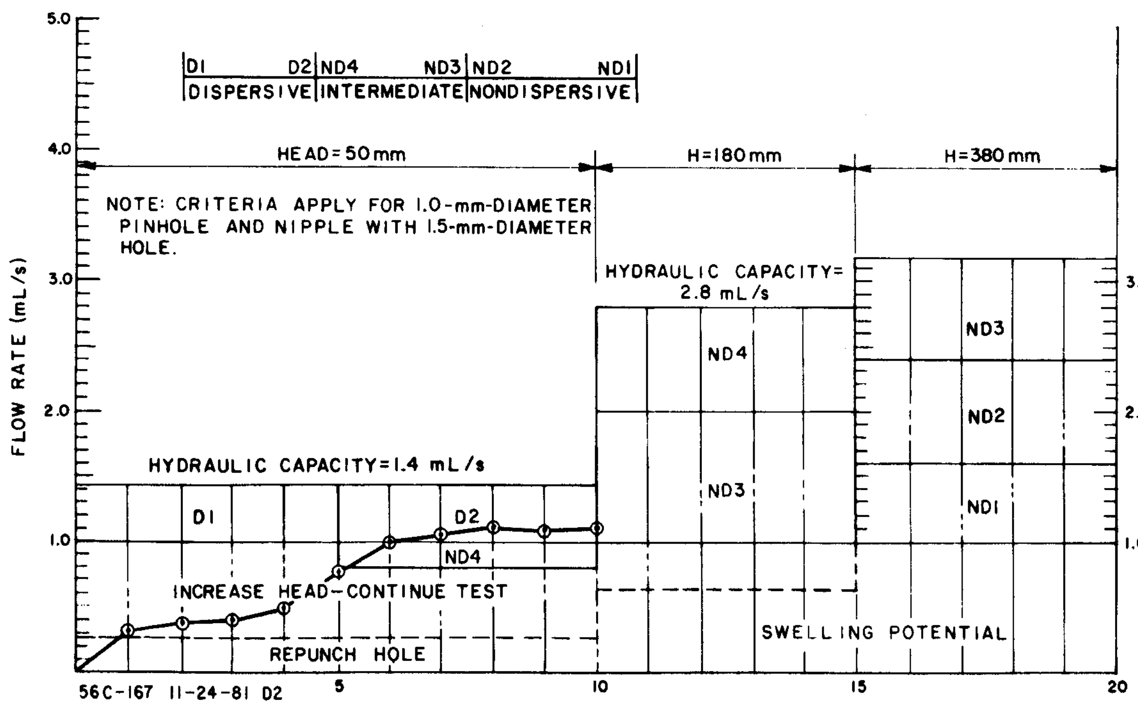


DISPERSIVE GRADE VS FLOW RATE



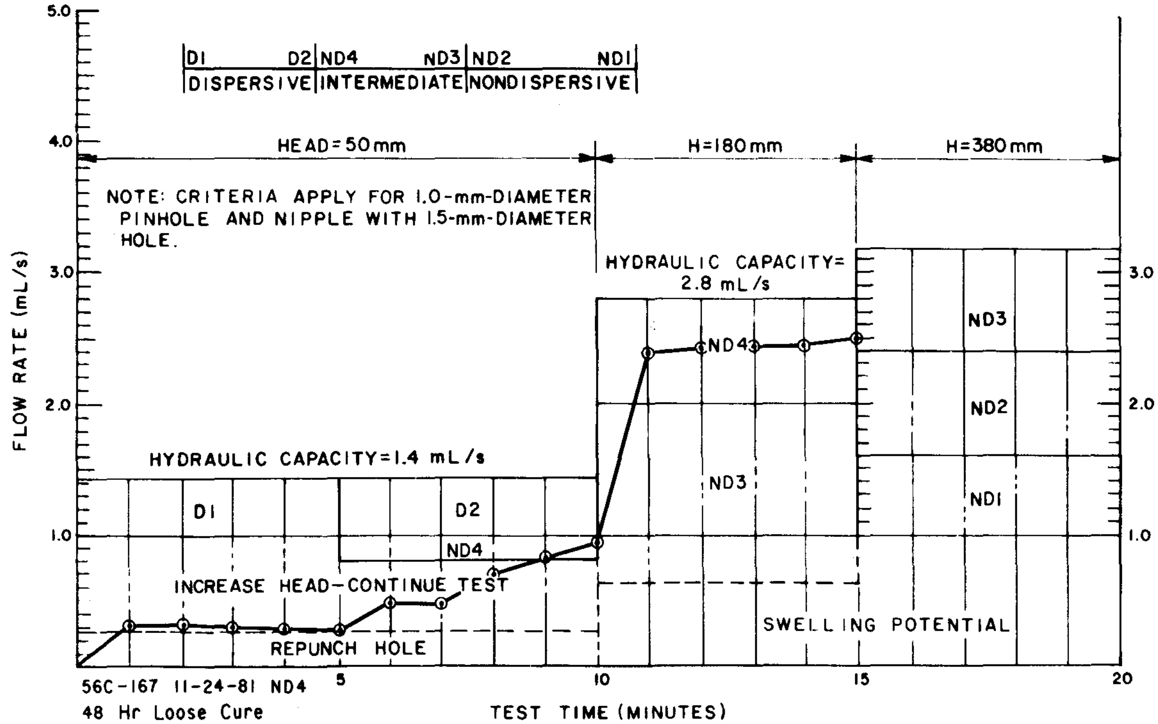
56C-167 11-25-81 ND3
48 Hr Loose Cure
1.0% Lime

