HYDRAULIC TESTING OF PLASTIC FILTER FABRICS

By Yung Hai Chen, M. ASCE, Daryl B. Simons,
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September 1981

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Hydraulic Testing of Plastic Filter Fabrics

By Yung Hai Chen,[1] M. ASCE, Daryl B. Simons,[2] F. ASCE and Phillip M. Demery[3]

Introduction

Plastic filter fabrics are made from synthetic fibers. They are of two types, i.e., either a woven fabric featuring distinct open areas, or a nonwoven fabric that consists of a random fibrous mass of uniform thickness with torturous paths through the fabric. The fabric fiber consists predominantly of polyvinylidene chloride, nylon, polyester, or polypropylene yarns, filaments, or fibers. These synthetic yarns give rise to the term "plastic." However, the terms filter fabric and cloth filters are synonymous with plastic filter.

Filter fabrics, being both economical and durable, can be used as an alternative to a graded filter. Filter fabrics are economical because costs of both natural filter material and construction are increasing. Like granular filters, plastic fabric filters are designed to be highly permeable to water and yet constrain soil particles.

Plastic filter fabrics have been used to help protect coastal structures associated with rivers, lakes, canals, dams, and drainage systems of all types. Principally, the filters serve as bank protection, subdrainage protection, and as a means of protecting the foundation soil. These filters retain their strength undiminished by long exposure to salt or fresh water. Many successful applications of plastic filters have been documented, such as the usages of plastic filters to protect beaches in Florida (1), to control the erosion problems at bridges (4) by the Corps of Engineers, and to serve as a road support on a soft, spongy Alaskan soil (7).

An interaction exists between the plastic filter fabric characteristics, soil type used, and ground-water conditions. In analyzing the effectiveness of a filter fabric, the performance mechanism must be investigated considering the aforementioned variables. In establishing a conducive testing environment, it is possible to study the hydraulic properties of plastic filters associated with various soil types and water head. It is the intent of this study to provide information

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regarding nonwoven filter fabric performance in the hope of developing an adequate set of guidelines and criteria for plastic filter fabric selection, particularly for subsurface drainage systems where filter fabrics are predominantly of the nonwoven type.

Previous Laboratory Test and Selection of Filters

In selecting a plastic filter, the fabric permeability should be adequate to pass water from the soil while having a pore structure that at the same time will hold back soil. This rationale suggests that design specifications could be developed based on soil type, ground-water conditions, and filter cloth characteristics. Although current field applications show plastic filters have promise, hydraulic characteristics testing has so far failed to relate filter and soil characteristics with system performance.

The Corps of Engineers is one of the few agencies to document results of their hydraulic characteristics testing (2). Using soil types of known gradation, the Corps has established a set of guidelines pertaining to the use of plastic filters. Their results indicate that filter cloth selection is dependent on the D_{85} size of the soil, the EOS (equivalent opening size), and a term denoted as a gradient ratio. Two types of tests were conducted by the Corps: (1) Filtration tests; and (2) gradient tests.

Based upon analysis of the filtration tests, the Corps of Engineers recommended the following criteria be used in selecting a plastic filter. When the filter fabric is adjacent to granular materials containing 50% or less by weight of silt (material of little or no plasticity, passing the No. 200 sieve): (1) The fabric pore size estimated by EOS should be smaller than the D_{85} of the soil where the D_{85} is the diameter of the particle in which 85% by weight of the soil if finer; and (2) the open area of woven filters should not exceed 50%.

When the filter fabric is adjacent to soils having little or no cohesion containing more than 50% silt by weight: (1) EOS should be no larger than the opening in the United States Standard Sieve No. 70; and (2) open area of woven fabrics should not exceed 10%. To reduce the chance of clogging, no fabric should be specified with an EOS sieve number larger than the opening of a United States Standard Sieve No. 100 (0.0059 in., 0.15 mm). Filter fabrics require a sand blanket of thickness equal or larger than 6 in. to be placed between the filter and the soil for soils with 85% or more smaller than the No. 200 sieve.

The gradient ratio is a parameter the Corps of Engineers uses in filter comparison. This parameter is developed from permeameter testing and is a result of hydraulic gradient manipulation:

$$C = \frac{h_i}{h_t} \quad \quad (1)$$

in which C = the gradient ratio; h_i = the hydraulic gradient at the lowest 1 in. of soil plus filter cloth; and h_t = the hydraulic gradient over the 2 in. of soil between one and 3 in. above the fabric. Another definition for h_t is the total hydraulic gradient. If the gradient ratio becomes greater than three within 24 h, the Corps of Engineers suggests that the filter cloth is being plugged.

The design concept of the parameter is that as plugging occurs, there is a water pressure buildup immediately above the plastic filter. Some filter fabrics being tested developed a gradient ratio greater than 1.0 when subjected to a silty sand.

Rosen and Marks (7) studied the behavior of plastic filters at the University of Tennessee in 1975. Unlike the Corps of Engineers' filtration tests which were conducted for 60 h, their experiment was conducted 21 days–28 days or until the flow through the system became constant. Furthermore, the filtration and gradient ratio tests were conducted simultaneously. Twenty soil types were tested altogether, however, only one filter fabric was considered, i.e., Mirafi 140 (a nonwoven filter). The soil types were produced by adding various amounts of either silt, kaolinite, or montmorillonite to a river sand base soil.

Testing indicated a soil compaction occurred within the soil. This was deduced from permeability decreases as well as analysis of hydraulic gradients. The percentage of soil actually trapped in the fabric was quite small and did not vary significantly with soil type. The more soil was well graded, the smaller the amounts of fine particles that passed through the filter cloth. Rosen and Marks concluded that the design criteria of plastic filters must be the same as those established for conventional aggregate filters. The nonwoven filter tested was determined to be effective in subdrainage applications for a relatively wide range of soil conditions.

Ogink (6) investigated the characteristics of the fabric aperture and the blocking of fabrics by sand particles. Willardson and Walker (8) conducted tests to evaluate the response of using filter fabrics as drain envelope material to problem soils needing drainage. These writers, the Corps of Engineers, and other investigators have provided the public with some basic guidelines on filter cloth use. It is still the practice in some Corps districts not to use filter cloth within critical regions. The testing has opened the door for filter cloth applicability; however, it is time to alleviate the trial and error methodology of applying the filter cloths while at the same time, broadening the scope of the plastic filter fabric industry.

Laboratory Testing—Engineering Research Center, Colorado State University

Test Apparatus.—The experimental set up (5) included a large head box, a small rectangular constant head box, 12 permeameters, a manometer board with tubes, weighing containers, recirculating pump, and drainage. Fig. 1(*a*) shows the flow diagram for these apparatus. This system allows for the testing of 12 filter systems simultaneously under identical hydraulic heads.

The large head box was constructed to intercept the city water and then convey this water to the small rectangular head box. This large wooden box was square with 8 ft (2.95 m) sides and 2 ft (0.61 m) depth. The purpose of the large head tank was two fold. The tank was fitted with a network of steamlines so that the water could be heated and maintained at a desired warmer temperature by using a thermostat. Also the tank served as a stilling basin to decrease the inflow turbulence and air entrainment.

