WAR DEPARTMENT

CORPS OF ENGINEERS, U. S. ARMY

INVESTIGATION OF FILTER REQUIREMENTS FOR UNDERDRAINS

TECHNICAL MEMORANDUM NO. 183-1

U. S. WATERWAYS EXPERIMENT STATION

VICKSBURG, MISSISSIPPI

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INVESTIGATION OF FILTER REQUIREMENTS FOR UNDER DRAINS

I. INTRODUCTION

Scope of this memorandum

1. This memorandum constitutes a report on the investigation made to determine the minimum grain size of filter materials required to prevent (a) infiltration of fines into the filter material; (b) infiltration of filter material into various types of commercial under-drain pipes.

2. The report covers the tests which have been carried out at the U. S. Waterways Experiment Station to verify the results of previous investigations, and to secure additional information applicable to designs of under-drainage systems with various commercial types of drain pipe. The testing program was divided into two parts, (a) laboratory tests in pyralin permeameters, and (b) outdoor tests in a 36-ft flume using full-size lengths of 6-in. diameter under-drain pipes.

Previous investigations

3. The characteristics of filter sands for water treatment have been studied extensively during the past fifty years. However, the results of these investigations have been but little used outside the field of water treatment itself. Twenty years ago Terzaghi successfully used and patented in Austria a reverse filter to control the seepage under a dam on a pervious foundation. In selecting a filter material for this situation he envisioned two requirements which must be fulfilled. First, the filter material must be many times more pervious than the fine base material,

and second, the filter material must not be so coarse as to allow the fine particles of the base material to wash through the filter material. His criteria for fulfilling these requirements, based on the grain size curves for the filter and base materials, were as follows:

a. The 15 per cent size of the filter material should be at least four times as large as the 15 per cent size of the base material. (This would make the filter material roughly more than ten times as pervious as the base material.)

b. The 15 per cent size of the filter material should not be more than four times as large as the 85 per cent size of the base material. (This would prevent the fine particles of the base material from washing through the filter material.)

4. In 1939, G. E. Bertram carried out in the Soil Mechanics Laboratory at Harvard University an experimental study of filter requirements directed toward the establishment of fundamental relationships. The results of this study were published by the Graduate School of Engineering of Harvard University in a brochure entitled, "An Experimental Investigation of Protective Filters." The materials used in this investigation were uniform sizes of Ottawa sand and crushed quartz. Bertram found that stable conditions would prevail (i.e., no fines would wash into the filter) when the 15 per cent size of the filter material was not more than eight to ten times larger than the 85 per cent size of the fine base material. The 15 per cent size of the filter material which he used was 10 to 15 times as large as the 15 per cent size of the base material. He found also that the limiting sizes were the same regardless of whether the flow was upward or downward, and regardless of the magnitude of the hydraulic gradient. A few tests were performed with graded materials but limiting sizes were not

determined. No vibrations, shocks, or jars were applied to the materials during any of the tests.

5. Investigations of filter materials based principally on the above findings have been performed by various districts in connection with control of seepage through and beneath embankments and are listed and discussed in Technical Memorandum 175-1, "Seepage Studies" March 1941, U. S. Waterways Experiment Station.

Authorization

6. Reference is made to the basic letter from the Director, U. S. Waterways Experiment Station, through the President, Mississippi River Commission, to the Chief of Engineers dated February 21, 1941, subject: "Proposed Design Tests for Airport Construction," and to the second indorsement thereto. These communications outlined and authorized this investigation.

Personnel

7. This study was performed by the Soil Mechanics Laboratory of the U. S. Waterways Experiment Station. Chief of the laboratory is Cleveland R. Horne, Assistant Engineer. The performance of the tests was initiated under the supervision of William R. Perret, Junior Physicist, and carried to completion under the supervision of John D. Watson, Associate Engineer, who prepared this memorandum. The entire investigation and preparation of this memorandum were under the direction of Captain Kenneth E. Fields, C.E., Director of the U. S. Waterways Experiment Station.

II. LABORATORY TESTING

Objectives and general procedure

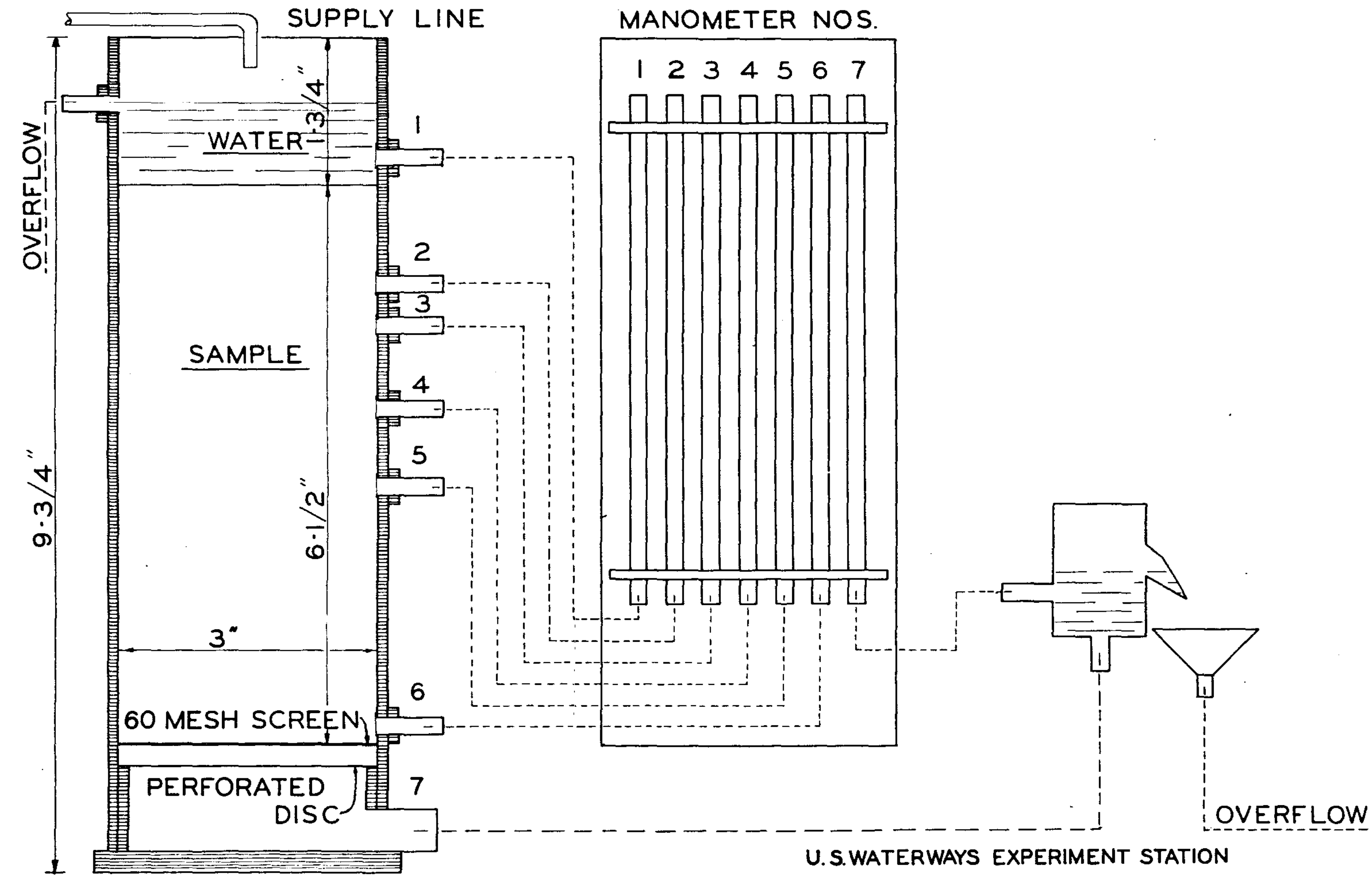
8. The objectives of the laboratory tests were to determine first the limiting size of filter material which is required to hold a base material of fine sand, and second the limiting sizes of filter materials which would not pass through the openings in the walls of porous or perforated pipe.

9. The first objective was accomplished with the use of a 3-in. diameter pyralin permeameter (see Plate 1) into which was placed a thick layer of filter material and a thin layer of fine base material.

10. The second objective was accomplished with the use of a pyralin permeameter 8-3/8 in. in diameter (see Plate 2) which could accommodate interchangeably a porous concrete disc or a wooden disc with holes bored in it, simulating the pipe walls of several kinds of commercial pipe. The filter material which passed through these discs was collected in the base of the permeameter, dried, and weighed at the end of each test.

Selection of materials

11. Natural soils vary widely in gradation, and it is not possible to have a specific filter material for all natural soils which will provide adequate drainage, and at the same time prevent piping, or transportation of the fines by seeping water. It was not intended in this investigation to choose filter materials for many types of natural soils. The plan was rather to choose a fine-grained natural soil highly susceptible to movement by flowing water, and to select a filter material which would drain this



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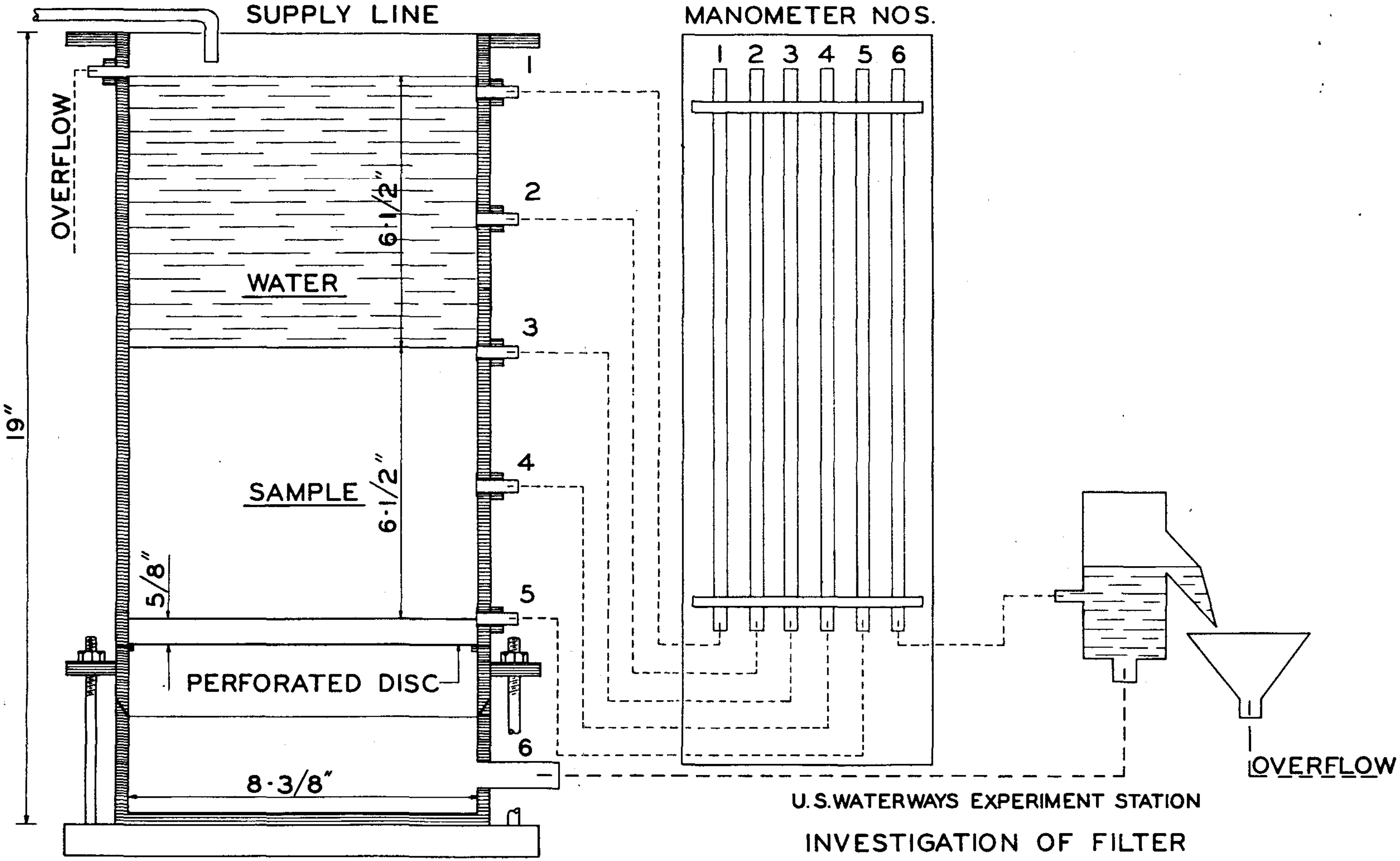
REQUIREMENTS FOR UNDER DRAINS

SMALL PERMEAMETER



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INVESTIGATION OF FILTER REQUIREMENTS FOR UNDER DRAINS

LARGE PERMEAMETER

soil without piping. The assumption is then made that if Terzaghi's criterion can be successfully applied to the filter material which will hold this particular soil, it will be safe to apply his criterion in the selection of filter materials for all natural soils. The natural soil which is most susceptible to piping is assumed to be a very fine sand and coarse silt. Such a material is entirely lacking in cohesion, and the particles are sufficiently small to be moved by very low velocities of water.

12. In an attempt to approach this natural soil which is most susceptible to piping, several soils already available in the laboratory were tried out. The first soil used was a loess having a particle size ranging approximately from 0.05 mm down to 0.005 mm. This range of particle sizes covers the usual designation of silt. The material proved to be so impervious that the velocity with which water would pass through it was not sufficient to produce any large movement of particles. The next material used was a sandy loam, a well-graded material containing some particles from coarse sand (size 1.0 mm) down to clay (size 0.005 mm). This material was also too impervious. A medium-fine sand (size range from 0.50 down to 0.10 mm), known locally as National Park sand, was then tried but it was judged to be too coarse. A fine sand (size range from 0.40 down to 0.07 mm) was located in nearby Clear Creek, and this material was used in several tests, being designated as No. 11. However, a still finer sand (size range from 0.30 down to 0.05 mm, or approximately from a 48 mesh to a 200 mesh screen and having a uniformity coefficient of 1.75) was found along the Mississippi River, and this material proved to be nearer the ideal material than any other here available. This fine sand (designated Nos. 13 and 14) was

therefore used as a base material in all of the filter tests subsequently performed. For a grain size curve of these materials see Plate 3.