DISPERSIVE GRADE VS FLOW RATE

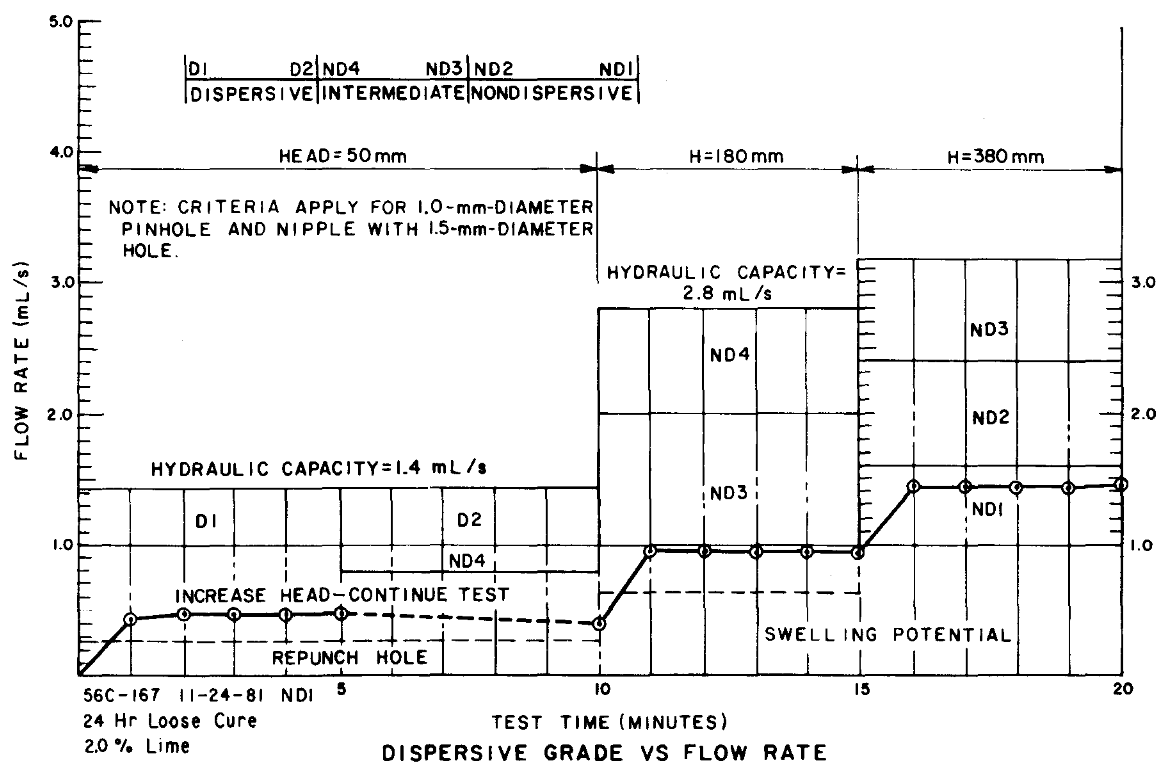


56C-167 11-24-81 D2
48 Hr Loose Cure
0.5% Lime

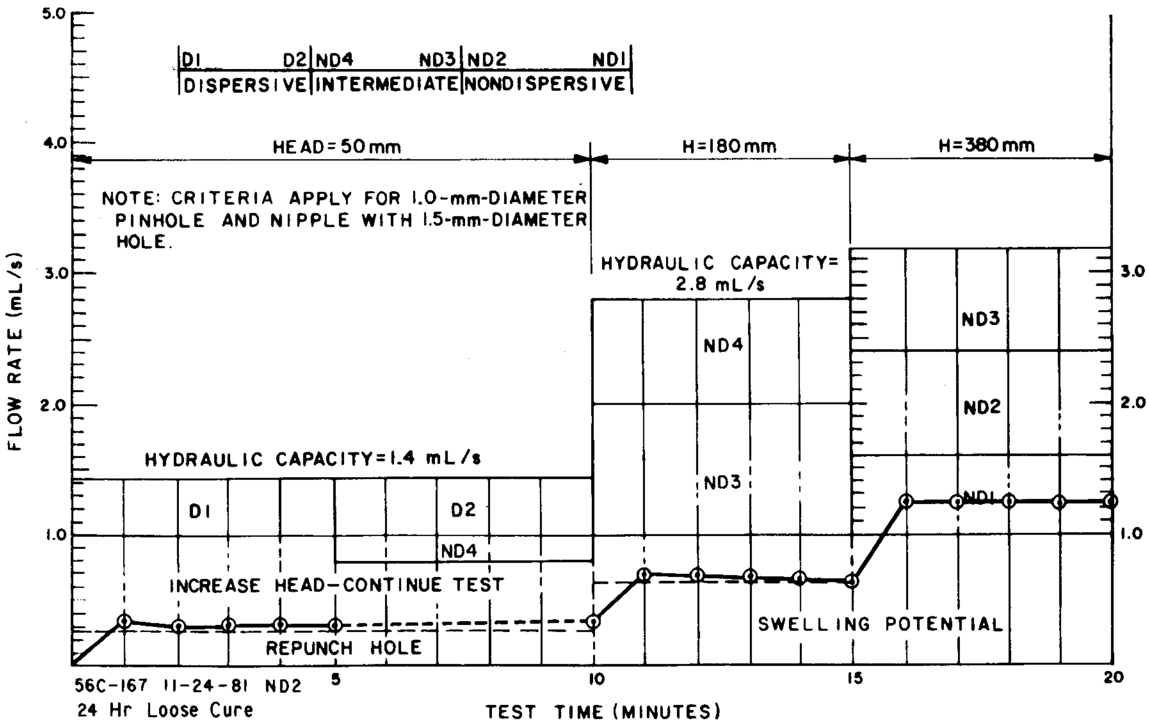
DISPERSIVE GRADE VS FLOW RATE



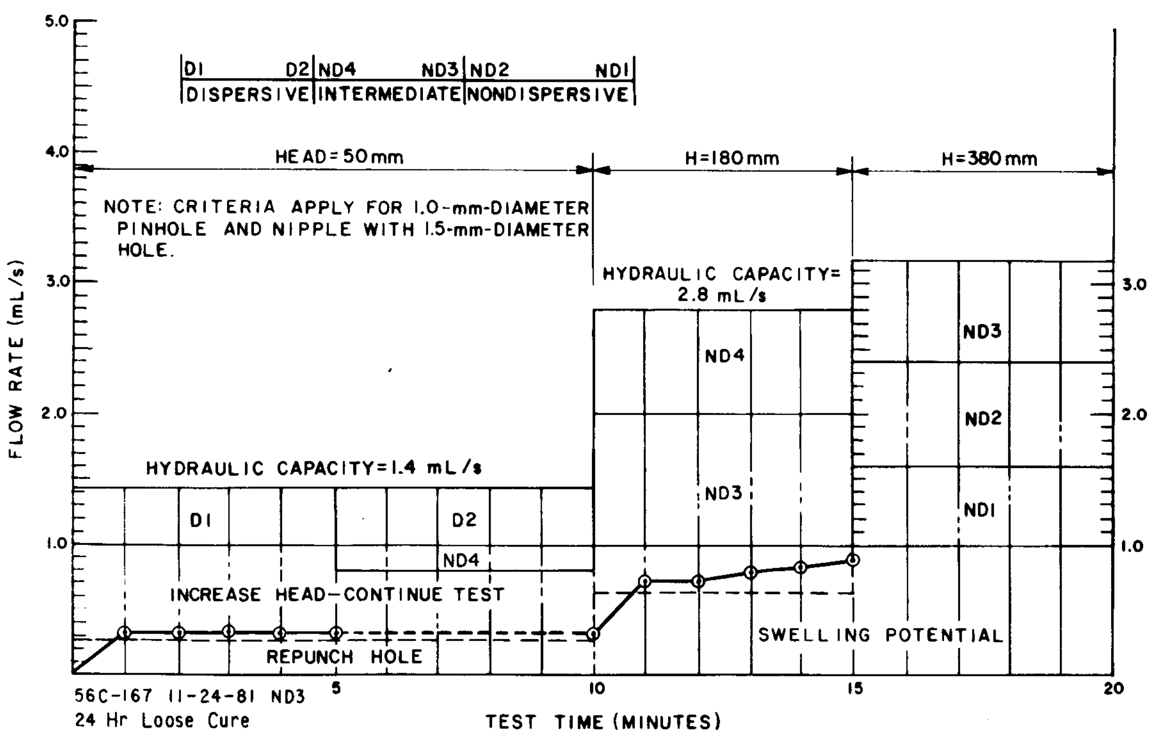
DISPERSIVE GRADE VS FLOW RATE



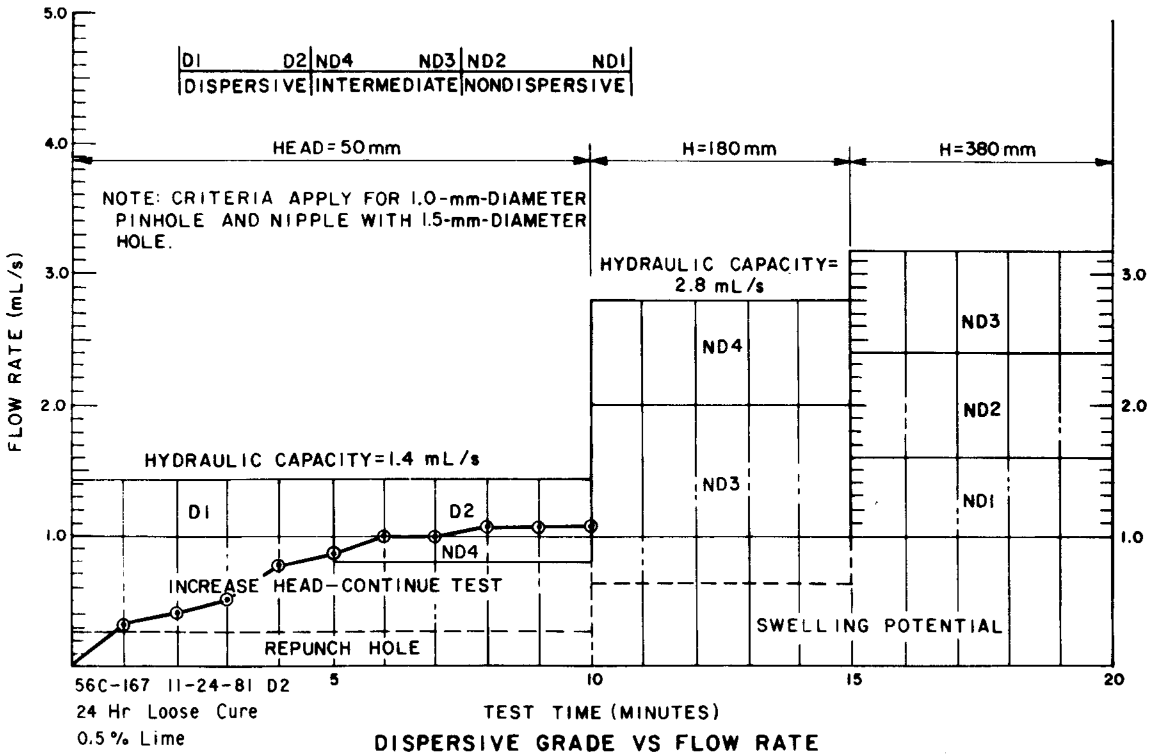
DISPERSIVE GRADE VS FLOW RATE



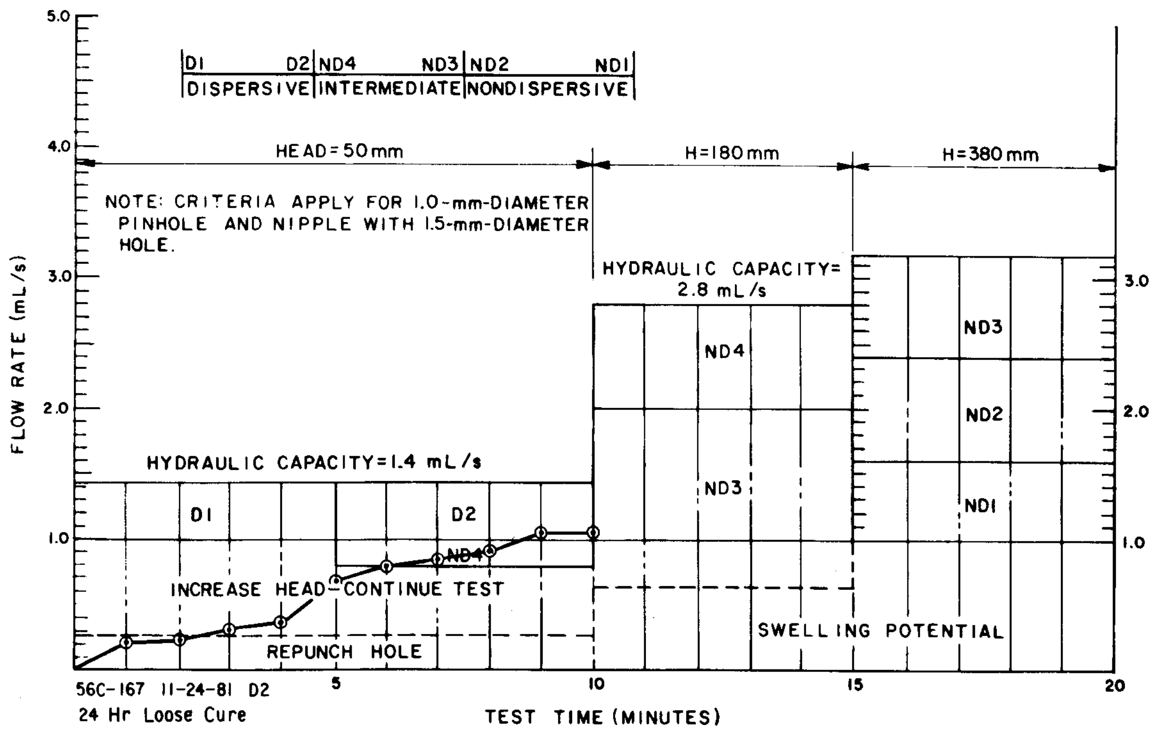
DISPERSIVE GRADE VS FLOW RATE



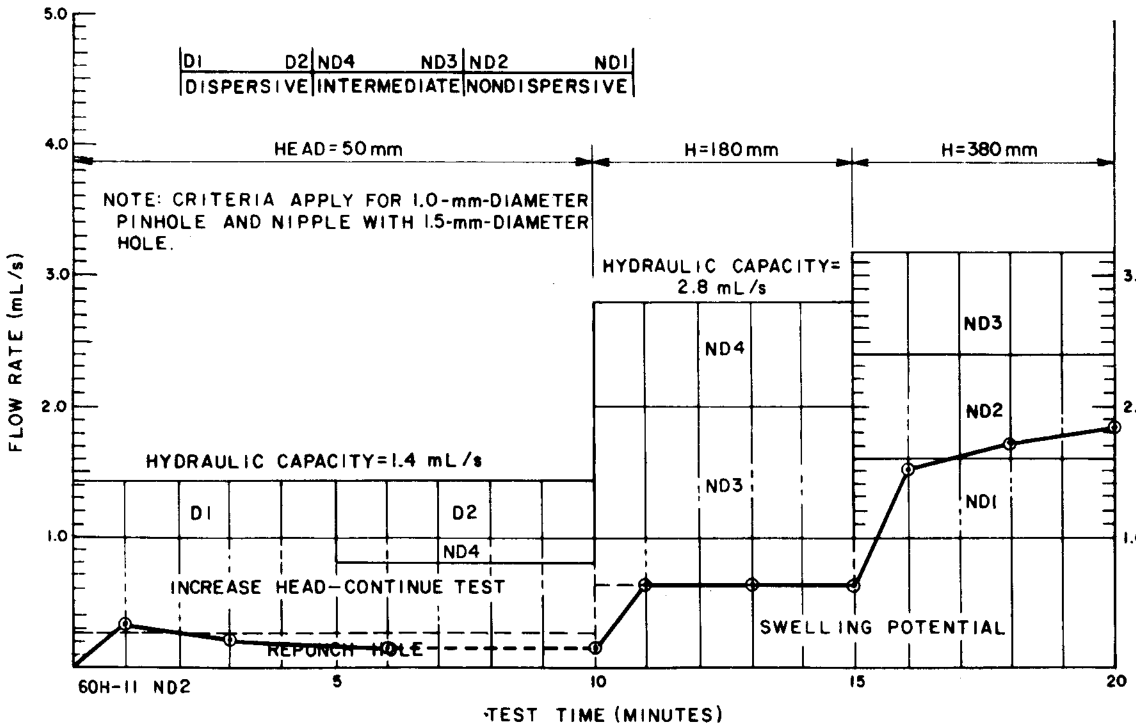
DISPERSIVE GRADE VS FLOW RATE



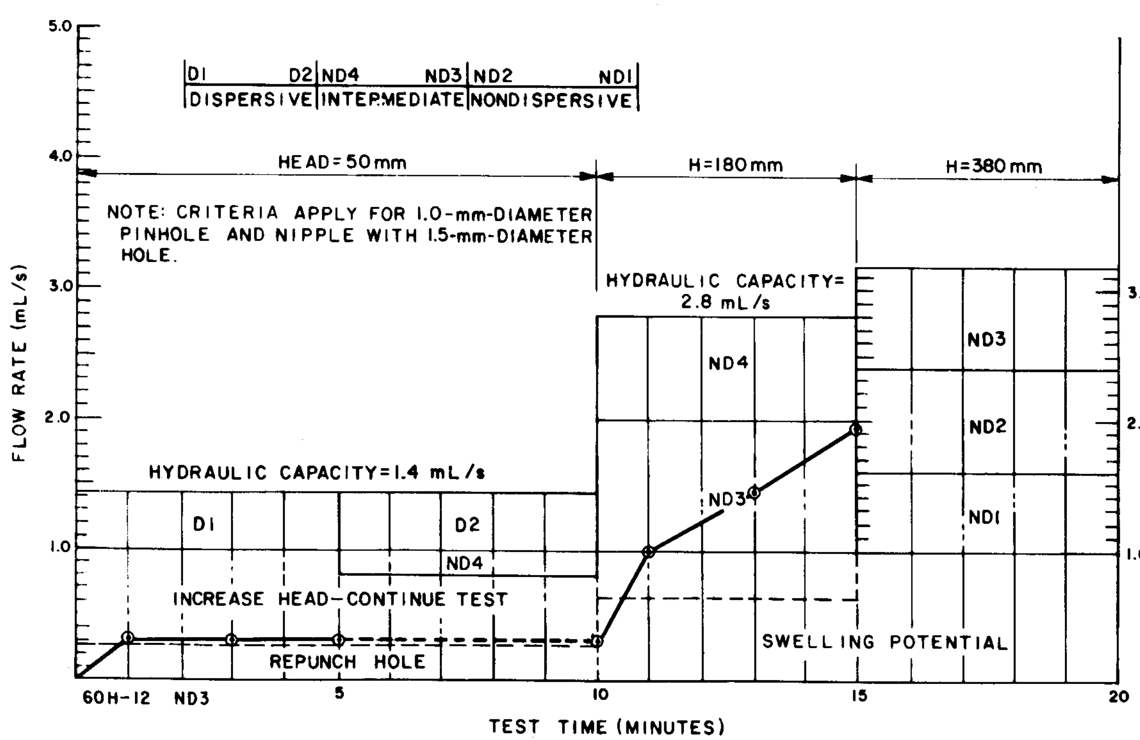