The small constant head box, 2 ft (0.61 m) in width, 4 ft (1.22 m) in length, and 2 ft (0.61 m) in depth, could be moved in a vertical direction along a support in order to vary the hydraulic head. Water supplied to each of the

12 permeameters via the 12 outlets was maintained at constant pressure head by means of the constant head box. Plastic tubing connected the head box outlet to the permeameters. The cylindrical permeameters were constructed of clear Lucite ®, 11.5 in. (292 mm) in diameter, with three distinct sections [see Fig. 1(*b*)]. The top section consisted of a gate valve to regulate incoming water flow and a distributor head to spread out the flow once the water entered the permeameter system. Standpipes were connected to the top of the permeameters to allow the air to escape before any serious accumulations developed. The middle section was used to contain a 4-in. (102-mm) deep soil column.

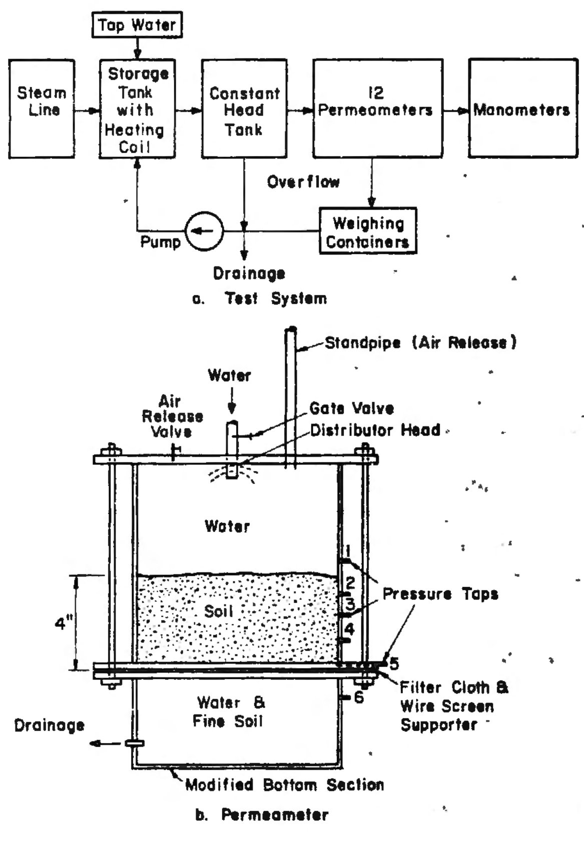

FIG. 1.—Laboratory Test System

The top and middle permeameter sections fit together flush with the plastic filter and screen support positioned directly below. A third section was attached to the bottom of the screen support to close the system from the surroundings. In order to measure the pressure head exerted on the soil column and the filter fabric, six pressure taps were installed on the vertical wall of each permeameter and connected to manometers. The first pressure tap was located 1 in. above the soil surface, whereas the second, third, and fourth pressure taps lay at 1 in. increments within the soil depth starting at the soil surface.

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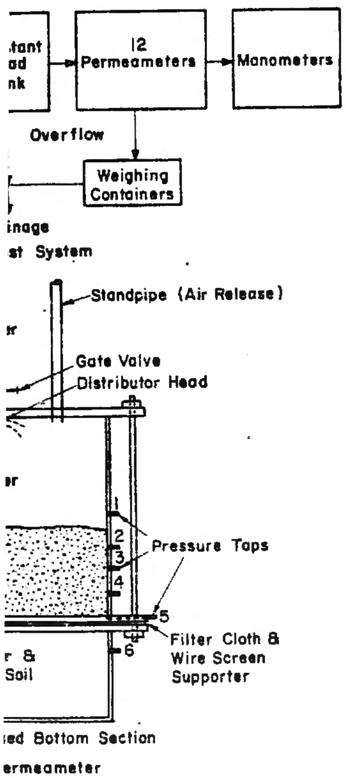

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The fifth pressure tap was located 0.125 in. (3.2 mm) above the filter fabric and the sixth pressure tap was secured on the bottom section below the filter fabric.

A 5.0 hp pump was connected to the system to recirculate the water. It was thought that in recirculating the water, temperature fluctuations and air bubbles would be minimized. However, the pump was later removed to increase the fresh water supplied to the system in order to decrease the amount of bacterial activity within the system.

Test Procedure.—In order to conduct objective testing of the plastic filter fabrics, test condition consistency as well as uniformity must be maintained: (1) Consistent in that all soil types are subject to the same initial conditions; and (2) uniform in that for any one particular test, the soils are equal in size distribution and density for all permeameters. Of the two objectives, consistency was more difficult to maintain. The permeameters are all of the same size and shape. A constant head was applied to the system, equally to each of the 12 permeameters. The difficulty lay within the initial soil saturation procedure. In saturating, water flow was in an upward direction, thereby pushing the air pockets up and out of the soil sample. Every effort was made to keep the upward flow slow enough that the soil was saturated uniformly while at the same time displacing only air pockets. Even so, local piping still occurred. In testing soil types with fine particulates, it was advantageous to add a 3-in. layer of pebbles on top of the 4-in. soil column. This surcharge of pebbles significantly reduced piping effects.

The other objective that must be considered in testing is soil uniformity. The soil in each of the 12 permeameters must be of the same size distribution and density. Soil components were mixed in a small cement mixer for an 8-h period. This careful mixing of soil components which comprised a soil type, assured an approximate uniformity. Once the soil was placed within the permeameters, it was compacted to an appropriate depth that would provide a nearly maximum density. Three distinct layers of the soil column were individually compacted.

The testing procedure began with the heating and chlorination of water in the large head tank. The steam lines within the large head box and the thermostat were set so that the water temperature within the system was approximately room temperature, 68° F. Once sterilized, 25 lbs (11.3 kg) of soil was placed in each of the twelve permeameters, and compacted to a thickness of 4.16 in. (106 mm). This corresponded to a soil density of 100 lbs/cu ft (1,600 kg/m^3). The soil was then ready to be saturated. The permeameters were filled in upward direction to approximately 1 in. (25.4 mm) above the top soil surface. The saturation process usually required 8 h, depending on soil composition. Once the saturation process was completed, the transport line was connected to the permeameter inlets. Water entered the system in a downward direction and sprayed against the inside permeameter walls through the distributor heads. The inch of water above the soil depth during saturation guaranteed dissipation of the incoming water energy. This eliminated soil surface erosion and other soil disturbances. The permeameters were allowed to fill and the pressure readings to stabilize. Once the systems reached stabilized conditions, water inflow was adjusted so that a constant head was applied upon the soil depth in each permeameter. After adjustments were made, a further increment of time was necessary for pressure and flow stabilization. When all of the permeameters indicated the required constant head. testing began.

The data collection program includes measurements of discharges and pressures. Discharge measurements were collected on a daily basis from each of the permeameter outlet taps. Once all discharge and pressure measurements were terminated, the permeameter systems were dismantled. The bottom section of the permeameter served as a sediment trap for the fine particles which passed through the filter fabric. Soil and filter samples were analyzed to determine the bacterial activity within the soil and filter fabric. The bacteria analysis was performed by a microbiologist and the tested filter fabrics were analyzed with a scanning electronic microscope to determine filter clogging or bacterial activity, or both.