13. The first consideration in the choice of a filter material was the selection of a material which would be readily available in all localities. The easiest way to accomplish this was to find out what mixture of concrete sands and gravels would make an acceptable filter material. On Plate 4 are shown the Department's specifications for concrete sand. The grain size curve of a local concrete sand (Material No. 9) is also shown on Plate 4, and it falls principally within the limits of the Department's specifications. Since this material contained very little gravel, it was decided to add some medium and fine gravel in the expectation that this gravel would prevent the material from running into those drainage pipes with large openings. Twenty per cent by weight of medium and small gravel (Material No. 10) was added to 80 per cent by weight of the coarse sand (Material No. 9) giving the mixture called Material No. 18. Its grain size distribution is shown on Plate 4. It was this mixture which was principally used in these tests for a filter material. By successively removing the fines from this filter material, it was possible to determine the limiting size of filter material which would prevent the fine base material from washing through the filter material.

Procedure for small permeameter tests

14. The procedure for testing with the small permeameter was as follows. A given filter material was placed in the permeameter under water and compacted by jarring. When the layer of filter material was about 6 in. deep, a thin layer of fine base material was placed, also under water, on

top of the filter material. Then a downward flow of water was begun. The loss of head between various points along the vertical axis of the permeameter was observed in manometer tubes (see Plate 1). It was intended at first to trace the movement of the fine base material into the filter material by observing the variations in head losses through the filter material. It was found, however, that visual observation furnished the most positive criterion for recording large movements of fine base material through the filter material. When the base material really washed out, its movement could be noticed visually in three ways: (a) holes appeared in the top surface of the fine base material, (b) the fine particles could be seen through the transparent walls of the permeameter moving downward through the filter material, (c) the fine particles washing entirely through the filter material were collected in the base of the permeameter. Therefore, direct observation furnished the most positive criterion for recording large movements of fine base material through the filter material.

15. Since the movement of the fine base material was not measured by the change in head loss and consequently the permeability of various layers of the filter material, the use of deaired water was not required, and was therefore discontinued after the preliminary tests.

16. When there was no apparent movement of the fine base material, the manometers served to show that whatever readjustment did take place was confined to the uppermost half or three-quarters of an inch of the filter material. Test 4 shown on Plate 5 serves as an illustration of this point. In this test 5-3/4 in. of filter material, No. 9, retained on a 20-mesh sieve, was loaded into the permeameter, and one-quarter of an inch of base material

No. 11 was added. The first observation on the manometers indicated the coefficient of permeability in the filter material between piezometers Nos. 2 and 3 to be 435×10^{-4} cm per sec. This value was only one-tenth the coefficient of permeability of the material by itself, and it showed that in loading some of the fine base material had sifted into the uppermost layer of the filter material. After two and a half hours of flow this value was unchanged. Then the permeameter was tapped lightly with a rubber mallet. After another two and a half hours of flow, observation on the head loss in the manometers indicated a coefficient of permeability for this layer of only 116×10^{-4} cm per sec. This indicated that the tapping had caused some more of the fines to fall into the uppermost layer of filter material. With three more hours of flow this coefficient of permeability rose to 240×10^{-4} cm per sec. This increase indicated that some of the fines, which had been shaken down by the tapping, were slowly washing out. However, because there was in the whole operation no appreciable change in the head loss between piezometers Nos. 3 and 7, it may be inferred that there was no significant movement of the fine base material through the filter.

Tests in small permeameter

17. The small permeameter was used principally to determine the limiting size of filter material which is required to hold a base material of fine sand. Three fine sands, Nos. 11, 13, and 14, were used as base materials. The filter materials were varied, both as to size and gradation, in order to determine the limits for an efficient filter. A number of tests were required for this determination, but only a few of them are discussed below and these may be regarded as typical. Table 1 lists pertinent data for most of the tests performed.

TABLE 1

Small Permeameter Tests

Test No.	Base Mtl. No.	Filter Mtl. No.	Filter K in 10^{-4} cm/sec	15% Size F / 85% Size B	Hydraulic Gradient	Initial Piping	Remarks
3-A	11	9-retained on 28 m.	4200		2	None	No tapping.
3-B	11	10	14000	8.7		Complete washout	No observations
4	11	9-retained on 20 m.	5000	4.8	1.7	None	Tapping reduced filter K in top 1/2".
5	11	18	275	1.3	2		Hole in base material layer made first 7 observations valueless. No movement of fines noted in later observations
6	11	9-retained on 14 m.	8750	6.9	1 & 2	At one side	Any tapping caused rapid washing of base material into filter. No tapping or piping after increasing hydraulic gradient
8	13	18-retained on 20 m.	8350	5.9	1.7	One sm. hole	Tapping caused base material to wash through very rapidly.
9	13	18-retained on 65 m.	415	1.1	2	None	No visible movement. Tapping reduced upper filter K.
10	13	18-retained on 48 m.	650	1.7	2	None	Tapping produced hole at one pt. No further piping after filling it.
11	13	18-retained on 35 m.	1450	2.2	2	None	Tapping produced hole at one pt. No further piping after filling it.
12	13	18-retained on 28 m.	3850	3.6	2	None	Tapping produced visible movement of fines through filter. No washout.
14	13	18-retained on 20 m.	10900	5.9	2	None	First tapping produced complete washout.
15	13	18-retained on 28 m.	7000	4.1	2	None	Filter somewhat coarser than in Test No. 12. Tapping caused base material to move into filter. Added base material did not move with repeated tappings.
16	13	18-retained on 35 m.	1350	2.4	2	None	No visible movement; tapping reduced filter K in top 1/2" to 1/10th of original value.
17	13	18-retained on 35 m.	1375	2.4	2	None	No visible movement; no appreciable change in K due to tapping.
19	14	18-retained on 28 m.	3900	3.6	1.7	None	No visible movement; but tapping reduced K of filter in top 1/2" to 1/10th of original value.
21	13	22 (#21 Retained on 35 m)	2300	2.8	1 & 2	None	High gradient produced no movement; but tapping caused 50% reduction of filter K in top 1-1/2".
22	14	22	2100	2.8	1 & 2	None	Tapping caused 50% reduction of filter K in top 1-1/2".
23	14	23 (#21 retained on 28 m)	9300	5.0	2	Fines piped into filter	Tapping caused hole to develop at one point, but no piping occurred after adding more base mtl.
24	14	23	9300	5.0	2	Fines piped into filter	Tapping caused hole to develop at one point, but no piping occurred after adding more base mtl.

18. Test No. 3. In Test No. 3 fine base material No. 11 was placed on top of filter material No. 10 (see Plate 6 for grain size curves). Both materials were packed into the permeameter under water. During the packing operation only a small amount of the base material moved into the filter material. However, as soon as flow was started the fine base material all washed through the filter. The ratio of the 15 per cent size of the filter to the 85 per cent size of the base was 8.7.

19. Test No. 4. In Test No. 4 filter material No. 9 retained on a 20-mesh sieve (see Plate 7 for the grain size curves and also paragraph 16). With water flowing through the permeameter under a hydraulic gradient of 1.7, there was no movement of the fine base material (see Plate 5). However, when the sides of the permeameter were tapped with a rubber mallet, some fines moved into the uppermost half inch of the filter. There was, however, no general movement of the fines. The ratio of the 15 per cent size of the filter to the 85 per cent size of the base was 4.8.

20. Test No. 6. Base material No. 11 retained on a 200-mesh sieve was unstable on a filter of No. 9 retained on a 14-mesh sieve (see grain size curves on Plate 8). Piping developed as soon as flow was started with a hydraulic gradient of one. Any tapping on the permeameter caused a rapid washing of fines all the way through the filter. Additional base material was put on top of the filter and the hydraulic gradient was raised to two, but this change did not seem to increase the susceptibility to piping. The ratio of the 15 per cent size of the filter to the 85 per cent size of the base was 6.9.

21. Test No. 5. Filter material No. 18 was a mixture of 80 per cent of No. 9 with 20 per cent of No. 10. It was well graded and had a coefficient

of permeability of 275 x 10^{-4} cm per sec. (See grain size curves on Plate 9.) The fine base material was No. 11 retained on a 200-mesh sieve. Tapping on the side of the permeameter caused some fines to settle into the uppermost half inch of the filter, but no general movement was observed. The ratio of the 15 per cent size of the filter to the 85 per cent size of the base was 1.3.

22. Test No. 8. That part of filter material No. 18 which was retained on a 20-mesh sieve was used in Test No. 8 as a filter for a base of material No. 13 (see Plate 10). Piping developed as soon as flow began. Tapping the permeameter caused the fine base material to wash rapidly. The hydraulic gradient was 1.7. The ratio of the 15 per cent size of the filter to the 85 per cent size of the base was 5.9.

23. Test No. 15. That part of filter material No. 18 which was retained on a 28-mesh sieve was used in Test No. 15 as a filter for base material No. 13 (Plate 11). Though tapping on the side of the permeameter caused most of the fine base material to wash into the filter, no fine material washed completely out. The uppermost half inch of the filter still consumed 70 per cent of the head loss. Additional fine base material was then put on top of the filter, and further tapping did not produce piping. At the end of the test the base layer and the uppermost half inch of the filter together consumed 98 per cent of the head loss. The ratio of the 15 per cent size of the filter to the 85 per cent size of the base was 4.1.

24. Test No. 24. A filter material was made up from 80 per cent of No. 18 which was retained on a 28-mesh sieve and 20 per cent of gravel from 1 to 3/8 in. diameter. This filter material designated No. 23, was used in Test No. 24 to support a base of material No. 14 (see Plate 12). Tapping

on the side of the permeameter caused piping at one point. Then the top of the base layer was levelled off and no further movement of fines was observed. The ratio of the 15 per cent size of the filter to the 85 per cent size of the base was 5.0. However, this filter material was better graded than the fine base material, and the two grain size curves were therefore far from parallel. The 90 per cent size of the filter was 64 times larger than the 90 per cent size of the base material. With so wide a range of grading any segregation in the filter material would leave spots with large open voids. The fine base material did run readily into holes of this nature, though this movement did not constitute a washout. Still the coefficient of permeability of the filter material was reduced to one-third its original value, so that its efficiency as a filter media was that much impaired.

25. In each of the tests cited above (paragraphs 18 to 24), as well as in other tests, a relatively stable condition prevailed when the ratio of the 15 per cent size of the filter to the 85 per cent size of the base was 5 or less. Whenever this ratio exceeded 5, an unstable condition prevailed, and the fine base material would wash rapidly through the filter material. These results indicate a margin of safety in Terzaghi's stipulation that the 15 per cent size of the filter shall be not more than four times as large as the 85 per cent size of the base. It was found, however, that the introduction of large-size particles into the filter material makes it possible for the fine base material to move more readily into the filter material (compare Tests Nos. 4, 15, and 24, on Plates 7, 11 and 12). Even if this movement does not constitute a washout, the permeability of

the filter is reduced, and its efficiency for draining is thereby impaired. It would, therefore, seem prudent to require that the grain size curves for the filter and base materials should be approximately parallel; or, at least, that at equal ordinates to the two curves (filter and base materials) the particle size of the filter should not be more than a fixed number of times (say twenty-five) larger than the particle size of the base material. The two materials used in Test No. 5 (see Plate 9) have nonparallel grain size curves but at no point of equal ordinates along these two curves is the filter material more than 25 times larger than the base material. This stipulation was not fulfilled with the materials used in Test Nos. 15 and 24 (see Plates 11 and 12).

Special tests with small permeameter

26. Test No. 7. In addition to the tests made with the small permeameter to determine the limiting size of filter materials, several special tests were also made with this small permeameter. Such a test was No. 7, using filter material No. 18, to discover if the tapping on the sides of the permeameter had any effect on the filter material itself. A layer of filter material, 6.35 in. deep, was packed very loosely into the permeameter. No fine material was put on. Flow was started and the loss of head throughout the layer of filter material was uniform. Then the side of the permeameter was tapped with a rubber mallet, and with successive tappings the height of the sample sank progressively to 6.20 in. After each tapping, the loss of head through the sample became more nonuniform (a greater portion of the head being lost in the lower half), and the coefficient of permeability of the uppermost layer increased. There was no change in the head

loss between observations in which there were no tappings. Obviously the vibrations were causing a downward migration of the fine particles, as well as a compaction. If the filter material originally had been packed densely, this migration of the fine particles with vibrations would have been less likely to occur. This result serves to indicate that any filter material for drainage purposes should always be packed densely. Such packing will not be achieved if moist sand and gravel is merely dumped into the drainage ditch.

27. Test No. 18. Test No. 18 was another special test which deserves mention. In this test the fine base material was placed beneath the filter material and the flow of water was upward through the permeameter. The filter material was No. 18 retained on a 28-mesh sieve, and the fine base material was No. 14. Some filter material was placed in the bottom of the permeameter, and a half inch of fine base material was placed on it. Then 3.6 in. of filter material was placed on top of the fine base material. When upward flow was commenced with a hydraulic gradient of one, no change or movement was apparent. But when the hydraulic gradient was raised to two and a half, the layer of fines and filter material raised up and piping developed immediately. With a slight jarring all the base material washed upward and completely through the filter material. Subsequently, the permeameter was repacked with 5.4 in. of filter material on top of a half-inch layer of fine base material. Under these conditions the hydraulic gradient was raised to three and no movement was observed. However, tapping on the side of the permeameter caused both materials to rise up about a half inch, and the fine base material washed completely through the filter material.