DISPERSIVE GRADE VS FLOW RATE



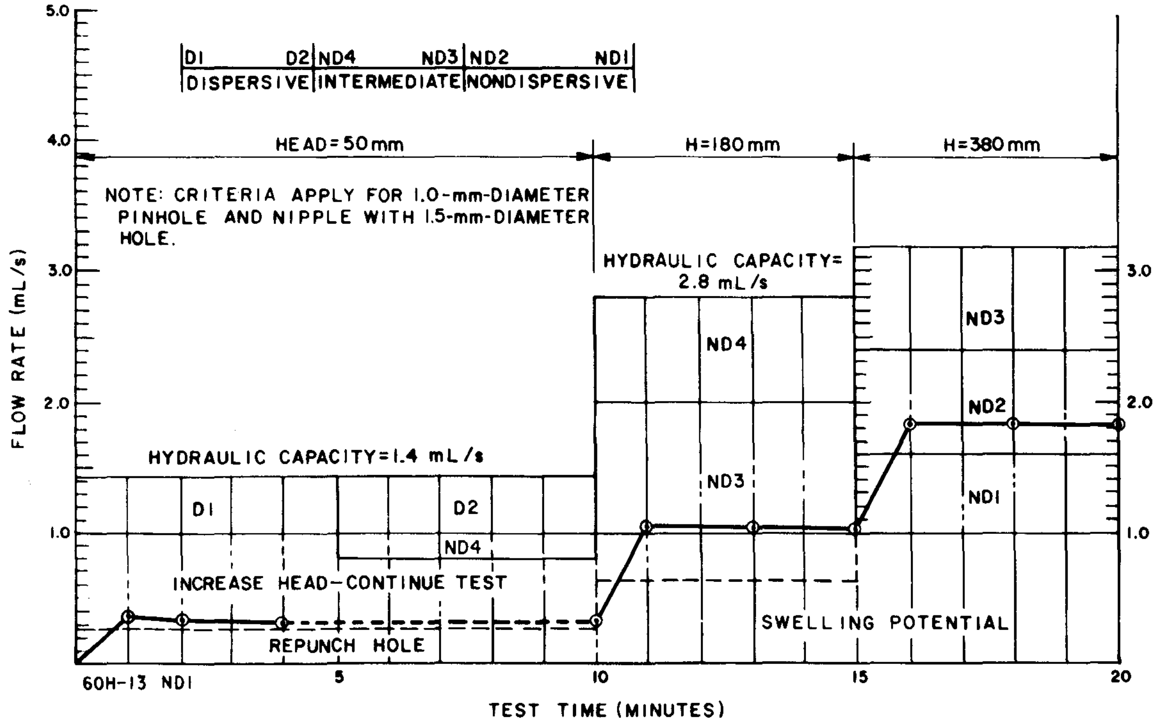
DISPERSIVE GRADE VS FLOW RATE



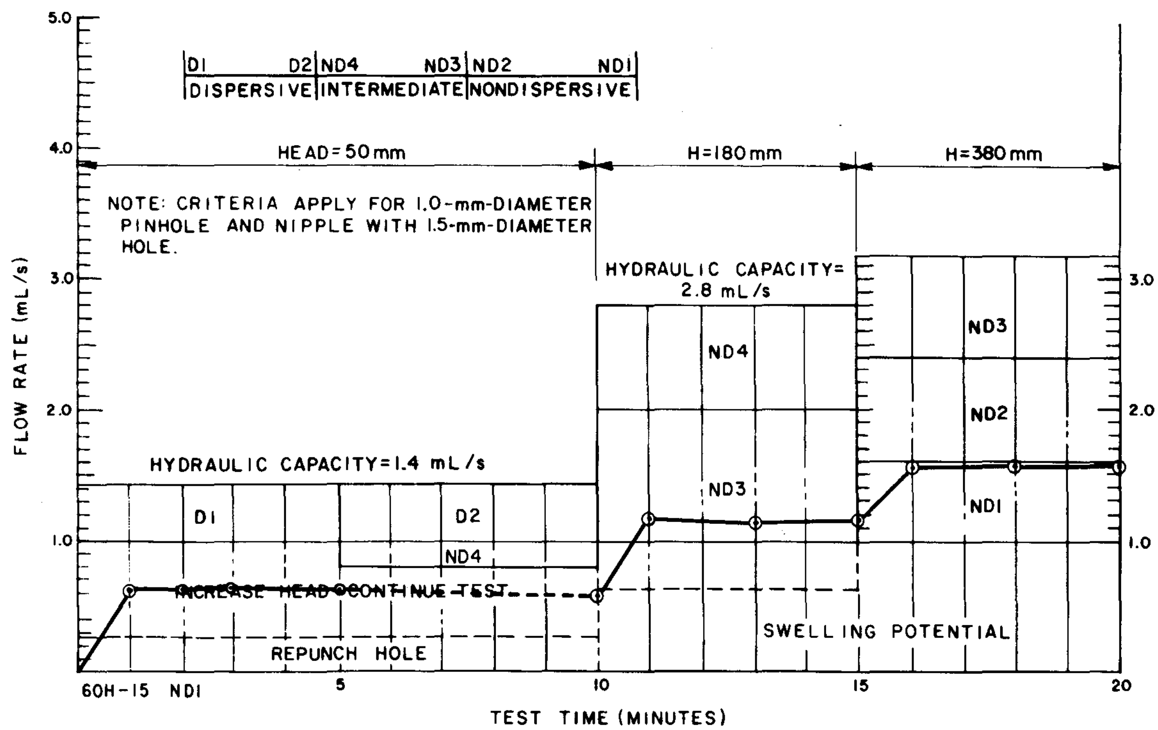
DISPERSIVE GRADE VS FLOW RATE



DISPERSIVE GRADE VS FLOW RATE



DISPERSIVE GRADE VS FLOW RATE



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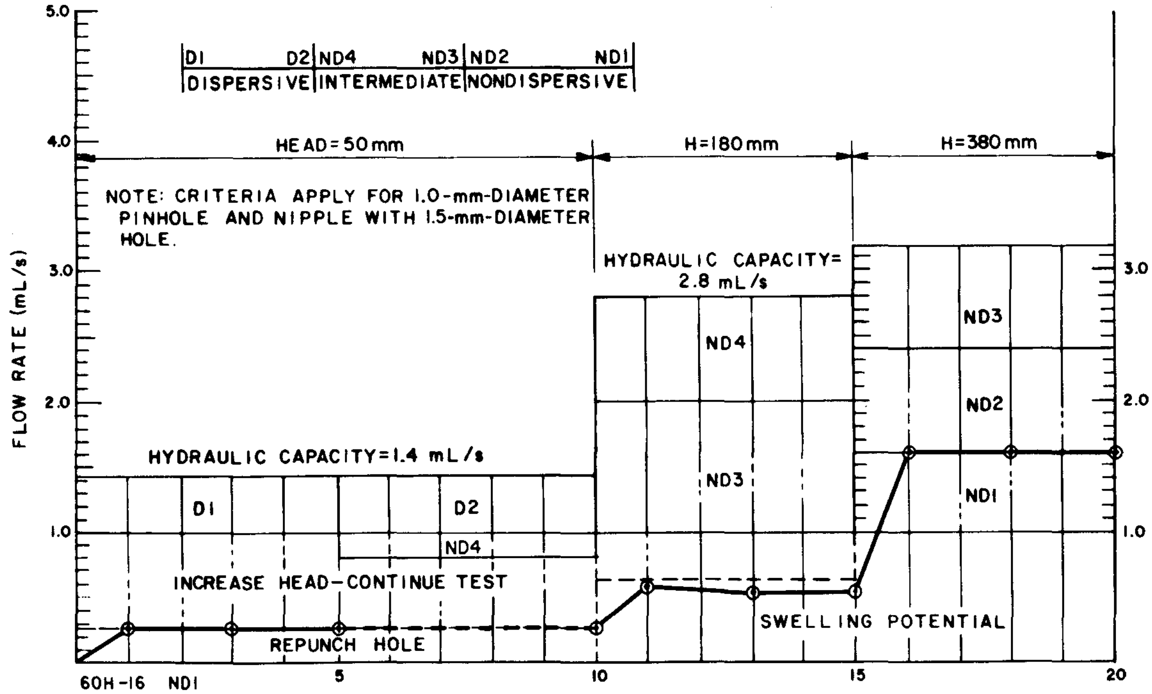
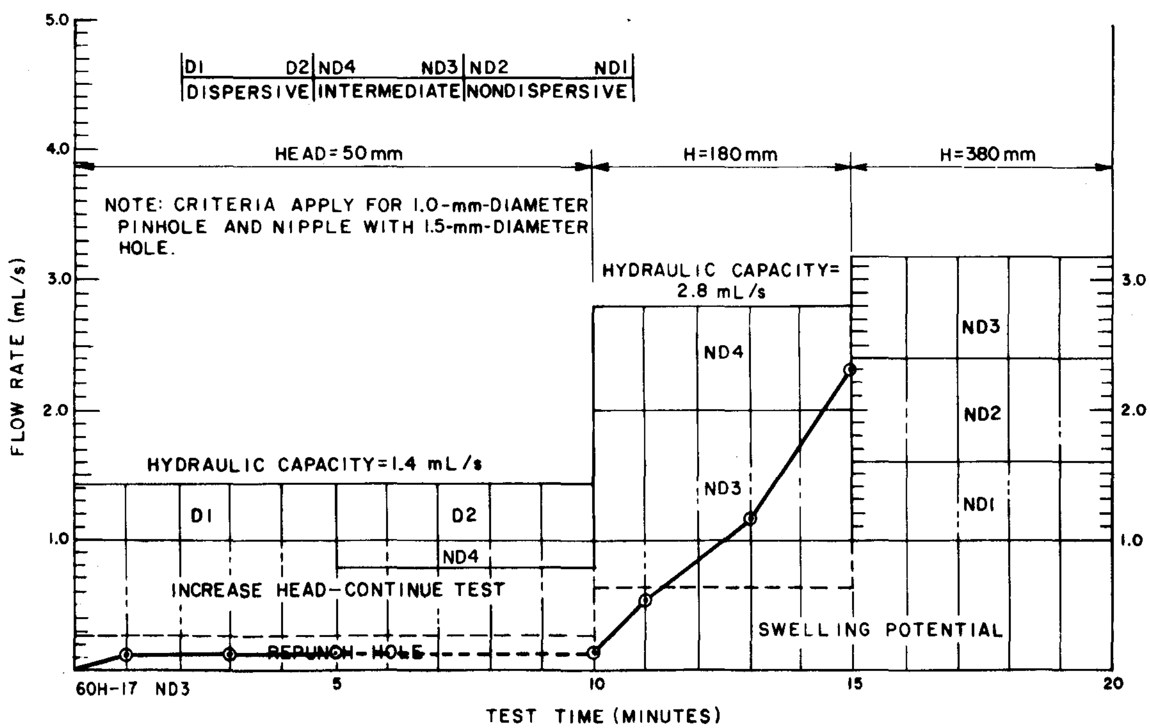


DISPERSIVE GRADE VS FLOW RATE



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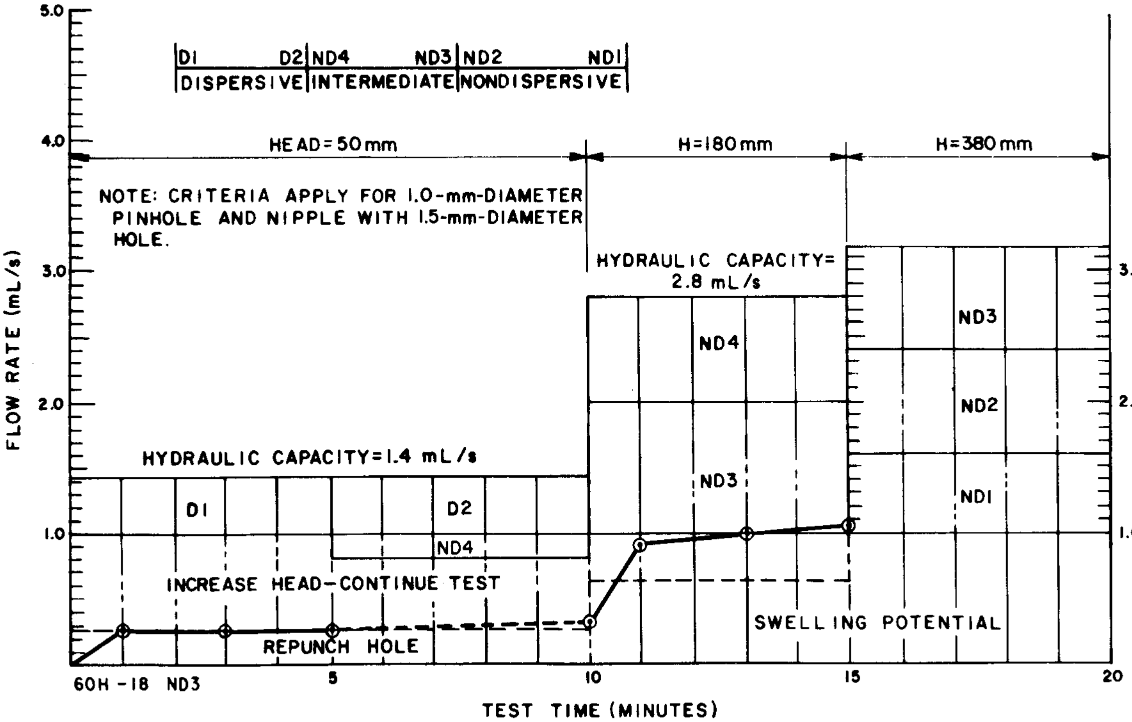