Tested Soil, Filter Fabrics, and Water Head.—Four soil types were used to analyze filter fabric performance. These four soil types represent a variety

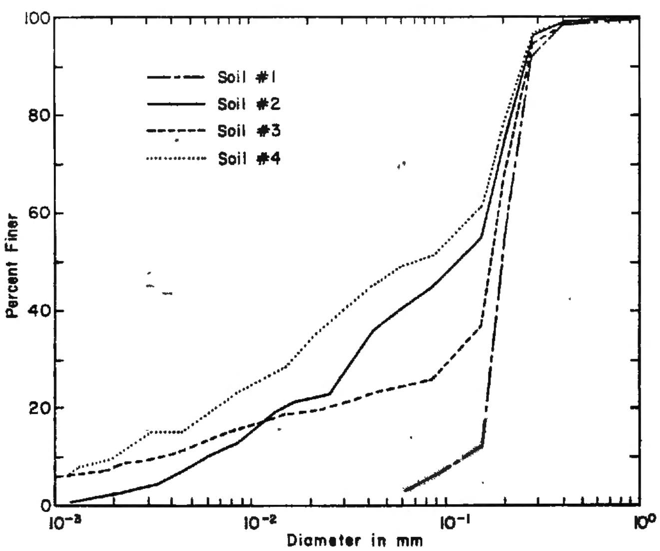

FIG. 2.—Size Distributions for Tested Soils

of fine soils which the Corps of Engineers felt to be critical to plastic filter usage. The soil size distributions are shown in Fig. 2. These soils are classified as sand (Soil Type 1), sandy loam (Soil Type 2), sandy loam (Soil Type 3), and loam (Soil Type 4), in the Triangular Soil Classification. Kaolinite was used as the clay component in testing. This type of clay was chosen for its insignificant swelling nature.

A different plastic filter was placed within each filter tube. Table 1 lists the various filter fabrics and the corresponding equivalent opening sizes used in the four soil tests. All the filter fabrics tested were nonwoven fabrics. For Soil Type 1, the hydraulic gradient (head difference between pressure Taps 1 and 6 divided by the soil thickness) imposed on the test was 2.5 ft (762 mm) of water depth upon 1 ft (305 mm) of soil. For Soil Type 2, the hydraulic

gradient simulated 3 ft of water
and 4 the hydraulic gradient was
ft of soil for 800 h. After 800 h

TABLE 1.—

Soil test (1)	Filter used (2)	EOS ranges: United States standard sieve size (3)
1	1	80–100
	2	70–100
	3	140–170
	4	40–50
	5	80–100
	6	70–100
	7	40–50
	8	70–80
	9	40
	10	50
	11	100
	12	—
2	1	80–100
	2A	70–100
	3	140–170
	Z	—
	R	30
	7A	40–50
	8	70–80
	9	40
	10A	50
	3-01	20
	12	—
3	2A	70–100
	9	40
	10A	50
	3-01	20
4	2A	70–100
	9	40
	10A	50
	3-01	20

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Analysis and Consideration

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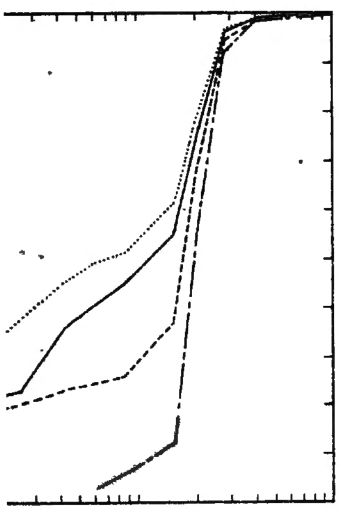

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gradient simulated 3 ft of water depth upon 1 ft of soil. For Soil Types 3 and 4 the hydraulic gradient was maintained at 3 ft of water depth upon 1 ft of soil for 800 h. After 800 h the hydraulic gradient was increased 1 1/2

TABLE 1.—Tested Filter Fabrics

Soil test (1)	Filter used (2)	EOS ranges: United States standard sieve size (3)	Mean opening size, in millimeters (4)	EOS/D_{85} (5)	EOS/D_{15} (6)
1	1	80–100	0.17	0.65	1.06
	2	70–100	0.18	0.69	1.13
	3	140–170	0.10	0.38	0.63
	4	40–50	0.36	1.38	2.25
	5	80–100	0.17	0.65	1.06
	6	70–100	0.18	0.69	1.13
	7	40–50	0.36	1.38	2.25
	8	70–80	0.20	0.77	1.25
	9	40	0.42	1.62	2.63
	10	50	0.30	1.15	1.88
	11	100	0.15	0.54	0.88
	12	—	—	—	—
2	1	80–100	0.17	0.71	17.0
	2A	70–100	0.18	0.75	18.0
	3	140–170	0.10	0.42	10.0
	Z	—	—	—	—
	R	30	0.52	2.17	52.0
	7A	40–50	0.36	1.50	36.0
	8	70–80	0.20	0.83	20.0
	9	40	0.42	1.75	42.0
	10A	50	0.30	1.25	30.0
	3-01	20	0.95	3.97	95.0
	12	—	—	—	—
3	2A	70–100	0.18	0.72	24.0
	9	40	0.42	1.68	56.0
	10A	50	0.30	1.20	40.0
	3-01	20	0.95	0.80	126.7
4	2A	70–100	0.18	0.78	45.0
	9	40	0.42	1.83	105.0
	10A	50	0.30	1.30	75.0
	3-01	20	0.95	4.12	347.5

ft each day until it reached 10 ft of water depth upon 1 ft of soil. Then the hydraulic gradient was lowered to the original value.

Analysis and Consideration

Method of Analysis.—The hydraulic analysis of the filter fabrics consisted of a six-phase study. These six phases include a water filtration discharge study, a water pressure analysis, an analysis of sediment discharges through the plastic filters, a soil size distribution analysis, an analysis of permeability changes, and a bacteria as well as a fabric fiber analysis. To avoid confusion, the following terminology is used.

1. "Filter fabric *n*" denotes the tested filter fabric identified by the Number "*n*."
2. "Filter tube *n*" denotes a permeameter device for testing the filter fabric identified by the number "*n*."

Using the measured discharges and pressure distributions, the gradient ratio and the permeability coefficients based on the average and bottom inch pressure gradients were computed.

The governing equation for soil permeability computation was given by Darcy's law

$$Q = KiA \quad (2)$$

in which Q = the water discharge; K = the permeability coefficient of the soil; i = the hydraulic gradient; and A = the cross-sectional area of the soil.

The average hydraulic gradient was computed by dividing the water head applied to the filter systems by 4.16 in. of soil depth. The bottom hydraulic gradient was computed by dividing the pressure recorded within the bottom inch of soil by 1 in. of soil. Knowing the average water velocity and the hydraulic gradients the permeability coefficients based upon the average and bottom pressure gradients were computed for each filter tube.