Failure in these two cases was due to the high seepage pressure which lifted the filter material. Failure by piping appeared to be a subsequent effect. Such uplifting would be prevented in normal under-drain installation by the weight of the surcharge.

Procedure for large permeameter tests

28. The procedure for testing with the large permeameter was as follows: one of several interchangeable disc bases was fitted into the permeameter (see Plate 2). Two of these discs were made of porous concrete, simulating the walls of pipe made of porous concrete. Two others were perforated wooden discs, simulating perforated clay and perforated concrete pipe. The annular space between the edge of the disc and the inside wall of the permeameter was calked tightly with cotton. With the disc fitted into the permeameter as a base, a given gradation of filter material was placed in the permeameter, oven-dry in some tests, under water in others. When the filter material was placed dry, the amount which passed through the disc during the loading was taken out and weighed. A downward flow of water through the permeameter was begun and continued for 15 or 20 minutes. It was observed that very little material would wash out after the first few minutes of flow. The weight of material which washed out by flow into the base of the permeameter was estimated. Then the permeameter was tapped 15 times with a rubber mallet. The total quantity of material washed out by flow and shaken out by tapping was collected, dried, and weighed.

Tests with large permeameter

29. The large permeameter was used principally to determine the limiting sizes of filter materials which would not pass through the openings in

the walls of porous or perforated pipe. Though the discs were not exact replicas of pipe walls, still it was possible in this way to determine very closely the sizes of filter materials which would not pass through commercial under-drain pipes which had walls of similar porous materials, or walls with the same size and number of perforations.

30. Porous pipe. The first base disc used with the large permeameter was made of stone chips and Portland cement, and was 8-3/8 in. diameter and 1 in. thick. This disc was supplied by the Walker Cement Products Company of Little Ferry, N. J., and it was intended that this disc should be similar to the walls of Walker Poroswall Rapid Drain Pipe, manufactured by this company. The coefficient of permeability of this disc was 4500×10^{-4} cm per sec. The different amounts of several sizes of uniform sand which would pass through this disc in 15 minutes of flow under a hydraulic gradient of two, and also with the same flow and tapping are given in the following tabulation:

Sand	Estimated Weight passing in 15 min of flow	Total Weight passing after flow and tapping
28-35 mesh	None	10 g
35-48 mesh	30 g	74 g
48-65 mesh	40 g	98 g

31. A disc 8-3/8 in. in diameter and 1-1/4 in. thick was supplied by the Smith Porous Drain Pipe Corporation of Pittsburgh, Pennsylvania, to represent the wall of their drain pipe which is made of slag and cement. The coefficient of permeability of this disc was 5500×10^{-4} cm per sec. The quantities of several sizes of sand which would pass through this disc

in 15 minutes of flow under a hydraulic gradient of two, and also with the same flow and tapping are given in the following tabulation:

Sand	Estimated Weight passing in 15 min of flow	Total Weight passing after flow and tapping
35-48 mesh	None	5 g
48-65 mesh	None	11 g
65-100 mesh	15 g	53 g
100-150 mesh	30 g	100 g

From these results it is apparent that these porous concrete pipes could be successfully used as underdrains in medium to fine sands without adding coarser filter material, provided that the pipe joints were tightly sealed.

32. Perforated pipe. Two wooden discs 8-3/8 in. in diameter were used to represent the walls of perforated pipe. One, 0.8 in. thick and containing twenty-five 3/8 in. diameter holes, represented perforated concrete pipe. The other, 0.6 in. thick and containing twelve 5/8-in. diameter holes, represented perforated clay pipe. The open area of the twenty-five 3/8 in. diameter holes was equivalent to the amount of open area in a 1-ft length of perforated concrete pipe. The open area of the twelve 5/8-in. diameter holes was equivalent to the amount of open area in a 4-in. length of perforated clay pipe. In the concrete pipe the perforations extend around less than half the periphery of the pipe, while in the clay pipe the perforations extend around its entire periphery.

33. Table 2 lists the amounts of filter material passing through the perforated discs, when placed oven-dry, washed through by flow, and shaken through when the permeameter was repeatedly tapped with a rubber mallet. Two filter materials, Nos. 18 and 21, were used, with the finer particles

successively removed. The grain size curve for material No. 21, a mixture of 80 per cent No. 18 and 20 per cent gravel from 1 to 3/8 in., is shown on Plate 13. The results of these tests indicate that a uniform material will wash out much more readily than a well-graded material of the same average size. It should, however, be borne in mind that the uniform material would be more pervious than a well-graded material of the same average size.

34. It was shown in the small permeameter tests that in order to prevent a fine sand from washing into a filter material the 15 per cent size of the filter material must be less than five times as large in diameter as the 85 per cent size of the fine sand. It has also been shown that a filter material chosen according to this criterion for a base material of fine sand is very susceptible to running or falling into a pipe with openings or perforations in the walls of 3/8 to 5/8 in. in diameter. It was desirable to know if a very well-graded filter material could be found to cover both conditions successfully. Hence, a filter mixture was made up in the laboratory with sizes from 1-1/2 in. gravel down to fine sands less than 0.25 mm in diameter (see Plate 14). While this artificial mixture might have been successful as a filter, the large particles which it contained did not prevent the smaller particles from running through the disc with 5/8-in. diameter holes. A total of 400 grams of this mixture passed through this disc when placed dry and then subjected to flow and tapping. A grain size curve for the material passing through is shown on Plate 14, along with the grain size curve for the original mixture. Though the 400 grams which passed through constituted only 4 per cent of the amount of material which went into the permeameter, still if 400 grams (approximately 1 lb) went into every foot of drain pipe, the clogging would be serious. It is, therefore,

TABLE 2

Weight of Material Passing through Perforated Discs

Discs	Filter Material	Passed when Loaded Oven-dry in grams	Washed out by Flow in grams	Washed out by Flow and Tapping in grams
Wooden disc simulating perforated concrete pipe Diameter 8-3/8 in. Thickness 0.8 in. Holes 25 Hole diameter 3/8 in.	No. 18 retained on			
	28 mesh	300	30	161
	20 mesh	75	25	156
	14 mesh	62	2	93
	10 mesh	101	1	36
	8 mesh	82	2	15
	6 mesh	42	0.5	12.5
	No. 21 retained on			
	28 mesh	56	1	18
	20 mesh	14	1	12
Wooden disc simulating perforated clay pipe Diameter 8-3/8 in. Thickness 0.6 in. Holes 12 Hole diameter 5/8 in.	No. 18 retained on			
	6 mesh	286	8	124
	4 mesh	248	2	33
	3 mesh	98	0.5	9.5
	No. 21 retained on			
	14 mesh	60	0.1	8

evident that while a well-graded material is less susceptible to washing out than is a uniform material of the same average size, still it is not possible to have a well-graded filter material which will not pass into a pipe which has large openings in the walls. The only adequate protection for a drain pipe having large openings would be two layers of different sizes of filter materials.

35. Finally, one test (No. 13) was performed in the large permeameter in which the direction of flow was from bottom to top. The filter material was No. 21, a mixture of 80 per cent of No. 18 and 20 per cent of gravel from 1 to 3/8 in. The wooden disc with 3/8-in. diameter holes was placed on top of this filter material. Flow under a hydraulic gradient of one was maintained for four hours; then it was raised to two for four hours; but under neither condition was any movement of the filter material observed. Manifestly, if the pipe has only one-half of its periphery perforated and is placed with the perforations on the underside, less material is likely to pass into the pipe than if the perforations are uppermost. Furthermore, only those perforations at the very bottom of the pipe would be subject to clogging by a deposition of silt inside the pipe.

III. FULL-SCALE TESTS IN OUTDOOR FLUME

Objectives

36. The original objective of this investigation was to obtain a filter material that would prevent the infiltration of fines into the filter and which in turn would not wash into and clog the drain pipe. However, it was found in preliminary tests (Part II) that it was impossible to obtain a filter material which would prevent the movement of fine base materials and yet not pass into a pipe which has large openings in the walls. As it was first considered essential that the filter prevent the movement of the fine base materials, the filter material used in the flume test to determine the comparative efficiency of various commercial pipes was selected as a material most likely to be readily available and at the same time be satisfactory for holding a fine base material. Consequently, in this test, all drain pipe was tested with only one layer of a single grade of filter material. The efficiency of the various drain pipes was not tested with multiple layer filters.

37. As the amount of material which would wash into various types of underdrain pipes cannot be determined exactly from small-scale laboratory measurements, a flume 36 ft long, 2 ft wide, and 4 ft deep was built out-of-doors. In this flume, standard lengths of 6-in. diameter underdrain pipes were tested under field conditions.

38. Information which was desired from these tests was as follows:

a. Amount of filter material which would wash into the pipe.

b. Hydraulic characteristics, or "n" value for each pipe.

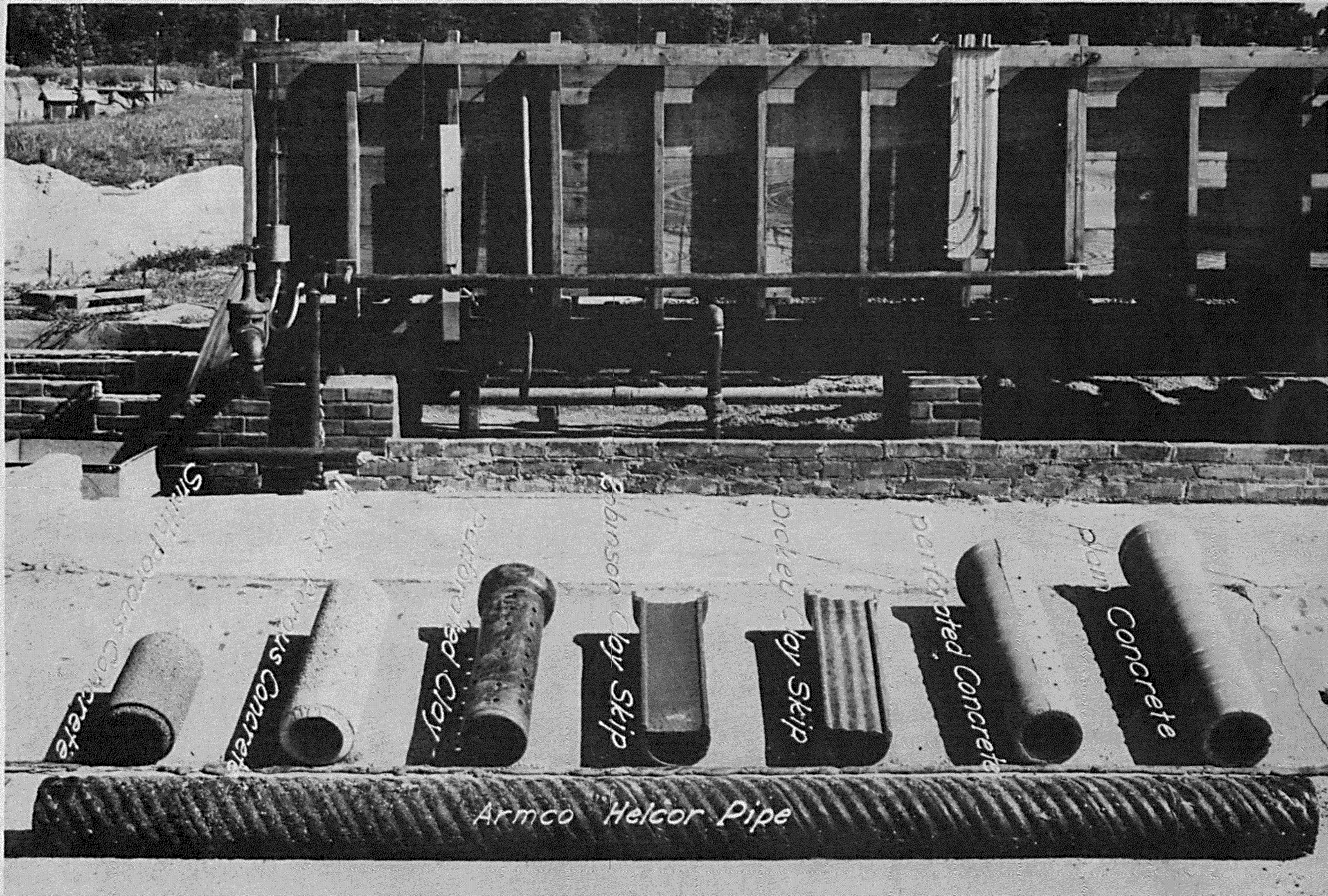
c. Quantity of water which would seep into the pipe covered with 12 in. of filter material; and the effect of 1/2 in. of fine sand on top of the filter material on reducing the flow.