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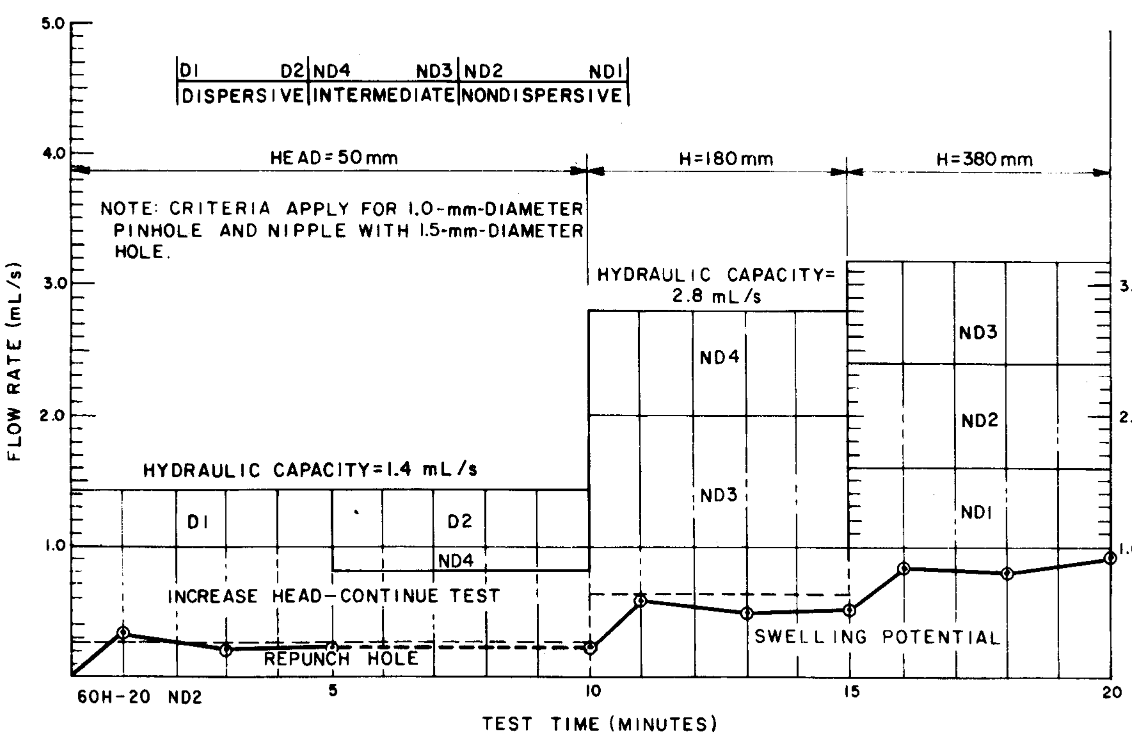

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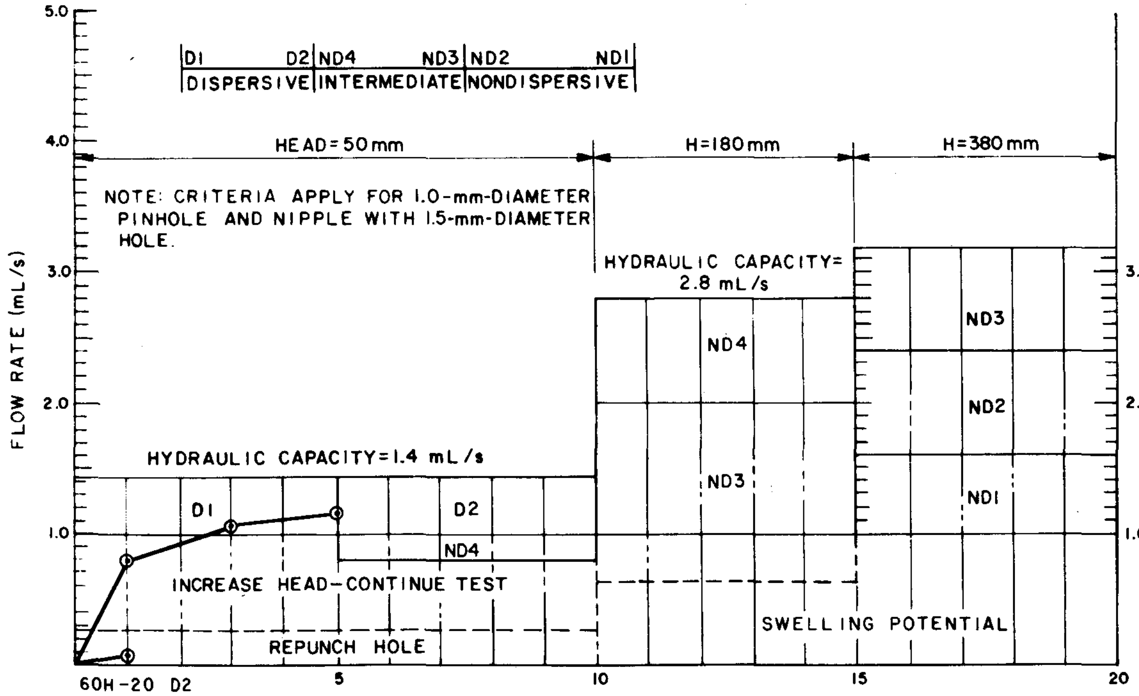
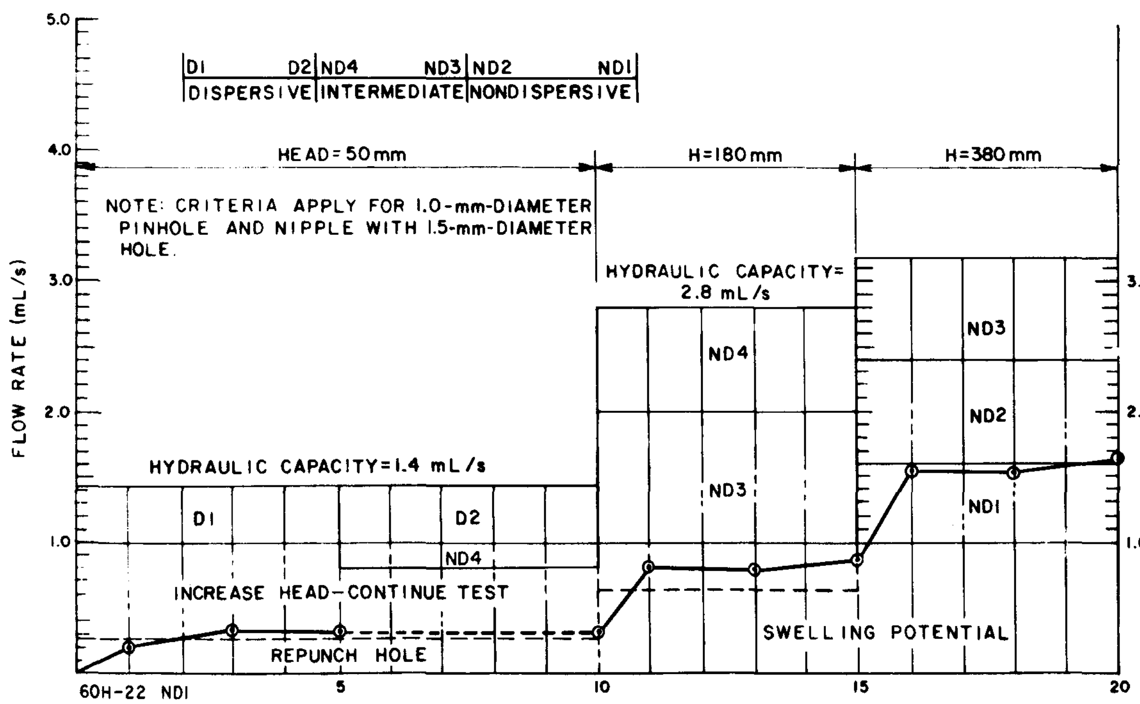
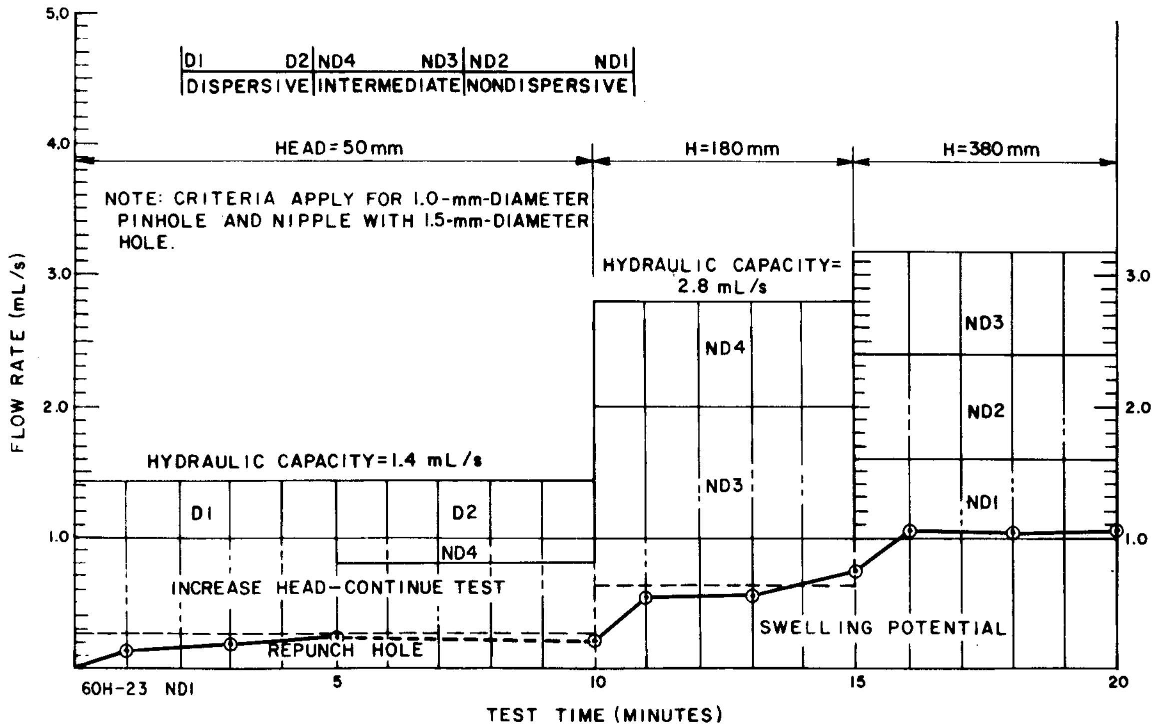