The gradient ratio calculated using Eq. 1 was the index used by the Corps of Engineers to indicate that a filter fabric was clogging. The value was a ratio of the hydraulic gradient within the bottom inch of soil (including the filter fabric) to the average hydraulic gradient. Due to the fact that the average hydraulic gradient for the four soils tested was maintained at a constant value during most of the testing time, the gradient ratio would therefore be an indicator of the pressure buildup within the bottom inch of soil.

Upon dismantlement of the filter tubes, a core sample of the tested soil was analyzed to determine the bacterial activity within the soil. The tested filter fabrics were examined using a scanning electronic microscope and analyzed by a microbiologist to determine the extent of soil plugging and bacterial activity. The small amounts of fine particulate that passed through the fabrics were weighed at this time. However, most of the soil testing considered large concentrations of particles that were finer than the opening sizes of the plastic filters. Therefore much of the sediment passing through the fabrics occurred when the dry soil was placed in the filter tubes.

Soil 1 Tests.—For Soil 1 tests, it was found that each of the filter systems experiences a declining flow rate with time. Fig. 3, plotted using discharge data from filter tube 2, shows a typical filtration response for Soil 1 tests. The discharges declined from the initial value of 600 cc/min to a final value of approximately 10 cc/min after 1,000 h of testing. The pressure distribution showed a definite increase in pressure difference after 50 h of testing between the top first and second inch of soil. After about 50 h, a brownish-red soil layer developed within the top 2 in. of soil. When dismantling, this dark layer

in the soil was found to be a heavy accumulat
mold particles, and small trapped silt and det
a sticky capsular material which could retard
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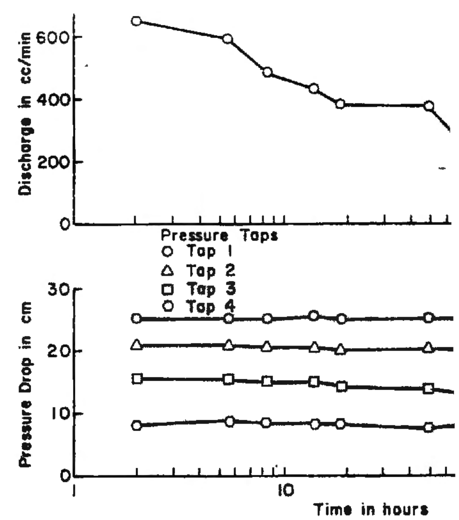

FIG. 3.—Typical Flow Rate and Pressure Distribu

microscopic photographs are shown in Fig. 4.
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As the bacteria grew within the soil, the wat
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Fig. 6 is a plot of the initial and final discharge
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in the soil was found to be a heavy accumulation of two bacterial types, some mold particles, and small trapped silt and debris. The bacterial types were of a sticky capsular material which could retard the water flow. The laboratory environment serves as an excellent atmosphere for bacterial activity due to the constant lighting and warm temperatures. However, city water with a chlorine residual of 1 ppm–2 ppm was used in testing. Evidently most of the residual chlorine was dissipated within the constant head tank with the remaining chlorine unable to control microbial activity below the top inch of soil. The filter cloths had some bacteria attached but under a light microscope they did not appear damaged or deteriorated. A scanning electron microscope was used to evaluate each filter fabric for possible soil or bacterial blockage within the fibers. Each filter fabric examined showed no indication of fabric clogging. Samples of the

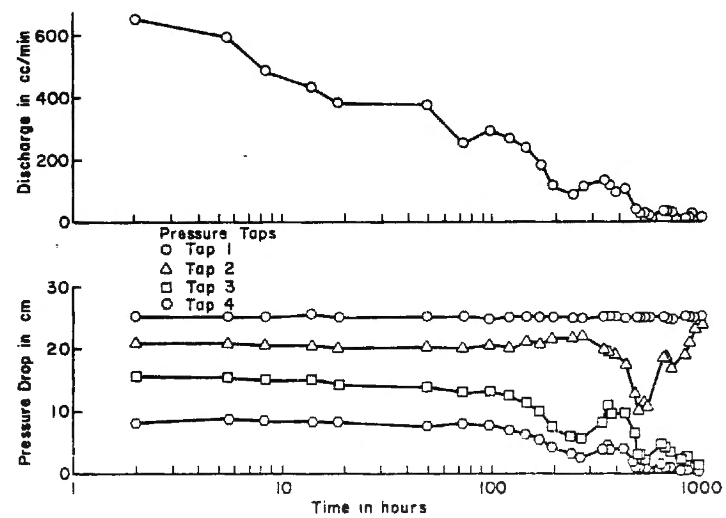

FIG. 3.—Typical Flow Rate and Pressure Distribution for Soil 1 and Filter Fabrics

microscopic photographs are shown in Fig. 4. The figure shows the control (original fabric) and one filter section both magnified 30 times. The microscopic photographs confirmed the findings of the light microscope for Soil 1 tests.

As the bacteria grew within the soil, the water velocity was greatly reduced as indicated by the flow rate decrease. This decreased the soil permeability accordingly as shown in Fig. 5. The bottom inch of soil experienced a smaller reduction in permeability than the average soil permeability as shown in Fig. 5. It is believed that the plugging of the filter system mainly occurred because of bacterial activity in the top 2 in. of soil which caused a big pressure drop across this soil layer. This is shown by the reduction in gradient ratio shown in Fig. 5. Initially the gradient ratio was larger than 1.0 due to a larger compaction in the lower portion of soil. The ratio began decreasing as the pressure drop increased within the top 2 in. of soil.

Fig. 6 is a plot of the initial and final discharges versus the equivalent opening sizes (EOS) of the filter fabrics tested. Due to data scatter no definite correlation could be initially drawn between the EOS of the filter fabrics and the water discharges. An equation representing the weighted vertical permeability through multiple soils is

$$V = \frac{\Delta H}{\frac{d_1}{K_1} + \frac{d_2}{K_2}} \quad \ldots \quad (3)$$