Description of flume

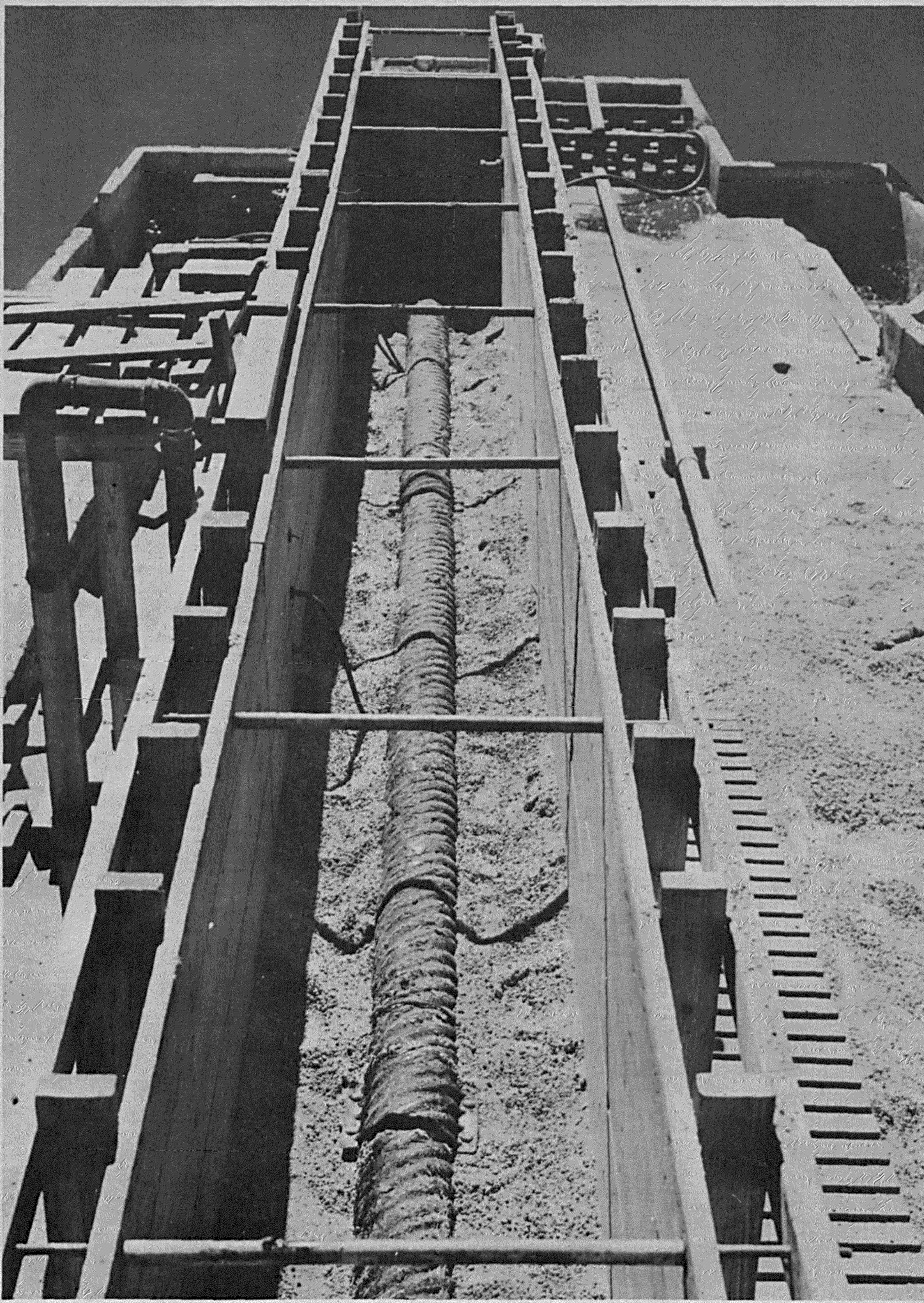
39. The outdoor flume (see Photographs 1 and 2) was a rectangular wooden box, divided into three compartments: forebay, 1-1/2 ft long; test section, 29-1/2 ft long; tailbay, 5 ft long. Water entered the forebay through a 3-in. diameter pipe, the entrance velocity being broken by a series of baffles. The quantity of water flowing was measured by a Venturi meter in the 3-in. supply line. Thirty feet of pipe was set to grade on wooden blocks in the test section. Calking was placed between the wooden bulkheads and the outside of the pipe. At 5 ft from the upper and lower bulkhead, holes were drilled into the underside of the pipe, and piezometers were attached to obtain the depth of water in the pipe. These piezometers were connected to manometer boards on the outside of the flume. The filter material was placed around and above the pipe until the pipe had a minimum cover of 12 in. of filter material. The filter material was level on top while the pipe was laid on a 1 per cent slope. A 2-in. pipe supplied water to the top of the filter material. In the tailbay a hopper caught all of the filter material washing out of the pipe. Another series of baffles intercepted the flow before it passed over a 90 degree V-notch weir. A hook gage gave the discharge head over the weir.

Types of pipes tested

40. The types of underdrain pipes which were tested in this investigation are given, with their manufacturers, in Table 3, and are shown in Photograph 1.



Photograph 1. Flume and types of pipe tested.



Photograph 2. Metal pipe set to grade in flume.

Filter material

41. The filter material selected for use in the flume was the coarsest sand and gravel possible which would hold fine base materials. This filter material was obtained by mixing a concrete sand (70 per cent) and a medium gravel (30 per cent). The concrete sand (previously referred to as material No. 9) was screened on a 30-mesh sieve before mixing with the medium gravel (previously referred to as material No. 10). A grain size curve of the resulting mixture is shown on Plate 15. It was intended that this mixture should be very similar to material No. 18 which had been retained on a 28-mesh sieve. The maximum dry density of this material when vibrated and tamped in the laboratory was 118 lbs per cu ft, and the density in its loosest condition was 104 lbs per cu ft.

42. The fine base material which was put into the flume on top of the filter material was material No. 14.

Test procedure

43. The general procedure for all flume tests was as follows: the pipe to be tested was installed to grade (1 per cent in all cases) by setting it on wooden blocks, and the piezometers were attached to holes on the underside of the pipe. Uniform flow was then established at various depths through the pipe from forebay to tailbay. The depth of flow in the pipe and the rate of discharge were observed, and the "n" value computed from the data obtained.

44. After measuring the rate of flow the flume was flooded again by inserting a plug in the lower end of the drain pipe, and additional filter material was placed under water over the top of the pipe. This filter

material was levelled off when 12 in. of filter material covered the pipe at its upper end. Because of the slope of the pipe there was a distance of 15-1/2 in. between the top of the pipe and the top of the filter material at the lower end of the flume. Then the depth of water on top of the filter material was increased to 12 in. by a flow from the 2-in. line which went to the top of the flume, and the plug was withdrawn from the lower end of the pipe. Water would flow rapidly down through the filter material into the pipe and out the tailbay. However, the 12-in. head of water on top of the filter could not be maintained, since the 2-in. line to the top of the flume could not supply water as fast as it was seeping out through the filter and drain pipe. The quantity of water seeping through the filter material and out the pipe was determined by the head on the V-notch weir at the end of the tailbay. The quantity of filter material washed into the pipe was collected in a hopper in the tailbay and was dried and weighed after each test. These filter flows were not continued for more than 20 minutes, since the 12-in. head was consumed within this period, and sometimes the pipe was already clogged up before this time had elapsed. It was found that the filter material subject to washing would move in a short time.

45. With water still standing in the flume over the top of the filter material, 1/2 in. of fine sand (material No. 14) was placed on top of the filter material. Since the filter material had been designed to carry this fine sand without piping, there was no loss of fine material. Inasmuch as this operation resulted only in a large reduction of the rate of infiltration and was not found to have any significant bearing on the performance of the pipes, it was not done except in one test.

Amount of material washing into pipe

46. It was originally planned to design a filter material, which would hold the base material and would not wash into the pipe, for each type of drain pipe. However, it soon became evident that there was no single filter material available which would fulfill both these criteria for pipe with the larger openings. Using a filter material, which based on laboratory tests was the coarsest possible without allowing the inwash of fines from the base material, field tests were performed to observe which types of drain pipes were most suitable for draining the selected filter material without the use of multiple layer filters. Measurements of the quantities of filter material which were washed into the various pipes were made according to the general procedure described in paragraph 44. These results are tabulated in Table 3; the quantity of filter material washed into the pipe during the 20 minutes of flow is expressed in lbs (dry wt) per ft for each type of pipe tested.

47. From the data shown in Table 3 it is seen that the porous concrete of both types and the perforated (1/4 to 3/8 in. holes) corrugated metal pipe covered with tar were most satisfactory in preventing the filter from washing into the pipe. It must be pointed out that in the tests with the corrugated metal pipe and the porous concrete, there are no unsealed joints at which the flow and inwash of filter material may concentrate.

48. The perforated (3/8 in. holes) concrete pipe with unsealed bell and spigot joints collected a considerable quantity of material. The least amount of filter material washed into the pipe was with the perforations down as was the case for the metal pipe. Inasmuch as the perforations in the corrugated metal pipe and the concrete pipe were approximately of the

TABLE 3

FILTER MATERIAL ALLOWED TO PASS BY VARIOUS TYPES OF DRAIN PIPES

Pipe	Manufacturer	Perforations or Slots			Filter Material washed in lbs/ft pipe
		Size	No./ft	Location	
Porous concrete, bevel joints, sections 2 ft long	Walker Cement Products Co. Little Ferry, New Jersey	—	—	—	0.01
Porous concrete, lap joints, sections 1 ft long	Smith Porous Drain Pipe Corp. Pittsburgh, Pennsylvania	—	—	—	0.03
Perforated corrugated metal pipe coated with tar, sections 10 ft long, split collar couplings (perforations around 1/3 periphery)	(Armco) by Dixie Culvert and Pipe Co., Memphis, Tenn.	3/8"*	40	Down	0.03
		3/8"*	40	Up	0.2
Perforated concrete pipe, unsealed bell and spigot joints, sections 2-1/2 ft long (perforations around 1/2 periphery)	Choctaw Culvert and Machinery Co., Memphis, Tenn.	3/8"	24	Down	1.3
		3/8"	24	Up	2.3
Perforated clay pipe, unsealed bell and spigot joints, sections 2 ft long (perforations around entire periphery)	W.S. Dickey Clay Manufacturing Co., Birmingham, Ala.	5/8"	30		3.7
Plain concrete pipe, unsealed bell and spigot joints, sections 3 ft long	Choctaw Culvert & Machinery Co. Memphis, Tenn.	—	—	—	7.5
Semicircular cradle invert clay (skip) pipe, 1/2 in. open slot on top, unsealed bell and spigot joint, sections 2 ft long.	W.S. Dickey Clay Manufacturing Co. Birmingham, Ala.	1/2"	—	Top	8.4
	Robinson Clay Product Co. Akron, Ohio	1/2"	—	Top	Test void**

NOTE: All joints were unsealed except in the case of the corrugated metal pipe; however, the bevel and lap joints of the porous concrete pipe were of such a degree of tightness that little or no inwash of fines occurred.

* Base size of holes in metal 3/8" but tar reduced effective size of perforations by approximately 50 per cent.

** An excessive amount of filter material washed into this pipe at one of the 1/2-in. joints which made the test void.

same size and spacing, the increase of material washed into the concrete pipe was attributed to its unsealed joints and to the fact that the tar and corrugations on the metal pipe tended to prevent wash of material along the pipe. However, it is believed that if the bell and spigot joints were sealed with mortar, the perforated concrete pipe would perform as satisfactorily in this material as the perforated metal.

49. The perforated clay pipe, with unsealed bell and spigot joints and large perforations (5/8 in.) extending completely around its periphery, allowed considerably more of the filter material to pass than the perforated metal and concrete pipes which had smaller perforations extending only around half the pipe. Even though the flow was not concentrated at the unsealed joints, it is believed that a considerable percentage of the filter material washed into the pipe at the joints.

50. The plain concrete pipe with unsealed bell and spigot joints was found to allow excessive quantities of filter material to pass. With this type of pipe all of the drainage flow is concentrated at the joints and this tendency toward excessive washing of the filter material is to be expected.

51. The clay skip pipe also allowed an excessive quantity of the filter material to pass. For this pipe, as in the plain concrete, the flow is completely concentrated at the bell and spigot joints which are designed to provide a gap around the bottom semicircumference and a slot (1/2 in. opening) across the flat top surface. These joints are considerably more open and inducive to the washing in of the filter material than are the joints of the plain concrete pipe.

52. It must be pointed out again that these tests were made with the one well-graded filter material (see paragraph 41) which was selected as the material most likely to be readily available and at the same time satisfactory for holding a finer base material. The pipes which were found to collect excessive quantities of this filter material, namely the clay skip pipe, plain concrete and the perforated clay pipe with joints open, could probably be used satisfactorily with a double or triple layer graded filter. Such a filter, however, should be designed according to the considerations presented in Part II of this report.

Tests to determine "n" values

53. During the course of the investigation, efforts were made to determine the hydraulic characteristics and "n" values for the various drain pipes. Inasmuch as the outdoor flume was not set up for a comprehensive study of "n" values, the results are not included in this report. However, in general, the "n" values determined were in reasonable agreement with the accepted values used today.

Tests to measure surface infiltration

54. The tests to determine the rate of surface infiltration of water were made by measuring the amount of water supplied to the surface of the filter material, and which then percolated down to the drain pipe. In these tests the quantity of water draining through the 12-in. filter into the 29.5-ft length of pipe varied from 0.30 to 0.40 cu ft per sec (135 to 180 gal per min) for the various types of pipe. The over-all coefficient of permeability of the filter and pipe, computed from these observed rates, ranged from 1000 to 2000 x 10^{-4} cm per sec. In general it was found that

none of the pipe tested, except whenever it would become clogged by the inwash of filter material, would limit or materially affect the over-all efficiency of the filter. To some extent, pipes with the larger openings would at first drain more rapidly than pipes with the smaller openings, but the larger openings permitted larger quantities of the filter material to wash into the pipe. Similarly, drainage into the perforated pipes was faster when the perforations were turned up than when the perforations were turned down; but, when the perforations were up, more material washed into the pipe and the permanence of this increased efficiency would be less certain.

55. The test with the 1/2-in. layer of fine sand added on top of the 12-in. filter was made with only one pipe. In this test the rate of infiltration was reduced from over 130 gal per min to approximately 2 gal per min. The thin layer of sand thus acted to impair the effectiveness of the filter and pipe.

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IV. CONCLUSIONS

Filter materials

56. From the laboratory study of the filter materials and also from the observation of their performance in the flume tests, the following conclusions are summarized:

- a. A fine material will not wash through a filter material if the 15 per cent size of the filter material is less than five times as large as the 85 per cent size of the fine base material.

- b. In addition to meeting the above size specification, the grain size curves for filter and base materials should be approximately parallel in order to minimize washing of the fine base material into the filter material.

- c. Filter materials should be packed densely in order to reduce the possibility of any change in the gradation due to movement of the fines.

- d. A filter material is no more likely to fail when flow is in an upward direction than otherwise, unless the seepage pressure becomes sufficient to cause flotation or a "quick" condition of the filter.