DISPERSIVE GRADE VS FLOW RATE



DISPERSIVE GRADE VS FLOW RATE



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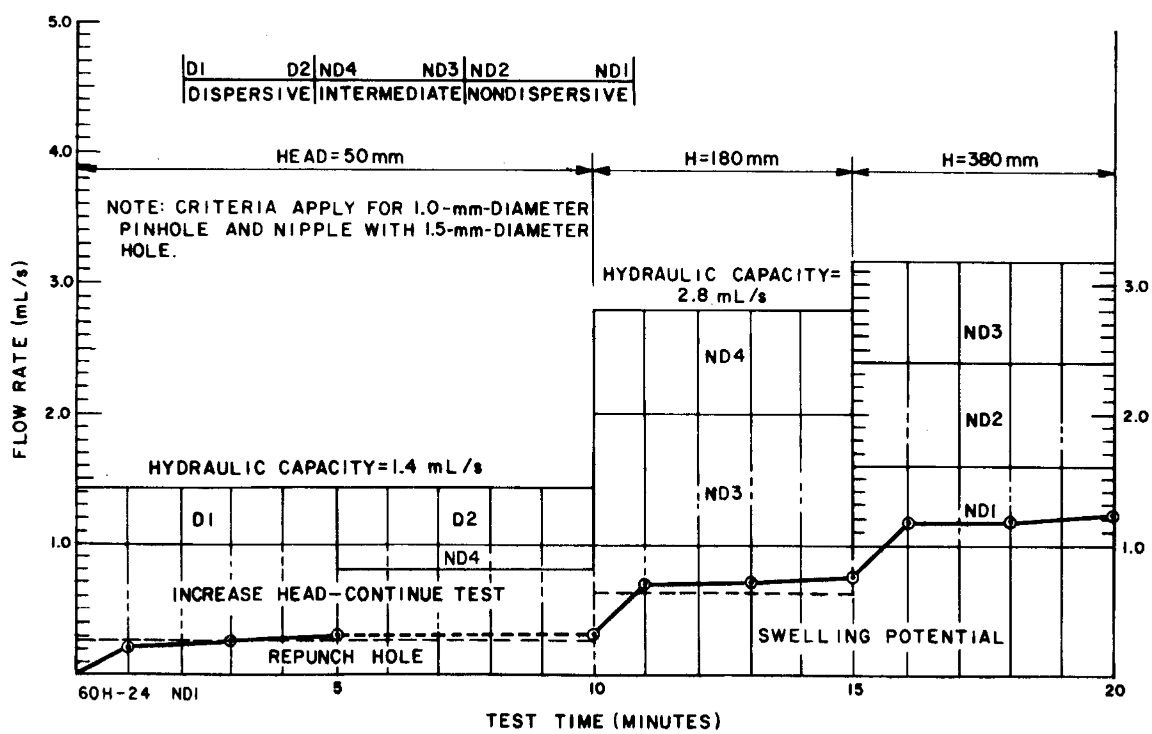
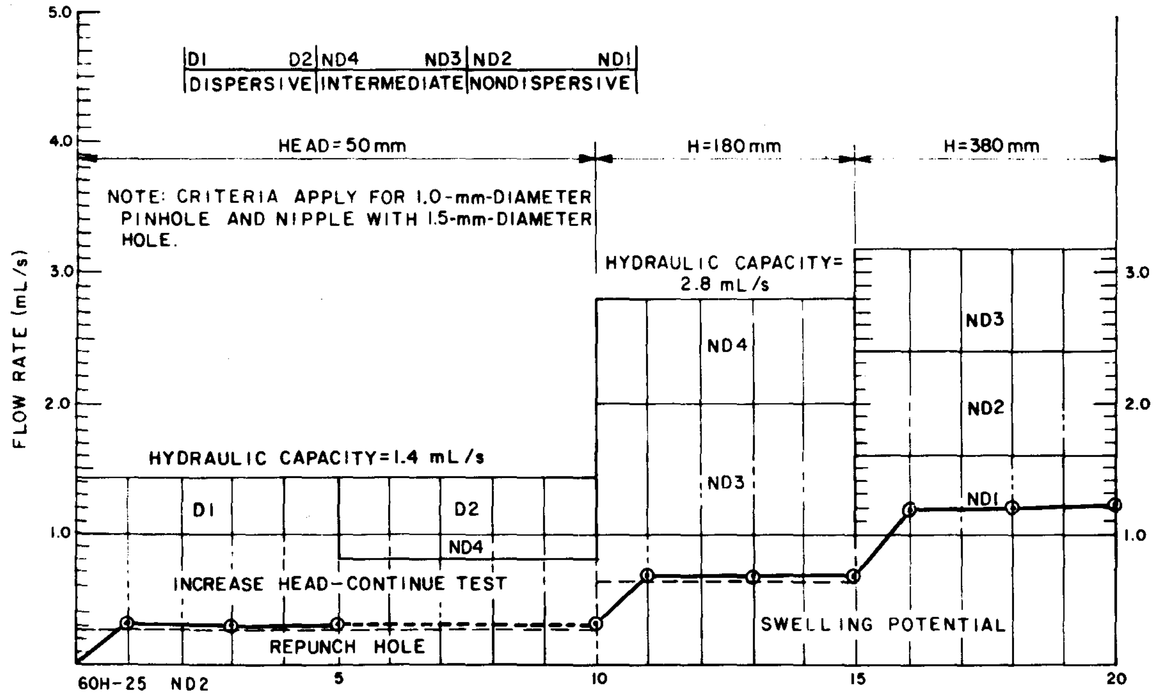
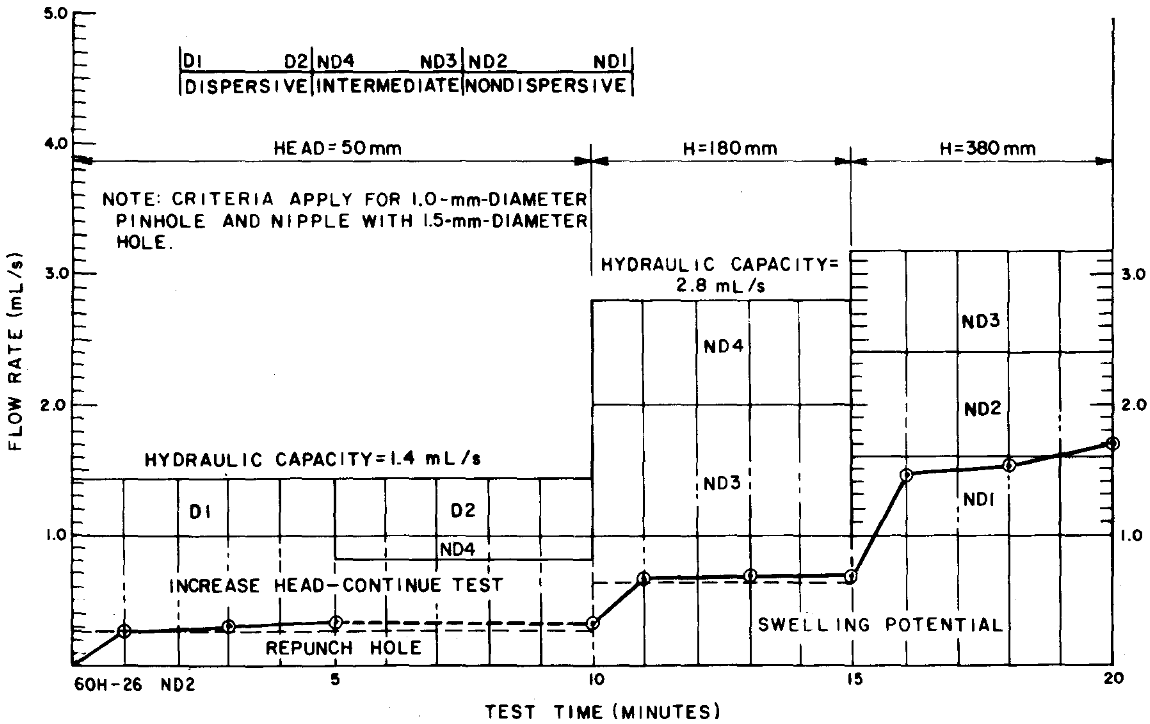