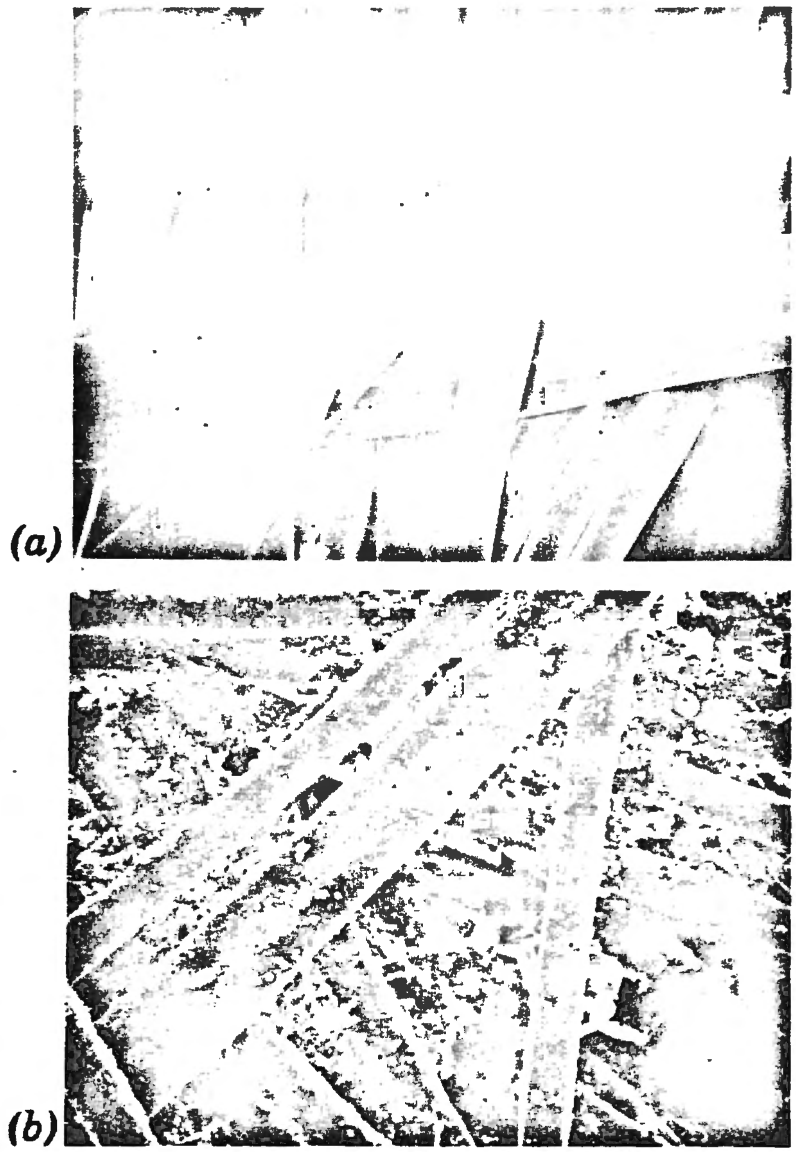

FIG. 4.—Photomicrographs of Filter Fabric for Soil 1 Test Magnified 30 Times: (a) Control Section; and (b) Test Section

in which V = the measured velocity; d_i
soil layer of a permeability; and K_i and Δ

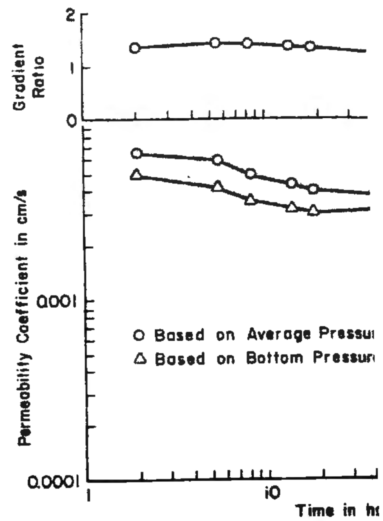

FIG. 5.—Typical Gradient Ratio and Permeab
Fabrics

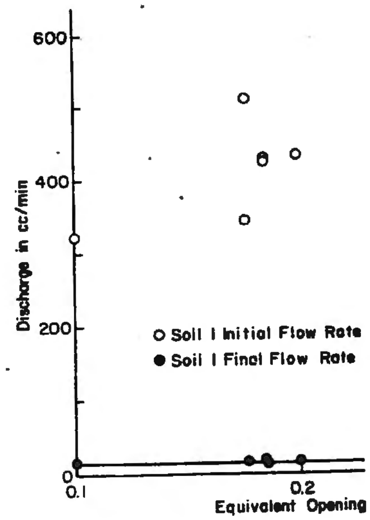

FIG. 6.—Discharge Versus Equivalent C

soil. The equation shows that if the thickness
soil system is small, the effect of this layer
be minimal. If this layer was that of the pla
would have negligible effect upon the filter s

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bric for Soil 1 Test Magnified 30 Times: (a)

in which V = the measured velocity; d_i (i = 1 or 2) = the thickness of a soil layer of a permeability; and K_i and ΔH = the water head applied to the

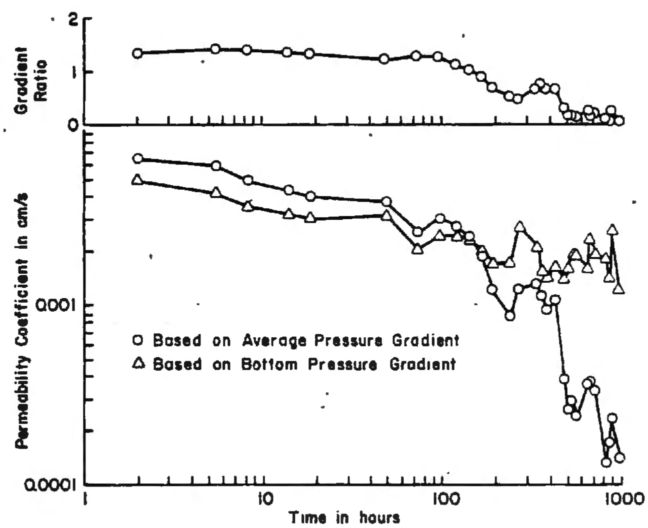

FIG. 5.—Typical Gradient Ratio and Permeability Coefficients for Soil 1 and Filter Fabrics

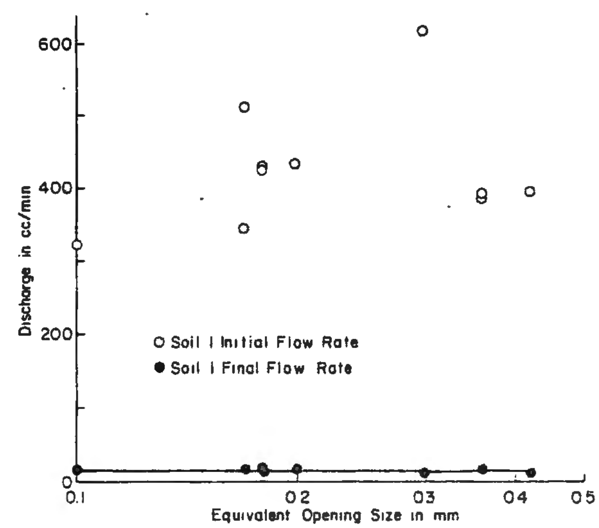

FIG. 6.—Discharge Versus Equivalent Opening Size for Soil 1 Tests

soil. The equation shows that if the thickness of an individual layer in a multiple soil system is small, the effect of this layer upon the measured velocity would be minimal. If this layer was that of the plastic filter, initially the filter fabrics would have negligible effect upon the filter system.

At the end of testing the discharge response was independent of the filter opening size. This suggested that the soil (after the growth of microorganisms) controlled the hydraulic responses of the system regardless of the type of fabric used. The sediment amounts that passed through the filter fabrics were less than 15 g, i.e., 0.1 wt% of soil in permeameter. The mean sediment concentration for the Soil 1 tests was below 3 ppm. There was no indication that a relationship existed between EOS and passing sediment weight.