- e. A well-graded filter material is less susceptible to running through the drain pipe openings than a uniform material of the same average size. However, even a filter material having a wide range of gradation cannot be used successfully over a drain pipe having large openings, since enough fine particles to cause serious clogging will move out of the well-graded material into the pipe.

Underdrains

57. The tests on the rate of surface infiltration through the filter into the pipes indicated the following:

- a. The rate of infiltration through the filter bed was not materially limited or affected by any of the pipes tested as long as they did not become clogged.

b. Large openings in the drain pipe result in somewhat higher rate of infiltration but also increase the tendency for filter material to collect in and clog the pipe.

c. Drain pipes with perforations around only half or less of their circumference drain the filter more rapidly when the perforations are up, but less material will wash in when the perforations are down.

58. The tendencies for the filter material to wash into and clog the pipe are of primary importance in comparing the various commercial pipes. Tests performed to determine the amount of materials washed into underdrain pipes showed the following:

a. Perforated drain pipes having many small openings, preferably on the underside of the pipe only, and porous concrete pipes, are less subject to infiltration of small gravel and sand than other types of drain pipe. The smallest quantities of filter material were washed into the porous concrete, the perforated metal and the perforated concrete pipes. The quantity of material washed into the perforated clay with perforations all around the circumference was excessive.

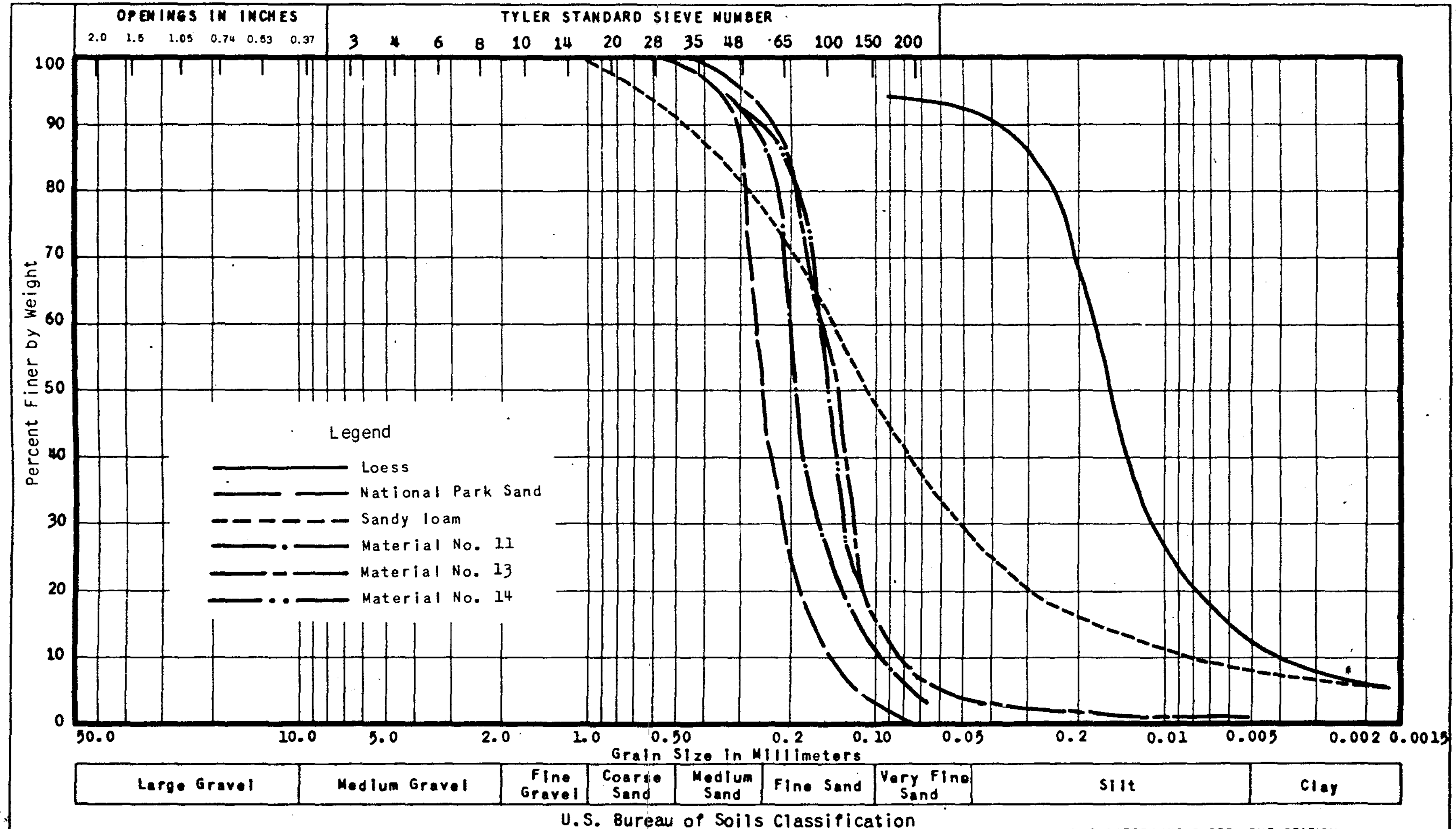
b. The perforated metal and perforated concrete pipe should be placed with perforations down.

c. In the tests of the plain concrete and the clay skip pipes, in both of which drainage was concentrated at the joints, serious quantities of the filter material washed into the pipe.

d. The porous concrete with bevel or lap joint, and the perforated concrete and clay with bell and spigot joint, should be placed with the joints tight and preferably sealed with mortar.

e. The porous concrete pipe will also drain without clogging in clean, medium-fine sands without other filter media, providing the joints are tight.

59. Where it is feasible to design and use a graded filter, consisting of several layers with coarse gravel near the openings of the pipe, pipes with the larger openings would probably operate satisfactorily.



U S WATERWAYS EXPERIMENT STATION
INVESTIGATION OF FILTER
REQUIREMENTS FOR UNDER DRAINS

GRAIN SIZE CURVES
FINE BASE MATERIALS

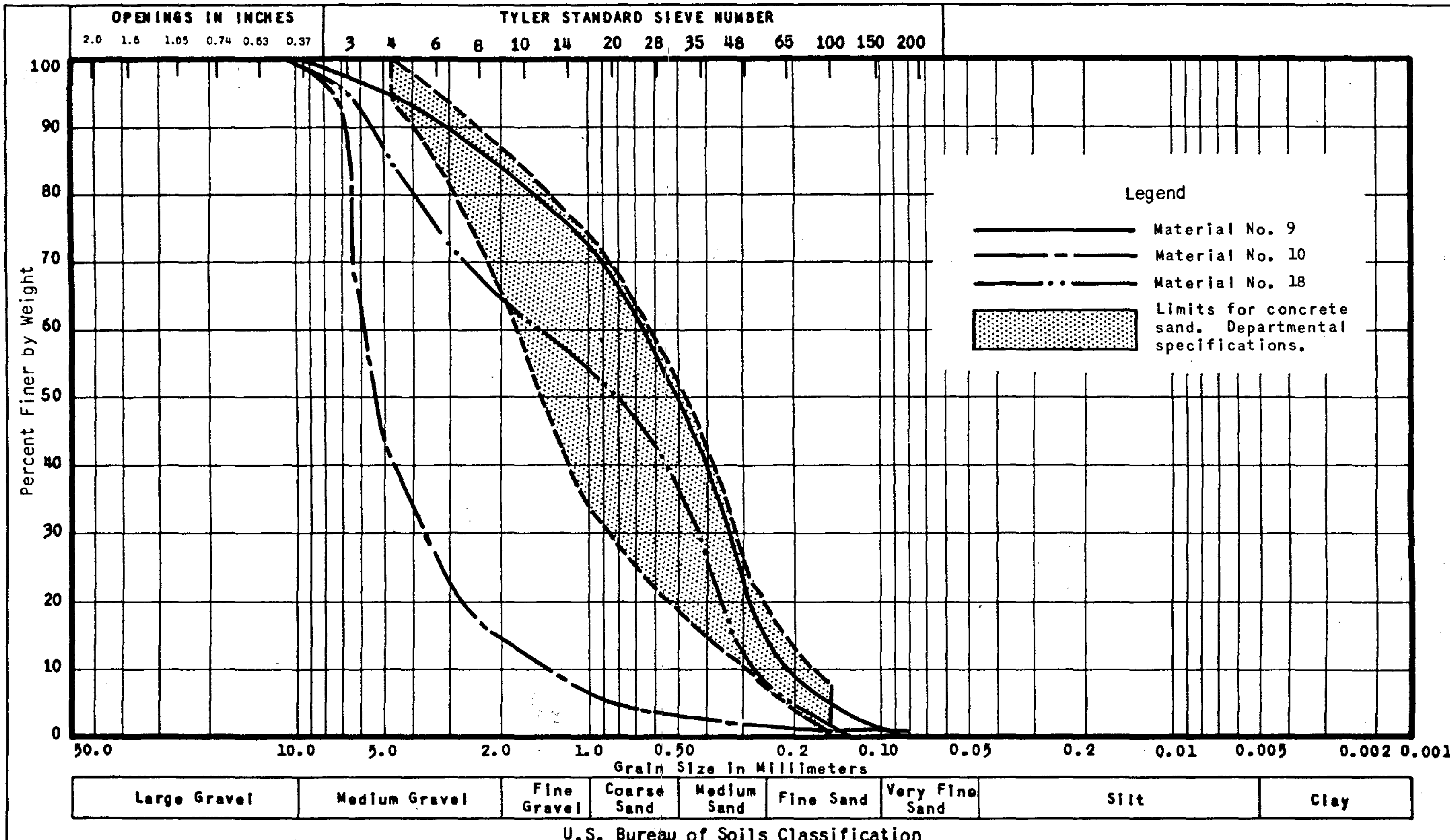
PREPARED BY J D W

PLATE 3

WAR DEPARTMENT

CORPS OF ENGINEERS, U.S. ARMY

PLATE 4



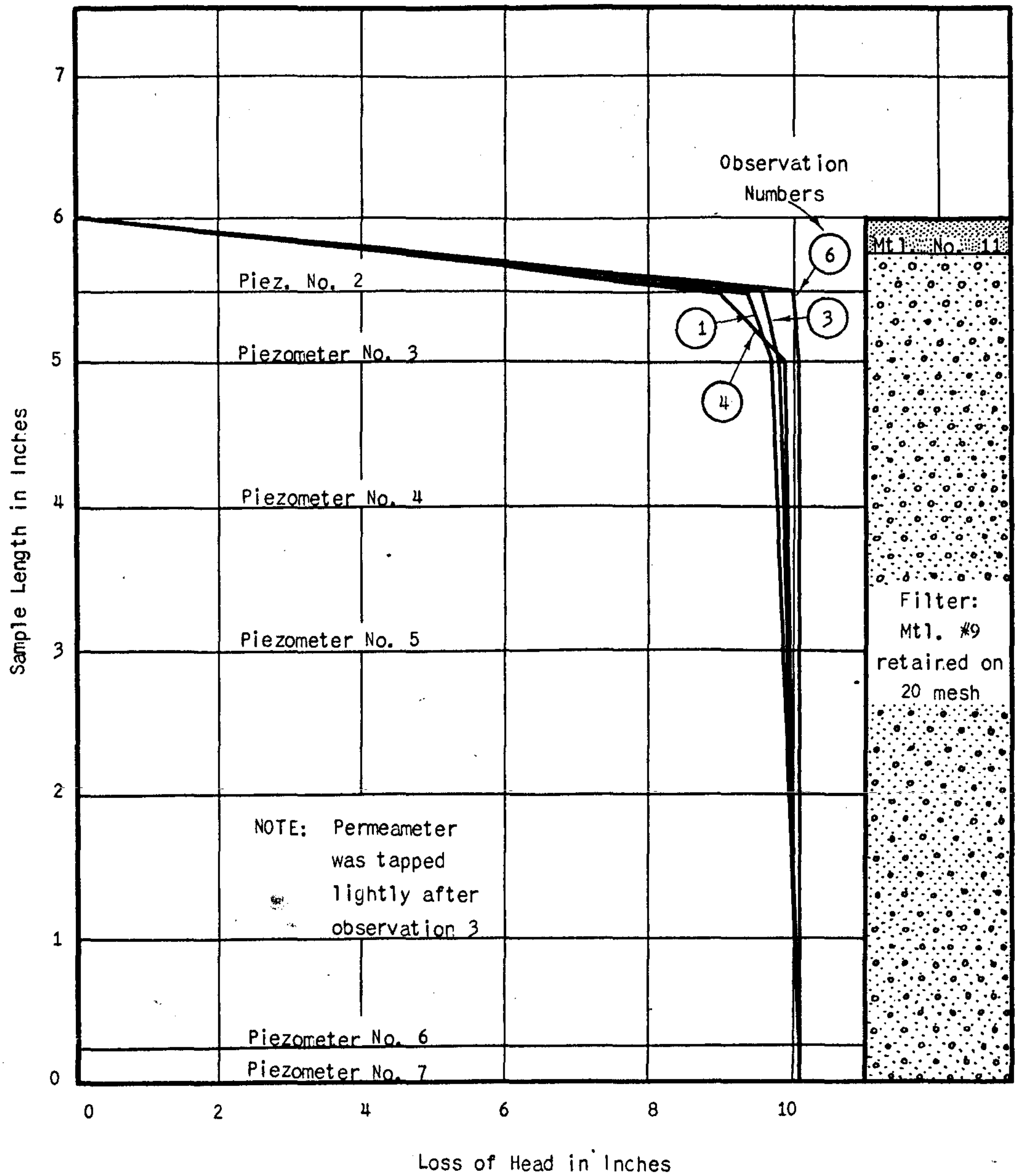
U. S. WATERWAYS EXPERIMENT STATION

INVESTIGATION OF FILTER REQUIREMENTS FOR UNDER DRAINS

GRAIN SIZE CURVES

FILTER MATERIALS

PREPARED BY J D W.