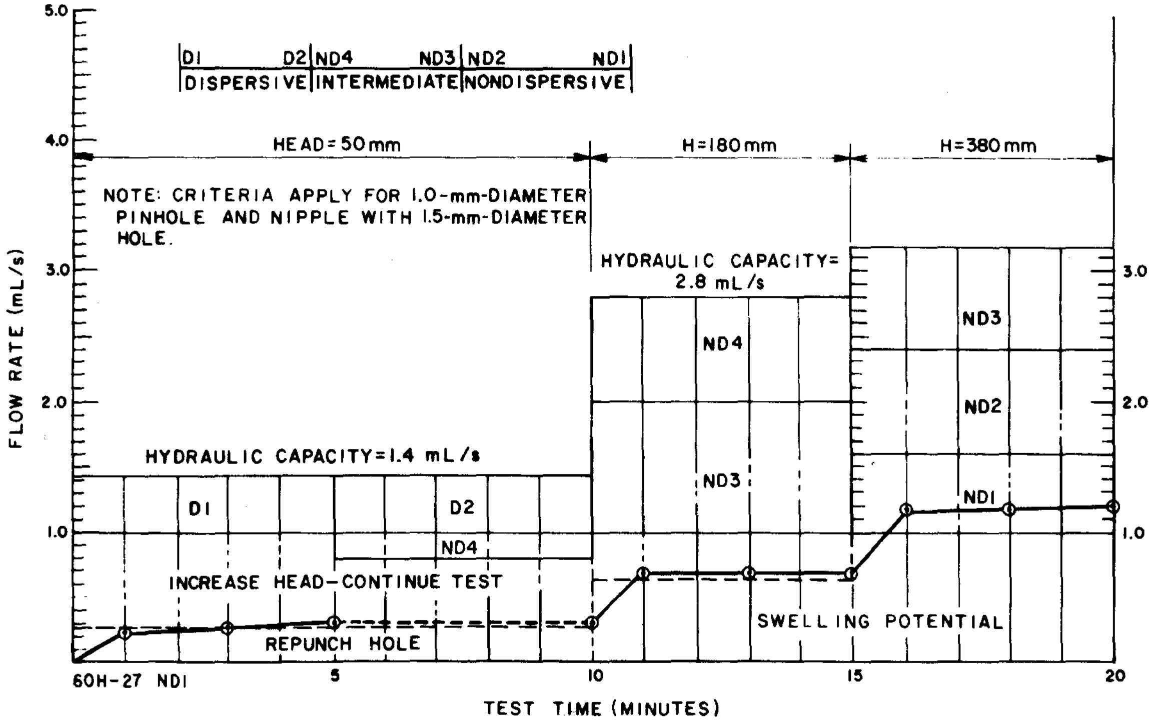
DISPERSIVE GRADE VS FLOW RATE



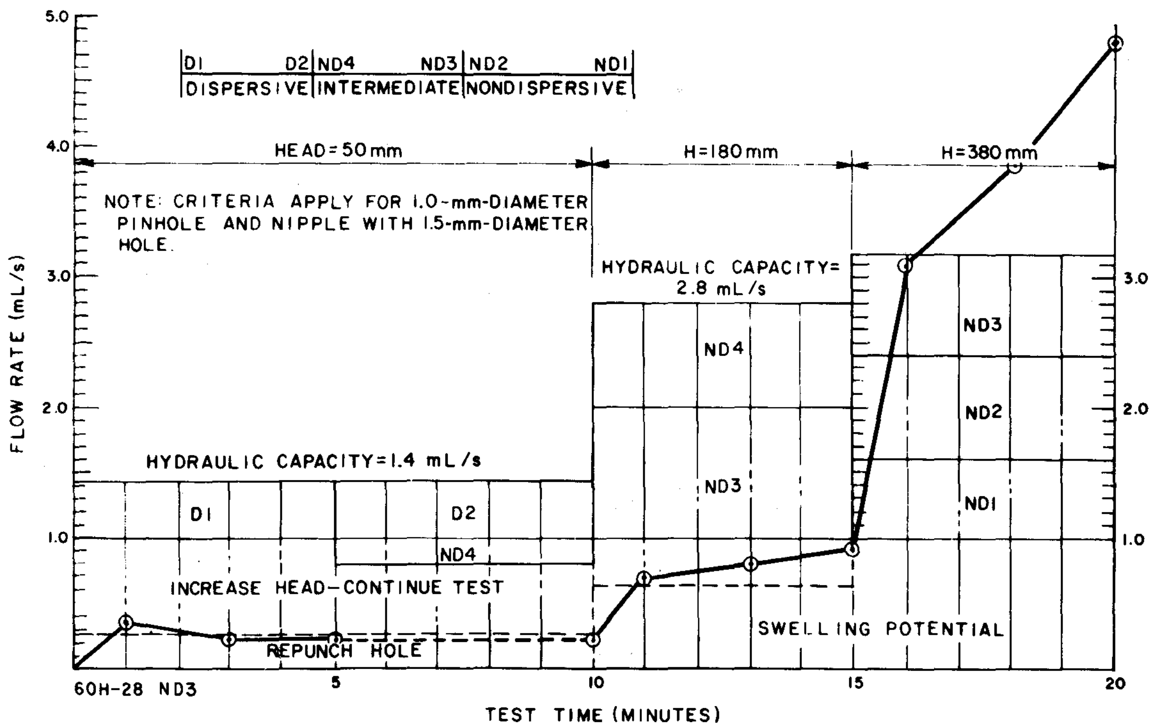
DISPERSIVE GRADE VS FLOW RATE



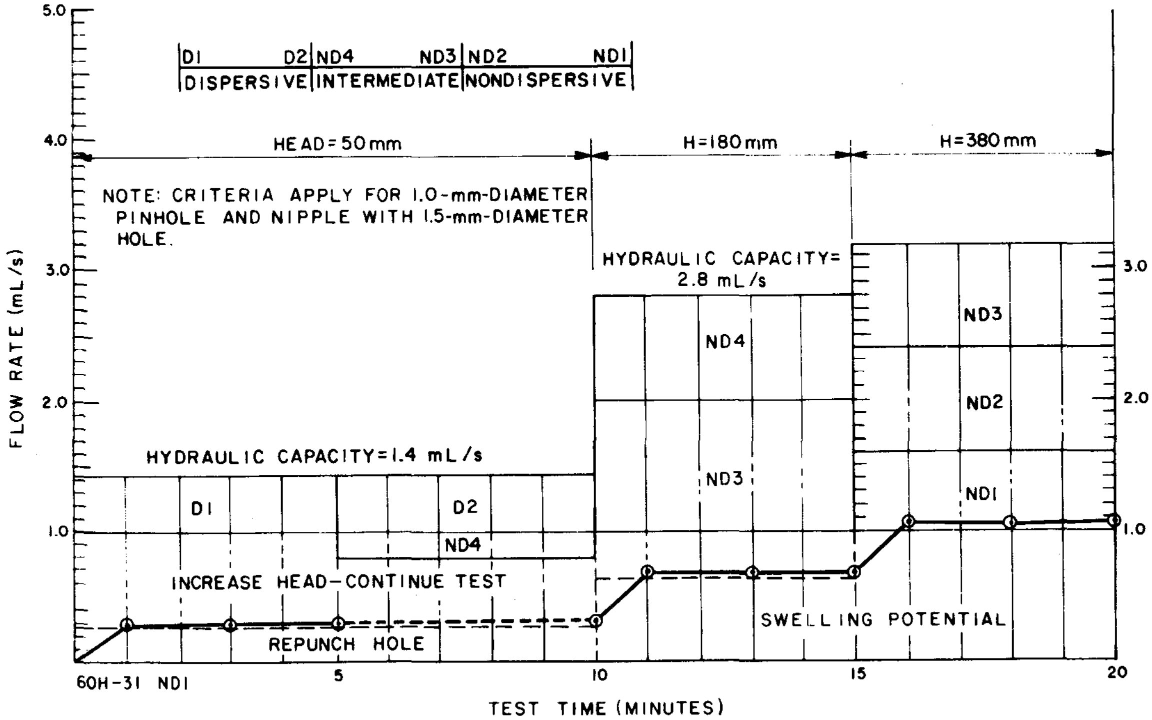
DISPERSIVE GRADE VS FLOW RATE



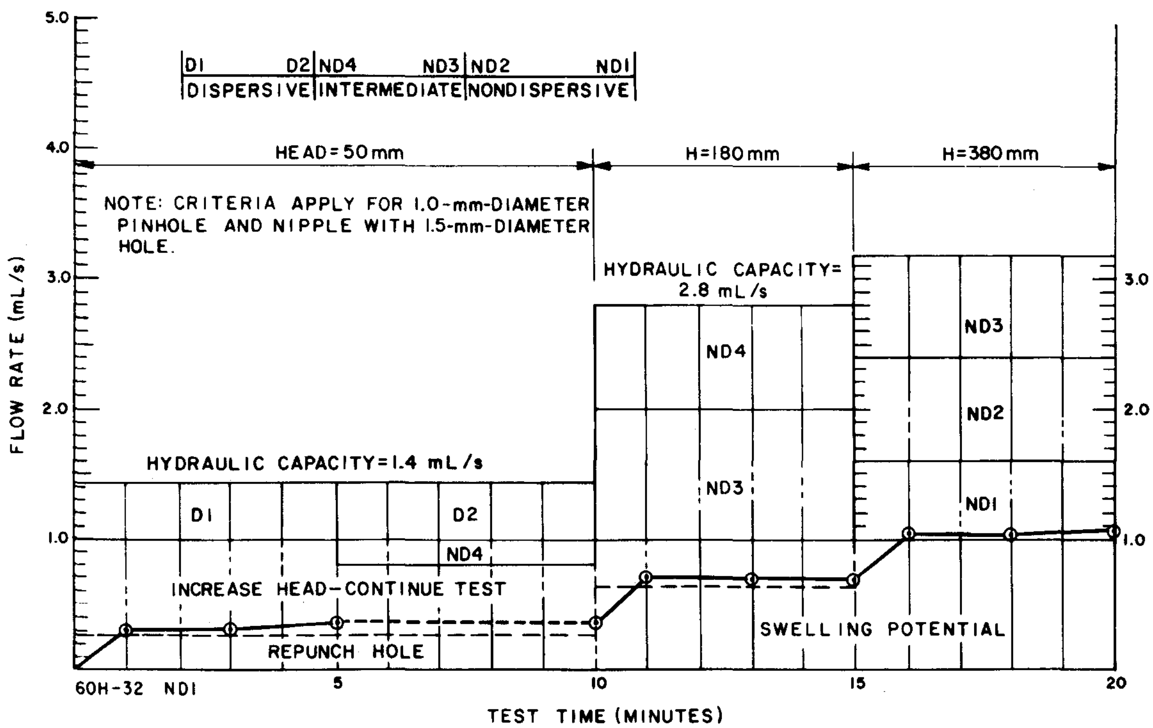
DISPERSIVE GRADE VS FLOW RATE



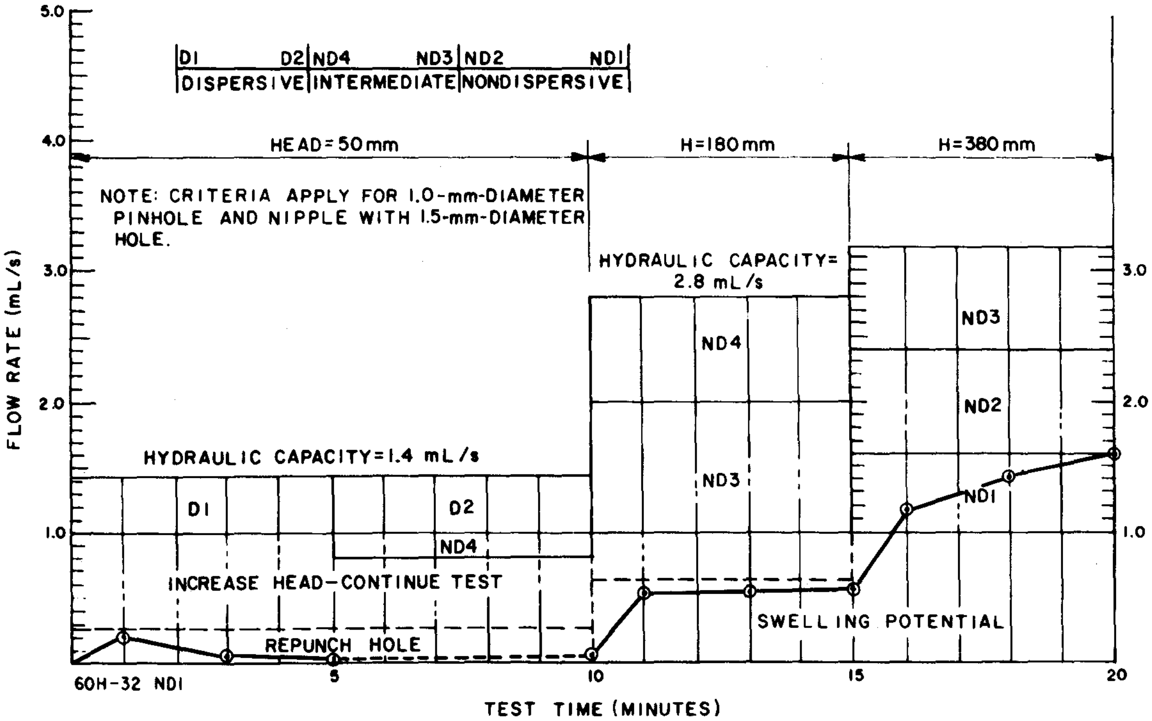
DISPERSIVE GRADE VS FLOW RATE



DISPERSIVE GRADE VS FLOW RATE



DISPERSIVE GRADE VS FLOW RATE



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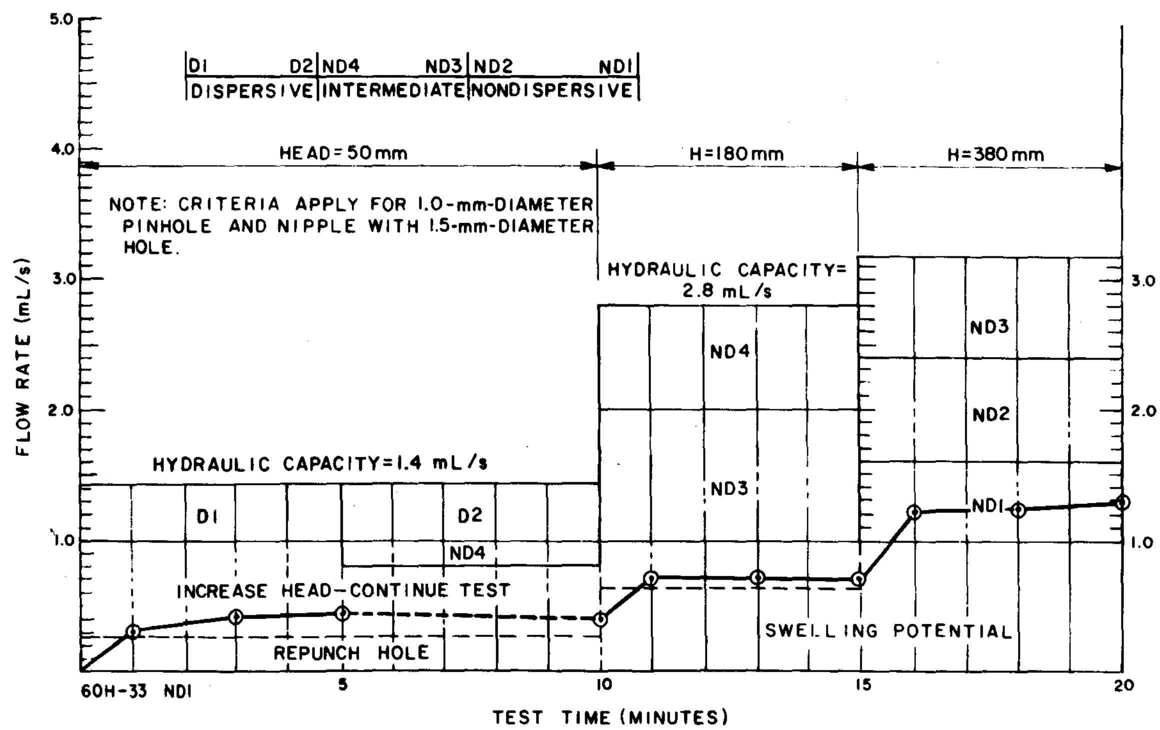