Soil 2 Tests.—The majority of the filter test system was characterized by a nearly constant flow rate of about 100 cc/h. Most of the pressure differences were approximately constant. Fig. 7 shows a typical example. This figure shows that the pressures measured by Tap 2 approached that of Tap 1. The two most probable causes were that the soil above Tap 2 was disturbed by air introduced to the soil from the manometer lines or the soil was disturbed when first saturated.

The pressure distributions for Soil 2 tests indicate that 15 cm of water head were lost within both the top 2 in. and the bottom 2 in. of soil. However, pressures recorded within the bottom inch were consistently low. It is believed that when this fine soil type was initially placed within the filter tubes some fine particles immediately above the plastic filters passed through the fabrics leaving a layer of more permeable soil. When the bottom inch of soil was more permeable than the other 3 in. of soil, the pressure drop within the bottom inch would be less.

Based on the same reasoning, the permeability coefficient of the bottom-inch soil was greater than the overall permeability coefficient as shown in Fig. 8. This feature was reflected by the changes of the gradient ratio with time. The initial value of gradient ratio was below 1.0. However, the general increasing trend in gradient ratio coupled with the reduction of permeability within the bottom inch of soil suggests that the lower portion of soil was slowly being compacted.

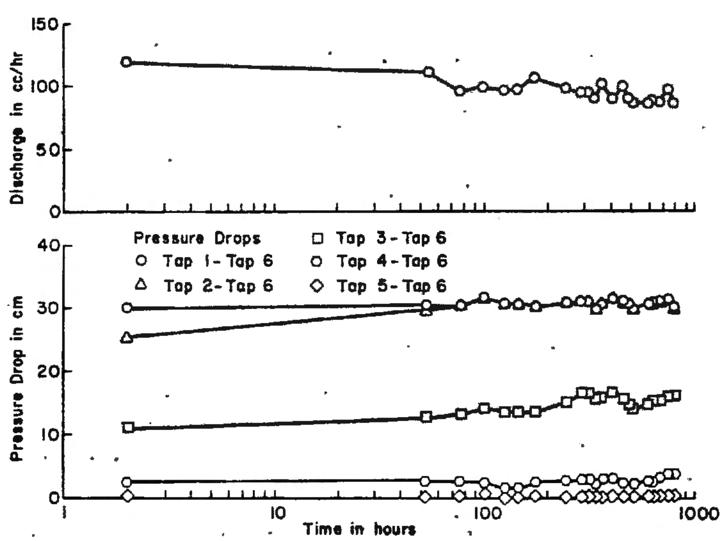

FIG. 7.—Typical Flow Rate and Pressure Distribution for Soil 2 and Filter Fabrics

Microscope examination of Soil 2 it wa bacteria existed within the soil with virtu filter fabrics. The bacterial activity was c the chlorine concentration of the water to soil at 400° F to kill any viable organism the filter fabrics were free of bacteria b by microscopic examination that the fabric

The fact that the water discharge was i suggests that Soil 2 controlled the hydra It was found that Soil Type 2 with a la less permeable than the filter fabrics te the plastic filters under Soil 2 performed the filter fabrics was not measurable due particulate.

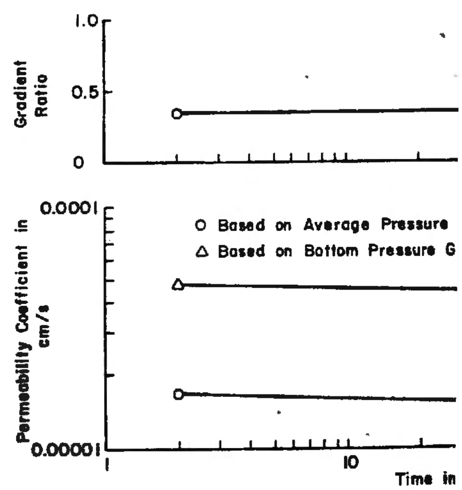

FIG. 8.—Typical Gradient Ratio and Perme Fabrics

Soils 3 and 4 Tests.—Soils 3 and 4 te as Soil 2 tests for the first 800 h test and decreased as described earlier. Duri flow rates of filter tubes decreased fron tests and from about 60 cc/h–10 cc/h for to the bacterial growth in the filter fabric

Upon bacterial analysis it was found existed within the soil, however a signif within the filter fabrics. These bacteria supporter, and then grew into the filter this particular bacterial growth rate in a sp it was found that the bacteria developed the reduction in the filtration rates. The

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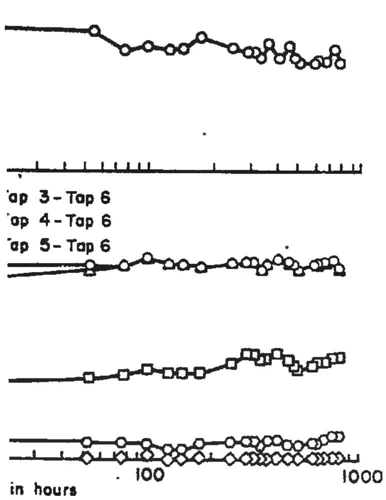

s Distribution for Soil 2 and Filter Fabrics

Microscope examination of Soil 2 it was found that a negligible amount of bacteria existed within the soil with virtually no bacterial attachment to the filter fabrics. The bacterial activity was controlled in Soil 2 tests by boosting the chlorine concentration of the water to 10 ppm and by initially baking the soil at 400° F to kill any viable organisms. Not only was it determined that the filter fabrics were free of bacteria blockage but it was also established by microscopic examination that the fabrics were not clogged by soil particles.

The fact that the water discharge was independent of the filter fabric tested suggests that Soil 2 controlled the hydraulic responses of the filter system. It was found that Soil Type 2 with a large percentage of silt and clay was less permeable than the filter fabrics tested. Within the tested EOS ranges the plastic filters under Soil 2 performed the same. The sediment that passed the filter fabrics was not measurable due to the small amounts and very fine particulate.

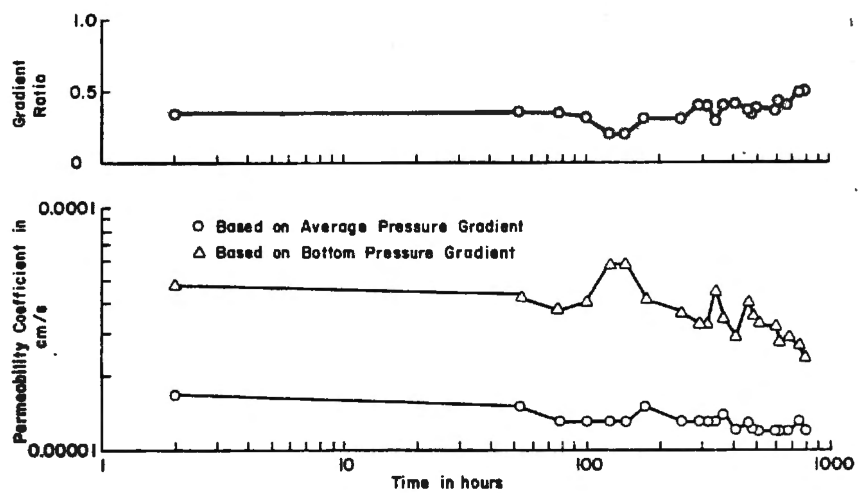

FIG. 8.—Typical Gradient Ratio and Permeability Coefficients for Soil 2 and Filter Fabrics

Soils 3 and 4 Tests.—Soils 3 and 4 tests operated at the same water head as Soil 2 tests for the first 800 h test period, and then the head increased and decreased as described earlier. During the constant head test period, the flow rates of filter tubes decreased from about 250 cc/h–50 cc/h for Soil 3 tests and from about 60 cc/h–10 cc/h for Soil 4 tests. The reason was attributed to the bacterial growth in the filter fabrics.