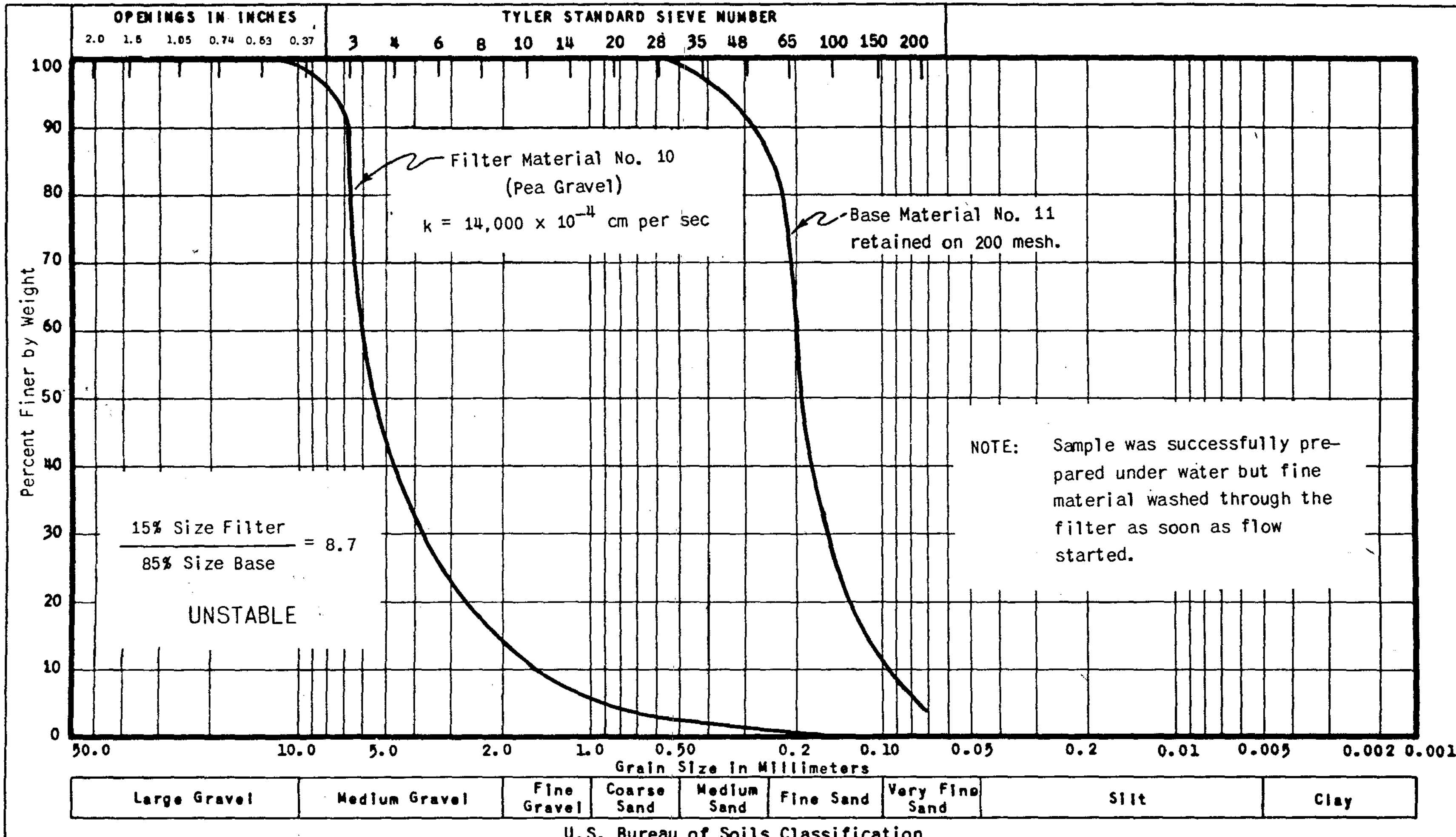


U. S. WATERWAYS EXPERIMENT STATION
INVESTIGATION OF FILTER
REQUIREMENTS FOR UNDER DRAINS

HEAD LOSS DIAGRAM

TEST NO. 4 SMALL PERMEAMETER

PREPARED BY J. D. W.

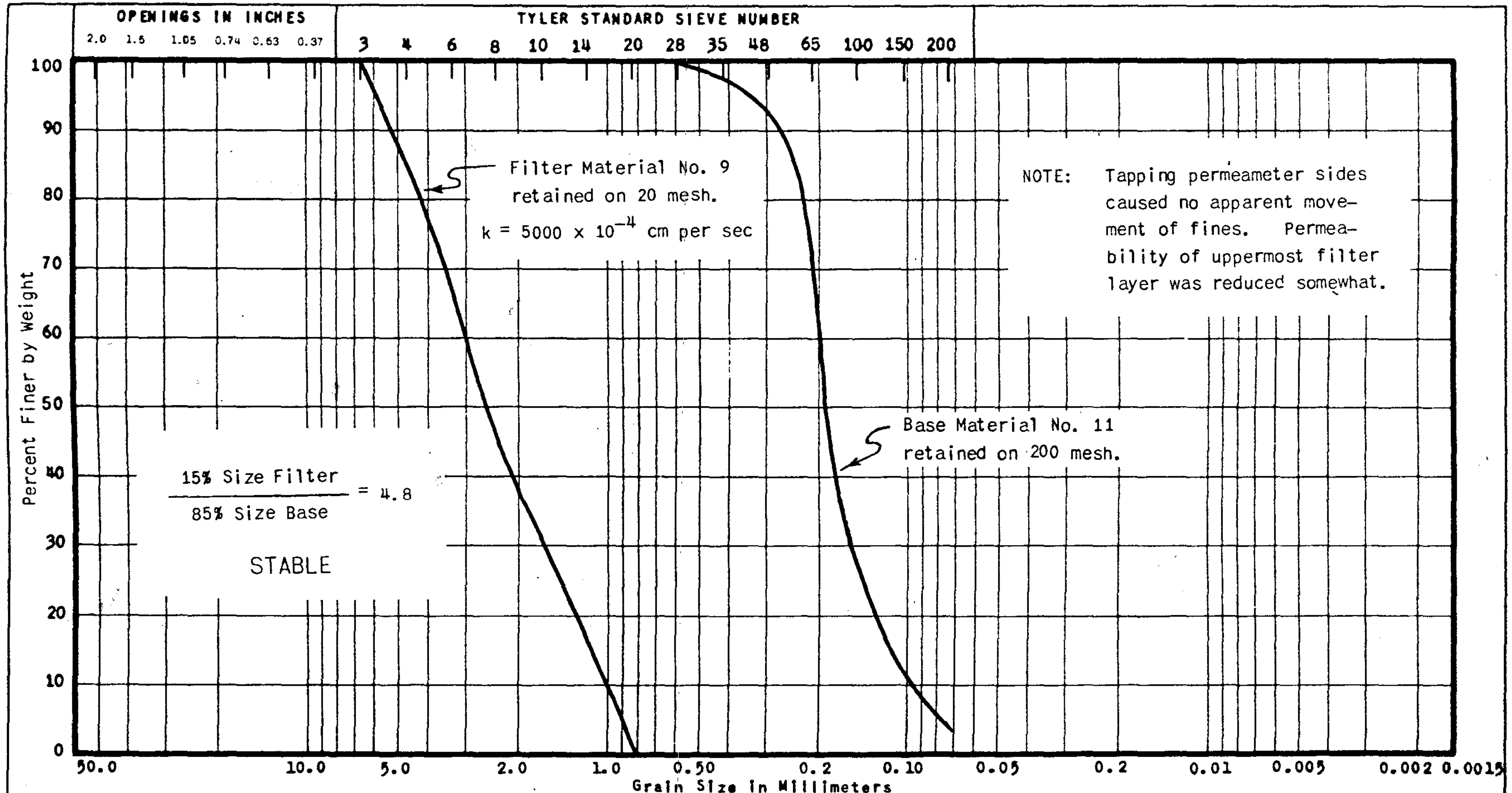


U. S. WATERWAYS EXPERIMENT STATION
INVESTIGATION OF FILTER
REQUIREMENTS FOR UNDER DRAINS

GRAIN SIZE CURVES

TEST NO.3B SMALL PERMEAMETER

PREPARED BY J D W



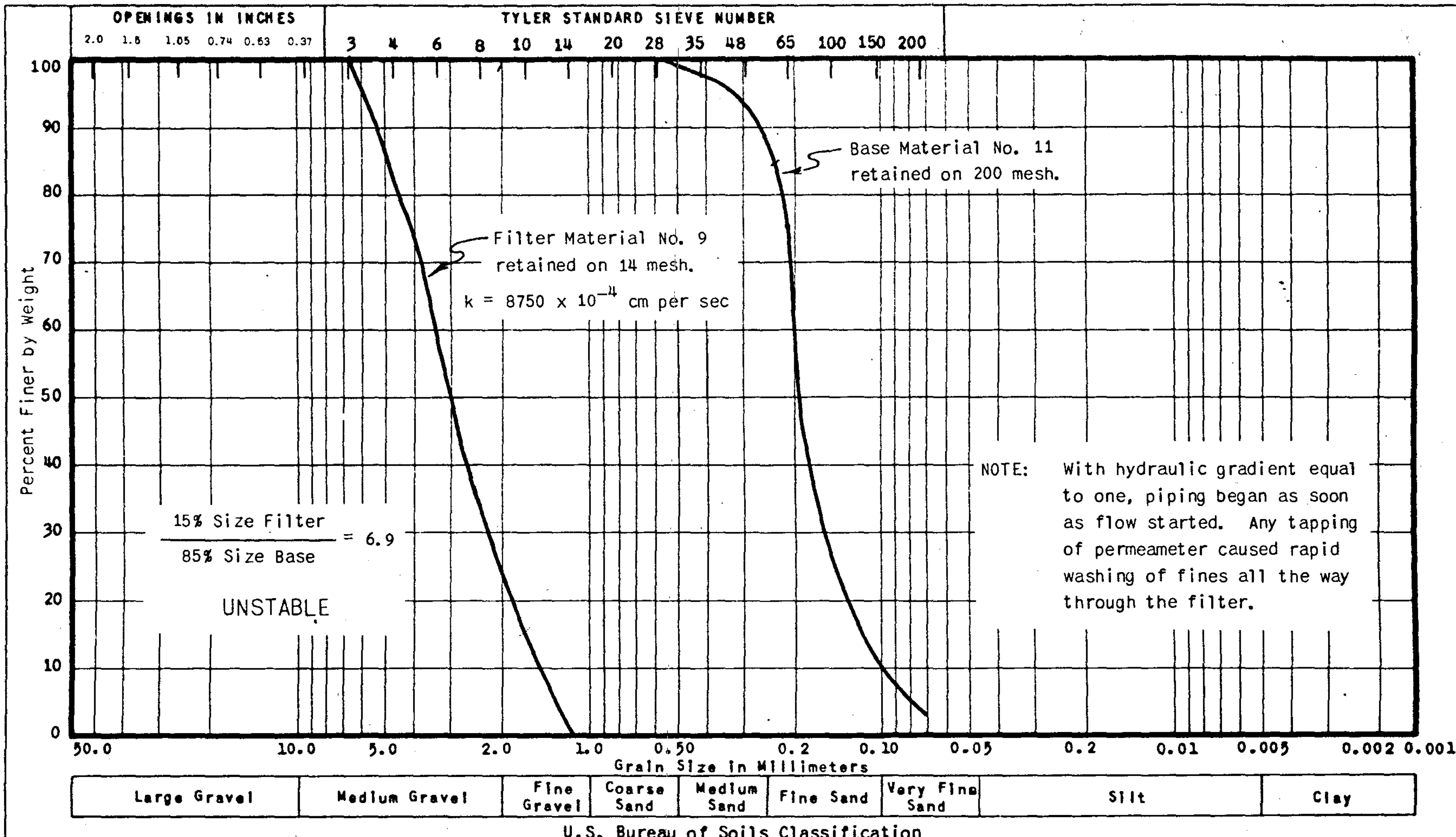
Large Gravel	Medium Gravel	Fine Gravel	Coarse Sand	Medium Sand	Fine Sand	Very Fine Sand	Silt	Clay

U.S. Bureau of Soils Classification

U. S. WATERWAYS EXPERIMENT STATION
INVESTIGATION OF FILTER
REQUIREMENTS FOR UNDER DRAINS
GRAIN SIZE CURVES
TEST NO. 4 SMALL PERMEAMETER
PREPARED BY J D W