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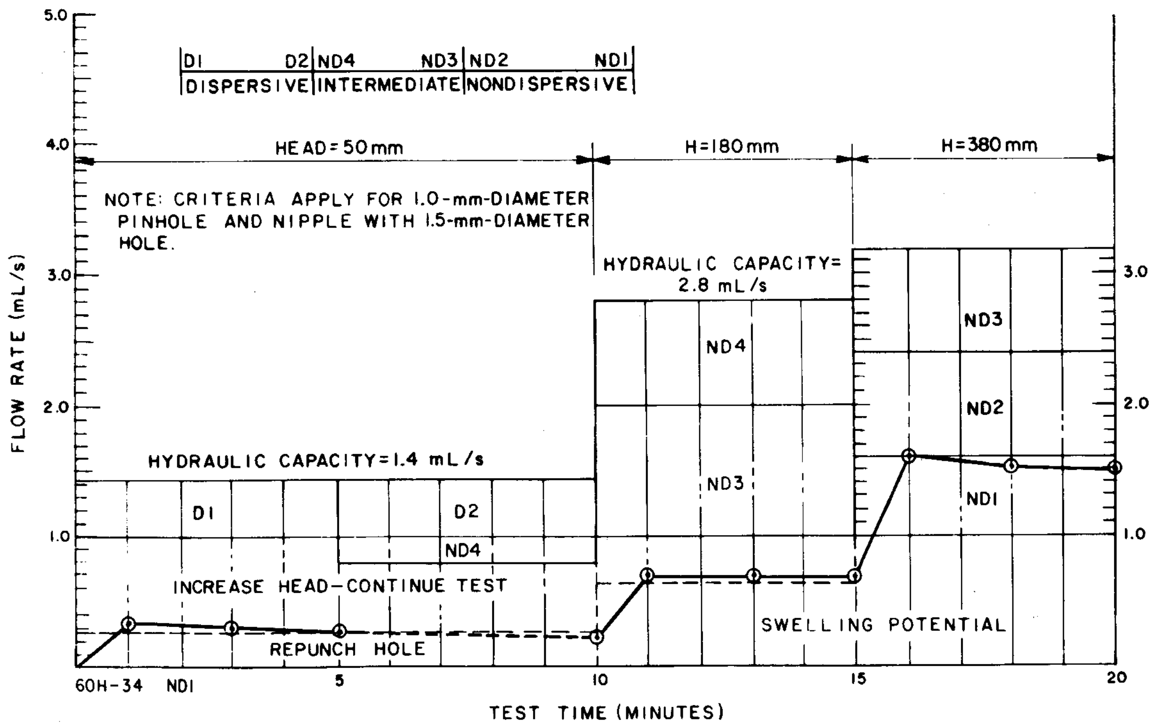
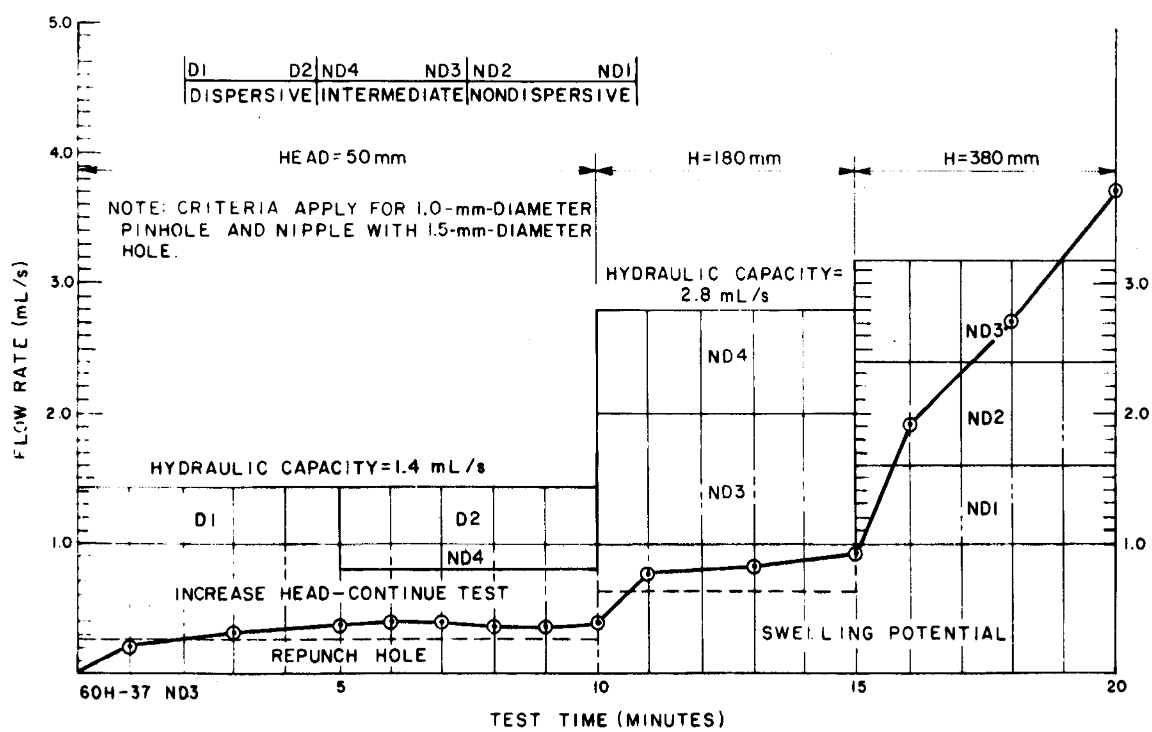
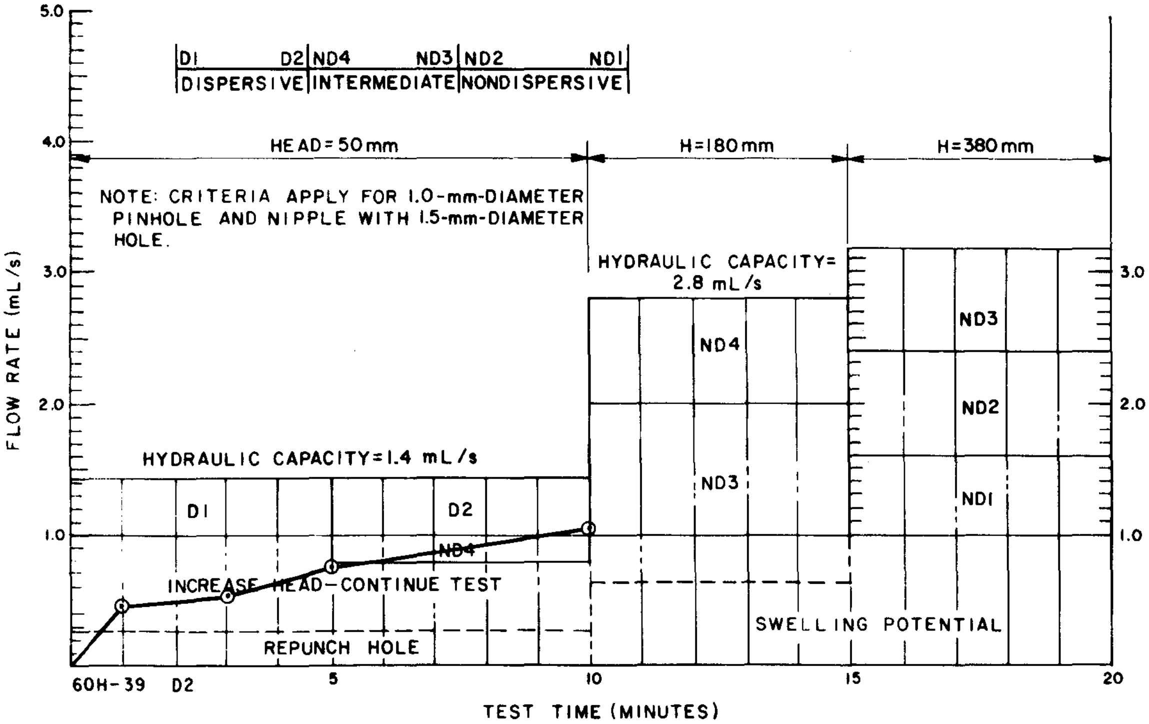


DISPERSIVE GRADE VS FLOW RATE



DISPERSIVE GRADE VS FLOW RATE



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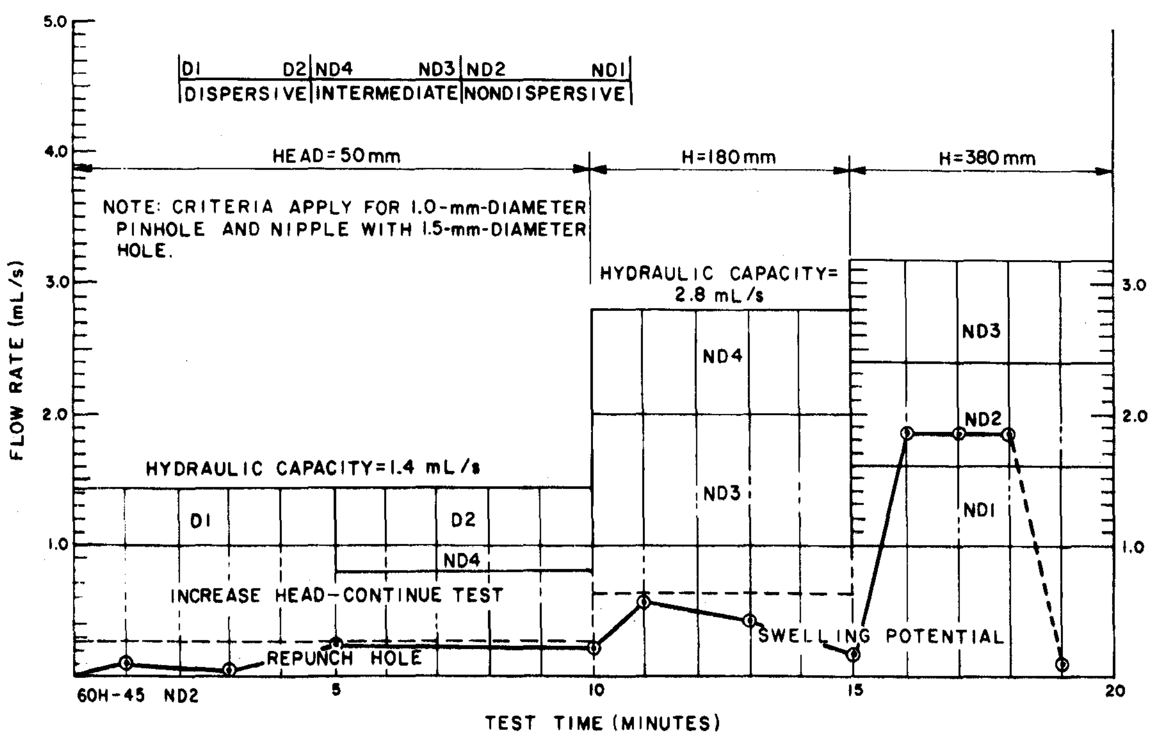

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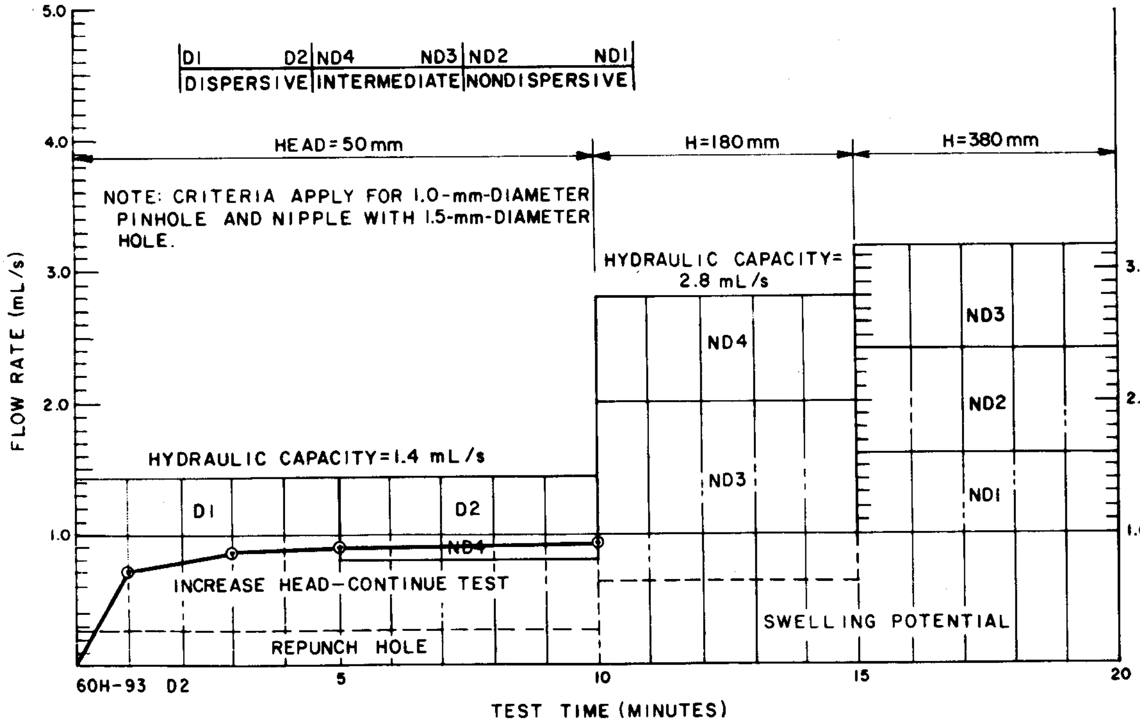

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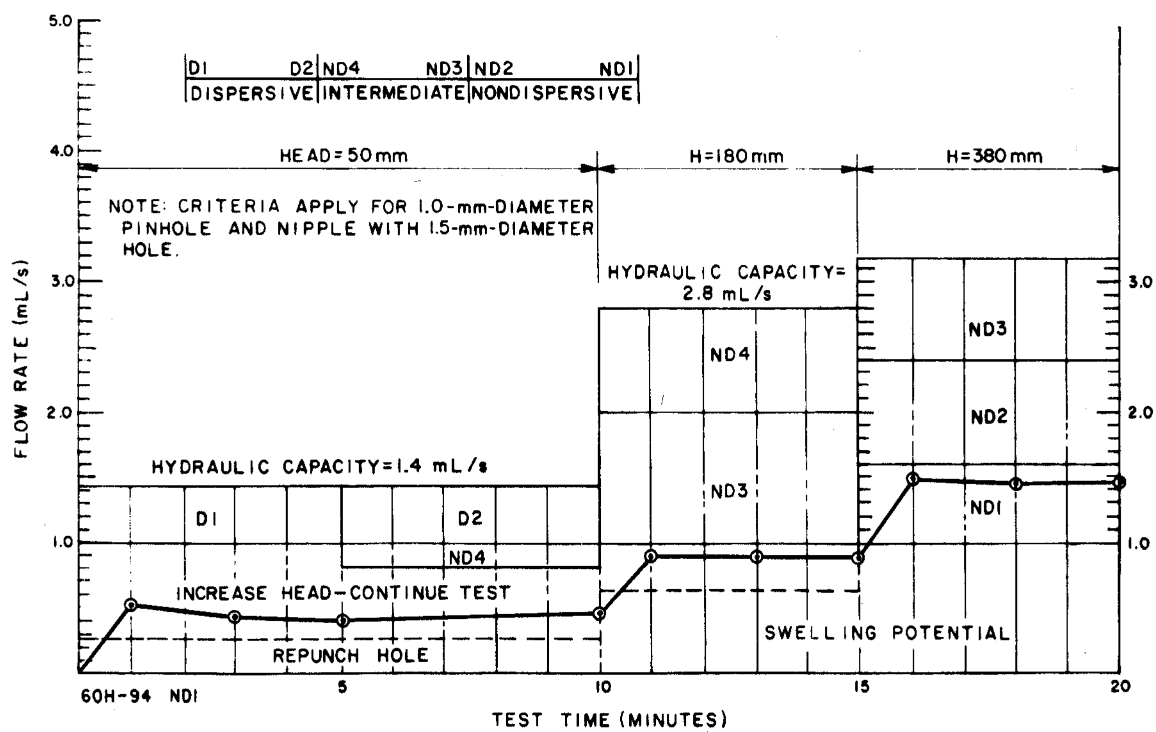