Upon bacterial analysis it was found that a negligible amount of bacteria existed within the soil, however a significant amount of iron bacteria existed within the filter fabrics. These bacteria originally propagated upon the metal supporter, and then grew into the filter fabric directly above. In simulating this particular bacterial growth rate in a special laboratory under ideal conditions, it was found that the bacteria developed in about 8 days. This coincided with the reduction in the filtration rates. The amount of iron bacteria present within the filter fabrics had a significant effect on the water flow rates. The same test preparation procedure applied for Soils 3 and 4 as applied for Soil 2. However, the metal support screen used beneath the plastic filter was painted with only one coat of galvanizing compound rather than five coats. This single coating of galvanizing compound was not sufficient in preventing rust accumulation upon the metal which then supported microbial growth.

The water head was increased by raising the constant head tank after 800 h of testing. A direct correlation existed between the water head increase and the flow rate. Once the water head was lowered at 1150 h to the original height, the flow rate approached a constant value approximately equal to the discharge recorded immediately before the head increase.

The gradient ratio was initially below 1.0 for the majority of the filter tubes due to disturbance caused by backfill saturation before the test. At 80 h the gradient ratio increased above the value of 1.0 while the permeability of the bottom inch of the soil decreased from about 4×10^{-5} cm/s–2×10^{-5} cm/s for Soil 3 tests and from about 1×10^{-5} cm/s to 8×10^{-6} cm/s for Soil 4 tests. It is believed that as bacteria was developing in the filter fabric the water velocity reduced and the pressure drop within the bottom inch of soil increased. By Hour 750 the bacteria had significantly affected the discharge. After Hour 800 the water head was raised. The permeability coefficients within this time range were relatively constant at about 5×10^{-6} cm/s for Soil 3 tests. This indicates that the velocity through the system directly corresponded with the increase in hydraulic gradient. Although the filter fabrics accumulated bacteria, the soil was virtually unchanged.

Like the previous two soil tests, a correlation between water discharge and the fabric EOS could not be established for the Soil 3 tests. The aforementioned weighted permeability equation shows that the filter fabric had negligible effect upon the filter system. Therefore, the soil initially controlled the hydraulic responses of the system. At the end of testing, the soil also controlled the hydraulic responses. Even though the bacterial growth was initiated on the metal support screen, the activity spread through the filter fabrics to the adjacent layer of soil.

Analysis of Results.—A filter fabric may serve as a permeable solid constraint or a real filter. Quite often a particular soil layer within a multiple layer soil system or a homogeneous soil body, if having adequate size distributions, can work as a filter to limit the migration of fine particles within the soil. In this case, the soil layer serves as a soil filter and the filter fabric actually works as a permeable constraint to stop adjacent soil particles from washing through the fabric. Because there are few fine particles reaching the fabric, the filter fabric will not be clogged by soil. According to a filtration study, for a filter fabric to constrain large particles

$$\frac{\text{Filter Pore Size } (P_{95} \text{ or EOS})}{D_{85} \text{ (of soil)}} \leq 3 \quad \text{(4)}$$

in which P_{95} = pore diameter in fabric of which 95% is finer; EOS = the equivalent opening size of a fabric; and D_{85} = the soil particle diameter of which 85% is finer. However, the Corps of Engineers suggested that

$$\frac{\text{EOS}}{D_{85} \text{ (of soil)}} < 1$$

Our experimental results show that even th
from 0.38 for Soil 1 Test–1.83 for Soil 4
of soil particles through filter fabrics was
5 is too restrictive. Therefore, an average r

$$\frac{\text{EOS}}{D_{85} \text{ (of soil)}} \leq 2$$

An average hole size in soil is about on
Therefore, a layer of soil can stop the p
this particle is larger than one-fifth of th
soil layer. For a soil layer to become a
then

$$\frac{D_{85}}{D_{50}}, \frac{D_{50}}{D_{35}}, \frac{D_{35}}{D_{15}} < 5$$

Natural soil usually satisfies this condition.

TABLE 2.—Gradations

Soil (1)	D_{85}/D_{50} (2)	D_{50}/D_{35} (3)	D
1	1.30	1.08	
2	2.00	2.86	
3	1.47	1.21	
4	3.28	3.15	

of silt and clay, then the filtration rate a
that the performance of the filter system wi

In all the tests conducted in this study it wa
the hydraulic responses regardless of the ty
used. This indicates that the four soils teste
their size distributions (Table 2) satisfy Ec
satisfactory criteria for evaluating a soil filt

When the soil body is not a filter, then s
can be carried by water through soil voids
as a real filter to limit the loss of soil pa
clogging of fabric, it is necessary to allow
following condition is then required:

$$\frac{\text{Filter Pore Size } (P_{95} \text{ or EOS})}{D_{15} \text{ (of soil)}} \geq 2$$

$$\frac{\text{EOS}}{D_{85}\text{ (of soil)}} < 1 \qquad (5)$$

Our experimental results show that even though the range of EOS/D_{85} varied from 0.38 for Soil 1 Test–1.83 for Soil 4 test as shown in Table 1, the loss of soil particles through filter fabrics was very small. This indicates that Eq. 5 is too restrictive. Therefore, an average ratio is proposed:

$$\frac{\text{EOS}}{D_{85}\text{ (of soil)}} \leq 2 \qquad (6)$$

An average hole size in soil is about one-fifth of the soil particle diameter. Therefore, a layer of soil can stop the passage of a particle if the size of this particle is larger than one-fifth of the size of particles establishing the soil layer. For a soil layer to become a soil filter a reasonable condition is then

$$\frac{D_{85}}{D_{50}}, \frac{D_{50}}{D_{35}}, \frac{D_{35}}{D_{15}} < 5 \qquad (7)$$

Natural soil usually satisfies this condition. If the soil contains more than 30%

TABLE 2.—Gradations of Tested Soils

Soil (1)	D_{85}/D_{50} (2)	D_{50}/D_{35} (3)	D_{35}/D_{15} (4)	Silt and clay content, in percent (5)
1	1.30	1.08	1.14	3
2	2.00	2.86	4.20	41
3	1.47	1.21	1.87	24
4	3.28	3.15	5.50	50

of silt and clay, then the filtration rate and soil migration become so small that the performance of the filter system will not be affected by filter fabrics.

In all the tests conducted in this study it was determined that the soil controlled the hydraulic responses regardless of the type or the opening size of the filter used. This indicates that the four soils tested in this study are soil filters. Since their size distributions (Table 2) satisfy Eq. 7, this equation is considered as satisfactory criteria for evaluating a soil filter.