WAR DEPARTMENT

CORPS OF ENGINEERS, U.S. ARMY

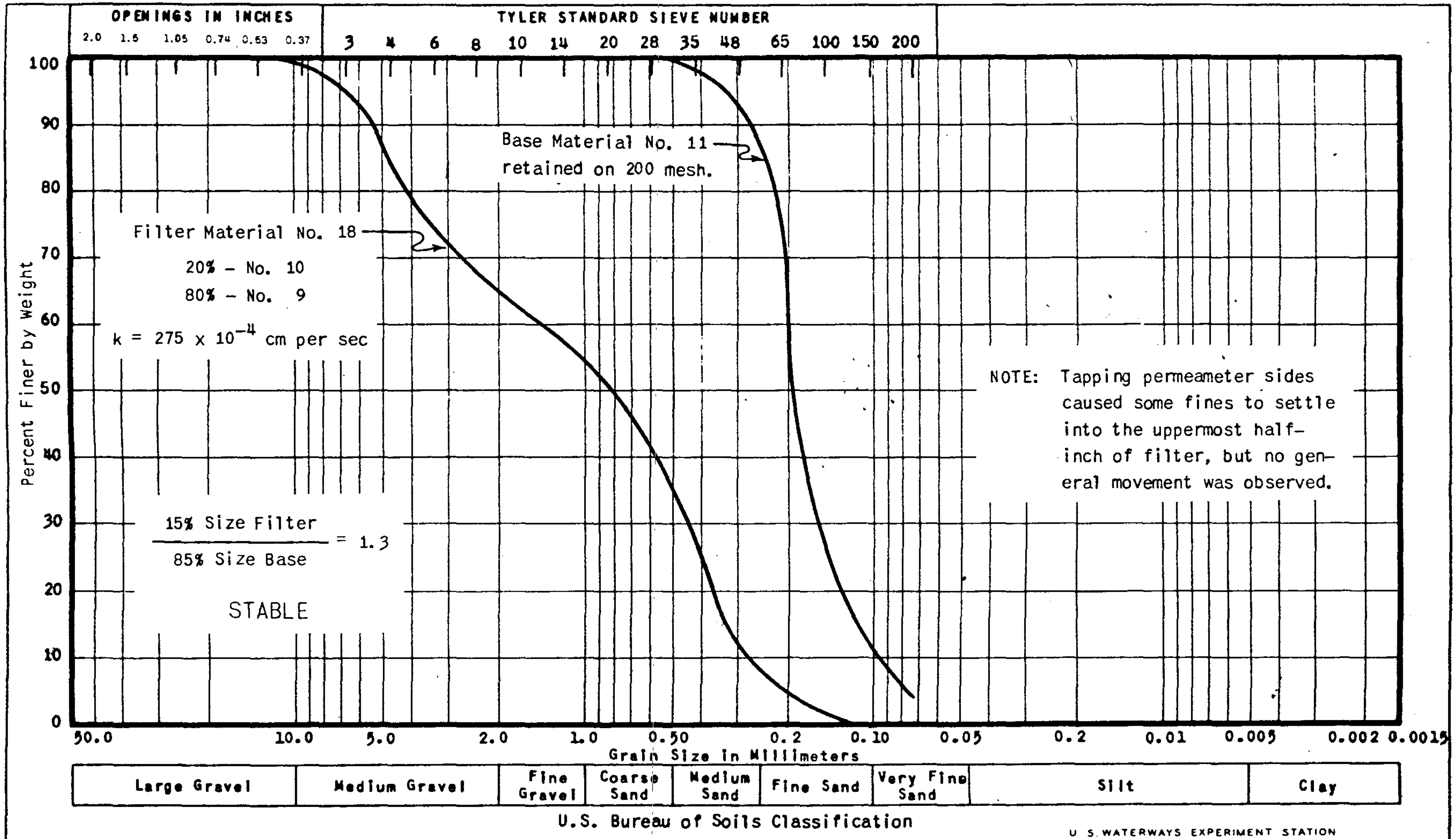


U S WATERWAYS EXPERIMENT STATION
INVESTIGATION OF FILTER
REQUIREMENTS FOR UNDER DRAINS

GRAIN SIZE CURVES

TEST NO. 6 SMALL PERMEAMETER

PREPARED BY J D W



U. S. WATERWAYS EXPERIMENT STATION
INVESTIGATION OF FILTER
REQUIREMENTS FOR UNDER DRAINS

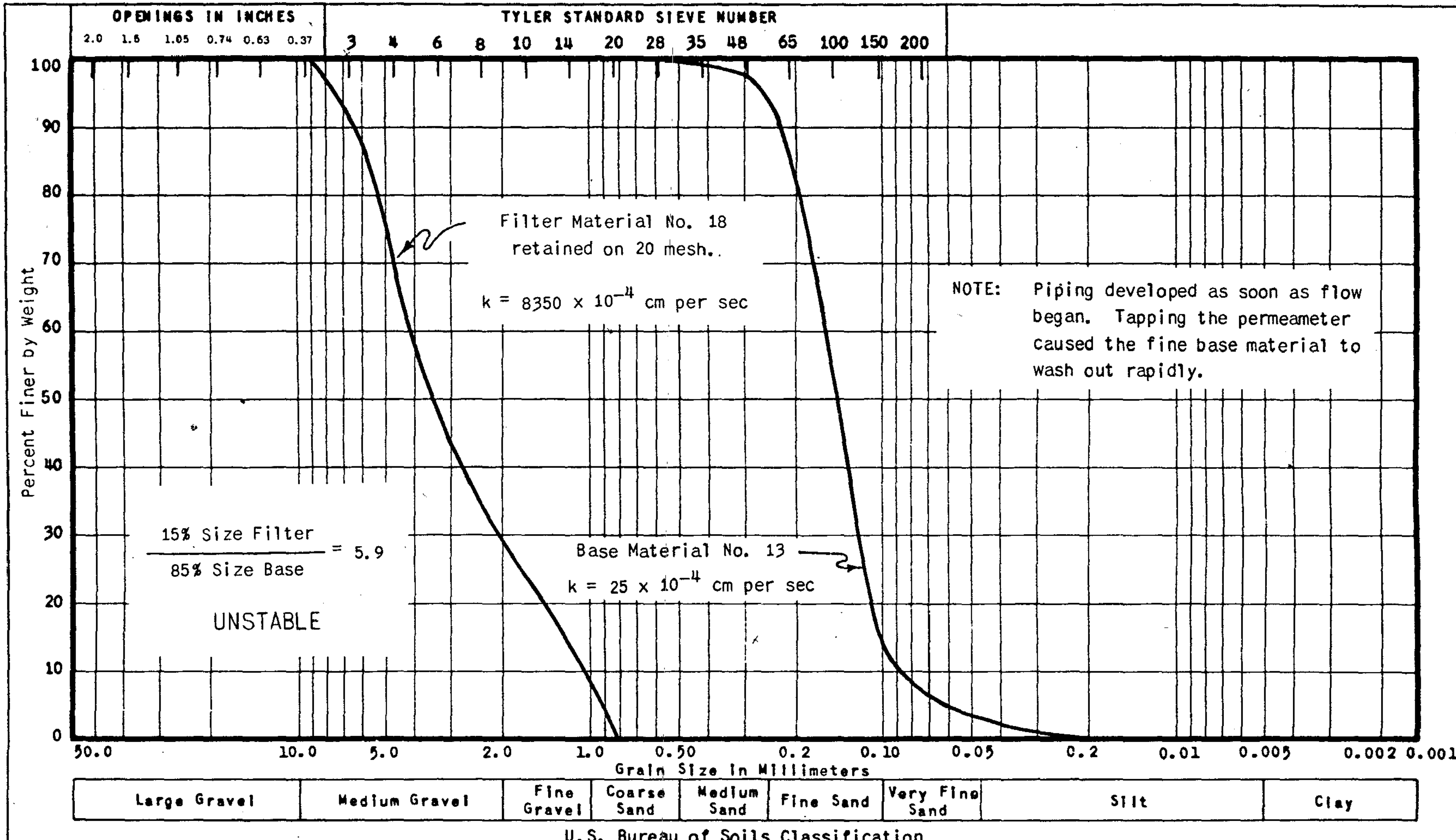
GRAIN SIZE CURVES
TEST NO. 5 SMALL PERMEAMETER

PREPARED BY J D W

PLATE 10

WAR DEPARTMENT

CORPS OF ENGINEERS, U.S. ARMY



U S WATERWAYS EXPERIMENT STATION
INVESTIGATION OF FILTER
REQUIREMENTS FOR UNDER DRAINS

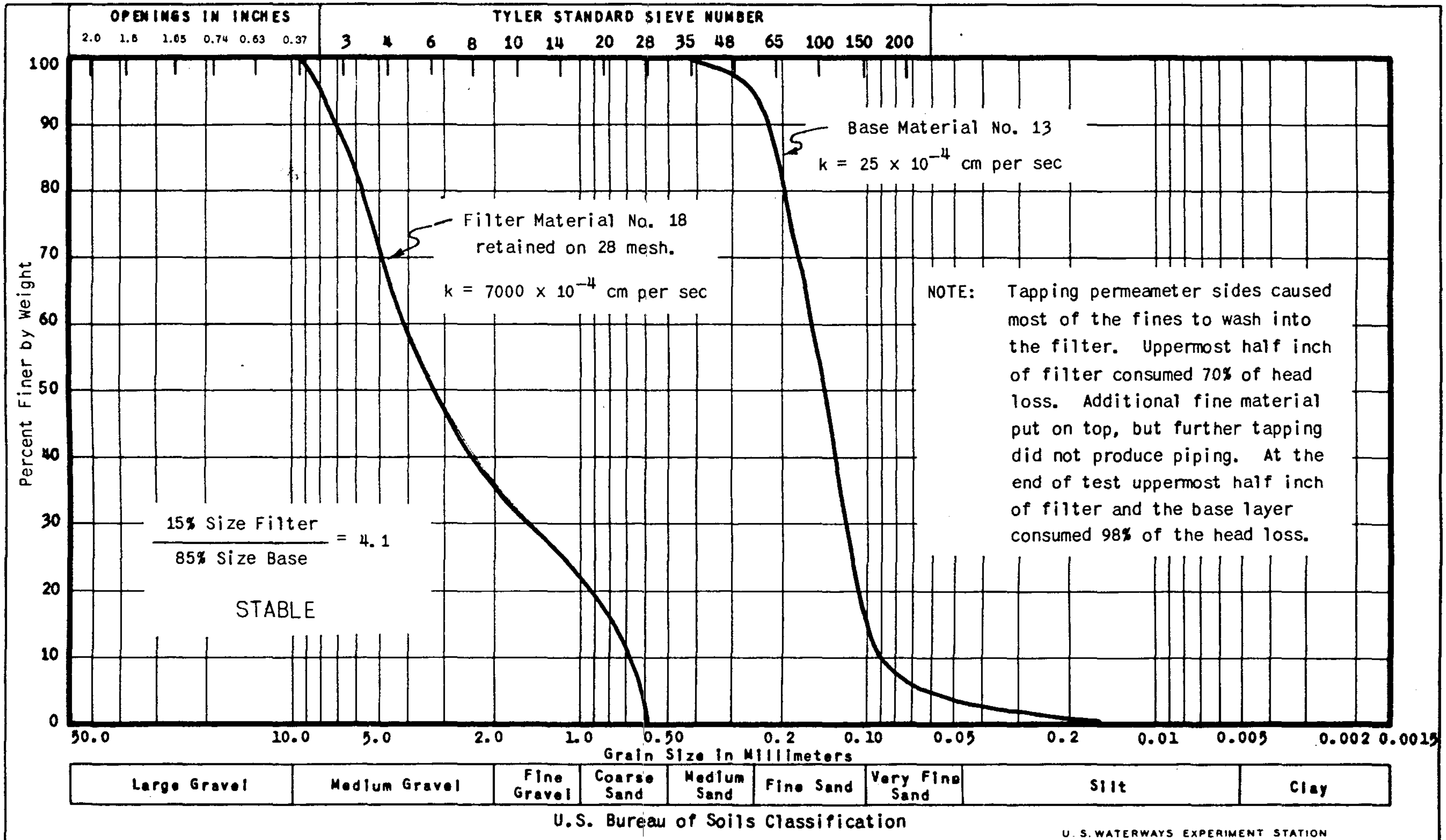
GRAIN SIZE CURVES

TEST NO. 8 SMALL PERMEAMETER

PREPARED BY J D W

WAR DEPARTMENT

CORPS OF ENGINEERS, U.S. ARMY



U. S. WATERWAYS EXPERIMENT STATION
INVESTIGATION OF FILTER
REQUIREMENTS FOR UNDER DRAINS

GRAIN SIZE CURVES

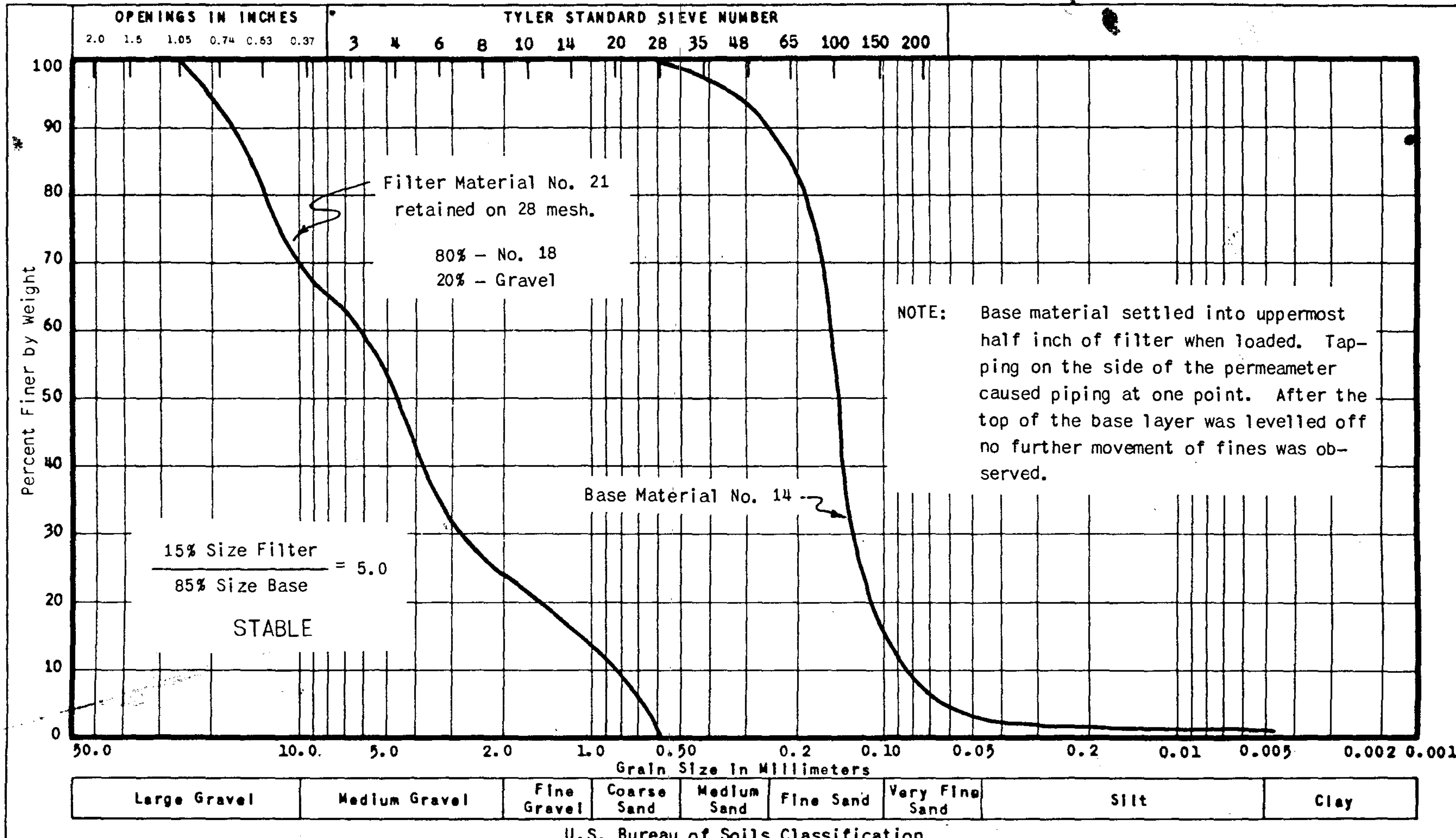
TEST NO. 15 SMALL PERMEAMETER

PREPARED BY J. D. W.