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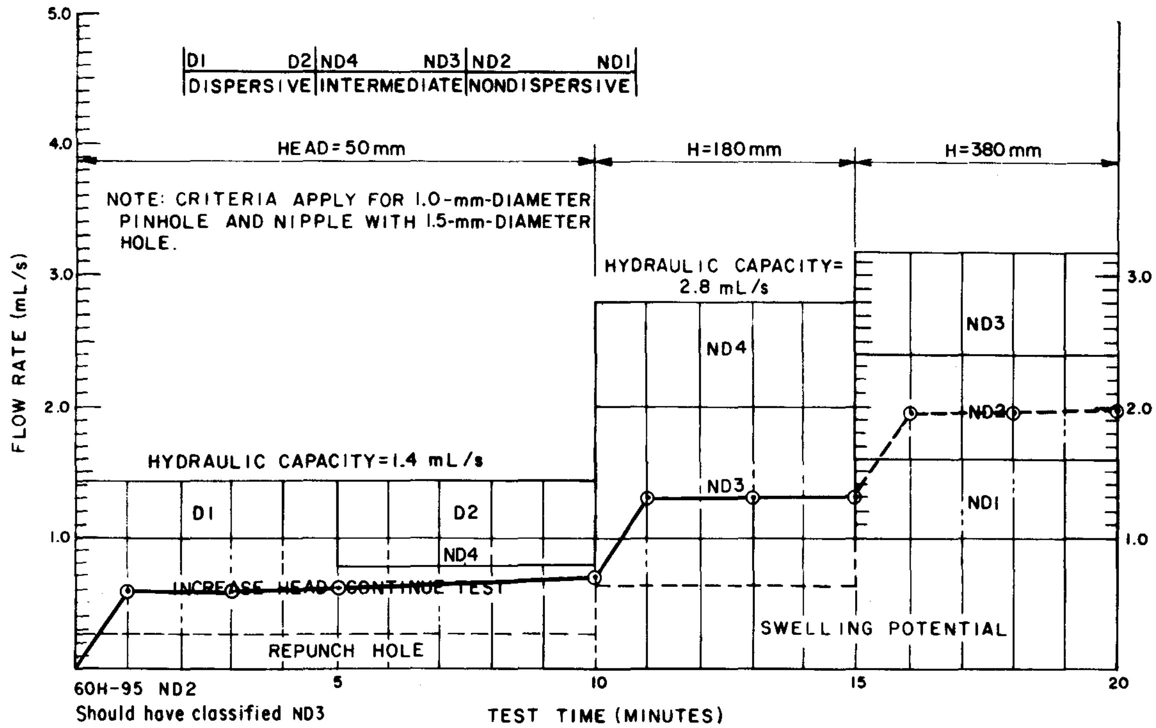
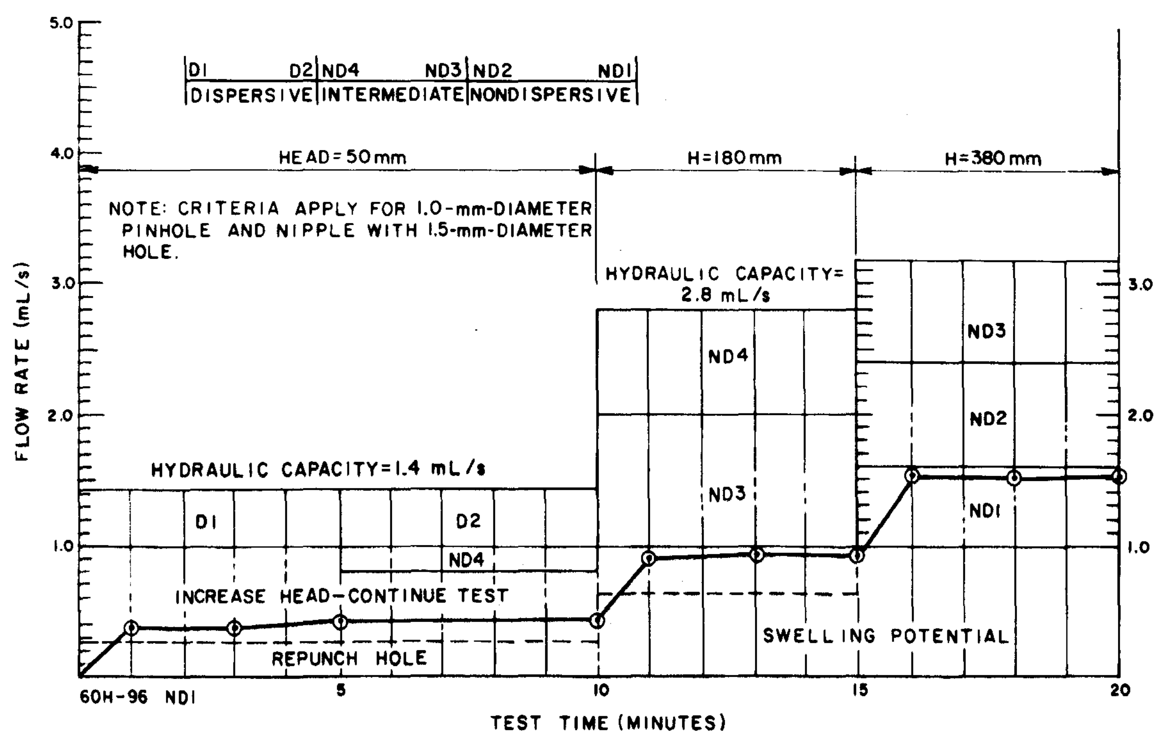
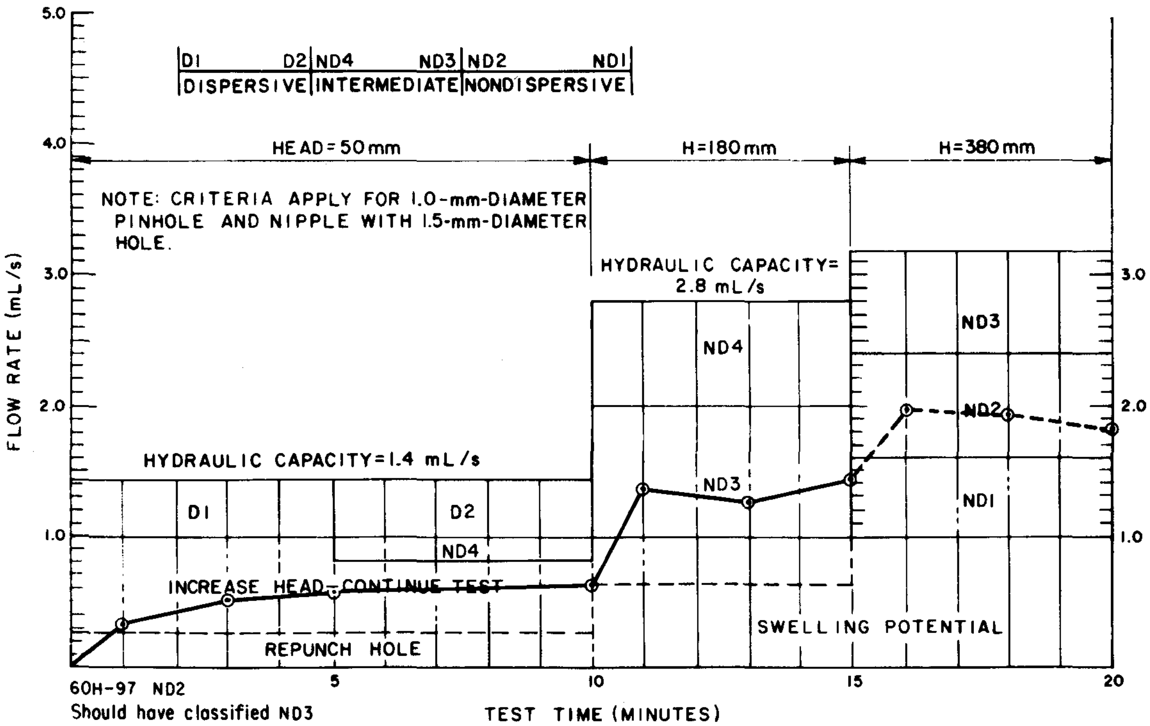


DISPERSIVE GRADE VS FLOW RATE



DISPERSIVE GRADE VS FLOW RATE



DISPERSIVE GRADE VS FLOW RATE

APPENDIX D

PRECISION, ACCURACY, AND REPRODUCIBILITY LIMITS OF PINHOLE TEST EQUIPMENT

The precision, accuracy, and reproducibility of flow rate measurements are discussed in this appendix, and are defined:

Precision—The degree of mutual agreement among individual measurements.

Accuracy—The degree of agreement of individual or average measurements with an accepted reference value.

Reproducibility—The degree of mutual agreement among repeated data sets of individual measurements.

Table D-1 summarizes the results of flow rate data collected from tests conducted in accordance with the flow rate test procedures previously discussed in the main body of this report. The precision of flow rate measurements increases with the increasing collection intervals until a point where operator reaction time no longer significantly influences the final flow rate determination. The data in table D-1 show no significant trend for assessing precision among the 15-, 20-, 30-, or 60-second effluent collection intervals. The precision of flow rate measurements using a 15-second collection period is summarized in table D-2.

Table D-1.—*Flow rate data summary using a 1.5-mm nipple*

Test No.	d_p, mm	H_L, mm	Time, s	Water volume collected, mL					Q(Avg.), mL/s	No. of readings
				Avg.	Min.	Max.	S.D.[1]	Var.[2]		
1	1.0	50	60	18	15	22	2.5	5.8	0.30	10
2	1.5	50	30	25	24	26	0.74	0.49	0.84	10
3	1.5	50	20	20	20	21	0.73	0.48	1.0	10
4	2.0	50	30	37	35	38	0.95	1.2	1.2	10
5*	2.0	50	30	14	13	15	0.72	0.45	0.45	10
6	2.5	50	15	20	19	20	0.32	0.09	1.3	10
7	2.5	50	15	16	15	17	0.79	0.56	1.1	10
8	3.0	50	15	20	19	20	0.53	0.25	1.3	6
9	3.0	50	15	17	15	18	0.94	0.80	1.1	10
10	3.5	50	15	20	19	20	0.42	0.16	1.3	10
11	3.5	50	15	20	18	21	0.92	0.76	1.3	10
1	1.0	180	30	20	21	23	6.4	3.6	0.67	10
2	1.5	180	30	56	55	59	1.4	1.8	1.9	10
3	1.5	180	30	58	57	60	0.95	0.81	1.9	10
4	2.0	180	30	76	73	79	2.0	3.7	2.5	10
5*	2.0	180	20	20	19	21	0.81	0.59	1.0	10
6	2.5	180	15	42	40	43	1.2	1.4	2.8	10
7	2.5	180	15	34	32	36	1.5	2.0	2.3	10
8	3.0	180	15	40	40	43	0.82	0.61	2.7	6
9	3.0	180	15	37	33	39	1.9	3.21	2.5	10
10	3.5	180	15	37	35	38	0.97	0.84	2.4	10
11	3.5	180	15	29	28	30	1.2	1.2	1.9	10
1	1.0	380	30	35	32	36	1.2	1.2	1.2	10
2	1.5	380	30	87	84	89	1.6	2.4	2.9	10
3	1.5	380	15	47	43	51	2.9	7.6	3.1	10
4	2.0	380	30	114	112	116	1.4	1.8	3.8	10
5*	2.0	380	30	47	45	50	1.5	2.0	1.6	10
6	2.5	380	15	63	60	67	2.3	4.7	4.2	10
7	2.5	380	15	51	48	54	1.7	2.6	3.4	10
8	3.0	380	15	61	60	64	1.8	2.8	4.0	6
9	3.0	380	15	59	58	64	2.0	3.6	4.0	10
10	3.5	380	15	53	48	56	2.6	6.0	3.5	10
11	3.5	380	15	47	44	50	2.2	4.2	3.1	10

[1] Standard deviation.
[2] Variance.
* Data on test No. 5 were unreliable by inspection.

Table D-2.—*Precision and reproducibility at 15-second collection interval*

Test No.	H_L, mm	Q, mL/s	No. of readings	Hydraulic capacity, mL/s	Range selected,[1] mL/s
6	50	1.3	10		
7	50	1.1	10		
8	50	1.3	6		
9	50	1.1	10		
10	50	1.3	10		
11	50	1.3	10		
All data.	50	1.2	56	1.2	±0.2
6	180	2.8	10		
7	180	2.3	10		
8	180	2.7	6		
9	180	2.5	10		
10	180	2.4	10		
11	180	1.9	10		
All data.	180	2.4	56	2.4	±0.3
6	380	4.2	10		
7	380	3.4	10		
8	380	4.0	6		
9	380	4.0	10		
10	380	3.5	10		
11	380	3.1	10		
All data.	380	3.7	56	3.7	±0.5

[1] This range is reflected on figures 14 and 15 in main body of this report.

Mission of the Bureau of Reclamation

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.

A free pamphlet is available from the Bureau entitled "Publications for Sale." It describes some of the technical publications currently available, their cost, and how to order them. The pamphlet can be obtained upon request from the Bureau of Reclamation, Attn D-922, P O Box 25007, Denver Federal Center, Denver CO 80225-0007.