When the soil body is not a filter, then significant amounts of fine particles can be carried by water through soil voids. In this case, a filter fabric works as a real filter to limit the loss of soil particles through the fabric. To avoid clogging of fabric, it is necessary to allow the passage of fine particles. The following condition is then required:

$$\frac{\text{Filter Pore Size } (P_{95} \text{ or EOS})}{D_{15}\text{ (of soil)}} \geq 2 \qquad (8)$$

If the discharge is large enough to carry significant amount of fine particles and piles them upon the surface of filter fabric to form a cake, this cake could reduce water flow locally.

Comparing the experimental results with the Corps of Engineers' criteria described earlier, it is found that the Corps of Engineers' criteria are too conservative. The following procedure is recommended for selecting a filter fabric.

1. Determine the soil permeability coefficient from laboratory tests or from available information.
2. Determine the size distribution of soil layers to be protected.
3. Apply Eq. 7 to determine whether or not the soil layer can serve as a filter.
4. Select a range of filter fabric having permeability coefficients equal to or larger than that of soil. If the soil layer is a filter, then use Eq. 6 to select a suitable fabric. If the soil layer is *not* a filter, then use both Eqs. 6 and 8 for selecting the fabric. For the latter case, if the discharge is unusually high, then local clogging of filter fabric may occur.

It is possible that bacterial accumulations may be responsible for localized plugging of a disturbed field soil, similar to that experienced in the Soil 1 test. Many subdrainage systems contain perforated iron pipe. It has been shown in Soil Tests 3 and 4 that bacteria which metabolize iron compounds can attach to the filter fabrics and then penetrate and spread through the soil. Iron bacteria has caused drainage problems in areas with high iron content. Bacterial problems may contribute to some failures of either fabric or graded aggregate filters.

Summary and Conclusions

Plastic filter fabrics should be designed to let water pass and yet retain soil particles. Filter fabrics are relatively inexpensive and are easy to install. For these reasons they offer a possible alternative to a graded filter system. Because long-term field experience is still limited, some people are reluctant to use these new cloths. The United States Army Corps of Engineers has used filter fabrics more than any other single agency in the United States. In order to evaluate the hydraulic performance of filters, the Corps of Engineers developed their own design guidelines in 1972. Prior to this time, very little was known about the hydraulic responses of the manufactured filter fabrics. Even today, the majority of engineers who consider using plastic filters refer to the design concepts developed by the Corps of Engineers. Work at Colorado State University and other research centers is resulting in changes of design concepts.

Four different soil types were used to evaluate the filter fabric performances within this study. Each soil test consisted of measuring the water discharge and pressure distribution within a number of filter tubes. Permeameters containing a 4-in. depth of soil plus a filter fabric comprised a filter system. From the measured data, soil permeabilities and gradient ratios were computed with time.

Based on the analysis of the laboratory tests and field experience with filter fabrics, the following conclusions are drawn.

1. A natural soil is generally well graded a particles to limit the migration of fines. Theref fabric quite often works actually as a permea a filter. In this case, clogging of a fabric by fin
2. If the permeability of the soil is less th fabric and the soil is a filter which restricts then the soil controls the hydraulic responses fabrics perform the same.
3. When the soil body is not a soil filter, particles can be carried by water through soil works as a real filter to limit the loss of soil avoid clogging of filter fabric it is necessary to a If the discharge is large enough to carry sign and pile them on the surface of filter fabric t could occur.
4. Bacterial activity within the soil or upon t responses of a filter system.
5. For 1,000 h of continuous testing the filte effect upon the hydraulics of the filter system.
6. The gradient ratio developed by the Cor clogging should be analyzed for a longer period system could experience system instabilities using finer soils.
7. The two basic design criteria to prevent Corps of Engineers state the D_{85} of the soi filter, determined by the EOS test, when usi or less by weight of silt and when using soi silt, the P_{95} should be smaller than the openi Sieve No. 70. These criteria may apply wit velocities; however, with fine sands containing clay, or both, the soil will definitely control not apply. Using a wide range of opening si 200, with soils of large fine concentrations, the filter with little or no fine particle migratio
8. Generally speaking, the Corps of Engine conservative. A design procedure is proposed further verification.

Acknowledgment

This work was supported by the E. I. DuPont Del. and Colorado State University Experime

Appendix I.—References

1. Barrett, R. J., "Use of Plastic Filters in Co Conference on Coastal Engineering, ASCE, Tok
2. Calhoun, C. C., Jr., "Development of Design C for Plastic Filter Cloths," *Technical Report S-* Waterways Experiment Station, Vicksburg, Miss.

1. A natural soil is generally well graded and can serve as a filter to soil particles to limit the migration of fines. Therefore, under this condition, a filter fabric quite often works actually as a permeable solid constraint rather than a filter. In this case, clogging of a fabric by fine particles does not occur.

2. If the permeability of the soil is less than the permeability of the filter fabric and the soil is a filter which restricts the migration of fine particles, then the soil controls the hydraulic responses of the system and different filter fabrics perform the same.

3. When the soil body is not a soil filter, then significant amounts of fine particles can be carried by water through soil voids. In this case, a filter fabric works as a real filter to limit the loss of soil particles through the fabric. To avoid clogging of filter fabric it is necessary to allow the passage of fine particles. If the discharge is large enough to carry significant amounts of fine particles and pile them on the surface of filter fabric to form cake, then local clogging could occur.

4. Bacterial activity within the soil or upon the filter can control the hydraulic responses of a filter system.

5. For 1,000 h of continuous testing the filter fabrics tested had no detectable effect upon the hydraulics of the filter system.

6. The gradient ratio developed by the Corps of Engineers to indicate filter clogging should be analyzed for a longer period of time. The Corps of Engineers system could experience system instabilities that are especially prevalent in using finer soils.

7. The two basic design criteria to prevent soil movement developed by the Corps of Engineers state the D_{85} of the soil be larger than the P_{95} of the filter, determined by the EOS test, when using granular soils containing 50% or less by weight of silt and when using soils containing more than 50% of silt, the P_{95} should be smaller than the opening in the United States Standard Sieve No. 70. These criteria may apply with coarse sands with large water velocities; however, with fine sands containing more than 30% silts or nonswelling clay, or both, the soil will definitely control the system and the standard will not apply. Using a wide range of opening sizes, i.e., EOS 20 to greater than 200, with soils of large fine concentrations, very little soil will pass through the filter with little or no fine particle migration within the soil.

8. Generally speaking, the Corps of Engineers' criteria is too restrictive and conservative. A design procedure is proposed in this study which will require further verification.

Acknowledgment

This work was supported by the E. I. DuPont Chemical Company, Wilmington, Del. and Colorado State University Experiment Station, Fort Collins, Colo.

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2. Calhoun, C. C., Jr., "Development of Design Criteria and Acceptance Specifications for Plastic Filter Cloths," *Technical Report S-72-7*, United States Army Engineers, Waterways Experiment Station, Vicksburg, Miss., June, 1972.