PLATE 11

WAR DEPARTMENT

CORPS OF ENGINEERS, U.S. ARMY



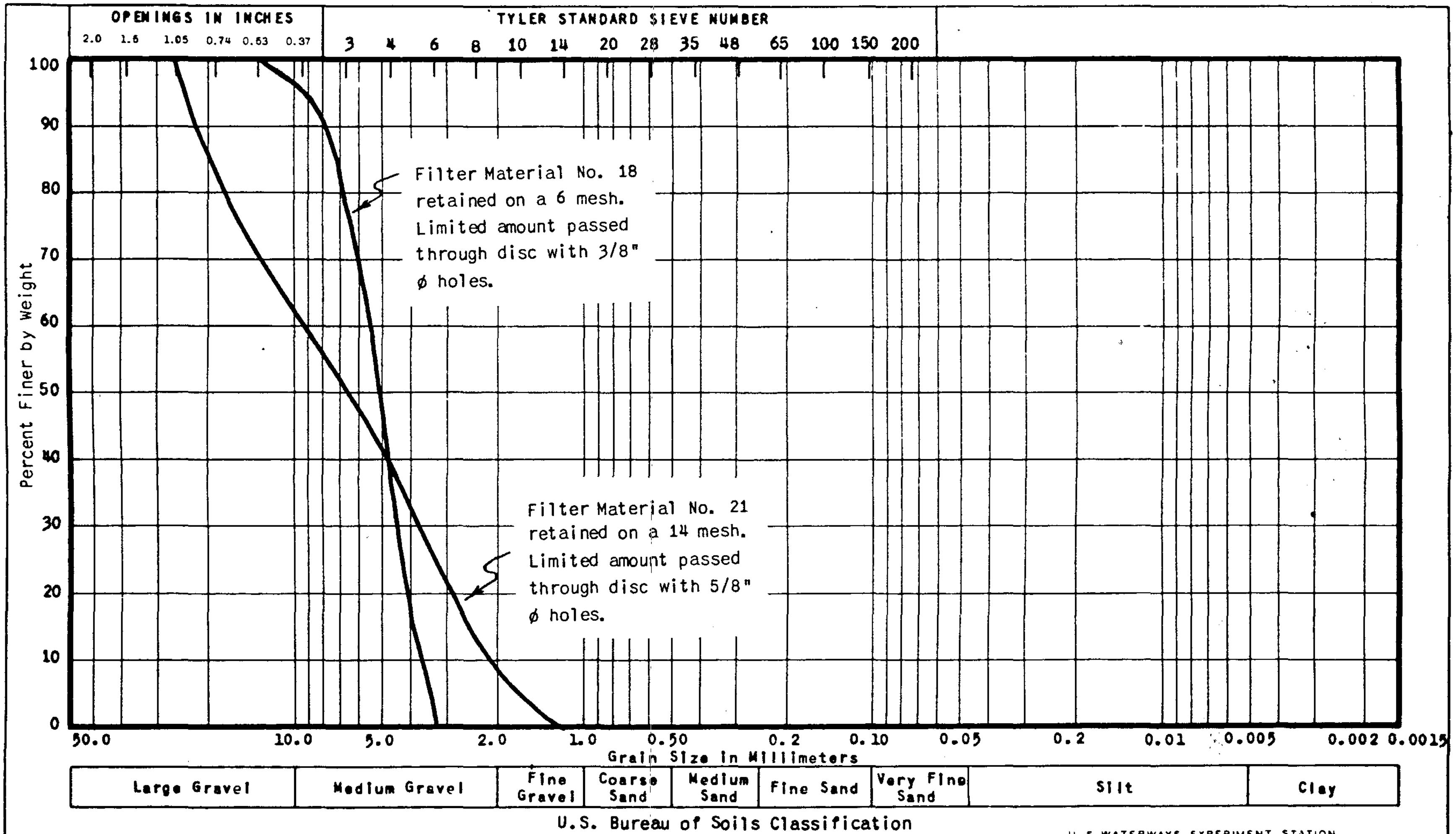
U. S. WATERWAYS EXPERIMENT STATION

INVESTIGATION OF FILTER REQUIREMENTS FOR UNDER DRAINS

GRAIN SIZE CURVES

TEST NO. 24 SMALL PERMEAMETER

PREPARED BY J D W



U. S. WATERWAYS EXPERIMENT STATION
INVESTIGATION OF FILTER
REQUIREMENTS FOR UNDER DRAINS

GRAIN SIZE CURVES

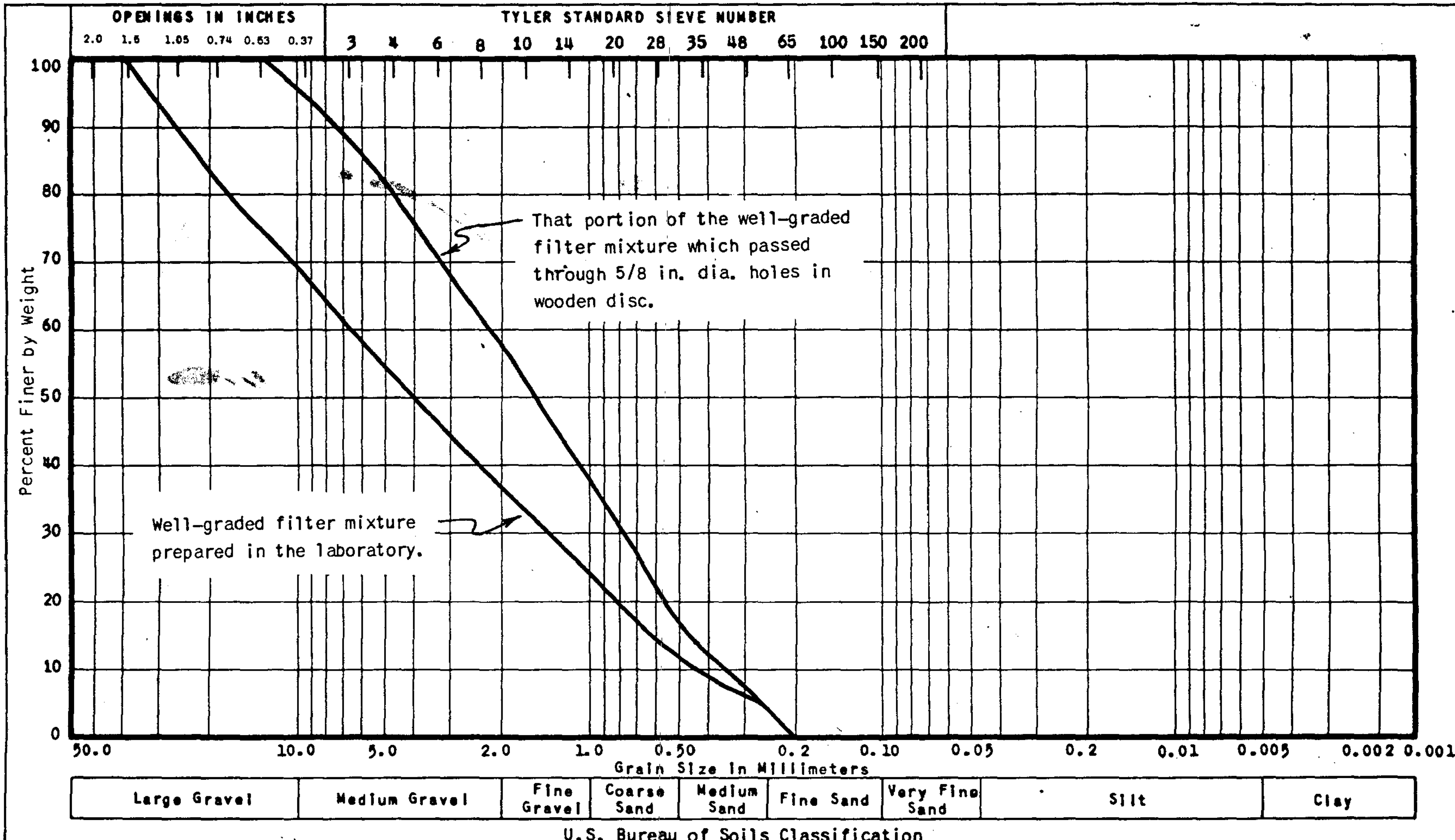
FILTER MATERIALS-PERFORATED DISCS

PREPARED BY J D W

PLATE 14

WAR DEPARTMENT

CORPS OF ENGINEERS, U.S. ARMY



U. S. WATERWAYS EXPERIMENT STATION

INVESTIGATION OF FILTER REQUIREMENTS FOR UNDER DRAINS

GRAIN SIZE CURVES

WELL GRADED-FILTER MIXTURE

PREPARED BY J D W

WAR DEPARTMENT

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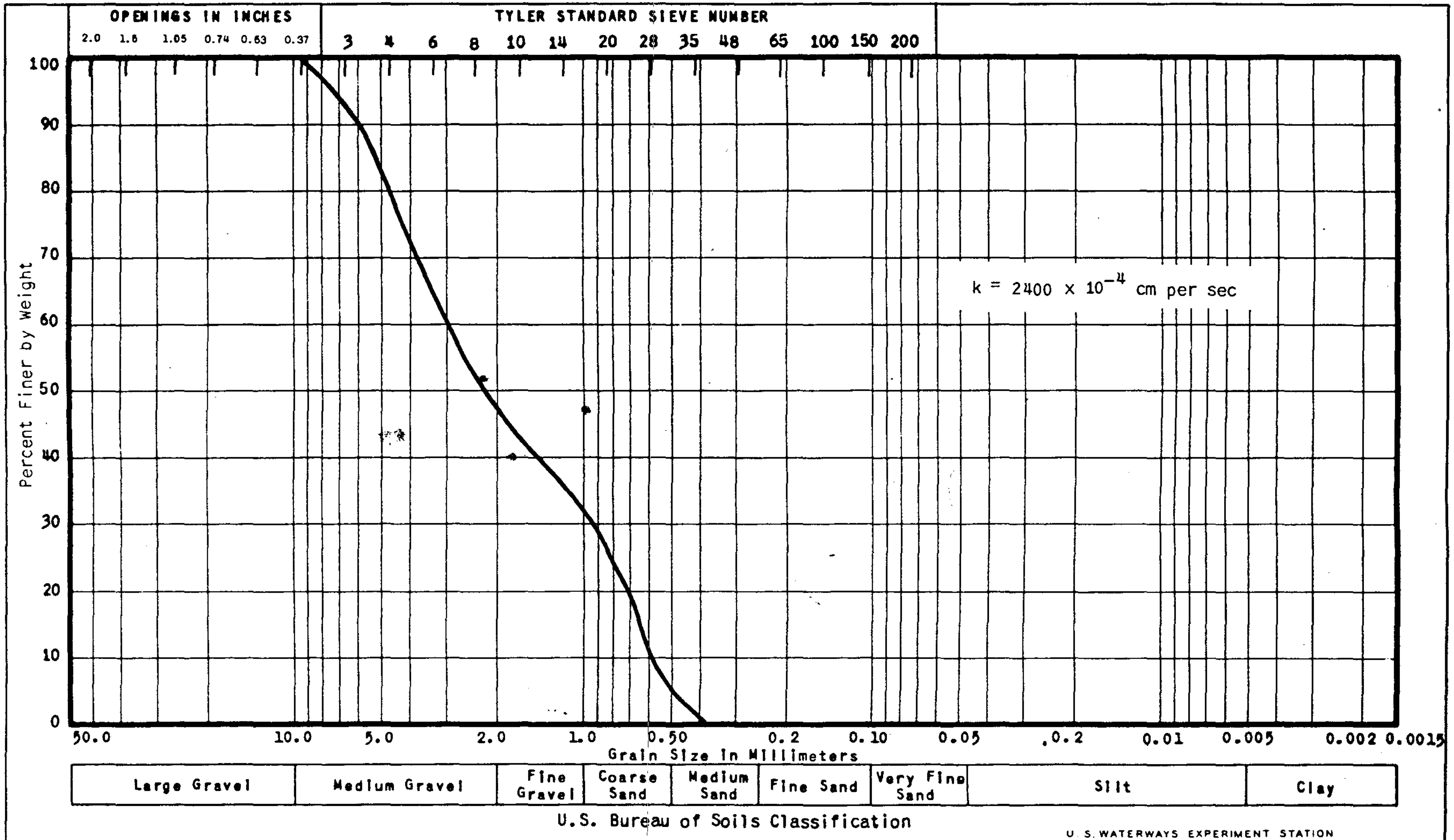

U. S. WATERWAYS EXPERIMENT STATION

INVESTIGATION OF FILTER REQUIREMENTS FOR UNDER DRAINS

GRAIN SIZE CURVES

FILTER MATERIAL-FLUME TESTS

PREPARED BY J. D. W.

PLATE 15